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Partitioning Planning Studies: Preliminary Evaluation of Metal and Radionuclide Partitioning in High-Temperature Thermal Treatment Systems

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PARTITIONING PLANNING STUDIES: PRELIMINARY EVALUATION OF METAL AND RADIONUCLIDE PARTITIONING IN HIGH-TEMPERATURE THERMAL TREATMENT SYSTEMS

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EXECUTIVE SUMMARY

A preliminary study of toxic metals and radionuclide partitioning during high-temperature processing of mixed waste has been conducted during Fiscal Year 1996 within the Environmental Management Technology Evaluation Project. The study included:

(a) identification of relevant partitioning mechanisms that cause feed material to be distributed between 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.

This preliminary study was conducted 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. This document presents the results and recommendations resulting from this study that may serve as an impetus for developing and implementing these predictive tools.

Metals, radionuclides, and inorganic material are not destroyed in thermal treatment systems but are partitioned into one or more solid, molten, or gaseous phases. Toxic metals and radionuclides must eventually be immobilized by the treatment process to meet transportation and disposal site acceptance criteria. High-temperature melter treatment systems are designed to immobilize the toxic metals and radionuclides in the glass-ceramic final waste form produced from the process. Repeated demonstrations have shown that the glass-ceramic waste forms from melter systems are generally very long-lived, durable, and non-leaching, whereas the secondary streams from the offgas control systems are generally particulate or aqueous streams that are less likely to meet acceptance criteria. The disadvantages of excessive partitioning to the offgas common to both melter systems and incineration systems include (a) a decreased ability to contain and account for toxic metals and radionuclides, (b) greater potential for fouling of the air pollution control system due to particulate accumulation, (c) increased volumes and masses of the secondary streams from the offgas system, (d) increased chance of criticality in the system due to undesirable partitioning and hold-up of plutonium in the offgas system, and (e) a less efficient overall waste volume reduction.

This preliminary study focused on process partitioning in high-temperature plasma arc and incineration systems anticipated as leading candidates for potential treatment of transuranic and low-level mixed waste. Tasks performed in the study were:

- Identification of the relevant mechanisms for partitioning of metals and radionuclides into solid, molten, and gaseous phases.
- A survey of thermal treatment system test facilities and projects that have been used or will be used to perform waste treatment tests or partitioning studies.
- A review and summary of experimental partitioning data and results from past and existing test programs for the most applicable treatment technologies to determine if data and results are sufficient to fully characterize elemental partitioning.

- A review of computer codes and existing modeling tools that have been or could be used to predict elemental partitioning in order to identify the effectiveness and deficiencies of these tools.

- Generation of conclusions and recommendations for a proposed study for improving experimental data acquisition and evaluation, as well as partitioning modeling, to enable prediction of toxic metal and radionuclide partitioning based on feed input characteristics, process design, and process operating conditions.

Evaluation of Treatment Systems and Partitioning Data

A survey of 91 melter and incinerator test systems and operating facilities was conducted to identify those systems that were used or might be used in the future to obtain partitioning data. The survey included identification of the typical operating conditions, presence or absence of radionuclides and metals during tests, availability of partitioning data, current system status, and extent of any operating experience. More detailed analysis of experimental data and partitioning results was then intentionally limited primarily to graphite electrode arc melters, plasma torch arc melters, and rotary kiln incinerators that have been identified in numerous studies to have the greatest applicability for treating heterogeneous mixed wastes.

The primary partitioning mechanisms in high-temperature treatment systems are temperature- and convection-dependent. These mechanisms include compound formation via chemical reaction, volatilization and condensation of volatile compounds, and particulate entrainment into the exiting offgas. The relative contribution of any mechanism depends on the properties of the input feed material, treatment system design, and operating conditions. Since the carry-over of toxic metals and radionuclides to the offgas system depends on both volatilization and entrainment, relatively non-volatile elements such as uranium, plutonium, and americium may still significantly and undesirably partition to the offgas as entrained particulate.

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. A survey of reported experimental data and results from 20 thermal treatment demonstration 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) to the offgas phase exiting 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.

- 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.

- Complete volatilization of an inorganic species occurs when its local partial pressure is less than the species vapor pressure. When partial pressure equals the species vapor pressure and the gas phase is saturated, no further volatilization occurs with increasing inorganic species in the feed although the amount of entrained material is the offgas will increase with feed rate. Elements where a large fraction of material volatilizes at low feed concentrations include arsenic, barium, chromium, and zinc.

- 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 were 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.

- 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.

- The presence of a layer of insulating unmelted feed (cold top) reduces the thermal radiation to the upper plenum and may reduce the amount of molten and volatilized material entrained in the offgas. However, the presence of a dry, dusty cold top may increase the amount of feed dust entrainment. Tests conducted in a graphite electrode arc melter were inconclusive in demonstrating a direct relationship between reduced offgas emissions and the presence of a cold top.

Evaluation of Partitioning Models and Codes

A variety of computational codes and databases calculate the thermodynamic equilibrium concentrations based on the minimization of Gibbs free energy for all specified reactions. The usefulness of any of these chemical equilibrium programs is dependent on the size and accuracy of the thermodynamic database in the desired temperature ranges. These programs are differentiated by their cost, level of documentation, user-friendliness, and the assumptions used in calculations. Most equilibrium calculations assume all constituents are in intimate contact with each other at uniform or average reaction conditions. Earlier models of an unsteady-state DC arc melter system and the steady-state operation of a glass-melter have used staged thermodynamic models to describe the different environments within a melter system in which constituents come in contact. This staged approach divides the melter into a series of theoretical unit operations, or stages, with unique conditions and feedstreams. ASPEN PLUS, a flow-sheet modeling program that performs process simulations of interconnected unit operations using basic engineering relationships such as mass and energy balances as well as phase and chemical equilibrium, has been used to model a melter system as a series stages at unique operating conditions with distinct feed streams entering each stage.

The PULSE code, developed at the Idaho National Engineering Laboratory (INEL) to model aerosol transport, offers a way to simulate partitioning phenomena in the vapor and particulate phases in a melter system. The model accounts for many of the phenomena that contribute to particulate entrainment including vapor condensation, particle formation, particle growth, particle agglomeration, and particle deposition. FIDAP is a general purpose finite element program for simulating fluid flow, heat transport, and mass transport that has been used at the INEL to predict the steady-state temperature, velocity, and current density profiles in the molten phase of a generic plasma arc melter.

A comprehensive model to predict metal partitioning in an incinerator that accounted for reactor thermal behavior (bulk and local temperatures), particle entrainment, metal reactions and vaporization, aerosol dynamics (condensation and coagulation), and particle capture exists and it has been used to model metals partitioning in a hazardous waste incinerator. Although the model was not validated due to insufficient data, it can provide useful qualitative information. A sensitivity analysis with the model indicated that the combustion chamber temperature and chlorine content in the waste feed were among the more important parameters affecting metal partitioning. Other parameters found to have a less significant effect on metal partitioning included the sulfur content of waste feed, gas residence time, entrained particle size distribution, local oxygen concentration, concentration of entrained particles, and gas cooling rate.

An integrated model that describes all relevant partitioning mechanisms in plasma arc melters has not been developed. Earlier melter models have not integrated a chemical equilibria model with a model code that describes vapor condensation, particle formation, particle growth, and particulate entrainment. An integrated model using ASPEN PLUS, PULSE, and FIDAP offers the potential of modeling all relevant partitioning mechanisms in a melter system in a nearly simultaneous fashion. ASPEN PLUS and PULSE are both written in FORTRAN which makes it possible to bring these codes together so that the partitioning mechanisms involving chemical reaction-thermodynamics and vapor condensation-particle distribution can be accounted for at the same time. A computational fluid dynamics code, such as FIDAP, can be used to identify temperature zones and the volumetric flow rates or fluid velocity within a melter system in the absence of experimental data. In addition, since ASPEN PLUS is well-suited to model typical unit operations in an air pollution control system; an integrated model may also simulate partitioning mechanisms in the melter-offgas handling system.

Recommendations

The ability to describe and predict elemental partitioning in a thermal treatment system can be valuable in optimizing operating conditions to achieve preferred elemental distribution; provide a cost-effective method for interpolating between experimental results of test conditions and for evaluating worst-case operating scenarios; serve as a tool in the design and scale-up of a thermal treatment system; and be used to demonstrate to process evaluators, stakeholders, and others that the partitioning mechanisms are understood and controllable within desired ranges. Recommendations made in the report are to:

- Develop an integrated partitioning model using ASPEN PLUS, PULSE, and FIDAP to describe all relevant partitioning mechanisms in a melter system in a nearly simultaneous fashion. ASPEN PLUS would be used to calculate thermodynamic equilibria in a melter system represented as a multistaged system; PULSE code would describe particle transport as well as particle formation and growth in the gas phase; and the FIDAP code would be used to approximate temperature and velocity profiles within the melter system to identify process parameters for each stage. In addition, since ASPEN PLUS is well-suited to model typical unit operations in an air pollution control system, extend the application of the integrated model to include partitioning in a melter-offgas handling system.

- Advocate the importance and necessity for detailed experimental data of input, output, and process conditions in new test programs not only to evaluate system performance (especially partitioning of feed materials) in terms of operating conditions but also to identify relevant partitioning mechanisms in order to predict future performance under untested conditions.

- Further evaluate published and raw experimental data from selected existing thermal treatment systems in order to better relate partitioning results to available process data as well as compare partitioning results from different test systems and treatment technologies.

- Perform process model sensitivity studies using chemical thermodynamic codes and databases to demonstrate the effect of key process parameters on the volatilities and distribution of toxic metals and radionuclides. The effects of different input feed compositions, allowable output products, and extremely high temperatures should be evaluated.

- Support development and demonstration of innovative in-furnace measurement technologies for measuring temperatures and compositions by participating in demonstrations of those technologies and encouraging implementation of these technologies in mixed waste treatment demonstration tests.

PARTITIONING PLANNING STUDIES: PRELIMINARY EVALUATION OF METAL AND RADIONUCLIDE PARTITIONING IN HIGH-TEMPERATURE THERMAL TREATMENT SYSTEMS

1. INTRODUCTION

Thermal treatment of hazardous, radioactive, and mixed waste converts organic material into combustion gases, destroys hazardous organics, and reduces the remaining waste volume and mass. Metals, radionuclides, and inorganic material are not destroyed but are distributed, or partitioned, into one or more solid, molten, or gaseous phases, depending on treatment process design and operating conditions. Since toxic metals and radionuclides cannot be destroyed, they need to be adequately immobilized into final waste forms that can meet transportation and disposal requirements. If toxic metals and radionuclides partition to a vitrified slag final waste form typical for plasma arc melters, then they are effectively immobilized and can meet or surpass expected requirements. If these species partition significantly to the offgas as volatilized or entrained materials, then these materials must be efficiently controlled in an offgas system and removed from the offgas; the offgas system secondary wastes may be more hazardous than the original waste and require more stringent and costly containment, handling, and treatment prior to final disposal; and, there is greater potential for increased criticality concerns and fouling from particulate deposits in the offgas system.

The primary process partitioning mechanisms include chemical reactions, vaporization and condensation of volatile compounds, and particulate entrainment. The distribution of elements between phases is a function of the process design, waste feed properties, and operating conditions. The partitioning of toxic metals and radionuclides can be significantly influenced by the properties of heterogeneous mixed waste (composition, levels of contamination, particle size, etc.) which can vary widely within individual waste containers and between different waste streams as well as the system configuration and operating conditions. Knowledge and control of toxic metals and radionuclide partitioning in different potential mixed waste treatment processes are important technology development, evaluation, and licensing issues.

Test programs can experimentally investigate the effects of different process designs, feed mixtures, and operating conditions on total mass distribution and elemental partitioning. Such testing, while providing important real-world data, cannot hope to evaluate all likely test permutations given normal cost and time constraints. The necessary test data can also be difficult or impossible to obtain with existing diagnostic, sampling, and analysis technologies. While there have been a number of thermal treatment system evaluation and demonstration test programs conducted for mixed waste treatment, experimental partitioning data obtained has generally been insufficient to confidently and completely describe elemental partitioning under different possible system design and operating conditions. Empirical or theoretical models can be useful to estimate the elemental or species partitioning under untested conditions. However, to date such modeling has not been emphasized due to the potential complexity of models that could adequately account for the possible partitioning mechanisms as well as the lack of experimental data, such as operating temperature and composition ranges in all phases, to validate the models.

To date, there have been no significant attempts to evaluate relationships between process conditions and partitioning data from prior and current demonstration tests. This lack of evaluation has been due, in part, to a lack of funding to specifically look at results across various tests, to sporadic process data obtained from most tests, a focus of prior tests on demonstrating simple operation of technologies in terms of one or two key process results without the detailed measurements necessary to understand the entire process, and, in some cases, inadequate diagnostic and measurement technologies. A preliminary study to evaluate the state of knowledge about toxic metals and radionuclide partitioning during high-temperature mixed waste treatment has been conducted during Fiscal Year 1996. This study was conducted within the Environmental Management Technology Evaluation Project. The study included evaluations of mechanisms that cause and control feed material partitioning between different treatment system effluents, existing test data from applicable demonstration test programs, and theoretical or empirical partitioning models.

This preliminary study was conducted to provide sufficient information to define a more complete and detailed technical program that would eventually enable the prediction of toxic metals and radionuclide partitioning in the most applicable mixed waste thermal treatment processes using experimental data and models. This document presents the results of the preliminary study, conclusions, and recommendations for the more detailed technical program for predicting toxic metal and radionuclide partitioning.

1.1 Need for Accurate Experimental Data

Accurate experimental data are required in order to correlate the effect of system variables on partitioning between phases exiting and remaining in a thermal treatment system. The mass (or mass flow rate), composition, and other characterization data for each phase entering, exiting, or remaining in a thermal treatment system are necessary to conduct material balances. Most of the partitioning mechanisms are known to be a function of temperature; therefore, accurate measurement of local and average temperatures in the gas and molten phases is important to confirm the presence or absence of temperature gradients and the effect of temperature on process results. Measurement of local and average gas velocities is necessary if it is suspected that gas velocities significantly affect entrainment of solid and condensed vapor particulates in the exiting offgas.

Mass, elemental, and species analysis data are important in conducting a material balance to account for all material fed into the system. The ability to achieve complete or near-complete closure on the system and to characterize the species make-up of the input and effluent streams confirms or provides insight as to the nature and extent of elemental partitioning to each phase as well as reflects favorably on the applicability and accuracy of the sampling and analysis methods used. In addition, experimental data are useful as model input as well as a means for evaluating the accuracy of model results. Finally, the ability to achieve near-complete mass closure on key elements throughout the system assures process designers, operators, and stakeholders that the process conditions and partitioning mechanisms are adequately understood to account for nearly all material passing through the system.

1.2 Need for Process Models

The primary partitioning mechanisms expected in a thermal treatment system are chemical reactions, species volatilization and condensation, and particulate entrainment. These mechanisms, in turn, are functions of temperature, fluid mixing, and turbulence. Models that can accurately describe these partitioning mechanisms or the process variables that effect the mechanisms can be useful in estimating elemental partitioning as a function of operating and waste feed conditions. Partitioning data under actual operating conditions are desirable to confirm the accuracy of model results and the validity of model assumptions. In the absence of such data, process models may still provide insight about the most significant partitioning mechanisms under certain conditions and estimate elemental partitioning that might occur under typical and atypical process conditions. Process models may be able to:

- Provide estimates of operating conditions such as temperature and temperature gradients that are difficult to obtain experimentally but that may have a large impact on partitioning.

- Enable interpretation of experimental results using theoretical relationships to relate partitioning results to partitioning mechanisms.

- Serve as a tool for scaling up treatment system designs.

- Identify design requirements for the downstream offgas system.

- Provide a basis for optimizing process conditions to minimize undesired partitioning to the offgas system.

- Provide a safer and more efficient means of investigating worst-case scenarios.

1.3 Study Objectives

This study was conducted to:

- Evaluate the state of knowledge about toxic metals and radionuclide partitioning in high-temperature treatment systems.

- Provide sufficient information to define a more complete and detailed technical program that may enable the prediction of toxic metals and radionuclide partitioning in the most applicable mixed waste thermal treatment processes using experimental data and models.

1.4 Tasks

This study was implemented with two main tasks and several subtasks. The tasks were:

- A review of existing experimental partitioning data from earlier tests. Subtasks included:

(a) identification of the relevant partitioning mechanisms and data needed to describe the effects of these mechanisms on partitioning under different conditions;

(b) a survey of thermal treatment test programs in which partitioning has been evaluated;

(c) a summary of measured partitioning results that occurred under specific test conditions, including indication of the usefulness and deficiencies of the experimental data for determining partitioning; and,

(d) identification of conditions under which partitioning has not been adequately determined using past experimental data.

- A review of computer codes and existing models that describe one or more partitioning mechanisms in order to identify the effectiveness and deficiencies of these models in predicting partitioning.

2. REVIEW OF THERMAL TREATMENT SYSTEMS

High-temperature thermal treatment systems considered in this study include melters and incinerators. Melters are generally considered high-temperature systems designed to melt, vitrify, or slag noncombustible material. Incineration of combustible material can also take place in an appropriately designed melter. Melter designs are further characterized by the mode and location of energy input into the system. Incinerators are generally designed for full oxidation of organic materials, including destruction of hazardous organics, while producing fully oxidized combustion gases and either a slagged or non-slagged bottom ash of the non-combustible material. In both melter and incinerator systems, feed material may volatilize or become entrained in the offgas.

The melter or incinerator is usually part of an integrated waste treatment system, as shown in Figure 2-1, which may also include input waste processing, a secondary combustion chamber, an offgas system, as well as final and secondary waste processing. The secondary combustion chamber is designed to fully oxidize organic material and the offgas system is designed to capture or neutralize toxic or radioactive volatile and particulate material that may pose a threat to the community and the environment. The offgas control system, as well as final and secondary waste processing, must meet the necessary design, operating and disposal requirements.

This study focuses on metal and radionuclide partitioning to each phase exiting or remaining in the primary thermal treatment system. A survey of 91 melter and incinerator test systems and operating facilities was conducted to identify those systems that were used or might be used in the future to obtain elemental partitioning data. Key information concerning these test programs and facilities is presented in Appendix A and includes system location, typical operating conditions, the presence or absence of metals and radionuclides during tests, the availability of partitioning data, the current system status, and the extent of any operating experience.

2.1 Melters

Melters used in mixed waste treatment demonstrations or facilities have been categorized according to the mode and location of energy input into the system.

2.1.1 Graphite electrode melter[1,2]

These furnaces use electrical energy transferred from graphite electrodes and converted to thermal energy in plasma arc or joule (resistance) heating regions to heat, volatilize, and melt feed material in a molten bath. The electrodes may be submerged in the molten bath or be positioned above the waste to create a high-temperature plasma region, similar in temperatures to the plasma regions in plasma torch systems but without the forced gas flow. When the electrodes touch or are submerged in the molten bath, the high-temperature plasma arc region is smaller, there is more direct contact and a greater chance of chemical reactions between the electrodes and the melt, and increased joule heating of the melt. Different process configurations have been developed that use direct current (DC) or alternating current (AC). One or more top electrodes and none, one, or more bottom or ground electrodes are used in DC designs, while the predominant AC design uses three electrodes in a triangular configuration. Fourteen graphite electrode arc melter testing or production facilities are listed in Table A-1 in Appendix A.

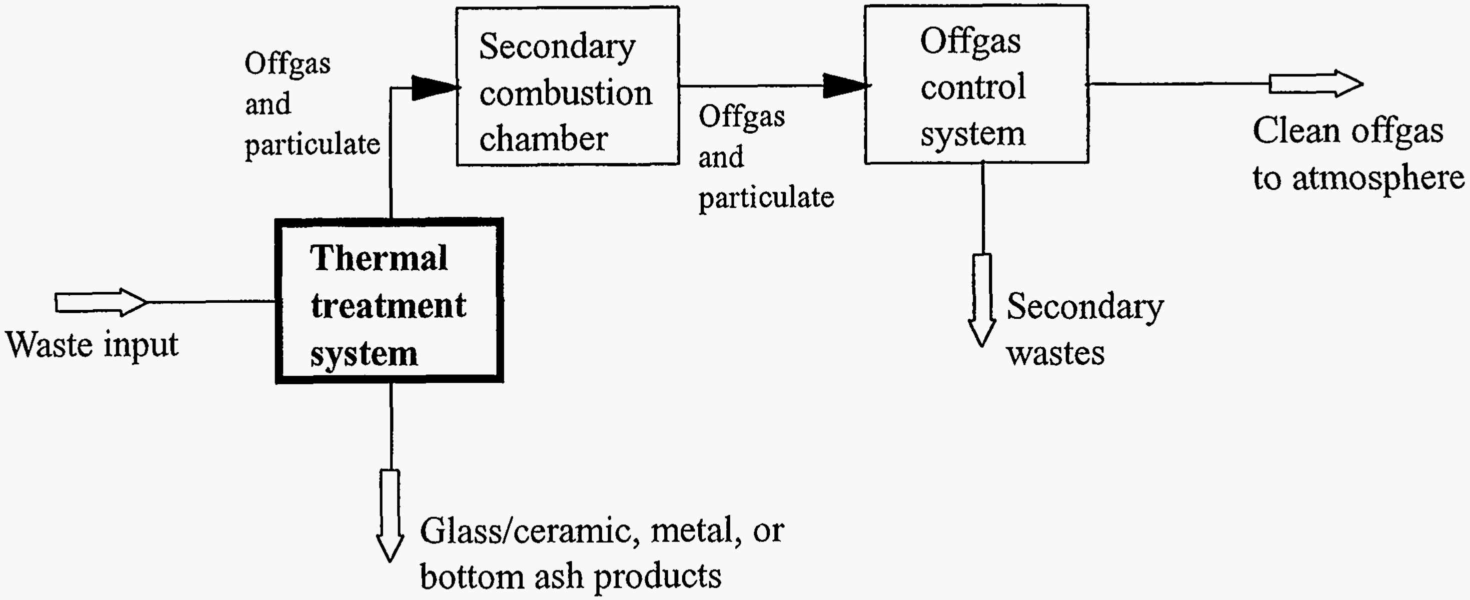

Figure 2-1. Conceptual integrated waste treatment system.

2.1.2 Plasma torch melter[3,4]

In plasma torch melters, heat is generated when a gas is passed between two ionizing electrodes. When there is electric arcing between the two electrodes, the gas is ionized in the arc and heated to very high temperatures, typically in excess of 5,000°C. A plasma plume results when there is a forced gas flow from the torch. If the cathode and anode are both located within the torch, this is referred to as nontransferred arc mode. A transferred arc mode exists when the cathode is located in the torch and the anode is located at the reactor base so that the electrical current is transferred from the torch through the media being processed. The high-temperature process allows for rapid heat-up, volatilization, and melting of feed materials. Several process designs have been developed to minimize the maximum process temperature in order to increase equipment service life. These systems include a plasma arc melter with a moving torch above a stationary hearth and another with a stationary torch above a rotating hearth. Fifteen past, current, or planned plasma torch melter systems are summarized in Table A-2 of Appendix A.

2.1.3 Joule-heated melter[1]

Joule-heated melters pass an electrical current between two submerged electrodes. Electrical energy is converted to thermal energy by resistance heating of the melt. Joule-heated melters require the electrical conductivity of the melt to be in an acceptably narrow range. If the electrical conductivity is too low, the voltage will be too high, and the electrical current and heating power will be too low. If the conductivity is too high, then the current will be too high with very little voltage. Molten metal collected in the bottom of the bath can short out the electrodes. The various types of joule-heated melters used or planned for use in mixed waste treatment are listed in Table A-3 in Appendix A. No detailed data evaluations were performed for joule-heated melters in this study because they are not applicable in treating the wide variety of heterogeneous mixed wastes in the Department of Energy (DOE) inventory.

2.1.4 Other melters and molten-phase thermal treatment systems[2,3,5,6]

Other melter and molten-phase thermal treatment systems include induction melters, microwave melters, externally-heated melters, molten salt treatment systems, and molten metal systems. Applications of these systems to waste treatment are summarized in Table A-4. None of these thermal treatment systems were used in a more detailed preliminary data evaluation of this study because sufficient data was not available.

A variety of melters have been designed to melt the waste into a molten glass. An induction melter uses a time-varying electromagnetic field in a crucible generated from an alternating current passing through a coil around the crucible. It has been used to melt metals in the metals industry. A hybrid melter has been developed that combines a plasma torch with an induction melter. Microwave melters use microwave energy to heat and melt inorganic feed materials such as incinerator bottom ash, sludges, and soils. Dry waste materials are vitrified inside a metal disposal container in either a batch or continuous mode after any significant moisture has been removed. Application is limited to dry or nearly dry inorganic wastes. A furnace heated externally by electrical resistance has been designed to maintain a molten glass bath at 1,000 to 1,100°C and integrate normally volatile components, such as cesium, into a glass matrix. A frit is simultaneously added to a sized waste stream to achieve waste loadings approaching 80% by weight.

Other molten-phase thermal treatment systems include molten salt and molten metal systems. A molten salt process continuously introduces waste and air into a sodium bicarbonate melt at a temperature of 750° to 1,000°C. Supplemental fuel may be required if waste is not sufficiently combustible. The process is restricted for use to waste feeds with low-ash and low-water content, and all waste feed must first be reduced in size to facilitate rapid heat and mass transport. Molten metal processing uses a molten pool of metal (i.e., iron) to destroy organics, dissolve nonvolatile metals, and melt nonmetal inorganics into a glassy slag matrix.

The maximum size of solid waste feed may be limited. Fluxing agents may be required to enhance slag formation. The molten metal furnace is operated under a reducing atmosphere to minimize the formation of metal oxides and to produce synthesis gas rather than oxidized combustion gas. While molten metal processing was included in the detailed evaluation, there is presently very little partitioning data available due to the proprietary nature of this process.

2.2 Incinerators

2.2.1 Rotary kiln[2]

A rotary kiln is a cylindrical refractory-lined shell mounted on a slight incline. Waste fed into the high end moves through the cylinder as a result of the rotation of the kiln. Kiln rotation also enhances solid material mixing. Rotary kilns typically require a secondary combustion chamber to ensure complete destruction of hazardous organic constituents in the gas phase (as do the above-listed melters, when combustible feed materials are fed to the system). Depending on the designed operating temperature of the kiln and feed materials, the rotary kiln may be a slagging or nonslagging incinerator. Twelve rotary kiln systems used to test or treat mixed or hazardous wastes are listed in Table A-5 in Appendix A.

2.2.2 Vertical shaft incinerator[7]

Vertical shaft incinerators utilize heat generated from the incineration of waste near the bottom of the process to dry and volatilize material fed at the top of the shaft. As a result of this configuration, a secondary combustion chamber is normally required to completely incinerate organic volatiles driven off in the shaft incinerator. Non-incinerable materials and ash are removed from the bottom of the incinerator. Most vertical shaft incinerators listed in Table A-6 in Appendix A that are used to treat mixed or radioactive waste are located outside of the United States.

2.2.3 Controlled-air incinerator[2]

Controlled-air incinerators limit the amount of combustion air available in the stationary primary treatment chamber. Waste fed into the primary chamber is pyrolyzed in an oxygen-deficient atmosphere to limit gas velocities and reduce particulate entrainment. Near the outlet of the primary chamber, the combustion air is often staged to be slightly higher than required for stoichiometric combustion to assure adequate burnout of fixed carbon in the bottom ash. The incomplete combustion gases and volatile organics are mixed with an oxygen-rich environment in a secondary chamber to achieve complete gas-phase combustion. Four controlled-air incinerators used to treat radioactive waste are listed in Table A-6.

2.2.4 Other incinerator types

A fluidized bed incinerator is a refractory-lined vessel containing a bed of heated inert granular material that is fluidized with combustion air as waste feed is introduced.[2] The fluidization of material results in rapid heat transfer to the waste, good mixing, and good combustion at relatively low temperatures. Limestone can be added to the bed to provide in-bed acid gas scrubbing capability and eliminate the need for an offgas scrubber. Offgas particulate removal is required so that carryover material can be recovered and returned to the incinerator. A vertical high-temperature slagging incinerator has been designed to destroy organic material and produce a stable leach-resistant product from the incineration of plutonium-contaminated waste.[8] These and other incinerators are listed in Table A-7 in Appendix A.

2.3 Most Applicable Thermal Treatment Systems for Mixed Waste

Several prior studies have been conducted by DOE to evaluate and rank potential thermal treatment technologies that are most likely to be considered to treat DOE wastes and, therefore, are processes in which the partitioning mechanisms should be investigated and modeled. These studies generally agree that graphite electrode melters, the plasma torch melters, and the rotary kiln incinerators have the greatest applicability for treating heterogeneous mixed wastes.

One study evaluated eight different incinerator and 11 melter configurations for potential effectiveness in treating waste.[2] The highest ranked incinerator types were rotary kiln and controlled-air incinerators, while the highest ranked melter types were plasma hearth and graphite electrode arc melters. A rotary kiln or plasma hearth furnace could require the least waste feed preparation.[9] Five different melter configurations were evaluated for use in the Advanced Mixed Waste Treatment Project.[1] The 3-electrode, 3-phase alternating-current graphite electrode melter at the DOE Albany Research Center [formerly U.S. Bureau of Mines (USBM)] and the 2-electrode direct-current graphite electrode arc melter at the Idaho National Engineering Laboratory (INEL) were identified as the best system designs.

The 91 systems listed in Appendix A represent a significant portion of the systems being investigated to potentially treat or to study the conditions for treatment of hazardous, radioactive, or mixed waste. More detailed system descriptions of 53 thermal treatment processes and systems, most of which are graphite electrode melters, plasma torch melters, and rotary kiln incinerators, are presented in Appendix B. The system descriptions include mode of operation; operation status; pertinent description of the process including size, process volume, energy input or process temperature, and materials of construction; waste feed preparation requirements such as sorting or sizing; and components in the air pollution control system. In addition, figures and schematics of the thermal treatment process or the integrated treatment system may also be included in Appendix B.

The most relevant partitioning mechanisms that occur in plasma arc melters and rotary kiln incinerators are presented in Chapter 3. The partitioning mechanisms present in each thermal treatment system are compound formation or destruction via chemical reactions, vaporization and condensation of process materials, and entrainment of particulate material into the offgas. The experimental data believed necessary for identifying and predicting contributions of these partitioning mechanisms are summarized in Chapter 4. Actual experimental data from different melter and incineration treatment systems are evaluated to determine if sufficient data has been collected to identify all relevant partitioning mechanisms and whether it can be used to predict the partitioning or distribution of elements or compounds between the solid, molten, and gaseous phases exiting from or remaining in each system.

3. ELEMENTAL PARTITIONING MECHANISMS

Waste feed constituents are partitioned into one or more solid, molten, or gaseous phases as the result of chemical and physical processes depending on the system design and operating conditions. Partitioning mechanisms in high-temperature thermal treatment systems are considered to be primarily temperature-dependent or convection-dependent. Temperature-dependent partitioning mechanisms are strongly influenced by the thermal energy input and include compound formation or destruction via chemical reactions as well as vaporization and condensation of process materials. The primary convection-dependent partitioning mechanism is the entrainment of particulate material into the offgas from feed dust, fine fly ash, or aerosols evolved or ejected from molten materials. A more detailed description of each mechanism is presented below.

3.1 Temperature-dependent Partitioning Mechanisms

3.1.1 Chemical Thermodynamic Equilibrium

An important partitioning mechanism is the distribution of elements as the result of chemical reactions within the treatment system. An exact description of the distribution requires knowledge of all constituents, of all possible reactions, and the reaction rate constants. In most cases, not all possible chemical reactions are known, but the most important reactions and constituents can be identified. Accurate and comprehensive reaction rate data are generally not available. In the absence of reaction rate information, it is often assumed that all reactions achieve chemical equilibria in a relatively short period of time compared to the total residence time of the reactants. The Gibbs free energy is related to chemical potential by the following equation[10]:

$$\left(\frac{dG}{d\epsilon}\right)_{T,P} = \sum_{i=1}^{m} \nu_{ij}\mu_i, \qquad j = 1,2,3,\ldots r \tag{1}$$

where

G	Gibbs free energy
ϵ	extent of reaction
T	temperature
P	pressure
ν_{ij}	stoichiometric coefficient (reactants are negative, products are positive) for species I in jth reaction
μ_i	chemical potential of species I.

Chemical equilibria are achieved when the Gibbs free energy for all specified reactions have been minimized, so that Eqn (1) becomes

$$\sum_{i=1}^{m} \nu_{ij}\mu_i = 0. \tag{2}$$

This method of estimating species distribution in all phases is dependent on the input data as well as any assumptions concerning the input data. The calculated equilibrium concentrations depend on the species considered as possible reactants and products. If an important species containing the element in question is omitted, the predicted concentration values can be significantly different from the actual concentrations.

Equilibrium concentrations are a strong function of temperature; therefore, it is important that the calculation temperature is representative of the actual temperature in the system or specific region in the system. If the rate of a chemical reaction is sufficiently slow that the assumption of chemical equilibrium is inappropriate, it may be appropriate to neglect the reaction when performing chemical equilibrium calculations.[11] If the mass transfer rates within and between solid, liquid, and gaseous phases are not sufficient to guarantee that all species are in intimate contact with each other or if chemical reaction kinetics are slow, the calculated equilibrium concentrations may not reflect actual concentrations.

3.1.2 Volatilization

When the total feed rate of a chemical species into a thermal treatment process is small enough that is impossible to saturate the gas surrounding the waste at the operating conditions, the species will completely vaporize, or volatilize, into the gas if there are no significant mass-transfer limitations. This remains the case until, with increasing species feed rate, a saturation point is reached where the species partial pressure in the gas cannot increase further. Once the saturation point has been reached, no further volatilization will occur and the only means of increasing the species emission rate is by particle entrainment. The total species emission rate can be expected to continue to increase with increasing feed rate; however, since only a fraction of feed is entrained, the total species emission rate becomes a decreasing fraction of the total feed rate. Therefore, it is important to know if the saturation point has been reached when determining the partitioning mechanisms responsible for transporting feed material to the offgas exiting a thermal treatment process. Metal emission rates from a rotary kiln incinerator test burn showed lead emission rates to increase proportionally with lead feed rates (with chlorine in waste) because the gas phase was not saturated with the lead species while there was no significant increase in emission rates with increased metal feed rate for chromium, silver, and barium indicating that the gas was saturated with these metals.[12]

One way species volatility is characterized is by the volatility temperature of a species defined as the temperature at which its effective vapor pressure equals 10^{-6} atm.[13] For a given species, the lower its volatility temperature or the higher its vapor pressure at a given temperature, the more volatile it is relative to other species. Actinides, such as plutonium and uranium, generally demonstrate extremely low volatility at normal operating temperatures although volatilities can vary between different species containing the same element. For example, actinide oxides typically exhibit lower volatility than actinide chlorides.[14] Some radioactive elements, such as cesium, exhibit high volatility and are usually distributed primarily in the gas phase exiting a thermal treatment system. A number of toxic metals or compounds containing these metals, such as lead, cadmium, and zinc, exhibit high volatility and can be expected to be distributed among all phases remaining in and exiting a treatment process. Other toxic metals and related compounds exhibit lower volatility and generally remain in the solid or molten phases in the system. Since volatilization of toxic metals and radionuclides is usually not desirable, condensation and capture of these volatilized materials in an air pollution control system becomes important. Mercury exhibits high volatility at typical operating conditions and can require special equipment in the air pollution control system to remove it from the offgas.

3.1.3 Vapor Condensation

When conditions in a thermal treatment process change so that the gas is supersaturated (normally resulting from a saturated gas being cooled), condensation of a volatilized species will occur. Heterogeneous condensation involves the accumulation of condensate on an existing surface such as particulate matter or the reactor walls. Homogeneous condensation results in the formation of new submicron particles from the condensing vapors. In general, heterogeneous condensation is thermodynamically favored over homogeneous condensation. However, when sufficient sites for heterogeneous condensation do not exist or when supersaturation pressures are sufficiently high, homogeneous condensation may occur.[15]

The rate of heterogeneous condensation is proportional to the difference between the species concentration in the gas phase and the equilibrium concentration defined by the surface temperature. The proportionality constant is the product of surface area and the mass-transfer coefficient. Homogeneous condensation is a function of temperature, surface tension, droplet mass, species partial pressure, liquid density, and the supersaturation ratio. The supersaturation ratio is the ratio of the species vapor pressure at a given temperature to the saturation vapor pressure and is a strong function of temperature. The supersaturation ratio must be greater than unity, generally due to rapid cooling, for homogeneous condensation to occur. Another temperature-dependent partitioning mechanism is thermophoresis in which vapor deposition occurs as the result of a steep temperature gradient at a wall surface.

3.2 Convection-dependent Partitioning Mechanisms

Convection-dependent partitioning mechanisms include fluid mixing, particle entrainment, particle agglomeration, and particle deposition. Fluid mixing and turbulence in solid, molten, and gas phases promote mass and energy transfer within the system which can affect thermodynamic equilibrium concentrations and the extent of chemical reactions. Fluid mixing in the molten phases results from or can be promoted by steep temperature gradients generated by highly localized energy input, plasma torch gases directed at the melt surface, and sparging gases (such as oxidants) injected below the melt surface. The compositional uniformity in the molten phase is a function, in part, of fluid mixing and turbulence.

Particulate entrainment is the transport of solid matter from the thermal treatment process into the offgas stream. The local gas velocity must be sufficient to transport a particle of a given size and density. Gas velocities and velocity gradients (turbulence) in the gas phase are a function of temperature and temperature gradients in the system; gas generated by chemical reactions and volatilization; gas introduced into the system; and the system configuration. Potential sources of entrainable material include untreated feed dust, partially pyrolized or combusted feed materials, ash particulate, condensed vapor particles, fragments produced from imploding condensed vapor particles, and molten slag or metal ejected from the bulk molten fluids. Particulate agglomeration is the adhesion of smaller particles to each other when they collide due to Brownian motion, gravitational settling, turbulence, or other forces to form larger particles. Particle deposition results in the accumulation of particles onto a stationary surface. Particle deposition can result from laminar diffusion, turbulent deposition, gravitational settling, centrifugal settling (in pipe bends), or other forces. Particle deposition reduces the total amount of entrained material and particle agglomeration, while it does not by itself reduce the amount of entrained material, does usually result in more particle deposition and easier downstream particulate removal due to the formation of larger particles.

3.3 Partitioning Mechanisms in Thermal Treatment Processes

Each of the identified partitioning mechanisms occurs to some extent within plasma torch and arc melters and rotary kiln incinerators although the relative importance of each mechanism in a particular furnace system is dependent upon the system configuration, operational parameters, chemical constituents, and waste feed type.

Key parameter variations in a graphite electrode arc melter configuration include the size of the melter, the diameter and number of top-down electrodes (at least one or two for DC, three for AC), the distance between electrodes, the distance between electrodes and the molten surface, and the waste feed location. Generic schematics of an AC graphite electrode arc melter and a DC graphite electrode arc melter with one top-down electrode are shown in Figures 3-1 and 3-2, respectively. The electrodes in an AC melter

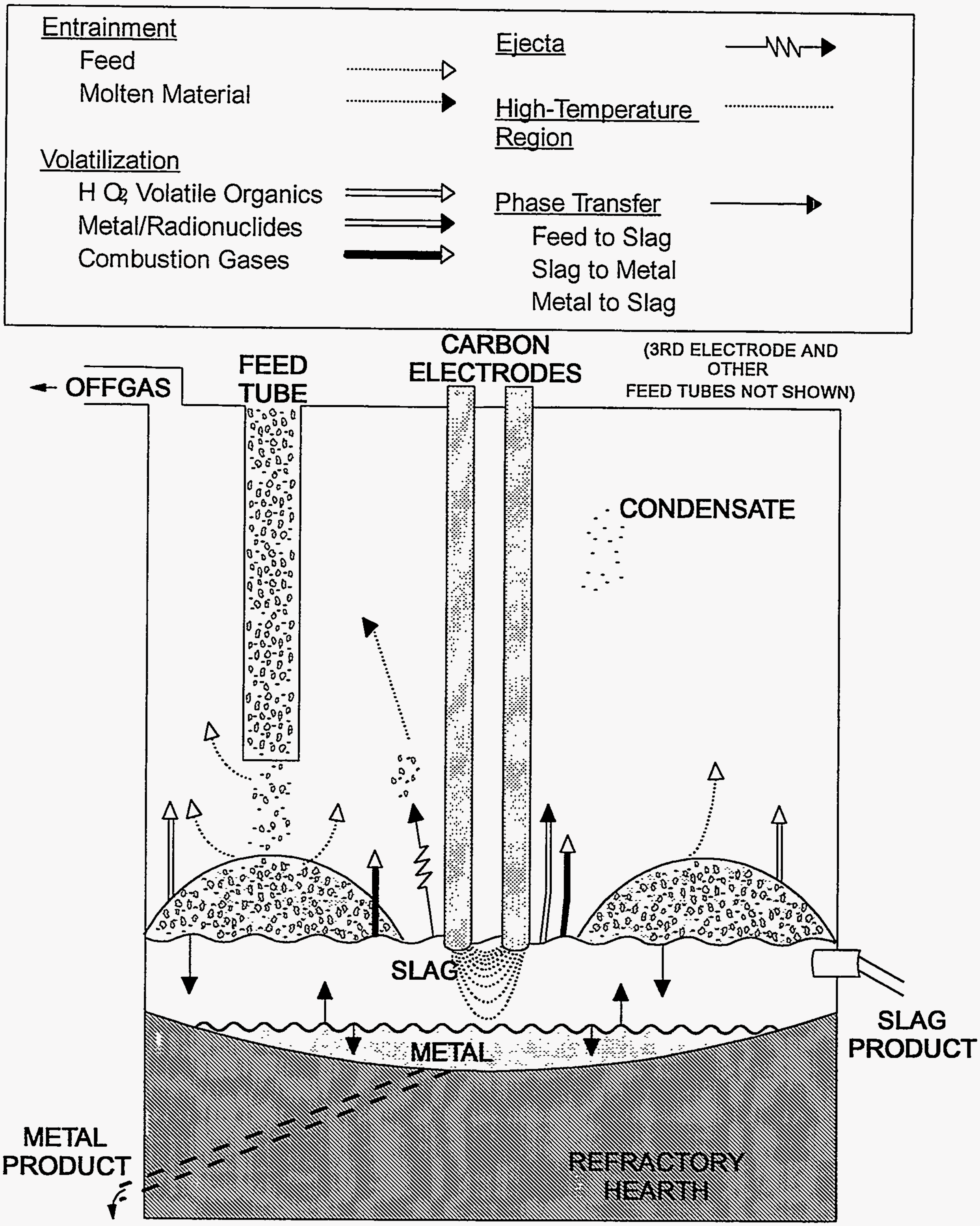

Figure 3-1. Partitioning mechanisms in a graphite electrode AC arc melter.

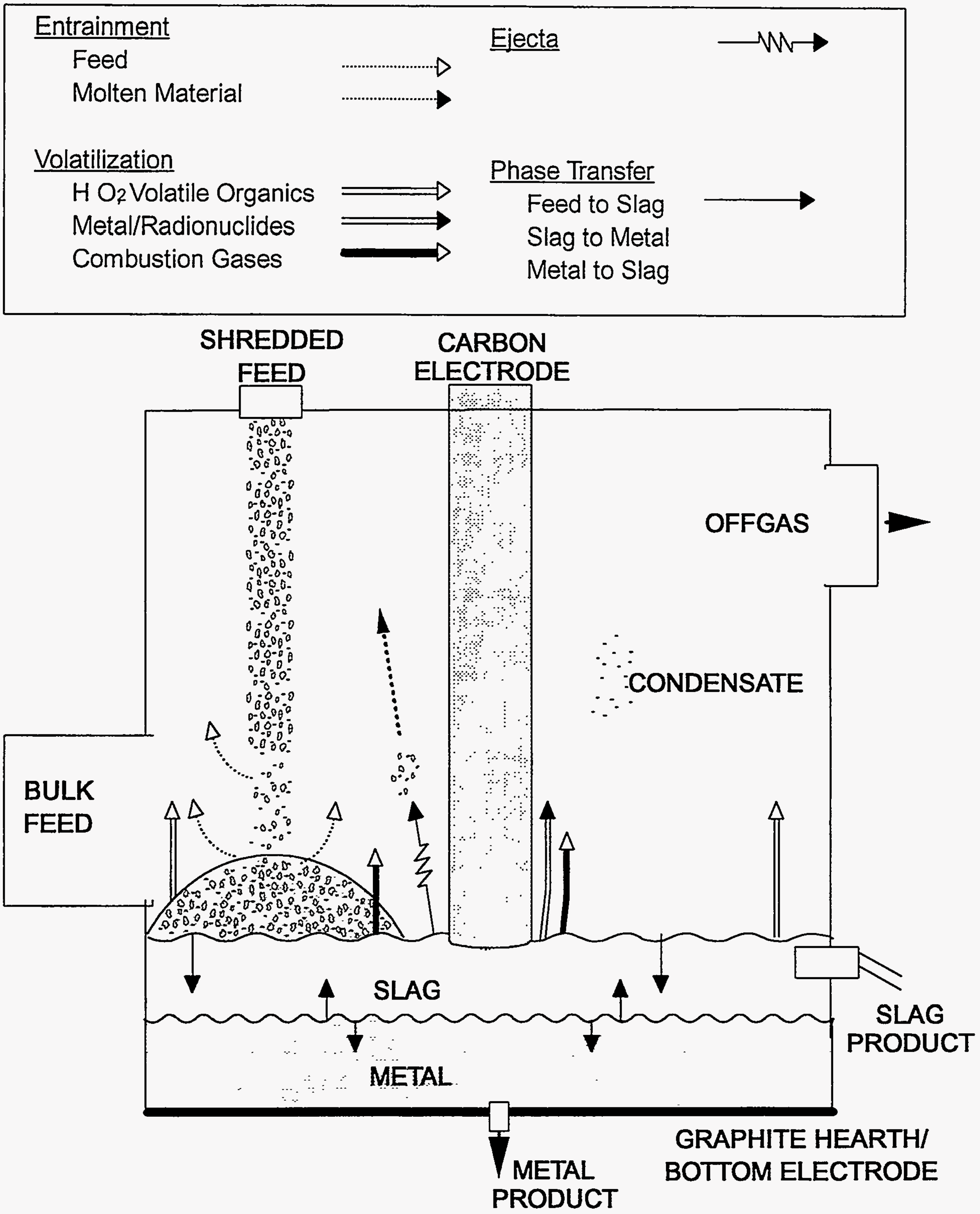

Figure 3-2. Partitioning mechanisms in a graphite electrode DC arc melter.

are generally centered in equilateral-triangle formation. The region around the stationary electrodes may be significantly hotter than the melt regions near the wall particularly if there is incomplete melt mixing or the walls are cooled. Because the graphite electrodes are slowly oxidized and consumed in continuous operation, they are slowly fed into the furnace as new electrode sections are added. Electrical power control is typically maintained by continually moving the electrodes up or down to vary the electrical resistance by changing the degree of submerged electrode contact with the melt or gap above the melt in order to keep the electrical current or voltage within a set range. If the electrodes are in contact with the molten slag there will be a minimal plasma arc at the electrode tips.

The partitioning mechanisms acting between phases, such as volatilization and entrainment, as well as the melting and diffusion of material into and between the molten phases are indicated in each figure. Particulate entrainment results from solid and molten material being swept out of the system by gases fed into and generated within the melter. Some of the feed material is converted to gases by evaporation of water, generation of pyrolysis and combustion gases, and volatilization of toxic metals, radionuclides, and other compounds. The oxidation of graphite electrodes or carbonaceous waste material result in the formation of carbon monoxide and carbon dioxide as well as the reduction of chemical species in the melt. Reduced elemental metals are generally more volatile than oxidized metals. A denser molten metal phase will form below the molten slag layer if the waste feed contains metal oxides that are chemically reduced to the elemental metal phase or metals that are not completely oxidized. If sulfur, copper, and other metals are present in the proper concentration, a matte consisting of metal sulfides can form a separate phase between the molten metal and slag. A matte phase is not shown in the figures.

Entrainment of feed material and ejected molten slag into the offgas is dependent on particulate size and density as well as local gas velocities. Feed material introduced into the system as sized particles to minimize heat and mass transfer resistance may result in increased feed dust entrainment. This entrainment can be reduced somewhat by introducing material through a feed tube close to the melt surface. Volatilized material may condense in cooler plenum gas with larger entrained and condensed particles falling back to the melt surface. Most ejected molten material should solidify rapidly since gas temperatures are typically cooler than the melt temperatures. Some of the ejected, entrained, or condensed volatile matter may accumulate on furnace surfaces. If the furnace surfaces are relatively cool, vapor deposition may become problematic; however, the deposits generally tend to break off or melt and drain off the walls after reaching a maximum thickness. Process operating conditions may include the presence of a layer of insulating unmelted feed (cold top) floating on the melt which reduces the thermal radiation to the upper plenum. The cold top may also act as a vapor trap to condense and reflux volatiles into the melt and may reduce the amount of molten and volatilized material entrained in the offgas. However, the presence of a dry, dusty cold top may increase the amount of feed dust entrainment.

Variations in general plasma torch melter configurations include placing the plasma torch or hearth in motion while the rest of the system is stationary or possesses limited mobility. A schematic of a generic plasma torch melter with whole-drum feed, stationary hearth, and a movable torch is shown in Figure 3-3. A primary advantage of a whole-drum system over the sized-feed system is the reduced cost and risk of sorting and sizing of the waste along with possibly less particulate entrainment. However, the time required to destroy and dissolve the waste can be expected to be greater. A schematic of a plasma torch system with a rotating hearth and a torch with restricted mobility is shown in Figure 3-4. When the torch can move with respect to the melt surface, energy can be focused as needed on cooler zones or distributed evenly across the melt surface to minimize the formation of local hot spots.

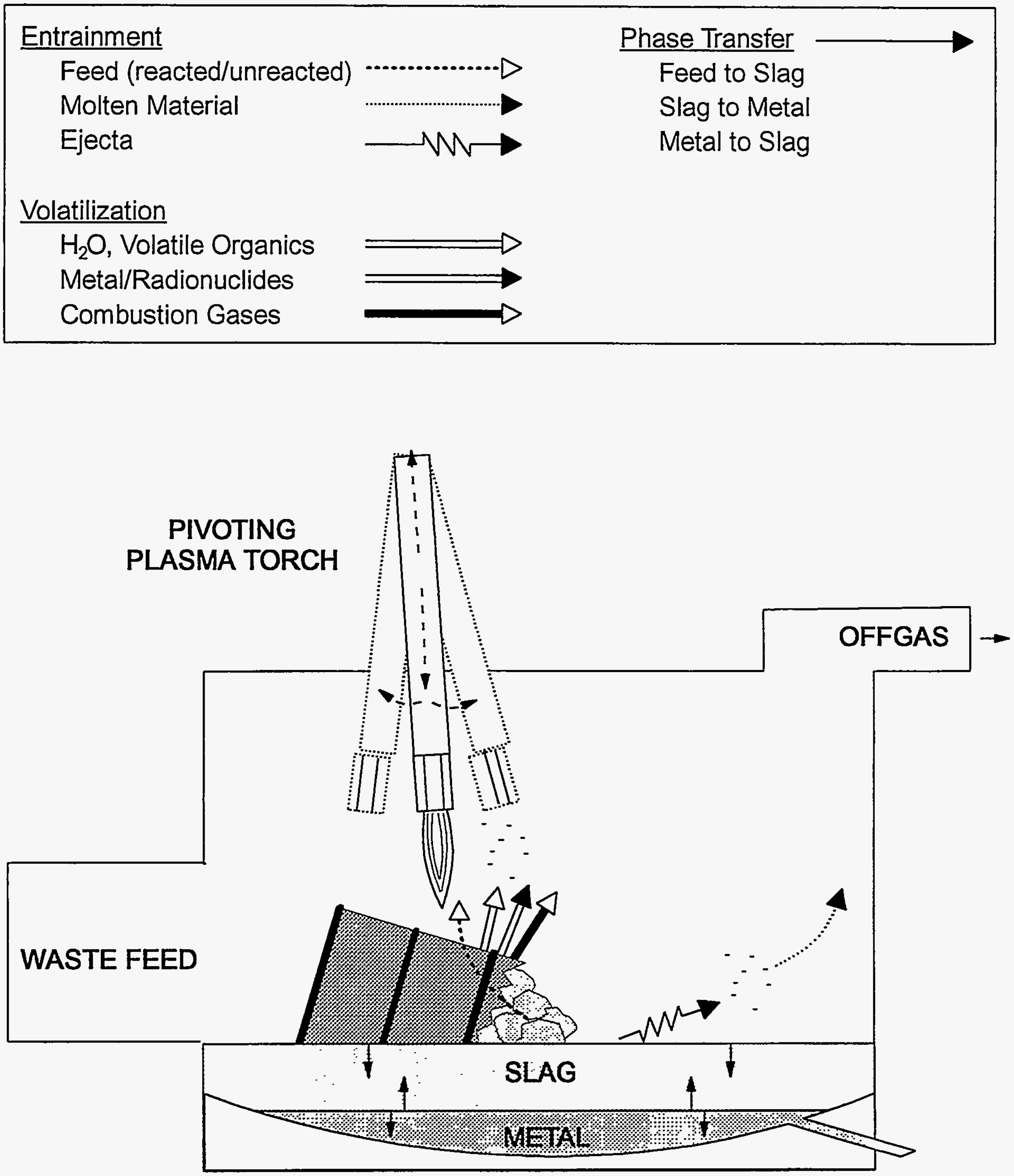

Figure 3-3. Partitioning mechanisms in a fixed-hearth plasma torch melter.

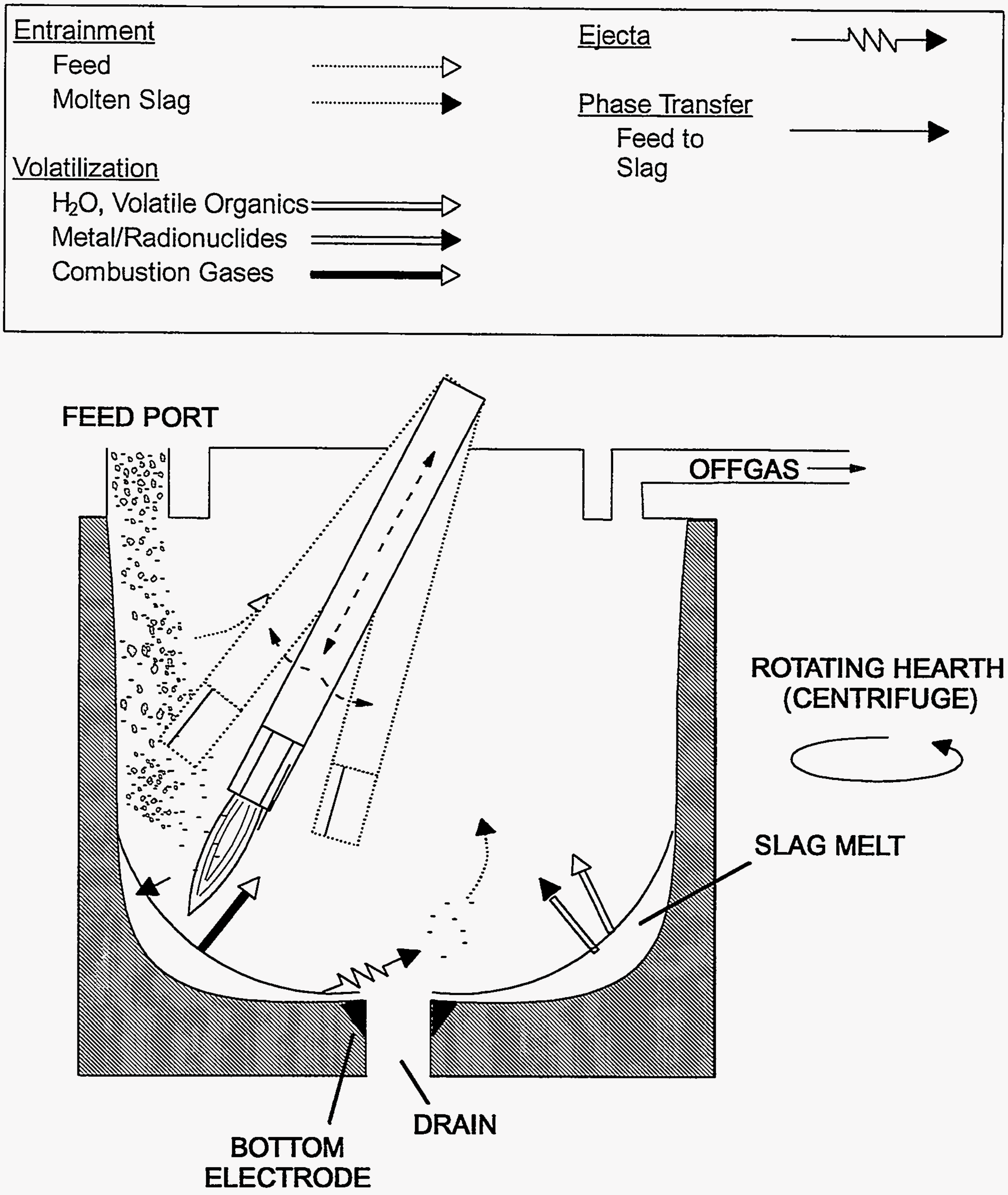

Figure 3-4. Partitioning mechanisms in a centrifugal hearth plasma torch melter.

The partitioning mechanisms that occur in plasma torch melter systems are similar to those seen in graphite electrode arc melter systems allowing for variations in process and operational conditions. Depending on the torch gas and distance from the melt, the impinging of the torch gas into the melt may cause increased turbulence and melt ejection. The torch gas may increase feed dust entrainment more than in the more quiescent graphite electrode configuration. In the plasma torch systems, there is no chemical reduction of melt species by graphite oxidation since there are no graphite electrodes but carbonaceous wastes may still produce reducing conditions in the melt depending upon the amount of oxygen present in the waste. A plasma torch may also utilize various gases in the torch, including air, that may yield a more oxidizing environment. Chemical oxidation can lower the volatility of some melt species because oxides generally have lower vapor pressures than the corresponding reduced species of the same element.

A generic schematic of a rotary kiln incinerator is shown in Figure 3-5. Variations in the process design and operating conditions of a rotary kiln include the direction of air flow over the waste (concurrent or countercurrent) as well as the angle of incline and rotation rate of the cylindrical incinerator. In nonslagging kiln operation, the peak kiln temperatures are much lower than typical melter temperatures. This can tend to reduce volatilization of high vapor pressure toxic metals and radionuclides. The continuous (although slow) kiln rotation mixes the solid material and reduces the mass transfer resistance in gas-solid oxidation reactions; however, the solid mixing can increase feed dust and fly ash entrainment into the offgas. Since kilns are typically fuel-fired for heat generation, gas flows and gas velocities are generally higher than in comparably sized melter configurations which can lead to increased particulate entrainment. The resulting bottom ash and flyash generated from rotary kiln incinerator systems are generally not suitable as a final waste form for mixed waste treatment and require additional handling and stabilization processing.

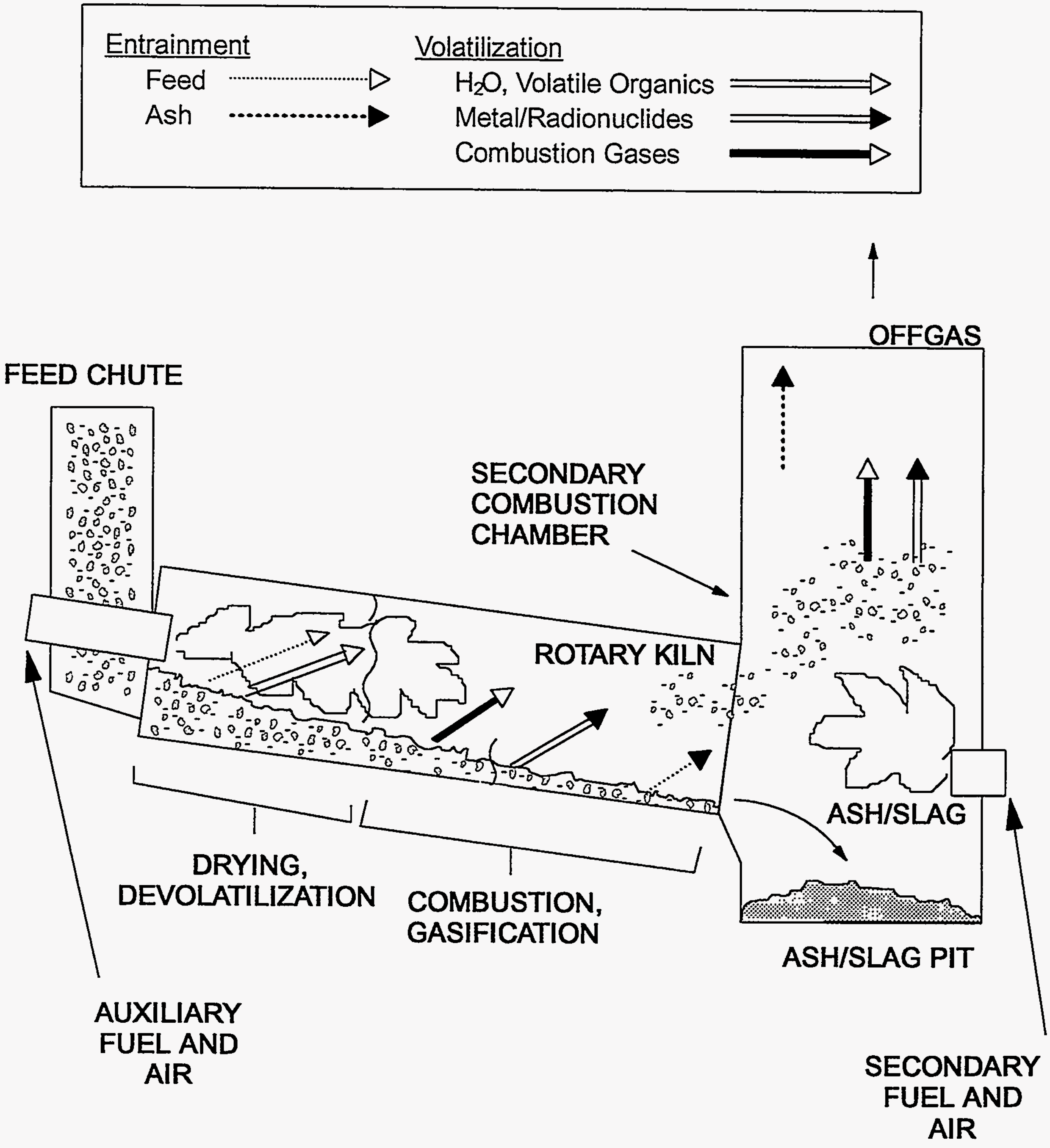

Figure 3-5. Partitioning mechanisms in a rotary kiln incinerator.

4. EXPERIMENTAL PROCESS AND PARTITIONING DATA

Global and elemental mass balance calculations require knowledge of the total mass or mass flow rate in each phase and its elemental concentrations. The total mass or mass flow rates entering, exiting, or remaining in the system allow for a global mass balance. An elemental mass balance can be performed for each element that is analyzed for in the masses or streams entering, exiting, or remaining in the system. Assumptions are inherently made when identifying the type and quantity of data necessary to characterize a thermal treatment process. Typical process assumptions include:

- No significant temperature or concentration gradients exist within the molten and gas phases in the system; therefore, each phase exhibits uniform properties that can be measured in a single measurement or sample;

- Continuous systems operate at steady state and there is no significant hold-up of feed material in the system or added output material such as dissolved refractory oxidized metals from ducting;

- The mass or mass flow rate of a process stream can be defined as the difference between the mass or mass flow rate of the feed and all other process streams;

- All chemical constituents are in intimate contact with each other;

- Species resident time is sufficient that all chemical reactions are at thermodynamic equilibrium;

- The presence of elements or species in the offgas solids carried into the offgas system results from one of two partitioning mechanisms - volatilization or entrainment;

- The composition of particulate (in the feed, bottom ash, or offgas particulate) does not vary with particle size.

- Sample analyses accurately indicate the composition of analyzed samples.

The primary assumption often made when measuring process variables is that the data collected is representative of the phase sampled. If the assumption is valid, a temperature measurement can be made in a continuous phase without concern of probe position, smaller sample sizes could be collected from molten phases and analyzed, and less chemical analysis of offgas particulates would be necessary. Elemental homogeneity within a single phase, such as a slag, may be assumed when taking a sample for analysis; however, incomplete mixing or crystallization within the melt during cooling may prevent a representative sample from being collected. Significant concentration variation within a phase will affect the type and number of samples required to properly characterize its composition. Appreciable mass accumulation or depletion within the system also can be detrimental to a material balance. It is often a challenge to determine the total mass remaining in the system due to feed and melt spattering, slag build-up, interactions with the refractory wall, and accumulation in the offgas system and connecting ductwork. In addition, sample concentrations may not be accurate due to analytical limitations. The relative accuracy of concentration measurements generally decreases as the absolute concentration decreases, particularly as the concentration approaches the detection limit.

The assumptions of uniform temperature, chemical species in intimate contact with each other, and sufficient residence within the system to achieve equilibria impact the calculation of constituent partitioning between solid, molten, and gas phases remaining in or exiting a thermal treatment system. Equilibrium constants are strong functions of temperature, so temperature variations could have a significant impact on predicted constituent concentrations. In addition, not all chemical species introduced into the treatment system necessarily experience the same conditions. Some species may volatilize before the waste is melted or incinerated. Gaseous compounds may be exposed to higher temperatures near the plasma arc.

Assumptions can be made to justify not collecting additional experimental data. In many cases, the mass of one output stream is defined as the difference between the feed mass and the mass of the other output streams. Using the difference method to define a process stream implies all other streams are accurate, but this may not be the case. Average gas velocities are generally calculated based on the exit gas velocity or flow rate because of the inherent difficulty in measuring gas velocities within the treatment system due to more difficult sampling conditions.

Failure to achieve closure in global and elemental material balances may indicate a lack of knowledge of the relevant partitioning mechanisms or inadequate sampling and analysis methods as well as bring into question the validity of partitioning results calculated from mass balances. Accurate and sufficient measurement of process conditions and results is necessary to conduct material and energy balances as well as to correlate elemental partitioning to process conditions. Process operating conditions and results that need to be measured or otherwise determined include:

- **Mass or mass flow rate, chemical composition, and physical nature of waste feed, additives and co-reactants.** The total mass or mass flow rate of waste feed combined with the feed composition define the species or elemental mass entering the system. Feed composition may be defined in terms of chemical species, elements, or material composition. Material composition specifies the bulk materials in the waste (i.e., wood, paper, soil). The chemical make-up of these bulk materials may or may not have been measured. Additives and co-reactants include oxidants, slag-forming additives, torch gases, and graphite electrode consumption. This information is necessary to complete mass balances and to account for possible effects on local mixing, temperatures, and concentrations. The physical nature of the bulk material may introduce heat and mass transfer resistances in the system that prevent all phases and species from being uniformly distributed.

- **Temperatures in each significant phase.** Multipoint measurements are required to identify temperature gradients in the system. These data are difficult to obtain with existing temperature measurement technologies. Measurements can be taken in the plenum gas as well as at or below the slag melt surface. Average temperatures within the system may be inferred indirectly by temperature measurement of the refractory wall. Theoretical maximum temperatures can be calculated from energy input data such as power, voltage, current, or current density data.

- **Mixing and velocity in gas and molten glass phases.** Mixing and velocity data are used to characterize phase uniformity, the extent of chemical reactions, and aerosol entrainment.

- **Other operating condition parameters.** Other important physical data include the presence and extent of cold top coverage of the melt, melt viscosity, and the achievement of steady-state conditions.

- **The mass or mass flow rate, elemental or chemical species composition, and physical properties of each phase exiting or remaining in the system.** This includes glass or slag, metal, and ash phases; offgas solids; offgas or stack gas not collected as a solid or liquid phase; and accumulated material remaining within the system. Particle size distribution and particle-specific data of offgas particulates, such as density, crystallinity, and elemental composition, can be used to differentiate between entrained feed dust, ejected melt material, and condensed volatilized material.

4.1 Process Variables and Results Measured in Thermal Treatment Systems

A survey of different thermal treatment test systems and production facilities listed in Appendix C was conducted to determine how many of these variables and parameters were measured. Tables 4-1 through 4-5 show the measurements that were made in selected melters and incinerators. An "X" in the box indicates that the parameter in question was measured. A blank box denotes that no measurements were made of that parameter. All columns denoted as rate refers to direct measurements or calculations of mass flow rate from measured mass fed into or collected from the system over a measured time period.

Feed and energy parameters that can be measured are listed in Table 4.1. Feed composition can be reported in terms of elemental species, specific chemical compounds, or bulk material constituents. Chemical species compositions are generally analyses made for the oxides of certain elements but also may include analyzing for actual species expected to be present in the material. Material compositions denote the types of components present in the bulk material, and additional chemical or elemental analysis of these bulk materials may or may not be known. The physical nature of the waste affects whether all species are in intimate contact with each other during the treatment process. While chemical species composition can be estimated from knowledge of bulk material composition, and elemental composition can be calculated from knowledge of chemical species composition, chemical specials and bulk material composition generally cannot be estimated from an elemental composition. Each type of compositional analysis is important because it provides information that is necessary to predict and describe component distributions throughout the system. Particle size of the feed material and composition of the feed as a function of particle size can provide useful information pertaining to potential particulate entrainment.

Possible operating parameters that may be measured are listed in Table 4.2. Operating temperatures are arranged in the table according to location in the system. The first four columns pertain to the melt temperature. The melt temperature may be measured at or below the surface. The melt temperature may be determined indirectly by measurement of the refractory hearth temperature. If any of these measurements are made at more than one location, this is indicated in a separate column. The next four columns list temperatures in the gas space above the waste. The plenum gas column indicates that temperature probe measurements were made within the void space above the ash or molten phase. Measurement of plenum gas temperature at more than one location can confirm the assumption of a well-mixed gas volume. The plenum gas temperature may be measured at the exit of the treatment system. The plenum gas temperature may also be determined indirectly by measurement of the refractory hearth temperature. Measurement of the temperature at the source of energy input can indicate the possible maximum temperature in the system. For incinerators this would be a flame temperature, for plasma torch melters it is the torch temperature, and for electrode systems it is the arc temperature. Theoretical maximum temperatures can be calculated from energy input data, such as power, voltage, current, or current density data. While all or some of these variables are usually measured in plasma arc or torch systems, rotary kiln incinerators are typically characterized by the actual or designed power output.

Table 4-1. Material and energy input information measured in key melters and incinerators.

Test Series	Surrogate or actual feed input, including additives							Other gaseous inputs		Energy input		
	Feed Rate	Feed Mass	Composition			Particle size	Composition of particle size ranges	Rate	Composition	Voltage	Current	Power
			Elemental	Chemical species	Material							
1. PNNL Bench Scale DC Arc Furnace (Rad)[a 16,17]												
Initial	X	X	X	X	X			X	X	X	X	X
2nd & 3rd	X	X	X	X	X			X	X	X	X	X
3. INEL Small Arc Melter[b 18-20]												
Initial		X	X	X	X					X	X	X
F.O.		X	X	X	X					X	X	X
Mod I		X	X	X	X					X	X	X
Volatil.	X	X	X	X	X					X	X	X
Redox		X	X	X	X			X	X	X	X	X
PSPI		X	X	X	X					X	X	X
Mod II	X	X	X	X	X					X	X	X
6. Mark I Furnace[c 21]		X			X			X	X	X	X	X
8. Mark II Furnace[c 22-24]	X	X		X	X			X	X	X	X	X
11. USBM AC, 3 Electrode Arc Melter[d 25-29]												
Phase 1	X	X	X	X	X	X		X	X	X	X	X
Phase 2	X	X	X	X	X			X	X	X	X	X
Ash	X	X	X	X	X	X		X	X	X	X	X
WHC	X	X	X	X	X			X	X	X	X	X
19. PHP (POP Unit)[e 30,31]	X	X			X			X	X			X
22. PEAT[f 32,33]					X			X	X			
26. PACT-1[g 34]		X			X			X	X			
27. PACT-2[h 35]		X			X			X	X	X	X	X
28. PACT-6[i 35,36]												
Ce Series		X			X			X	X	X	X	

Table 4-1. Material and energy input information measured in key melters and incinerators (continued).												
	Surrogate or actual feed input, including additives							Other gaseous inputs		Energy input		
			Composition									
Test Series	Feed Rate	Feed Mass	Elemental	Chemical species	Material	Particle size	Composition of particle size ranges	Rate	Composition	Voltage	Current	Power
Sludge Series		X			X			X	X	X	X	
NO_x Series		X			X			X	X	X	X	
62/63. MMT[j] [37,38]	X											
66. ACERC[k] [39-41]		X	X	X	X	X						
68. SWIFT RKS[l] [42,43]	X	X	X		X			X				
69. TSCA[m] [44-46]	X		X		X			X	X			
71. EPA IRF[n] [47-50]	X		X	X				X				X
73. Rollins HWI[o] [51,52]	X		X	X				X				
76. APTUS HWI[p] [53-55]	X		X	X	X							X
85. SEG[q] [56]												
86. WERF[r] [57-59]		X										
89. LLNL TF[s] [14,60-63]		X	X	X		X		X				

a. Pacific Northwest National Laboratory, Richland, WA
b. Idaho National Engineering Laboratory, Idaho Falls, ID
c. Massachusetts Institute of Technology, Cambridge, MA
d. Albany Research Center (formerly known as the U.S. Bureau of Mines), Albany, OR
e. Plasma Hearth Process (Proof of Principle Unit), Retech, Inc., Ukiah, CA
f. Plasma Energy Applied Technology Thermal Destruction and Recovery System, Huntsville, AL
g. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (1-ft ID), Retech, Inc., Ukiah, CA
h. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (1.5-ft ID), Retech, Inc., Ukiah, CA. Pu tests performed at Argonne National Laboratory-West.
i. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (6-ft ID), Retech, Inc., Ukiah, CA
j. Molten Metals Technology (MMT) Catalytic Extraction Process (CEP)
k. Advanced Combustion Engineering Research Center (ACERC) Bench-Scale Rotary Reactor, University of Utah
l. Solid Waste Incineration Test Facility (SWIFT) Rotary Kiln System, Energy and Environmental Research, Santa Ana, CA
m. Toxic Substance Control Act (TSCA) Mixed Waste Rotary Kiln Incinerator, Oak Ridge National Laboratory
n. Environmental Protection Agency (EPA) Incineration Research Facility (IRF) Rotary Kiln Incinerator, Jefferson, AK
o. Rollins Environmental Service Hazardous Waste Rotary Kiln Incinerator, Deer Park, TX
p. APTUS Hazardous Waste Rotary Kiln Incinerator, Coffeyville, KS
q. Scientific Ecology Group (SEG) Controlled-Air Incinerator, Oak Ridge, TN
r. Waste Experimental Reduction Facility (WERF) Controlled-Air Incinerator, Idaho National Engineering Laboratory
s. Lawrence Livermore National Laboratory (LLNL) Transpiration Furnace, Livermore, CA

Table 4-2. Operating information measured in key melters and incinerators.

	Operating temperatures									Velocities and mixing			Furnace internal conditions			
Test series	Melt surface	Melt/ash sub-surface	Melt multi-position	Hearth refractory	Plenum gas	Plenum gas multi-point	Plenum gas exit	Plenum refractory	Flame/ Torch/ Arc	Ash/melt mixing[a]	Plenum exit gas velocity	Local plenum gas velocity	Cold top?	Slag viscosity	Metal phase?	Steady state?
1. PNNL Bench Scale DC Arc Furnace (Rad)[b] [16,17]																
Initial				X	X		X				X					
2nd & 3rd				X	X		X				X					
3. INEL Small Arc Melter[c] [18-20]																
Initial																
F.O.																
Mod I																
Volatil.		X											X			
Redox		X														
PSPI																
Mod II		X											X		X	
6. Mark I[d] [21]			X	X												
8. Mark II[d] [22-24]	X		X	X			X	X								
11. USBM AC, 3 Electrode Arc Melter[e] [25-29]																
Phase 1		X		X			X	X					X		X	
Phase 2		X		X			X	X					X	X	X	
Ash		X	X	X			X	X					X	X	X	
WHC		X	X	X				X					X	X	X	
19. PHP POP[f] [30,31]										X					X	
22. PEAT[g] [32,33]															X	
26. PACT-1[h] [34]																
27. PACT-2[i] [35]					X											
28. PACT-6[j] [35,36]																
Ce Series					X											X
Sludge Series					X											X

Table 4-2. Operating information measured in key melters and incinerators (continued).

	Operating temperatures									Velocities and mixing			Furnace internal conditions			
Test series	Melt surface	Melt/ash sub-surface	Melt multi-position	Hearth refrac-tory	Plenum gas	Plenum gas multi-point	Plenum gas exit	Plenum refrac-tory	Flame/ Torch/ Arc	Ash/melt mixing[a]	Plenum exit gas velocity	Local plenum gas velocity	Cold top?	Slag viscosity	Metal phase?	Steady state?
NO_x Series					X											X
62/63. MMT[k][37,38]																X
66. ACERC[l][39-41]		X			X											
68. SWIFT[m][42,43]		X					X	X								X
69. TSCA[n][44-46]							X									
71. EPA IRF[o][47-50]							X									X
73. Rollins[p][51,52]							X		X							
76. APTUS[q][53,54]							X				X					
85. SEG[r][56]																X
86. WERF[s][57-59]							X									
89. LLNL[t][14,60-63]					X	X		X								

a. Includes local velocity measurements and visual observations of melt mixing and turbulence
b. Pacific Northwest National Laboratory, Richland, WA
c. Idaho National Engineering Laboratory, Idaho Falls, ID
d. Melter furnace, Massachusetts Institute of Technology, Cambridge, MA
e. Albany Research Center (formerly known as the U.S. Bureau of Mines), Albany, OR
f. Plasma Hearth Process (Proof of Principle Unit), Retech, Inc., Ukiah, CA
g. Plasma Energy Applied Technology Thermal Destruction and Recovery System, Huntsville, AL
h. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (1-ft ID), Retech, Inc., Ukiah, CA
i. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (1.5-ft ID), Retech, Inc., Ukiah, CA. Pu tests performed at Argonne National Laboratory-West.
j. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (6-ft ID), Retech, Inc., Ukiah, CA
k. Molten Metals Technology (MMT) Catalytic Extraction Process (CEP)
l. Advanced Combustion Engineering Research Center (ACERC) Bench-Scale Rotary Reactor, University of Utah
m. Solid Waste Incineration Test Facility (SWIFT) Rotary Kiln System, Energy and Environmental Research, Santa Ana, CA
n. Toxic Substance Control Act (TSCA) Mixed Waste Rotary Kiln Incinerator, Oak Ridge National Laboratory
o. Environmental Protection Agency (EPA) Incineration Research Facility (IRF) Rotary Kiln Incinerator, Jefferson, AK
p. Rollins Environmental Service Hazardous Waste Rotary Kiln Incinerator, Deer Park, TX
q. APTUS Hazardous Waste Rotary Kiln Incinerator, Coffeyville, KS
r. Scientific Ecology Group (SEG) Controlled-Air Incinerator, Oak Ridge, TN
s. Waste Experimental Reduction Facility (WERF) Controlled-Air Incinerator, Idaho National Engineering Laboratory
t. Lawrence Livermore National Laboratory (LLNL) Transpiration Furnace, Livermore, CA

Velocities and mixing measurements identify the level of turbulence and homogeneity in a phase. A well-mixed phase supports an assumption that chemical constituents are in intimate contact with each other. A highly segregated phase can result in mass transfer-limited reactions and local chemical equilibria that yield a different concentration distribution. The degree of mixing can be quantified by multipoint measurements indicating where significant variations in properties occur as a function of position. Mixing may only be qualified by visual observations. Exit gas velocities are measured at the exit of the system whereas local gas velocities are real-time measurements made within the system itself. Other furnace operating conditions and parameters that may impact species partitioning include the presence of unmelted feed material on top of the molten phase (commonly referred to as a cold top) and molten slag properties such as viscosity. These variables may not have been measured directly but only characterized by visual observation.

When analyzing partitioning data from experimental tests, it is important to know whether the system is at or near steady state. Strictly defined, steady state implies all process variables (i.e., temperature, concentration, flow rates) do not vary significantly with respect to time. Steady-state conditions can only be achieved in continuous systems in which feed material and output streams are continually drawn in and out of the system, although continuous systems operated for short periods of time will not necessarily achieve steady state. Batch and semi-continuous systems can provide important partitioning data, but cannot be operated at steady-state conditions. Batch systems do not have feed material added during operation while semi-continuous systems may continually feed material over a limited time period. During these modes of operation, output streams are not withdrawn continually (except for gases and volatiles). In some cases, output streams may be withdrawn during a semi-continuous process but not in a continuous fashion. A thermal treatment system is considered to be at or near steady state if there is continual feeding of waste material and withdrawing of output streams while maintaining process variables at near constant values for a period of time significantly greater than the average feed solids or melt residence time. Operating periods at least four times greater than the average residence time are sufficient to meet this criterion.[64]

Measured process results include mass and mass flow rate exiting or remaining in the process, average process residence time of the solid and molten phases, elemental or species composition, and physical properties. The extent of this data collected from different thermal treatment systems for ceramic, ash, and metal phases are listed in Table 4.3; for offgas solids and offgas exiting the system in Table 4.4; and, for residual material accumulated and remaining within the process in Table 4.5.

The average residence time is an indication of how long feed material remains in the system until it is tapped out as a molten product or collected as bottom ash. Volatilized feed material has a short residence time in the system. Average solids residence times have been reported for incinerator systems. While not typically measured in melter systems, it can be calculated from feed or tap rates and molten phase volume. Longer residence times provide species with increased opportunity to partition into molten or gas phase. Feed partitioning to the offgas as entrained particulate or volatilized species might decrease if the feed material residence time was reduced. Physical properties of the system products include the number and type of phases, crystalline structure, particle size distribution, leachability, and density. In evaluating parameters of the offgas, it is important to note the location at which the sample or measurement is made. The offgas flow rate and composition could be measured at locations either in the plenum itself, at the exit of the plenum, or downstream of the plenum at various locations in the air pollution control system. The composition of the offgas was broken down into four key sub-groups that are typically measured using continuous emissions monitors or some other method. These sub-groups include: (1) oxygen and nitrogen, (2) carbon dioxide and water as products of complete combustion, (3) acid gases which may include NO_x, sulfur dioxide, hydrogen chloride, and other halogen gases, and (4) incomplete combustion products, which may include carbon monoxide, total hydrocarbons, and speciated hydrocarbons. For the holdup material it is important to note the location of the deposits formed besides evaluating other properties such as composition, phases, crystal structures, density, and other durability properties.

The thermal treatment plasma arc melter system with the most measured variables was the USBM AC arc melter. The mass or mass flow rate and composition were measured for the feed and all resulting phases and streams exiting the melter, including the offgas. The system temperature was measured in four distinct regions, including the melt itself. The phase structure and leachability of the glass-ceramic and offgas solids were determined. Data collection was extensive in the PNNL Bench-scale DC Arc Melter and the INEL Small Arc Melter but less so than for the USBM melter. The melt temperature was not measured directly in the PNNL system. The elemental compositions of the glass-ceramic, metal, and offgas solids were determined but no other properties were measured. The melt temperature was measured in the INEL melter but almost no sampling of the offgas or offgas solids was conducted. The only reaction product analyzed for elemental composition was the glass-ceramic. The rotary kiln incineration systems with the most comprehensive measurements were the EPA Incineration Research Facility and the Solid Waste Incineration Test Facility (SWIFT). The composition of the waste feed, bottom ash, and offgas solids were measured. In some tests, the particle size distribution of the offgas solids was measured. Material exiting the primary combustion chamber was not collected and sampled until it had passed through a secondary combustion chamber. The operating temperature in most incineration systems was characterized by the exit gas temperature.

The most measured variables in all systems include feed composition and system gas temperature. Feed composition may be reported by elements, chemical species, or bulk material type. In electric melter systems, voltage and current use are usually recorded. Chemical analysis of the solid and molten phases in the system and material transported in the offgas is frequently conducted. The least-common variables measured include melt and gas temperatures as a function of position, gas velocities within or exiting the treatment system, mixing characterization in the melt, measurement of mass and composition of offgas, and particle size distribution of material collected in the air pollution control system. 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.

4.2 Experimental Data Measurement Techniques

Measurement devices and methods used to measure temperature, elemental concentration, particle size distribution, and gas velocity in select thermal treatment systems and processes listed in Section 4.1 and Appendix A are summarized in Table 4.6. The capabilities and limitations of each device or method are discussed below.

4.2.1 Temperature

Thermocouples were the primary means of temperature measurement used in a variety of melter and incinerator systems. Thermocouples are simple and inexpensive, and provide a quick response time to changes in temperature, particularly in gas streams. A suction pyrometer (also known as a high-velocity temperature probe) was used to measure gas temperatures in the U.S. Bureau of Mines (USBM) melter[26] and in a differential bed reactor at the University of Utah.[11] A suction pyrometer shields the thermocouple from the radiant heat emitted from hotter regions in order to more accurately measure local gas temperatures.

Table 4-3. Glass-ceramic (or bottom ash) and metal product material information measured in key melters and incinerators.

	Glass-ceramic or bottom ash product									Metal product							
				Composition		Physical properties								Physical properties			
Test series	Rate	Mass	Avg. residence time	Elemental	Species	Phases, crystal structures, particle size	Leachability	Density	Other properties	Rate	Mass	Avg. residence time	Elemental composition	Phases, crystal structures	Leachability	Density	Other properties
1. PNNL Bench Scale DC Arc Furnace (Rad)[a] [16,17]																	
Initial		X		X							X		X				
2nd & 3rd		X		X							X		X				
3. INEL Small Arc Melter[b] [18-20]																	
Initial																	
F.O.																	
Mod I																	
Volatil.				X													
Redox				X		X											
PSPI																	
Mod II		X		X	X						X						
6. Mark I[c] [21]																	
8. Mark II[c] [22-24]																	
11. USBM AC, 3 Electrode Arc Melter[d] [25-29]																	
Phase 1	X	X			X	X	X	X			X						
Phase 2	X	X		X		X	X	X			X		X				
Ash	X	X		X		X	X	X			X		X				
WHC	X	X		X		X	X	X			X		X				
19. PHP POP[e] [30,31]	X	X		X	X	X	X	X	X		X		X				
22. PEAT[f] [32,33]							X										
26. PACT-1[g] [34]		X		X													
27. PACT-2[h] [35]				X		X	X										
28. PACT-6[i] [35,36]																	
Ce Series		X		X													

Table 4-3. Glass-ceramic (or bottom ash) and metal product material information measured in key melters and incinerators (continued).

	Glass-ceramic or bottom ash product									Metal product							
				Composition		Physical properties								Physical properties			
Test series	Rate	Mass	Avg. residence time	Elemental	Species	Phases, crystal structures, particle size	Leachability	Density	Other properties	Rate	Mass	Avg. residence time	Elemental composition	Phases, crystal structures	Leachability	Density	Other properties
Sludge Series						X	X										
NO_x Series						X	X										
62/63. MMT[j] [37,38]				X		X											
66. ACERC[k] [39-41]				X					X								
68. SWIFT[l] [42,43]			X	X	X	X			X								
69. TSCA[m] [44-46]			X	X			X										
71. EPA IRF[n] [47-50]		X	X	X	X		X										
73. Rollins[o] [51,52]																	
76. APTUS[p] [53,54]	X		X	X													
85. SEG[q] [56]																	
86. WERF[r] [57-59]		X		X			X										
89. LLNL TF[s] [14,60-63]		X		X	X	X											

a. Pacific Northwest National Laboratory, Richland, WA
b. Idaho National Enginering Laboratory, Idaho Falls, ID
c. Melter furnace, Massachusetts Institute of Technology, Cambridge, MA
d. Albany Research Center (formerly known as the U.S. Bureau of Mines), Albany, OR
e. Plasma Hearth Process (Proof of Principle Unit), Retech, Inc., Ukiah, CA
f. Plasma Energy Applied Technology Thermal Destruction and Recovery System, Huntsville, AL
g. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (1-ft ID), Retech, Inc., Ukiah, CA
h. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (1.5-ft ID), Retech, Inc., Ukiah, CA. Pu tests performed at Argonne National Laboratory-West.
i. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (6-ft ID), Retech, Inc., Ukiah, CA
j. Molten Metals Technology (MMT) Catalytic Extraction Process (CEP)
k. Advanced Combustion Engineering Research Center (ACERC) Bench-Scale Rotary Reactor, University of Utah
l. Solid Waste Incineration Test Facility (SWIFT) Rotary Kiln System, Energy and Environmental Research, Santa Ana, CA
m. Toxic Substance Control Act (TSCA) Mixed Waste Rotary Kiln Incinerator, Oak Ridge National Laboratory
n. Environmental Protection Agency (EPA) Incineration Research Facility (IRF) Rotary Kiln Incinerator, Jefferson, AK
o. Rollins Environmental Service Hazardous Waste Rotary Kiln Incinerator, Deer Park, TX
p. APTUS Hazardous Waste Rotary Kiln Incinerator, Coffeyville, KS
q. Scientific Ecology Group (SEG) Controlled-Air Incinerator, Oak Ridge, TN
r. Waste Experimental Reduction Facility (WERF) Controlled-Air Incinerator, Idaho National Engineering Laboratory
s. Lawrence Livermore National Laboratory (LLNL) Transpiration Furnace, Livermore, CA

Table 4-4. Offgas solids and offgas information measured in key melters and incinerators.

	Offgas solids								Offgas							
			Chemical Composition			Physical properties				Sample location			Chemical Composition			
Test series	Rate	Mass	Average elemental	Average species	Size-dependent	Phases, crystallinity, particle size	Leachability	Density	Flow rate	Plenum	Plenum exit	Post-APC	O_2, N_2	CO_2, H_2O	Acid gases[a]	Incomplete combustion products[b]
1. PNNL Bench Scale DC Arc Furnace (Rad)[c] [16,17]																
Initial		X	X						X			X	X	X		
2nd & 3rd		X	X						X			X	X	X		
3. INEL Small Arc Melter[d] [18-20]																
Initial																
F.O.																
Mod I																
Volatil.																
Redox																
PSPI																
Mod II																
6. Mark I Furnace[e] [21]				X		X										
8. Mark II Furnace[e] [22-24]									X		X	X		X	X	X
11. USBM AC, 3 Electrode Arc Melter[f] [25-29]																
Phase 1		X		X		X	X		X			O_2	X	X	SO_2, HCl	CO
Phase 2		X	X			X	X		X		X	O_2	X	X	X	X
Ash		X	X			X	X		X		X	X			SO_2, HCl	X
WHC		X	X			X	X		X		X	X				
19. PHP POP[g] [30,31]	X	X				X	X		X		X	X	X	X	X	X
22. PEAT[h] [32,33]												X	X	X	X	X
26. PACT-1[i] [34]	X	X														
27. PACT-2[j] [35]												X				
28. PACT-6[k] [35,36]																
Ce Series	X	X							X			X	O_2	CO_2	NO_x	X

Table 4-4. Offgas solids and offgas information measured in key melters and incinerators (continued).

	Offgas solids								Offgas							
			Chemical Composition			Physical properties				Sample location			Chemical Composition			
Test series	Rate	Mass	Average elemental	Average species	Size-dependent	Phases, crystallinity, particle size	Leachability	Density	Flow rate	Plenum	Plenum exit	Post-APC	O_2, N_2	CO_2, H_2O	Acid gases[a]	Incomplete combustion products[b]
Sludge Series			X						X			X	O_2	CO_2	NO_x	X
NO_x Series									X			X	O_2	CO_2	NO_x	X
62/63. MMT[l] [37,38]														CO_2		CO
66. ACERC[m] [39-41]			X								X					THC
68. SWIFT[n] [42,43]		X				X					X	X	O_2	CO_2	X	X
69. TSCA[o] [44-46]			X			X			X		X	X	X	X	X	CO
71. EPA IRF[p] [11-50]		X	X		X	X	X	X	X		X	X	O_2	CO_2	X	CO, HC
73. Rollins[q] [51,52]		X	X	X							X		X	CO_2	X	X
76. APTUS HWI[r] [53-55]		X	X						X		X	X	O_2	X	HCl	CO
85. SEG[s] [56]																
86. WERF[t] [57-59]		X	X				X		X		X		O_2			
89. LLNL TF[u] [14,60-63]									X		X					

a. Acid gases include NO_x, SO_2, HCl, and other halogen gases.
b. Incomplete combustion products include CO, total hydrocarbons (THC), and speciated hydrocarbons
c. Pacific Northwest National Laboratory, Richland, WA
d. Idaho National Engineering Laboratory, Idaho Falls, ID
e. Massachusetts Institute of Technology, Cambridge, MA
f. Albany Research Center (formerly known as the U.S. Bureau of Mines), Albany, OR
g. Plasma Hearth Process (Proof of Principle Unit), Retech, Inc., Ukiah, CA
h Plasma Energy Applied Technology Thermal Destruction and Recovery System, Huntsville, AL
i. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (1-ft ID), Retech, Inc., Ukiah, CA
j. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (1.5-ft ID), Retech, Inc., Ukiah, CA. Pu tests performed at Argonne National Laboratory-West.
k. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (6-ft ID), Retech, Inc., Ukiah, CA
l. Molten Metals Technology (MMT) Catalytic Extraction Process (CEP)
m. Advanced Combustion Engineering Research Center (ACERC) Bench-Scale Rotary Reactor, University of Utah
n. Solid Waste Incineration Test Facility (SWIFT) Rotary Kiln System, Energy and Environmental Research, Santa Ana, CA
o. Toxic Substance Control Act (TSCA) Mixed Waste Rotary Kiln Incinerator, Oak Ridge National Laboratory
p. Environmental Protection Agency (EPA) Incineration Research Facility (IRF) Rotary Kiln Incinerator, Jefferson, AK
q. Rollins Environmental Service Hazardous Waste Rotary Kiln Incinerator, Deer Park, TX
r. APTUS Hazardous Waste Rotary Kiln Incinerator, Coffeyville, KS
s. Scientific Ecology Group (SEG) Controlled-Air Incinerator, Oak Ridge, TN
t. Waste Experimental Reduction Facility (WERF) Controlled-Air Incinerator, Idaho National Engineering Laboratory
u. Lawrence Livermore National Laboratory (LLNL) Transpiration Furnace, Livermore, CA

Table 4-5. Hold-up material information measured in key melters and incinerators.

	Holdup and other interaction material (skull, deposition, refractory adsorption/dissolution, etc.)							
			Chemical Composition			Physical properties		
Test series	Mass	Location	Average elemental	Average species	Local and size-dependent	Phases, crystal structures	Density	Other durability properties
1. PNNL Bench Scale DC Arc Furnace (Rad)[a] [16,17]								
Initial	X	X						
2nd & 3rd	X	X						
3. INEL Small Arc Melter[b] [18-20]								
Initial								
F.O.								
Mod I								
Volatil.								
Redox								
PSPI								
Mod II	X	X						
6. Mark I Furnace[c] [21]								
8. Mark II Furnace[c] [22-24]								
11. USBM AC, 3 Electrode Arc Melter[d] [25-29]								
Phase 1								
Phase 2								
Ash								
WHC								
19. PHP POP[e] [30,31]								
22. PEAT[f] [32,33]								
26. PACT-1[g] [34]	X	X	X					
27. PACT-2[h] [35]								
28. PACT-6[i] [35,36]								
Ce Series		X	X					
Sludge Series		X	X			X		
NO$_x$ Series								

Table 4-5. Hold-up material information measured in key melters and incinerators (continued).

Test series	Holdup and other interaction material (skull, deposition, refractory adsorption/dissolution, etc.)							
			Chemical Composition			Physical properties		
	Mass	Location	Average elemental	Average species	Local and size-dependent	Phases, crystal structures	Density	Other durability properties
62/63. MMT[j] [37,38]								
66. ACERC[k] [39-41]			X					
68. SWIFT[l] [42,43]		X	X					
69. TSCA[m] [44-46]								
71. EPA IRF[n] [47-50]								
73. Rollins[o] [51,52]								
76. APTUS HWI[p] [53-55]								
85. SEG[q] [56]								
86. WERF[r] [57-59]		X	X					
89. LLNL TF[s] [14,60-63]		X	X					

a. Pacific Northwest National Laboratory, Richland, WA
b. Idaho National Enginering Laboratory, Idaho Falls, ID
c. Melter furnace, Massachusetts Institute of Technology, Cambridge, MA
d. Albany Research Center (formerly known as the U.S. Bureau of Mines), Albany, OR
e. Plasma Hearth Process (Proof of Principle Unit), Retech, Inc., Ukiah, CA
f. Plasma Energy Applied Technology Thermal Destruction and Recovery System, Huntsville, AL
g. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (1-ft ID), Retech, Inc., Ukiah, CA
h. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (1.5-ft ID), Retech, Inc., Ukiah, CA. Pu tests performed at Argonne National Laboratory-West.
I. Plasma Arc Centrifugal Treatment Rotating Hearth Furnace (6-ft ID), Retech, Inc., Ukiah, CA
j. Molten Metals Technology (MMT) Catalytic Extraction Process (CEP)
k. Advanced Combustion Engineering Research Center (ACERC) Bench-Scale Rotary Reactor, University of Utah
l. Solid Waste Incineration Test Facility (SWIFT) Rotary Kiln System, Energy and Environmental Research, Santa Ana, CA
m. Toxic Substance Control Act (TSCA) Mixed Waste Rotary Kiln Incinerator, Oak Ridge National Laboratory
n. Environmental Protection Agency (EPA) Incineration Research Facility (IRF) Rotary Kiln Incinerator, Jefferson, AK
o. Rollins Environmental Service Hazardous Waste Rotary Kiln Incinerator, Deer Park, TX
p. APTUS Hazardous Waste Rotary Kiln Incinerator, Coffeyville, KS
q. Scientific Ecology Group (SEG) Controlled-Air Incinerator, Oak Ridge, TN
r. Waste Experimental Reduction Facility (WERF) Controlled-Air Incinerator, Idaho National Engineering Laboratory
s. Lawrence Livermore National Laboratory (LLNL) Transpiration Furnace, Livermore, CA

Table 4-6. Measurement devices and methods used in select thermal treatment systems.

Thermal treatment system	Ref.	Measurement device or method			
		Temperature	Chemical composition	Physical characterization	Gas velocity or volumetric flow rate
1. PNNL Bench-scale DC Arc Furnace	16,17	Thermocouples Type 'K' (plenum) Type 'S' (hearth)	ICP[a]-AES[b] ICP-MS[c] (cations) Scintillation counter; Portable alpha monitor (Pu)	Particulates: Isokinetic sampling	Volumetric flow meters
3. INEL Small Arc Melter	18-20	Thermocouples: Type 'C' (slag) Type 'K' (offgas) RTD Optical pyrometer (melt surface)	ICP/AES FLAA[d] (Cs) SEM[e]/EDS[f] XRF[g] EPA Modified Method 5 (offgas train)	Crystallinity: XRD[h]	MKS mass flow meters, rotameters
6. Mark I Furnace	21	Thermocouple (furnace shell) Optical pyrometer (hearth)	ICP/AES FLAA	Crsyallinity: SEM/EDS Slag Leachability: TCLP[i]	Rotameter Calibrated differential pressure
8. Mark II Furnace	22-24	Thermocouple (offgas) Millimeter wave radiometer (Melt surface)	Offfgas: Microwave plasma analysis GC/MS	Particulates: Isokinetic sampling train	Dry gas flowmeter
11. USBM AC 3-Electrode Arc Melter	25-29	Thermocouples (shell, inner wall, hearth, gas, slag) Infrared pyrometer (tap hole slag)	ICAP[a] GFAAS[d] (cerium) CVAAS[j] (mercury) Instrumental NAA[k] (lanthanides, actinides) Offgas particulates/metals EPA Draft Method 29 Multiple Metals Train	Crystallinity: XRD Particle size: Sieve trays Slag density: Water displacement	Hot-wire anemometer (air) S-pitot tubes (offgas) Mass flow meters (air)
19. PHP (POP unit)	30,31	Thermocouple Offgas	ICAP AAS[d] XRF (coupon surface)	Particle size: Cascade impactor Crystallinity: XRD	S-type pitot tubes (offgas velocity)
21. PEC Tilt Furnace	65	Thermocouples (wall, hearth, melt)	ICP XRF (Al, Si, Fe oxides) SEM/EDS	Microstructure: SEM/EDS	
28. PACT-6	35,36	None	ICP-AES (Slag metals) SEM/EDS Hot-gas sampling system	Crystallinity: SEM/EDS Slag Leachability: TCLP	

Table 4-6. Measurement devices and methods used in select thermal treatment systems (continued).

Thermal treatment system	Ref.	Measurement device or method			
		Temperature	Chemical composition	Physical characterization	Gas velocity or volumetric flow rate
66.ACERC Rotary Reactor	39-41	Thermocouple	ICAP FLAA (cesium) EMPA[l] (Pb, Cr, Cd)	Morphology: SEM/EMPA	
68. Solid Waste Incineration Test Facility (SWIFT)	42,43	Thermocouples (gas) Thermocouples (refractory wall) Thermocouple (kiln bed)	Basic EPA Method 5 sampling train GC/MS (organics) ICAP (metals) AAS[d] (As, Hg, Se, Ti) CEMS (permanent gases)	Particulates: Gravimetric method Particle size: Cascade impactor	Flow meters and rotameters (air, natural gas, O_2)
69. TSCA Mixed Waste Rotary Kiln Incinerator	44-46	Thermocouples (gas)	ICP-MS SEM/EDS	Morphology: SEI/BEI[m]	
71. EPA IRF Rotary Kiln Incinerator	47-50	Thermocouples (gas, solids bed)	ICAP	Particle size: Cascade impactor	Volumetric flow meters
76. APTUS/Rollins HWI (Coffeyville, KS)	53-55	Thermocouples: K-type (offgas)	ICAP (toxic metals) AAS (Pb, As, Hg, Sb, Se) Gravimetric (particulate metal)	Modified Method 5 sampling train Afterburner particulates: Nonisokinetic sampling Other particulates: Isokinetic sampling	Gas velocity: EPA Method 2 S-type pitot tube
89. LLNL Transpiration Experiments	14,60-63	Thermocouple Type-K (gas)	ICP-MS (uranium) XRF XRD/TEM[n] α/γ counter (Pu,Am)	Morphology: XRD/TEM	Mass flow controllers
90. ACERC Differential Bed Reactor	11	Suction pyrometer (gas)	ICP		

a. Inductively coupled plasma/Inductively coupled argon plasma
b. Atomic emission spectroscopy
c. Mass spectroscopy
d. (Flame(FL)/Graphite furnace(GF)) atomic absorption spectroscopy (AAS)
e. Scanning electron microscopy
f. Energy dispersive spectroscopy
g. X-ray fluorescence
h. X-ray diffraction
i. Toxicity Characteristic Leaching Procedure
j. Cold vapor atomic absorption spectroscopy
k. Neutron activation analysis
l. Electron microprobe analyzer
m. Secondary electron imaging/Backscatter electron imaging
n. Transmission electron microscopy

Several methods of measuring or characterizing the temperature of molten phases in melter systems have been used. In the USBM melter, a sacrificial thermocouple was occasionally placed directly in the melt to measure the temperature before it was destroyed.[25] A thermocouple was placed directly in the melt in the Plasma Energy Corporation (PEC) Tilt Furnace.[65] A water-cooled thermocouple was eventually developed and used in the INEL Small Arc Melter to characterize slag temperatures without being destroyed.[18] The recorded temperature was a function of the slag temperature as well as the flow rate and temperature of the water cooling the probe. Another indirect measure of the melt temperature is the measurement of the hearth wall temperature. Thermocouples were placed in the bottom of the PNNL Bench-scale DC Arc Furnace to measure the hearth temperature.[16] This was the only indication of glass temperature. Thermocouples placed in refractory or attached to furnace walls also serve as a measure of refractory wear. Other systems that measured hearth or wall temperatures were the USBM melter[25] and the PEC tilt furnace.[65]

Optical pyrometers relate the spectral intensity of a radiating material to its temperature. Optical pyrometry has been used to nonintrusively measure the tapped slag temperatures in the USBM melter.[25] Since the method measures the slag temperature after it has passed through a water-cooled slag tap, the temperature measured was an indirect measurement of the slag melt temperature within the melter. A millimeter wave radiometer has been developed at the Massachusetts Institute of Technology as a new approach for measuring furnace and glass temperatures.[22] This instrumentation offers the potential advantages of measuring temperature in an environment not completely transparent to traditional infrared pyrometers and providing a spatially-resolved surface temperature profile in the furnace chamber. The millimeter wave radiometer has also been used to measure in-furnace temperatures in the PNNL engineering-scale melter[17] and will likely find applications in other furnace systems. This is one of few instruments with the potential to measure in-furnace melt surface temperature as a function of position, although further development and testing is required to demonstrate instrumentation accuracy and reliability.

Past experimental data and model results suggest that significant temperature gradients may exist within thermal systems, particularly a high-temperature melter system. Plasma temperatures can reach as high as 13,000 K, but temperatures just a few centimeters away are much lower at 9,000 K.[66] Particles passing through a plasma arc heat to temperatures approaching 3,000 K or higher, depending on particle size and plasma characteristics.[67] Finite-element process modeling of a graphite electrode arc melter suggests that the molten phase temperature at the centerline below the electrode can exceed 3,000 K.[68,69] Some melters, such as plasma arc centrifugal treatment (PACT) furnaces, are operated to minimize local hot spots by not having the energy source fixed relative to the waste or molten phase. However, is often difficult to measure the melt phase temperature in these systems.[35] Detailed temperature measurements in a molten phase as a function of position relative to the energy source in the PACT systems have not been conducted.

4.2.2 Element and Species Concentration

Different spectroscopic methods have been used to identify elemental compositions in waste feed, solid particulates, and solidified melts. Standard laboratory analysis of extracted samples includes inductively-coupled plasma spectroscopy (ICP) to identify the elemental composition of a sample matrix. Samples are heated to plasma temperatures so that the unique radiation emitted by each element can be measured by atomic emission spectroscopy (AES). ICP/AES were used to identify total metal concentrations in the product slags generated in the PACT-6 system.[35] A mass spectrometer (MS) can be used in conjunction with ICP to measure cations at lower detection levels than standard ICP. ICP-MS were used to analyze for up to 25 metals in the TSCA incinerator.[44] Better analysis sensitivities for some elements in some matrices can be achieved using graphite furnace atomic absorption spectroscopy (GFAAS). Various other spectroscopic methods have been used to identify specific elements. Cesium was analyzed by flame atomic absorption spectroscopy[18,39] and graphite furnace atomic absorption.[28] Cold-vapor atomic absorption spectroscopy was used to analyze for mercury.[28] Using neutron activation analysis was proposed to analyze a limited number of metal and slag phases.[27] X-ray fluorescence (XRF) was used to determine alumina, silica, and iron oxide contents in vitrified soils that could not be analyzed by ICP due to incomplete nitric acid leaching.[65]

Regardless of whether ICP or GFAAS is used, samples are generally first dissolved into solution by acid or microwave digestion before being introduced into the plasma. If complete dissolution of solid samples is not achieved and the entire sample or aliquot is not analyzed, then results of such analysis must be considered suspect. ICP analysis was used to identify chemicals leached from vitrified soil samples although the method could not be used on alumina, silica, and iron alumina-silicates that did not completely dissolve during the leaching procedure.[65] EPA Method 3050 specifies sample digestion by nitric acid, although a method using hydrofluoric acid has been used to achieve more complete sample digestion.[40] Hydrofluoric acid was used to prepare uranium for analysis during LLNL transpiration furnace experiments.[62]

Scanning electron microscopy (SEM) is usually closely associated with energy-dispersive x-ray spectroscopy (EDS) to obtain data on particle structure and crystallinity as well as elemental composition within the sample. Image analysis with the EDS technique allows elemental determinations to be made on either large field samples or on individual particles at higher magnification.[44] The imaging technique of backscattered electron imaging was used with SEM to identify uranium-containing particulates in an offgas stream.[44] SEM/EDS were used in conjunction to examine slag microstructure and identify the relative distribution of elements between glassy and crystalline phases in vitrified samples.[35,65] An electron microprobe analyzer was used in conjunction with SEM to identify chromium, lead, and cadmium in a cross-section of individual particles as a function of treatment temperature.[40] X-Ray diffraction was used to confirm the mineralogy of ash samples and used in conjunction with transmission electron microscopy (TEM) to identify phases present and disposition of uranium in uranium oxide-loaded ash samples.[60]

A variety of methods can be used with varying degrees of success to identify how the different elements are related chemically in compounds or crystals.[70] X-Ray fluorescence spectroscopy (XRF) is the only commonly-used analytical method that can identify molecular structures in solids. XRF can determine various phase formations in solids but cannot provide information on glassy or amorphous material that also may be present. X-Ray diffraction can identify molecular phases in solids, although obtaining quantitative results requires careful work with calibration samples. X-Ray photoelectron spectroscopy can determine molecular compositions by the differences in the energy level of photoelectrons due to molecular structure. An extremely sensitive detector is required to discriminate differences in photoelectron energy. Energy dispersive X-ray spectroscopy can be used to indirectly determine molecular compositions. Once the elemental composition has been measured by this method, computer software can be used to calculate the most probable molecular species using a thermodynamic database.

Radionuclide concentrations are often determined by the measuring the radiation emitted by the sample. A scintillation counter and a portable alpha counter have been used to measure plutonium concentration during experiments performed in the PNNL Bench-scale DC Arc Furnace.[16] During LLNL transpiration furnace experiments, a high alpha count in a dust filter due to PuO_2 entrainment enabled gamma counting to be used to more accurately measure plutonium[61], while uranium was detected by ICP-MS analysis.[62]

The analysis of metals and radionuclides in the exiting offgas stream is dependent on the sampling methods used to capture particulates and volatiles. A modified EPA Method 5 offgas sampling train consisting of a series of bubblers containing nitric acid solutions for the digestion of metals was used during tests in the INEL Small Arc Melter.[18] Total particulate and metals determinations were performed during USBM melter tests using the draft EPA Method 29 modified to include the measurement of total particulate in addition to metals.[26] A hot gas sampling train was designed to sample gases exiting the secondary combustion chamber of the PACT-6 melter without stream cooling that normally causes the premature condensation on exiting particulate matter, with a nonrepresentative sample of metal partitioning collected for analysis.[35] The hot gas sampling train method and equipment have not been fully perfected and are still considered developmental. Eventually, it is expected to obtain more representative particulate samples present at high temperatures in the offgas.

4.2.3 Particle Size Distribution

An Anderson cascade impactor train was used to determine the particle size distribution of the afterburner flue gas particulate in the EPA Incineration Research Facility rotary kiln incineration system.[49] In the same system, another series of tests determined particle size distributions by centrifugal classification.[47] Electro-optical scanning methods were used to examine samples of dispersed particles containing strontium and uranium collected in the air pollution control system downstream from the Toxic Substances Control Act (TSCA) incinerator.[44] Microcharacterization indicated that strontium-containing particulate was predominantly in the form of 10-μm diameter spherical particles. Uranium-containing particles were identified via backscattered electron imaging with a typical morphology of 10-30 μm hollowed spheres, suggesting suspension heating within the system, which is consistent with the liquid-waste-fired operation of the TSCA incinerator.

Similar instrumentation designed for the nonintrusive measurement of offgas properties is being developed. The use of two-color laser transmissometry to measure average particle diameter and particle number density in the offgas stream upstream and downstream of specific unit operations in an air pollution control system was investigated at the Diagnostic Instrumentation and Analysis Laboratory (DIAL).[71]

4.2.4 Gas Velocity

The easiest location to measure gas velocity or volumetric flow rate is after the gas exits the system. The average gas velocity inside the furnace can be calculated from the measured value after correcting for variations in gas temperature and system geometry. A number of systems used volumetric or mass flow meters to measure offgas flow rate in the offgas system. In gas streams with low particulate concentrations, conventional methods of measuring gas velocity, such as a pitot tube or hot-wire anemometer, have been used in the USBM melter[26] and an APTUS/Rollins hazardous waste incinerator.[55] The S-type pitot tubes are the only reliable standard method when a gas stream has significant particulate matter or high temperatures. The *in situ* gas velocity inside a field-scale rotary kiln incinerator was measured with a robust bi-directional probe sensitive for use in low velocity environments (as low as $0.3\ \text{m s}^{-1}$) and relatively insensitive to flow orientation.[72] Results indicated strong vertical stratification of velocity with the greatest values corresponding to the top of the kiln.

A mobile laser Doppler velocimeter developed at the DIAL has been used to measure particle velocities with a coal-fired furnace.[73] The laser and the optics were positioned on a base inside a mobile instrument laboratory. Two incident laser beams were transmitted via optical fibers (30 m long) to the test site. The two laser beams cross inside the test section that forms the probe volume. The use of a single pair of fiber optic links permits only single-component velocity measurement. The other perpendicular velocity component was measured by rotating the beams 90° at the probe head.

4.2.5 Simultaneous Multivariable Measurements

While not directly related to a thermal treatment process or system, a measurement system was developed at the Idaho National Engineering Laboratory that integrated a laser Doppler velocimeter (LDV) system with a scattered light particle size measurement and a high-speed two-color pyrometer for the simultaneous measurement of particle size, velocity, and temperature.[67] The particle size is determined from the absolute magnitude of scattered laser light, particle velocity is determined by a dual crossed-beam LDV, and temperature is determined from a measurement of light emitted by the individual incandescent particles at two wavelengths. This system was used to characterize particle behavior in a commercial plasma torch as it pertains to spray coating. The principles demonstrated in this system may be useful in characterizing key process variables within a thermal treatment process.

4.3 Evaluation of Existing Experimental Data

Results from tests and measurements for a number of lab-scale, pilot-scale, and full-scale test systems and production facilities were surveyed to determine if sufficient process data and results had been collected that could be used to identify significant partitioning mechanisms or validate partitioning models. The quality of data collected and reported from these processes was evaluated to determine its usefulness. From the 91 systems listed in Appendix A, test data from published reports and publications were obtained for 20 thermal treatment systems that consisted primarily of plasma arc melter and incinerator systems. Experimental data for most of these systems have been compiled in Appendix C. Other processes and systems were not considered because either they were not as applicable to heterogeneous mixed waste treatment or test data related to partitioning results were not readily available.

The quality of data available for these 20 thermal treatment systems in describing global and elemental mass balances, as well as species or elemental partitioning, was characterized as good, fair, or poor. Good experimental data are defined as being of sufficient quantity and quality that all partitioning mechanisms in an existing system can be identified and characterized as well as possibly provide insight into partitioning mechanisms in other similar systems. Experimental data of good quality reflect real conditions (waste feed composition, operating modes, and process conditions), are accurate (i.e., mass closures between 70-130%), and rely on a minimum number of assumptions. Fair experimental data are insufficient in quantity or quality to fully characterize all partitioning mechanisms in the system. Data collected may be accurate but incomplete so that only some partitioning mechanisms and elemental distributions can be quantified. Test configurations or operating conditions may not reflect conditions in a probable large-scale production system. Interpretation of experimental data may be based on many assumptions due to lack of process knowledge. Experimental data considered to be of poor quality consist of incomplete material balance data or extensive material balance data of highly questionable quality or accuracy. Data are inadequate for quantitative evaluations, although qualitative evaluations are possible. Data quality ratings for the 20 systems are summarized in Table 4.7. These ratings are in no way a reflection on the overall effectiveness of the system in treating mixed waste. The ratings in Table 4.7 simply reflect the number of process variables measured and reported as discussed in Section 4.1 and the accuracy and usefulness of the data collected in identifying elemental or species partitioning in the system.

A summary of global mass balance data from select thermal treatment systems is listed in Table 4.8. In many of these systems, elemental mass balances were determined by identifying the elemental mass or mass fraction of initial feed material in each output stream. In order to allow comparison of elemental partitioning between phases in different thermal treatment systems, the normalized mass percent of the initial

Table 4-7. Global mass balances and partitioning data assessment for select thermal treatment systems.

System	Grade	Comments
1. PNNL Bench Scale DC Arc Melter[16,17] Richland, WA	fair	1. Element mass balance closures varied widely over nine tests. 2. Plutonium partitioning data obtained. 3. Small scale, short run times, and semi-continuous operation mean steady state not achieved.
3. INEL Small Arc Melter[18-20] Idaho Falls, ID	fair	1. Fair general mass balance data. 2. Good element partitioning data for toxic metals and radionuclide surrogates.
6. Mark I Furnace[21] MIT, Cambridge, MA	fair	1. No mass balance data for APCS solids making closure impossible. 2. Most data are percentages rather than mass amounts. 3. Elemental composition analyses for slag and metals given. 4. Cs and Ce results are presented with insufficient background data.
8. Mark II Furnace[22-24] MIT, Cambridge, MA	poor	1. No general or elemental mass balance data presented.
11. USBM AC, 3-electrode Arc Melter[25-29] Albany Research Center, Albany, OR	good	1. Contains extensive global and elemental mass balance information.
19. Plasma Hearth Process (POP Unit)[30,31] Retech Inc., Ukiah, CA	fair	1. Contains detailed mass balance information on Ce and RCRA metals. 2. Semi-continuous process with short run times.
22. Plasma Energy Applied Tech. (PEAT) Thermal Destruction & Recovery System[32,33] Huntsville, AL	poor	1. No mass balance data are contained in the references.
26. Rotating Hearth Furnace (PACT-1)[34] TREAT Facility, ANL-W Idaho Falls, ID	fair	1. No global mass balance data presented. 2. Good mass balance data on Ce and Pu. 3. Total feed period = 12 minutes.
27. Plasma Arc Centrifugal Treatment (PACT-2)[35] Retech, Inc., Ukiah, CA	poor	1. No detailed material balance data presented.
28. Plasma Arc Centrifugal Treatment Furnace (PACT-6)[35,36] WETO Facility, Butte, MT	fair	1. Mass balance measurements are very difficult in this system since a "skull" of material remains in the rotating hearth.
62/63. Molten Metals Technology (MMT) Quantum-Catalytic Extraction Process (CEP)[37,38] Fall River, MA; Oak Ridge, TN	poor	1. No detailed material balance data presented. 2. Little or no operating data provided because of proprietary nature of process.

Table 4-7. Global mass balances and partitioning data assessment for select thermal treatment systems (continued).

System	Grade	Comments
66. ACERC Bench-scale Rotary Kiln Reactor[39-41] University of Utah, Salt Lake City, UT	fair	1. Toxic metals, radionuclide surrogate recoveries range between 40-120% attributed to sample/analysis method.
68. SWIFT Pilot-Scale Rotary Kiln System[42,43] Santa Ana, CA	good	1. Partitioning data for 10 metals at nine test conditions. 2. Some particulate concentration and particle size distribution data.
69. TSCA Mixed Waste Incinerator[44-46] Oak Ridge National Laboratory	fair	1. All radionuclide and metal go to air pollution control system.; therefore, no real partitioning data between phases in incinerator because there is no ash stream. 2. Some particle size distribution data obtained. 3. Tests not designed to indicate effect of varying process conditions.
71. EPA Incineration Research Facility[47-50] Jefferson, AK	good	1. Tests documenting operating conditions as well as total and elemental material balance data. 2. Waste feed and incinerator output stream well characterized for metal concentrations. 3. Particulate and offgas flow rate data measured in some tests.
73. Rollins Environmental Services[51,52] Deer Park, TX	poor	1. No total or elemental material balance data. 2. Limited metals emission rate data presented without identifying specific metal emission rates.
76. APTUS/Rollins HWI[53-55] Coffeyville, KS	fair	1. No overall material balance data but characterization of waste feed by element as well as the normalized elemental distribution between the slag and offgas provides insight to partitioning mechanisms.
85. SEG Radioactive Waste Incinerator[56] Oak Ridge, TN	poor	1. No general material balance data collected. 2. Few operating parameters reported. 3. Nuclide release expressed as percentage of predicted average releases.
86. WERF Incinerator[57-59] INEL, Idaho Falls, ID	poor	1. No specific test performed to conduct material balances. 2. Partitioning data are piecemeal. The data were collected during various burn campaigns. As a result, only qualitative statements of elemental partitioning can be made.
89. LLNL Transpiration Furnace[14,60-63] LLNL, Livermore, CA	fair	1. Extensive number of tests performed measuring reaction products from Pu and U-containing samples, but large portion of tests were invalid due to cross-contamination, sample sintering, and dust carryover.

Table 4-8. Global mass balance data in various thermal treatment systems.

Facility	% distribution of feed material to:				
	Ash/Slag	Metal	APCS solids	Offgas	Closure
EPA IRF[a]					
Test Series 1 [b,48]					
Test 4	58		13	29	100
Test 5	60		11	29	100
Test 6	54		14	32	100
Test 7	60		9	31	100
Test 8	60		11	29	100
Test 9	64		9	27	100
Test 10	55		10	35	100
Test 11	54		12	34	100
Test Series 2 [c,47]					
Test 1	65		4	31	100
Test 2	67		2	31	100
Test 3	67		1	32	100
Test 4	67		1	32	100
Test 5	65		4	31	100
Test 6	64		5	31	100
Test 7	64		4	32	100
Test 8	67		1	32	100
Test 9	67		2	31	100
INEL Small Arc Melter[d,18,19,20]					
Test 1[e]	83		3.66	13.34	100
Test 2[f]	85.2		2.66	12.14	100
Test 3[g]	84.72		5.39	9.89	100
Test 4[h]	85.43		2.19	12.39	100
Test 5[i]	80.62		1.62	17.76	100
Test 6[j]	84.35		2.81	12.84	100

a. Environmental Protection Agency Incineration Research Facility, Rotary Kiln Incinerator, Jefferson, AK.

b. Rotary kiln incinerator tests with a venturi/packed column scrubber. Integrated feed metal concentrations, range for tests 4-11 (ppm): As (19-33), Ba (33-39), Bi (75-120), Cd (4-6), Cr (61-68), Cu (230-310), Pb (26-34), Mg (16,100-17,900), Sr (140-200). Solids carryover in the APCS was assumed to be residual clay unaccounted for by kiln ash (100% clay) and assumed 7% water in original feed clay. Offgas fraction assumed to equal 100-% Feed in Kiln Ash - % Feed in APCS Solids.

c. Rotary kiln incinerator tests with a single stage ionizing wet scrubber. Integrated feed metal concentrations, range for 9 tests (ppm): As (36-56), Ba (295-460), Bi (260-400), Cd (8-12), Cr (37-45), Cu (290-445), Pb (39-50), Mg (18,100-19,900), Sr (315-480). Solids carryover in the APCS was assumed to be residual clay unaccounted for by kiln ash (100% clay) and assumed 7% water in original feed clay (excluding water added in aqueous metal solution). Offgas fraction assumed to equal 100 - % Feed in Kiln Ash - % Feed in APCS Solids.

d. Located at INEL Research Center, Idaho Falls. Volatilization tests done in FY-94. All tests used IEB4/A-40 having 5 wt% each of TiO_2 and ZrO_2 and with HVPMs & surrogates in oxide form at 1% each. Specific mat'ls used were PbO, ZnO, CdO, Cr_2O_3 as the HVPMs and Cs_2CO_3, CeO_2, Sm_2O_3 as surrogate radionuclides. The controlled parameters tested included: cold cap vs non-cold cap conditions, using or not using a graphite feed tube extender, and thermally desorbing water from the simulated waste mix prior to processing in the arc melter. Mass of starter ring subtracted from total slag mass before calculating global mass balance. Offgas percentage distribution was calculated assuming 100% closure.

e. ARM082394: 0.75 kg IEB4/A-40, no cold cap, no extension tube, 22.6 g/min for 100 min., 2.257 kg fed. Max. slag temp.=2005°C.

f. ARM082694: 1.5 kg IEB4/A-40, cold cap, no extension tube, 97.9 g/min for 33 min., 3.23 kg fed. Max. slag temp.=2113°C.

g. ARM090694: 1.5 kg IEB4/A-40, no cold cap, extension tube, 56.8 g/min for 52 min., 2.95 kg fed. Max. slag temp.=1962°C.

h. ARM090894: 1.5 kg IEB4/A-40, cold cap, extension tube, 70.3 g/min for 47 min., 3.303 kg fed. Max. slag temp.=1677°C.

i. ARM092094: 1.5 kg IEB4/A-40, no cold cap, extension tube, thermal desorption, 84.6 g/min f or 48 min., 4.063 kg fed. Max. slag temp.=1625°C.

j. ARM092294: 1.683 kg IEB4/A-40, cold cap, extension tube, thermal desorption, 115.8 g/min for 30 min., 3.473 kg fed. Max. slag temp.=1763°C.

Table 4-8. Global mass balance data in various thermal treatment systems, (continued).

	% distribution of feed material to:				
Facility	Ash/Slag	Metal	APCS solids	Offgas	Closure
USBM[k]					
Phase 1[l,25,27]					
S60[m]	84.4	0.37	1.32	10.3	96
S60-IV[n]	84.3	0.01	1.97	13.3	99
N80-Interval[o]	88.4	0.73	2.76		108
N80-IV-Interval[p]	83.6	1.73	2.27	14.3	101
M60-Interval[q]	78.4	11.8	1.82	10.7	102
Phase 2[r,26,28]					
BWID nominal avg.[s]	66	10	9	22	105
IWPF + Cleanout[t]	54	6	6	29	94
Plasma Hearth Process POP Tests[u,30,31]					
M1[v]	43.6		2.45	-1.81	44.2
M2[v]	60		2.35	1.45	63.8
M3[w]	63.8		3.45	3.52	70.8
M4[w]	74.1		3.7	5.78	83.6
M5[x]	55.1		7.25	3.12	65.4
M6[x]	43.3		4.12	1.1	48.5

k. United States Bureau of Mines, AC 3-electrode Arc Melter, DOE Albany Research Center, Albany, Oregon.

l. FY-93 Phase 1 (baseline) test program. Test feed mixtures were prepared by mixing soil from the RWMC with selected buried waste surrogate materials. All waste mixtures contained 0.35-0.42% CeO_2 added as a surrogate for the TRU radionuclides, particularly PuO_2.

m. S60: The S-0 series is organic oils and solvents immobilized by mixing with Micro-Cell E ($CaSiO_3$) and Oil-Dri (SiO_2). S60 is 60% RWMC soil and 40% simulated thermally oxidized S-0. Gypsum (CaSO4.2H2O) and NaCl were added to provide the desired S and Cl concentrations.

n. S60-IV: This is the S60 mixture with added zircon (66% ZrO_2) and ilmenite (65% TiO_2) to provide around 3% ZrO_2 and 6% TiO_2 in the feed mixture.

o. N80/N80-Mod: N-0 contains evaporator salts and consists mostly of Na and K nitrates with limited amounts of other wastes and small amounts of Oil-Dri. The surrogate waste mixture N80 is 80% RWMC soil and 20% simulated N-0. For N80-Mod the N80 mixture was modified (to reduce slag viscosity) w/limestone & mill scale in the ratio 100 lb N80:37.5 lb limestone:20.7 lb mill scale.

p. N80-IV/N80-IV-Mod: This is the N80 mixture with additions of zirconia and ilmenite to provide around 3% ZrO_2 and 6% TiO_2 in the feed mixture. In N80-IV-Mod the N80-IV was modified (to reduce slag visc.) w/pebble lime & mill scale in the ratio 22.4 lb CaO & 20.7 lb mill scale for every 100 lb N80-IV.

q. M60/M60-Mod: The M-0 waste is a variety of unleached scrap metals. M60 is 60% RWMC soil and 40% simulated thermally oxidized M-0 waste, assumed to be primarily elemental metals, not metal oxides. For M60-Mod the N80-IV-Mod mixture w/add'l pebble lime was fed. A 3-lb metal alloy ingot (50%Ce, 50%Fe) was added to investigate partitioning of metallic Ce.

r. FY-95 Phase 2 test program. Feed mixtures were nonradioactive surrogates for mixed and alpha-contaminated waste at the INEL SDA and TSA.

s. The BWID test mixtures were designed to be a nominal mixture of buried waste and soil. The nominal composition was 37.5% hazardous metals, 24.3% solid combustibles, 23.25% silicated organics, 7.29% nitrate salts, and 7.66% metal hydroxide sludges.

t. The IWPF series consisted of two waste types: (1) liquid chlorinated and nonchlorinated organics absorbed in silica-based absorbents, and (2) solid combustibles such as paper, rags, and plastic.

u. Proof of Principle (POP) PHP Unit at RETECH, Ukiah, CA. Metal and slag phase were reported as total solid phase. Offgas mass flowrate calculated as: (exhaust gas - feed gas input)*mass flowrate.

v. Inorganic sludge: 3.5% activated C, 3.5% cationic exchange resin, 40% water, 10% vermiculite, 14% iron oxide, 10.5% hydrated lime, 7% alumina blasting grit, 7% NaNO3, 3.5 MgO, 0.4% RCRA metals (0.1% each Cd, Cr, Pb, Ni), 0.3% cerium (IV) oxide, 0.3% cesium chloride.

w. Heterogeneous debris: 5% activated C, 5% cationic exchange resin, 10% water, 10% bulk alumina refractory, 16% wood, 5% PVC gloves, 10% latex gloves, 10% mild steel, 10% glass bottles, 8% concrete, 10% diatomaceous earth, 0.4% RCRA metals (0.1% each Cd, Cr, Pb, Ni), 0.3% cerium (IV) oxide, 0.3% CsCl.

x. Organic sludge: 10% activated C, 5% cationic exchange resin, 15% water, 10% vermiculite, 10% iron oxide, 10% hydrated lime, 5% alumina blasting grit, 10% ethylene glycol, 10% lathe cutting oil, 7% mineral oil, 0.1% each Cd, Cr, Pb, Ni, 3.5% napthalene, 3.5% 1,2-dichlorobenzene, 0.3% cerium (IV) oxide, 0.3% CsCl.

feed element in a particular phase of a thermal treatment system was tabulated. The normalized mass percent of a feed element in an output stream is defined as the ratio of the element mass in the output stream to the total element mass identified in all output streams. The normalization of the data does not reflect whether closure on the overall elemental mass balance was achieved. In normalizing the data, the assumption is made that the errors that lead to poor elemental mass closure are random and affect all output streams equally. The normalized mass percent of a feed element in the ceramic-glass and metal phases in different plasma arc melters is listed in Tables 4.9 and 4.10, respectively. The normalized mass percent of a feed element in the bottom ash collected from different incinerators is summarized in Table 4.11. The normalized weight percent of a feed element collected in the air pollution control system (APCS) from various thermal treatment systems is summarized in Table 4.12. The normalized mass percents of feed elements exiting a furnace were inferred from data collected from the APCS, which consists of one or more processes designed to collect or eliminate specific components, particulates, liquids, or gases.

In reviewing the experimental results from the thermal treatment systems, some elements exhibit high volatility and, in many cases, partition almost completely (greater than 90% feed) to the offgas phase exiting 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, furnace temperature, chlorine content in the waste feed, and waste type.

Increases in the feed concentrations that are relatively low can result in greater volatilization until the local gas phase is saturated. This is particularly true with elements with high vapor pressures. There is also greater potential for experimental error due to sampling and analytical error, feed material segregation, and poor material recovery at low feed concentrations. 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 for which greater partitioning to the air pollution control system at low feed concentrations were observed included 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 appeared to partition increasingly to the offgas with increasing temperature included 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 were reported to be 100% in the SWIFT rotary kiln incinerator. This was due in part to the atomization of the liquid feed as well as the absence of significant bottom ash to analyze. In the same system with solid waste types, the percentage of feed elements in the air pollution control system was significantly less.

While one or more operating parameters were observed to affect elemental partitioning, not all experimental data necessarily indicated a particular functionality. In the following sections, the accuracy of global mass balances as well as the extent and nature of elemental partitioning data are reviewed.

4.3.1 Global mass balances

In many of the melter and incinerator treatment systems, global mass balances were not rigorously conducted. Material balances at the EPA Incineration Research Facility measured the mass of the bottom ash and solid material collected in the air pollution control system although the fraction of feed material exiting in the offgas was not measured but calculated by difference. One system in which global mass balances were rigorously conducted was the DOE Albany Research Center [formerly U.S. Bureau of Mines (USBM)] AC 3-phase, 3-electrode arc melter.[25,26] Experimental data from the USBM system usually included measurements of mass or mass flow rates of the surrogate waste feed, the glass-ceramic product, the metal phase, the offgas solids collected in the air pollution control system, and the offgas vented to the environment. Elemental sample analysis looked for more than 40 elements. Total mass closure between 90 and 110% were achieved. In experiments with the INEL small arc melter[18], the mass and composition of the surrogate waste feed, slag, accumulation in the melt chamber above the slag, and particulates captured in the exhaust lines and filter trains were measured. No offgas flow rate or composition measurements were made. Global mass balance closures between 80and 90% were achieved with the difference being attributed to unmeasured gaseous evolution of volatilized moisture and carbonate decomposition products. Tests were performed under semi-continuous conditions with no slag or metal phases tapped during the tests. The Plasma Hearth Process proof-of-principle test unit was operated in batch mode for a period of two hours to demonstrate its ability to process surrogate mixed waste streams.[30] The average total mass balance closure was 88%.

4.3.2 Toxic and hazardous metals partitioning

Solid waste is considered a hazardous waste if its exhibits the characteristic of toxicity. Eight specific metals listed under the Resource Conservation and Recovery Act (RCRA) regulations, if found in concentrations equal to or in excess of maximum limits in the extract from a Toxicity Characteristic Leaching Procedure (TCLP) conducted on a representative sample of waste, result in solid waste being designated as hazardous waste. The metals include arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver.[74] Universal treatment standards identifying wastewater and nonwastewater treatment standard levels for the most prohibited hazardous wastes includes limits for the eight metals listed above as well as antimony, beryllium, nickel, thallium, vanadium, and zinc.[74]

In the EPA Incineration Research Facility (IRF), average material balances for 9 metals ranged between 25 to 150%.[47] In the Plasma Hearth Process proof-of-principle test unit, the mass closure for volatile toxic metals ranged between 25 to 300%. Accuracy of elemental mass balances is highly dependent on the total element mass. In the USBM AC arc melter, mass balances on elements present in large quantities ranged between 90 to 110%.[26] The distribution of feed material between phases varies depending on the feed composition, element concentration in the feed, and operating conditions. In the EPA IRF, the partitioning of feed barium, cadmium, and lead to the ash increased when low feed concentrations were increased by an order of magnitude.[47,48] As discussed in Section 3.1, after the gas phase reaches its saturation concentration for each of these metals, additional feed metal will accumulate in the ash. Conversely, when the waste feed consists mainly of liquid organic waste with little ash content, a significant fraction of feed metals exits from the furnace and is collected in the air pollution control system. This was seen in the USBM AC arc melter[25] and the TSCA mixed waste incinerator.[44]

Enrichment of metals in the fine-particulate fractions was observed in the afterburner offgas of the EPA IRF with an average of about 50% of the flue-gas particulate material less than 10µm.[47]

Table 4-9. Normalized mass percent of feed element in slag/glass from various melters.

Facility	PNNL[a,16]									PACT-1[b,34]			
Series #	1[c]	2[d]	3[e]							1[f]		2[g]	
Run #			1[h]	2[i]	3[j]	4[k]	5[l]	6[m]	7[n]	1[o]	2[p]	1[q]	2[r]
Element													
Ag	99.34	99.16		66.67	87.88								
Al	97.68	99.2	99.35	97.49	97.77	92.26	96.4	96.32	95.67				
Ba	94.89	98.68	98.64	98.46	95.01	92.53	95.56	96.7	96.43				
Ca	95.74	98.72	99.38	98.01	98.11	93.26	96.06	97.07	96.27				
Ce	99.98	99.99	99.1	96.01	94.23	88.66	99.71	96.72	93.94	99.96	99.91		
Cr			98.05		88.02	85.09	53.39	89.2	73.07				
Mg	95.24	92.51	97.61	90.91	92.67	85.13	92.15	82.57	87.83				
Mn	89.15	97.74	98.83	96.65	94.11	85.23	93.56	90.38	94.39				
Ni	62.17	99.65	89.79	4.26	4.64	5.8	5.83	88.44	26.99				
P	54.34	98.41					0	95.31	0				
Pb		0	0	18.59	0	0	0	0	0				
Pu	98.61	99.98	99.85	98.75	99.17	93.31	97.39	92.99	97.51			99.95	99.97
Ti	97.96	99.68	99.86	99.66	98.88	92.93	97.68	94.13	97.38				
Zn		0	78.79			0	0	0	84.88				

a. Pacific Northwest National Laboratory Bench scale DC Arc Furnace (Rad).

b. Rotating Hearth Furnace (PACT-1) at the TREAT Facility, ANL-W.

c. Metals-R: surrogate consists of INEL soil, lime, and metals (approx. 50% by mass; mostly carbon steel). "R" designation refers to a reducing process atmosphere. Plutonium nitrate solution added to a concentration of 300 nCi/g.

d. S-0: waste composed of organic wastes, oils, and solvents absorbed on Micro-Cell E and Oil Dri. Contains no mixed soil. Contains highest fraction of volatile organics and chlorides of any TRU-contaminated waste at INEL. Plutonium also added to 300 nCi/g concentration.

e. Nom-60: consists on nominal INEL waste blended with 60% INEL soil nominal composition. Waste consists of materials such as metals, solid combustibles, silicated organics, nitrate salts, and metal hydroxide sludges.

f. Ukiah tests, August 10th and 12th, 1993, using transuranic surrogate cerium oxide. The feeding period lasted about 12 minutes with a feed rate of 12 kg/hr.

g. Idaho tests, Nov. 16th and 18th, 1993, at TREAT. Tests were performed with plutonium. The feeding period lasted about 12 min. at a feed rate of 12 kg/hr.

h. Nom-60 with no additives (baseline).

i. Nom-60 with 75 x lead of that in baseline mixture.

j. Nom-60 with 5 x iron of that in baseline mixture.

k. Nom-60 with 2.5 x sodium of that in baseline mixture.

l. Nom-60 with 2 x chloride of that in baseline mixture.

m. Nom-60 with 5 x carbon of that in baseline mixture. Of 745 g of feed material fed to the system, approximately 485 g of the feed was unmelted and surrounded the metal product.

n. Nom-60 with high plenum oxygen.

o. Low metals content. A 2600 g charge (INEL soil, water) was added to the hearth and melted prior to adding the feeder charge (INEL soil, water, CeO_2).

p. High content of metals and organic chlorides. Hearth charge (INEL soil, water, iron) melted first, then added feeder charge (INEL soil, water, PVC, CeO_2).

q. No metals. Hearth and feeder charges consisted of only INEL soil. Feeder charge contained 5660 nCi of plutonium.

r. High content of metals and organic chloride. Hearth charge of INEL soil and iron; Feeder charge had INEL soil, PVC, and 7660 nCi of plutonium.

Table 4-9. Normalized mass percent of feed element in slag/glass from various melters, (continued).

Facility	PACT-6[s]	USBM[t]							INEL Small Arc Melter[u,18,19,20]					
Series #		1[v,25,27]					2[w,26,28]							
Run #	1-4[x,35,36]	1[y]	2[z]	3[aa]	4[bb]	5[cc]	1[dd]	2[ee]	1[ff]	2[gg]	3[hh]	4[ii]	5[jj]	6[kk]
Element														
Al		99	99.1	98.3	98.4	98.9	96.4	87.5	98.9	99.08	98.41	99.61	99.66	99.62
As				41.3	49.5	10.8	0	0						
Ba		96.3	96.7	96.1	94.9	94.2	88.3	37.2						
Ca		98.4	96.3	98.7	98.3	97.6	93.5	87.9	96.39	92.3	96.84	99.39	99.81	99.63
Cd							0	0	16.53	14.55	1.68	2.19	20.07	1.18
Ce	99.76	97.4	98.1	97.4	93.9	96.3	99.7	99.4	94.87	97.78	96.71	98.51	98.98	98.64
Cr		99.3	99.2	98.3	97.5	55.6	2.29	0.37	98.49	98.39	90.07	97.33	98.34	98.04
Cs		61.8	54.9		10	79.6	2.88	0	78.8	76.33	53.39	82.39	84	83.59
Fe		99.1	99.3	99	99.3	21.6	6.94	19.2	41.53	45.09	46.3	55.78	58.24	62.57
K							49.5	0.34	93.2	95.69	88.55	96.62	97.7	97.41
Mg		99.84	99	98.6	98.6	98.6	90	23.1	95.26	93.42	94.3	98.61	98.58	99.25
Na							38.6	5.1	88.43	90.32	88.42	95.1	94.09	93.69
Ni		97.9	98.1	97	98.3	3.4	0.22	1.29	95.96	98.75	99.27	83.63	97.23	93.87
P		54.7	38.2	59.4	46.4	23.7	8.58	13.8	74.35	77.74	62.96	82.88	85.24	47.72
Pb		74.8	48.2	52.2	64.5	10.9	0.21	0	23.36	44.4	18.59	38.98	48.52	12.32
Si		98.8	99.1	98.2	98	94.6	89.3	64.3	98.56	99.03	98.51	99.05	99.31	98.87
Sm									86.67	96.69	97.36	84.22	98.09	98.72
Ti		99.6	99.8	99.8	99.8	98.6	83	46.3	99.6	99.22	96.92	97.54	99.7	99.45
Zn		70.5	72.5	58.6	77.9	29.4	5.69	1.47	30.02	73.92	48.75	47.83	52.98	15.25
Zr		99.3	99.99		95.1	86.5	98.9	98.4	99.6	99.22	96.92	97.54	99.7	99.45

s. Plasma Arc Centrifugal Treatment Furnace (PACT-6), WETO Facility, Butte, MT.

t. United States Bureau of Mines, AC 3-electrode Arc Melter, Albany Research Center, Albany, Oregon.

u. Located at INEL Research Center, Idaho Falls. Volatilization tests done in FY-94. All tests used IEB4/A-40 having 5 wt% each of TiO_2 and ZrO_2 and w/HVPMs & surrogates in oxide form at 1% each. Specific mat'ls used were PbO, ZnO, CdO, Cr_2O_3 as the HVPMs and Cs_2CO_3, CeO_2, Sm_2O_3 as surrogate radionuclides. The controlled parameters tested included: cold cap vs non-cold cap conditions, using or not using a graphite feed tube extender, and thermally desorbing water from the simulated waste mix prior to processing in the arc melter.

v. FY-93 Phase 1 (baseline) test program. Test feed mixtures were prepared by mixing soil from the RWMC with selected buried waste surrogate materials. All waste mixtures contained 0.35-0.42% CeO_2 added as a surrogate for the TRU radionuclides, particularly PuO_2.

w. FY-95 Phase 2 test program. Feed mixtures were nonradioactive surrogates for mixed and alpha-contaminated waste at the INEL SDA and TSA.

x. A significant amount of solidified melt accumulated in the system over the three tests. The normalized distribution was calculated using the total amount of cerium collected in the offgas and slag pour during the three tests.

y. S60: The S-0 series is organic oils and solvents immobilized by mixing with Micro-Cell E ($CaSiO_3$) and Oil-Dri (SiO_2). S60 is 60% RWMC soil and 40% simulated thermally oxidized S-0. Gypsum ($CaSO_4 \cdot 2H_2O$) and NaCl were added to provide the desired S and Cl concentrations.

z. S60-IV: This is the S60 mixture with added zircon (66% ZrO_2) and ilmenite (65% TiO_2) to provide around 3% ZrO_2 and 6% TiO_2 in the feed mixture.

aa. N80/N80-Mod: N-0 contains evaporator salts and consists mostly of Na and K nitrates with limited amounts of other wastes and small amounts of Oil-Dri. The surrogate waste mixture N80 is 80% RWMC soil and 20% simulated N-0. For N80-Mod the N80 mixture was modified (to reduce slag viscosity) w/limestone & mill scale in the ratio 100 lb N80:37.5 lb limestone:20.7 lb mill scale.

bb. N80-IV/N80-IV-Mod: This is the N80 mixture with additions of zirconia and ilmenite to provide around 3% ZrO_2 and 6% TiO_2 in the feed mixture. In N80-IV-Mod the N80-IV was modified (to reduce slag visc.) w/pebble lime & mill scale in the ratio 22.4 lb CaO & 20.7 lb mill scale for every 100 lb N80-IV.

cc. M60/M60-Mod: The M-0 waste is a variety of unleached scrap metals. M60 is 60% RWMC soil and 40% simulated thermally oxidized M-0 waste, assumed to be primarily elemental metals, not metal oxides. For M60-Mod the N80-IV-Mod mixture w/add'l pebble lime was fed. A 3-lb metal alloy ingot (50%Ce, 50%Fe) was added to investigate partitioning of metallic Ce.

dd. The BWID test mixtures were designed to be a nominal mixture of buried waste and soil. The nominal composition was 37.5% hazardous metals, 24.3% solid combustibles, 23.25% silicated organics, 7.29% nitrate salts, and 7.66% metal hydroxide sludges.

ee. The IWPF series consisted of two waste types: (1) liquid chlorinated and nonchlorinated organics absorbed in silica-based absorbents, and (2) solid combustibles such as paper, rags, and plastic.

ff. ARM082394: 0.75 kg IEB4/A-40, no cold cap, no extension tube, 22.6 g/min for 100 min., 2.257 kg fed.

gg. ARM082694: 1.5 kg IEB4/A-40, cold cap, no extension tube, 97.9 g/min for 33 min., 3.23 kg fed.

hh. ARM090694: 1.5 kg IEB4/A-40, no cold cap, extension tube, 56.8 g/min for 52 min., 2.95 kg fed.

ii. ARM090894: 1.5 kg IEB4/A-40, cold cap, extension tube, 70.3 g/min for 47 min., 3.303 kg fed.

jj. ARM092094: 1.5 kg IEB4/A-40, no cold cap, extension tube, thermal desorption, 84.6 g/min f or 48 min., 4.063 kg fed.

kk. ARM092294: 1.683 kg IEB4/A-40, cold cap, extension tube, thermal desorption, 115.8 g/min for 30 min., 3.473 kg fed.

Table 4-9. Normalized mass percent of feed element in slag/glass from various melters, (continued).

Facility	Plasma Hearth Process POP Tests[ll,30,31]					
Series #	1[mm]		2[nn]		3[oo]	
Run #	M1	M2	M3	M4	M5	M6
Element						
Al	95.69	96.96	97.74	98.77	95.8	94.38
C	32.13	25.37	39.78	35.71	11.74	10.91
Ca	97.8	98.46	97.37	99.01	94.66	96.92
Cd	4.25	5.99	3.57	4.76	1.07	1.48
Ce	99.44	99.61	94.87	95.24	95.8	97.22
Cl		27.67	4.8	4.41		1.63
Cr	87.65	91.07	88.1	92.31	82.01	88.73
Cs	5.59	7.83	4.42	21.05	1.07	1.48
Fe	96.6	97.61	91.23	81.63	66.47	75
K	30.74	38.93				
Mg	99.72	99.8	99.46	99.48	98.15	99.18
Mn			58.12	60	71.7	38.65
Na	61.21	73.91	52.61	66.67	3.66	13.04
Ni	93.01	92.73	59.68	75	39.45	63.64
P			64.91	93.75	77.38	90.43
Pb	6.63	9.26	5.26	6.25	2.95	9.5
S			15.61	75	43.18	34.43
Si	88.59	90.53	93.04	95.24	89.53	90.59
Zn			0.61	0.99	0.94	11.19

ll. Proof of Principle (POP) Unit at RETECH, Ukiah, CA.

mm. Inorganic sludge: 3.5% activated C, 3.5% cationic exchange resin, 40% water, 10% vermiculite, 14% iron oxide, 10.5% hydrated lime, 7% alumina blasting grit, 7% NaNO3, 3.5 MgO, 0.4% RCRA metals (0.1% each Cd, Cr, Pb, Ni), 0.3% cerium (IV) oxide, 0.3% cesium chloride.

nn. Heterogeneous debris: 5% activated C, 5% cationic exchange resin, 10% water, 10% bulk alumina refractory, 16% wood, 5% PVC gloves, 10% latex gloves, 10% mild steel, 10% glass bottles, 8% concrete, 10% diatomaceous earth, 0.4% RCRA metals (0.1% each Cd, Cr, Pb, Ni), 0.3% cerium (IV) oxide, 0.3% CsCl.

oo. Organic sludge: 10% activated C, 5% cationic exchange resin, 15% water, 10% vermiculite, 10% iron oxide, 10% hydrated lime, 5% alumina blasting grit, 10% ethylene glycol, 10% lathe cutting oil, 7% mineral oil, 0.1% each Cd, Cr, Pb, Ni, 3.5% napthalene, 3.5% 1,2-dichlorobenzene, 0.3% cerium (IV) oxide, 0.3% CsCl.

Table 4-10. Normalized mass percent of feed element in metal phase from various melters.

Facility	PNNL[a,16]									USBM[b]		
Series #	1[c]	2[d]	3[e]							1[f, 25,27]	2[g,26,28]	
Run #			1[h]	2[i]	3[j]	4[k]	5[l]	6[m]	7[n]	5[o]	1[p]	2[q]
Element												
Ag	0			33.33	11.98						0	3.97
Al	2.206		0	0	0.97	5.3	2.12	1.42	2.496	0.3	0.04	0
As										82.4	84.6	17.51
Ba	4.9		0.95	0	4.42	6.31	3.33	0.806	2.68	0.6	0.78	0.09
Ca	3.19		0	0	0.94	5.18	2.46	0	2.07	0.2	0	0
Ce	0		0.84	3.84	5.75	11.26	0	2.74	5.9	<0.1	0	0
Cr			1.86		11.93	14.91	46.52	10.72	26.53	44.1	97.51	93.94
Cs										1	0	0
Fe										78.1	92.18	63.18
Mg	3.12		0	0	3.05	5.995	2.49	0	3.17	0.3	0	0
Mn	10.765		0.78	2.48	5.47	14.49	4.86	6.09	4.62		69.96	22.66
Ni	37.74		10.2	95.51	95.33	94.1	94.06	11.3	72.42	96.5	99.63	93.77
P	45.49						97.26	3.03	92.9	64.5	78.59	13.77
Pb			0	14.74	20.69	0	0	0	0	16.8	10.44	0.57
Pu	1.39		0	0.56	0.83	6.61	1.74	5.74	2.07			
Si										2.2	2.56	0.52
Ti	2.03		0	0	0.97	6.28	2.04	5.34	2.39	0.6	13.52	6.08
Zn			3.03			57.69	0	2.9	3.49	4.8	0	0
Zr										0.2	0.96	0.59

a. Pacific Northwest National Laboratory Bench scale DC Arc Furnace (Rad).

b. United States Bureau of Mines, AC 3-electrode Arc Melter, Albany Research Center, Albany, Oregon.

c. Metals-R: surrogate consists of INEL soil, lime, and metals (approx. 50% by mass; mostly carbon steel). "R" designation refers to a reducing process atmosphere. Plutonium nitrate solution added to a concentration of 300 nCi/g.

d. S-0: waste composed of organic wastes, oils, and solvents absorbed on Micro-Cell E and Oil Dri. Contains no mixed soil. Contains highest fraction of volatile organics and chlorides of any TRU-contaminated waste at INEL. Plutonium also added to 300 nCi/g concentration.

e. Nom-60: consists on nominal INEL waste blended with 60% INEL soil nominal composition. Waste consists of materials such as metals, solid combustibles, silicated organics, nitrate salts, and metal hydroxide sludges.

f. FY-93 Phase 1 (baseline) test program. Test feed mixtures were prepared by mixing soil from the RWMC with selected buried waste surrogate materials. All waste mixtures contained 0.35-0.42% CeO_2 added as a surrogate for the TRU radionuclides, particularly PuO_2.

g. FY-95 Phase 2 test program. Feed mixtures were nonradioactive surrogates for mixed and alpha-contaminated waste at the INEL SDA and TSA.

h. Nom-60 with no additives (baseline).

i. Nom-60 with 75 x lead of that in baseline mixture.

j. Nom-60 with 5 x iron of that in baseline mixture.

k. Nom-60 with 2.5 x sodium of that in baseline mixture.

l. Nom-60 with 2 x chloride of that in baseline mixture.

m. Nom-60 with 5 x carbon of that baseline mixture. Of 745 g of feed material fed to the system, approximately 485 g of the feed was unmelted and surrounded the metal product.

n. Nom-60 with high plenum oxygen.

o. M60: The M-0 waste is a variety of unleached scrap metals. M60 is 60% RWMC soil and 40% simulated thermally oxidized M-0 waste, assumed to be primarily elemental metals, not metal oxides.

p. The BWID test mixtures were designed to be a nominal mixture of buried waste and soil. The nominal composition was 37.5% hazardous metals, 24.3% solid combustibles, 23.25% silicated organics, 7.29% nitrate salts, and 7.66% metal hydroxide sludges.

q. The IWPF series consisted of two waste types: (1) liquid chlorinated and nonchlorinated organics absorbed in silica-based absorbents, and (2) solid combustibles such as paper, rags, and plastic.

Table 4-11. Normalized mass percent of feed element in bottom ash from various incinerators.

Facility	ACERC[a,39,40,41]							SWIFT[b,42,43]								
Series #																
Run #	1[c]	2[d]	3[e]	4[f]	5[g]	6[h]	7[i]	1[j]	2[k]	3[l]	4[m]	5[n]	6[o]	7[p]	8[q]	9[r]
Element																
Ag								70	24	70	70	82	92	0	0	93
As								94	99	99	80	92	99			95
Ba								98	98	99	98	99	98			98
Cd	18	10	30			45	20	8	10	10	34	13	26	0	0	8
Cr	58	25	45	50	30			96	96	99	97	97	96	0	0	97
Hg								0	0	0	0	0	0	0	0	0
Ni								98	98	99	98	99	98	0	0	98
Pb	62			48	38	47	22	21	13	23	51	40	62	0	0	62
Sb								96	98	99	99	99	99			100
Tl								13	15	29	18	18	13	0	0	29

a. Advanced Combustion Engineering Research Center, Bench-scale Rotary Reactor. Composition of surrogate: peat (12%), water (71%), FeSO4 (6%), CaCO3 (12%). Ultimate analysis: water (73.75%), C (8.4%), H (0.86%), N (0.18%), S (1.08%), Cl (<0.01%), O (6.11%), Ash (9.62%). A spiking solution containing the toxic metals Cd, Cr, Pb, and Ni was added to the waste mixture as aqueous solutions. The metal concentration in the spiking solution was: Cd (1895 ppm), Cr (1720 ppm), Pb (4752 ppm), and Ni (1905 ppm).

b. Solid Waste Incineration Test Facility, Rotary Kiln System. Solid Waste Type E: paper (45%), polyethylene (25%), latex (20%), PVC (10%); Solid Waste Type F: paper (55%), polyethylene (25%), latex (20%); Liquid Waste Type G: benzene (95%), chlorobenzene (5%). Metal conc. (mg/kg feed)
Types E/F: Sb (538), As (38), Ba (85,741), Cd (9), Cr (1,860), Pb (7,426), Hg (446), Ni (7,297), Ag (5,435), Tl (545).
Type G: Cd (10), Cr (2,267), Pb (9,114), Hg (542), Ni (8,963), Ag (6,663), Tl (663).

c. Base feed composition (Ca=5%), kiln temp.=815°C, purge gas=ambient air.

d. Base feed minus calcium carbonate (Ca=0%), kiln temp.=815°C, purge gas=ambient air.

e. Base feed plus calcium carbonate (Ca=10%), kiln temp.=815°C, purge gas=ambient air.

f. Base feed composition (Ca=5%) plus NaCl (Cl=5%), kiln temp.=815°C, purge gas=ambient air.

g. Base feed composition (Ca=5%) plus PVC (Cl=5%), kiln temp.=815°C, purge gas=ambient air.

h. Base feed composition (Ca=5%), kiln temp.=815°C, purge gas=1% CO in N_2.

i. Base feed composition (Ca=5%), kiln temp.=980°C, purge gas=ambient air.

j. Waste type E, PCC temp. of 1832°F, SCC temp. of 2012°F, salt present in scrubber water.

k. Waste type E, PCC temp. of 1832°F, SCC temp. of 2012°F, salt present in scrubber water.

l. Waste type E, PCC temp. of 1832°F, SCC temp. of 2012°F, no salt present in scrubber water.

m. Waste type F, PCC temp. of 1832°F, SCC temp. of 2012°F, no salt present in scrubber water.

n. Waste type E, PCC temp. of 1600°F, SCC temp. of 1800°F, salt present in scrubber water.

o. Waste type F, PCC temp. of 1600°F, SCC temp. of 1800°F, salt present in scrubber water.

p. Waste type G, PCC temp. of 1832°F, SCC temp. of 2012°F, salt present in scrubber water. Since this is a liquid waste, no kiln ash was generated.

q. Waste type G, PCC temp. of 1600°F, SCC temp. of 1800°F, salt present in scrubber water. Since this is a liquid waste, no kiln ash was generated.

r. Waste type E, PCC temp. of 1400°F, SCC temp. of 1600°F, salt present in scrubber water.

Table 4-11. Normalized mass percent of feed element in bottom ash from various incinerators, (continued).

Facility	EPA IRF[s]										APTUS[t,53,54,55]	
Series #	1[u,48]	2[v,47]	3[w,49]				4[x,50]				1[gg]	2[hh]
Run #			1[y]	2[z]	3a[aa]	3b[bb]	1[cc]	2[dd]	3[ee]	4[ff]		
Element												
Ag											90.59	95.85
As	94.6	93	96.8	76.9	ND	ND	70.2	68.3	69.3	87.8	23.82	74.73
Ba	88.6	97	97.8	94.2	69	70	92.2	91.3	92.3	92	97.56	97.45
Be											99.69	99.83
Bi	70	72									98.2	99.09
Ca											100	0
Cd	<28.9	46	91	87.8	ND	ND	22.5	42.9	59.5	75.6	81.68	93.6
Cr			88.9	68.5	83	69	67.8	84	85.1	90.8	99.27	99.85
Cu	84.8	91	99	94.9	75	88					92.95	88.56
Hg			31.4	3.47	< 31	< 35	<87.5	<92.3	<92.3	<91.7	27.19	16.06
Mg	99.8	99.93									99.7	99.57
Mn											98.57	99.07
Ni			88.3	70.3	129	108					99.38	99.26
Pb	35.5	94	99.1	90.5	52	68	91.1	89.5	88.1	92.7	18.32	17.71
Sb											46.19	52.97
Se											99.58	93.11
Sr	99.7	99.4									80.55	87.1
Te											100	100
Tl											98.37	30.69
Zn			98.4	94.6	48	81					15.03	37.1

s. Environmental Protection Agency Incineration Research Facility, Rotary Kiln Incinerator, Jefferson, AK.

t. APTUS Hazardous Waste Rotary Kiln Incinerator, Coffeyville, KS. The 5 feed streams that made up the feed matrix were: contaminated soil (PCBs), contaminated soil (PCBs) and latex paint, debris (largely paint filters), blended liquids containing PCBs, and aqueous waste with negligible metals content. A surrogate metals mixture included Bi, Mg, Sr added in solid form to each drum fed to the kiln. Copper was present at sufficient concentrations in the shredded capacitors.

u. Rotary kiln incinerator tests with a venturi/packed column scrubber. Integrated feed metal concentrations, range for tests 4-11 (ppm): As (19-33), Ba (33-39), Bi (75-120), Cd (4-6), Cr (61-68), Cu (230-310), Pb (26-34), Mg (16,100-17,900), Sr (140-200). Kiln exit temperatures ranged from 825-928°C.

v. Rotary kiln incinerator tests with a single-stage ionizing wet scrubber. Integrated feed metal concentrations, range for 9 tests (ppm): As (36-56), Ba (295-460), Bi (260-400), Cd (8-12), Cr (37-45), Cu (290-445), Pb (39-50), Mg (18,100-19,900), Sr (315-480). Kiln exit temperatures ranged from 819-929°C for the 9 tests.

w. Test series on contaminated soils from Drake Chemical Superfund Site.

x. Test series on contaminated soil from Chemical Insecticide Corporation (CIC) Superfund Site. Target kiln exit gas temperature was 1800°F.

y. Metal concentration in feed, ppm: As (16), Ba (167), Cd (1.1), Cr (18), Cu (49), Pb (439), Hg (0.1), Ni (17), Se (<10), Ag (<2), Zn (302). Kiln temp. of 824°C.

z. Metal concentration in feed, ppm: As (62), Ba (57), Cd (2), Cr (12), Cu (43), Pb (77), Hg (0.3), Ni (15), Se (<10), Ag (<2), Zn (251). Kiln temp. of 824°C.

aa. Metal concentration in feed, ppm: As (11), Ba (194), Cd (<1), Cr (20), Cu (35), Pb (443), Hg (0.2), Ni (12), Se (<10), Ag (<2), Zn (272). Kiln temp. of 824°C. Only the composition in the kiln ash was reported, therefore, normalization of the numbers was not performed.

bb. Same metal concentration in feed as Test 3a. Test 3b was performed at a kiln temperature of 546°C. Only the composition of the kiln ash was reported, therefore, normalization of the numbers was not performed.

cc. Soil feed composition in mg/kg: chlordane (14), alpha-BHC (<2), gamma-BHC (<2), p,p'-DDE (5.5), p,p'-DDD (7.3), p,p'-DDT (65).

dd. Soil feed composition in mg/kg: chlordane (17), alpha-BHC (<2), gamma-BHC (<2), p,p'-DDE (6.7), p,p'-DDD (7.3), p,p'-DDT (92).

ee. Soil feed composition in mg/kg: chlordane (<10), alpha-BHC (<2), gamma-BHC (<2), p,p'-DDE (3.4), p,p'-DDD (4.3), p,p'-DDT (41).

ff. Soil feed composition in mg/kg: chlordane (13), alpha-BHC (<2), gamma-BHC (<2), p,p'-DDE (4.8), p,p'-DDD (6.4), p,p'-DDT (46).

gg. Condition 1 had a waste feed chlorine content of approximately 10%. Caustic slag containing appreciable quantities of Pb, As, Zn, and Sb was added to each drum of solids feed. Condition 1 has 2-3 times the feed rate of Cr, Cu, Pb, and Zn. The As level is 2 orders of magnitude higher than for Condition 2. The Be level is also substantially higher.

hh. Condition 2 had a waste feed chlorine content of approximately 20%. Tellurium slag containing Te, Sb, Pb, Ni, and Zn was added. The Te level is 50 times higher than for Condition 1. The kiln was operated at 1700°F, while the afterburner was maintained at 2206°F.

Table 4-12. Normalized mass percent of feed element captured in the APCS of various thermal treatment systems.

Facility	PACT-1[a,34]				PACT-6[b,35,36]	INEL Small Arc Melter[c,18,19,20]					
Series #	1[d]		2[e]								
Test #	1[f]	2[g]	1[h]	2[i]	1-4[j]	1[k]	2[l]	3[m]	4[n]	5[o]	6[p]
Element											
Al						1.1	0.92	1.59	0.39	0.34	0.38
Ca						3.61	7.7	3.16	0.61	0.19	0.37
Cd						83.47	85.45	98.32	97.81	79.93	98.8
Ce	0.04	0.09			0.24	5.13	2.22	3.29	1.49	1.02	1.36
Cr						1.51	1.61	9.93	2.67	1.66	1.96
Cs						21.2	23.67	46.61	17.61	16	16.4
Fe						0.81	0.59	1.91	0.6	0.35	0.68
K						6.8	4.31	11.45	3.38	2.3	2.59
Mg						4.74	6.58	5.7	1.39	1.42	0.75
Na						11.57	9.68	11.58	4.9	5.91	6.31
Ni						4.04	1.25	0.73	16.37	2.77	6.13
P						25.65	22.26	37.04	17.12	14.76	52.3
Pb						76.64	55.6	81.41	61.02	51.48	87.7
Pu			0.05	0.03							
Si						1.44	0.97	1.49	0.95	0.69	1.13
Sm						13.33	3.31	2.64	15.78	1.91	1.28
Ti						0.4	0.78	3.08	2.46	0.3	0.55
Zn						69.98	26.08	51.25	52.17	47.02	84.8
Zr						0.4	0.78	3.08	2.46	0.3	0.55

a. Rotating Hearth Furnace (PACT-1) at the TREAT Facility, ANL-W.

b. Plasma Arc Centrifugal Treatment Furnace (PACT-6), WETO Facility, Butte, MT.

c. Located at INEL Research Center, Idaho Falls. Volatilization tests done in FY-94. All tests used IEB4/A-40 having 5 wt% each of TiO_2 and ZrO2 and w/HVPMs & surrogates in oxide form at 1% each. Specific mat'ls used were PbO, ZnO, CdO, Cr_2O_3 as the HVPMs and Cs2CO3, CeO2, Sm2O3 as surrogate radionuclides. The controlled parameters tested included: cold cap vs non-cold cap conditions, using or not using a graphite feed tube extender, and thermally desorbing water from the simulated waste mix prior to processing in the arc melter.

d. Ukiah tests, August 10th and 12th, 1993, using transuranic surrogate cerium oxide. The feeding period lasted about 12 minutes with a feed rate of 12 kg/hr.

e. Idaho tests, Nov. 16th and 18th, 1993 at TREAT. Tests were performed with plutonium. The feeding period lasted about 12 min. at a feed rate of 12 kg/hr.

f. Low metals content. A 2600 g charge (INEL soil, water) was added to the hearth and melted prior to adding the feeder charge (INEL soil, water, CeO2).

g. High content of metals and organic chlorides. Hearth charge (INEL soil, water, iron) melted first, then added feeder charge (INEL soil, water, PVC, CeO2).

h. No metals. Hearth and feeder charges consisted of only INEL soil. Feeder charge contained 5660 nCi of plutonium.

i. High content of metals and organic chloride. Hearth charge of INEL soil and iron; Feeder charge had INEL soil, PVC, and 7660 nCi of plutonium.

j. A significant amount of solidified melt accumulated in the system over the three tests. The normalized distribution was calculated using the total amount of cerium collected in the offgas and slag pour during the three tests.

k. ARM082394: 0.75 kg IEB4/A-40, no cold cap, no extension tube, 22.6 g/min for 100 min., 2.257 kg fed.

l. ARM082694: 1.5 kg IEB4/A-40, cold cap, no extension tube, 97.9 g/min for 33 min., 3.23 kg fed.

m. ARM090694: 1.5 kg IEB4/A-40, no cold cap, extension tube, 56.8 g/min for 52 min., 2.95 kg fed.

n. ARM090894: 1.5 kg IEB4/A-40, cold cap, extension tube, 70.3 g/min for 47 min., 3.303 kg fed.

o. ARM092094: 1.5 kg IEB4/A-40, no cold cap, extension tube, thermal desorption, 84.6 g/min f or 48 min., 4.063 kg fed.

p. ARM092294: 1.683 kg IEB4/A-40, cold cap, extension tube, thermal desorption, 115.8 g/min for 30 min., 3.473 kg fed.

Table 4-12. Normalized mass percent of feed element captured in the APCS of various thermal treatment systems, (continued).

Facility	PNNL[q,16]							
Series #	1[r]	2[s]	3[t]					
Test #			1[u]	2[v]	3[w]	4[x]	5[y]	6[z]	7[aa]
Element								
Ag	0.66	0.84		0	0.14				
Al	0.11	0.8	0.65	2.51	1.26	2.44	1.48	2.27	1.83
Ba	0.21	1.32	0.41	1.54	0.57	1.16	1.11	2.5	0.89
Ca	1.06	1.28	0.61	1.99	0.94	1.55	1.48	2.93	1.66
Ce	0.02	0.01	0.07	0.15	0.02	0.07	0.29	0.55	0.16
Cr			0.09		0.05	0	0.1	0.07	0.4
Mg	1.64	7.49	2.39	9.09	4.28	8.87	5.35	17.43	8.99
Mn	0.08	2.26	0.39	0.87	0.42	0.28	1.58	3.53	0.99
Ni	0.09	0.35	0.01	0.22	0.03	0.09	0.12	0.26	0.59
P	0.16	1.59					2.74	1.66	7.1
Pb		100	100	66.67	79.31	100	100	100	100
Pu	0	0.02	0.15	0.69	0	0.08	0.87	1.27	0.41
Ti	0.02	0.32	0.14	0.34	0.16	0.29	0.28	0.53	0.22
Zn		100	18.18			42.31	100	97.1	11.63

q. Pacific Northwest National Laboratory Bench scale DC Arc Furnace (Rad).

r. Metals-R: surrogate consists of INEL soil, lime, and metals (approx. 50% by mass; mostly carbon steel). "R" designation refers to a reducing process atmosphere. Plutonium nitrate solution added to a concentration of 300 nCi/g.

s. S-0: waste composed of organic wastes, oils, and solvents absorbed on Micro-Cell E and Oil Dri. Contains no mixed soil. Contains highest fraction of volatile organics and chlorides of any TRU-contaminated waste at INEL. Plutonium also added to 300 nCi/g concentration.

t. Nom-60: consists on nominal INEL waste blended with 60% INEL soil nominal composition. Waste consists of materials such as metals, solid combustibles, silicated organics, nitrate salts, and metal hydroxide sludges.

u. Nom-60 with no additives (baseline).

v. Nom-60 with 75 x lead of baseline concentration.

w. Nom-60 with 5 x iron of baseline concentration.

x. Nom-60 with 2.5 x sodium of baseline concentration.

y. Nom-60 with 2 x chloride of baseline concentration.

z. Nom-60 with 5 x carbon of baseline concentration. Of 745 g of feed material fed to the system, approximately 485 g of the feed was unmelted and surrounded the metal product.

aa. Nom-60 with high plenum oxygen.

Table 4-12. Normalized mass percent of feed element captured in the APCS of various thermal treatment systems, (continued).

Facility	USBM[bb]							Plasma Hearth Process POP Tests[cc,30,31]					
Series #	1[dd, 25,27]					2[ee,26,28]		1[ff]		2[gg]		3[hh]	
Test #	1[ii]	2[jj]	3[kk]	4[ll]	5[mm]	1[nn]	2[oo]	M1	M2	M3	M4	M5	M6
Element													
Ag						100	96						
Al	1	0.9	1.7	1.6	0.8	3.52	12.5	4.31	3.04	2.26	1.23	4.2	5.62
As			58.7	50.5	6.8	15.4	82.5						
Ba	3.7	3.3	3.9	5.1	5.2	10.9	62.7						
C						21.4	41.2	67.9	74.6	60.2	64.3	88.3	89.1
Ca	1.6	3.7	1.3	1.7	2.2	6.5	12.1	2.2	1.54	2.63	0.99	5.34	3.08
Cd						100	100	95.8	94	96.4	95.2	98.9	98.5
Ce	2.6	1.9	2.6	6.1	3.6	0.3	0.57	0.56	0.39	5.13	4.76	4.2	2.78
Cl						99.7	99.4		72.3	95.2	95.6		98.4
Cr	0.7	0.8	1.7	2.5	0.3	0.2	5.68	12.3	8.93	11.9	7.69	18	11.3
Cs	38.2	45.1		90	19.4	97.1	100	94.4	92.2	95.6	78.9	98.9	98.5
Cu						1.47	23.2						
Fe	0.9	0.7	1	0.7	0.3	0.88	17.7	3.4	2.39	8.77	18.4	33.5	25
Hg						100	100						
K						50.5	99.7	69.3	61.1				
Mg	0.16	1	1.4	1.4	0.1	9.98	76.9	0.28	0.2	0.54	0.52	1.85	0.82
Mn						7.45	76.8			41.9	40	28.3	61.4
Mo						11.1							
Na						61.4	94.9	38.8	26.1	47.4	33.3	96.3	87
Ni	2.1	1.9	3	1.7	0.1	0.15	4.94	6.99	7.27	40.3	25	60.6	36.4
Pb	25.2	51.8	47.8	35.5	72.3	89.4	99.4	93.4	90.7	94.7	93.8	97.1	90.5
P	45.3	51.8	40.6	53.6	11.8	12.8	72.4			35.1	6.25	22.6	9.57
S						78.3	80.2			84.4	25	56.8	65.6
Se						100	100						
Si	1.2	0.9	1.8	2	1.4	8.13	35.1	11.4	9.47	6.96	4.76	10.5	9.41
Ti	0.4	0.2	0.2	0.2	0.8	3.45	47.6						
Zn	29.5	27.5	41.4	22.1	65.8	94.3	98.5			99.4	99	99.1	88.8
Zr	0.7	0.01		4.9	13.3	0.16	0.98						

bb. United States Bureau of Mines, AC 3-electrode Arc Melter, Albany Research Center, Albany, Oregon.

cc. Proof of Principle (POP) Unit at RETECH, Ukiah, CA.

dd. FY-93 Phase 1 (baseline) test program. Test feed mixtures were prepared by mixing soil from the RWMC with selected buried waste surrogate materials. All waste mixtures contained 0.35-0.42% CeO_2 added as a surrogate for the TRU radionuclides, particularly PuO_2.

ee. FY-95 Phase 2 test program. Feed mixtures were nonradioactive surrogates for mixed and alpha-contaminated waste at the INEL SDA and TSA.

ff. Inorganic sludge: 3.5% activated C, 3.5% cationic exchange resin, 40% water, 10% vermiculite, 14% iron oxide, 10.5% hydrated lime, 7% alumina blasting grit, 7% NaNO3, 3.5 MgO, 0.4% RCRA metals (0.1% each Cd, Cr, Pb, Ni), 0.3% cerium (IV) oxide, 0.3% cesium chloride.

gg. Heterogeneous debris: 5% activated C, 5% cationic exchange resin, 10% H_2O, 10% bulk alumina refractory, 16% wood, 5% PVC gloves, 10% latex gloves, 10% mild steel, 10% glass bottles, 8% concrete, 10% diatomaceous earth, 0.4% RCRA metals (0.1% ea Cd,Cr,Pb,Ni), 0.3% CeO_2, 0.3% CsCl.

hh. Organic sludge: 10% activated C, 5% cationic exchange resin, 15% water, 10% vermiculite, 10% iron oxide, 10% hydrated lime, 5% alumina blasting grit, 10% ethylene glycol, 10% lathe cutting oil, 7% mineral oil, 0.1% each Cd, Cr, Pb, Ni, 3.5% napthalene, 3.5% 1,2-dichlorobenzene, 0.3% cerium (IV) oxide, 0.3% CsCl.

ii. S60: The S-0 series is organic oils and solvents immobilized by mixing with Micro-Cell E ($CaSiO_3$) and Oil-Dri (SiO_2). S60 is 60% RWMC soil and 40% simulated thermally oxidized S-0. Gypsum (CaSO4.2H2O) and NaCl were added to provide the desired S and Cl concentrations.

jj. S60-IV: This is the S60 mixture with added zircon (66% ZrO_2) and ilmenite (65% TiO_2) to provide around 3% ZrO_2 and 6% TiO_2 in the feed mixture.

kk. N80/N80-Mod: N-0 contains evaporator salts and consists mostly of Na and K nitrates with limited amounts of other wastes and small amounts of Oil-Dri. The surrogate waste mixture N80 is 80% RWMC soil and 20% simulated N-0. For N80-Mod the N80 mixture was modified (to reduce slag viscosity) w/limestone & mill scale in the ratio 100 lb N80:37.5 lb limestone:20.7 lb mill scale.

ll. N80-IV/N80-IV-Mod: This is the N80 mixture with additions of zirconia and ilmenite to provide around 3% ZrO_2 and 6% TiO_2 in the feed mixture. N80-IV-Mod, N80-IV was modified (reduce slag visc.) w/pebble lime & mill scale in ratio 22.4 lb CaO & 20.7 lb mill scale for every 100 lb N80-IV.

mm. M60/M60-Mod: The M-0 waste is a variety of unleached scrap metals. M60 is 60% RWMC soil and 40% simulated thermally-oxidized M-0 waste, assumed to be primarily elemental metals, not metal oxides. For M60-Mod the N80-IV-Mod mixture w/add'l pebble lime was fed. A 3-lb metal alloy ingot (50%Ce, 50%Fe) was added to investigate partitioning of metallic Ce.

nn. The BWID test mixtures were designed to be a nominal mixture of buried waste and soil. The nominal composition was 37.5% hazardous metals, 24.3% solid combustibles, 23.25% silicated organics, 7.29% nitrate salts, and 7.66% metal hydroxide sludges.

oo. The IWPF series consisted of two waste types: (1) liquid chlorinated and nonchlorinated organics absorbed in silica-based absorbents, and (2) solid combustibles such as paper, rags, and plastic.

Table 4-12. Normalized mass percent of feed element captured in the APCS of various thermal treatment systems, (continued).

Facility	TSCA[pp,44,45,46]							SWIFT[qq,42,43]								
Series #	2[rr]			3[ss]												
Test #	1[tt]	2[uu]	3[vv]	2[ww]	3[xx]	4[yy]	5[zz]	1[aaa]	2[bbb]	3[ccc]	4[ddd]	5[eee]	6[fff]	7[ggg]	8[hhh]	9[iii]
Element																
Ag				61	55	49	48	30	76	30	30	18	8	100	100	7
As								6	1	1	20	8	1	100	100	5
Ba								2	2	1	2	1	2	100	100	2
Be				65	70	49	36									
Cd								92	90	90	66	87	74	100	100	92
Cr				141	105	97	88	4	4	1	3	3	4	100	100	3
Cs				74	82	61	47									
Hg								100	100	100	100	100	100	100	100	n/a
Mo				150	140	123	79									
Ni								2	2	1	2	1	2	100	100	2
Pb				99	110	63	45	79	87	77	49	60	38	100	100	38
Sb								4	2	1	1	1	1	100	100	0
Sr				90	87	68	63									
Tl								87	85	71	82	82	87	100	100	71
U	4.3	30.1	70.9	78	81	52	37									

pp. Toxic Substances Control Act Incinerator at the K-25 site in Oak Ridge, TN. TSCA only reported the mass % of feed material in APCS; therefore, normalization of the data was not performed.

qq. Solid Waste Incineration Test Facility, Rotary Kiln System. Solid Waste Type E: paper (45%), polyethylene (25%), latex (20%), PVC (10%); Solid Waste Type F: paper (55%), polyethylene (25%), latex (20%); Liquid Waste Type G: benzene (95%), chlorobenzene (5%). Metal conc. (mg/kg feed) Types E/F: Sb (538), As (38), Ba (85,741), Cd (9), Cr (1,860), Pb (7,426), Hg (446), Ni (7,297), Ag (5,435), Tl (545). Type G: Cd (10), Cr (2,267), Pb (9,114), Hg (542), Ni (8,963), Ag (6,663), Tl (663).

rr. Feed consisted of two separate feeds: aqueous feed, ppm: U (229), P (2500), S (<500), PCB (4.1), Cl (<500), ash (0.1%); Organic feed: U (0.398 ppm), P (7510 ppm), S (4753 ppm), PCB (3000 ppm), Cl (10.475% organic), ash (1.81%).

ss. The feed for this study was a blend of 3 types of waste: Primary organic: ash (0.42%), Cl (<0.1%), F (0.0072%), S (0.3531%), Pb (18,21,24 ppm), Be (3.7, 4,4.2 ppm), Hg (2 ppm), PCB (100 ppm), U (23.9 Bq/g). Secondary organic: ash (0.08%), Cl (0.1089%), F (0.0046%),S (0.3515%), Pb (<8.1,<8.2,<8.2 ppm), Be (0.99,1.1,1.2 ppm), Hg (0.67,0.7,0.71 ppm), PCB (92 ppm), U (5.96 Bq/g) Aqueous feed: (ash (<0.02%), Cl (<0.1%), F (0.0005%), S(<0.1%), Pb (<7.3,<7.4,<7.4 ppm), Be (<0.044,<0.044,<0.045 ppm), Hg (<0.08 ppm), PCB (34 ppm), Sr (110 ppm), Cs (57 ppm), U (0.007 Bq/g)

tt. 8/27/90 primary feed analysis (ug/g): Al (22), Ba (5.4), Be (0.31), Cd (<0.3), Cl (22,000), Cr (440), Cu (33), Fe (1800), Hg (<0.5), Mn (91), Na (42), Ni (640), P (5100), Pb (23), U polar (918), Zn (61); Radionuclides (pCi/g): U alpha (380), U-235 (2.58), U-235 isotopic wt% (0.41). Aqueous feed analysis (mg/L): Al (21), Ba (0.54), Be (<0.03), Cd (<0.29), Cl (1370), Cr (43), Cu (8.7), Fe (1100), Mn (22), Na (440), Ni (25), P (120), Pb (160), Zn (58); Radionuclides (pCi/g): U alpha (0.37), U-235 (0.35), U-235 isotopic wt% (0.92).

uu. Tests performed on 1/18/91.

vv. 12/11/91: aqueous feed rate is 304 lbm/h, organics feed rate is 398 lbm/h.

ww. 75 kg/h of primary organic feed, 135 kg/h of secondary organic, and 99 kg/h aqueous waste.

xx. 76 kg/h of primary organic feed, 133 kg/h of secondary organic, and 125 kg/h aqueous waste.

yy. 82 kg/h of primary organic feed, 141 kg/h of secondary organic, and 120 kg/h aqueous waste.

zz. 82 kg/h of primary organic feed, 140 kg/h of secondary organic, and 115 kg/h aqueous waste.

aaa. Waste type E, PCC temp. of 1832°F, SCC temp. of 2012°F, salt present in scrubber water.

bbb. Waste type E, PCC temp. of 1832°F, SCC temp. of 2012°F, salt present in scrubber water.

ccc. Waste type E, PCC temp. of 1832°F, SCC temp. of 2012°F, no salt present in scrubber water.

ddd. Waste type F, PCC temp. of 1832°F, SCC temp. of 2012°F, no salt present in scrubber water.

eee. Waste type E, PCC temp. of 1600°F, SCC temp. of 1800°F, salt present in scrubber water.

fff. Waste type F, PCC temp. of 1600°F, SCC temp. of 1800°F, salt present in scrubber water.

ggg. Waste type G, PCC temp. of 1832°F, SCC temp. of 2012°F, salt present in scrubber water.

hhh. Waste type G, PCC temp. of 1600°F, SCC temp. of 1800°F, salt present in scrubber water.

iii. Waste type E, PCC temp. of 1400°F, SCC temp. of 1600°F, salt present in scrubber water.

Table 4-12. Normalized mass percent of feed element captured in the APCS of various thermal treatment systems, (continued).

Facility	EPA IRF[jjj]								APTUS[kkk,53,54,55]	
Series #	1[lll,48]	2[mmm,47]	3[nnn,49]		4[ooo,50]					
Test #			1[ppp]	2[qqq]	1[rrr]	2[sss]	3[ttt]	4[uuu]	1[vvv]	2[www]
Element										
Ag									9.41	4.15
As	5.4	7	3.2	23.1	29.8	31.7	30.7	12.2	77.18	25.27
Ba	11.4	3	2.17	5.8	7.79	8.7	7.69	8	2.44	2.55
Be									0.31	0.17
Bi	30	28							1.8	0.91
Ca									0	100
Cd	71.1	54	8.97	12.2	77.5	57.1	40.5	24.4	18.32	6.4
Cr			11.1	31.5	32.2	16	14.9	9.21	0.73	0.15
Cu	15.2	9	0.97	5.13					8.05	11.44
Hg			68.6	96.5	<12.5	<7.69	<7.69	<8.33	72.81	83.94
Mg	0.2	0.07							0.3	0.43
Mn									1.43	0.93
Ni			11.7	29.7					0.62	0.74
Pb	64.5	6	0.9	9.52	8.89	10.5	11.9	7.25	81.68	82.29
Sb									53.81	47.03
Se									0.42	6.89
Sr	0.3	0.6							19.45	12.9
Te									0	0
Tl									1.63	69.31
Zn			1.61	5.4					84.97	62.9

jjj. Environmental Protection Agency Incineration Research Facility, Rotary Kiln Incinerator, Jefferson, AK.

kkk. APTUS Hazardous Waste Rotary Kiln Incinerator, Coffeyville, KS

lll. Rotary kiln incinerator tests with a venturi/packed column scrubber. Integrated feed metal concentrations, range for tests 4-11 (ppm): As (19-33), Ba (33-39), Bi (75-120), Cd (4-6), Cr (61-68), Cu (230-310), Pb (26-34), Mg (16,100-17,900), Sr (140-200).

mmm. Rotary kiln incinerator tests with a single stage ionizing wet scrubber. Integrated feed metal concentrations, range for 9 tests (ppm): As (36-56), Ba (295-460), Bi (260-400), Cd (8-12), Cr (37-45), Cu (290-445), Pb (39-50), Mg (18,100-19,900), Sr (315-480).

nnn. Test series on contaminated soils from Drake Chemical Superfund Site.

ooo. Test series on contaminated soil from Chemical Insecticide Corporation (CIC) Superfund Site.

ppp. Metal concentration in feed, ppm: As (16), Ba (167), Cd (1.1), Cr (18), Cu (49), Pb (439), Hg (0.1), Ni (17), Se (<10), Ag (<2), Zn (302). Kiln temp. of 824oC.

qqq. Metal concentration in feed, ppm: As (62), Ba (57), Cd (2), Cr (12), Cu (43), Pb (77), Hg (0.3), Ni (15), Se (<10), Ag (<2), Zn (251). Kiln temp. of 824oC.

rrr. Soil feed composition in mg/kg: chlordane (14), alpha-BHC (<2), gamma-BHC (<2), p,p'-DDE (5.5), p,p'-DDD (7.3), p,p'-DDT (65).

sss. Soil feed composition in mg/kg: chlordane (17), alpha-BHC (<2), gamma-BHC (<2), p,p'-DDE (6.7), p,p'-DDD (7.3), p,p'-DDT (92).

ttt. Soil feed composition in mg/kg: chlordane (<10), alpha-BHC (<2), gamma-BHC (<2), p,p'-DDE (3.4), p,p'-DDD (4.3), p,p'-DDT (41).

uuu. Soil feed composition in mg/kg: chlordane (13), alpha-BHC (<2), gamma-BHC (<2), p,p'-DDE (4.8), p,p'-DDD (6.4), p,p'-DDT (46).

vvv. Condition 1 had a waste feed chlorine content of approximately 10%. Caustic slag containing appreciable quantities of Pb, As, Zn, and Sb was added to the waste. Condition 1 has 2-3 times the feed rate of Cr, Cu, Pb, and Zn. The As level is 2 orders of magnitude higher than for Condition 2. The Be level is also substantially higher.

www. Condition 2 had a waste feed chlorine content of approximately 20%. Tellurium slag containing Te, Sb, Pb, Ni, and Zn was added. The Te level is 50 times higher than for Condition 1.

The distribution of the more volatile metals was shifted to the fine particulate more so than those of the less volatile metals. In the SWIFT pilot-scale rotary kiln system[42], no trend was observed in correlating metals partitioning to the kiln offgas particulate concentration. Changes in waste chloride composition and kiln temperature in different tests also influenced metal partitioning. Particle size distributions of the offgas particulate exhibited a bimodal distribution around means of 0.5 μm and 10 μm. The submicron particles are indicative of vapor condensation and the larger particles of solids entrainment.

4.3.3 Radionuclide and surrogate partitioning

The partitioning of any and all radionuclides between phases is important in the final disposition of the waste form. Radionuclides of interest include actinides such as uranium and transuranic (TRU) elements (i.e., plutonium, americium) as well as radioisotopes of other elements (i.e., Fe-55, Co-60, Sr-90). Most isotopes can be represented by a nonradioactive isotope of the same element. Lanthanide-based compounds have been used as nonradioactive surrogates for TRU consitituents in partitioning tests. Cerium and praseodymium are examples of lanthanides that have been used.

Detailed material balance data was collected for cerium and plutonium distribution in radioactive and nonradioactive tests using a bench-scale PACT-1 rotating hearth furnace system.[34] Cerium mass closures of 100% and 128% were achieved in two tests. Plutonium mass closures of 116% were achieved with an average error of 23% for two tests. In all tests, more than 99.95% of cerium and plutonium were observed in the slag. For each element, tests were performed with and without polyvinyl chloride present. A limitation of these tests was that surrogate feed was fed into the system for only 12 minutes. Efforts to perform mass balances for cerium in a larger plasma arc centrifugal furnace (PACT-6) were complicated by the accumulation of a large volume of residual skull material in the 6-ft diameter chamber designed to protect the refractory. A series of three tests was conducted at the same operating conditions to minimize the interference of material accumulation.[35] An average of 0.24% of the feed cerium was detected outside the primary chamber over the course of the three tests. Three methodologies were used to account for cerium accumulation in the skull and calculate the total cerium recovery. The three methods calculated cerium recoveries ranging from 66 to 120%.

In experiments with the INEL small arc melter[18], elemental mass closures for radionuclide surrogates were between 20 and 30%. In the Plasma Hearth Process proof-of-principle test unit[30,31], mass closure for cerium was between 40 to 60%. On a normalized basis, approximately 2% of the feed cerium appeared in the offgas system. Partitioning of strontium, cesium, uranium, and different toxic metals was studied at the Toxic Substances Control Act (TSCA) mixed waste incinerator at the Oak Ridge National Laboratory.[44] Results indicated that because of the low ash content of the waste feed, all species were partitioned to the air pollution control system. A series of radioactive parametric tests was performed with a surrogate waste containing plutonium on the PNNL bench-scale DC arc furnace to investigate the effect of waste composition and operating conditions on partitioning.[16] Nine different conditions were tested once with Pu mass balance closures ranging between 110-240%.

In the tests performed on the PNNL bench-scale DC arc furnace[16], the greatest fraction of feed plutonium observed exiting the system was during two experiments with additional chlorine and carbon in separate feed mixtures. In the high-chlorine feed mixture, it was suggested by the investigators that more volatile plutonium chlorides left the melter in the gas phase. In the high-carbon test, nearly 50% of the feed mixture did not melt, suggesting that increased particulate carryover was the reason for the highest fraction of all feed elements exiting the system as well as making it difficult to know how much of each feed element dissolved in the melt phase. It was also observed in the PNNL tests that the normalized fraction of feed plutonium exiting the system was two to four times greater than the fraction of feed cerium exiting the system under nearly all feed conditions. This suggests that cerium may not be the perfect surrogate to model plutonium partitioning to the offgas stream. Results from some tests were rejected due to unrepresentative sampling of the feed and glass phase. The majority of plutonium partitioned to the glass phase. Less than 3% of feed plutonium entered the metal phase and this was attributed mostly to glass contamination or nonequilibrium conditions in this very small-scale semi-continuous melter. In crucible tests performed at the Argonne National Laboratory[75], partition coefficients (plutonium in slag/plutonium in metal) of $7x10^6$ were measured with borosilicate slag and of $3x10^6$ with calcium, magnesium silicate slag. It was observed that plutonium in the metal phase is generally the result of slag entrainment in the molten metal or slag adherence within surface imperfections of the cooled metal.

In tests performed in the PNNL bench-scale DC arc furnace, the percentage of feed plutonium in the offgas as the result of volatilization was estimated to be the difference between the percentages of feed plutonium and feed titanium partitioning to the offgas.[16] The use of titanium to differentiate between entrainment and volatilization is based on two assumptions. The first of these assumptions is that titanium and all of its species have zero volatility. The second assumption is that all other elements and their species that are compared to titanium will entrain in the same proportions as titanium and its species. While the very low volatility of titanium and its species supports the first assumption, there is no evidence to support the second assumption of entrainment proportional to the feed composition, particularly in a heterogeneous waste feed. This method of estimating fraction volatilizationonly applies to low volatility elements or compounds.

In most tests, no significant difference was observed. In several tests, the difference attributed to volatilization ranged between 0.3 and 1.7% of plutonium fed into the system. When the normalized weight percent of feed plutonium and titanium in the offgas were used, the differences for the same tests ranged from 0.19 to 0.74%. The investigators suggested the apparent increase in plutonium volatility may be due to higher melt temperatures or the presence of specific elements, such as carbon, lead, chlorine, and sodium. The same method was used in subsequent tests performed in the PNNL bench-scale DC arc furnace with waste feed mixtures containing decreasing amounts of soil and larger proportions of metals and organic constituents.[17] In these tests, the percentage of titanium in the feed partitioned to the offgas was significantly greater than that of plutonium. This directly contradicts the trends observed in earlier tests. Investigators suggested that this may be attributable to the higher organic content in the later tests. The percentage of feed titanium in the offgas ranged between 0.7 to 5.4% and was proportional to the percentage feed mass collected as offgas solids. The percentage of feed plutonium in the offgas ranged between 0.3 to 2.0%. The investigators then used praseodymium to represent nonvolatile material. Experimental results indicated that significantly less feed praseodymium was observed in the offgas that feed plutonium. This can be attributed to, in part, a poorer praseodymium mass closure (30-45%) compared to plutonium (110-125%). After normalizing the partitioning results, the difference between the percentages of each feed plutonium and praseodymium in the offgas was insignificant. These results are summarized in Table 4-13.

The same approach is used in this report to evaluate the extent of entrainment and volatilization of radionuclide surrogates in the offgas in the INEL small arc melter and the USBM AC 3-electrode arc melter. A summary of the normalized weight percent feed titanium, cerium, and plutonium in the offgas in the PNNL, INEL, and USBM melters are listed in Table 4-13. The feed mixtures in the INEL and USBM melters did not contain plutonium. A comparison of cerium and plutonium differences in the PNNL tests suggests there may be no correlation between the two values and the cerium difference would not necessarily predict in which cases greater plutonium partitioning would occur.

A series of tests was conducted with the USBM AC 3-electrode arc melter in which a cold top of unmelted feed material was present on top of the molten phase in the furnace.[26] The cold top is thought to reduce material volatilization by serving as a radiation shield between the melt and plenum that results in a lower plenum temperature. The cold top thickness was not measured directly but inferred from measurements from plumb bob readings of feed burden height directly beneath the feed tubes. There was no means to determine the presence or thickness of cold top in the higher temperature regions between the electrodes. A better, more direct, method to detect the presence and thickness of a cold top layer is needed. Offgas analysis indicated the amount of metals and particulate emissions from the furnace were greatest during tests when a cold top was present. Emission values were lowest during a test when no cold top was present. These results are contrary to what would be expected. Offgas analysis consisted of a single emissions measurement for each test. More detailed and comprehensive testing and analysis is required before a relationship between offgas emission and operating conditions can be established.

4.4 Additional Partitioning Tests

The Mixed Waste, Characterization, Treatment, and Disposal Focus Area (referred to as the Mixed Waste Focus Area or MWFA) was formed to develop and facilitate implementation of technologies to meet the Department of Energy commitments for characterization, treatment, and disposal of mixed low-level and transuranic waste. The MWFA has identified a High Temperature Melter Development Strategy to provide adequate program coordination to ensure that high temperature technology is available as an option for the treatment of applicable DOE mixed waste inventories.[76] The MWFA has plans in FY-97 to coordinate various melter and subsystem development programs to ensure that the data and test results needed to evaluate the technologies are available in a timely manner. Other activities that are either planned or proposed for support by the MWFA during FY-97 include investigating additional treatment technologies; offgas system performance and monitoring technology development; and waste form studies, development, and test programs.

4.4.1 MWFA High Temperature Melter Development Strategy

The MWFA melter strategy consists of several components with the primary emphasis on plasma hearth melter systems, the DC arc melter systems, and basic research on high-temperature radionuclide chemistry and thermodynamics via the DOE/Russian program. In addition to the plasma hearth and DC arc melter systems, the MWFA melter development and management portfolio includes the joule-heated Transportable Vitrification System (TVS) being jointly developed by the Savannah River Site (SRS) and the Oak Ridge National Laboratory and the combustion-based Vortec melter system being demonstrated at Paducah Gaseous Diffusion Plant. Both system designs are commercially available and are targeted for special high profile application demonstrations to be completed in FY-97. As such, the TVS and Vortec systems are not the primary focus of the MWFA high-temperature melter development effort.

The plasma torch melter or Plasma Hearth Process (PHP) system consists of three melter systems - a nonradioactive bench-scale system, a radioactive bench-scale system, and a nonradioactive pilot-scale system. The melters were developed by SAIC in cooperation with Retech, Argonne National Laboratory West, and Lockheed Martin Idaho Technologies Company. The DC arc melter system is being developed by Pacific Northwest National Laboratory (PNNL). PNNL has two DC arc graphite electrode melters - a radioactive bench-scale melter and a radioactive engineering-scale melter. In addition to the PNNL melters, SRS has a radioactive bench-scale system that is being used exclusively to study the behavior of small particle size Pu^{238}.

Table 4-13. Comparison of normalized mass percent feed titanium, plutonium, and radioactive surrogates captured in the APCS of specific plasma arc melter systems.

PNNL[a,16,17]	Ti	Ce	Δ[b]	Pu	Δ[c]	Pr	Δ[d]
1:1[g]	0.02	0.02	0	0	-0.02	-	-
1:2[k]	0.32	0.01	-0.3	0.02	-0.3	-	-
1:3[n,o]	0.14	0.02	-0.07	0.15	0.01	-	-
1:4[r]	0.34	0.15	-0.19	0.09	0.35	-	-
1:5[u]	0.16	0.02	-0.14	0	-0.16	-	-
1:6[x]	0.29	0.07	-0.22	0.08	-0.21	-	-
1:7[bb]	0.28	0.29	0.01	0.87	0.59	-	-
1:8[dd]	0.53	0.55	0.02	1.27	0.74	-	-
1:9[ee]	0.22	0.16	-0.06	0.41	0.19	-	-
2:1[ff]	1.5	-	-	0.6	-0.9	0.66	-0.06
2:2[gg]	2.86	-	-	1.08	-1.78	0.79	0.29
2:3[hh]	5.61	-	-	0.8	-4.81	0.99	-0.19
2:4[ii]	2.82	-	-	0.43	-2.39	0.48	-0.05

USBM[e]	Ti	Ce	Δ[b]
1[h,25,27]:1[i]	0.4	2.6	2.2
1:2[l]	0.2	1.9	1.7
1:3[p]	0.2	2.6	2.4
1:4[s]	0.2	6.1	5.9
1:5[v]	0.8	3.6	2.8
2[y,26,28]:1[z]	3.6	0.3	-3.3
2:2[cc]	47.7	0.6	-47.1

INEL[f,18,19,20]	Ti	Ce	Δ[b]
1[j]	0.4	5.13	4.73
2[m]	0.78	2.22	1.51
3[q]	3.48	3.29	0.21
4[t]	2.46	1.49	-0.97
5[w]	0.3	1.02	0.72
6[aa]	0.55	1.36	0.81

a. Pacific Northwest National Laboratory Bench scale DC Arc Furnace (Rad).

b. Ce-Ti

c. Pu-Ti

d. Pu-Pr

e. United States Bureau of Mines, AC 3-electrode Arc Melter, Albany Research Center, Albany, Oregon.

f. Located at INEL Research Center, Idaho Falls. Volatilization tests done in FY-94. All tests used IEB4/A-40 having 5 wt% each of TiO_2 and ZrO_2 and with HVPMs & surrogates in oxide form at 1% each. Specific mat'ls used were PbO, ZnO, CdO, Cr_2O_3 as the HVPMs and Cs_2CO_3, CeO_2, Sm_2O_3 as surrogate radionuclides. The controlled parameters tested included: cold cap vs non-cold cap conditions, using or not using a graphite feed tube extender, and thermally desorbing water from the simulated waste mix prior to processing in the arc melter.

g. Metals-R: surrogate consists of INEL soil, lime, & metals (approx. 50% by mass; mostly carbon steel). "R" designation refers to a reducing process atmosphere. Pu nitrate sol'n added to a conc. of 300 nCi/g.

h. FY-93 Phase 1 (baseline) tests. Feed mixtures prepared by mixing RWMC soil with selected buried waste surrogate materials. All mixtures contained 0.35-0.42% CeO_2 as surrogate for TRU radionuclides (PuO_2).

i. S60: S-0 series is org. oils & solvents immobilized by mixing w/Micro-Cell E ($CaSiO_3$) & Oil-Dri (SiO_2). S60 is 60% RWMC soil & 40% S-0. Gypsum ($CaSO_4 \cdot 2H_2O$) & NaCl added to provide desired S & Cl conc.

j. ARM082394: 0.75 kg IEB4/A-40, no cold cap, no extension tube, 22.6 g/min for 100 min., 2.257 kg fed.

k. S-0: organic wastes, oils, & solvents absorbed on Micro-Cell E & Oil Dri. Contains no mixed soil. Contains highest fraction of volatile org. & chlorides of any TRU-cont. waste at INEL. Pu added to 300 nCi/g conc.

l. S60-IV: This is the S60 mixture with added zircon (66% ZrO_2) and ilmenite (65% TiO_2) to provide around 3% ZrO_2 and 6% TiO_2 in the feed mixture.

m. ARM082694: 1.5 kg IEB4/A-40, cold cap, no extension tube, 97.9 g/min for 33 min., 3.23 kg fed.

n. Tests 3-9 were conducted on Nom-60 which consists of nominal INEL waste blended with 60% INEL soil. Waste consists of metals, solid combustibles, silicated organics, nitrate salts, & metal hydroxide sludges.

o. Nom-60 with no additives (baseline).

p. N80/N80-Mod: N-0 contains evaporator salts and consists mostly of Na and K nitrates with limited amounts of other wastes and small amounts of Oil-Dri. The surrogate waste mixture N80 is 80% RWMC soil and 20% simulated N-0. For N80-Mod the N80 mixture was modified (to reduce slag viscosity) w/limestone & mill scale in the ratio 100 lb N80:37.5 lb limestone:20.7 lb mill scale.

q. ARM090694: 1.5 kg IEB4/A-40, no cold cap, extension tube, 56.8 g/min for 52 min., 2.95 kg fed.

r. Nom-60 with 75 x lead.

s. N80-IV-Interval: N80 mix w/zirconia & ilmenite to provide 3% ZrO_2 & 6% TiO_2 in the feed. N80-IV-Mod the N80-IV modified (to reduce slag visc.) w/22.4 lb pebble lime & 20.7 lb mill scale for every 100 lb N80-IV.

t. ARM090894: 1.5 kg IEB4/A-40, cold cap, extension tube, 70.3 g/min for 47 min., 3.303 kg fed.

u. Nom-60 with 5 x iron.

v. M60/M60-Mod: The M-0 waste is a variety of unleached scrap metals. M60 is 60% RWMC soil and 40% simulated thermally oxidized M-0 waste, assumed to be primarily elemental metals, not metal oxides. For M60-Mod the N80-IV-Mod mixture w/add'l pebble lime was fed. A 3-lb metal alloy ingot (50%Ce, 50%Fe) was added to investigate partitioning of metallic Ce.

w. ARM092094: 1.5 kg IEB4/A-40, no cold cap, extension tube, thermal desorption, 84.6 g/min f or 48 min., 4.063 kg fed.
x. Nom-60 with 2.5 x sodium.
y. FY-95 Phase 2 test program. Feed mixtures were nonradioactive surrogates for mixed and alpha-contaminated waste at the INEL SDA and TSA.
z. BWID mixtures were designed to be a nominal mixture of buried waste & soil. Nominal comp. was 37.5% haz. metals, 24.3% solid comb., 23.25% silicated org., 7.29% nitrate salts, & 7.66% metal OH^- sludges.
aa. ARM092294: 1.683 kg IEB4/A-40, cold cap, extension tube, thermal desorption, 115.8 g/min for 30 min., 3.473 kg fed.
bb. Nom-60 with 2 x chloride.
cc. The IWPF series consisted of two waste types: (1) liquid chlorinated and nonchlorinated organics absorbed in silica-based absorbents, and (2) solid combustibles such as paper, rags, and plastic.
dd. Nom-60 with 5 x carbon. Of 745 g of feed material fed to the system, approximately 485 g of the feed was unmelted and surrounded the metal product.
ee. Nom-60 with high plenum oxygen.
ff. Feed (Nom-45) consists of nominal INEL waste blended with 45% INEL soil. Waste consists of metals, solid combustibles, silicated organics, nitrate salts, and metal hydroxide.
gg. Feed (Nom-50, 2 x Na) consists of nominal INEL waste blended with 50% INEL soil. Waste consists of metals, solid combustibles, silicated organics, nitrate salts, and metal hydroxide. Sodium increased 2 times above baseline composition using NaOH.
hh. Feed (Nom-50, 75 x Pb) consists of nominal INEL waste blended with 50% INEL soil. Waste consists of metals, solid combustibles, silicated organics, nitrate salts, and metal hydroxide. Lead elevated 75 times above baseline composition using metallic lead.
ii. Feed (Nom-50, 2.5 x Cl) consists of nominal INEL waste blended with 50% INEL soil. Waste consists of metals, solid combustibles, silicated organics, nitrate salts, and metal hydroxide. Chlorine elevated 2.5 times above baseline composition using polyvinyl chloride.

Key attributes of the high-temperature melter strategy are:

- The TVS and Vortec system are targeted for special application demonstrations in FY-97. The TVS will treat 80,000 kg mixed waste sludge at the Oak Ridge site. The Vortec system will treat contaminated homogeneous soils at the Paducah site.

- The SRS facility will address special process and handling issues involving Pu^{238}.

- The DOE/Russian program is directed to obtain additional radionuclide partitioning data to support the understanding of plutonium partitioning under thermal processing conditions. A plasma torch melter will be used to facilitate this effort.

- The PHP and DC arc systems will work collaboratively to ensure high-temperature melter system treatment options are available for implementation in FY-97. Common feed matrices will be run on both systems to ensure that performance comparisons can be made and that the test data can be adequately compiled to demonstrate melter performance. The effects of feed variability will be evaluated with respect to toxic metal and plutonium volatility, offgas performance, waste form product quality, overall hardware performance, and processing rate. Because of the elaborate offgas systems associated with the PHP, PHP will be used to evaluate the process parameters that affect offgas performance. Product quality and hardware performance testing will be directed at the PHP systems and the DC arc engineering-scale system. Finally, processing rate, capacity, and on-line availability testing will be directed to the larger PHP and DC arc pilot-and engineering-scale systems.

By careful selection of key test objectives, diligent preparation of test plans, increased interaction between program researchers and active oversight, the MWFA intends to ensure high-temperature melter technology is available as an option for mixed waste treatment in FY-97.

4.4.2 MWFA-Supported Offgas System Activities

The MWFA is supporting (or considering support of) several relevant offgas system technology development and demonstration activities that may provide additional information concerning species partitioning, including:

- Offgas system evaluations and process monitoring and control in the above-mentioned PHP program

- The Controlled Emissions Demonstration at WETO that includes a variety of new offgas technology and system demonstrations such as innovative organic destruction technologies, high-temperature particulate filtration, long-term operation, non-catalytic NO_x removal technologies, mercury removal technologies, and continuous emissions monitoring. Specific technologies in these research areas have been proposed for testing.

- Full-scale, long-term continuous emissions monitor (CEM) testing at the TSCA incinerator CEM Test Bed

- Several planned or proposed CEM projects, including (a) the Continuous Emissions Monitor and Diagnostic Project (under the DC arc system demonstrations); (b) HEPA filter improvements, (c) Real Time Monitoring of Alpha Emissions; (d) Demonstrations of Continuous Emissions Monitoring Technologies - SRS; and, (e) CEM development and testing at the Diagnostic Instrumentation and Analysis Laboratory (DIAL).

5. EVALUATION OF EXISTING CODES AND MODELS

Experimental measurement of transient and steady-state values for process variables as a function of position and time in a thermal treatment system is generally limited by physical, technological, or cost constraints. Mathematical models can be useful in estimating difficult-to-measure process variations or relatively quickly identifying the effect of changing process variables on process results. Such models consist of equations describing fundamental processes, databases containing physical and chemical properties of probable constituents, and assumptions designed to reduce the amount of prerequisite information required or the number of calculations performed.

Modeling approaches for calculating properties in a thermal treatment system depends on available existing data and the level of detail and accuracy desired. Efforts to model process variables, computer codes and databases used to calculate chemical equilibrium concentrations, and equations describing vapor condensation and particulate entrainment are reviewed in this chapter. Results of computational programs estimating chemical equilibrium concentrations and particulate entrainment may be significantly affected by variations in process temperatures and convection-related variables.

5.1 Modeling Process Variables

Knowledge of the temperatures throughout a thermal treatment system is required to account for the effect of temperature on any solid and gas-phase reactions, material volatilization, and vapor condensation.[11] Some investigators have noted that model results of chemical equilibrium concentrations may be different if local temperatures are significantly greater than the bulk temperature.[25] Mixing in solid, molten, and gas phases influence mass and energy transport in the system. Local velocities and velocity gradients affect aerosol entrainment in the gas phase and promote heat and mass transfer in the solid and molten. Examples of computational codes to calculate temperature and velocity gradients in thermal treatment include TEMPEST, a computer code designed for use at the Hanford Waste Vitrification Plant; and FIDAP, a commercial finite-element code used at the INEL to model steady-state process variables in a molten phase.

TEMPEST is a versatile computational fluid dynamics code that offers analytical capabilities for a wide range of fluid dynamics and heat transfer problems.[77] TEMPEST uses a finite volume representation of computational cells. Finite volume cells are each treated as control volumes with flux quantities dependent upon the area of the cell face. Velocities, heat flux, and electric current flux are examples of cell-face quantities. Scalar variables used in TEMPEST are cell-centered quantities in that they apply to the entire cell volume. Examples of such variables include pressure, temperature, turbulent kinetic energy, and heat generation. The finite volume representation of computational cells effectively makes TEMPEST a finite-difference model. Some of its modeling features include one, two, or three space dimensions; Cartesian or cylindrical coordinates; time-accurate with steady state reached as a limit of the transient; a turbulence model; heat transfer in coupled fluid and solid regions; multiple electric fields in either fluid or solid regions (AC or DC current); mass transport in flow regions; specification of material properties by user input or selected from built-in values for 18 materials; temperature-dependent material properties; and, concentration-dependent properties.

The TEMPEST computer code was used to evaluate the effect of nonsoluble noble metals on the service life of a full-scale Hanford Waste Vitrification Plant (HWVP) joule-heated melter during the treatment of neutralized current acid waste.[78] The three-dimensional computer code numerically solved a base set of governing transport equations for continuity, momentum, and thermal energy in the melt. Submodels were used to calculate particle settling and concentration-dependent properties (density, electrical conductivity, and viscosity). The temperature profile in the melt was calculated and compared to experimental measurements in the engineering-scale melter. Between 40 and 120 hours of CPU time on an IBM-580 super workstation were required to bring the melter model to steady state after changing melter settings in the model. The code did not model element partitioning between phases due to chemical reaction, chemical equilibria, or volatilization.

FIDAP is a general purpose finite element program for simulating a wide variety of fluid flows plus the effects of heat transfer and the transport and reaction of chemical species.[79] The fluid flows include compressible or incompressible viscous flows and may be laminar or turbulent. FIDAP approaches two eddy viscosity approaches to turbulence. The flows may include two phases (such as flows with bubbles, fluids carrying particles or aerosols). The heat transfer capabilities include conduction, convection, and radiation modeling. Up to 15 transport equations may be used for modeling chemical species concentrations. Both bulk reactions and surface reactions can be modeled with appropriate rate kinetic data. The simulations can be either steady-state or transient and model flows in complex, arbitrary geometries that may be two-dimensional, axially symmetric, or three-dimensional.

The finite-element code FIDAP was used at the INEL to predict the steady-state temperature, velocity, and current density profiles in the molten phase of a generic plasma arc melter.[68] A two-dimensional model was used to describe the curved refractory geometry with the inclusion of a drain spout for molten slag at one end. Two graphite electrodes are equidistant from the center of the melter. Soil feed enters at points between the electrodes and the wall. In this model, the melter is effectively a long trough with no end effects considered; therefore, the model only approximates what may be occurring within a cylindrical melter with a single pour spout. The maximum predicted gas temperature was in excess of 12,000 K and the maximum predicted molten phase temperature was in excess of 3,000 K. The temperature and velocity profile in the gas phase above the waste and melt were modeled to define the flux condition at the melt-gas interface as a function of the energy input and the distance between the interface and the electrodes. Modeling of the gas and molten phases were not performed simultaneously. Model results were not compared with experimental results.

5.2 Chemical Thermodynamic Equilibrium Models and Databases

Constituent concentrations are generally calculated assuming chemical thermodynamic equilibria have been achieved in the system at an average operating temperature. Computer codes to calculate equilibrium concentrations can be divided into two categories based on the ability of the program to model unit operations and integrate results with other subprograms - flow-sheet modeling programs and specialized programs. Codes in each of these categories perform Gibbs free energy minimization calculations for determining chemical equilibrium concentrations of chemical reactants and products, and so have an accompanying data base of thermodynamic properties used in the calculations. A summary of flow-sheet modeling and specialized programs that can be used to calculate chemical thermodynamic equilibrium concentrations under process conditions is listed in Table 5-1.

5.2.1 Flow-sheet modeling programs

Flow-sheet modeling programs can simulate unit operations as stand-alones or part of a larger process; handle a large number of streams, species, and phases; and contain various reactor models. Generally, extensive graphical support is provided for on-screen viewing of process setup and printing results. Examples of flow-sheet modeling programs include METSIM and ASPEN PLUS. METSIM is a flow-sheet program for complex chemical and metallurgical processes with a Gibbs free-energy-minimization program for equilibrium-reactor simulations.[80] METSIM was used to describe the mass-transfer kinetics between multiple phases by representing the different phases and interfaces as a system of unit operations.[81] Each phase was represented by a mixer and stream splitter with recirculation. A stream from each splitter is brought together in a unit operation where they reach equilibrium and are divided into resulting phases. Each phase is returned to the bulk volume. Since METSIM is designed to deal with flows in continuous operations, the mass in a batch reactor is represented by a recirculation stream.

ASPEN PLUS is a flow-sheet modeling program that performs process simulations using basic engineering relationships such as mass and energy balances, phase and chemical equilibrium, and reaction kinetics. ASPEN PLUS process simulation code was used to model the steady-state operation of the main and secondary thermal treatment, the main air pollution control, and metal melting subsystems in a variety of integrated thermal treatment systems.[82] ASPEN PLUS was used to model melter thermodynamics for low-level mixed waste (LLMW) joule-heated vitrification systems at the SRS.[83] Conventional cold-top melters and stirred-melter designs were investigated. The cold-top melter was represented as a series of four coupled equilibrium reactor stages at increasing temperature. Gases produced in each stage rise to the stage above while the liquid is passed down to the stage below. The stirred melter was modeled as a single equilibrium stage. Model results were compared to those generated using STGSOL, a modeling tool widely used for high-temperature thermodynamic equilibrium for glass melters. Some problems were encountered in implementing property data due to the complex calculational structure of ASPEN PLUS. A drawback of the current simulations was the lack of implementation of a suitable activity coefficient model for oxides. The NIST database contains such activity models and the investigators intend to implement this database into ASPEN PLUS in order to improve the melter modeling results.

5.2.2 Specialized Programs

For preliminary investigation of process concepts, it is often easier and better to use the specialized programs instead using of flow-sheet modeling programs. A number of computer codes have been developed to calculate equilibrium concentrations for different reactions and are based on the principle that chemical equilibria have been achieved when the Gibbs free energy for all specified reactions has been minimized. The specialized programs are differentiated by their cost, level of documentation, user-friendliness, and the assumptions used in calculations. The computer codes generally make a number of assumptions such as ideal gas mixtures, pure condensed species, and no significant mass transfer limitations.

HSC Chemistry for Windows can be used for calculations of reaction outcomes, heat and material balances, equilibrium compositions, phase stability diagrams, and volatility temperatures. This code was used to calculate thermodynamic equilibria of mixtures of metals and radionuclides containing from 50 to 100 chemical species in condensed and gaseous states under typical incinerator conditions.[84] Calculations were performed over a temperature range of 500 K (227 C) to 1,600 K (1,327 C). Many uncertainties existed, in part, because of a lack of knowledge of the composition of the condensed state. In addition, no information on thermodynamic activities was available. However, calculation results were useful to predict relative concentrations of species in different mixtures. *HSC Chemistry* was used to compare elemental partitioning in two different types of thermal treatment systems: a conventional combustion chamber with excess air, represented by a rotary kiln with afterburner, and an oxygen-deficient pyrolysis unit, represented by a plasma arc furnace.[85] Different mixtures of metals, halogens, and other elements were investigated in oxidizing and reducing atmospheres at 1,500 K (1,227 C). *HSC Chemistry* was used to investigate suitable surrogates for technetium, uranium, and plutonium.[86] Phase stability diagrams for these elements and

Table 5-1. Flow-sheet modeling programs and specialized programs used to calculate chemical thermodynamic equilibria.

Flow-sheet Modeling Programs	Vendor or Location
ASPEN PLUS	**Aspen Technology Inc. Cambridge, MA**
METSIM	**Proware**
Specialized Programs	Vendor or Location
HSC Chemistry for Windows	**Outukompu Research Oy Finland**
NASA CET85 (1976) NASA CET89 (1986)	**NASA Lewis Research Center**
SOLGASMIX-PV	**Oak Ridge National Laboratory**
STGSOL	**University of Missouri, Rolla**
STEPSOL	**University of Missouri, Rolla**
STANJAN	**Stanford University**
PYROSIM	**Mintek (South Africa)**

potential surrogates over the temperature range of 1,000 to 5,000 K (727 to 4,727 C) were generated. These diagrams were two-dimensional plots for a specified temperature that showed the predicted main condensed chemical phases for the element in question as functions of the gas partial pressure in oxygen-chlorine and oxygen-hydrogen systems. Volatility temperatures and equilibrium concentrations under a fixed mass balance constraint were also calculated.

Computer codes developed at the NASA Lewis Research Center were used by a number of investigators to estimate the equilibrium concentrations of metals under thermal treatment operating conditions. The NASA CET85 computer code[87] was used to determine the equilibrium behavior of the metals in the waste under combustion conditions[13,88] and to predict metal emissions from hazardous waste incinerators.[53] The NASA CET89 computer code[89] was used to calculate chemical equilibria for barium, beryllium, chromium, lead, mercury, nickel, and silver.[15] Calculations were not performed for antimony, arsenic, cadmium, selenium, and thallium because insufficient thermodynamic data was available. The model used does not allow nonideal condensed solutions such as complex slags and glasses.

The computer program SOLGASMIX was developed to calculate equilibrium compositions in systems containing one gaseous phase, condensed mixtures, and condensed phases of invariant or variable stoichiometry.[90] The program can handle nonideal phases provided that activity coefficients are available. SOLGASMIX-PV is a modified version of SOLGASMIX that uses the ideal gas law so that the program is capable of calculating equilibria at a constant total gas volume with variable total pressure.[91] SOLGASMIX-

PV was used to model the thermodynamic behavior and optimize the reaction occurring during the direct oxide reduction of plutonium oxide to plutonium metal within a molten flux of calcium chloride.[92]

The program STGSOL models steady-state multi-stage countercurrent reactor systems and was used to model a slurry feed melter as a countercurrent reactor containing up to nine stages representing unique thermodynamic conditions in the system.[93] STGSOL is an extension of the SOLGASMIX algorithm for minimizing the total free energy of a system in order to calculate the equilibrium compositions. STGSOL 2.5 was used to predict the sequence and product of redox reactions and in assessing process variations in a continuous glass melter.[94] A series of five melting tests was conducted at the Pacific Northwest National Laboratory with reducing melter feeds. A standard state thermodynamic equilibrium program indicated the correct direction of variations but could not predict actual glass redox state as measured by Fe(II)/Fe(III). An improved computer model was built using STGSOL 2.5, a software program developed at University of Missouri-Rolla. The Gibbs free energy database for complex liquids by the National Institute of Standards and Technology was used in place of activity coefficients to partially handle the solution nonideality problem. Melting of the feed solids was envisioned as a 4-stage process. Stage 1 represents the initial stage of melting where all oxides remain as solids and each forms an invariant condensed phase. From Stage 2, all oxides are assumed to be in a liquid state and therefore form a solution. The redox and non-redox species form separate phases in equilibrium with each other and with the gas and the invariant condensed phases. Multiple oxides begin to form from Stage 3 at 1,323 K. Stage 4 represents the final fusion at 1,423 K. The oxidizing effect of plenum air is accounted for simply by adding O_2 into the two feed stages along with the feed solids. The effect of plenum air flow rate and the amount of formic acid addition was accounted for by the model.

The STEPSOL equilibrium program developed for the mineral processing field was used to predict the condensed and vapor phase compositions of arsenic and lead in a simulated slag under different atmospheric conditions.[95] The STEPSOL program allows for dilution effects and can treat the slag as an ideal solution, as an associated liquid, or if activity coefficients are known or can be estimated, as a nonideal solution. It was noted that at the time only one group of investigators has used STEPSOL to predict emissions from an incinerator.[96] The STEPSOL code was used to simulate the thermal treatment of buried mixed waste over a range of 800 to 2,400 K in a strong reducing environment. Model results showed that an insignificant fraction of plutonium compounds evaporate. Relatively more uranium, as a chloride and an oxyhydroxide, evaporates at these conditions. The code was limited to 14 input species which can limit the accuracy of equilibrium calculations. The calculations did not account for possible variations in melt temperature in the process.[97] The equilibrium solver STANJAN was also utilized to investigate the fate of metallic constituents during incineration.[98]

PYROSIM is used for the steady-state simulation of pyrometallurgical processes. It automatically performs energy-balance calculations, calculates elemental analysis of all product streams, and provides data on the distribution of elements between phases. One drawback is the inability of the program to handle solution models for nonideal solutions.[80] A batch flow model was used to calculate the amount and chemical composition of the products in a DC arc melter operated in a semi-continuous mode.[99] PYROSIM was utilized to calculate the compositions of equilibrated mixtures. In order to mimic the continuous removal of generated gases and vapors, the simulation was done in a ramping fashion using four unit operations in series at increasing temperatures with periodic gas removal. Thermodynamic data for each species was required and provided in two parts: the polynomial expansion of the heat capacity as a function of temperature and the enthalpy and entropy of formation at standard state which was retrieved from the F*A*C*T database.

5.2.3 Thermodynamic Databases

Thermodynamic databases generally consist of data compiled from many sources as well as property estimation equations. The usefulness of any of these chemical equilibrium programs is dependent on the size and accuracy of the thermodynamic database in the desired temperature ranges. If thermodynamic data, such as activity coefficients, were not available for compounds believed to be important reactants or reaction products in the desired temperature ranges, then the program may generate incorrect results.

5.3 Vapor Condensation and Particle Entrainment

5.3.1 Vapor Condensation

The PULSE code, developed at the INEL to model aerosol transport, offers a way to simulate partitioning phenomena in the vapor and particulate phases in a melter system. The model accounts for vapor condensation, particle formation, particle growth, particle agglomeration, and particle deposition. The transport code PULSE at the INEL was developed as an analytical tool for the study of the evolution and transport of fission product aerosols in long pipes.[100] This code was originally developed to model fission product transport in the effluent line of the Power Burst Facility test program at the INEL. A modified version, PULSE/MOD-ISV, was used to predict aerosol transport in the offgas system of the proposed In-Situ Vitrification (ISV) process.[101] The PULSE computer code models transient vapor and aerosol transport and deposition through circular and rectangular channels. Thermal boundary conditions can be specified as a function of time. Five states are considered, along with the mass transport coupling mechanisms relating them. These five states include two mobile states: vapor and aerosol, and three stationary states: condensate, chemisorbed, and deposited. The mobile phases of the aerosol are described in terms of local vapor composition as well as the particle concentration and size distribution, both of which can vary via the transport coupling mechanisms. The code is written in FORTRAN 77 and has been compiled on various platforms including work stations and personal computers.

5.3.2 Particle Entrainment

Several methods have been identified to estimate the amount of ash entrainment from rotary kiln and other incinerators.[13] One method[102] estimates ash entrainment, W_e, from a rotary kiln as a function of kiln rotation speed (N_r), gas velocity in the axial direction (V_a), and temperature (T)

$$W_e = C_0 N_r^{1/2} V_a^{\eta} T^{3/4} \tag{3}$$

where C_0 is a constant and η is a function of the quantity of entrainable fine particles in the waste. Typical values of η range between 0.5 and 4.0. Other investigators defined the total mass rate of entrained metal in a rotary kiln in terms of a nonlinear function of gas stream velocity, gas properties, kiln geometry, the saturation concentration of the metal, and an empirical factor that relates the saturate concentration to the waste-gas interface concentration, which is a function of the waste form.[103] The ash entrainment rate from other incinerators was estimated[13] based on particle settling velocities and gas flow rates.[104]

An average gas velocity inside a plasma arc melter furnace near the feed tubes was calculated to estimate the maximum particle size that could be entrained based on the stagnation velocity.[25] The gas velocity in the furnace was estimated based on the measured offgas volumetric flow rate, offgas and furnace bulk temperatures, and cross-section of the furnace just below the feed tubes. The average gas velocity was estimated be 0.5 ft s^{-1} although it was recognized that the actual gas velocity gradient would likely vary significantly because of internal configuration, gas recirculation, and back-diffusion along the furnace wall. The average particle size was estimated assuming a particle density, that the estimated velocity was the particle stagnation velocity, and that Stokes' Law for spherical particles applied (Reynolds number < 0.1). Calculations suggested that particles less than 66 μm in diameter could be entrained.

5.4 Comprehensive Partitioning Models

Methods for mathematically describing each partitioning mechanism have been identified. A comprehensive model that integrates these codes and equations to account for any interactions between partitioning mechanisms can be useful in estimating elemental distributions in real treatment systems. Efforts to develop an integrated approach of model partitioning mechanisms in thermal treatment systems are reviewed in this section.

5.4.1 Rotary kiln incinerators

A comprehensive model to predict metal partitioning in an incinerator that accounted for reactor thermal behavior (bulk and local temperatures), particle entrainment, metal reactions and vaporization, aerosol dynamics (condensation and coagulation), and particle capture has been developed.[13,88] The temperature history defines the background environment for the burning waste and the post-flame conditions for the condensing metal vapors. Temperature near burning waste depends strongly on the physical form of the waste. While several methods exist to model liquid waste incineration, the temperature for other waste forms must be estimated based on the bulk temperature and the adiabatic flame temperature. Chemical reactions and phase behavior are estimated given the temperature profile in the incinerator using the NASA CET85 code. The approach is based on the assumptions that all reactions achieve equilibrium at local conditions and all elements are intimately mixed. These assumptions are made in the absence of more detailed reaction kinetic data.

Modeling ash entrainment depended on the type of incinerator. For rotary kiln incinerators, the rate of entrainment was a function of the kiln rotation speed, gas flow rate in the axial direction, and system temperature.[102] The rate of entrainment in other incinerators was estimated knowing the particle settling velocities and gas flow rates.[104] Homogeneous and heterogeneous condensation of each metal species of interest were accounted for as well as particle coagulation. In addition, submodels describing different collection mechanisms in a variety of flue gas cleaning equipment were included.[104] The model did predict the major mode of ash emission (bottoms ash, flyash, or fugitive ash) from a municipal waste incinerator. However, insufficient data are available to completely validate the model. The model is still useful to identify qualitative behavior in an incinerator. A sensitivity analysis with the model indicated that the combustion chamber temperature and chlorine content in the waste feed were among the more important parameters affecting metal partitioning in an incinerator. Other parameters found to have a less significant effect on metal partitioning included the sulfur content of waste feed, gas residence time, entrained particle size distribution, local oxygen concentration, concentration of entrained particles, and gas cooling rate.

A computerized mathematical model of a refractory-lined municipal solid waste rotary kiln combustor with a vertically well-mixed bed has been developed.[105] Bed height varies with horizontal distance as fuel is consumed. The kiln contains a pyrolysis zone, followed by a combustion zone. A kinetic model for cellulose pyrolysis simulated the thermal destruction of municipal solid waste in the first zone. The combustion of particles in the second zone follows a shrinking-core model. Model behavior is in good agreement with the performance of commercial units. Another model was developed to predict the preferential movement of particles resulting from particle size and density differences within a rotary kiln.[106] The model determines the extent of fine particle segregation and is based on the principle of percolation in the active layer, whereby fines sift through the matrix of the bed to form a segregated core. The model results account for the effect of segregation on bed temperature nonuniformities in rotary kilns.

5.4.2 Plasma arc melters

In modeling the steady-state process variables in a graphite electrode melter, the FIDAP finite-element code was used at the INEL to estimate the temperature and velocity profiles.[68] Gas phase temperature and velocity profiles were calculated to provide boundary conditions at the melt surface for melt phase profiles calculations. *HSC Chemistry* was used to calculate equilibrium concentrations as a function of temperature. Equilibrium calculations were performed using an average temperature after the thermal analysis was performed.

An analysis of mixed waste treatment system performance was conducted using FLOW, an object-oriented process simulator for waste management systems under development at Oak Ridge National Laboratory.[107] The design philosophy of FLOW favors the quick, easy-to-use approximate models over a more rigorous and accurate model development. The plasma arc furnace process, once validated with appropriate experimental data, will be developed using the ASPEN program. The investigators noted that the extensive data needed to validate model results includes the measurement of the quantity and composition of particulate and vapors exiting the primary chamber, the measurement of the particle size distribution, and characterization of the service life of the primary chamber refractory and offgas system filters.

5.4.3 Proposed Comprehensive Partitioning Model for Plasma Arc Melters

A comprehensive partitioning model is proposed that attempts to integrate different models that describe unique partitioning mechanisms. Previous investigators have acknowledged the likelihood that constituents fed into a melter do not interact and react with all other constituents at the same time and under the same conditions. Modeling of an unsteady-state DC arc melter system[99] and the steady-state operation of a glass-melter[94] has used staged thermodynamic models to describe the different environments within a melter system in which constituents come in contact. This staged approach effectively divides the melter into a series of unit operations, or stages, with unique conditions and feedstreams. A flow-sheet modeling program, such as ASPEN PLUS, can model the melter as a series of connected unit operations and perform material balances as well as phase and chemical equilibrium calculations.

ASPEN PLUS does not have, nor does any chemical equilibrium code, the capabilities to account for vapor condensation, particle formation and growth, and particulate entrainment. The code PULSE, developed at the INEL, was written to model vapor condensation and evaporation, particle formation by vapor nucleation, particle growth by vapor condensation, particle agglomeration, and particle deposition. The fact that both ASPEN PLUS and PULSE are written in FORTRAN language offers an opportunity to bring these codes together in some format so that the partitioning mechanisms involving chemical reaction-thermodynamics and vapor condensation-particle distribution can be accounted for in a nearly simultaneous fashion. In addition, ASPEN PLUS is well-suited to simulate many of the unit operations in air pollution control systems. Thus, it may be possible to model a melter-offgas handling system in a single simulation. Information on the temperature and velocity profiles within a melter system are necessary to define the process conditions in each "unit operation" or stage within the melter as well as define flow rates between each stage. If experimental data defining these values are not available, a computational fluid dynamics code (such as FIDAP) can be used to identify temperature zones and the flow rates within the melter system. Such calculations would have to be performed first to identify initial conditions and process parameters for the flow-sheet and aerosol transport models. The integration of all these codes at some level offers the potential of modeling all these partitioning mechanisms in a melter system in a nearly simultaneous fashion.

6. CONCLUSIONS AND RECOMMENDATIONS

A preliminary study of toxic metals and radionuclide partitioning within high-temperature thermal treatment process and systems has been conducted to provide sufficient information to define a detailed technical approach to identify and understand the primary partitioning mechanisms and how they affect toxic metals and radionuclide partitioning in the most applicable mixed waste thermal treatment processes. Upon conducting a survey of the experimental data and elemental partitioning models that were available, the usefulness and inadequacies of the data and process models in characterizing all relevant partitioning mechanisms were identified. Based on conclusions from this study, recommendations are made for better evaluations of existing partitioning data, better data collection for ongoing DOE-supported thermal treatment demonstrations, and for improved modeling of the primary partitioning mechanisms and their affect on the constituent distribution under different operating conditions.

6.1 Conclusions

6.1.1 Thermal Treatment Systems

- Several prior studies conducted to evaluate and rank potential thermal treatment technologies generally agree that graphite electrode melters, the plasma torch melters, and the rotary kiln incinerators have the greatest applicability for treating heterogeneous mixed wastes.

6.1.2 Elemental Partitioning Mechanisms

- Primary partitioning mechanisms in high-temperature treatment systems are temperature- and convection-dependent. These mechanisms include compound formation via chemical reaction, volatilization and condensation of volatile compounds, and particulate entrainment into the exiting offgas. The relative contribution of any mechanism depends on the properties of the input feed material, treatment system design, and operating conditions.

6.1.3 Experimental Process and Partitioning Data

- To date, there has been no significant evaluation of relationships between process and partitioning data from past demonstration tests. This lack of evaluation has been due largely to sporadic process data from most tests, a focus of prior tests on demonstrating technologies at the expense of understanding the technologies with detailed process measurements, and inadequate diagnostic and measurement technologies.

- 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.

- There are significant technological limitations in measuring temperatures, velocities, and compositions in high-temperature in-furnace conditions. Reliable new technologies and methods for collecting these in-furnace measurements would be useful for obtaining difficult-to-obtain data.

- The melter system in which the most comprehensive data of input, output, and operating conditions were collected was the AC 3-electrode arc melter at the DOE Albany Research Center. The rotary kiln incinerator systems in which the most comprehensive data of input, output, and operating conditions were collected were the EPA Incineration Research Facility in Jefferson, Arkansas and the SWIFT Rotary Kiln System at Energy and Environmental Research in California.

- A survey of reported experimental data and results from 20 thermal treatment demonstration or operating systems revealed that the partitioning data was 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.

- 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 mass and composition of the unmeasured stream calculated by difference; sampling measurements that are not representative of the phase being sampled; transient rather than steady-state operating conditions; and, sample analyses and other measurements that are near or below detection limits.

- It is unclear if surrogates provide the partitioning data necessary to accurately describe radionuclide behavior. Cerium is often used as a surrogate for plutonium and may be the best candidate; however, some test results indicate that a larger fraction of feed plutonium is transported to the offgas stream than feed cerium. This could have profound impact on the anticipated requirements on the air pollution control system downstream from the thermal treatment system.

6.1.4 Partitioning Models and Computational Codes

- The ability to describe and predict elemental partitioning in a thermal treatment system can be valuable in optimizing operating conditions to achieve preferred elemental distribution; provide a cost-effective method for evaluating worst-case operating scenarios and interpolating between experimental results of test conditions; serve as a tool in the design and scale up of a thermal treatment system; and be used to demonstrate to process evaluators, stakeholders, and others that the relevant partitioning mechanisms are understood and controllable within desired ranges.

- An integrated model that describes all relevant partitioning mechanisms in a rotary kiln incinerator has been developed and used to identify the operating parameters that have the greatest effect on elemental distribution. An integrated model that describes all relevant partitioning mechanisms in a plasma arc melter has not been developed. Earlier melter models have not integrated a chemical equilibria model with a model code that describes vapor condensation, particle formation, particle growth, and particulate entrainment.

- ASPEN PLUS, a flow-sheet modeling program that performs process simulations of interconnected unit operations using basic engineering relationships such as mass and energy balances, as well as phase and chemical equilibrium, can be used to model a melter system as a series of unit operations or stages at unique operating conditions with distinct feed streams entering each stage. The thermodynamic database may require updating to incorporate thermodynamic properties of oxides and other chemical species expected in a melter environment.

- The PULSE code, developed at the INEL to model aerosol transport, offers a way to simulate partitioning phenomena in the vapor and particulate phases in a melter system. The model accounts for phenomena affecting particulate entrainment such as vapor condensation, particle formation, particle growth, particle agglomeration, and particle deposition.

- FIDAP is a general purpose finite element program for simulating fluid flow, heat transport, and mass transport that has been used at the INEL to predict the steady-state temperature, velocity, and current density profiles in the molten phase of a generic plasma arc melter.

- An integrated model using ASPEN PLUS, PULSE, and FIDAP offers the potential of modeling all relevant partitioning mechanisms in a melter system in a nearly simultaneous fashion. ASPEN PLUS and PULSE are both written in FORTRAN, which makes it possible to bring these codes together in a format so that the partitioning mechanisms involving chemical reaction-thermodynamics and vapor condensation-particle distribution can be accounted at the same time. A computational fluid dynamics code, such as FIDAP, can be used to identify temperature zones and the volumetric flow rates or fluid velocity within the melter system. In addition, since ASPEN PLUS is well-suited to model typical unit operations in an air pollution control system, an integrated model may be able to simulate all partitioning mechanisms in the melter-offgas handling system.

6.2 Recommendations

6.2.1 Experimental Process and Partitioning Data

- Evaluate published and raw experimental data of existing thermal treatment systems in order to better relate partitioning results to available process data as well as compare partitioning results from different test systems and treatment technologies.

- Advocate the importance and necessity for detailed experimental data on input, output, and process conditions in new test programs, not only to evaluate system performance (especially partitioning of feed materials) in terms of operating conditions, but also to identify relevant partitioning mechanisms in order to predict future performance under untested conditions.

- Support development and demonstration of innovative in-furnace measurement technologies for measuring temperatures and compositions.

6.2.2 Partitioning Models and Computational Codes

- Develop an integrated partitioning model using ASPEN PLUS, PULSE, and FIDAP to describe all relevant partitioning mechanisms in a melter system in a nearly simultaneous fashion. ASPEN PLUS would be used to calculate thermodynamic equilibria in a melter system represented as a multistaged system; PULSE code would describe particle transport, formation, and growth in the gas phase; and, the FIDAP code would be used to approximate temperature and velocity profiles within the melter system to identify process parameters for each stage. In addition, since ASPEN PLUS is well-suited to model typical unit operations in an air pollution control system, extend the application of the integrated model to include elemental or species partitioning in a melter-offgas handling system.

- Perform sensitivity studies using existing thermodynamic codes and databases to demonstrate the effect of key process parameters on the volatilities and distribution of toxic metals and radionuclides. The effects of different input feed compositions, allowable output products, and extremely high temperatures should be evaluated.

7. REFERENCES

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Appendix A

Summary of Melters, Incinerators, and Miscellaneous Thermal Treatment Systems

Table of Contents

Explanation of Tables

The tables presented in Appendix A are a summary of melters, incinerators, and miscellaneous thermal treatment systems around the world that could potentially provide partitioning data of metals and radioactive compounds that would be useful for building a model of partitioning behavior in various thermal treatment processes. The tables are arranged according to the type of thermal treatment process, i.e. arc melters are grouped together in one table, plasma torches comprise another table, incinerators grouped in a different table, etc. The first column in the table is used to give each system a number for ease of identification. Numbers in that column that are followed by an asterisk indicate that there is a system description of the technology in Appendix B. The second column in the table is the name of the respective system. Shaded cells in this column denote that a global summary of the system is provided in Appendix D. Footnotes, denoted by superscripted letters, can be found at the end of Table A-7, unless otherwise noted. References for each system can be found directly following Table A-7. Columns that are left blank or marked as "unknown" indicate that the data was not available in the reference. The list of systems is not intended to be exhaustive but rather includes the more notable systems with a potential for providing relevant data.

Table A-1. Summary of potential sources of metals and radioactive partitioning data for graphite el

	System	Location	Demonstration tests temperature range[a]	Size/scale	Power lev thermal rat
Arc Melters					
	-DC Graphite Electrode				
1*[c]	PNNL Bench scale DC Arc Furnace (Rad)	PNNL, Richland, WA	Hearth: up to 1,500°C; refrac. limit <1,800°C	Bench scale	2-4 kW
2	PNNL DC Arc Melter	PNNL, Richland, WA	Refractory limit: 1,800°C	Engineering scale	Unknown
3*	INEL Small Arc Melter	INEL Res. Ctr, Idaho Falls, ID	Slag: up to 2,200°C; refrac lim: 1,800°C	0.015 m^3 melt chamber; Bench scale	10-40 kW
4*	MeltTran Small Arc Melter	MeltTran Inc., Idaho Falls, ID	Slag: up to 2,200°C; refrac lim: 1,800°C	<0.017 m^3; Bench scale	10-200 kW
5*	SRS Small Arc Melter	Savannah River, SC	Slag: <2,200°C; refrac limit: 1,800°C	0.015 m^3 melt chamber; Bench scale	10-40 kW
6*	Mark I Furnace	MIT, Cambridge MA	Slag, published est: 1,400-1,600°C	Bench scale	15-35 kW
7*	Mark I-W DC Arc Melter	Clemson University, SC	Unknown		Maximum: 10
8*	Mark II Furnace	MIT, Cambridge MA	Slag: up to 2,200°C	Pilot scale	1.0 MW
9	SRS DC Arc Melter	Savannah River, SC	1,500°C	Small bench scale	Unknown
10*	EXIDE DC Arc Furnace	Reading, PA	Furnace: >1,650°C	Unknown	
	-AC Graphite Electrode				
11*	USBM AC, 3-electrode Arc Melter	Albany Research Ctr, Albany, OR	Skull wall operations; Slag: up to 2,200°C	0.14 m^3; Pilot scale	800 kVA
12*	SkyGas Submerged arc shaft furnace	Synergistics Lab, Libby, MT	Slag: >1,600°C	Production scale	Unknown
13*	Melt All Electric Fusion Proc. 3-phase electric arc furnace	Geotech Dev. Corp, King of Prussia, PA	Slag: up to 2,880°C	Industrial scale	2.0 MW
14*	Dakota Catalyst Products - 3-phase Electric Arc Furnace	Williston, ND	Slag: up to 2,200°C	Production scale	4 MW

rode arc melters.

Throughput; residence time	Toxic metals present[b]	Radio-nuclides present[b]	Partitioning data available	Current status	Experience/Comments
Batch mode, semi-cont. feed; <1 kg/h; <1.0 kg cap.	Yes	Yes	Limited data on Pu, no data on Pb partitioning	Operational tests in progress	10 radioactive tests done in FY95 and FY96
Semi-batch; 50 kg/h	Unknown	Yes	Unknown	Being used for testing	Plan to do tests with radioactive waste 97/98
Batch mode; 6 kg/h, 20 kg capacity	Yes	No	Toxic metals part. data and Cs, Ce, Sm, Nd	On loan to MeltTran, IF	Operated at the IRC from 6/92 to 9/94
3-200 kg/h	No	No	No	Available for testing	Private tests since 1995
Batch mode; 6 kg/h, 20 kg capacity				Being installed	None
Batch mode; 2 kg/h; up to 40 kg	No	No (Cs,Ce)	None	No longer operational	13 tests conducted during last half of FY92
Batch; maximum volume: 0.03 m^3	No	No	No	Operational	
250 kg/h	Limited by permit	No	No	Test bed ops for mm wave pyrometer	5 tests completed in '94
Batch mode; 2 kg/h				Unknown	None
Unknown	Pb, As, Cd	No	Unknown	Operational	
750 kg/h	Yes	No (Ce,Cs)	Toxic metals data and Cs, Ce	Available for testing	Tests conducted from FY91 through FY95
3,629 kg/h	No	No	None	Operational	Private system tests to convert combustibles to syngas
3800 kg/h (100 tons/day)	Unknown	No	Unknown	R&D facility in Niagara Falls available for testing	Commercial system for solid waste treatment and recycling; private tests for several years
2721 kg/h	Yes	No	Unknown	Operational	Processed spent catalysts since 1993

Table A-2. Summary of potential sources of metals and radioactive partitioning data for plasma tor

	System	Location	Demonstration tests temperature range[a]	Size/scale	Power lev thermal rat
Plasma torch Melters					
	-Fixed Hearth, Transferred				
15	Aerospatiale Plasma Torch Systems	France	Refractory limit: 1,800°C	Commercial	Unknow
16*	Star Ctr Bench Scale Plasma Hearth Process (PHP)	SAIC Star Center, Idaho Falls, ID	Unknown	Bench scale	Unknow
17*	Plasma Hearth Process (PHP) at TREAT	TREAT Facility, ANL-W	Refractory limit: 1,800°C	0.116 m^3; Bench scale	200 kW
18	RETECH Plasma Hearth Process - Pilot scale	RETECH, Ukiah, CA	Refractory limit: 1,800°C	Pilot scale	500 kW
19*	Plasma Hearth Process (Proof of Principle Unit)	RETECH, Ukiah, CA	SCC: 1,000°C	Hearth volume: 2.8 m^3; Field scale	1.2 MW
	-Fixed Hearth, Non-Transferred				
20*	Westinghouse Plasma Fired Cupola	Westinghouse Test Center, Madison, PA	Metal: <1,700°C	Production scale	75 kW-10
21*	Plasma Energy Corp. (PEC) Tilt Furnace	Raleigh, NC	Slag: 1,200-1,600°C	Large bench scale	150 kW
22*	Plasma Energy Applied Tech. (PEAT) Thermal Destruction & Recovery (TDR) system	Huntsville, AL	Unknown	Pilot scale	Choice of 7 170 kW
23	Sharpe Vitrification Technology	Anchorage, AK	Unknown	Industrial scale	Unknow
24	DC Plasma Torch Pot Melter	Georgia Inst. of Technology, Atlanta, GA	Unknown	Bench scale	100 and 250 torches
25	Dial Plasma Facility, DC non-transferred torch	Mississippi State University	Unknown	Large bench scale	100 kW and 2

melters.

	Throughput; residence time	Toxic metals present[b]	Radio-nuclides present[b]	Partitioning data available	Current status	Experience/Comments
	Unknown	Unknown	Unknown	Unknown	Available for testing	Unknown
	7 kg/h	Yes	No	Toxic metals and Ce, Cs partitioning data	Available for testing	
	Batch loading/feeding capability; 30 kg/h	Planned	Planned	Future data on mixed waste	Constructed; Shakedown in process	Cold tests 1996
	700 kg/h	Planned	No	Future data on radioactive surrogates	Construction complete FY96	No testing presently planned
	Semi-continuous 50-100 kg/h	Yes	No	Toxic metals and Ce, Cs partitioning data	Decommissioned 1995	Oper. 91-95; Pit-9 Cold test bed; MWIP Tests '94; PHP POP tests
	5,000 kg/h	Unknown	No	Unknown	Being used for testing	Commercial system used for foundry melting
	31 kg/hr (average)	Yes	No	Limited partitioning data	Unknown	Series of tests on INEL soil done in '91
	23-45 kg/h	Yes	No	Emissions inventory for medical waste; No slag information; Very little on offgas solids	Unknown	Tests conducted in San Diego, CA
	Unknown	Unknown	No	Unknown	Unknown	Commercial sys to treat oil industry wastes
	2 kg/h				Being used for testing	Not suitable for large-scale testing. Limited torch life.
W	2 kg/h	Unknown	No	Unknown	Operational; Used for testing	

Table A-2. (continued).

	System	Location	Demonstration tests temperature range^a	Size/scale	Power lev thermal rat
Plasma torch Melters (continued)					
-Rotating Hearth, Transferred					
26*	Rotating Hearth Furnace (PACT-1)	TREAT Facility, ANL-W	Unknown	Lab scale	Unknown
27*	RETECH Plasma Arc Centrifugal Treatment (PACT-2)	RETECH, Ukiah, CA	SCC: 1,093-1,200°C	Bench scale; 0.46 m (1.5 ft) diameter rotating chamber	200 kW
28*	Plasma Arc Centrifugal Treatment Furnace (PACT-6)	WETO Facility, Butte, MT	Slag temp. > 1,650°C; refractory/material limit <1,800°C	1.83 m (6 ft) diameter rotating chamber; Pilot scale	500-700 k
29	Pit-9 Centrifugal Plasma Furnace (PACT-8)	INEL Rad Waste Mgmt. Complex (RWMC)	Slag >1,650°C; Material limit <1,400°C	2.44 m (8 ft) diameter rotating chamber; Full scale	800-1200 k

Note: Refractory limits of 1,800°C are typical approximations for steady test operations. Peak temperature allowable conditions greater t

Throughput; residence time	Toxic metals present[b]	Radio-nuclides present[b]	Partitioning data available	Current status	Experience/Comments
12 kg/h	No	Yes	Yes	Rotating hearth removed and unit installed as fixed hearth at SAIC Star Ctr	Plutonium volatility tests in 1993
15 kg/h	Yes	No	Toxic metals, Cs and Ce partitioning data	Operational; Used for testing	Units sold commercially
0-225 kg/h	Yes	No	Toxic metals, Cs and Ce partitioning data	Operational; Being used for testing	Testing conducted from 1989 to the present
454 kg/h	Planned	Planned	No	Under construction (at Ukiah, CA)	Will remediate Pit-9 radioactive waste

this can be tested for short periods.

Table A-3. Summary of potential sources of metals and radioactive partitioning data for joule-heat

	System	Location	Demonstration tests temperature range^a	Size/scale	Power le thermal ra
Joule-heated Melters					
30	EnVitCo EV-16 Cold Top Melter	Clemson University Rich Environmental Research Lab, SC	Molybdenum electrode limit: <1,500°C; SCC: 649°C	Pilot scale; 0.07 m^3 capacity	NI*
31	Remote Actinide Melter	Clemson University, SC	Molybdenum electrode limit: 1,800°C	Bench scale	NI
32	WV-1/4 Stirred Tank Melter	Clemson University, Clemson, SC	Inconel 690 stirrer electrode limit: <1,100°C	Bench scale; 0.007 m^3 capacity	NI
33	Integrated DWPF Melter System (IDMS)	Savannah River Site, SC	Inconel 690 electrode limit: <1,200°C	Large bench scale	NI
34	SRS Shielded Cells Research Melter	Savannah River Site, SC	Inconel 690 electrode limit: 1,200°C	Bench scale	NI
35	SRS Non-radioactive Research Melter	Savannah River Site, SC	Inconel 690 electrode limit: 1,200°C	Bench scale	NI
36	SRS Large Stirred Melter	Savannah River Site, SC	Inconel 690 stirrer electrode limit: 1,100°C	Engineering scale	NI
37	EnVitCo Melter EV-005 (RUST)	Savannah River Site, SC	Molybdenum electrode limit: 1,500°C	Bench scale	NI
38	KfK-Hanford Melter	Savannah River Technology Center, SC	Inconel 690 electrode limit: 1,200°C	Pilot scale	NI
39	Defense Waste Processing Facility (DWPF) for HLW	Savannah River Site, SC	Inconel 690 electrode limit: <1,200°C	Production system	NI
40	Transportable Vitrification System (TVS)	Oak Ridge National Lab	Molybdenum electrode limit: 1,500°C	Pilot scale	NI
41	Duratek Melter	Fernald	Electrode limit: 1,200°C	Large bench scale	NI
42	Duratek Melter for silo wastes	Fernald	Electrode limit: 1,500°C	Pilot scale	NI
43	Duratek M-Area Melter	Fernald	Inconel electrode limit: 1,200°C	Pilot scale	NI

melters.

Throughput; residence time	Toxic metals present[b]	Radio-nuclides present[b]	Partitioning data available	Current status	Experience/Comments
40 kg/h (dry); 20 kg/h (wet)	Yes	NI	NI	Being used for testing	
10 kg/h	NI	NI	NI	Assembly to be completed 6/96	Incompatible with metals
5 kg/h (dry); 2 kg/h (slurry)	NI	NI	NI	Being used for testing	Patent rights under discussion with DOE
11 kg/h	NI	NI	NI	To be restarted Jan. 1996	
1 kg/h	NI	NI	NI	Being used for testing	
1 kg/h	NI	NI	NI	Being used for testing	
200 kg/h (dry); 100 kg/h (wet)	NI	NI	NI	Being installed	
10 kg/h	NI	NI	NI	Being used for testing	
40 kg/h	NI	NI	NI	In storage at SRS	Originally used for testing of Hanford flowsheet (EM-30)
100 kg/h	NI	NI	NI	Restarted 1/96	
150 kg/h (dry); 70 kg/h (wet)	NI	NI	NI	Radioactive startup 2/96	
12.5 kg/h	NI	NI	NI	Cold shutdown	Funding and possible rebuild needed to restart
37.5 kg/h	NI	NI	NI	Radioactive startup 4/96	
200 kg/h	NI	NI	NI	Startup April 1996	

Table A-3. (continued).

	System	Location	Demonstration tests temperature range^a	Size/scale	Power lev thermal rat
Joule-heated Melters (continued)					
44	Catholic University - Radioactive System	Vitreous State Lab., Washington D.C.	Electrode limit: 1,200°C	Bench scale	NI
45	Catholic University Radioactive research melter	Catholic Univ., Vit. State Lab, Washington D.C.	Electrode limit: 1,200°C	Small bench scale	NI
46	VSL high temperature melter	Catholic Univ., Vit. State Lab, Washington D.C.	Molybdenum/ceramic electrode limit: 1,500°C	Bench scale	NI
47	EnVitCo EV-101	Scientific Ecology Group (SEG)	Unknown	Pilot scale	NI
48	VE skull mobile melter	VECTRA Technologies	Molybdenum electrode limit: 1,500°C	Pilot scale	NI
49	PNL Small-scale High temperature melter	PNNL, Richland, WA	Monofrax E electrode limit: 1,550°C	Engineering scale	NI
50	PNL Hanford Test Melter	PNNL, Richland, WA	Inconel 690 electrode limit: 1,200°C	Bench scale	NI
51	PNL Research-Scale Melter	PNNL, Richland, WA	Inconel 690 electrode limit: 1,200°C	Small bench scale	NI
52	PNNL Pilot-scale High Temperature Joule-heated Melter	PNNL, Richland, WA	Monofrax E electrode limit: <1,550°C	Pilot-scale	NI
53	EnVitCo EV-501	EnVitCo, Inc.	Material of construction limits: <1,500°C	Pilot scale	NI
54	West Valley production melter	Unknown	Inconel 690 electrode limit: 1,200°C	Pilot scale	NI
55	West Valley research melter	Unknown	Inconel 690 electrode limit: 1,200°C	Bench scale	NI
56	Glass Tech Stirred Melter	Glass Tech, OH			

*Note: Not Included in the scope of this preliminary partitioning study becasue they are not being considered for processing the heterogene and metals. These kinds of materials are typically not amenable to treatment using current state of the art Joule heated melters wit

Throughput; residence time	Toxic metals present[b]	Radio-nuclides present[b]	Partitioning data available	Current status	Experience/Comments
4 kg/h	NI	NI	NI	Being used for testing	
0.4 kg/h	NI	NI	NI	Being used for testing	
1 kg/h	NI	NI	NI	Startup testing to begin FY96	
80 kg/h	NI	NI	NI	In use for production	Currently can't handle mixed waste (Part E permit in progress)
120 kg/h	NI	NI	NI	Available for testing	
13.6 kg/h slurry; 27.2 kg/h solids	NI	NI	NI	Available for testing	
10 kg/h	NI	NI	NI	Installation incomplete due to lack of funding	
0.7 kg/h	NI	NI	NI	Unknown	
120 kg/h	NI	NI	NI	Operational	
180 kg/h	NI	NI	NI	Commercial system available for construction	
50 kg/h	NI	NI	NI	Start operating 3/96	
2 kg/h	NI	NI	NI	Available for testing	

s mixed wastes that contain widely varying and sometimes unknown amounts of very refractory material
t significant feed characterization, sorting, control, and additives.

Table A-4. Summary of potential sources of metals and radioactive partitioning data for miscellane

	System	Location	Demonstration tests temperature range^a	Size/scale	Power lev thermal rat
Induction Melter					
57*	LANL Inductively Coupled Plasma (Induction heated melter)	Los Alamos Nat'l Lab, NM			
Hybrid Systems					
-Plasma Torch and Induction Melter					
58	Plasma induction cold crucible melter system (PICCM)	Georgia Institute of Technology, Atlanta, GA	Unknown	Large bench scale	Unknow
Microwave					
59*	Rocky Flats Microwave Melter	Rocky Flats Nuclear Weapons Plant, CO	1,300°C	Production system; 114 liter capacity	50 kW
60*	Kobe Steel Microwave Melter	Pu Waste Treat. Facility, Tokai Works, Japan	Slag: up to 1,450°C	Production system; 42 liter capacity	25 kW
Molten Salt					
61*	LLNL Molten Salt Bath	Lawrence Livermore Nat'l Lab (LLNL)	830-930°C	Bench scale: 15-cm ID	
Molten Metals					
62*	Molten Metals Technology (MMT) Melter-Catalytic Extraction Processing (CEP)	Fall River, Massachusetts	Bath temperature = 1,600-1,700°C	Assorted sizes ranging from bench-scale to prototype	
63*	MMT Quantum-Catalytic Extraction Processing (CEP)	SEG, Oak Ridge, TN	Bath temperature = 1,600-1,700°C	Bench scale	
64	MMT Quantum-Catalytic Extraction Processing (CEP)	Oak Ridge Reservation	Bath temperature = 1,600-1,700°C	Demonstration unit	
Resistance heated wall melter					
65*	Framatome Technologies Vitrification Process	Bollene, France	Melt: 1,000-1,100°C	Pilot scale	Unknow

s thermal treatment technologies.

Throughput; residence time	Toxic metals present^b	Radionuclides present^b	Partitioning data available	Current status	Experience/Comments
Continuous				Theoretical	
25 kg/h				Start testing in 1996	
Batch mode: 25 kg/h	Unknown	Yes	Unknown	Unknown	Used to treat plutonium contaminated sludges
Batch mode: 15 kg/h	Unknown	Yes	Unknown	Unknown	Processes plutonium contaminated incinerator ash
200 g/h	?	Yes	Data on Pu, U	Operational in 1990	
2,000-15,000 tons/yr	Yes	No	None	Operational	Prototype facility; Permitted as a recycling facility
	Yes	Yes	Limited partitioning data available	Operational as of 2/94	Bench-scale tests
5,000 tons/yr	Yes (eventually)	Yes (eventually)	None	In development (1994)	None; In development as of 1994
25 kg/h (organics)	Yes	Cs	No	Operational	Operating experience since 1990

Table A-5. Summary of potential sources of metals and radioactive partitioning data for rotary kiln

	System	Location	Demonstration tests temperature range[a]	Size/scale	Power leve thermal rati
Rotary kiln Incinerators[d,e]					
	-Non-Slagging Rotary kiln				
66*	ACERC Bench-scale Rotary Kiln Reactor	University of Utah, SLC, UT	315-980°C	Bench-scale: 10 cm long, 10-cm ID	
67*	ACERC Rotary Kiln Reactor	University of Utah, SLC, UT	650-980°C	Pilot scale: 0.6 m long, 0.6 m ID	
68*	SWIFT Pilot Scale RKS	EER - Santa Ana, CA	PCC: 760-1,000°C; SCC: 870-1,100°C	76.2-cm (30 in.) long; 60.96-cm (24 in.) ID	PCC: 132 k (450K Btu/ SCC: 44 k (150K Btu/
69*	TSCA Mixed Waste Incinerator	Oak Ridge National Lab. (ORNL)	PCC: 850-980°C; SCC: 980-1,200°C	Production scale	8.89 MW (30 MMBtu/
70*	SRS Consolidated Incineration Facility (CIF)	Savannah River Site (SRS), SC	PCC: 1,000°C; SCC: 1,100°C	Kiln: 2.4 m ID x 7.6 m long; SCC: 2.1 m ID x 6.4 m high; Production scale	
71*	EPA Incineration Research Facility (IRF)	Jefferson, Arkansas	Max. operating temp. = 900°C; SCC: 1,093°C, max. 1,200°C	Full-scale test fac.; IL 2.13 m, ID 0.95 m, vol. 1.74 m^3; afterburner IL 2.74 m, ID 0.91 m, vol. 1.8 m^3	
72*	EPA Rotary Kiln Incinerator Simulator (RKIS)	Research Triangle Park, NC	PCC: 816-1093°C; SCC: 1093-1204°C	Bench scale	73 kW (250K B
73*	Rollins Environmental Services (RES)	Deer Park, TX	PCC: 1,125°C (test burns); SCC: 1,200°C	Kiln: 10.7 m long x 3.7 m ID; SCC: 12.2 m H x 6.1 m ID; Production-scale	PCC: 23.4 M (80 MMBtu/ SCC: 29.3 M (100 MMBtu
	-Slagging Rotary kiln				
74	MAN GHH	Dormagen, Germany	SCC: >1,200°C	Production-scale	32.6 MW (1 MMBtu/h) ca
75*	Multi-purpose Incinerating Melter System (MIMS); Oscillating, horizontal kiln	Japan	PCC: 1,000-1,500°C	Demonstration unit	
76*	Aptus/Rollins HWI in Coffeyville, KS	Coffeyville, Kansas	Kiln: 870-1,040°C; SCC: 1,200°C	Production scale	18.1 MW (62 MMBtu/
77*	Aptus/Rollins HWI in Aragonite, UT	Aragonite, Utah		Kiln: 4.4 m ID, 12 m long; Production scale	35.1 MW (120 MMBtu

cinerators.

Throughput; residence time	Toxic metals present[b]	Radionuclides present[b]	Partitioning data available	Current status	Experience/Comments
60-70 g per batch	Yes	Surrogates	Some partitioning data is available	Operational (as of 1993)	
3500 g per batch	Yes	No	Yes	Unknown	
Semi-continuous feed: 7 kg/h (15 lb/h) for 1-1.5 hrs/trial	Yes	No	Both radionuclide and metals partitioning data	Operational	
FY93: 335 kg/h; FY94: 395 kg/h; solid/liquid; Solid residence time: 1-1.5 h	Yes	Yes	Both radionuclide and metals partitioning data	Operational	End of FY94≈3,000 hrs
Sol. res. time: 30-90 min. Designed to handle 327 kg/h solid and 85 kg/h liqid	Not yet	Not yet	No data avail. yet; Use model calc. & SWIFT test data for part. est.	Test burns Aug/Sept 1996 startup	A few test burns only
Solids: 50-70 kg/h; Residence time: 0.5-1.0 h; Gas residence time: 1.2 to 2.5 s	Yes	No	Metals partitioning data	Discontinued operations in spring 1996	
Solid residence time ≤ 1 h	Yes	No	None	Operational	Numerous studies performed to date
Gas residence time: 2-3 s; 3,800 kg/h solids (test burn)	Yes	No	Emission rates of toxic metals during test burn	Operational (at least as of 1994)	
45K metric tonnes/ yr (liq); 18K metric tonnes/yr (sol)	Probably	No	No partitioning data	Operational	Began operating in December 1994
Semicontinuous; 10 kg sim. waste fed intermittently to kiln in every batch op.	No	Co-60, Cs-137, Ru-106	Partitioning data is available although the quality of data is limited	Demonstration unit constructed in 1989	Additional test data scheduled to be completed by 1992
Solids: 680-1,770 kg/h; Residence time: 30-45 min	Yes	No	Metal partitioning	Operational	
Unknown	Yes	No	Test burn data may be available	Operational	As of 1993, 1,500 hrs shakedown

Table A-6. Summary of potential sources of metals and radioactive partitioning data for vertical sh

	System	Location	Demonstration tests temperature range[a]	Size/scale	Power lev thermal rat
Incinerators					
	-Vertical Shaft				
78*	Radwaste Treatment RD	Korea	PCC: 700-850°C; SCC: 800°C	Demonstration scale	
79*	Cogema	France	PCC: >= 800°C; SCC: 1,200°C	Pilot scale	69.4 kW (2 Btu/h) soli
80*	Karlsruhe Nuclear Research Center (KfK) Incinerator: α solids; β/γ solids; β/γ liquids	Karlsruhe, Germany	Solids shaft temp: lower section: 850°C; upper section: 1,000°C; SCC: 1,200°C	Pilot scale	
81*	DuPont Experimental Station HWI	Wilmington, Delaware	PCC: 1,038-1,093°C; SCC: 1,038-1,093°C	Production scale	11.7 MW (40 MM Bt
82*	Juelich Incineration System	Juelich Nuclear Research Center, Germany	PCC: 850-1,000°C; SCC: 1,200°C	Pilot scale	0.3 MW (1 MMBtu
83*	Juelich Incineration System - German Fuel Reprocessing Plant	Wackersdorf, Bavaria, Germany	PCC: 850-1,000°C; SCC: 1,200°C	Pilot scale	0.7 MW (2.4 MMBt
	-Controlled air				
84*	SRP LLW Incinerator	Savannah River Site (SRS), SC	PCC: 900-1,100°C; SCC: 950-1,150°C	Production scale	
85*	SEG Radioactive Waste Incinerator	Oak Ridge National Lab	SCC: <= 1,300°C	Production scale	3.36 MW (11.5 MMBt
86*	INEL WERF Incinerator	Idaho National Engineering Laboratory (INEL)	PCC: 870-1,150°C; SCC: 980-1,150°C	Production scale	1.465 MV (5 MMBtu/h) s 381 kW (1.3 MMBtu liquid
87*	Los Alamos CAI	Los Alamos National Lab		Production scale	

and controlled air incinerators.

	Throughput; residence time	Toxic metals present[b]	Radio-nuclides present[b]	Partitioning data available	Current status	Experience/Comments
	Semi-continuous feed; 20 kg/h for 2 h	Yes	Co, Mn, Cs	Some partitioning data is available	Operational (as of 1995)	
	Solids: 10 kg/h; SCC: Gas res. time = 2 s at 1,200°C	Yes	Yes	Poor partitioning data; Some data on Zn, Cl	Operational (as of 1994)	As of 1994, approximately 4,000 h
	α solids: 50 kg/h (60-70 kg/h in 1997); β/γ solids: 50 kg/h; β/γ liquids: 30 kg/h	Yes	Yes	No partitioning data	α solids: shut down mid '95, startup in early '97; β/γ solids & liq.: dismantled by end of '96	All three incinerators combined have over 100,000 hrs of operation experience
	408-680 kg/h (15-25 lb/min)	Yes	No	Metals partitioning data	Operational (as of 1993)	
	50 kg/h	Yes	Yes	None		3rd generation incinerator under construction (as of '88)
	100 kg/h	Yes	Yes	None		Modified design under construction (as of 1987)
	Maximum 180 L/h; 55-275 kg/h	No	Yes	Limited radionuclide partitioning data	Shutdown in 1988	
	Solids at 400-725 kg/h	No	Yes	Radionuclide partitioning data	Operational	Began in '89; From 89-90 > $1x10^6$ ft^3 burned
ls;	Maximum 180 kg/h; Average 63 kg/h	Yes	Yes	Both radionuclide and metals partitioning data	Operational	>10,000 hours
	Liquid: 91 kg/h; Solids: 45 kg/h	No	Yes	Radionuclide partitioning data in the APCS only	Shutdown in '87; Dismantled in '96	>2,000 hours

Table A-7. Summary of potential sources of metals and radioactive partitioning data for fluidized b

	System	Location	Demonstration tests temperature range^a	Size/scale	Power lev thermal rat
Incinerators					
	-Fluidized bed				
88*	RFP Fluidized Bed	Rocky Flats Plant (RFP)	525-600°C	Production scale	
	-Other				
89*	LLNL Transpiration Furnace	Lawrence Livermore Nat'l Lab (LLNL)	500-1,600°C	Bench-scale	
90*	ACERC Differential Bed Reactor (DBR)	University of Utah, Salt Lake City, UT	< 650°C	Bench scale: 0.6 cm thick bed	
91*	SCK/CEN High temperature slagging incinerator (HTSI)	Mol, Belgium	Main=1,700°C; Outlet=1,300°C; Post-combuster chamber=1,000°C	Pilot plant	

Notes:

a. There is much variation from system to system about how the temperatures are measured, estimated, or reported. Slag temperatures a the temperature capability is limited by the refractory, cooling systems, and kinds of materials processed, and often can be much highe exceed 2,000°C with appropriate refractories and cooling.

b. Present means these constituents were present in the tests. The test bed may or may not have the capability to test toxic metals.

c. Asterisks attached to the system number indicate that a system description is available.

d. In most cases, the temp. or range listed is that at which tests were conducted. Those indicated with max, min, <, or > are the operat For the incinerators listed, all temperatures shown are gas temperatures unless otherwise indicated.

e. There are hundreds of incinerators operating in the private sector. For brevity's sake, only a few are listed.

and miscellaneous incinerators.

Throughput; residence time	Toxic metals present[b]	Radio-nuclides present[b]	Partitioning data available	Current status	Experience/Comments
82 kg/h				Shutdown in 1986	>4,500 hours
Batch system	No	Yes	Partitioning data on Pu, U; solid, vapor	Operational (as of 1993)	
~4 g per batch	Yes	No	Yes	Unknown	
25-30 kg/h (solid waste); 1,700 Nm^3/h offgas generated	Yes	Yes	Partitioning data available	Operational (as of 1986)	As of 1986, > 12,000 hours

general very difficult to accurately measure and are often simply estimated. For most melters,
reported temperatures at which tests were run. Typical melter temperature limits can

constraints of the system. Solid temps in rotary kiln incin. are usually 100-200°C lower than the gas temp.

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Appendix B

System Descriptions of Selected Thermal Treatment Systems

System Descriptions of Selected Thermal Treatment Systems from Appendix A: Page #

Thermal treatment process: PNNL Bench scale DC Arc Furnace (Rad)

Location: Pacific Northwest National Lab, Richland, WA

Mode of operation (continuous,batch): Batch mode with feed capability. No tapping.

Status: The system is operational and conducting radioactive testing.

Process description/size/dimensions/materials of construction:

This is a DC arc melter with a single top mounted electrode (cathode) made of graphite and a fixed graphite hearth (anode). The hearth itself is 4.25 inches in diameter and 4.25 inches high. It uses nitrogen purge gas and therefore runs under reducing conditions. Material is fed into the melter using an auger feeder once the system has started operation. The entire system, including the APCS, is enclosed in a hood to limit the spreading of radioactive contamination.

Waste feed preparation/sorting/sizing requirements:

The system can process any dry feed that can be run through the auger feeder. Plutonium is added to the feed in solution form. The feed is then left to dry before processing in the arc melter.

Air pollution control system components:

The APCS consists of a chilled submerged bed scrubber followed by HEPA filters.

References:

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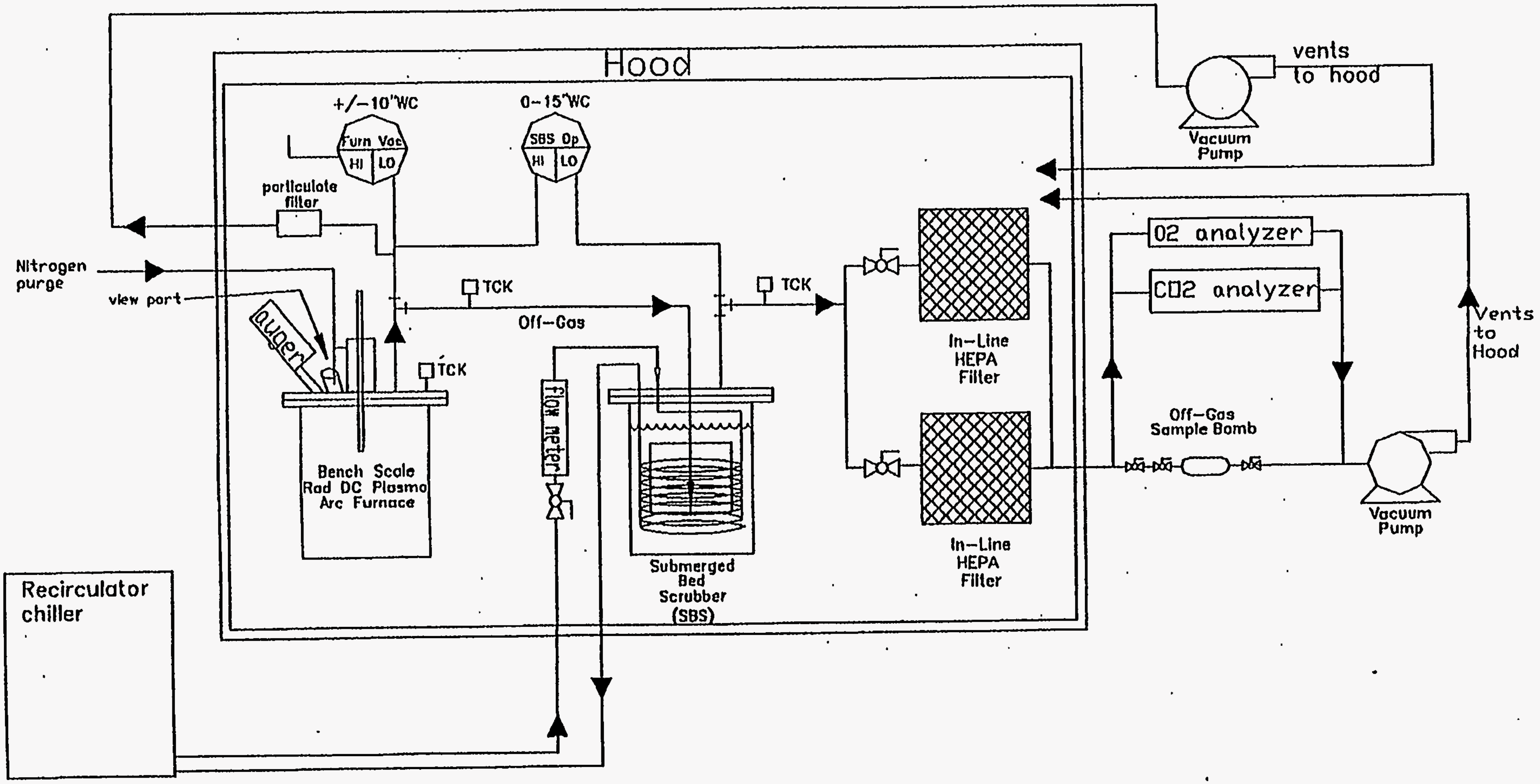
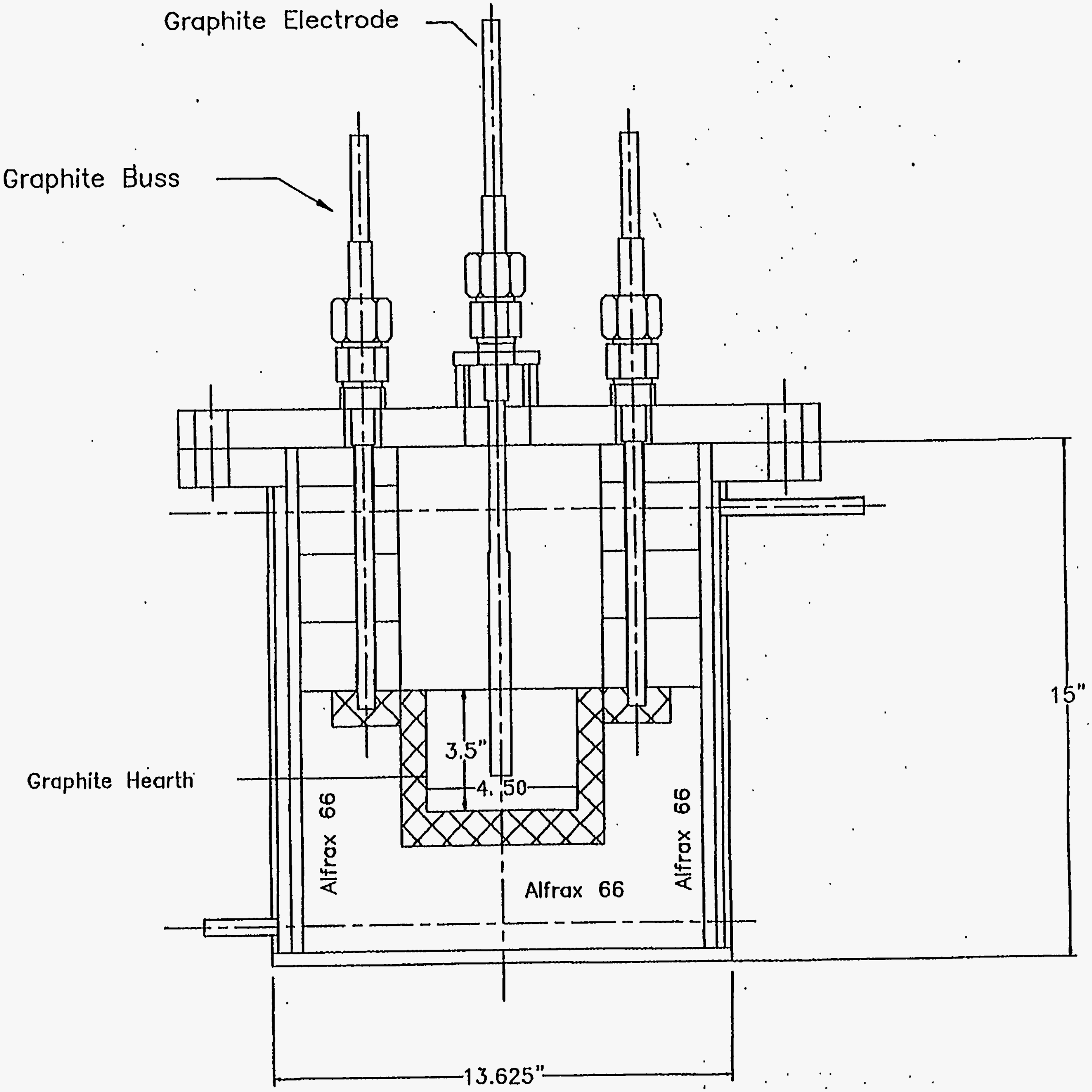
System Setup for the
DC Plasma Arc Furnace




Graphite Electrode
Graphite Buss
Graphite Hearth
3.5"
4.50
Alfrax 66
Alfrax 66
Alfrax 66
15"
13.625"

Thermal treatment process: INEL Small Arc Melter

Location: INEL, Idaho Research Facility, Idaho Falls, ID

Mode of operation (continuous,batch): Batch mode with feed capability. No Tapping.

Status: On loan to Meltran, Inc. located in Idaho Falls, ID.

Process description/size/dimensions/materials of construction:

This is a DC arc melter using two side by side carbon electrodes. The melter chamber is 9 inches in diameter and 14 inches high when lined with a cast ceramic crucible (1/2 inch thick). The chamber is constructed of double walls of stainless steel and water cooled. It operates at a power level of 10-40 kW. Typical operating current and voltages are 110 A and 180 V. Measured slag temperatures range from 1200-2200 C. Operation above 1800 C is limited to short periods of time due to refractory temperature limitations.

Waste feed preparation/sorting/sizing requirements:

All tests were done with feed mix reduced to particles less than approx. 2.0 mm in diameter although this was not required except for using the auger feeder to introduce material. Any size material that could be fitted into the crucible (9" diameter x 14" high) could be melted, although this was never tried.

Air pollution control system components:

Primary APCS - baghouse with high efficiency main filter and followed by HEPA filter.
Secondary APCS components (prior to primary system) used at various times included liquid nitrogen cooled cyclones and ice cooled cyclones to condense water vapor.

References:

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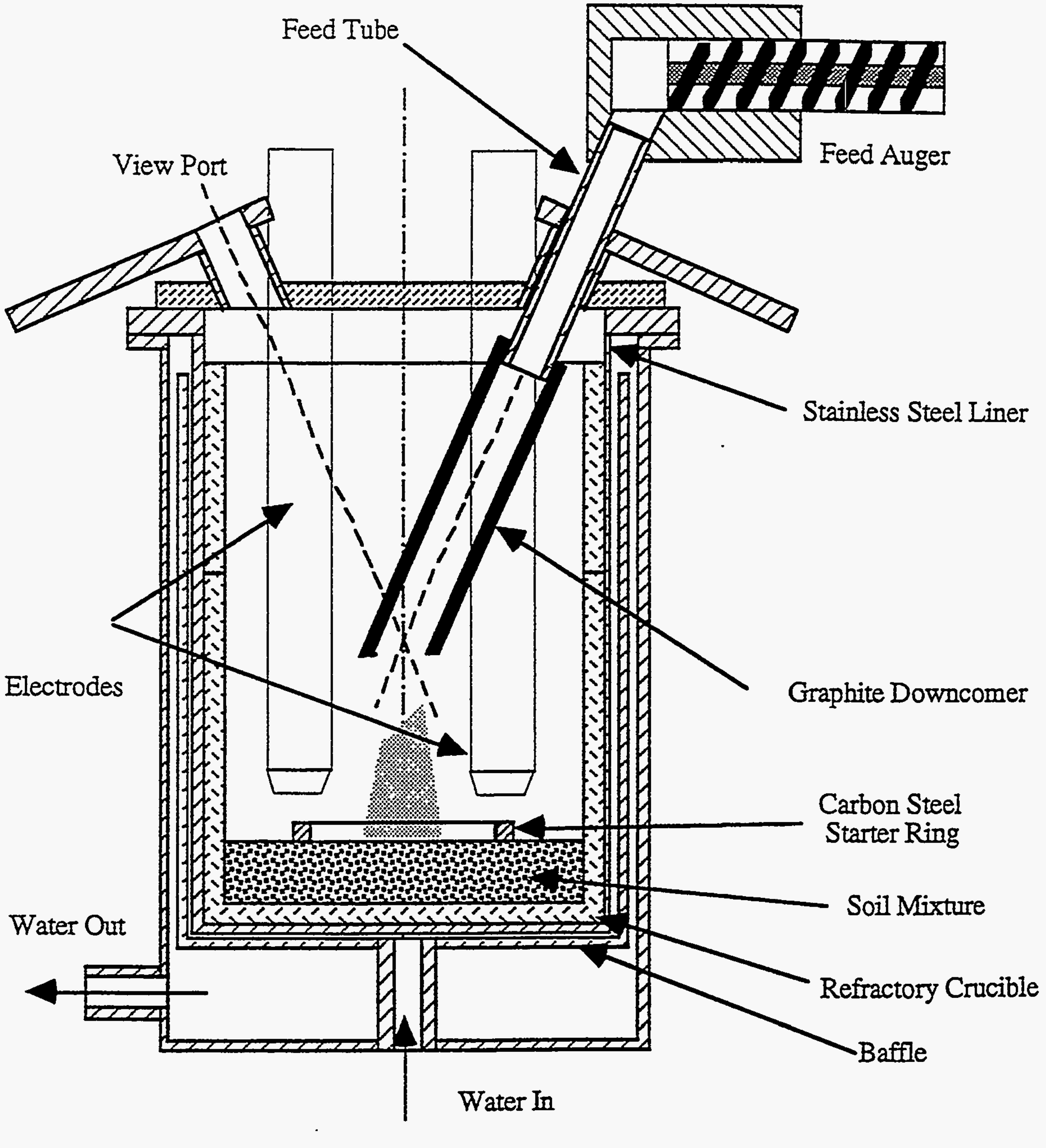


Figure 3.9 Schematic diagram of the modified arc melter crucible assembly showing the material feed system used during FY-94.

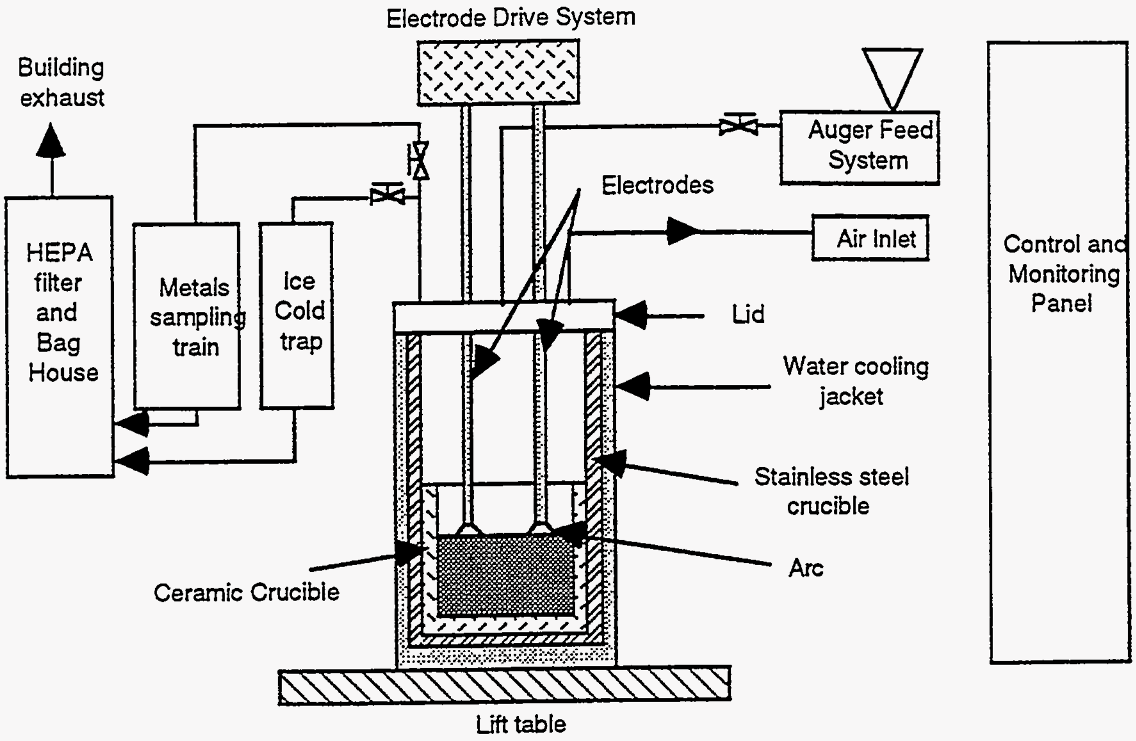


Figure 3.2: Schematic drawing of the modified bench scale arc-melter.

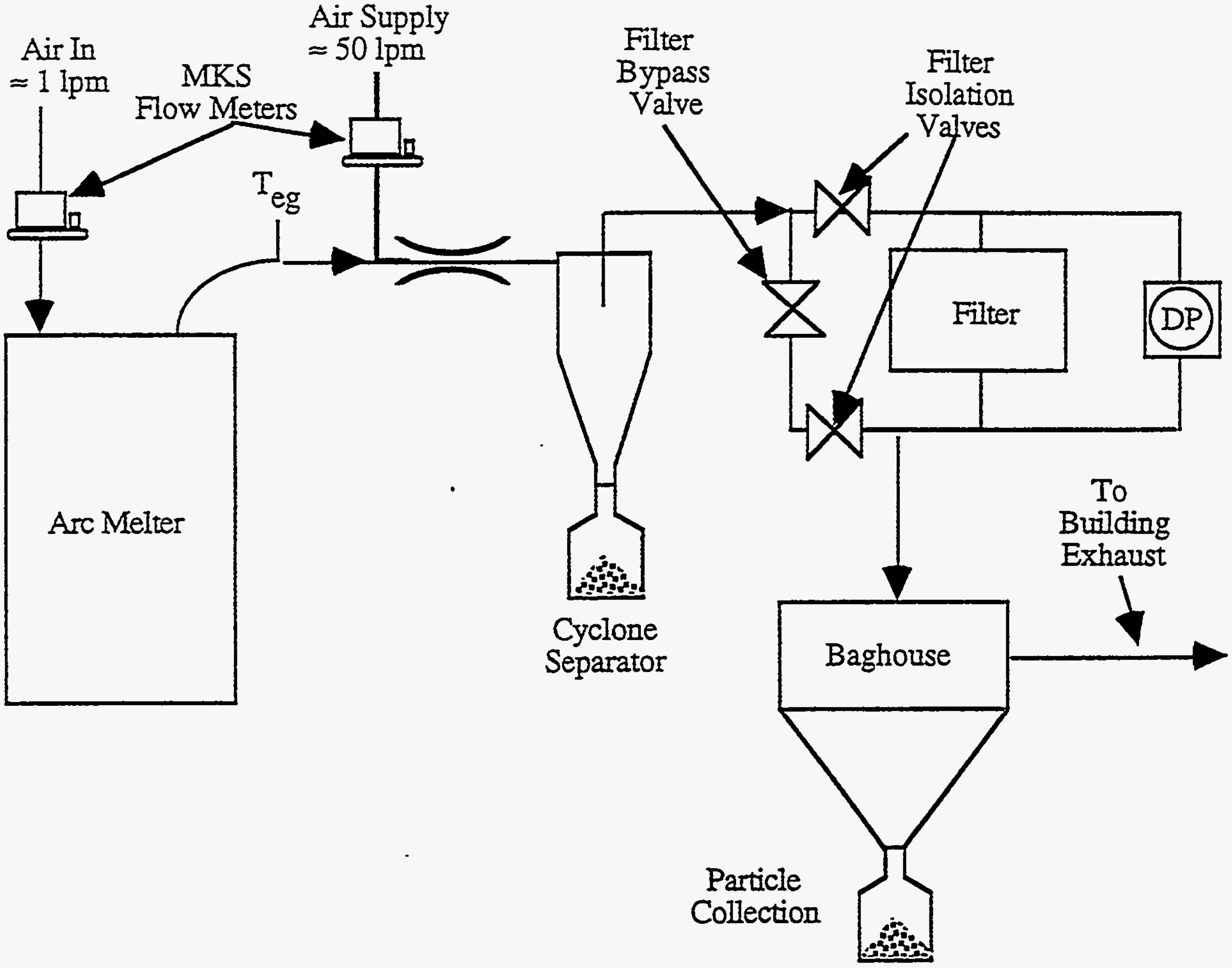


Figure 3.6 Schematic diagram of the modified offgas system utilized during the FY-94 tests.

Thermal treatment process: MeltTran Small Arc Melter

Location: Meltran, Inc., Idaho Falls, ID

Mode of operation (continuous,batch): Continuous

Status: Operational; Available for testing.

Process description/size/dimensions/materials of construction:

This is a DC arc melter using two side by side carbon electrodes. The melter chamber is an uncooled ruby refractory lined crucible with a tap hole. The system operates at a power level of 10-40 kW. Typical operating current and voltages are 110 A and 180 V. Operation above 1800 C is limited to short periods of time due to refractory temperature limitations.

Waste feed preparation/sorting/sizing requirements:

Feed mix must be reduced to a size that can be used by the auger feeder.

Air pollution control system components:

The primary APCS is a baghouse with high efficiency main filter and followed by HEPA filter.

References:

Thermal treatment process: SRS Small Arc Melter

Location: Savannah River Site, NC

Mode of operation (continuous,batch): Batch mode with feed capability. No Tapping.

Status: Being installed in a glove box.

Process description/size/dimensions/materials of construction:

A DC arc melter using two carbon electrodes. Melter chamber is 9 inches in diameter and 14 inches high when lined with a cast ceramic crucible (1/2 inch thick). The chamber is constructed of double walls of stainless steel and water cooled. Operates at a power level of 20-40 kW. Typical operating current and voltages are 110 A and 180 V. Operation above 1800 C only for short periods of time due to the temperature limitations on the refractory.

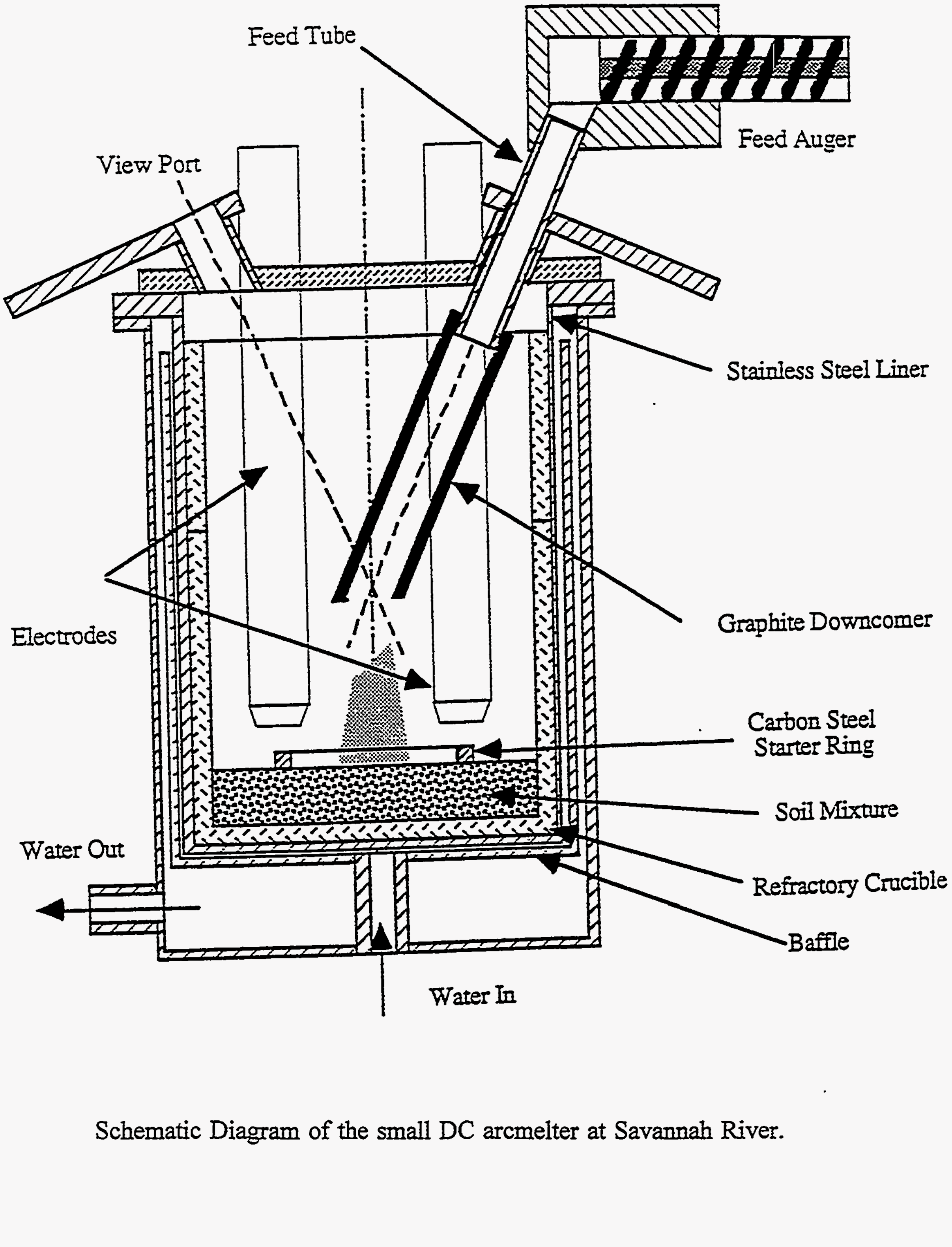
Waste feed preparation/sorting/sizing requirements:

Feed mix must be of a size compatible with using the auger feeder to introduce material.

Air pollution control system components:

Primary APCS - baghouse with high efficiency main filter and followed by HEPA filter.

References:



Schematic Diagram of the small DC arcmelter at Savannah River.

Thermal treatment process: Mark I Furnace
Location: MIT Plasma Fusion Center, Cambridge, MA
Mode of operation (continuous,batch): batch mode with feed capability
Status: unknown

Process description/size/dimensions/materials of construction:

A graphite electrode DC arc furnace. A graphite rod about 2 inches in diameter acts as the cathode and a graphite crucible 13 inches in diameter and 21 inches high acts as the anode. Material in the crucible is heated by the joule effect as current flows through the material from anode to cathode and by arc radiation heating if an arc is established.

Waste feed preparation/sorting/sizing requirements:

None. Anything that can fit in the crucible will be melted.

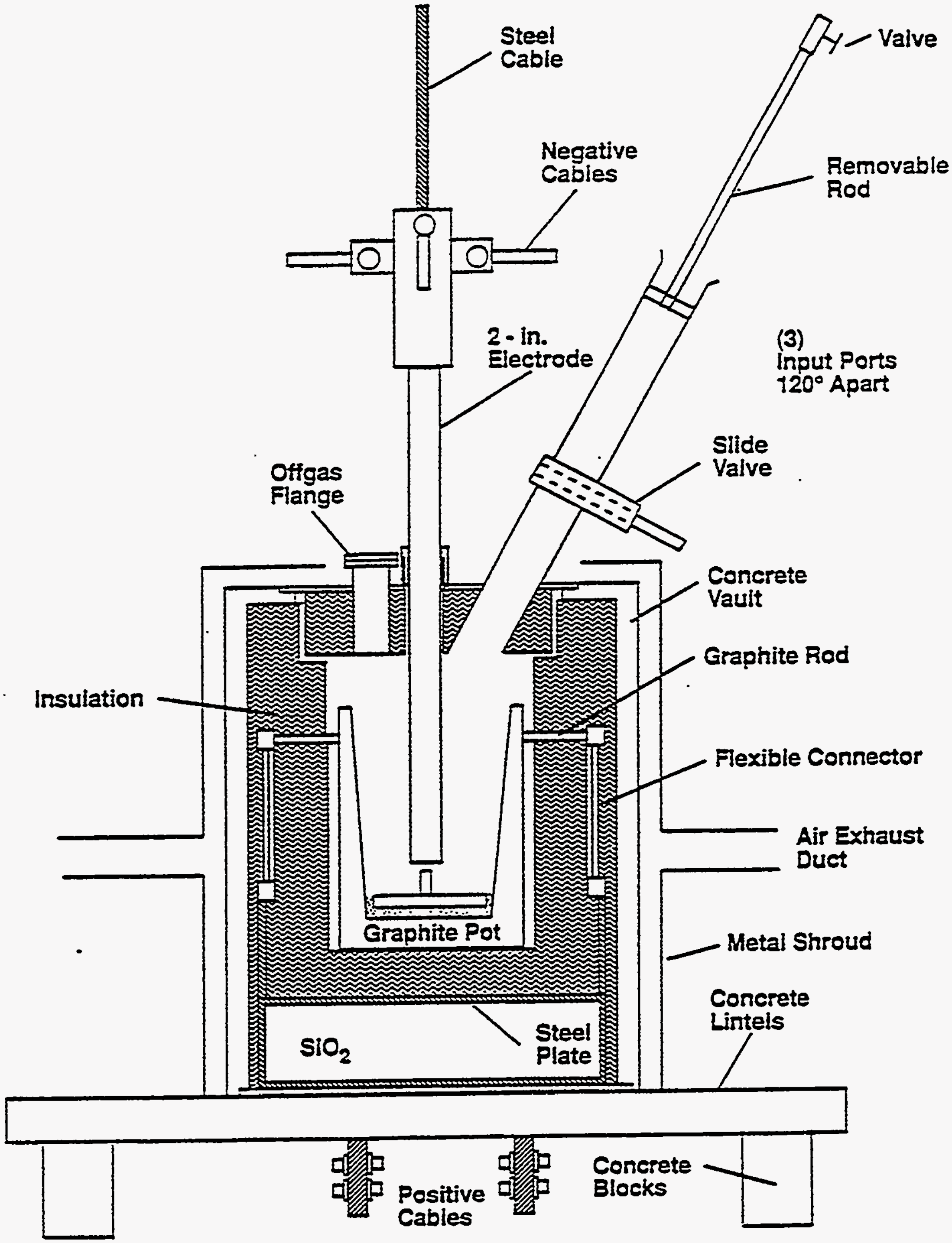
Air pollution control system components:

The APCS consists of a particulate "knock out" box which removes large particlulates from the exhaust stream. This is followed by a section with water spray nozzles to cool the exhaust before entering a venturi scrubber. The venturi scrubber utilizes a liquid recirculating system so that the water can be analyzed before disposal.

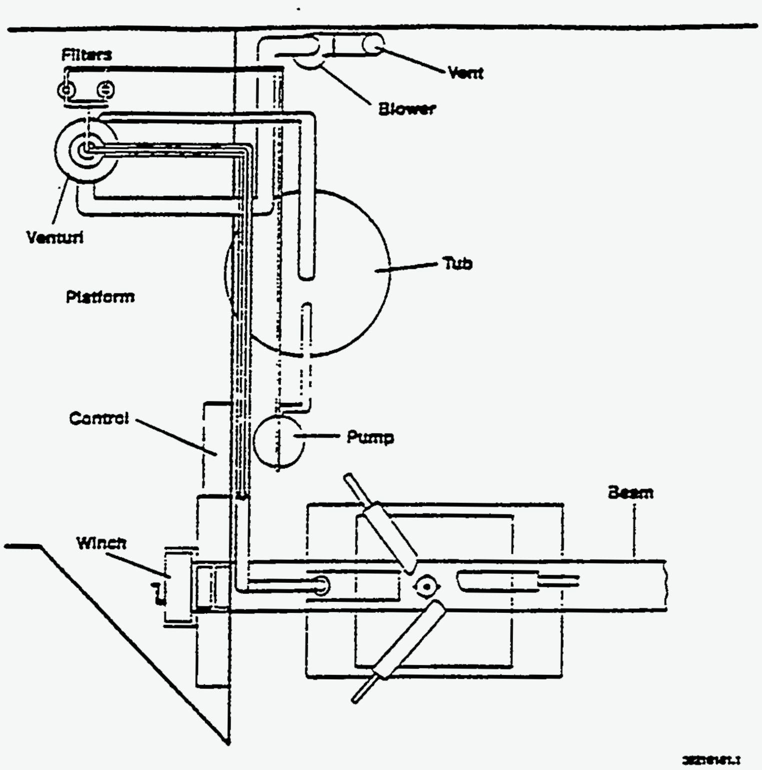
References:

J. E. Surma, et. al., *Evaluation of the Graphite Electrode DC Arc Furnace for the Treatment of INEL Buried Wastes*, Report No. PNL-8525 (UC-602), Battelle Memorial Institute, June, 1993.

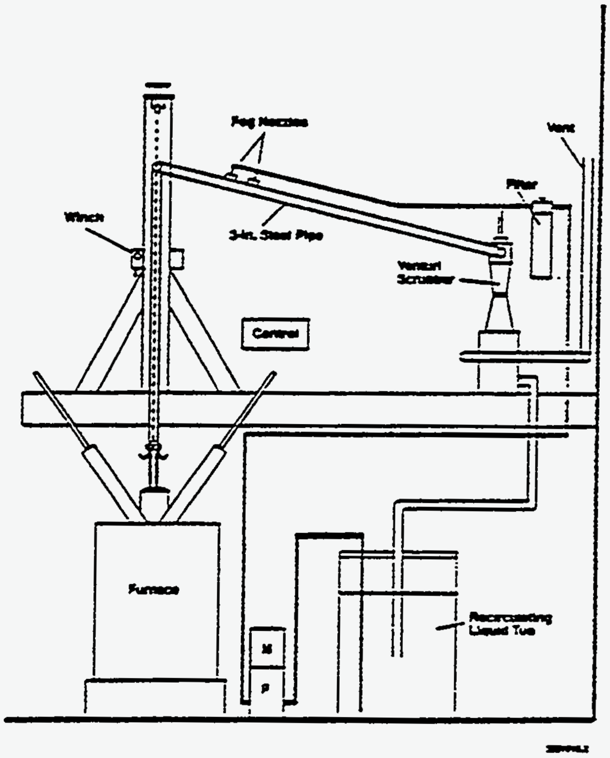
J. K. Wittle, et. al., "DC Graphite Arc Furnace and Diagnostic System for Soils," *Third International Congress on Toxic combustion By-Products, June 14-16, 1993, MIT, Cambridge, MA.*, Poster Presentation, Number 29 (1993).



Schematic of Mark I Furnace



Plan View of Mark I Installation



Elevation View of Mark I Installation

Thermal treatment process: Mark I-W DC Arc Melter

Location: DOE/Industrial Laboratory for Vitrification Research, Clemson University

Mode of operation (continuous,batch): Batch

Status: Operational

Process description/size/dimensions/materials of construction:

The Mark I-W water-cooled melter has a process capability of 1 ft^3 of feed in batch mode only. The system is comprised of a furnace assembly, electrode assembly, offgas equipment, water cooling system, N_2 purge system, electrical power supply, and a camera lens assembly. The furnace features a removable, stainless steel (SS) lower chamber and a SS fixed upper roof. The lower chamber contains 2 nested graphite crucibles. The outer graphite crucible is connected to the positive side of the power supply by graphite rods at 4 locations. The inner crucible rests in direct contact with the outer crucible and acts as the positive electrode for the melt.

The electrode superstructure houses the movable upper electrode and is mounted on top of the furnace roof. To create the arc, the movable upper electrode is lowered to contact the lower starter electrode. As the current is passed through the electrodes, the upper electrode is raised and a DC plasma arc is initiated.

The power supply (480 V, 3-phase, 60 Hz) is rectified, filtered, and chopped into 1000 Hz pulses using power transistors. The high frequency power is then transformed to the desired voltage and rectified to provide DC current. The power at 100% output is 133.3V and 750 A (100 kW).

Waste feed preparation/sorting/sizing requirements:

Batch tests were performed containing soils, bulk metals and metal shavings, and waste briquettes containing cement, refractory, and other materials typically found in mixed waste debris. No particular preparation, sorting, or sizing was reported.

Air pollution control system components:

Offgas system consists of: film cooler, quench chamber, venturi scrubber, induced draft blower, and a gas flow meter. The film cooler supplies air along the wall to condense vapors in the center of the pipe and decrease buildup of particulate matter on the pipe. Offgas then enters the quench chamber where it is cooled prior to entering the venturi for particulate capture.

References:

M.P. Speer, D.M. cash, S.J. Griner, D.L. Erich, and T.J. Overcamp, "Vitrification of mixed wastes in a DC Arc Melter", *AWMA Meeting*, Nashville, TN (June 1996).

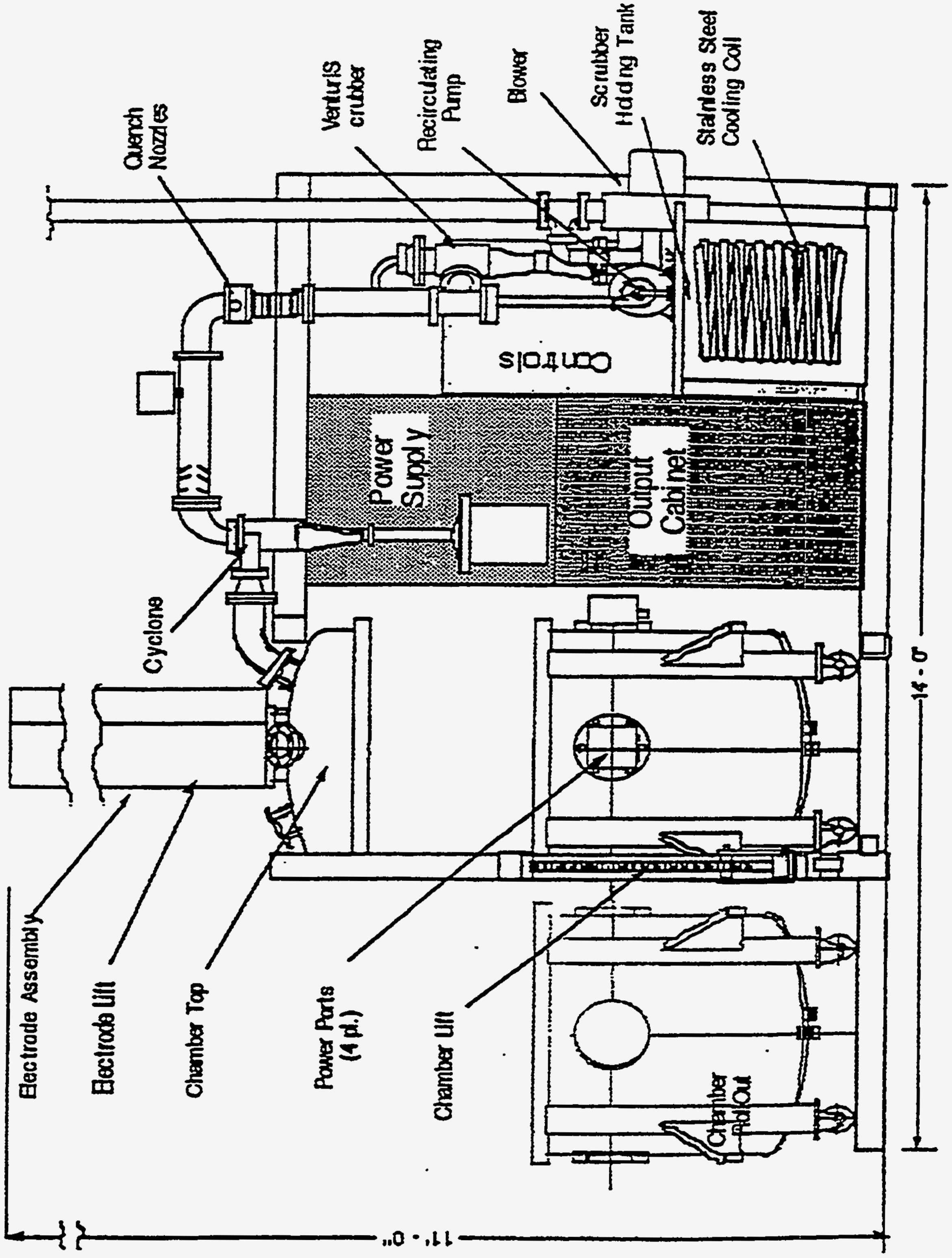


Figure 1. Schematic of the EPI Mark I-W melter system.

Thermal treatment process: Mark II Furnace

Location: MIT Plasma Fusion Center, Cambridge, MA

Mode of operation (continuous,batch): continuous, separate ports for metals and slag.

Status: operational, first tests in FY-94

Process description/size/dimensions/materials of construction:

A graphite electrode DC arc furnace. Has a coaxial graphite electrode (outer part: 16 inch O.D., 10 inch I.D., inner part: 6 inch O.D.)that can operate in non-transferred mode or transferred mode using the graphite hearth at the bottom of the melter as an anode. The melt chamber consists of a steel cylinder (6 ft in diameter, 7 ft 5 inches tall) lined with insulation and refractory brick. The hearth sits atop refractory brick and the entire furnace is supported by four water cooled legs.

Waste feed preparation/sorting/sizing requirements:

The feed is packaged in bags of about 20 kg.

Air pollution control system components:

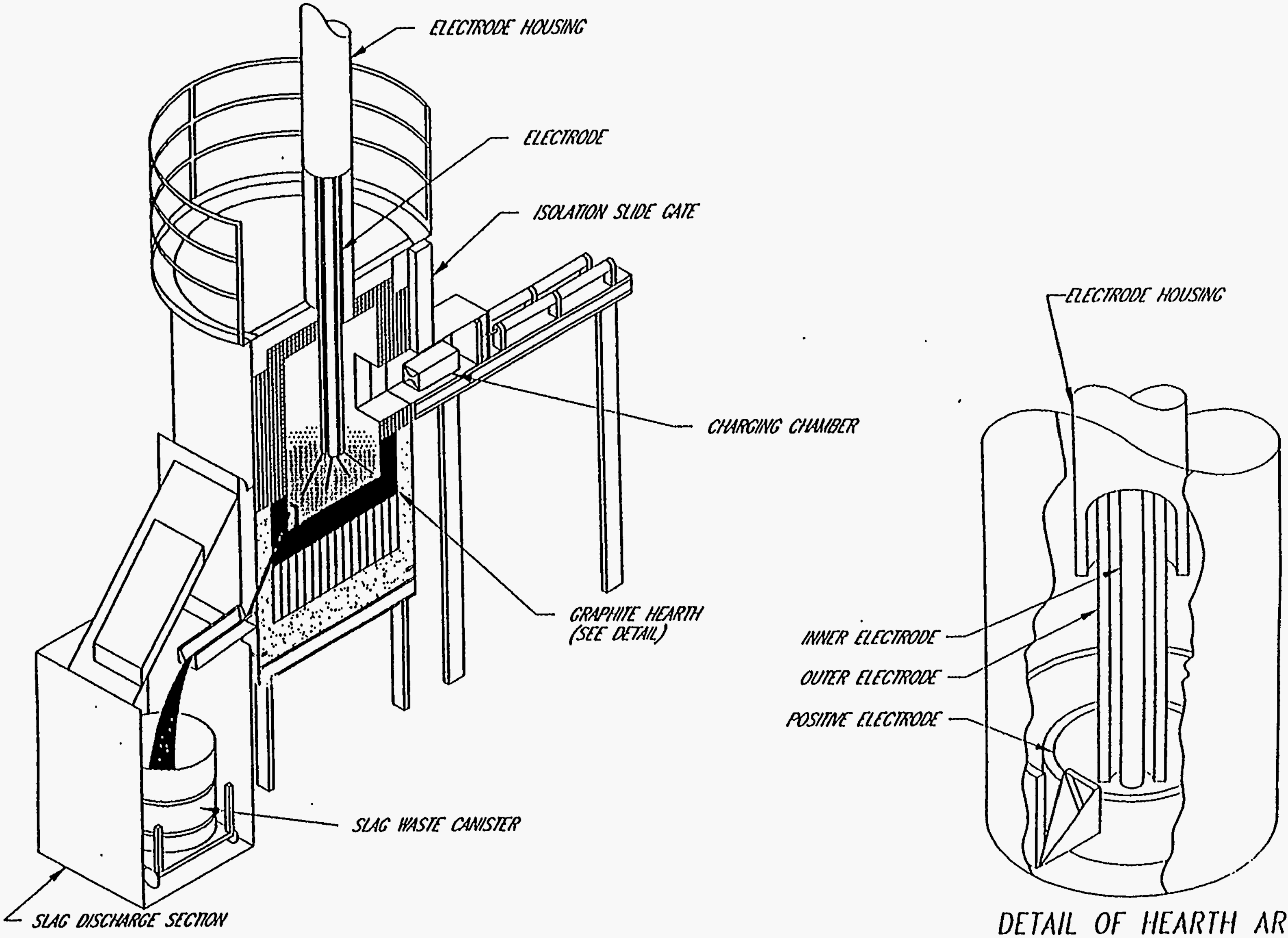
The off-gas system is composed of a water quench system followed by two venturi scrubbers arranged in series. Air blowers are used to force circulation of the exhaust gases. Water from the venturi scrubbers is recirculated and filtered. The system is designed to remove 95% of the particulates less than 0.5 microns and acid gases.

References:

J. K. Wittle, et. al., "DC Graphite Arc Furnace and Diagnostic System for Soils," *Third International Congress on Toxic Combustion By-Products*, June 14-16, 1993, MIT, Cambridge, MA, (1993).

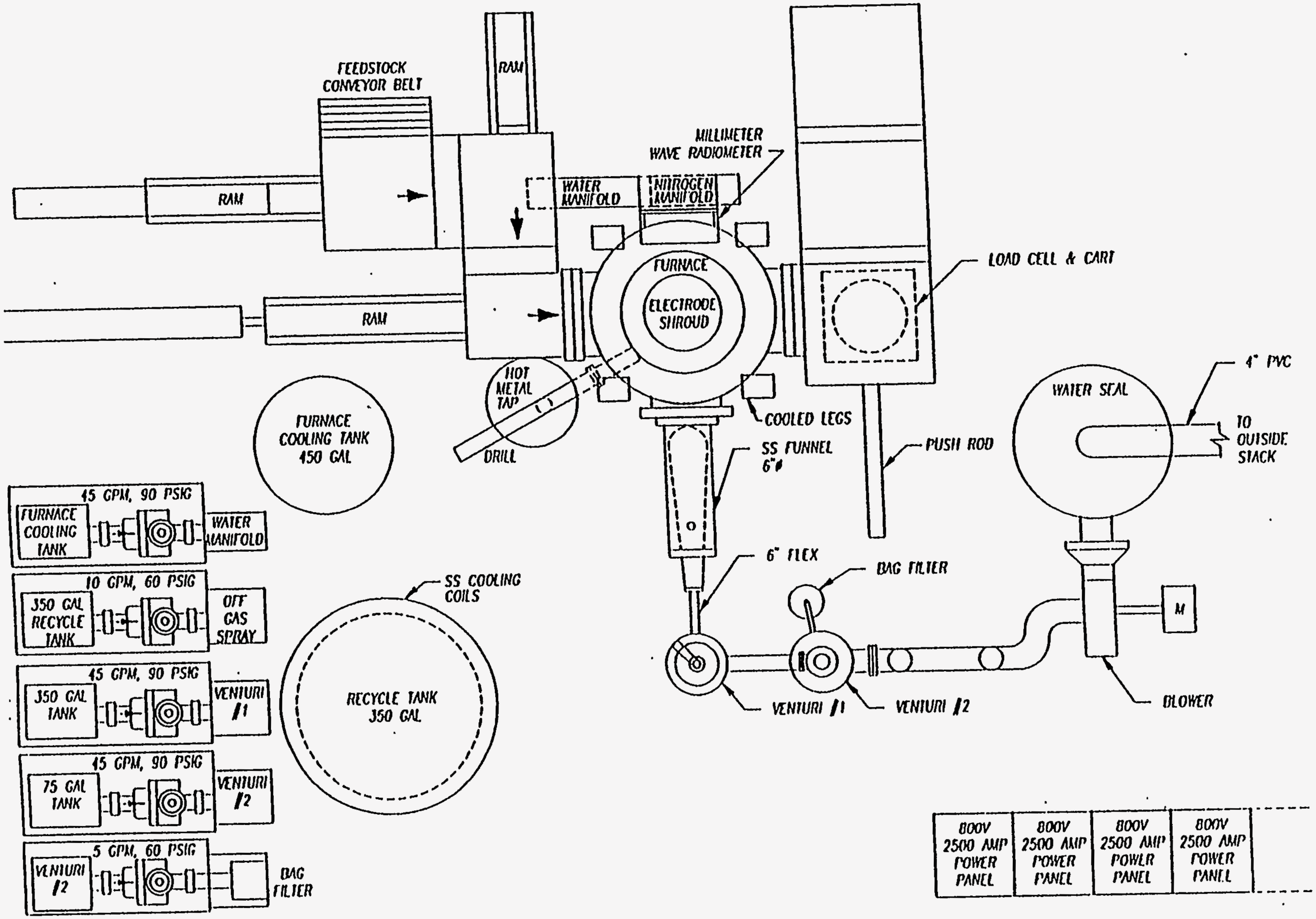
J. E. Surma, et. al., *FY-94 Summary Report Mark II DC ARC Furnace Testing*, Report No. PNL-xxxx, Battelle Memorial Institute, August, 1994.

J. L. Watkins, et. al., *Test Plan: FY93 Mark II DC Arc Furnace Tests*, Pacific Northwest Laboratory, Richland, WA, October, 1993.

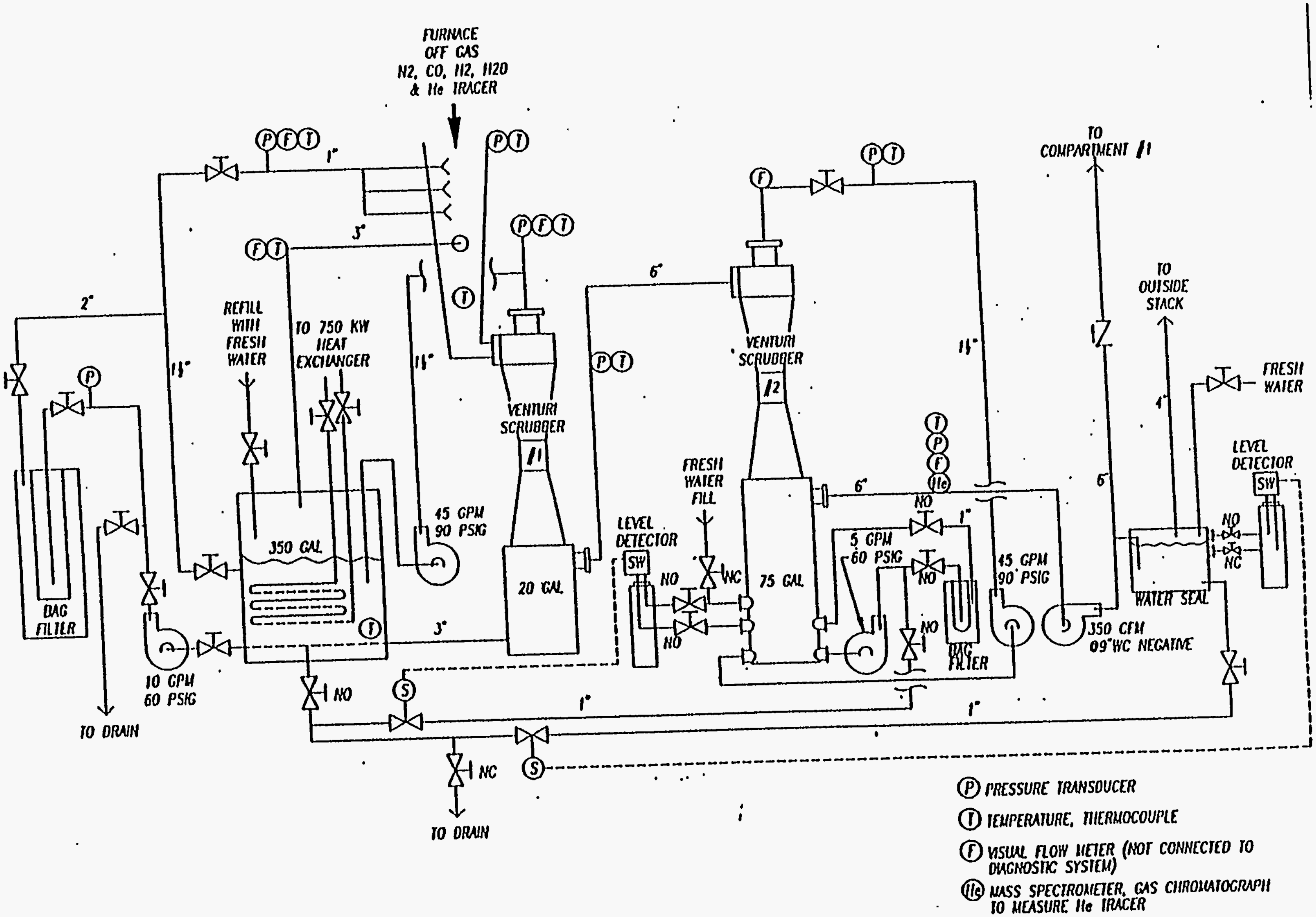


DETAIL OF HEARTH AREA

Mark II Graphite Electrode DC Arc Furnace



Test Assembly, Plan View



Offgas System P&ID

Thermal treatment process: Exide DC Arc Furnace
Location: Reading, PA
Mode of operation (continuous,batch): continuous
Status: operational

Process description/size/dimensions/materials of construction:

The system is a DC arc melter with a single top mount electrode (cathode) and with the hearth or melter chamber acting as the anode. The system is used to recycle lead from car batteries. Lead is tapped from the bottom of the melter chamber and slag is tapped from the side.

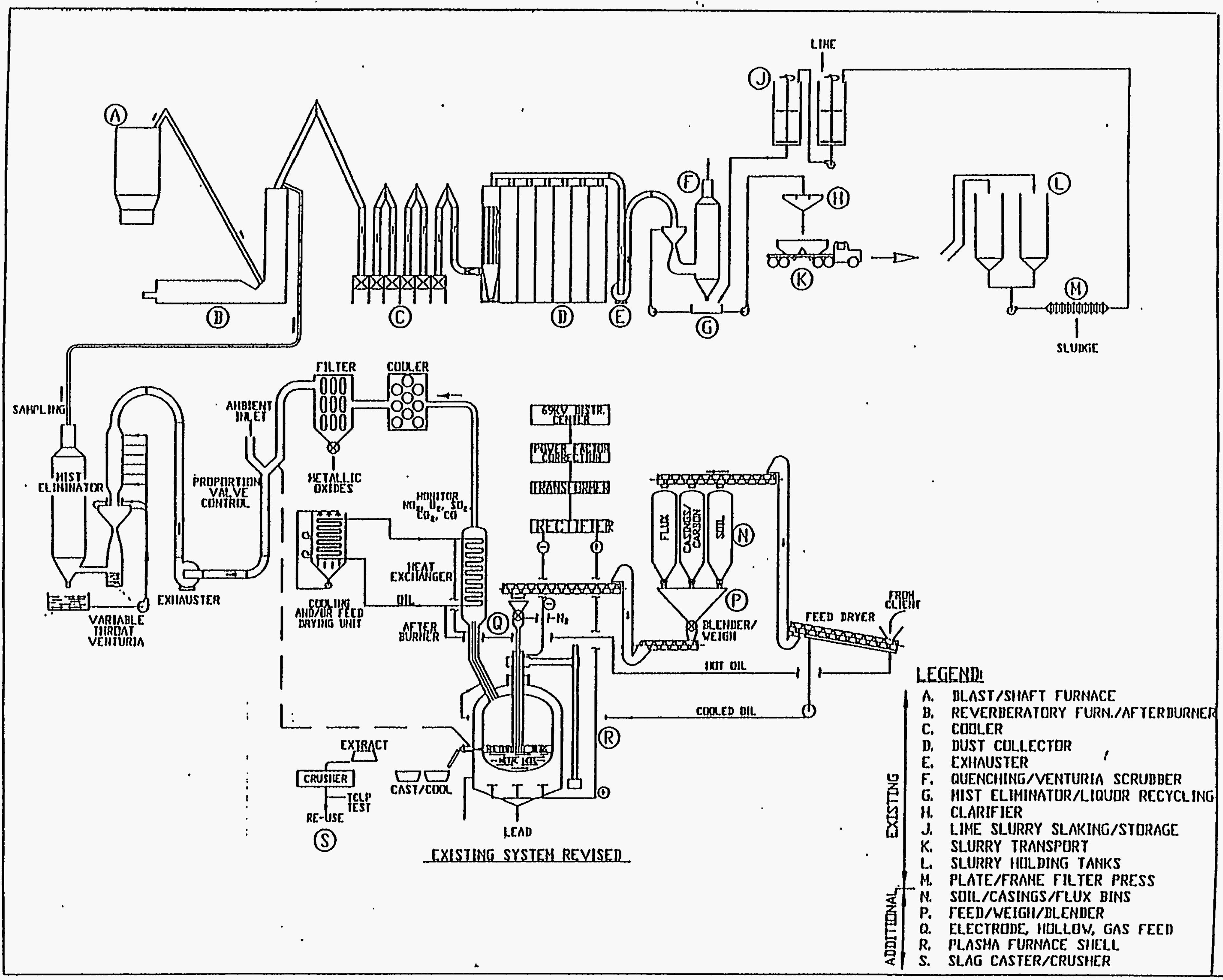
Waste feed preparation/sorting/sizing requirements:

unknown

Air pollution control system components:

The melter system has an extensive APCS consisting of a cooler section with a heat exchanger followed by an additional cooler section. The exhaust is then sent through a bank of filters and after dilution with ambient air through a variable throat venturi scrubber. Excess water is then removed in a mist eliminator section.

References:



EXISTING SYSTEM REVISED

Thermal treatment process: USBM AC, 3-electrode Arc Melter

Location: USBM, Albany Research Center, Albany, Oregon

Mode of operation (continuous,batch): Continuous

Status: Completed:
ASME Municipal Ash Test Series '91/'92
BWID Waste Ash & Soil Surrogate series 1993
BWID and Stored Waste "As Received" Test Series 4/95; Mixed Waste Surrogate and Soil Series
WHC LLW (Tank Wastes Surrogates) Assessment Test Series 1995, EM30
EM50 LFFA Funding Terminated FY95

Process description/size/dimensions/materials of construction: refractory lined, separate slag and metal taps, continuous feed, 4 top down feed tubes and rotary air lock auger feed system, air/pyrolysis plenum. The furnace is a stationary, refractory-lined, small industrial-scale electric arc melting furnace that is sealed for atmosphere control. The furnace has three moveable 4 in. diameter solid graphite electrodes, automatic power, and electrode vertical positioning control. Power is supplied by a fully instrumented 800 kVA 3-phase supply. The feed tubes, furnace roof and sidewalls, and copper slag tapping fixture are water cooled. Slag can be continuously tapped from the furnace. The copper, water-jacketed tapping fixture is six in. outside diameter and 7.5 in. long, with a 1.25 in. inside diameter. The furnace is refractory lined (chromic oxide-alumina bonded, 90% alumina super duty straight firebricks (Ruby)). The finished inside diameter of the furnace is about 46 in. at mid-height. The capacity of the hearth is approximately 5 ft^3 (1 tonne hearth). The furnace can process up to 750 kg/h of feed material.

Waste feed preparation/sorting/sizing requirements: The feed system was designed for measuring, controlling, and delivering aggregate and soil-type materials of sizes less than ½ inch diameter to the furnace. Efforts made to minimize segregation in the feed hoppers included adding the feed mixtures one barrel at a time and achieving near emptiness in the receiving bin before adding another barrel. The feed system is rated to deliver up to 2000 lb/h of minus 0.5 in. screened and dried material with a bulk density of approximately 80 lb/ft^3.

Air pollution control system components: Primary components were (a) refractory-lined ductwork serviced by two 800,000-Btu natural gas burners, (b) refractory-lined thermal oxidizer serviced by one 3-MMBtu natural gas burner, (c) evaporative gas cooler (EGC), (d) cooling air windbox, (e) cyclone, (f) pulse-jet baghouse, (g) acid gas scrubber, (h) cooler and condenser, (i) heat exchanger, (j) induced draft blower, and (k) activated carbon and HEPA filter banks.

References:

N. R. Soelberg, et. al., *Arc Melter Demonstration Baseline Test Results*, Informal Report No. EGG-WTD-11138, EG&G Idaho, Inc., July, 1994.

W. K. O'Connor, L. L. Oden, P. C. Turner, N. R. Soelberg, A. G. Chambers and G. L. Anderson, *Graphite Electrode Arc Melter Demonstration Phase 2 Test Results (DRAFT)*, External Report No. INEL-95/0502, September, 1995.

G. L. Anderson, et. al., *Test Plan Phase-1 Baseline Tests FY93 BWID Arc Melter Processing*, White Paper, EG&G Idaho, Inc., February 28, 1993.

N. R. Soelberg, et. al. *Test Plan for the BWID Phase 2 Electric Arc Melter Vitrification Test,* Report No. INEL-94/0004.

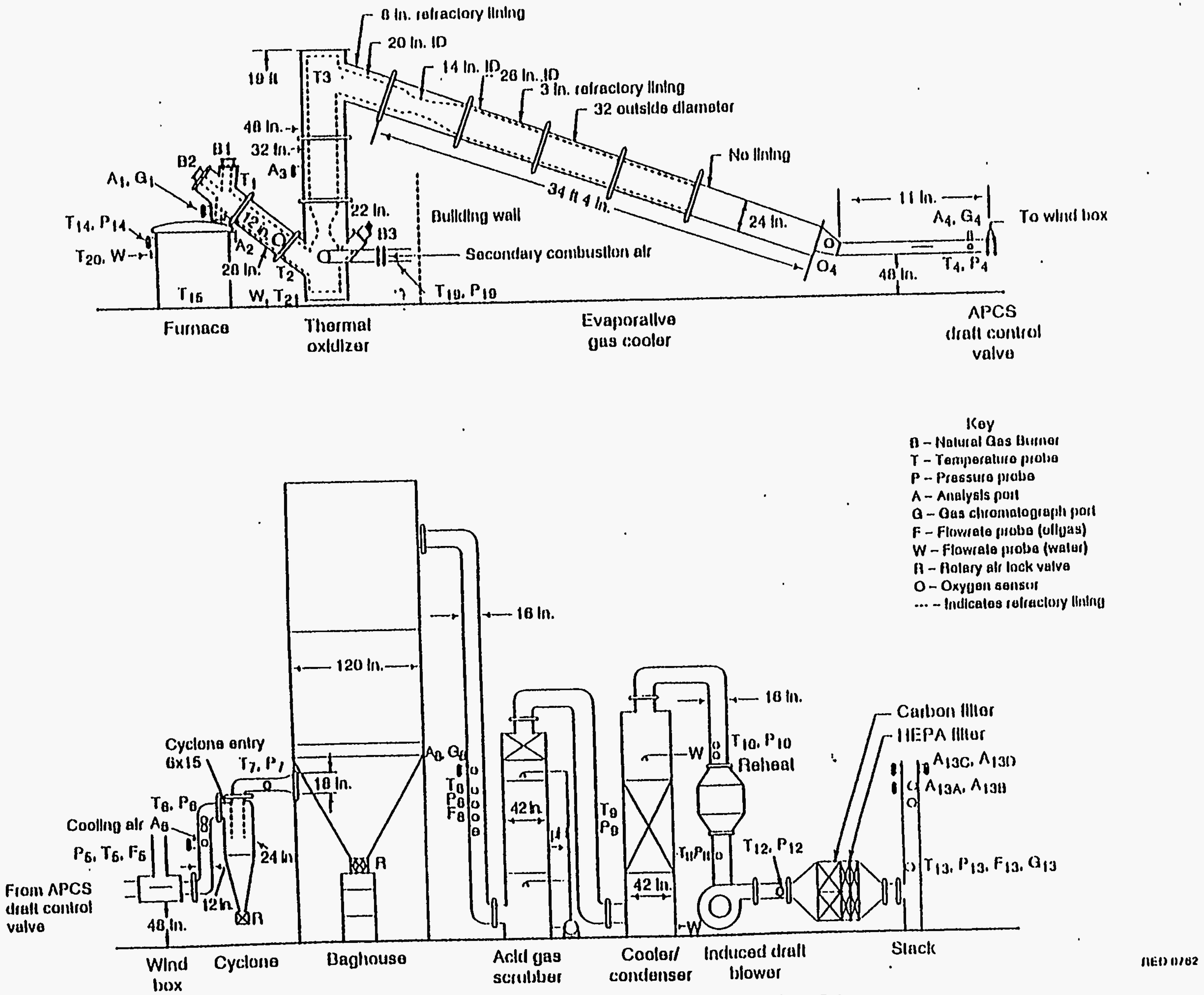
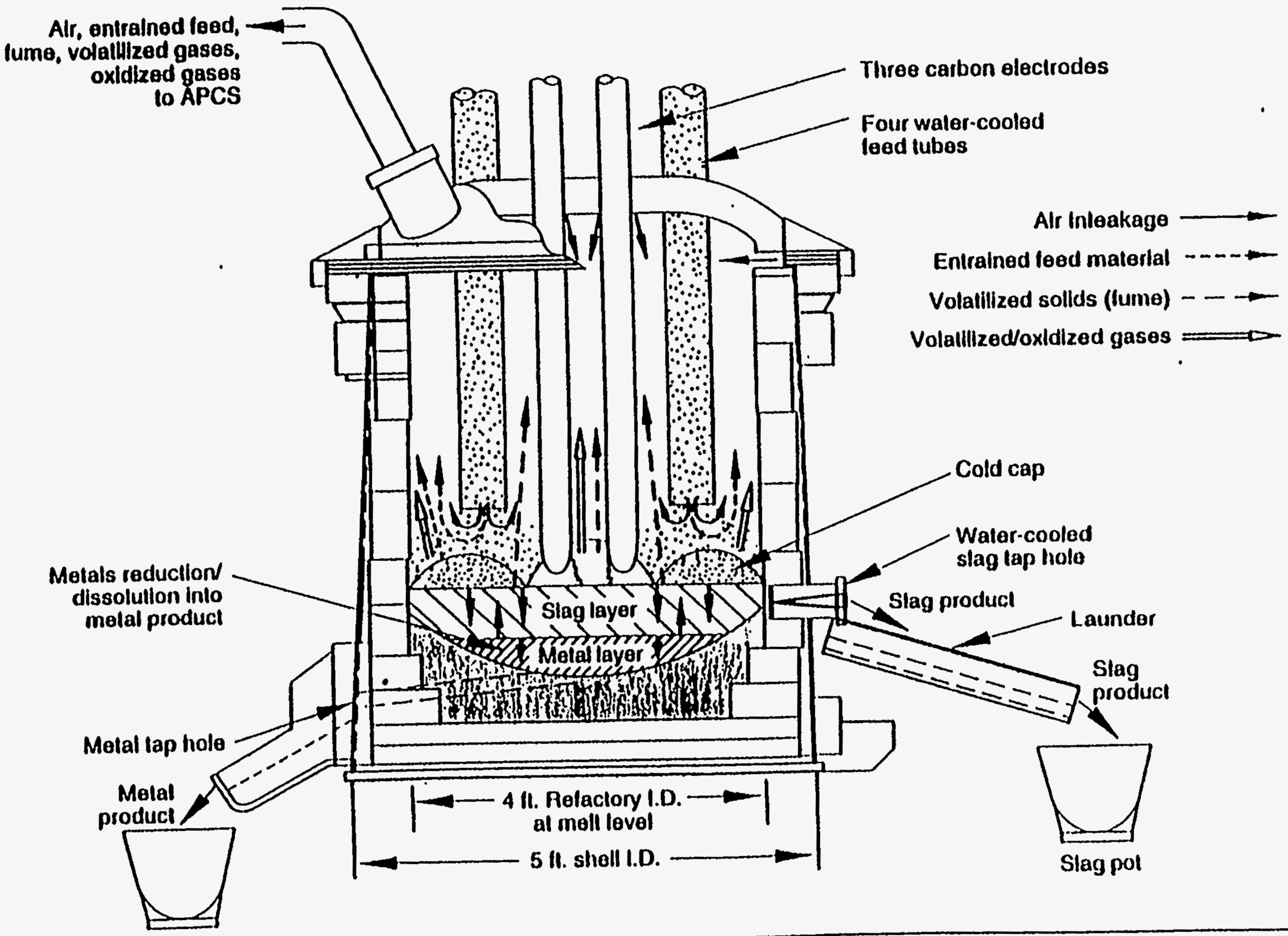
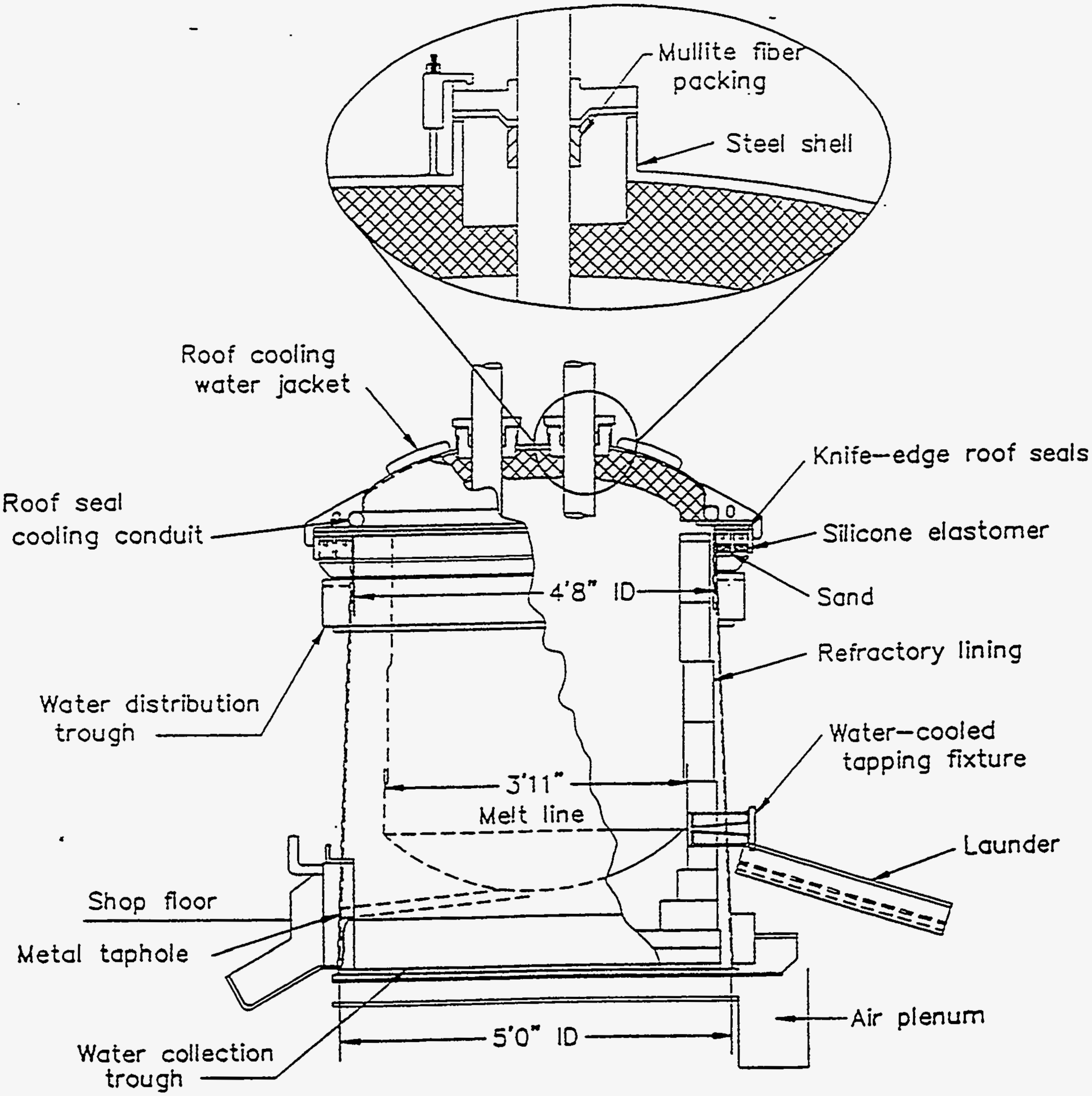


Figure 1. Arc melter test facility with furnace and offgas system. — USBM BWID TESTS 1995

FURNACE PROCESS MODEL





Vertical section of electric arc melting furnace.

Thermal treatment process: Skygas Submerged arc shaft furnace
Location: Scorpion Mining and Manufacturing Co., Synergistics Lab, Libby, MT
Mode of operation (continuous,batch): Continuous
Status: operational

Process description/size/dimensions/materials of construction:

"Carbonaeous" material is fed into a primary reactor with submerged carbon electrodes sticking in from the side that heat the materials fed in. Gases created from heating the hydrocarbon fuel exit the primary reactor at the top of the chamber and are fed into a secondary reaction chamber filled with incandecsent coke heated by an electric arc from an electrode protruding down the top of the chamber. This produces a synthetic fuel gas consisting primarily of hydrogen and carbon monoxide.

Waste feed preparation/sorting/sizing requirements:

This process requires a high hydrocarbon feed stock in order to produce the syngas.

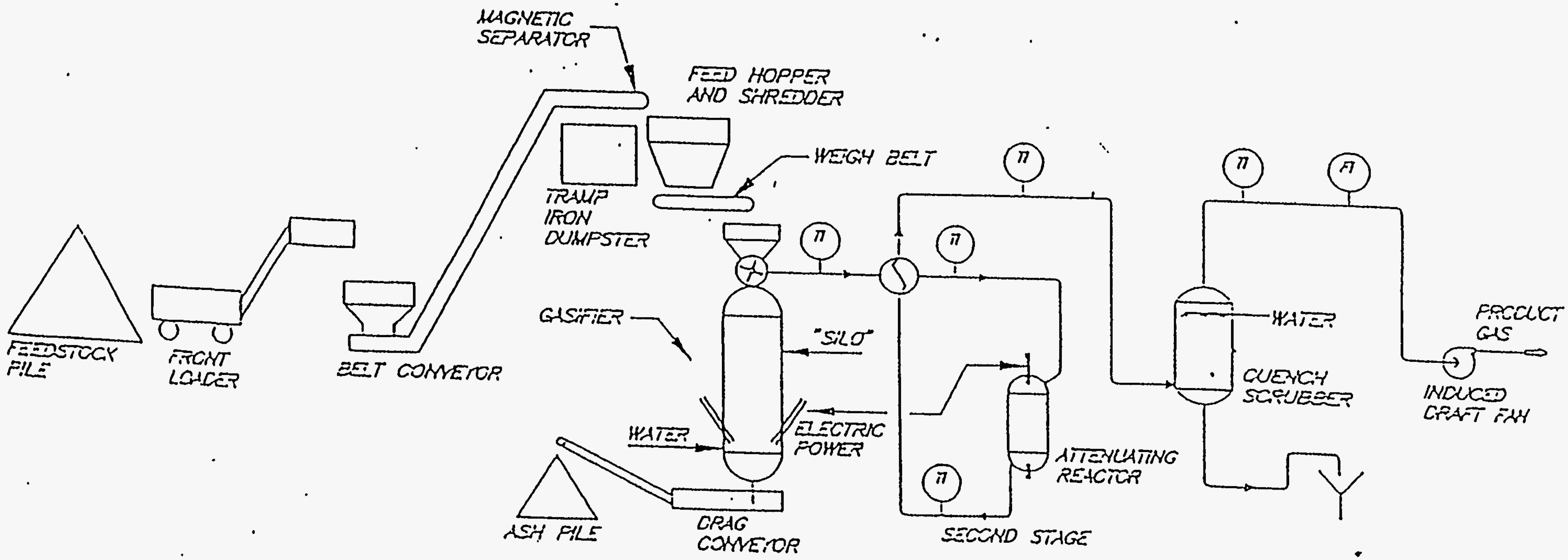
Air pollution control system components:

There are no APCS components. The exhaust is a fuel gas product.

References:

A. C. Lewis, "Skygas, Beyond Incineration and Landfills, Photo Electrokinetic Process for Disposal of Solid and Semi-Solid Wastes," White Paper, updated, January 14, 1994.

U. S. Patent Number: 5,069,765, "Method of Manufacturing Combustible Gaseous Products," Dec. 3, 1991



- * AGRICULTURAL WASTES
  WOOD CHIPS AND HOGWOOD
  PETROLEUM COKE
  COAL
  MUNICIPAL GARBAGE
  SLUDGE
  RUBBER TIRES

THE SKYGAS PROCESS
(CONVERTING CARBONACEOUS FEEDS* INTO MEDIUM BTU GAS)

United States Patent [19]

Lewis

[11] **Patent Number: 5,069,765**

[45] **Date of Patent: Dec. 3, 1991**

[54] METHOD OF MANUFACTURING COMBUSTIBLE GASEOUS PRODUCTS

[76] Inventor: Arlin C. Lewis, P.O. Box AU, Libby, Mont. 59923

[21] Appl. No.: **508,488**

[22] Filed: **Apr. 11, 1990**

Related U.S. Application Data

[63] Continuation of Ser. No. 198,741, May 25, 1988, abandoned.

[51] **Int. Cl.**^{5} **C01B 31/00**

[52] **U.S. Cl.** **204/173**; 204/170; 48/65; 48/202; 48/204

[58] **Field of Search** 204/168, 170, 173; 48/65, 202, 204

[56] **References Cited**

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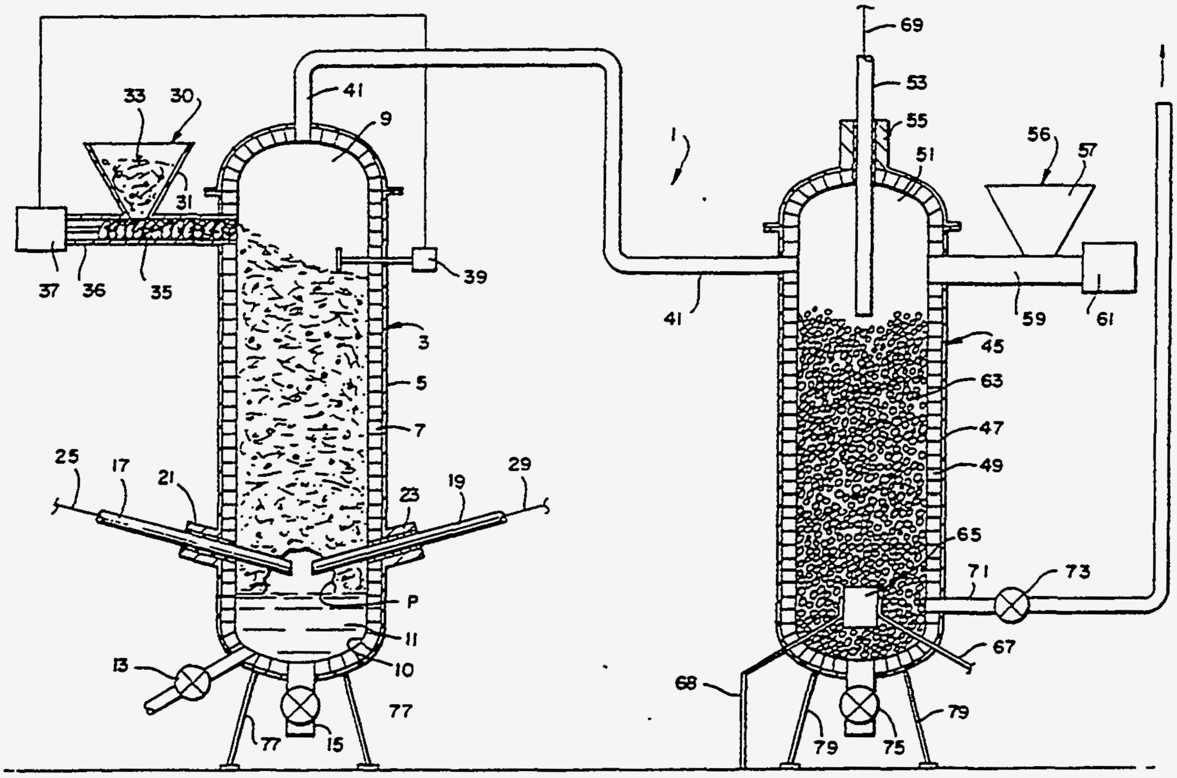
4,052,173	10/1977	Schulz	48/202
4,566,961	1/1986	Diaz et al.	204/168

Primary Examiner—John Niebling
Assistant Examiner—Steven P. Marquis
Attorney, Agent, or Firm—Bacon & Thomas

[57] **ABSTRACT**

An electric arc is used for reacting carbonaceous materials and water to produce a combustible gaseous product comprising hydrogen, carbon monoxide and methane as its major components, wherein the electrothermal and photochemical effects of the arc result in the production of active chemical species which cause and participate in the gasification reactions.

7 Claims, 1 Drawing Sheet



Thermal treatment process: Melt All Electric Fusion Process 3-phase electric arc furnace

Location: Geotech Development Corporation
King of Prussia, PA

Mode of operation (continuous,batch): Continuous

Status: operational (many systems sold world wide)

Process description/size/dimensions/materials of construction:

A submerged electrode 3-phase AC arc furnace which uses a proprietary "Melt All Electric Fusion Process" to control the power input to the furnace. The furnace is a water cooled double wall steel vessel. Temperatures in the melt zone vary up to 2870 C (5200 F). Pilot plant capability is 2 tons per hour. They manufacture larger plants that can handle over 4 tons per hour.

Waste feed preparation/sorting/sizing requirements:

Metals must be separated from the feed. Water content must be below 15% if possible and organics burned off (primarily to increase the electrical efficiency of the melter).

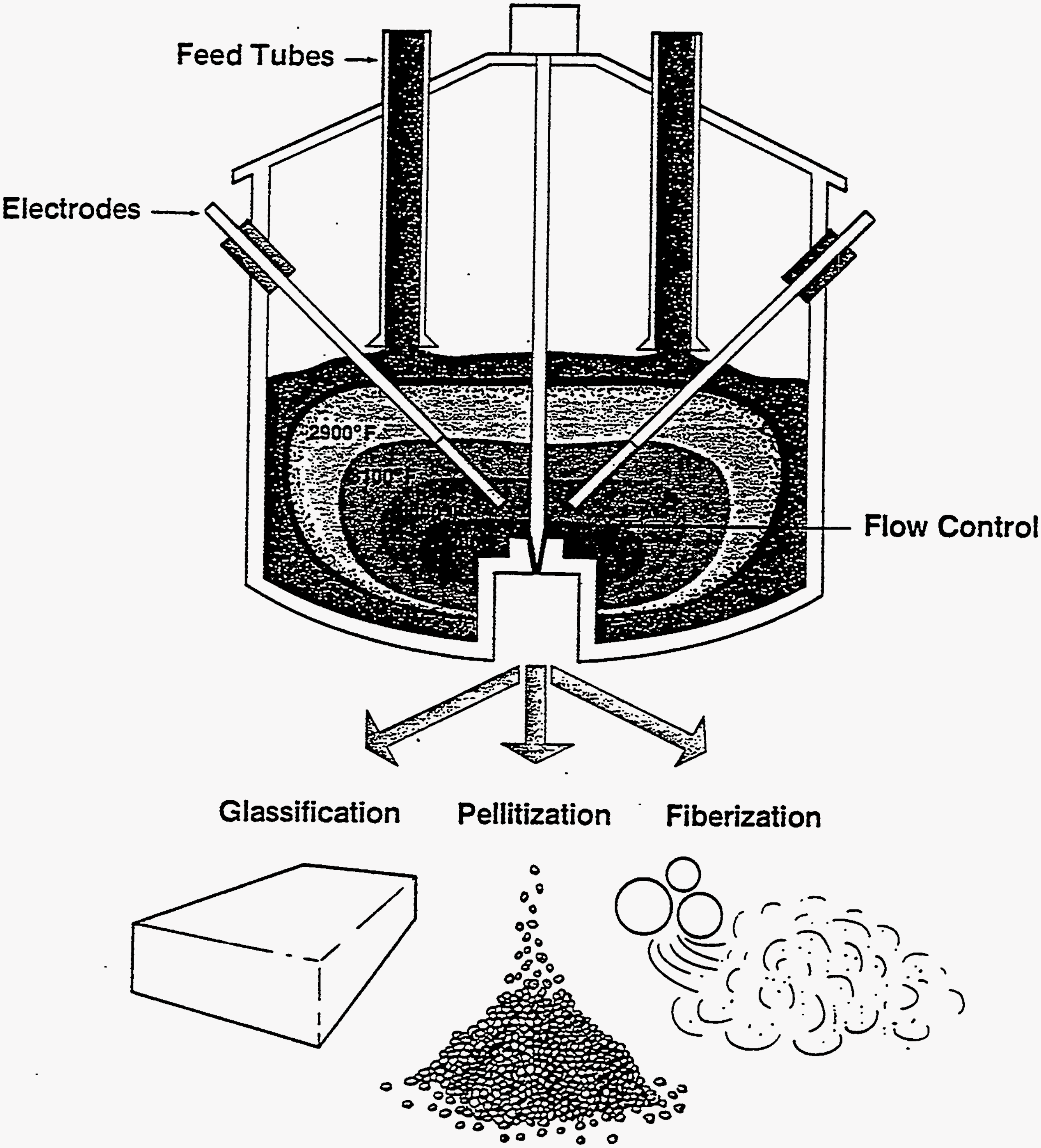
Air pollution control system components:

The basic components of APCS are a baghouse followed by a wet scrubber system.
The baghouse solids are recycled back into the melter.

References:

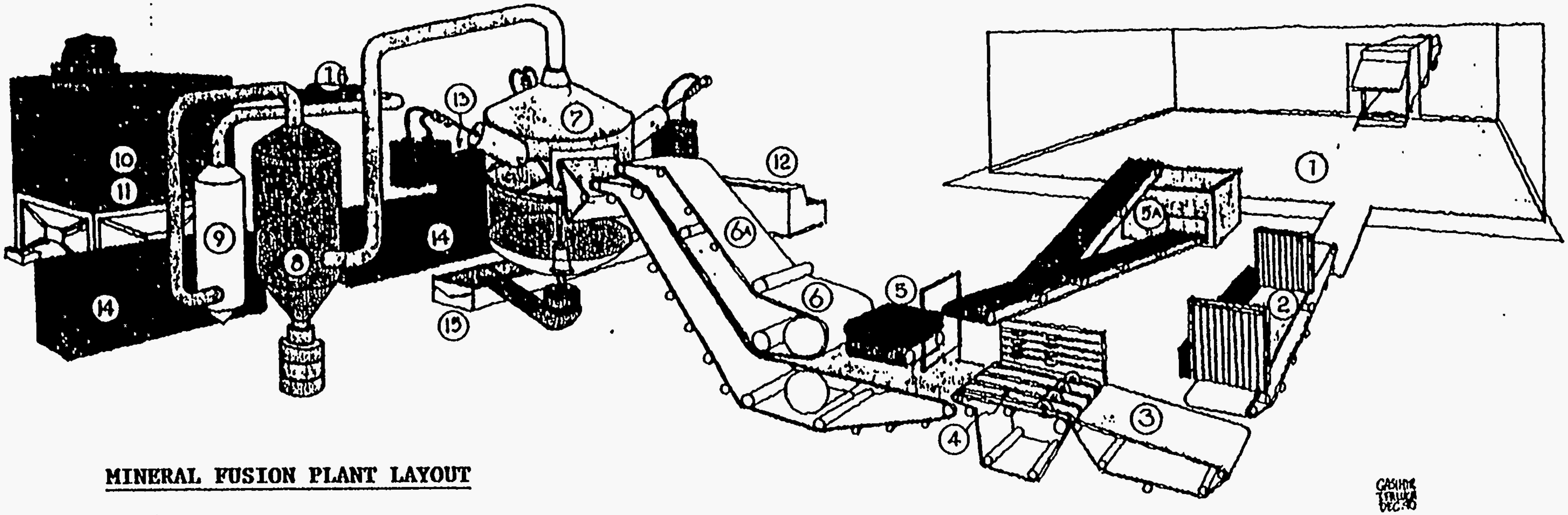
Geotech sales brochure, (circa 1993).

Mineral Fusion — Fiberization



GEOTECH DEVELOPMENT CORPORATION

MELT-ALL SYSTEM MINERAL FUSION PROCESS



MINERAL FUSION PLANT LAYOUT

1. Enclosed (N.P.) Day Bin
2. Retractable Conveyor
3. Enclosed Double Wall Conveyor (N.P.)
4. Bag Opener (N.P.)
5. Magnetic Separator (N.P.)
6. Roll Crusher & Furnace Feed (N.P.)
7. Fusion Furnace (N.P.)
8. Cyclone Separator
9. Impingjet Wet Scrubber
10. Baghouse
11. Final Filter (HEPA Filter)
12. Control Room
13. Service
14. SCR
15. Finished Product Retrieval
16. In-line Heater

N.P. - Negative Pressure
Enclosure for Material Flow 1 through 7 Not Shown

Thermal treatment process: Dakota Catalyst Products 3-phase Electric Arc Furnace

Location: Williston, ND

Mode of operation (continuous,batch): Continuous (Rotary kiln)
Batch (Arc melter)

Status: operational since 1993

Process description/size/dimensions/materials of construction:

This process treats spent alumina and alumina/silica based catalysts generated by the oil industry. Waste materials are first calcined in a rotary kiln under oxidizing conditions at 760-1200 C (1400-2200 F).

Process feed from the calciner is batch melted in a 4 MW electric arc furnace (3 phase?) with hollow graphite electrodes. Nitrogen can be feed through electrodes to induce plasma jet heating or it can operate in submerged arc mode or a short arc mode with no nitrogen flow. The typical process throughput is over 3 tons per hour. Slag temperatures can reach 2200 C (4000 F).

Waste feed preparation/sorting/sizing requirements:

The system can accept varied sizes of material up to 18 inches in diameter.

Air pollution control system components:

The rotary kiln APCS consists of 1) a cylone dust collector, 2) a secondary combustion chamber, 3) quench chamber, 4) a bag house and 5) a three stage counter current scrubber

The arc furnace APCS consists primarily of a baghouse.

References:

R. A. Howard, "Application of an Operating Production-Scale System for Treatment and Recycling Hazardous and Nonhazardous Spent Catalysts to the Treatment of Mixed Low Level Waste," White Paper, Dakota Catalyst Products, Inc., Nov 2, 1995.

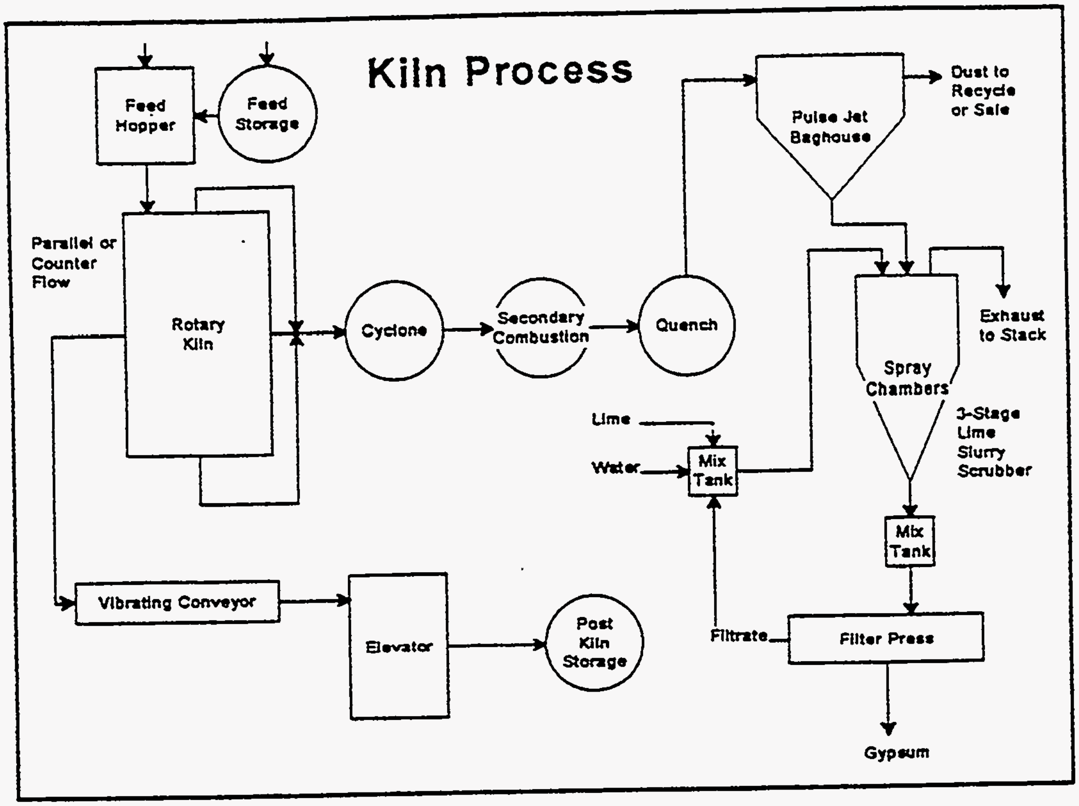


Figure 1, System I - Calcining

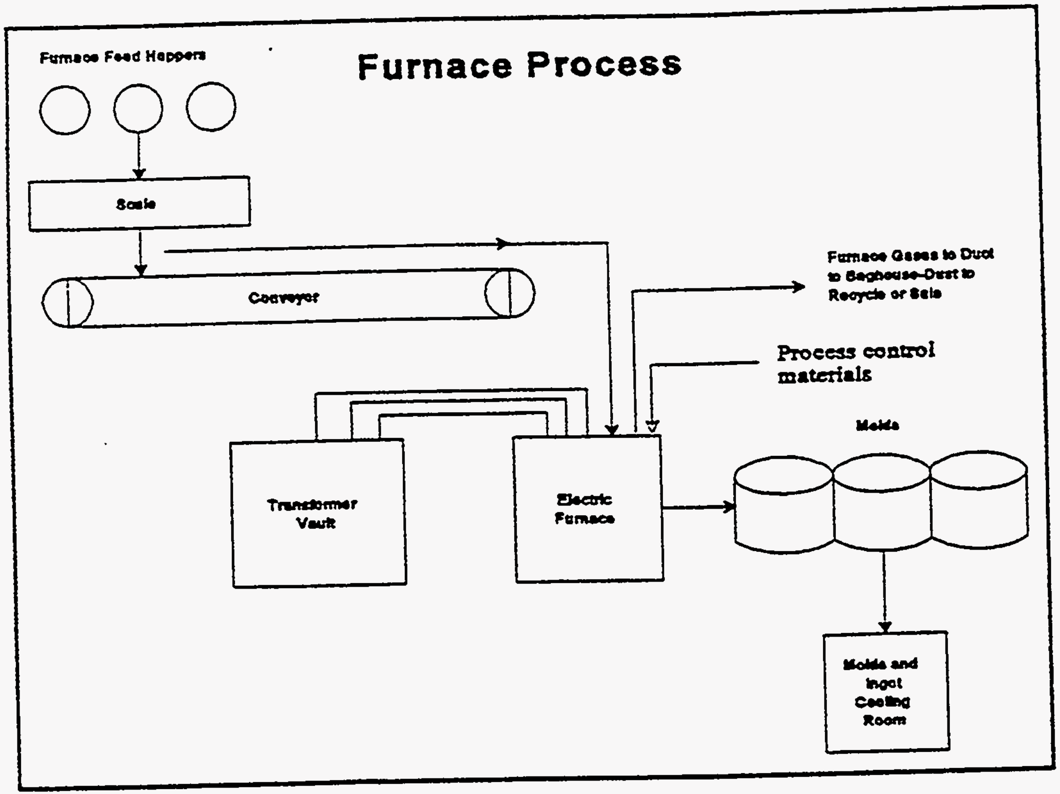


Figure 2, System II - Melting/Partitioning

Thermal treatment process: Star Ctr Bench Scale Plasma Hearth Process (PHP)

Location: Science and Technology Applications Research (STAR) Center, Idaho Falls, ID

Mode of operation (continuous,batch): continuous

Status: Available for testing

Process description/size/dimensions/materials of construction:

This system has been modified from the bench scale rotating hearth system into a fixed hearth system by SAIC. The plasma chamber is a horizontal cylinder with an approximate internal diameter of 31 inches and 30 inches long. The chamber is lined with refractory to prevent thermal losses and has 2 viewports, plus ports for the plasma torch, material feed and exhaust. A water cooled ram is used to push minidrums into the process chamber.

Waste feed preparation/sorting/sizing requirements:

Waste feed is contained in minidrums of approximately 1 Kg or less.

Air pollution control system components:

The APCS system consists of 1) a secondary combustion chamber, 2) air dilution sections to lower the temperature, 3) a sodium bicarbonate section to remove acid gases, and 4) a baghouse followed by HEPA filters.

References:

G. L. Leatherman, *Results of STAR Center Testing in Support of the Non-Radioactive Pilot Scale Plasma Hearth Process System*, Report No. SAIC-95/1313, Science Applications International Corp., October, 1996.

Thermal treatment process: Plasma Hearth Process (PHP) at TREAT

Location: TREAT Facility, ANL-W, ID

Mode of operation (continuous,batch): continuous

Status: Planned system (to be completed in FY-96)

Process description/size/dimensions/materials of construction:

The system consists of a 200 kW plasma torch mounted on a vacuum ball joint to allow movement. Movement of the torch is controlled hydraulically. The plasma chamber is a vertical cylinder with a domed top and having dimensions of approximately 47 inches in diameter and 62 inches high. The cylinder is of double walled construction with forced water cooling at 30 psig. The chamber will be lined with refractory.

Waste feed preparation/sorting/sizing requirements:

A feed chamber is designed to hold up to nine 1-gallon waste containers loaded with eeither surrogate or actual waste materials. A hydraulic ram will slowly push the containers into the hearth.

Air pollution control system components:

The APCS system consists of 1) a secondary combustion chamber, 2) an evaporative cooler, 3) HEPA filters followed by (4 a packed bed scrubber.

References:

R. L. Gillins, *Test Plan for Radioactive Testing of the Bench-Scale Plasma Hearth Process*, Report No. SAIC-94/1014, Science Applications International Corp., May, 1995.

S. D. Poling, et. al., *Conceptual Design Report for the Plasma Hearth Process Bench-Scale Radioactive System*, Report No. SAIC-94/1003, Science Applications International. Corp., March 9, 1994.

S. D. Poling, et. al., *System Design Description for the Plasma Hearth Process Radioactive Bench-Scale System Process Equipment*, Report No. SAIC-94/1157, Rev.: 0, May 1995, Science Applications International. Corp. (1994).

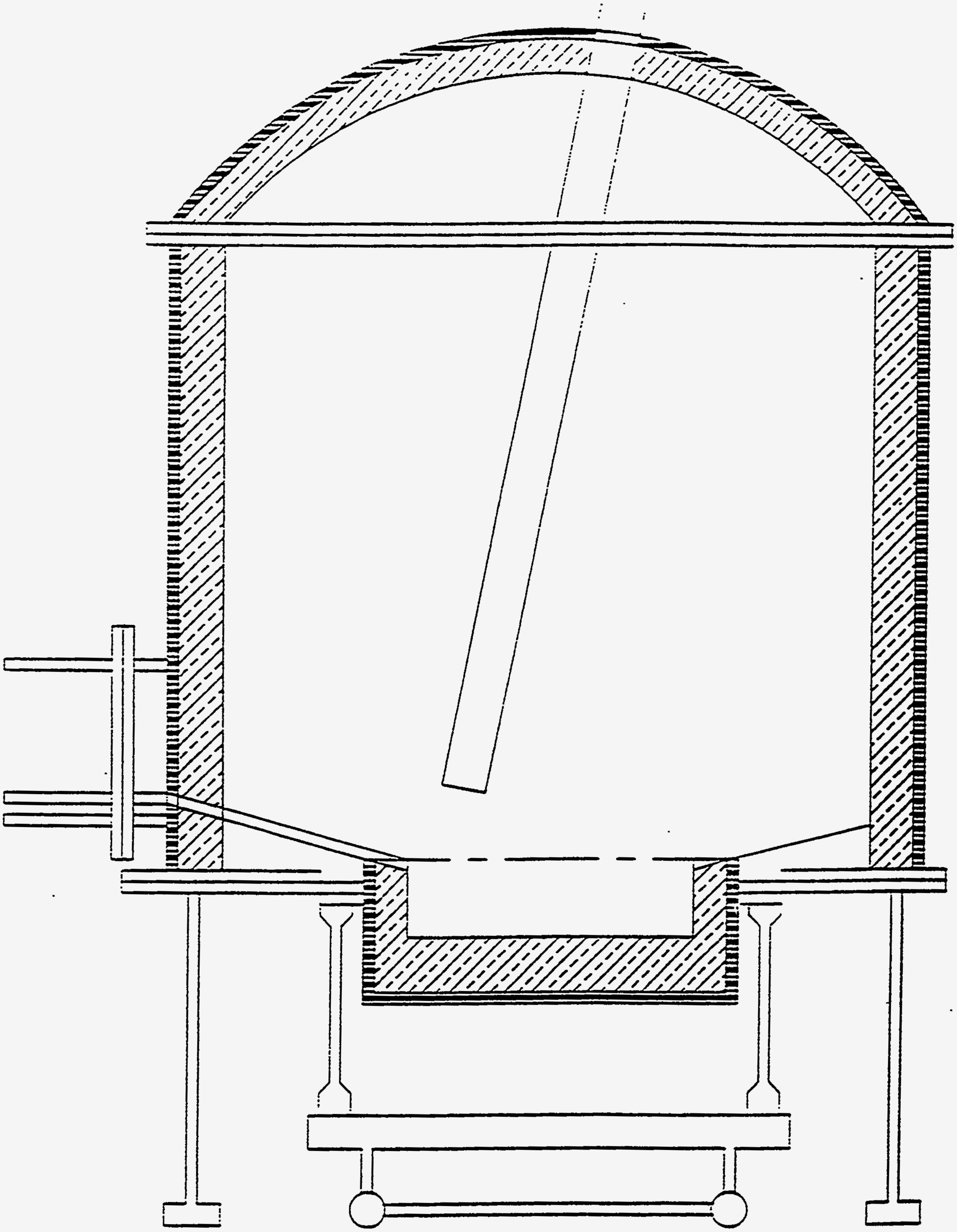


Figure C2 - Side View of the

PHP Bench-Scale System Primary Chamber and Crucible

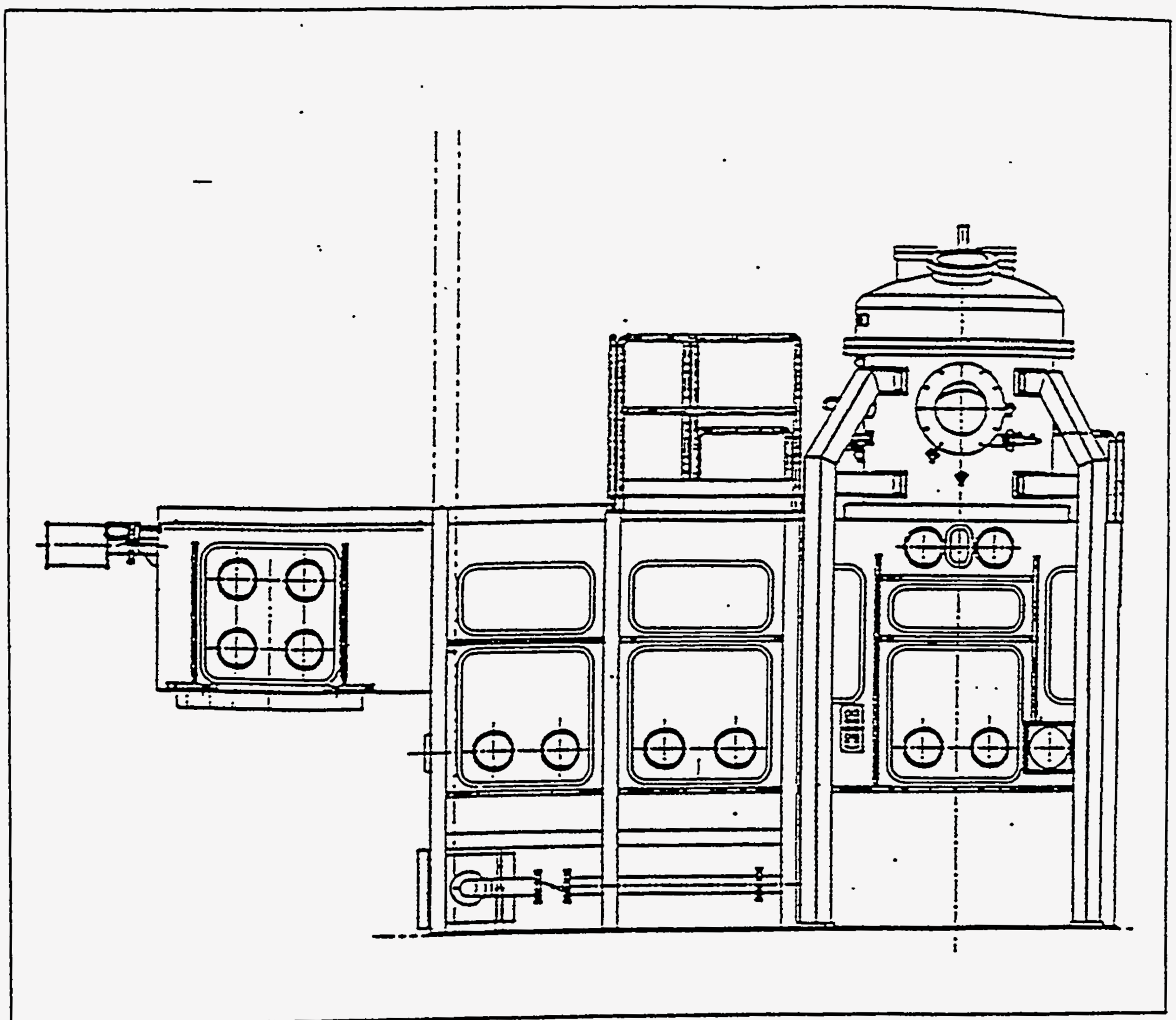


Figure 4. Plasma chamber and hearth handling enclosure

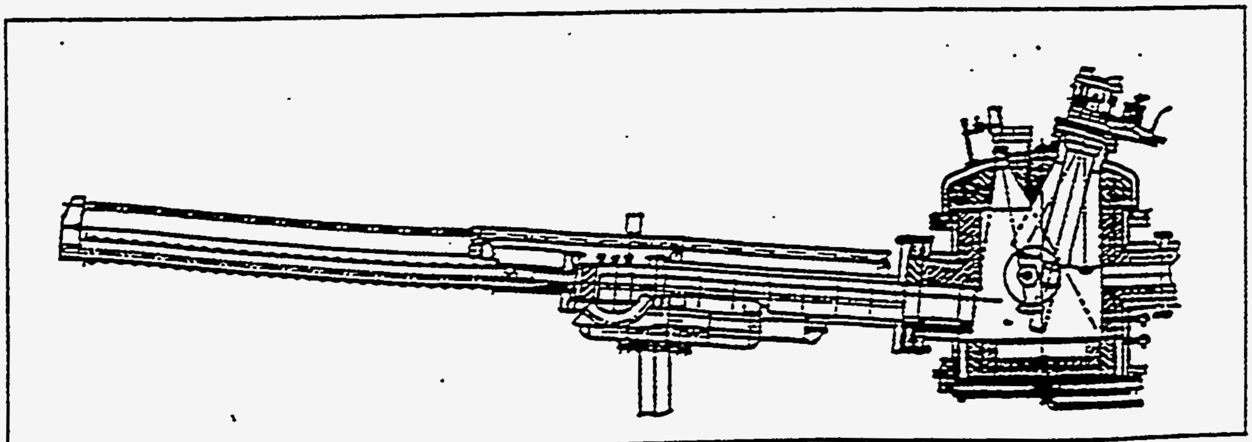
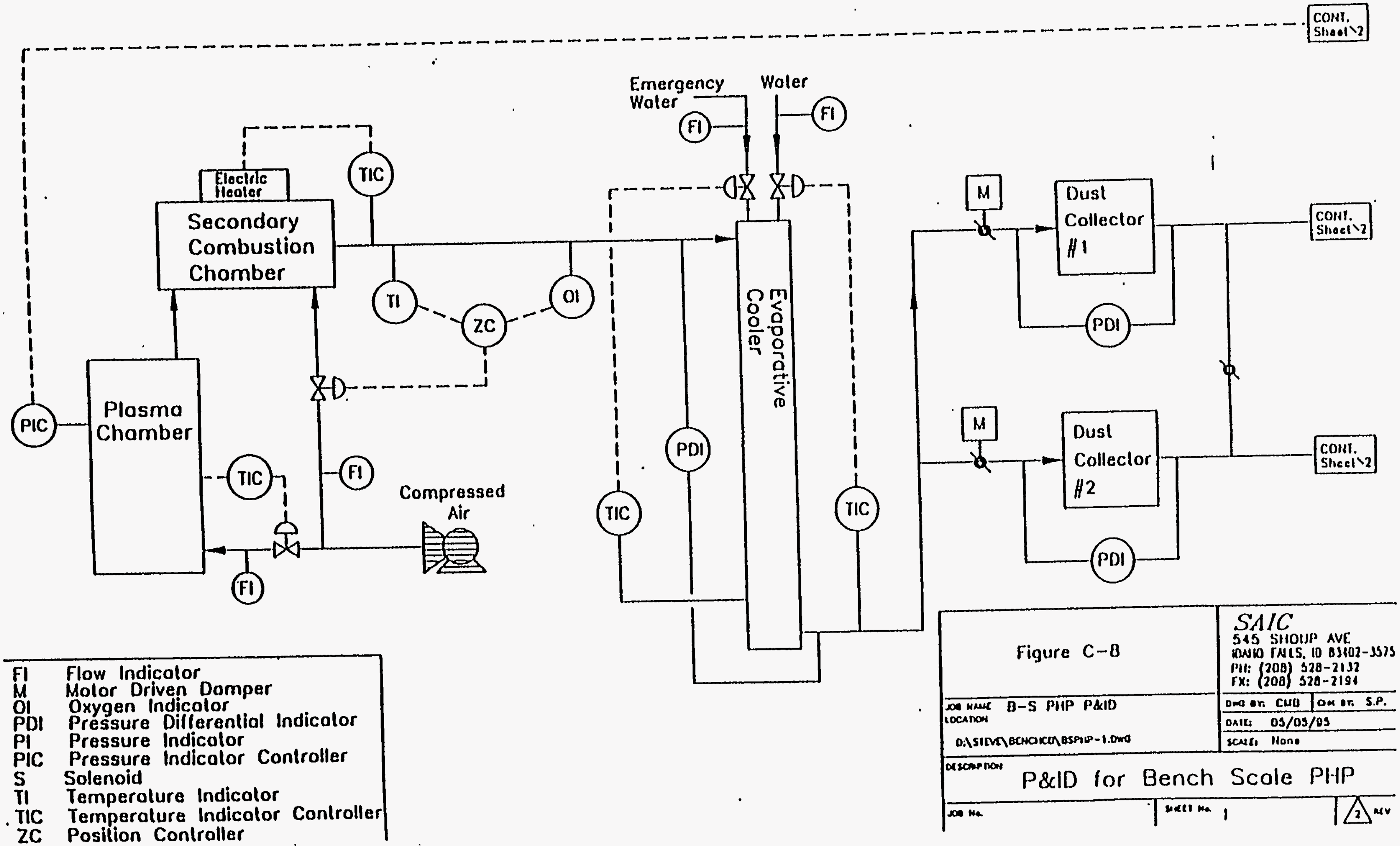


Figure 5. Cutaway view of plasma chamber and feed system



FI	Flow Indicator
M	Motor Driven Damper
OI	Oxygen Indicator
PDI	Pressure Differential Indicator
PI	Pressure Indicator
PIC	Pressure Indicator Controller
S	Solenoid
TI	Temperature Indicator
TIC	Temperature Indicator Controller
ZC	Position Controller

Figure C-8

SAIC
545 SHOUP AVE
IDAHO FALLS, ID 83402-3575
PH: (208) 528-2132
FX: (208) 528-2194

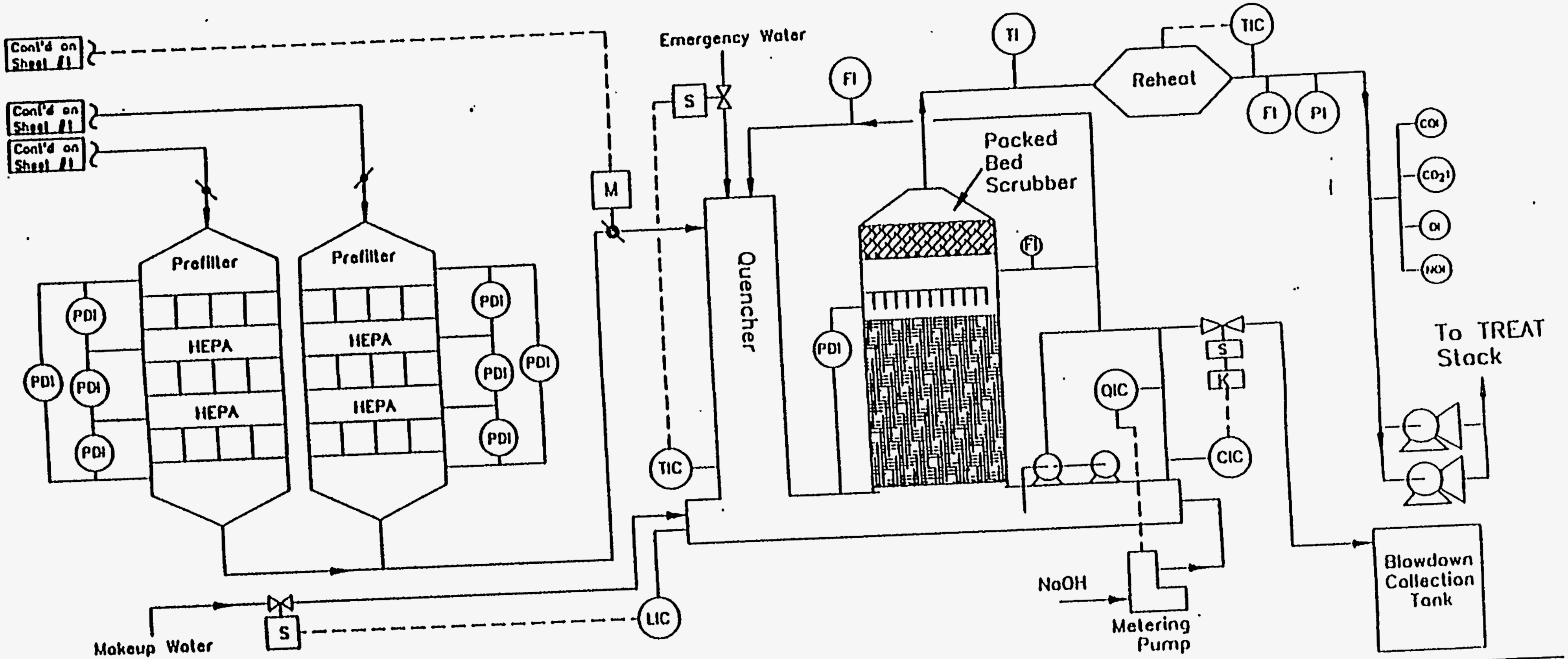
JOB NAME B-S PHP P&ID
LOCATION
D:\STEVE\BENCHCO\BSPHP-1.DWG

DWG BY: CMB
CHK BY: S.P.
DATE: 05/05/95
SCALE: None

DESCRIPTION P&ID for Bench Scale PHP

JOB No.
SHEET No. 1
REV 2

Figure 2. PHP bench-scale system simplified piping and instrumentation diagram



CIC	Conductivity Indicator Controller
CO_2I	Carbon Dioxide Indicator
COI	Carbon Monoxide Indicator
FI	Flow Indicator
K	Timer/Sequencer
LIC	Level Indicator Controller
M	Motor Driven Damper
NOI	Nitros Oxide Indicator
OI	Oxygen Indicator
PI	Pressure Indicator
PDI	Pressure Differential Indicator
QIC	Concentration Indicator Controller (pH)
S	Solenoid
TI	Temperature Indicator
TIC	Temperature Indicator Controller

Figure C-8 (Continued)

SAIC
545 SHOUP AVE
IDAHO FALLS, ID 83402-3575
PH: (208) 528-2183
FX: (208) 528-2194

DWG BY CMB | CH BY S.P.
DATE: 05/05/95
SCALE: None

JOB NAME B-S PHP P&ID
LOCATION D:\STEVE\BENCHCD\BSPHP-3.DWG
DESCRIPTION P&ID for Bench Scale PHP
JOB No.
SHEET No. 2
2 REV

Figure 2. PHP bench-scale system simplified piping and instrumentation diagram (cont.)

Thermal treatment process: Plasma Hearth Process (Proof of Principle Unit)

Location: Retech, Ukiah

Mode of operation (continuous,batch): continuous

Status: unknown

Process description/size/dimensions/materials of construction:

The system uses a 1.2 MW transferred DC arc plasma torch to provide process heat. The primary processing chamber is a refractory-lined, water-jacketed steel vessel with an internal volume of about 100 cubic feet. The inner walls are lined with a cast alumina refractory. Drums are fed into the chamber from a preloaded feed chamber using a hydraulic ram.

Waste feed preparation/sorting/sizing requirements:

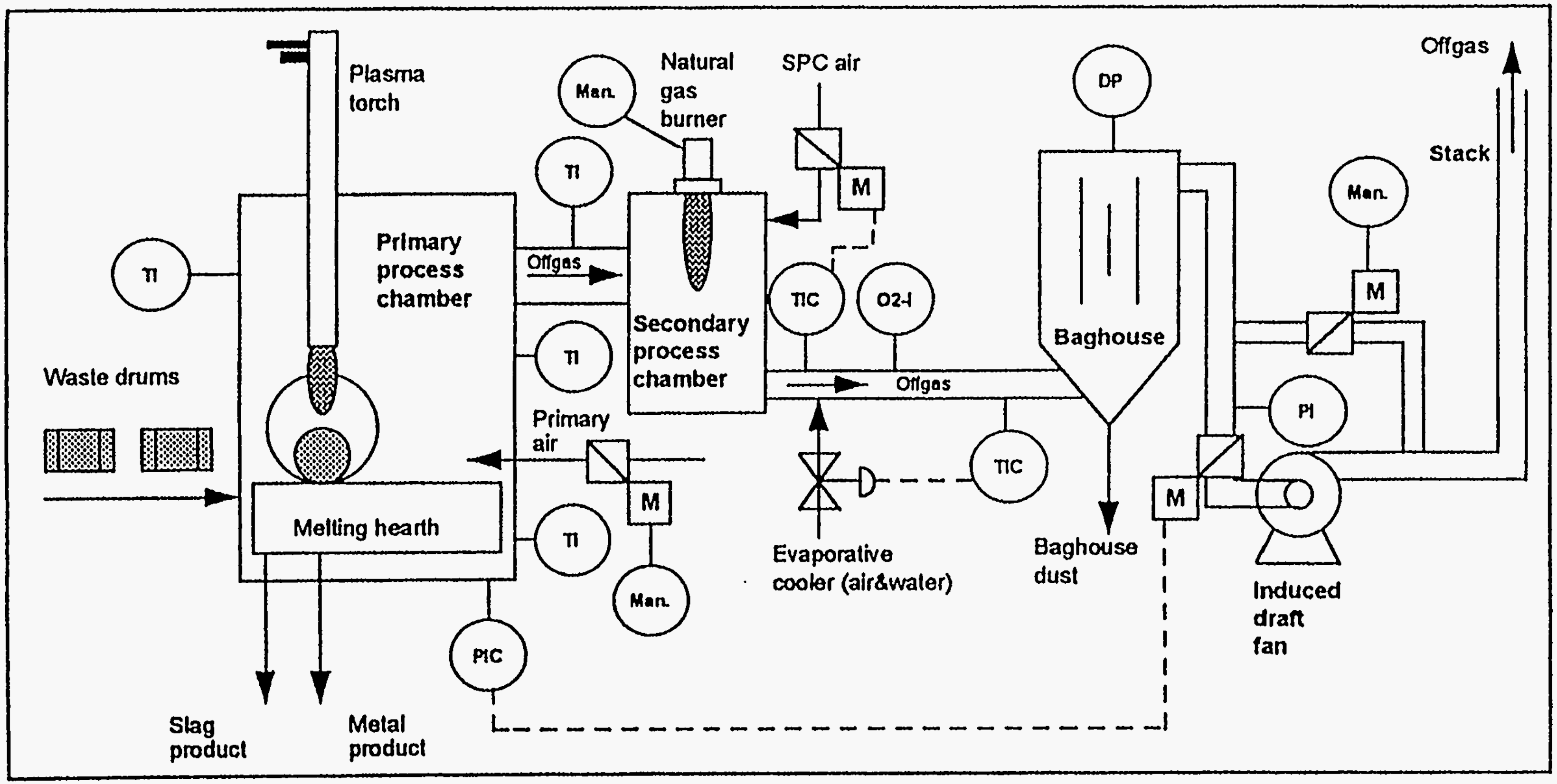
Feed materials are loaded into drums.

Air pollution control system components:

The APCS components consist of a secondary combustion chamber fired by natural gas. This is followed by an evaporative cooler and a conventional pulse-jet baghouse.

References:

G. R. Hassel, et. al., *Evaluation of the Test Results from the Plasma Hearth Process Mixed Waste Treatment Applications Demonstration,* Science Applications International Corp., Report No. SAIC-94/1095, October 1994.



PHP schematic diagram.

Thermal treatment process: Westinghouse Plasma Fired Cupola

Location: Westinghouse Plasma Test Center, Madison, PA

Mode of operation (continuous,batch): continuous

Status: Used commercially for foundry melting.

Process description/size/dimensions/materials of construction:

A non-transferred plasma torch is used to heat a cupola filled with coke. Slag and metal flow down through the coke to tap holes. There are four sizes of melter systems with torches ranging in power from 75 kW to 10 MW.

Waste feed preparation/sorting/sizing requirements:

Unknown

Air pollution control system components:

Unknown

References:

S. V. Dighe, et. al., "Plasma-Fired Cupola: An Innovation in Iron Foundry Melting," *90th Casting Congress May 11-15, 1986, Minneapolis, MN*, AFS Transaction Paper (1986).

S. M. Carter and F. T. Kaiser, "Plasma-Fired Cupola: An Operators appraisal and Economic Projections," *90th Casting Congress May 11-15, 1986, Minneapolis, MN*, AFS Transaction Paper (1986).

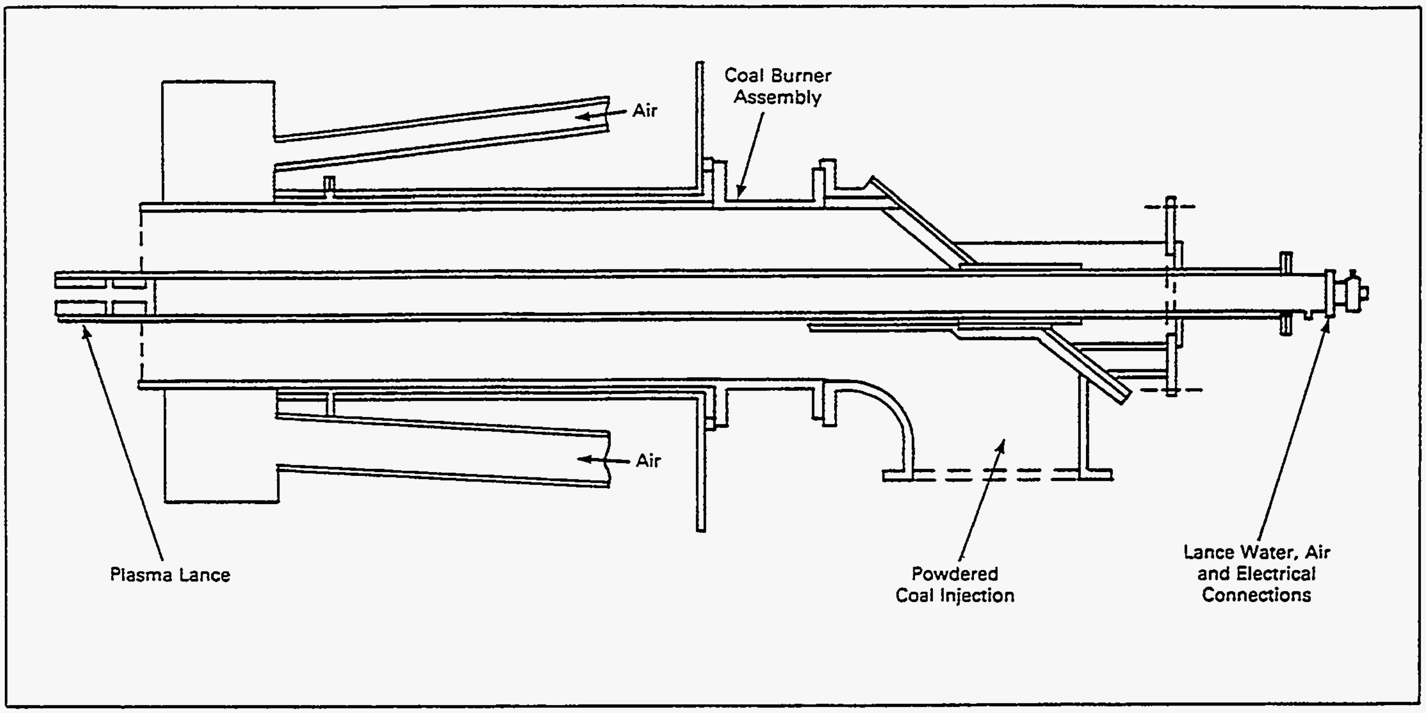


Figure 10: Lance Assembled in Burner

The plasma lance can be directly substituted for oil or gas ignitors in existing coal burners to eliminate the need for other auxiliary fuels. The lance will be located adjacent to the pulverized coal stream (see Figure 10).

Foundry Cupolas

Plasma systems are an economical solution to the foundry problem of recycling cast-iron and steel machining chips. A plasma system applied to an existing cupola allows direct charging of loose chips and borings as a low cost source of iron units. Additional advantages of a plasma-fired cupola include:

- Reduced Coke Rates
- Reduced Silicon Loss
- Increased Productivity
- Reduced Air Pollution Control
- Improved Process Control

Westinghouse is conducting a development program to design, test and operate a 2.5 ton/hr pilot cupola equipped with a plasma system. Following successful operation of the test cupola, a full-scale design is planned for a commercial-sized cupola (20-60 ton/hr). Figure 11 illustrates a sketch of a 60 ton/hr cupola converted to plasma firing.

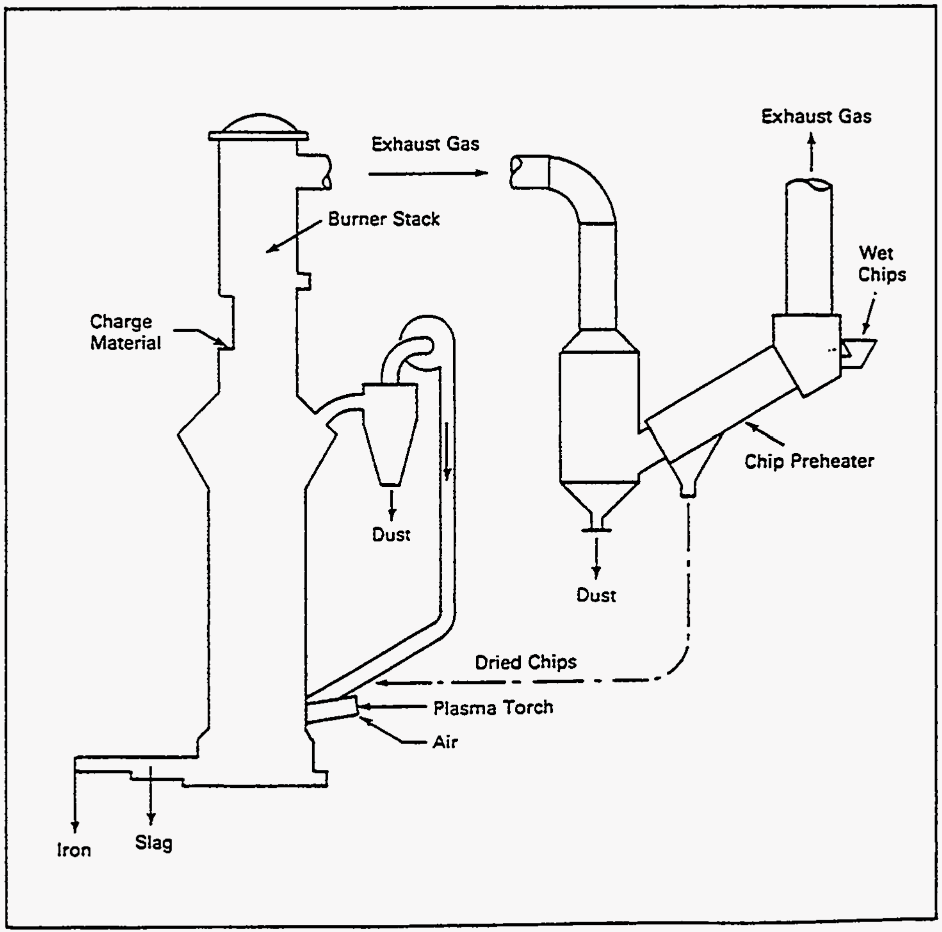


Figure 11: Production Cupola Flow Diagram With Chip Preheat

ndustrial Plasma Systems

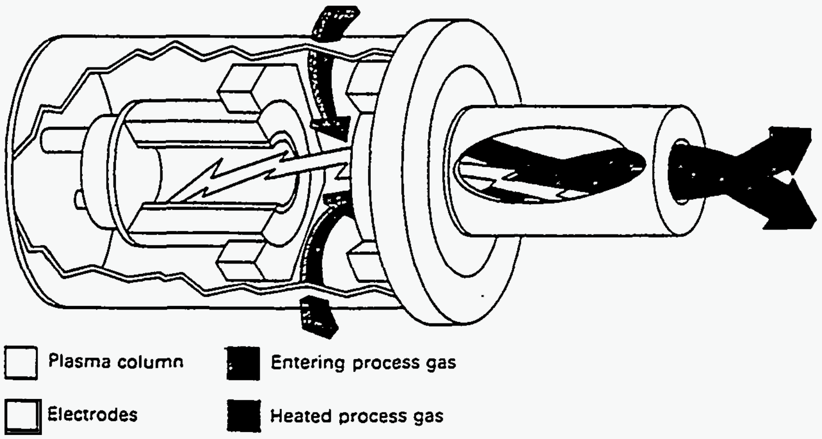
lasma System Description

lasma Subsystem Description

s mentioned earlier, a plasma heating sys- em for industrial applications consists of ve integral subsystems. These include (1) lasma torches for conversion of electrical nergy to process heat by direct heat trans- er between a rapidly rotating electric arc nd a process gas stream, (2) a power sup- ly with electrical characteristics designed match those of the plasma torch, (3) a ontrol and instrumentation system for terlocking the necessary subsystems and provide for acquisition of performance ata, (4) a cooling water system for removal f the heat losses and (5) a gas system to rnish the process gas to be heated.

asma Torch

s shown in Figure 3, a plasma torch con- sts of a closely-spaced pair of tubular ater-cooled electrodes within which an ectric arc discharge is magnetically rotated extremely high speeds. During operation, process gas is injected into the heater rough a spacing (approximately 1mm) etween the electrodes.



ure 3: Cross Section at Plasma Torch

arkover between the electrodes initiates e arc discharge when the power supply is ergized. The arc is immediately blown to e interior of the electrode by the incoming ocess gas. The arc current interacts with a agnetic field established by solenoid field ils located around both the upstream and wnstream electrodes to rotate the arc at proximately 1000 revolutions/second. The combination of high arc rotation speeds and high gas flow rates provides excellent heat transfer between the electric arc and the incoming process gas while also maximizing electrode life. It is this excellent arc/gas interaction which produces the superheated process gas and leads to the high thermal efficiencies obtained for this type of torch.

The superheated gas exits at the downstream end of the torch. The downstream electrode end can be designed to protrude through the refractory lining of a furnace or process reactor. The torch interfaces to the furnace or reactor by means of a mounting flange. Cooling water and process gas connections are made at the torch mounting flange and power connections are made at the upper end of the external cover. All connections are designed for quick assembly and removal to minimize servicing effort.

Complete servicing will consist of electrode and electrode seal replacement, followed by a water pressure leak test. Time required for maintenance servicing takes no longer than one-half hour by technically trained service personnel.

Thyristor Power Supply

The major components associated with a typical plasma power system are shown in Figure 4. The plasma torch is connected to a thyristor power supply which provides a current controlled D.C. output. Depending on input voltage, the thyristor power supply typically includes a high voltage breaker or contactor for independent control and protection. A manually operated isolating switch is associated with the device for personnel protection during maintenance. A water-cooled or air-cooled transformer may be used.

The secondary of the transformer is connected to the thyristor bridges. Several different types of DC bridge configurations are available, depending on customer and site requirements. Bridges are supplied as either forced air cooled or water cooled, depending on space available and site conditions.

The current controlled DC output of the thyristor bridge is connected to a series iron-core inductor (smoothing reactor). The inductor provides the required system impedance for arc stability. The plasma torch is connected to the load side of the inductor through a switch which provides a visible break for maintenance. Primary switchgear can be provided as an option.

The modular construction of the thyristor power supply (See Figure 5) reduces the user assembly and installation time, and material and labor costs. Water cooling reduces the package size and site preparation in addition to eliminating an oil-filled transformer with its associated hazards and required precautions. Installation is limited to making power, control, and water connections with a limited amount of field testing since all major components are factory assembled and tested.

The cabinet is typically supplied for indoor use with gasketed doors and panels. The unit can also be equipped with heaters and a weatherproof cabinet for outdoor service.

Control and Instrumentation System

Operation of the several plasma subsystems is controlled and interlocked to permit safe and simple operation of the overall plasma system. The control system consists of a console containing controls for the following: the cooling water flow, gas flow, field coil power, a display of various system parameters and a series of interlocked relays. Under selected conditions, these relays permit certain primary sensors to both trip and lock out the protective device of the power supply. Thus, the interlocking sensors insure predetermined values of field-coil current and cooling water flow, plasma torch electrode water flow, gas flow rate and any other system parameter selected. In addition, the control circuit contains appropriate alarms and trips to protect the integrity of the power supply and its components. All critical system parameters that are measured can also be equipped with an output for use with a data acquisition system or process controller.

A mechanically interlocked system is utilized to prevent improper sequence of equipment operation or access to electrical equipment while it is energized.

Industrial Plasma Systems

In general, the higher the temperature differential between the heat source and the material to be heated, the faster it can be processed. Heating materials rapidly is easily accomplished with a plasma system.

Typical Applications

In the emerging plasma industry several applications for plasma torch systems are in use while others are under consideration by industrial users. The following applications are in various stages of development ranging from analytical studies, bench-scale laboratory tests, pilot plants, semi-works to commercial operations:

- Combustion Replacement
- Boiler Ignition
- Foundry Melters
- Ironmaking
- Plasma Fired Blast Furnaces
- Production of Spheroidized Particles
- Production of Micro-Sized Particles
- Ferroalloy Production
- Nonferrous Metals Processing
- Processing of Metallurgical Waste
- Plasma Reformers
- Acetylene Production
- Chemical Processing
- Hazardous Waste Disposal
- R&D Applications

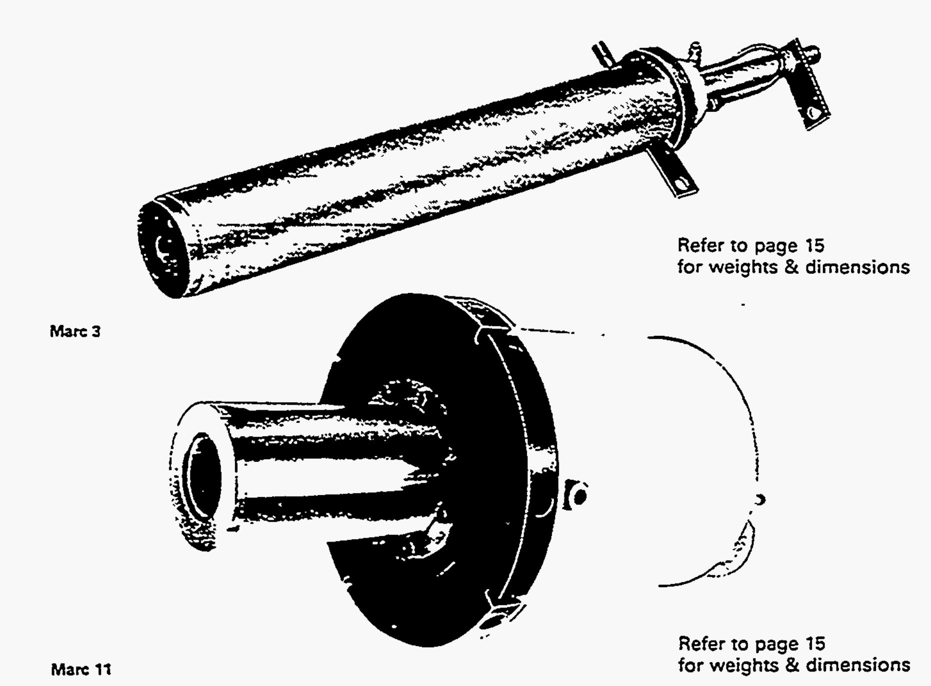


Figure 2: Typical Plasma Torch Designs

Ratings

The Westinghouse plasma system centers around the plasma torch. The plasma torch (shown in Figure 2) is an industrially suited, high-temperature process heating device which is designed to operate with high efficiency and minimal maintenance in an industrial environment. Table 1 lists the single unit plasma torches available from Westinghouse. Exact ratings depend on the application.

Benefits

- High Temperature Processing
- Torch Gas Flexibility (inert, reducing or oxidizing)
- Process Temperature Control
- Increased Heating Efficiency
- Increased Productivity
- Decreased Environmental Impact

Advantages of Using Plasma

What are the advantages of using a plasma gas over an ordinary gas for heating purposes? Plasmas have several outstanding advantages:

- Improved Heat Transfer
- Heating Independence of Gas Composition
- Ease of Process Control
- Process Fuel Flexibility

Table 1: Plasma Torch Ratings

Model	Power① (kW)	Typical Gas Flow②		Cooling Water Flow	
		(SCFM)	(Nm³/h)	(Gal/Min)	(m³/h)
Marc 3	75- 150	6- 12	10- 20	10	2
Marc 11	250- 2,000	30- 250	50- 400	70	15
Marc 31	1,000- 3,000	175- 450	300- 800	110	25
Marc 100	3,000-10,000	350-1,200	600-2,000	110-220	25-50

Efficiency to: 70% to 90%
Enthalpy to: 300 to 700 BTU/SCF (3 to 7 kWh/Nm³)

① Arc power rating will depend on gas composition.
② Gas flow will depend on gas composition.

Thermal treatment process: Plasma Energy Corp. (PEC) Tilt Furnace

Location: Raleigh, NC

Mode of operation (continuous,batch): Continuous

Status: unknown

Process description/size/dimensions/materials of construction:

A 150 kW non-transferred plasma torch installed in a refractory lined tilt furnace. Cupola dimensions: 16 inches in diameter and 16 inches high. Has tap holes for slag (upper tap hole) and metals (lower tap hole).

(PEC has many torch sizes that operate in both transferred and non-transferred modes. Several systems have been sold for municipal waste treatment and ash vitrification.)

Waste feed preparation/sorting/sizing requirements:

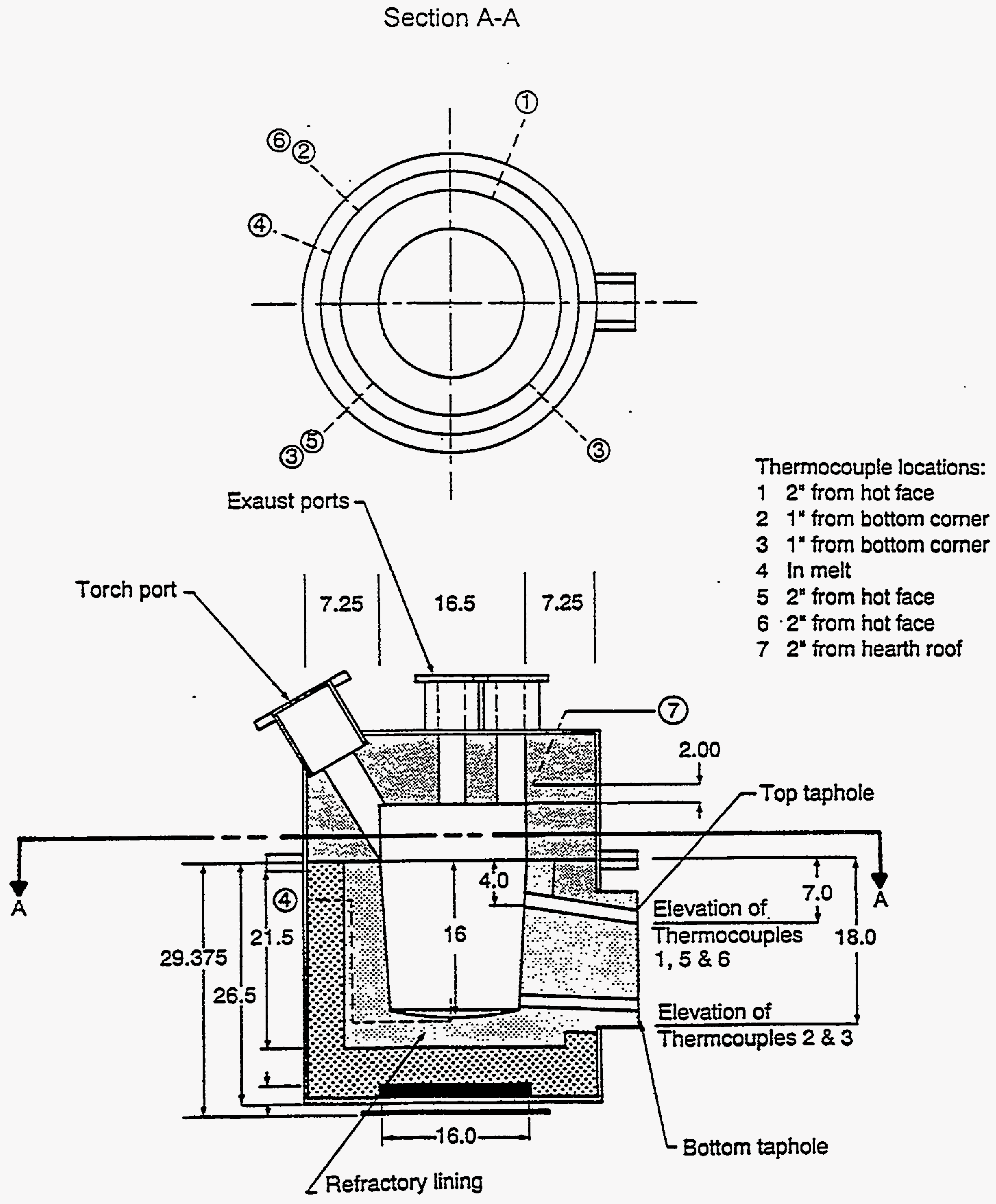
Feed size will be determined primarily by the type of feed system.

Air pollution control system components:

unknown

References:

B. A. Detering and J. A. Batdorf, *Plasma Treatment of INEL Soil Contaminated with Heavy Metals*, Report No. EGG-WTD-9925, January, 1992, EG&G Idaho, Inc. (1992).



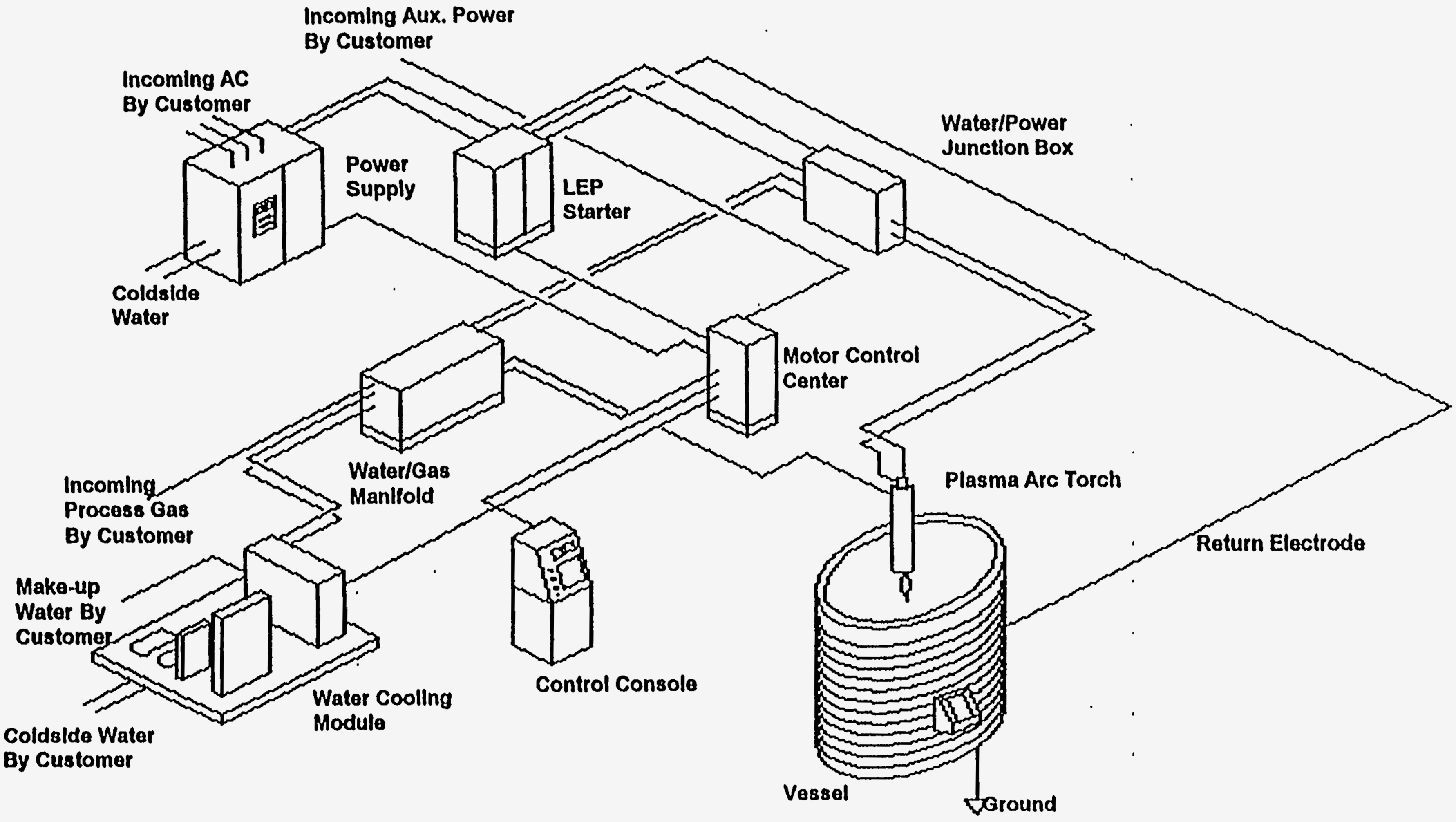
Thermocouple locations:
1 2" from hot face
2 1" from bottom corner
3 1" from bottom corner
4 In melt
5 2" from hot face
6 2" from hot face
7 2" from hearth roof

FN 8021-001

Tilt-Furnace Design

Figure 1. Plasma Energy Corp. Plasma Tilt Furnace used in these experiments.

PLASMA WASTE TREATMENT SYSTEM DIAGRAM



Plasma Energy Corporation

Thermal treatment process: Plasma Energy Applied Tech. (PEAT) Thermal Destruction and Recovery (TDR) system

Location: Plasma Energy Applied Technology, Inc. (PEAT), Huntsville, AL

Mode of operation (continuous,batch): continuous

Status: unknown

Process description/size/dimensions/materials of construction:

A non-transferred DC plasma torch is used to heat a melt chamber creating a controlled pyrolysis reaction with the waste material.
Size, dimensions, etc. are unknown.

Waste feed preparation/sorting/sizing requirements:

unknown

Air pollution control system components:

The APCS consists primarily of a wet scrubber system. The exhaust is flared off with natural gas.

References:

M. D. Springer, et. al., "A Versatile Thermal Destruction and Recovery System," White Paper, Plasma Energy Applied Technology, Inc.

M. D. Springer, et. al., "A Thermal Destruction and Recovery System for Medical Waste Powered by a Plasma Arc Torch," White Paper, Plasma Energy Applied Technology, Inc.

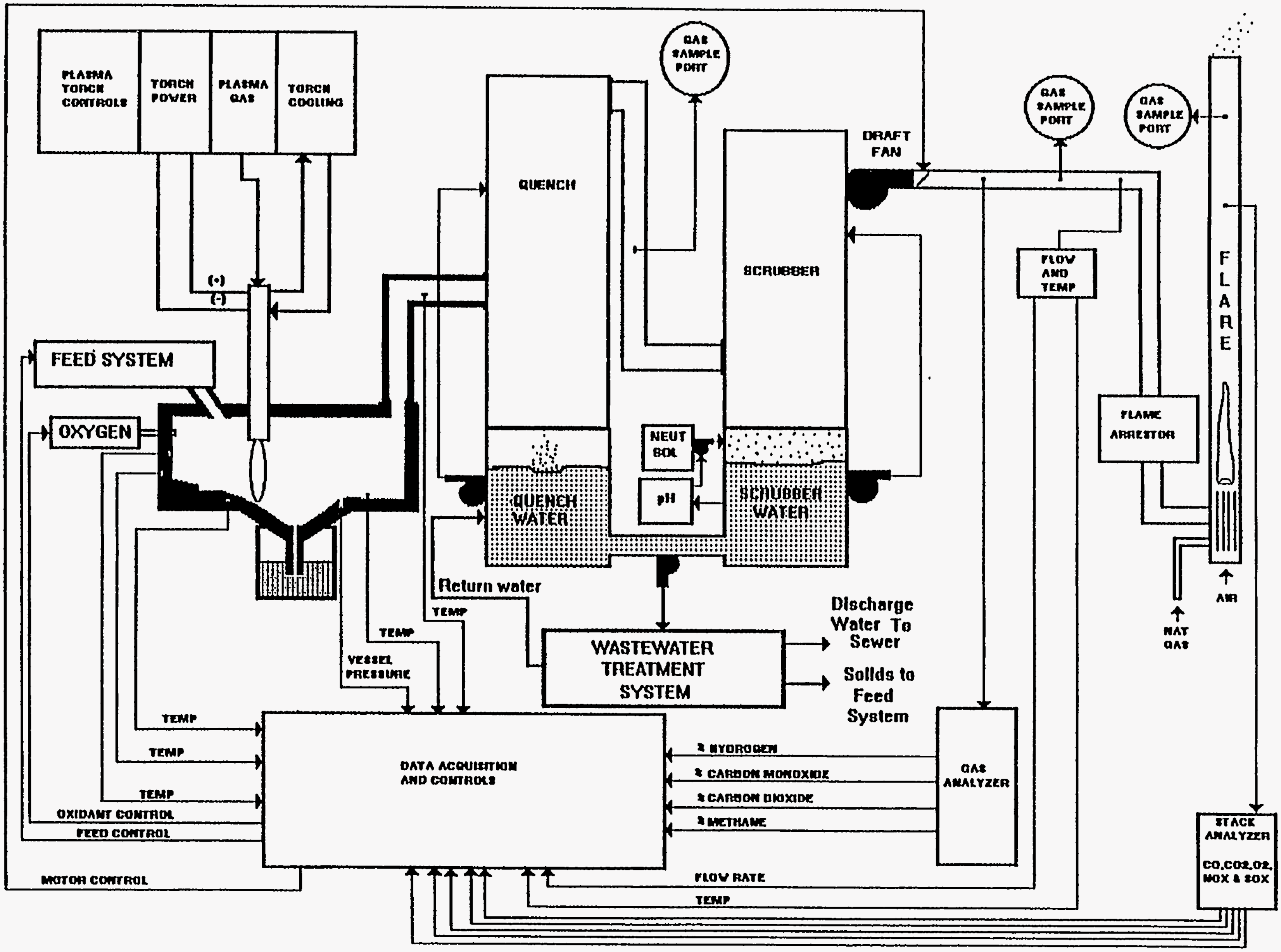


Figure 1. TDR Pilot Plant Schematic Diagram

Thermal treatment process: Rotating Hearth Furnace (PACT-1)

Location: TREAT Facility, ANL-W, ID

Mode of operation (continuous,batch): Batch mode with feed capability

Status: Removed to SAIC Star Center, Idaho Falls, ID

Process description/size/dimensions/materials of construction:

The system consists a 200 kW power supply and a plasma torch mounted vertically. Materials to be melted are placed on a rotating hearth below the torch. The plasma chamber is a horizontal cylinder a volume of approximately 0.35 m^3 The cylinder is of double walled construction with forced water cooling. The hearth is constructed of a castable refractory material with a cylindrical carbon insert. A vibratory feeder is used to introduce more material once the initial charge on the hearth is melted.

Waste feed preparation/sorting/sizing requirements:

Feed must be of size to go through the feeder system. Any object that can be placed on the hearth can be melted.

Air pollution control system components:

The APCS system is a closed loop system consisting of 1) a cold finger for metals removal, 2) a HEPA filter, 3) a carbon filter and (4 a compressor stage. Exhaust is then routed back to chamber and plasma torch.

References:

T. F. Yeast, et. al., "Volatility Studies in a Rotating Hearth Furnace," *1994 American Nuclear Society Meeting, November 13, 1994, Washington, D.C.*

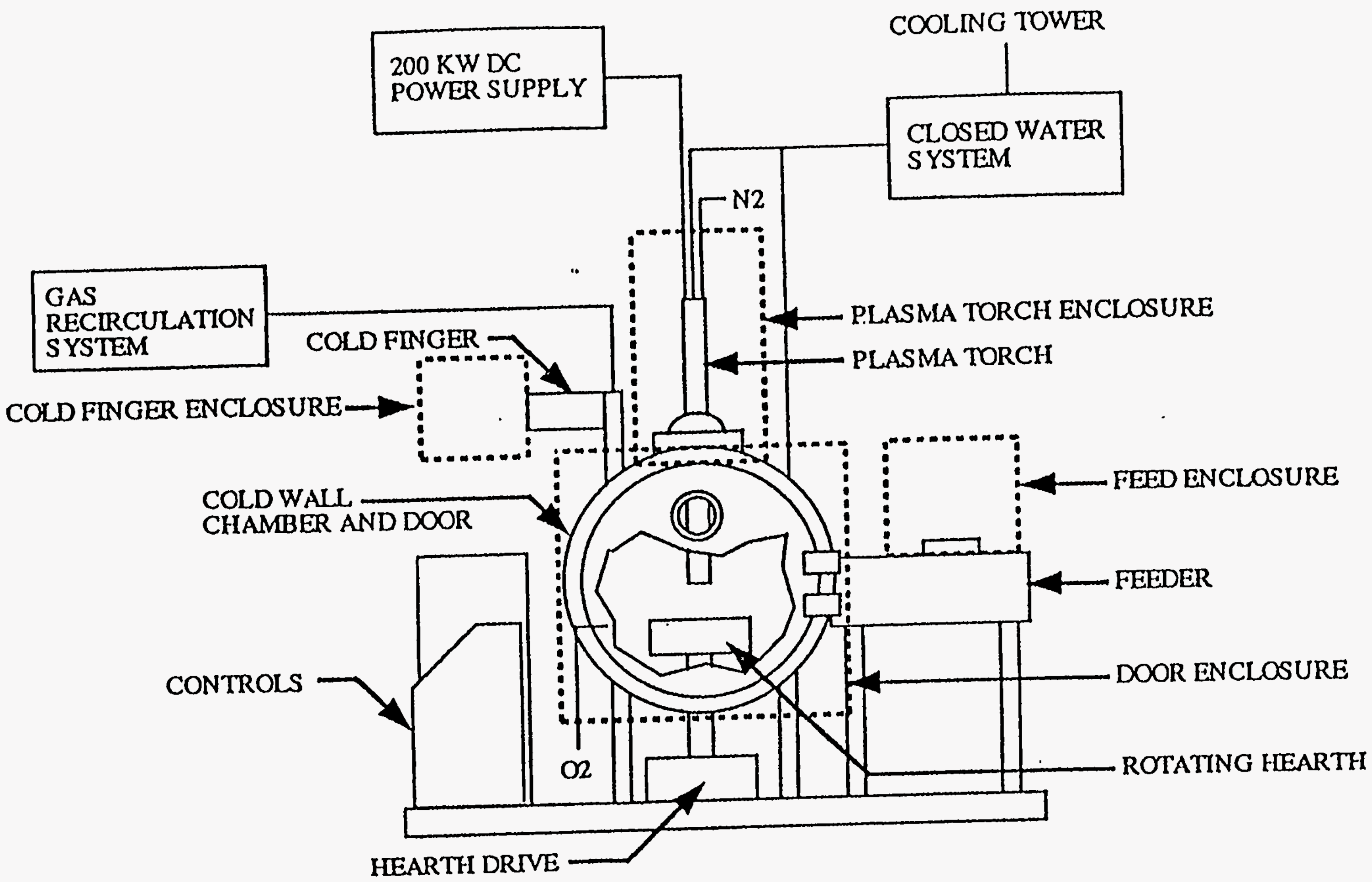


Figure 2. Elevation of the Plasma Arc Melter

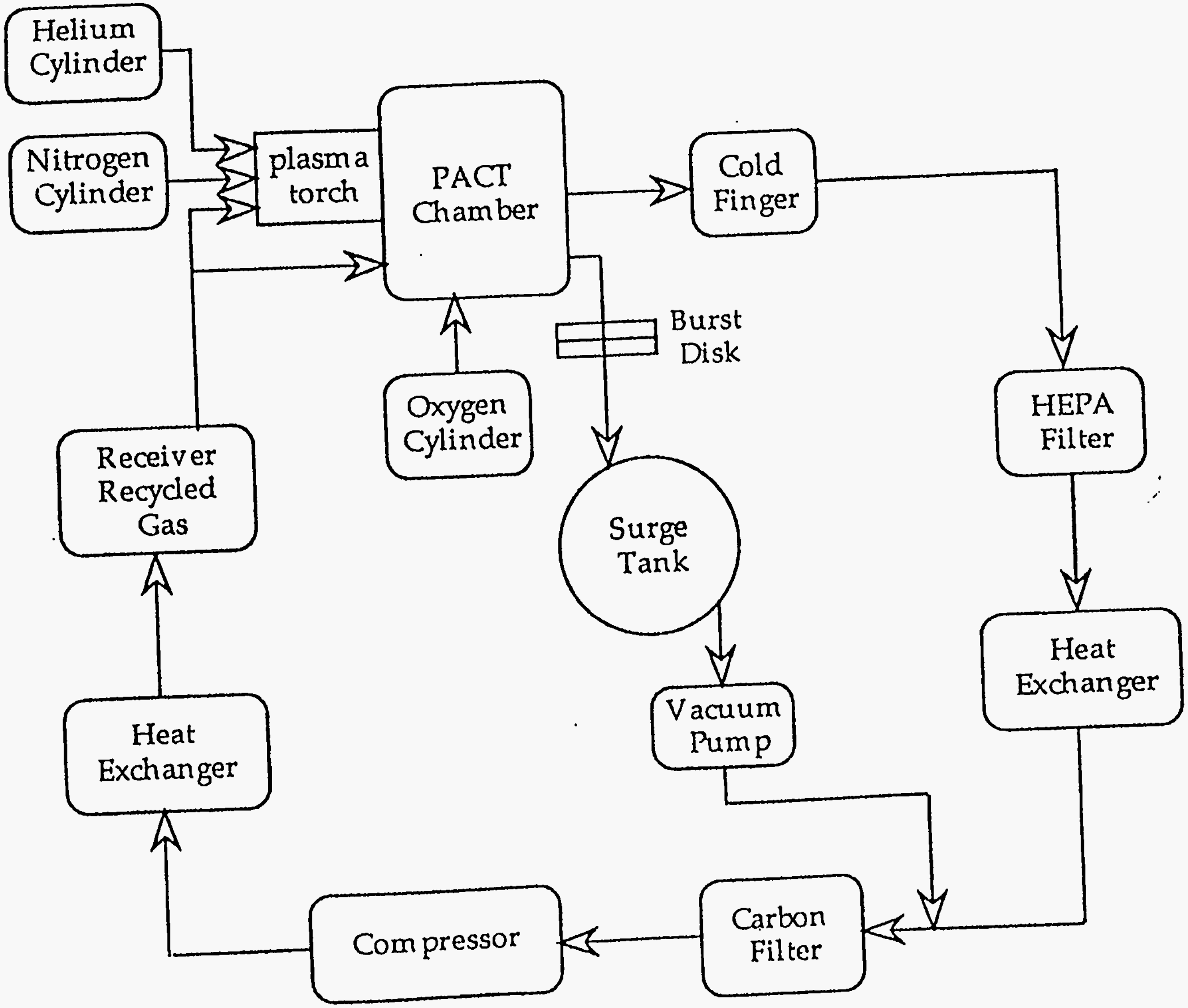


Figure 3. Flow Sheet for Test System Elements

Thermal treatment process: RETECH Plasma Arc Centrifugal Treatment (PACT-2)

Location: Retech, Inc., Ukiah, CA

Mode of operation (continuous,batch): continuous

Status: Commercial units sold to Moser-Glaser & Co., Muttenz, Switzerland.

Process description/size/dimensions/materials of construction:

Designed as a mobile system.

Consists of a double walled water cooled hearth that rotates at 20-70 rpm. Inside diameter is 2.0 ft. A transferred arc plasma torch inserted through the top heats materials in the hearth as it rotates. Slag is tapped through a central hole in the bottom of the hearth. Operates at up to 120 kW of input power with a 200 kW power supply (actual torch size is unknown).

Waste feed preparation/sorting/sizing requirements:

Waste materials must be of a size to be fed through an auger feeder. Some models have feed rates of up to 40 kg/hr.

Air pollution control system components:

The APCS consists of a refractory lined secondary combustion section designed to provide a minimum residence time of 2 seconds at a temperature of 1090 C. A wet scrubber system is used to remove particulates and acid gases.

References:

R. C. Eschenbach, et. al., "A Portable Vitrification System for Waste Treatment, white paper, Retech, Inc., July, 1994.

Test Results of Screening High-Metal-Content Wastes in a Plasma Centrifugal Frunace under the Minumum Additive Waste Stabilization Program, Volume I, Report No. PCF-D026, MSE, Inc., July, 1994.

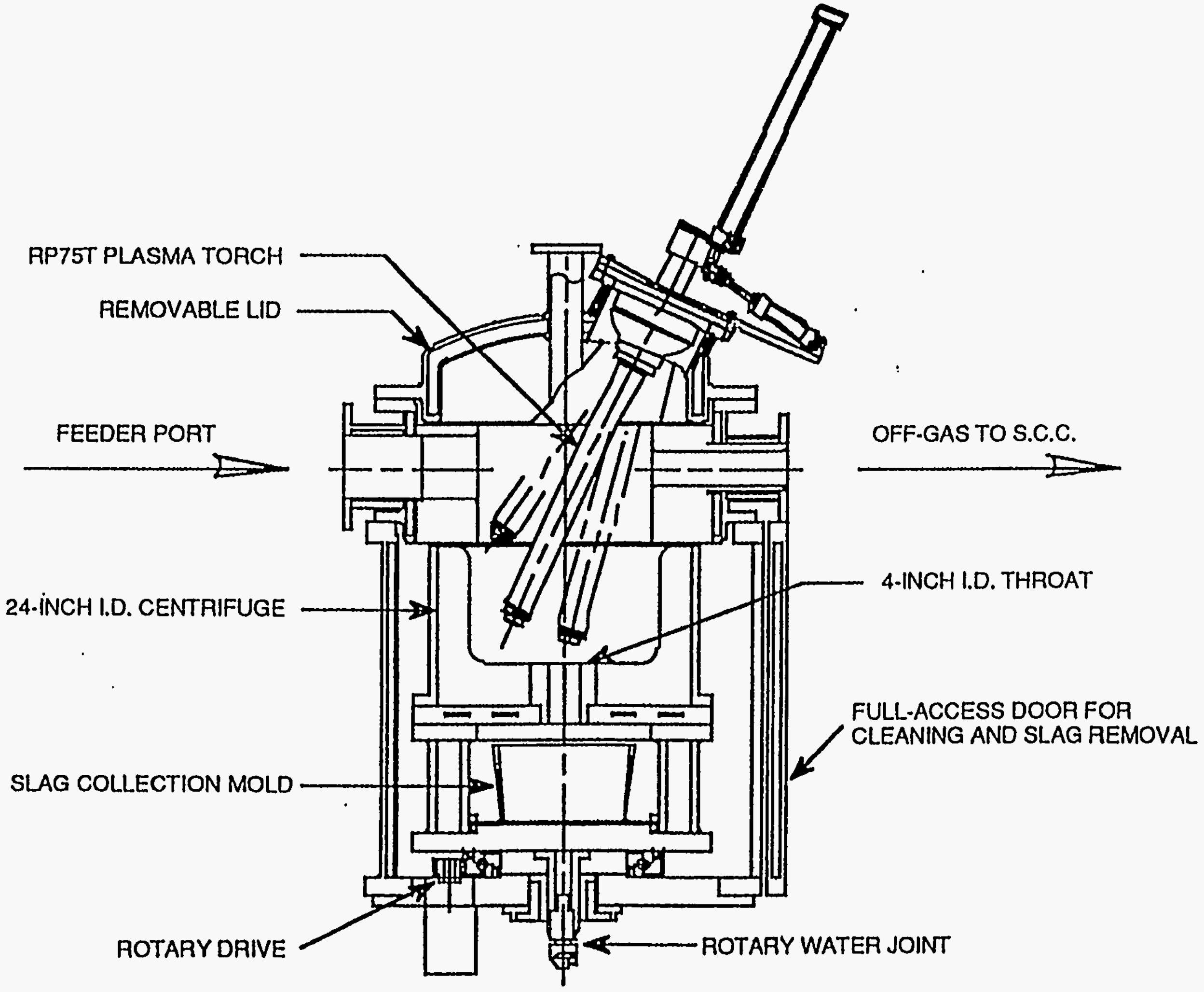


Figure 4. Elevation Cross-Section of PACT-2

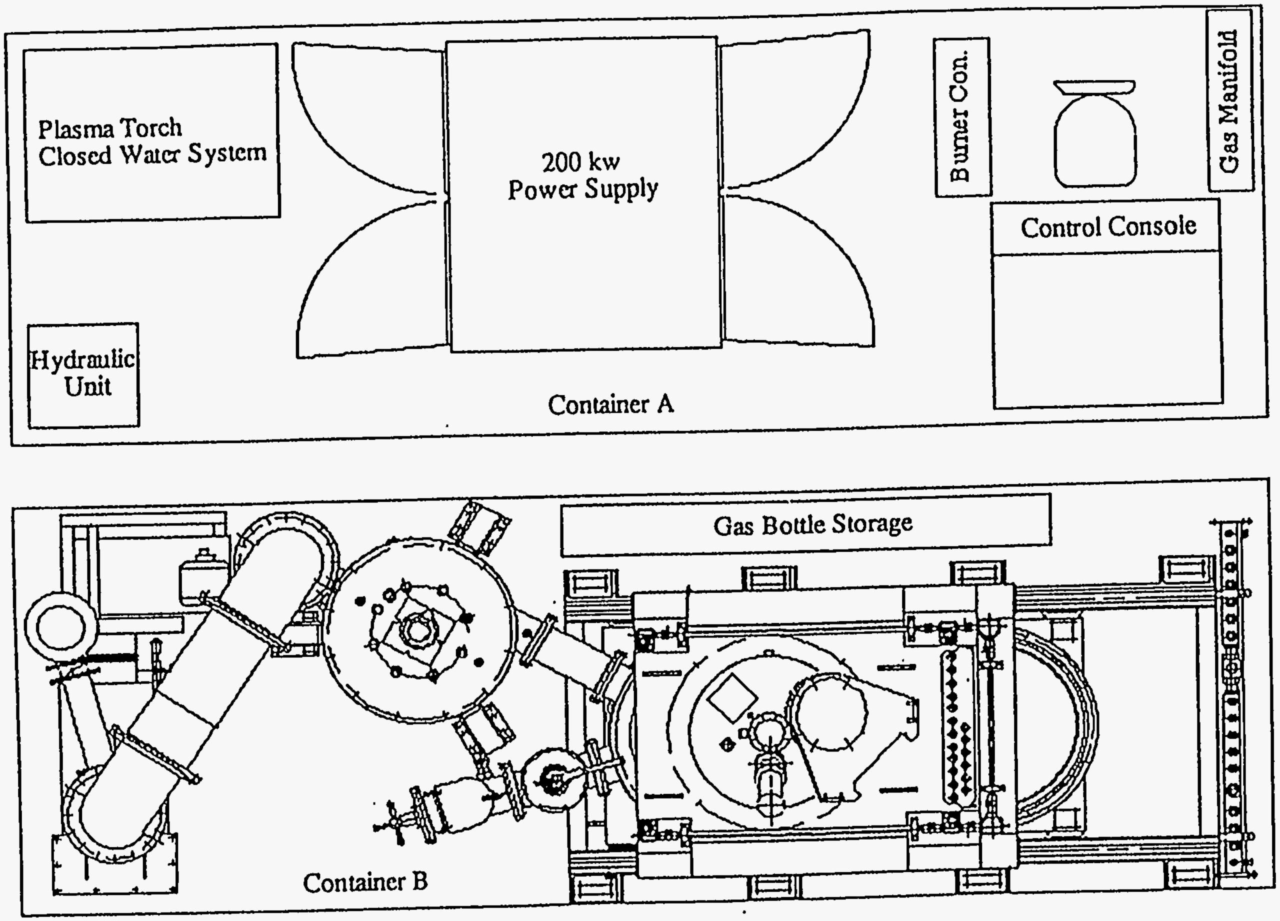


Figure 3. Plan View of PACT-2 System

Thermal treatment process: Plasma Arc Centrifugal Treatment Furnace (PACT-6)

Location: Western Environmental Technology Office (WETO), Butte, MT

Mode of operation (continuous,batch): continuous

Status: operational

Process description/size/dimensions/materials of construction:

Consists of a double walled water cooled hearth that rotates at 15-60 rpm. Inside diameter is 5.9 ft. A 600 kW transferred arc plasma torch inserted through the top heats materials in the hearth as it rotates. Slag (1370-1650 C) is tapped through a central hole in the bottom of the hearth. Within the (primary) melting chamber gas temperatures are 1093-1304 C and in the secondary chamber below gas temperatures are 649-1093 C.

Waste feed preparation/sorting/sizing requirements:

Waste Materials must be sized so they can be fed through an auger feeder or on a segmented conveyor belt.

Air pollution control system components:

The APCS consists of a secondary combustion section using natural gas and operating at an average temperature of 1800 C. This followed by a wet scrubber system which includes a quencher, a packed bed absorber/condenser/nucleator, a high energy scrubber, agglomerator, demister, reheater, baghouse and HEPA filters.

The PACT-6 system also acts as test bed for slip stream test bed (SSTB) in a separate reduced scale offgas treatment loop.

References:

"Plasma Arc Centrifugal Treatment Test Plan - Controlled Emission Demonstration Slip Stream Test Bed - Shakedown and Demonstration Tests," white paper, MSE, Inc.

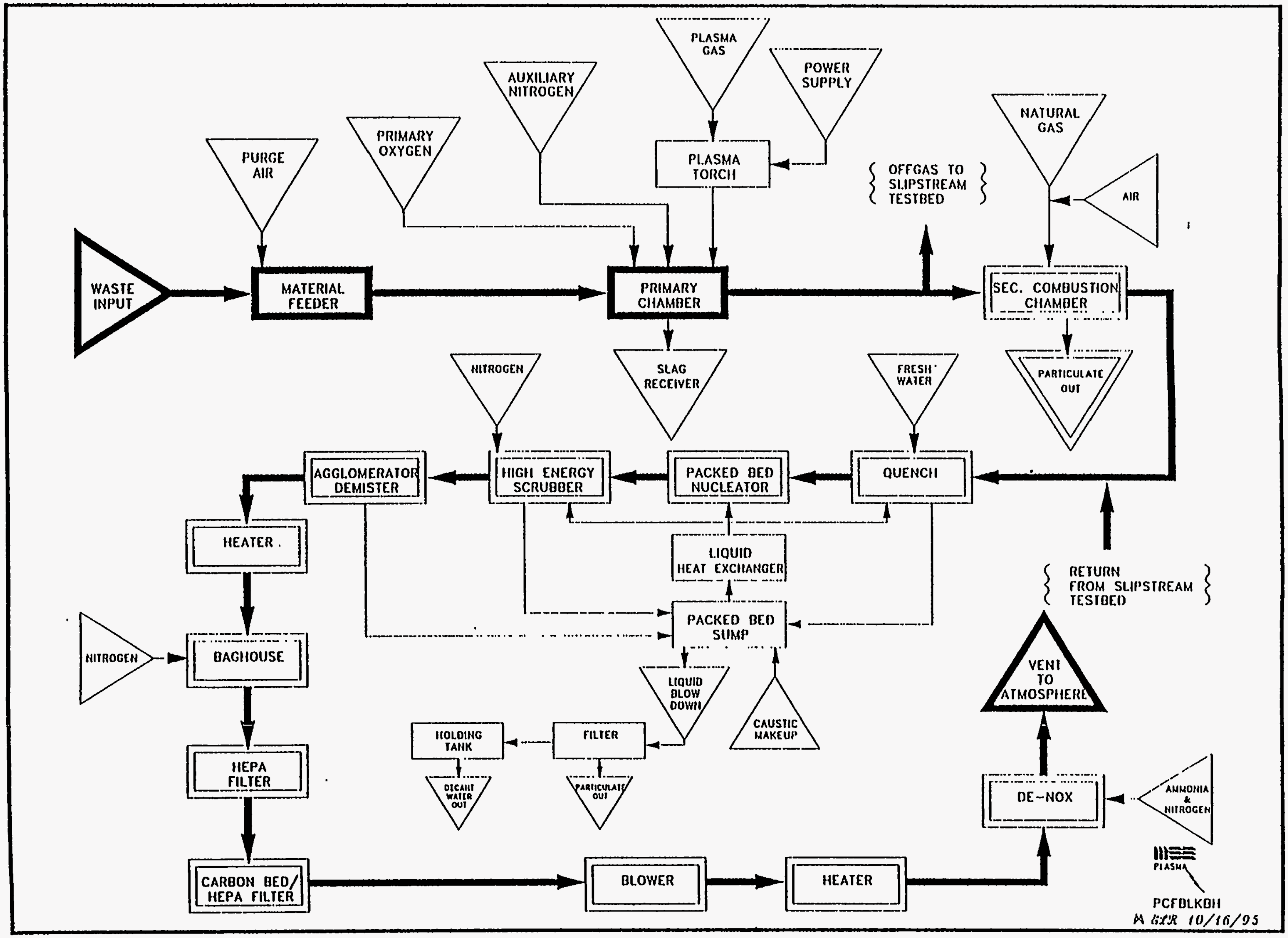
A. J. Viall, "Plasma Centrifugal Furnace Experiment Progress and Preliminary Test Results," white paper, MSE, Inc.

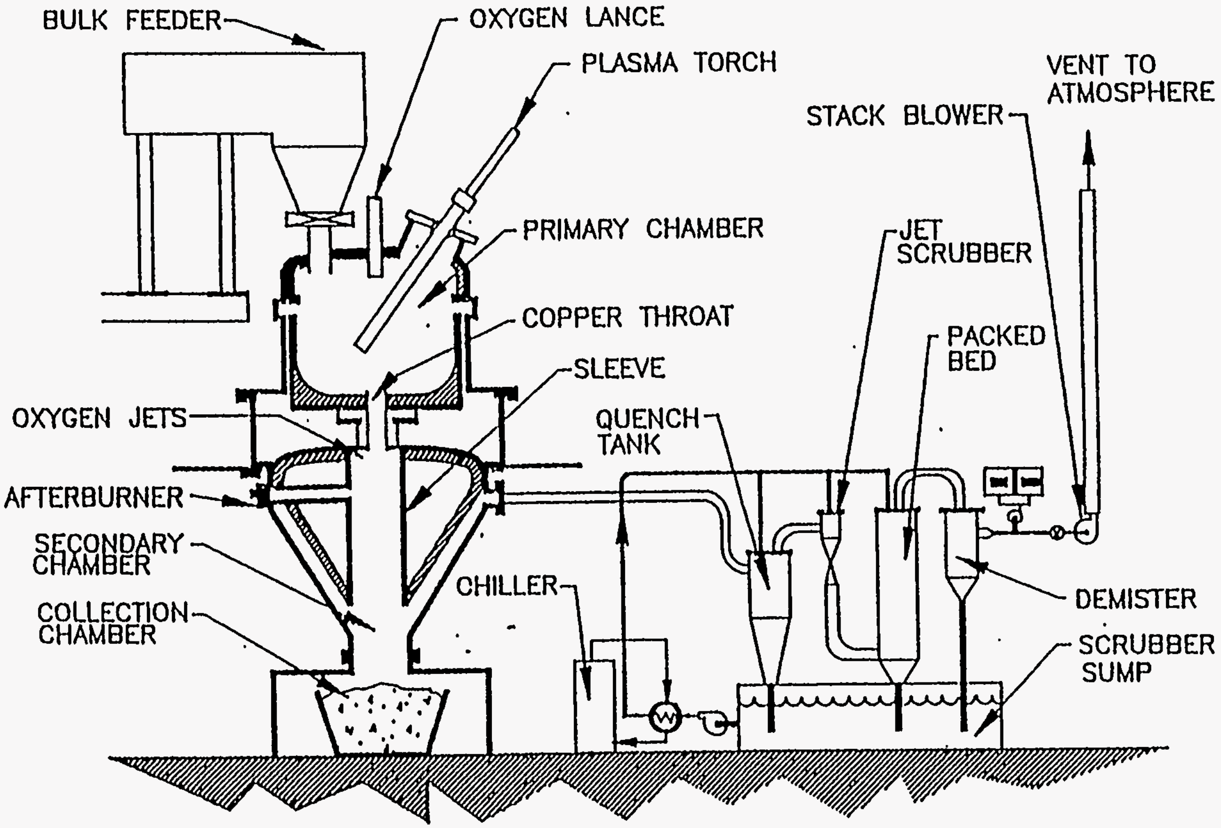
"Plasma Arc Furnace Experiments," HAZWRAP 1989 Annual Report, MSE, Inc.

M. P. Schlienger and R. C. Eschenbach, "Latest Developments with Plasma Centrifugal Furnace," *First INEL Waste Workshop*, Idaho Falls, ID, January 16-17, 1991.

Test Results of Screening High-Metal-Content Wastes in a Plasma Centrifugal Frunace under the Minumum Additive Waste Stabilization Program, Volume I, Report No. PCF-D026, MSE, Inc., July, 1994.

Block flow diagram for the PACT-6 system installed at the DOE WETO facility in Butte, Montana. Note take off and return points for the Pall/Thermatrix test bed.





The MSE/Retech dc plasma centrifugal reactor system (Whitworth et al. 1992).

Thermal treatment process: LANL Inductively Coupled Plasma (Induction heated melter)

Location: Los Alamos National Lab, NM

Mode of operation (continuous,batch): continuous

Status: theoretical

Process description/size/dimensions/materials of construction:

A low frequency field is inductively coupled to waste materials to heat them to process temperatures.

Waste feed preparation/sorting/sizing requirements:

Gas or liquid feeds are easier to use, but methods of feeding solids are also possible.

Air pollution control system components:

unknown

References:

R. A. Krakowski and K. A. Werley, "Prospects for Using Low-Frequency Induction Plasmas for Bulk-Chemical Processing: A Systems Analysis," *First INEL Workshop on Plasma Applications to Waste Treatment*, January 16-17, 1991, Idaho Falls, ID.

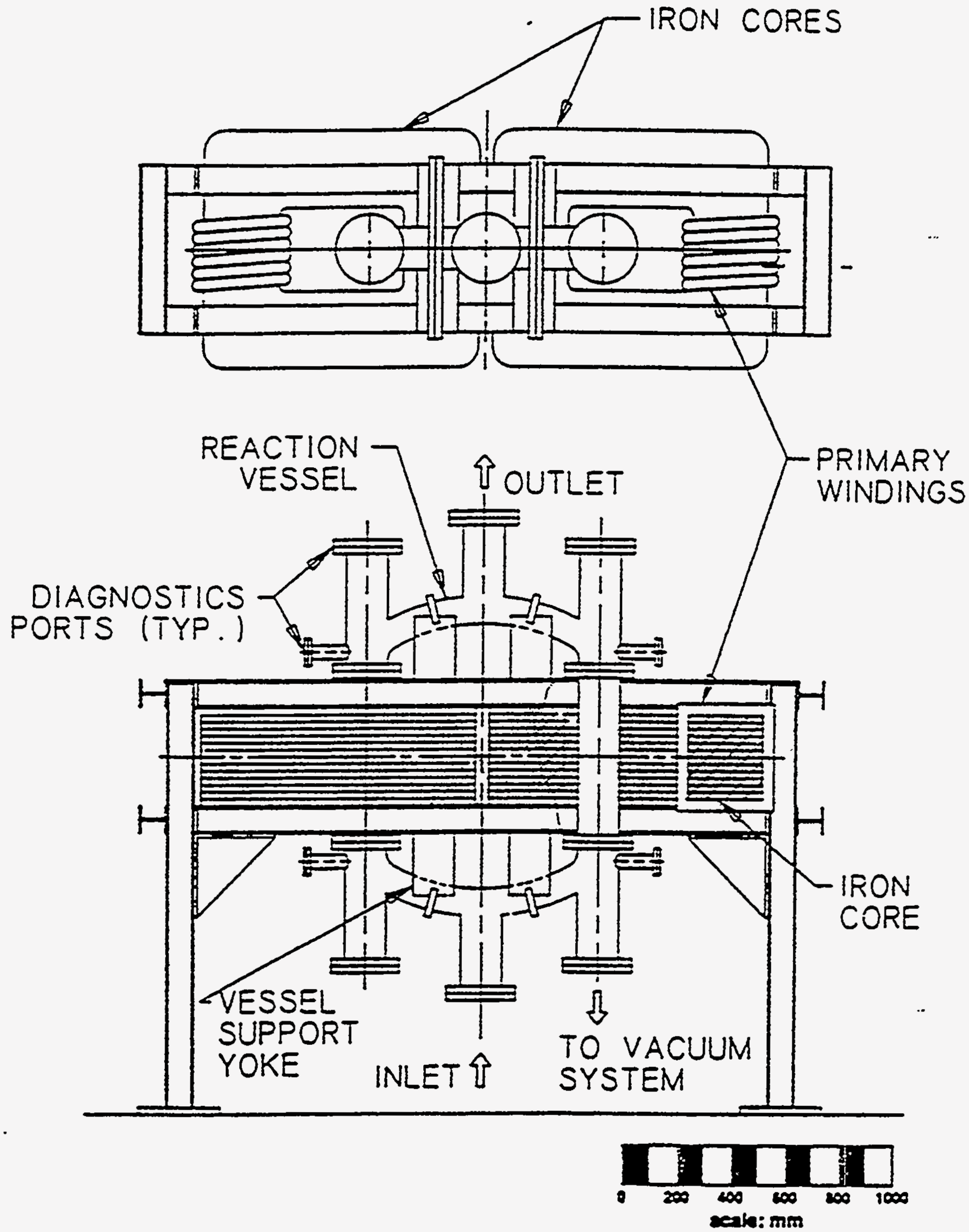


Figure 12. Preliminary design of low-frequency inductively coupled thermal plasma processing experiment. This design corresponds to $r_w \simeq 70$ mm and $A = 9$, which would require ~1,000 kW input power.

Thermal treatment process: Rocky Flats Microwave Melter

Location: Rocky Flats Nuclear Weapons Plant, CO

Mode of operation (continuous,batch): Continuous

Status: Unknown

Process description/size/dimensions/materials of construction:

Two systems were used for testing. A bench scale system operated at 2450 MHz and at a power level of 6 kW, and a pilot scale system operating at 915 MHz and 30 kW. A third 50 kW system (915 MHz) will be used for full scale processing. Microwave energy is funneled from the generator through waveguides and into a stainless steel resonant cavity measuring 52" x 52" x 39". A 30 gallon steel drum is placed below the cavity and microwave energy enters the drum through passive choke in the cavity floor. Material is melted in the drum as it feed in with an screw feeder system.

Waste feed preparation/sorting/sizing requirements:

Dried sludge must be sized so that it can be carried through an auger screw feeder.

Air pollution control system components:

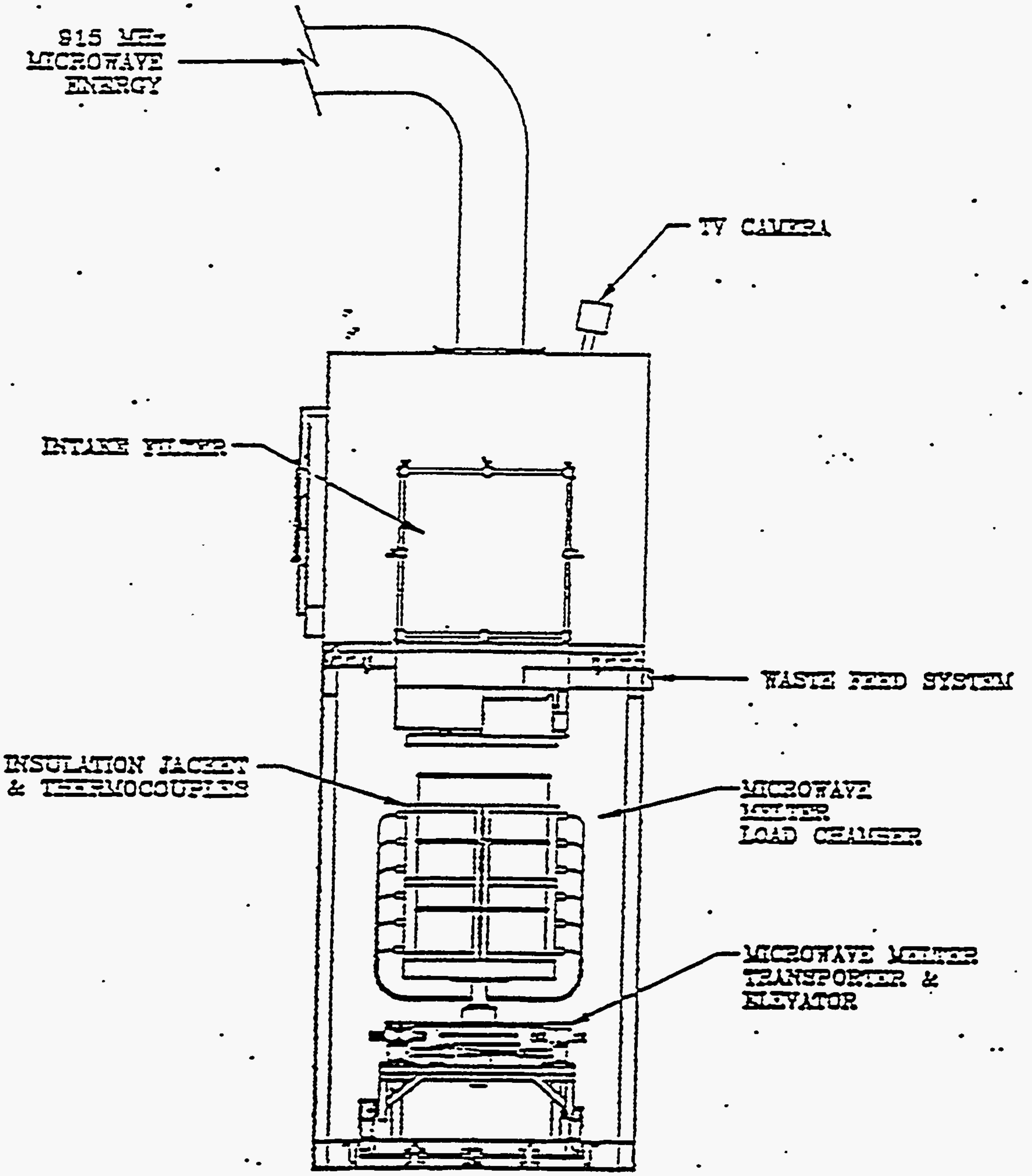
unknown

References:

R. D. Petersen, "Microwave Vitrification of Rocky Flats TRU Sludge", White Paper, EG&G Rocky Flats, Inc., (198?).

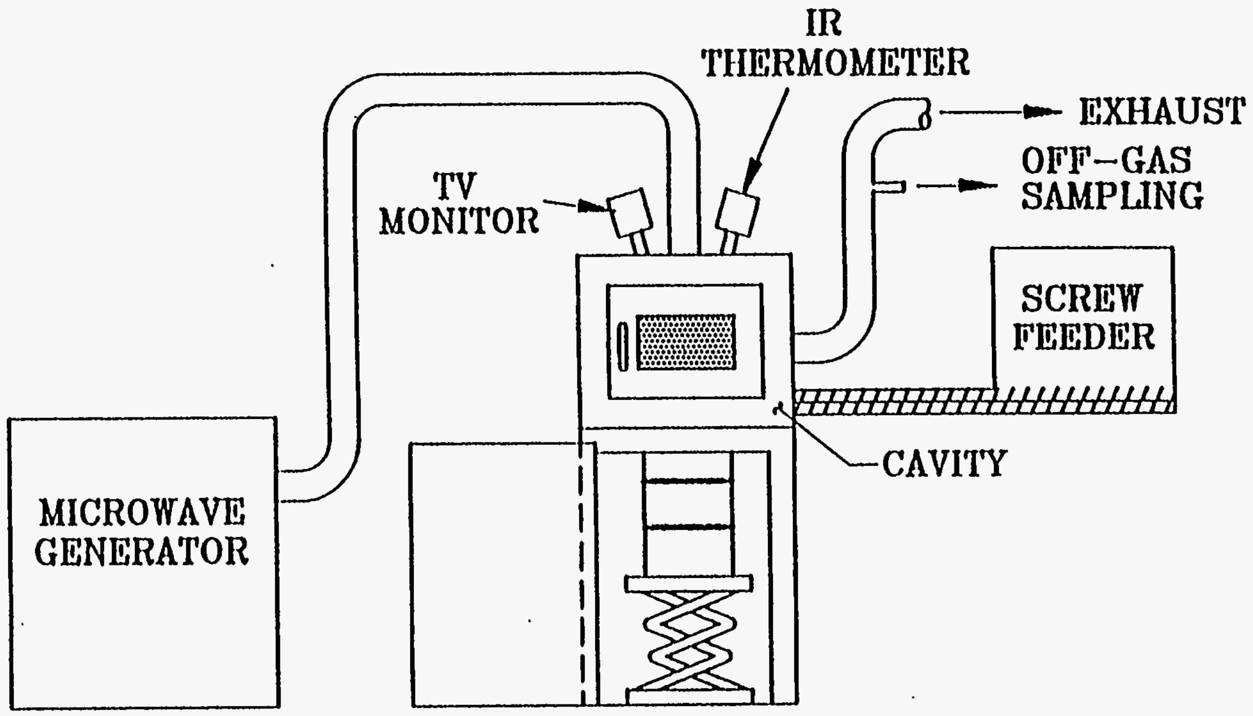
R. D. Petersen, "Microwave Vitrification of Rocky Flats TRU Sludge", *Spectrum, 1990.*

R. D. Petersen, A. J. Johnson, and S. D. Swanson, "Applicaiton of Microwave Energy for Solidificationof TRU Waste", ?.



IN-DRUM MICROWAVE SOLIDIFICATION

EG&G ROCKY FLATS



IN—DRUM VITRIFICATION PILOT SCALE SYSTEM

Thermal treatment process: Kobe Steel Microwave Melter

Location: Plutonium Wastes Treatment Facility, Tokai Works, Japan

Mode of operation (continuous,batch): Continuous

Status: Unknown

Process description/size/dimensions/materials of construction:

This is a small production system for treating plutionium contaminated wastes from the nuclear power industry. The system operates at a frequency of 915 MHz and at a power level of 25 kW. Microwave energy is funneled from the generator through waveguides and into a stainless steel resonant cavity measuring 2550(l) x 1120(w) x 3500(h) millimeters. A steel crucible with a volume of 42 liters is placed below the cavity so that microwave energy can enters and melt the waste. Material is melted in the crucible as it feed in with a screw feeder system.

Waste feed preparation/sorting/sizing requirements:

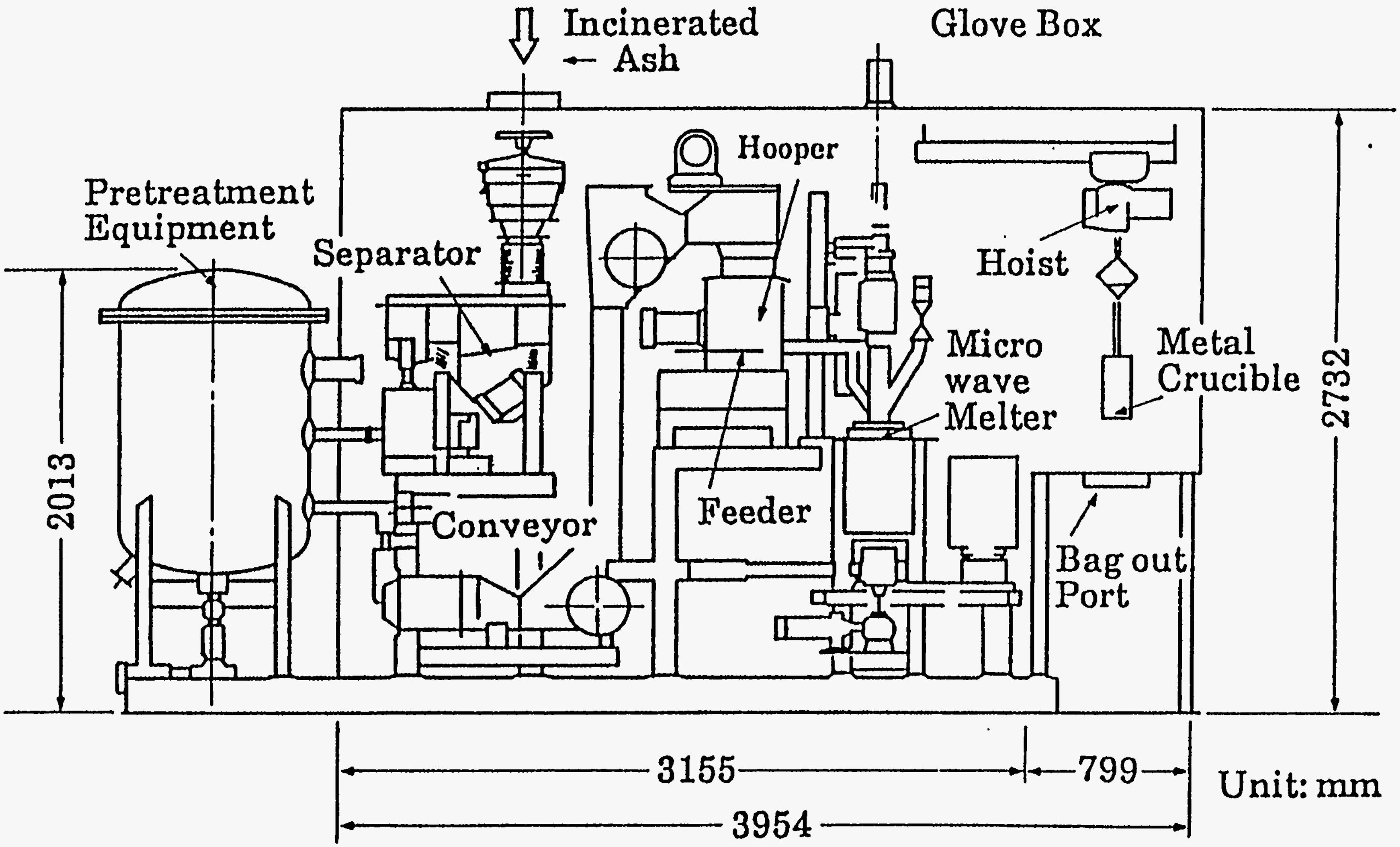
Materials must be sized so that it can be carried through an auger screw feeder.

Air pollution control system components:

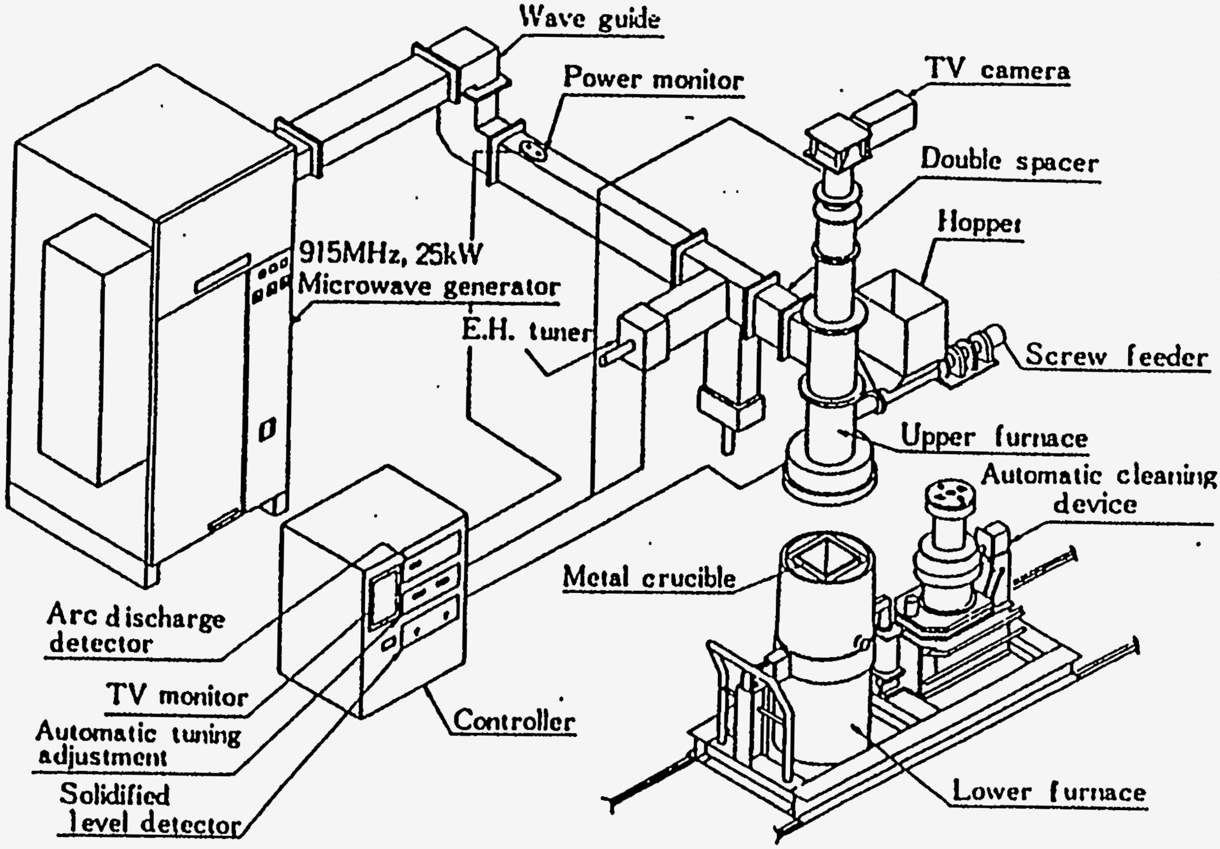
unknown

References:

F. Komatsu, A. Takusagawa, R. Wada and K. Asahina, "Application of Microwave Treatment Technology to Radioactive Waste," white paper, Kobe Steel Ltd. Kobe, Japan.



Composition of microwave equipment for hot test



Composition of microwave melter

Thermal treatment process: LLNL Molten Salt Bath

Location: Lawrence Livermore National Laboratory (LLNL)

Mode of operation (continuous,batch): Continuous (0.5 to 5 hr tests)

Status: Unknown

Process description/size/dimensions/materials of construction:

In the bench-scale units, the molten salt bath was contained in a round bottom alumina crucible, 15 cm ID and 91 cm high, that was housed in a close-fitting stainless steel vessel with a flange on top for inlet and outlet ports. This assembly was further surrounded by a furnace used as a preheater to melt the salt at the start of the oxidation process. However, once the oxidation process began, sufficient heat was generated by the burning of the waste feed material to maintain the melt at reaction temperature. Control of the feed rate and the use of added fuel, if needed, were used to control the temperature. About 5.5 kg of salt was used as the charge, which gave a molten salt height of 15 cm under sttagnant conditions but the salt height usually rises to twice that height becasue of foaming due to gas flow through the salt. The starting salt was usually Na_2CO_3 or a 90% w/o Na_2CO_3-10% w/o Na_2SO_4.

Waste feed preparation/sorting/sizing requirements:

The waste material-air mixture was introduced at slightly above atmospheric pressure into the bottom of the melt through a 3.8-cm ID alumina inlet tube extending in from the stainless steel top flange into the melt. The feed rate was typically about 200 g/h and run times ranging from 0.5 to 5 hours. The air flow rate was generally set to 0.071 scm/min which correspond to a linear gas velocity of about 30 cm s^{-1} of offgas exiting from the melt.

Air pollution control system components:

The offgas passed through a train and then was discharged to the atmosphere. The train generally consisted of a water condenser, a prefilter, a HEPA filter, and an aqueous scrubber, all in series. Either the prefilter or an isokinetic sampler in the line woth a 0.2-μm pore filter were used to sample the offgas for particulates. Prior to discharge after passing the HEPA filters, offgases were analyzed for CO_2, hydorcarbons, CO, NO_x, and O_2.

References:

O.H. Krikorian, *A Preliminary Assessment of Salt and Radionuclide Volatilities in the Molten Salt Processor*, UCRL-ID-105173, Lawrence Livermore National Laboratory, Livermore, CA (November,1990).

Thermal treatment process: Molten Metals Technology-Catalytic Extraction Process (CEP)

Location: R&D facility: Fall River, MA
Quantum-CEP: Scientific Ecology Group (SEG), Oak Ridge, TN

Mode of operation (continuous,batch): Continuous

Status: Operational

Process description/size/dimensions/materials of construction:

At the core of the process is a refractory-lined vessel containing a molten metal bath which acts as a catalyst and solvent in the dissociation of the feed, synthesis of the products, and/or the concentration of radionuclides. The molten metal may be Fe, Ni, or another metal. Upon introduction to the bath, the feed dissociates into its constituent elements and goes into metal solution. The addition of co-reactants enables reformation and partitioning of desired products. Bath is operated around 3000°F (1650°C). Prototype units capable of processing 2000-15,000 tons/yr of RCRA waste currently exist at Molten Metal Technology (MMT) R&D Facility in Massachusetts. Quantum-CEP is specifically designed to handle radioactive and mixed waste. A bench-scale process is operational at the SEG facility in Oak Ridge, TN. MMT has agreed to develop a commercial Quantum-CEP demonstration facility at the Oak Ridge Reservation with a capacity of 5000 tons/yr.

Previous experimental results using melt refining techniques with contaminated metals demonstrated that U and Pu can be selectively removed from the metal phase and concentrated in a separable, vitreous oxide phase. Residual concentrations ranging from 0.05 ppm to 2 ppm of such radioactive components were achieved using diffusion of oxidizing, vitreous-forming agents to partition the radioactive components from mild steel, stainless steel, Ni, Cu, and Al.

Waste feed preparation/sorting/sizing requirements:

The process is advertised to have minimal feed pretreatment and handling requirements. Feeds of most physical forms can be fed to the bath via multiple injection methods. Gases, fine solids, pumpable liquids, and some slurries can be fed in the bottom of the reactor. Larger solid particles, some liquids and slurries can be injected through top-mounted submerged lances. Choosing the appropriate means for feed addition and reactor design ensures the desired intimate contact and processing within the molten metal bath. While pretreatment is often unnecessary for effective processing, economics may be improved by preliminary drying or grinding.

Air pollution control system components:

The vessel is hermetically sealed to prevent emissions. In the case of Cs, since it is highly volatile and likely to be emitted into the offgas, Molten Metals Technology (MMT) has designed and is currently testing a proprietary Cs capture system. With this system, a decontamination factor (activity in feed/activity in offgas) for Cs exceeding 100,000 was reported.

References:

C.A. Herbst et al.,"Quantum-Catalytic Extraction Process application to mixed waste processing",*Proceedings Spectrum'94 Nuclear and Waste Management Meeting*, Atlanta (1994).

P. Nahass et al., "Quantum-CEP for mixed waste processing", *Federal Environmental Restoration and Waste Minimization Conference*, New Orleans, LA (1994).

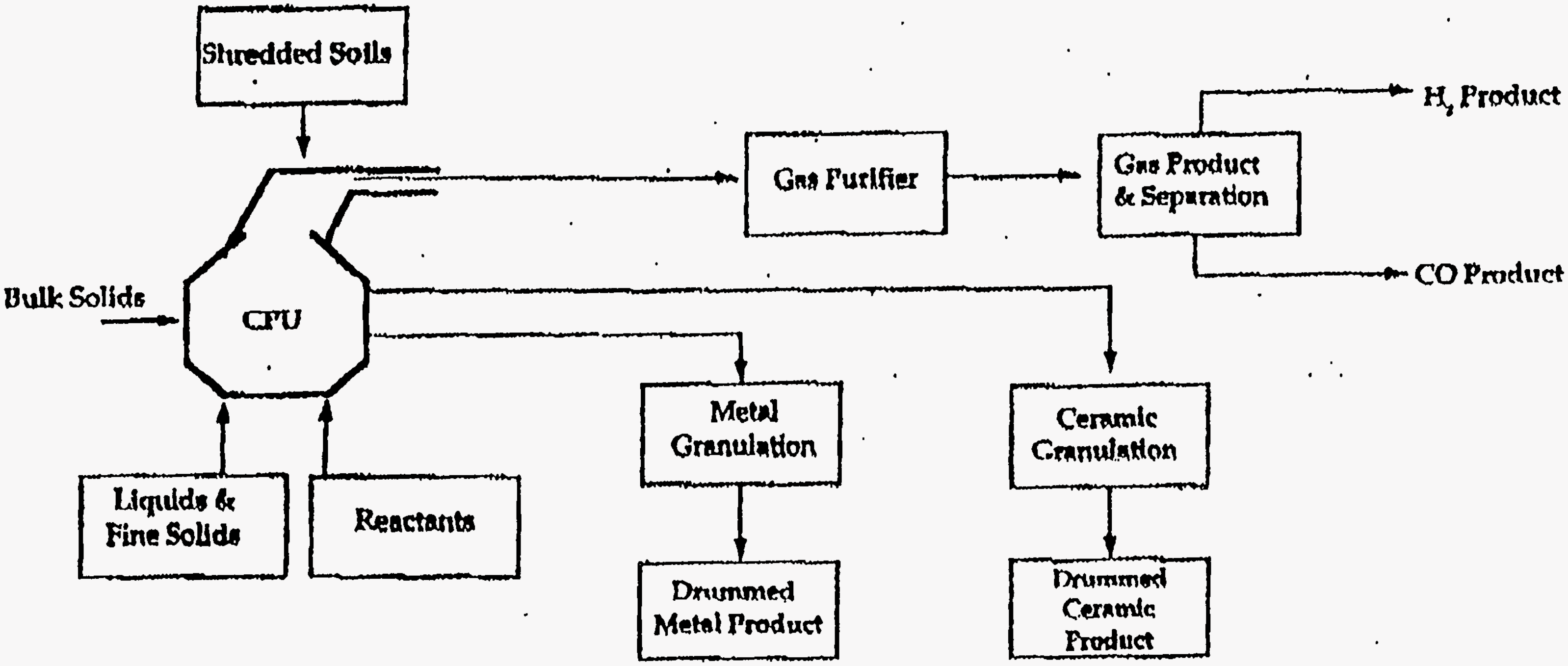


Figure 1. Simplified block diagram of the CEP process equipment (1994).

Thermal treatment process: Framatome Technologies Vitrification Process

Location: Bollene, France

Mode of operation (continuous,batch): Continuous

Status: Commercial size pilot plant operational since 1989

Process description/size/dimensions/materials of construction:

The Framatome Technologies Vitrification Process (FVP) consists of injecting finely crushed solid wastes and/or liquid wastes with air or other gases directly into the interior of a molten glass pool. Temperatures in the melt are maintained between 1,000 and 1,100°C. The molten glass is contained in a metallic pot or crucible which is heated indirectly by electrical resistance heaters that surround the outside of the melting pot. Any organic compounds in the waste feed system are pyrolized in the glass melt as they rise to the surface while inorganic compounds are retained and solubilized in the molten glass matrix.

The system can be operated at reducing or oxidizing mode. Supplementary gas injectors are provided at points where waste feed enters the molten glass pool. Either inert gas, excess air, or oxygen-rich streams are injected directly into the glass melt. The gaseous additive helps control the melt chemistry, and the agitation caused by the introduction enhances mass and heat transfer in the melt to ensure a homogenized glass mixture. The ability to add glass formers (frit) provides for both a continuous processing capability and permits the glass chemistry to be adjusted. The pilot plant has a capacity of about 25 kg/hr.

Waste feed preparation/sorting/sizing requirements:

Solid wastes are finely divided so that they can be pneumatically injected into the molten glass. To achieve a particle size of < 6 mm, solid wastes containing large particles must be crushed using one or more cryogenic crushing units. Various types of wastes (crushed solids, sludges, resins, etc.) and liquids are placed in specific feed hoppers and blended together or fed individually into the melt.

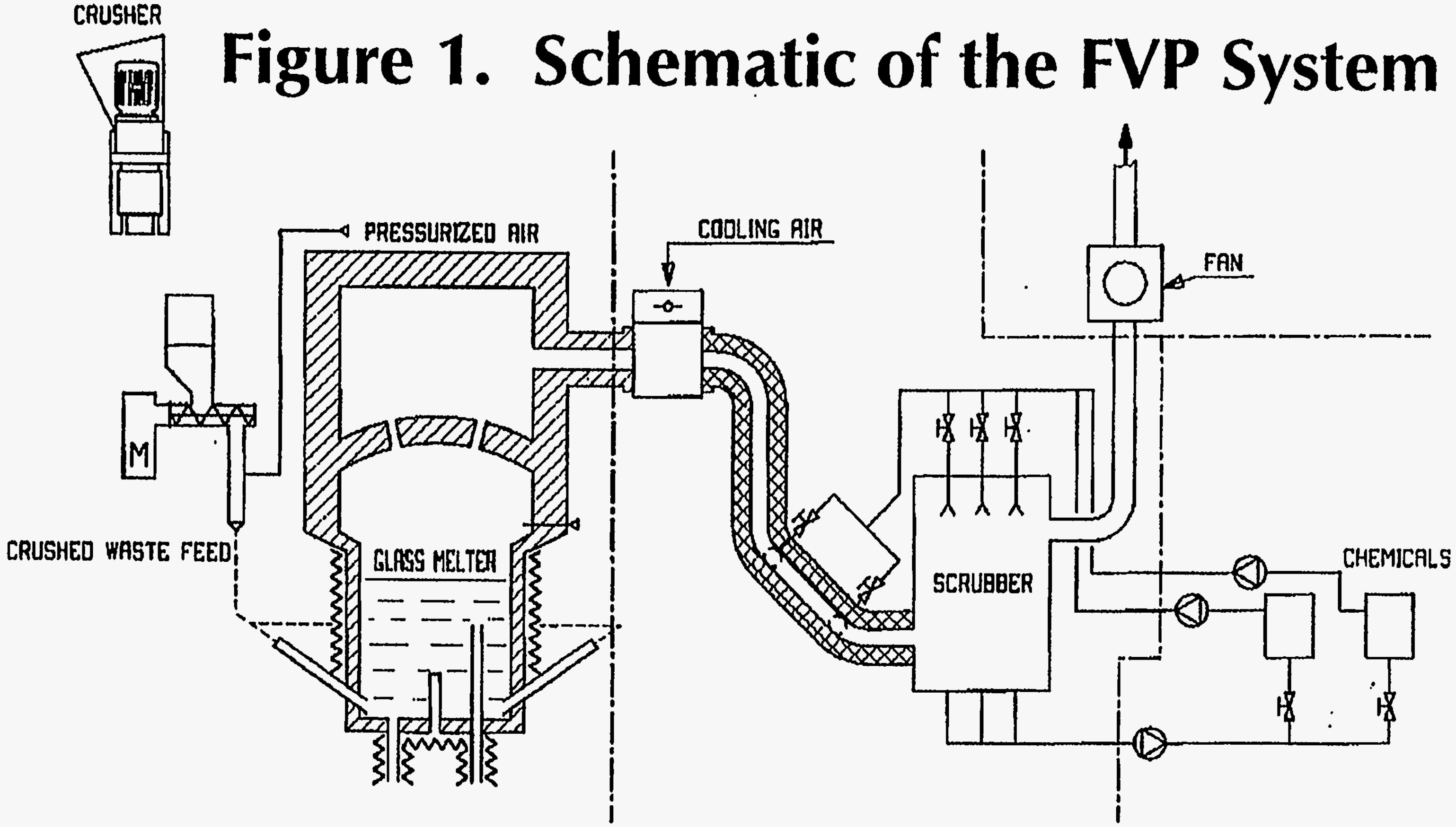
Air pollution control system components:

The combustion gases leave the combustion chamber via openings in the dome and pass into a post-combustion chamber where any remaining unburnt particles are oxidized. The sizing of the combustion and post-combustion chambers allow for sufficient residence time at temperature to minimize incomplete combustion products such as dioxins. Offgases are cooled using dilute air and are directed to the offgas/HEPA system where aerosols and pollutants are removed or neutralized.

References:

S.P. Hellman, L. Draus, J.J. Guiroy, and J.R. Murray, "Framatome Technologies' Vitrification Process", *EPRI Vitrification of Low-Level Waste Conference*, San Antonio, TX (December 1995).

Figure 1. Schematic of the FVP System



FRAMATOME
TECHNOLOGIES

FRAMATOME

Thermal treatment process: ACERC rotary kiln reactors

Location: ACERC, University of Utah

Mode of operation (continuous,batch): Batch

Status: Unknown

Process description/size/dimensions/materials of construction:

The bench-scale rotary kiln consists of a 10-cm long, 10-cm ID stainless steel tube. The volume of the heated chamber is 724 cm^3. The inside of the reactor is lined with ceramic material to isolate the reactor contents from the stainless steel. The end seal consists of a steel plate attached to a 2.5-cm OD tube. A ceramic cloth gasket is used to ensure a tight seal between the end seal and the reactor body. The end seal is bolted to a flange on the reactor body. Purge gases enter the reactor through a 1.9-cm ID tube. Temperature of the solids was monitored with a shielded, ungrounded K-type thermocouple running down the center of the purge-gas inlet. Gases exit through a quartz probe. The reactor is heated conductively. The generator is a 10-kW unit and is capable of heating the reactor to 980°C at a maximum rate of 50°C per minute.

The main section of the pilot-scale rotary kiln was 0.6 m long with a 0.6-m ID. The pilot-scale kiln simulator was used for testing at higher temperature (650-980°C). The burner section and main section rotate while the exhaust section is stationary. The bed temperature was measured by a thermocouple which extended into the middle of the kiln bed in the main section. A shielded suction pyrometer was used to determine the gas temperature. Waste was loaded through a blast-gate valve located in the exhaust section and solid samples were also taken via this opening. The advantage of using a batch system was that the removal of solid samples during the experiment simulated the collection of time-resolved samples as it moved through a full-scale facility.

Waste feed preparation/sorting/sizing requirements:

In order to estimate radionuclide partitioning in an incinerator, surrogate compounds were used to simulate the chemical nature of the radionuclide compounds.

The small size of the reactor allows for the separation of the chemical phenomena occurring in the waste from limitations imposed by heat and mass transport. As a result, special waste feed preparation requirements are not necessary.

Air pollution control system components: None

References:

R.G. Barton and J.S. Lighty, "Parametric study of vaporization of metal species from solids", *Proceedings 1993 Incineration Conference*, Knoxville, TN (1993).

R.G. Barton, J.S. Lighty, and J.M. Hillary, "Interactions of toxic and radioactive metals during thermal treatment of mixed waste", *Proceedings 1994 International Incineration Conference*, Houston, TX (1994).

E.G. Eddings, J.S. Lighty, and J.A. Kozinski, "Determination of metal behavior during the incineration of a contaminated montmorillonite clay", *Environ. Sci. Technol.*, 2

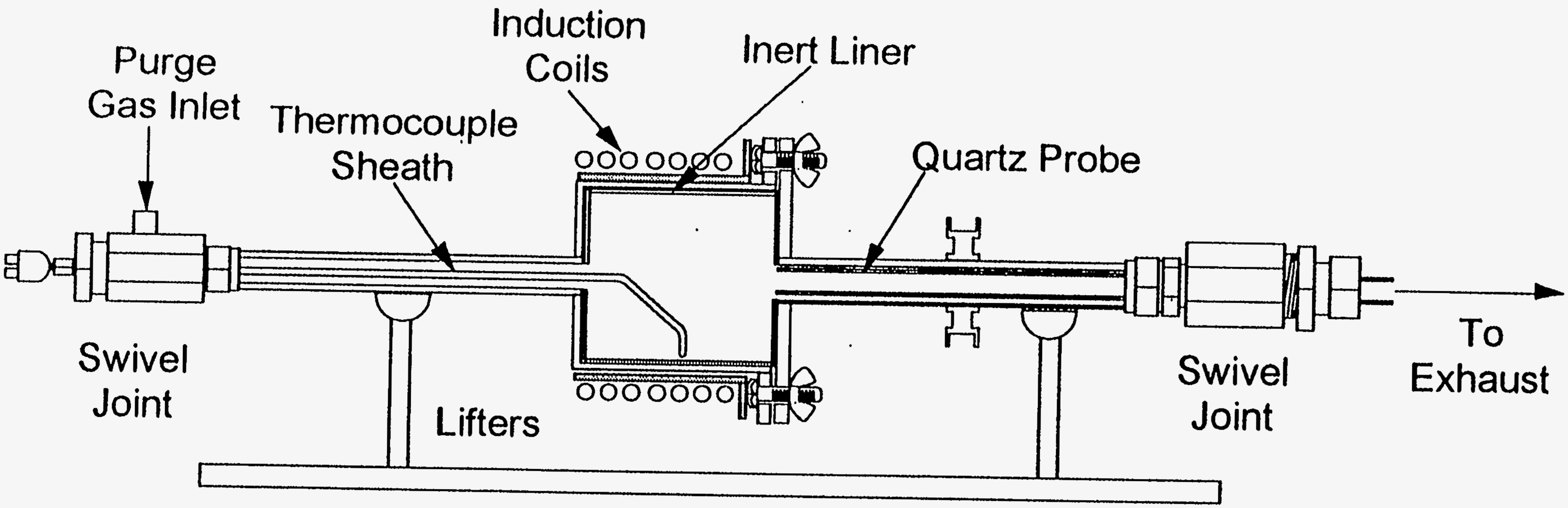


Figure 1. Schematic of bench-scale rotary kiln incinerator (1994).

Thermal treatment process: SWIFT Pilot Scale RKS

Location: Energy and Environmental Research, Santa Ana, CA

Mode of operation (continuous,batch): Continuous for specific campaign

Status: Operational(?)

Process description/size/dimensions/materials of construction:
The Savannah River Site plans to begin operation of the Consolidated Incineration Facility (CIF) to treat solid and liquid RCRA hazardous and mixed wastes. Trial burns were conducted at SWIFT using surrogates CIF wastes.

The primary combustion chamber (PCC) has a 30" ID by 24" long rotary section for solids treatment. The PCC offgas passes through a secondary combustion chamber (SCC). Both chambers use natural gas burners (PCC:0.45 MBtu/h; SCC:0.15 MBtu/h). The system is operated under negative pressure maintained by an induced draft fan which discharges to the facility stack.

In addition to T, P, and flow instruments, the SWIFT was equipped with an offgas continuous emissions monitoring system (CEMS). The CEMS measures dry volume % of O_2, CO_2, NO_x, CO, and SO_2. The CEMS was used to monitor both the PCC and SCC flue gases.

Waste feed preparation/sorting/sizing requirements:

Prior to testing, the waste feed batch size and charge rate limits had to be determined. The charge size limit was found to be 125 g of solid waste plus an equal weight of H_2O packed into a 28 g cardboard box. Water helped to slow the burning, thereby allowing a larger charge size without cause a O_2-deficient in the PCC during waste burning. Three (3) minutes was found to be a sufficient burn time.

Solid waste is charged to the kiln manually through a refractory gate. The gate is opened to allow a bucket containing the waste feed to enter the kiln and deposit the waste in the center of the rotating section. After the waste is dropped in the kiln, the bucket is withdrawn and the gate closed. The entire procedure takes about 5 s. High Btu organic liquid waste was burned in the kiln by a vortex burner. The burner replaced the natural gas burner in the PCC. The hazardous metals solution was injected directly into the center of the PCC through a H_2O-cooled atomization nozzle.

Air pollution control system components:

To simulate the CIF system, the Savannah River Technology Center provided a Model 20 Hydro-Sonic air-atomized pilot-scale scrubber and cyclone separator. Before entering the scrubber, hot combustion gases were cooled below the adiabatic saturation temperature (180°F) by a single nozzle counter-current flow quench in the duct leading to the scrubber. Stack gas samples were taken downstream of the scrubber to measured controlled emissions of particulate loading and heavy metals.

References: D.B.Burns,"Final report Consolidated Incineration Facility metals partitioning test", WSRC-TR-93-623, Westinghouse Savannah River Company, Aiken, SC (1993).

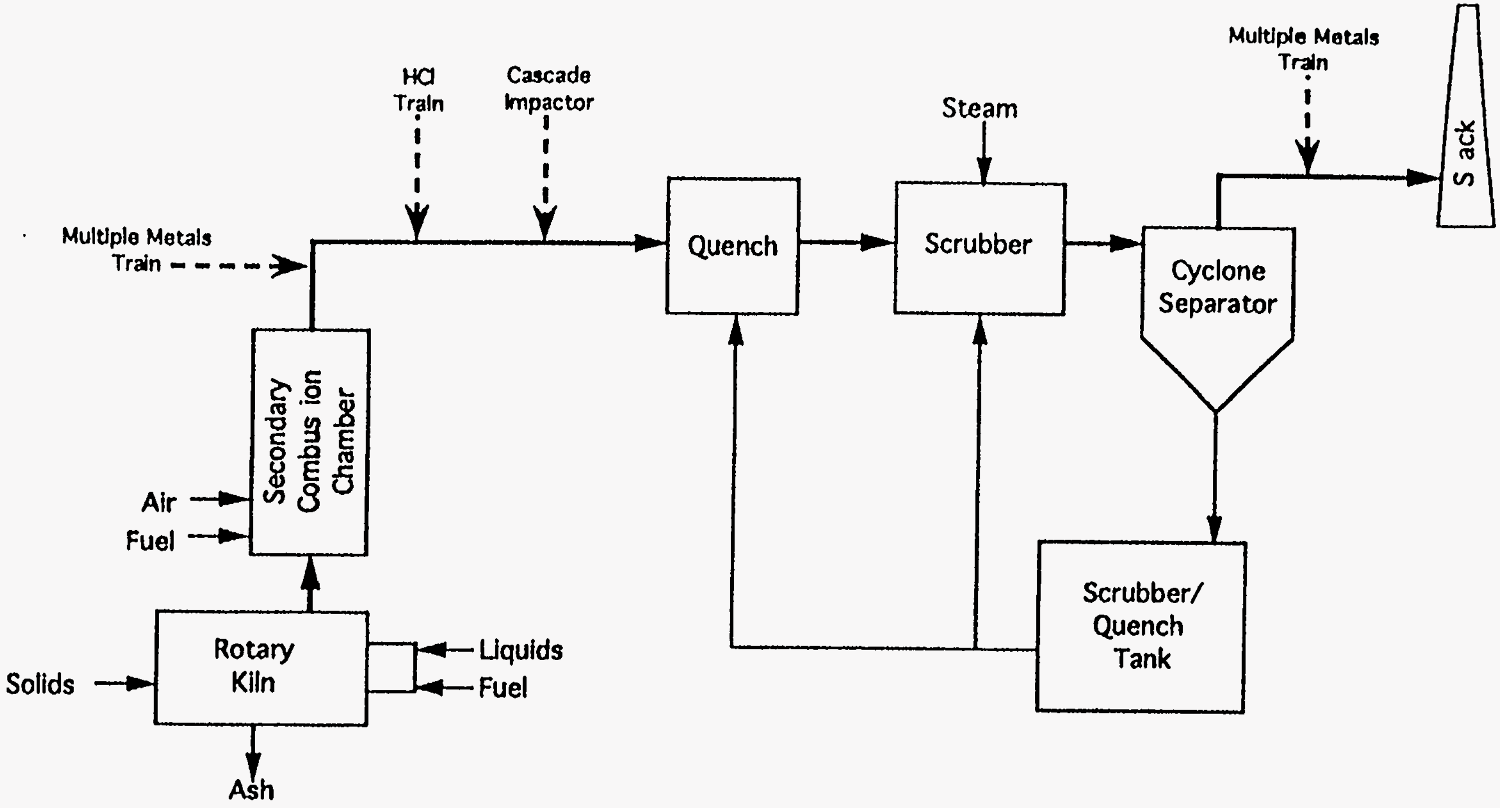


Fig. 1. EER Rotary Kiln Incinerator System. (1994)

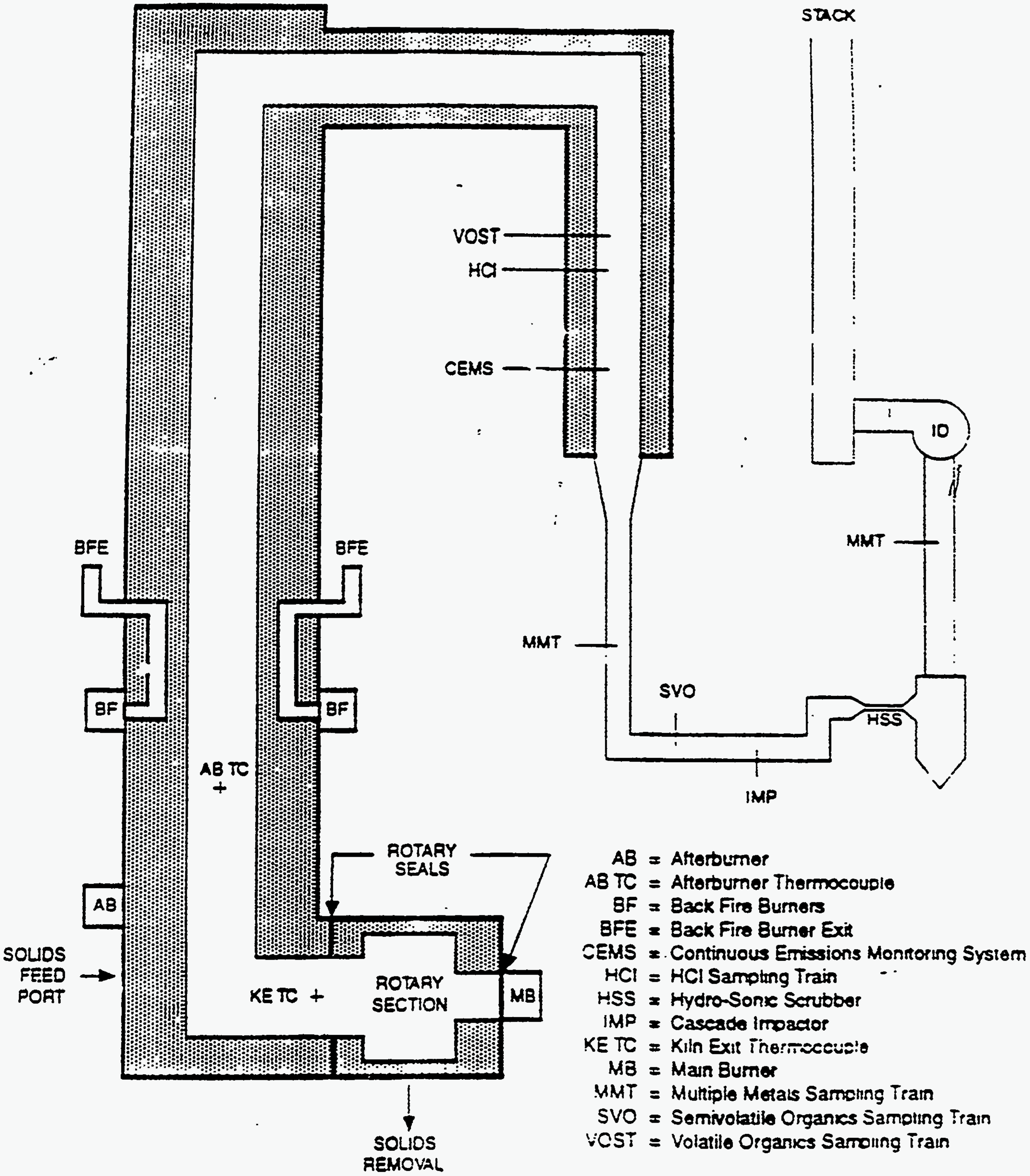


Figure 2. Solid Waste Incinerator Test Facility (SWIFT) schematic (1993).

Thermal treatment process: TSCA Mixed Waste Incinerator

Location: K-25 Site, Oak Ridge, TN

Mode of operation: Continuous; periodic shutdowns for maintenance or feed accumulation

Status: Operational

Process description/size/dimensions/materials of construction:

TSCA incinerator consists of liquid, solid, and sludge feed systems, a rotary kiln, a secondary combustion chamber (SCC), and an offgas treatment system as well as tanks and sumps for management of feeds and incinerator liquid effluents. Kiln assembly includes a rotary kiln equipped with liquid injection burners firing in the kiln, a mixing chamber and a wet ash removal system. A hydraulic ram system is used to feed solid waste into the rotary kiln. The residence time for solid waste in the kiln ranges from 1 to 1.5 hr at 850°C to 980°C. As combustion gases and solids exit the kiln, they enter a mix chamber where gas velocity is significantly reduced causing most solids to drop out into the ash handling system. The SCC is also equipped with a liquid injection burner. The combustion gas in the SCC achieves a residence time of greater than 3 s at 980°C to 1200°C.

Capacity is rated at 8800 kW (30 MBtu/hr) which is approximately 907 kg/h liquids or 454 kg/h solids. Average feed rates in FY93 and FY94 were 335 kg/h and 395 kg/h, respectively. This is about 3 million lbs/yr. The waste feeds principally contain low assay U and PCBs, although listed solvents and heavy metal containing sludges can also be incinerated.

Waste feed preparation/sorting/sizing requirements:

Waste materials are held in a storage area that includes a tank farm and shredding apparatus. Liquid waste is blended and prepared in the tank farm consisting of 15 tanks (341,000 L capacity).
Current burn plans (1991) call for incinerating the liquid waste inventory first, with minimal processing of solid wastes at this time.

Air pollution control system components:

The offgas treatment system includes a water spray quench tower, a venturi scrubber, a demister, a packed-column gas absorber followed by a two-stage ionizing wet scrubber (IWS), an induced draft (ID) fan, a 30-ft high, 52-in ID, exit stack. In the quench tower, the gas is cooled to 86°C. The venturi scrubber removes particulates over 1 μm. The packed bed scrubber removes acidic gas with a caustic/pH control system using a 20% caustic system. The IWS removes particulates less than 1 μm. The metal alloy ID fan maintains a negative pressure on the offgas system.

Blowdown liquid from the scrubber is sent to 30,000-gal purge tanks and then to a treatment facility for neutralization and solids removal. Wastewater will be processed through carbon beds to remove any organics, if necessary.

References:

L.V. Gibson et al., "Partitioning of Sr and Cs in the TSCA incinerator", *Proceedings of 1994 International Incineration Conf.*, Houston, TX (1994).

P. Siebach, B. Westich, and A. Murray, "Radioactive mixed waste incineration at the US DOE", *Proceedings 1992 International Incineration Conf.*, Albuquerque, NM (1992).

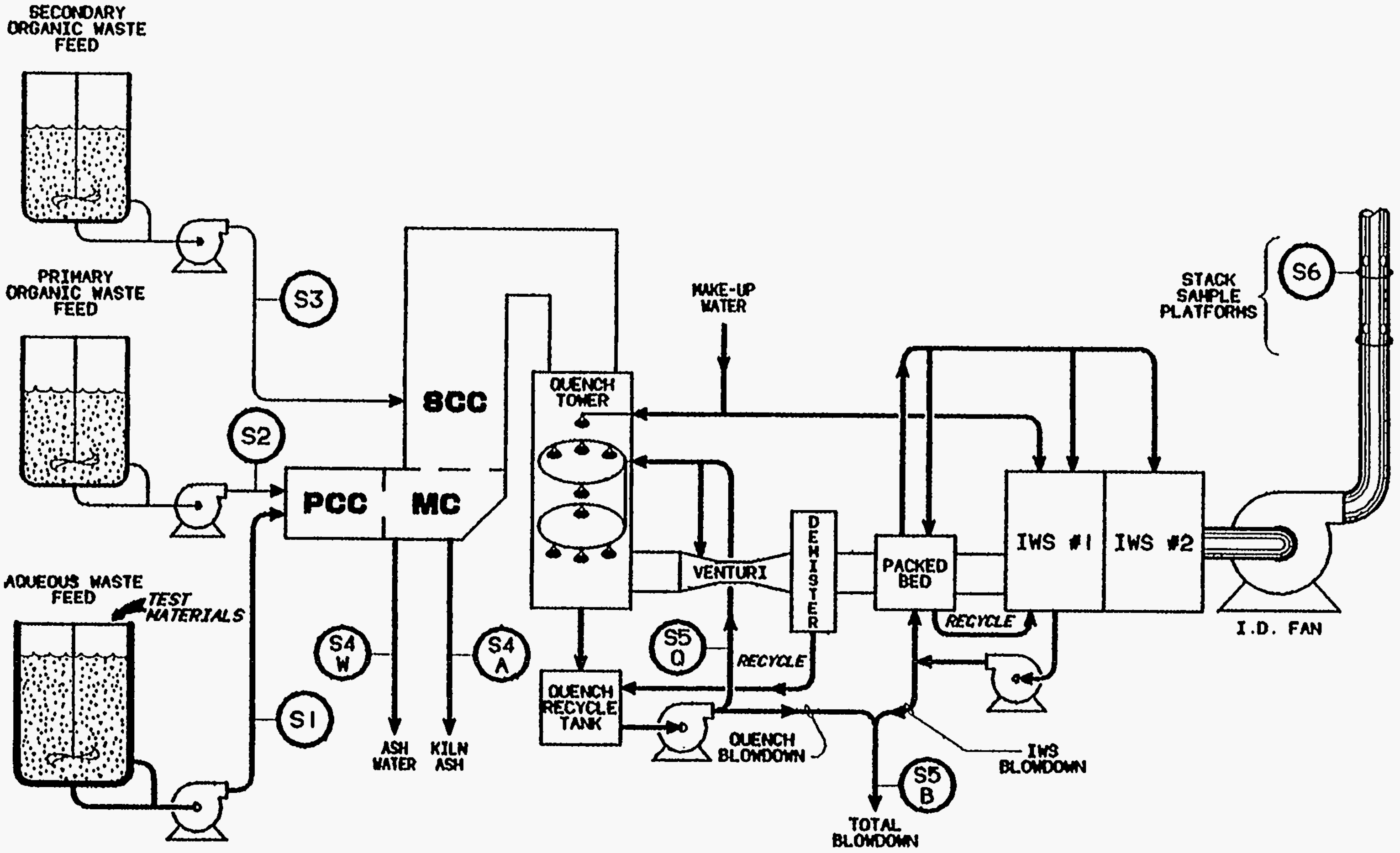


Fig. 1. TSCA incinerator process configuration and sampling points for partitioning study.

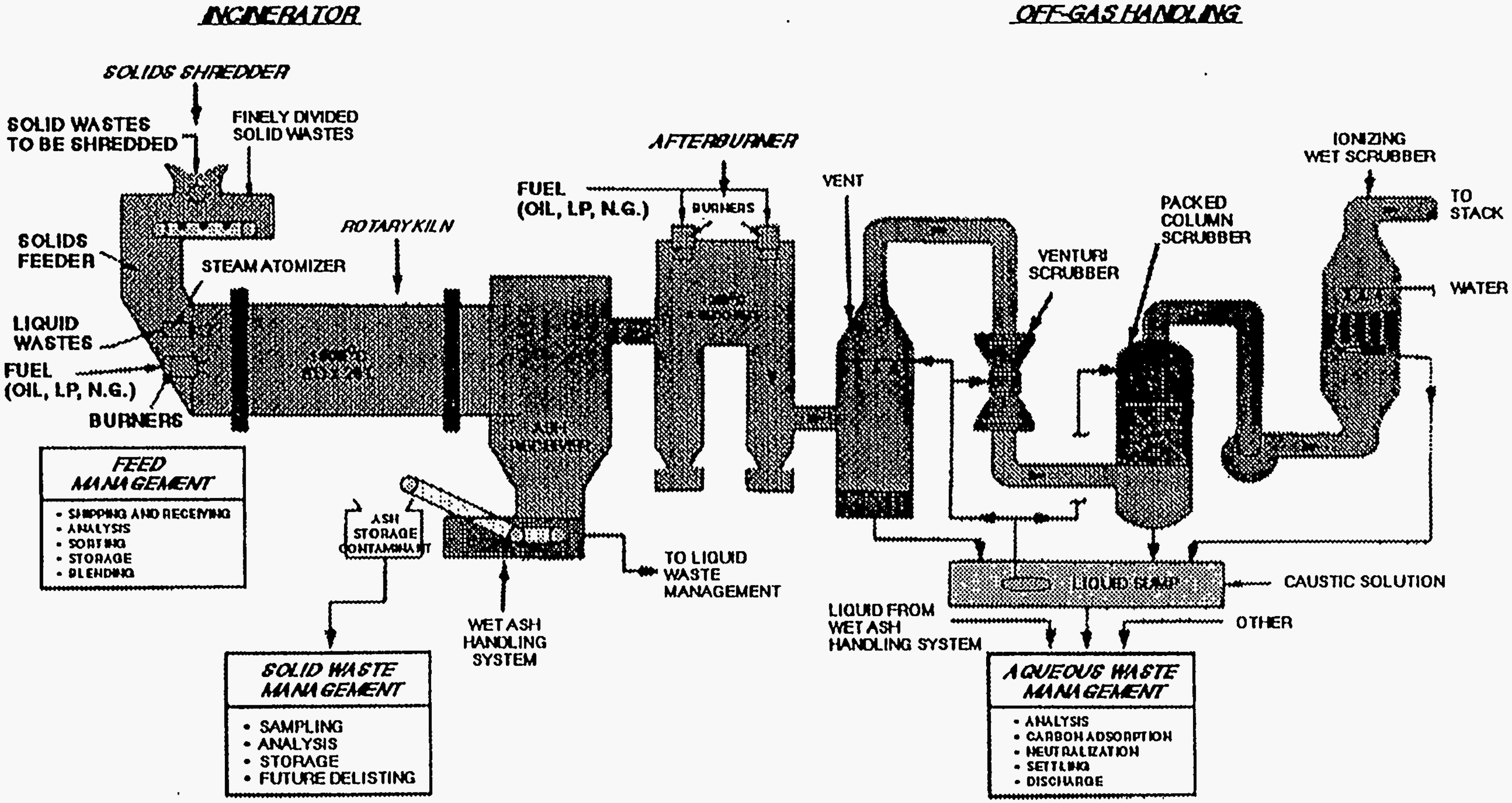


Fig. 2. The Oak Ridge toxic substances control act (TSCA) incinerator.

Thermal treatment process: SRS Consolidated Incineration Facility (CIF)

Location: Savannah River Site (SRS)

Mode of operation (continuous,batch): Continuous for liquid waste, batch for solid waste

Status: Operation scheduled (as of 1995) to begin in 1996

Process description/size/dimensions/materials of construction:

The CIF is designed for treatment of liquid and solid low-level radioactive, mixed and RCRA hazardous wastes. The incineration system consists of a 13 MBtu rotary kiln and a 5 MBtu secondary combustion chamber (SCC). The kiln is slightly tilted from the horizontal with an 8-ft ID, 25-ft length, and 0.2 to 2.0 rpm range of rotation speed. The SCC has a 7-ft ID and a 21-ft vertical length. The kiln has 4 burners mounted on its front face. Three (3) high intensity vortex burners will be used for continuous feed of organic liquid wastes, aqueous liquid wastes, and, when necessary, auxiliary fuel oil to maintain minimum operating temperature. Normal operating temperatures are 1832°F (1000°C) in the rotary kiln at 100% excess air and 2012°F (1100°C) in the SCC at 80% excess air. A ram feeder will be used for batch feed of solid wastes. Solids retention time in the kiln ranges from 30 to 90 min. An offgas residence time of 2 s is required in the SCC. No. 2 fuel oil burners are used in the kiln and SCC for startup, shutdown, idling and temperature control.

As of 1995, the CIF was under construction and scheduled to begin in 1996. A series of tests were performed by Energy and Environmental Research on its Solid Waste Incineration Test Facility (SWIFT) pilot-scale rotary kiln. In addition, a number of modeling efforts were made to predict incinerator performance and thermodynamic calculations were performed to estimate metals/radionuclide partitioning.

Waste feed preparation/sorting/sizing requirements:

Expected wastes for incineration are divided into 4 categories: solid waste, high heating value (HHV) liquid waste, low heating value (LHV) liquid waste, and Defense Waste Processing Facility (DWPF) waste. Based on a limited number of chemical analyses of CIF wastes and projection of waste generation, an overall waste feed elemental composition is assume: 79% (mass) C, 10% H, 5% O, 4.7% ash (Al, Si, S, Fe), 1% Cl, 0.3% toxic metals, and trace amounts of radionuclides. Ten (10) toxic metals and 19 radionuclides have been identified as potentially present in the waste. Maximum concentrations in each feed stream to the CIF have been determined.

Air pollution control system components:

SCC offgas is cooled to saturation in a liquid-recirculating quench. Particulates and acid gases in the quench offgas are removed by.a steam-atomized scrubber. The liquid/gas separation of the scrubbing mixture takes place in a cyclone scrubber. A mist eliminator removes entrained water droplets. Saturated scrubber offgas is reheated and filtered through HEPA filters prior to atmospheric discharge.

References:

T. Hang, "Process modeling study of CIF incinerator", WSRC-MS-94-0655, Westinghouse Savannah River Company, 1994.

M.G. Robinson et al., "Air emissions estimate for the Savannah River Site Consolidated Incineration Facility", *Proceedings 1995 International Incineration Conference*, Bellevue, WA (1995).

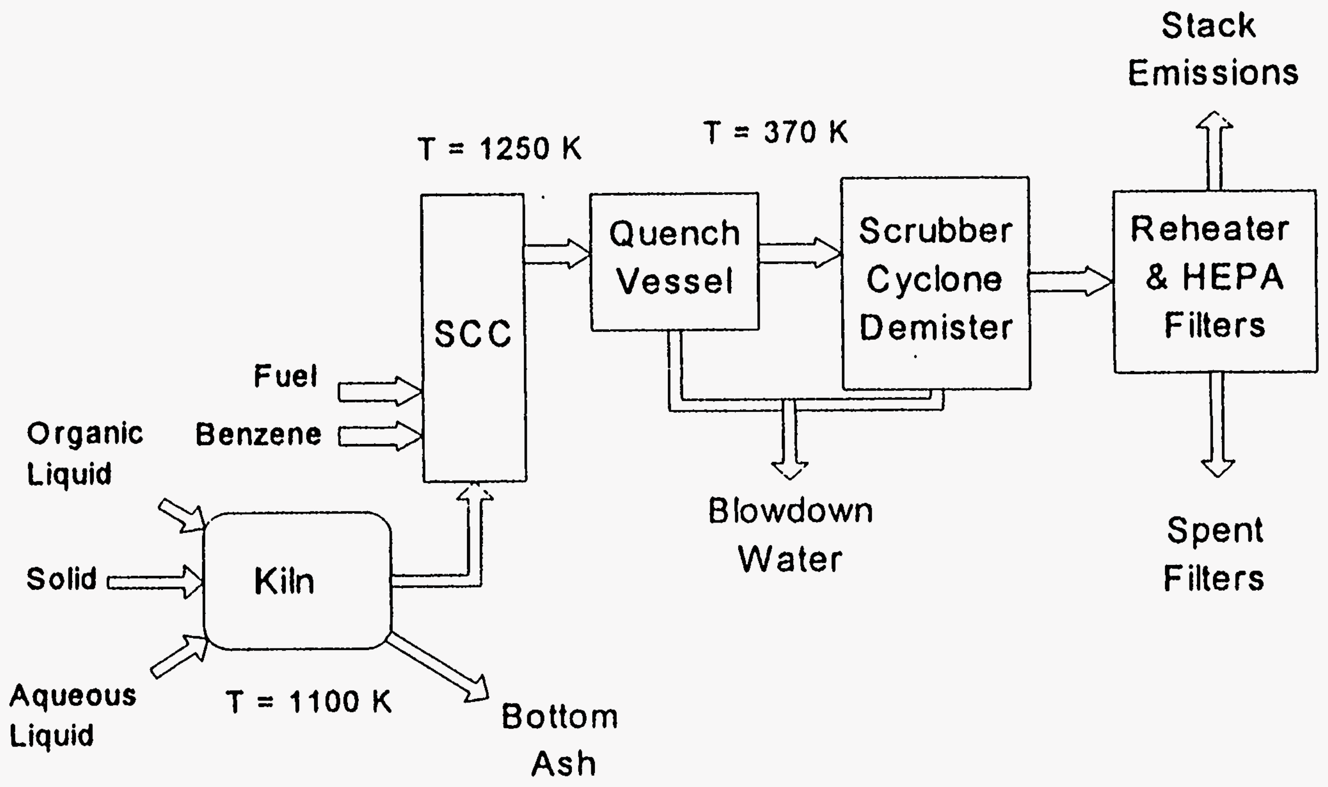


Fig. 1. Schematic of CIF.

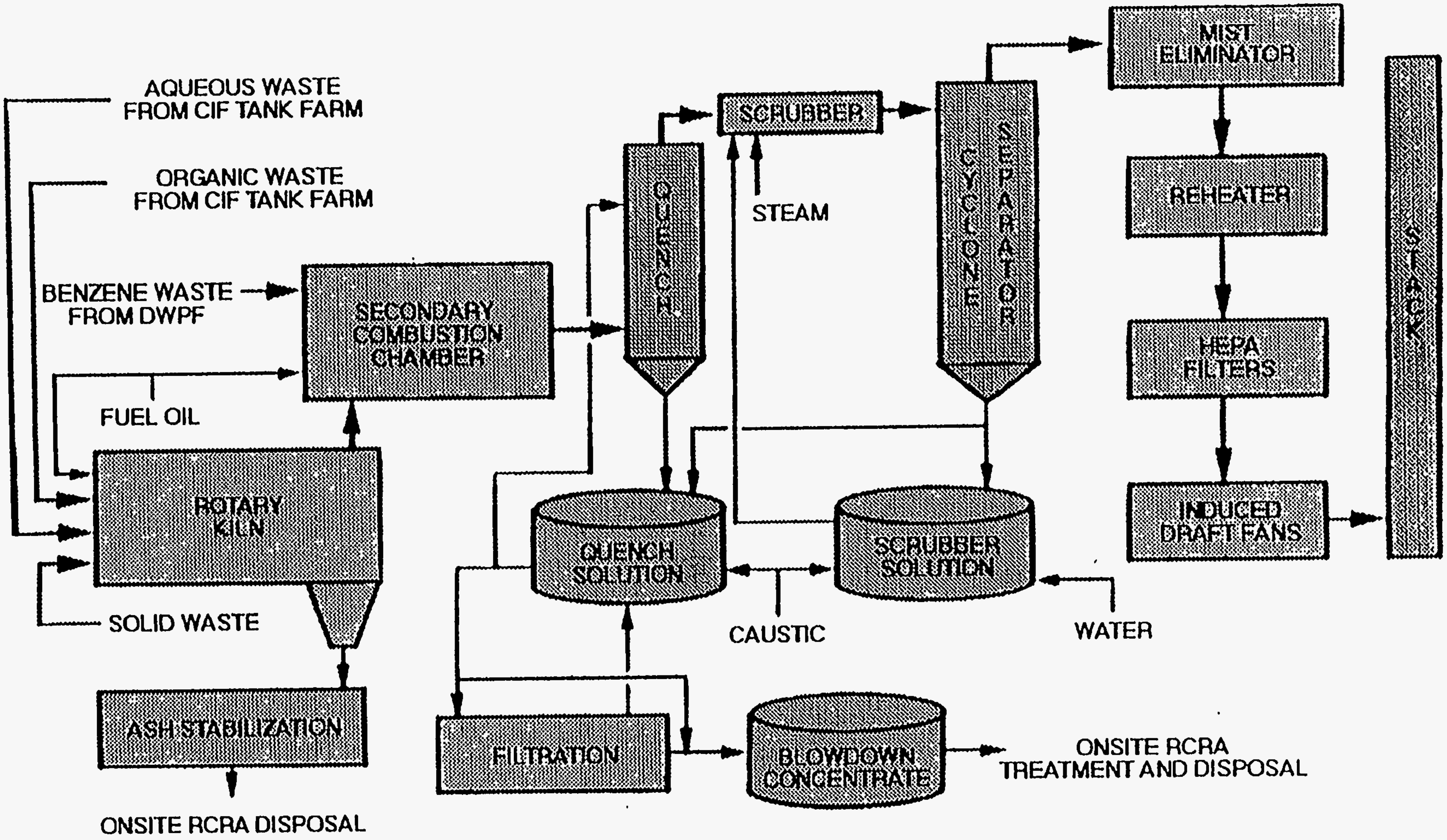


Fig. 6. Consolidated incineration facility - process diagram.

Thermal treatment process: EPA Incineration Research Facility (IRF)

Location: Jefferson, AK

Mode of operation (continuous,batch): Continuous for specific campaigns

Status: Operational

Process description/size/dimensions/materials of construction:

The rotary kiln incinerator system consists of a primary combustion chamber (PCC), a transition section, and a fired afterburner chamber. Kiln is constructed of 0.63-cm thick cold rolled steel and lined with high alumina castable refractory. Its dimensions are IL 2.13 m, ID 0.95 m, and a chamber volume 1.74 m^3. Its maximum operating temperature is 900°C. Rotation speed of the rotary kiln ranges between 0.2 to 1.5 rpm. Solids residence time is approximately 1 hour at a turn speed of 0.2 rpm. The afterburner is of similar construction and its dimensions are IL 2.74 m, ID 0.91 m, and a chamber volume of 1.8 m^3. Its maximum operating temperature is 1200°C. Gas residence time ranges between 1.2 to 2.5 s depending on gas temperature and excess air.

Waste feed preparation/sorting/sizing requirements:

Since this is a test facility, waste preparation varies depending on the waste type incinerated. Examples of materials incinerated include Superfund site soils, synthetically prepared clay-metal mixtures, and simulated low-level wastes.

Air pollution control system components:

Offgas exiting the afterburner flows through a quench section followed by a primary APCS. The primary APCS consisted of a venturi scrubber followed by a packed-column scrubber. Downstream of the primary APCS, a backup secondary APCS, comprised of a demister, an activated-carbon adsorber, and a HEPA filter, is in place.

In one case, a Calvert flux-force/condensation scrubber system was installed. This system consisted of a condenser absorber, collision scrubber, an entrainment separator, and a wet electrostatic precipitator followed by another entrainment separator.

References:

S. Venkatesh, L.R. Waterland, and J.W. Lee, "Trace metals partitioning in a rotary kiln incinerator", *Proceedings 1994 International Incineration Conference*, Houston, TX (1994).

L.R. Waterland and S. Venkatesh, "Dioxin emission measurements from a rotary kiln incinerator", *Proceedings 1994 International Incineration Conference*, Houston, TX (1994).

L.R. Waterland, *Operations and Research at the USEPA IRF - Annual Report for FY93*, EPA/600/R-94/091, Acurex Environmental Corp., Mountain View, CA (1993).

D.J. Fournier et al.,"The fate of trace metals in a rotary kiln incinerator with a venturi/packed column scrubber - Volume 1", Report No. EPA/600/2-90/043a (Sept 1990).

D.J. Fournier et al.,"The fate of trace metals in a rotary kiln incinerator with a single-stage ionizing wet scrubber - Volume 1", Report No. EPA/600/2-91/032a (July 1991).

"IRF - Incineration Research Facility", U. S. Environmental Protection Agency, Cincinnati, OH, EPA/600/M-89/027 (November 1989)

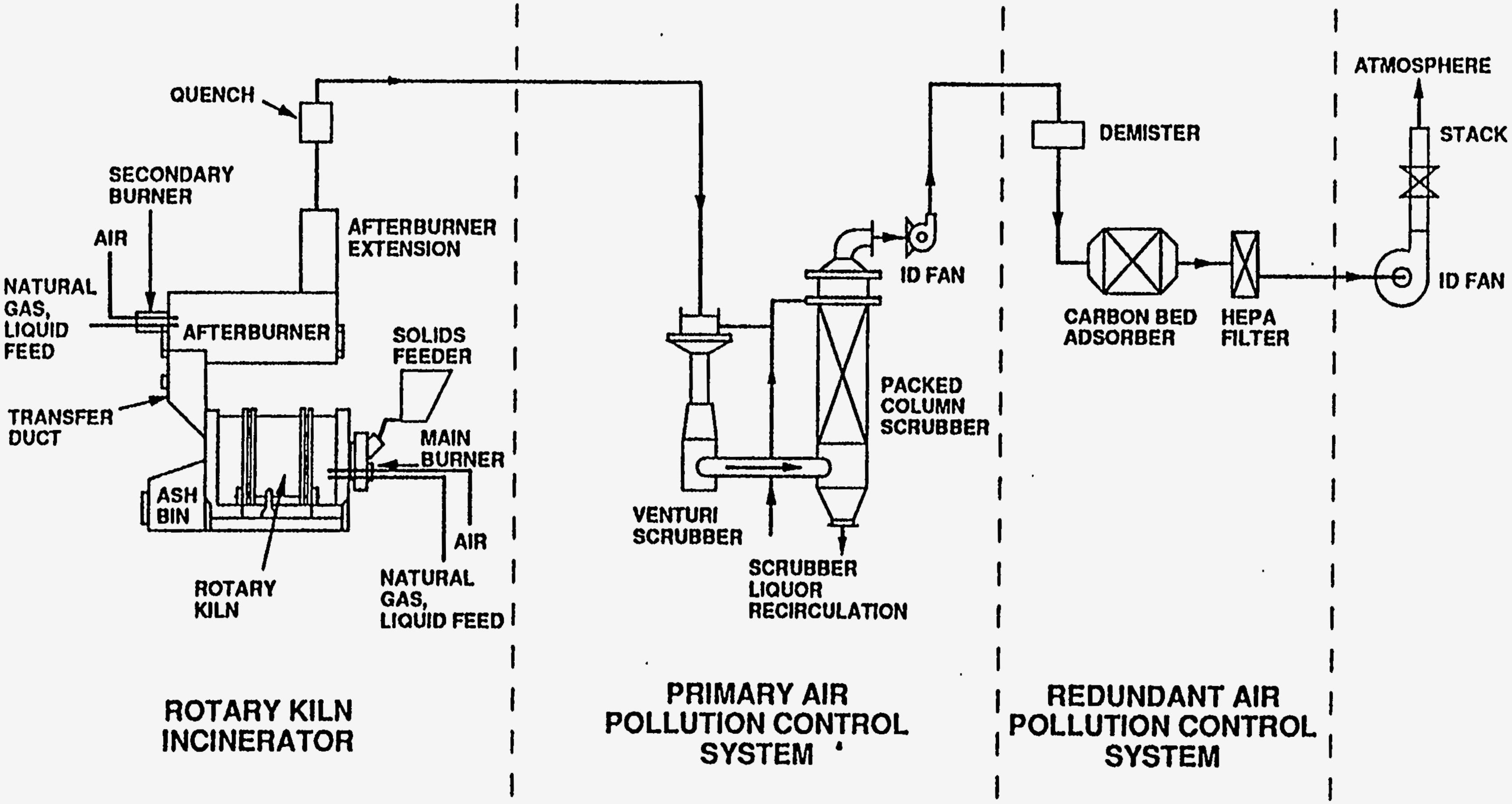


Figure 1. Schematic of the IRF rotary kiln incineration system for dioxin incineration (1994).

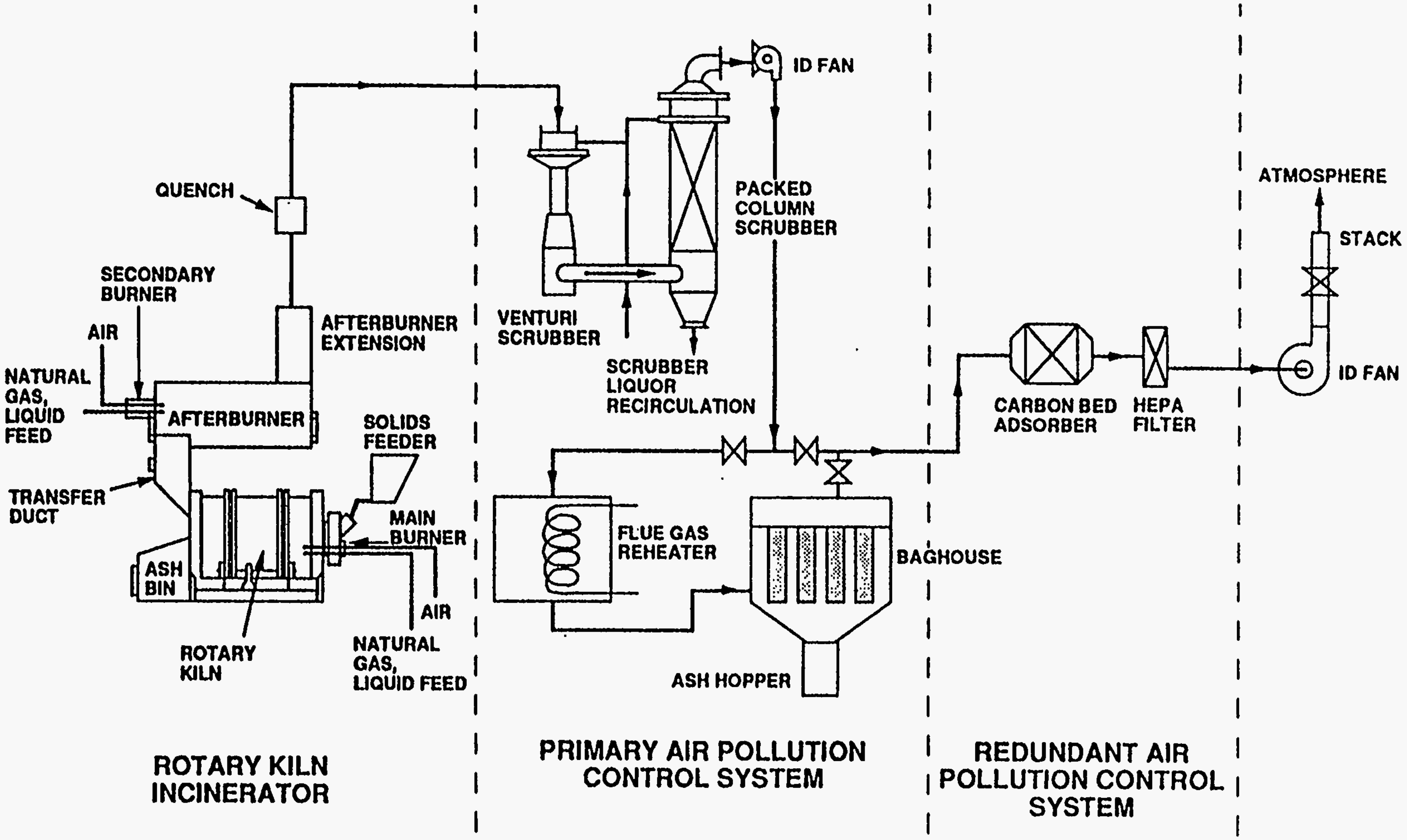


Figure 2. Schematic of IRF rotary kiln incineration system for metals partitioning tests (1994).

Thermal treatment process: EPA Rotary Kiln Incinerator Simulator (RKIS)

Location: Research Triangle Park, NC

Mode of operation (continuous,batch): Batch and continuous

Status: Operational

Process description/size/dimensions/materials of construction:

The EPA rotary kiln incinerator simulator (RKIS) is a flexible bench-scale rotary kiln incineration system fitted with an innovative secondary combustion chamber (SCC) or afterburner. The bench-scale simulator that exhibits the salient features of full-scale units with thermal ratings 20 to 40 times larger. The simulator matches the volumetric heat release, gas-phase residence time, and temperature profile of many full-scale units, and yet is flexible enough to allow parametric testing. The RKIS is permitted with a RCRA RD&D permit which allows a variety of surrogate or real hazardous waste materials to be burned. Primary areas of interest for this facility would be in examining phenomena associated with rotary kiln incineration of organic or metal containing wastes. The RKIS is equipped with two sets of continuous emission monitors that can allow simultaneous sampling of O_2, CO, CO_2, NO, and hydrocarbons upstream and downstream of the afterburners, including a computer-aided data acquisition system that provides real-time indicators of all monitored variables.

The main burner (PCC) firing rate is 73 kW (250,000 Btu/hr) and the afterburner firing rate is also 73 kW (250,000 Btu/hr). The PCC kiln diameter is 30 in. ID with a 24-in. long cylindrical recess. The SCC diameter is 24 in. along the plug flow section. Solid residence time can be up to 1 hr.

Fundamental combustion research is conducted at RTP. Application testing of HWIs is/was performed at the EPA IRF in Jefferson, AK.

Waste feed preparation/sorting/sizing requirements:

Batch charges generally consist of 1-qt containers but other incinerable solids can be fed continuously. For soil experiments, 1 gal of material produces approximately a 2% fill fraction of the kiln chamber.

Air pollution control system components:

References:

J.H. Wasser, 1991, *Ongoing Fundamental Hazardous Waste Incineration Research at EPA/RTP Facility*, EPA/600/D-91/108, PB91-196089, USEPA, Research Triangle Park, NC.

W.P. Linak et al., 1987, On the Occurrence of transient puffs in a rotary kiln incinerator simulator I. Prototype solid plastic wastes. *JAPCA*, **37**(1), 54-65.

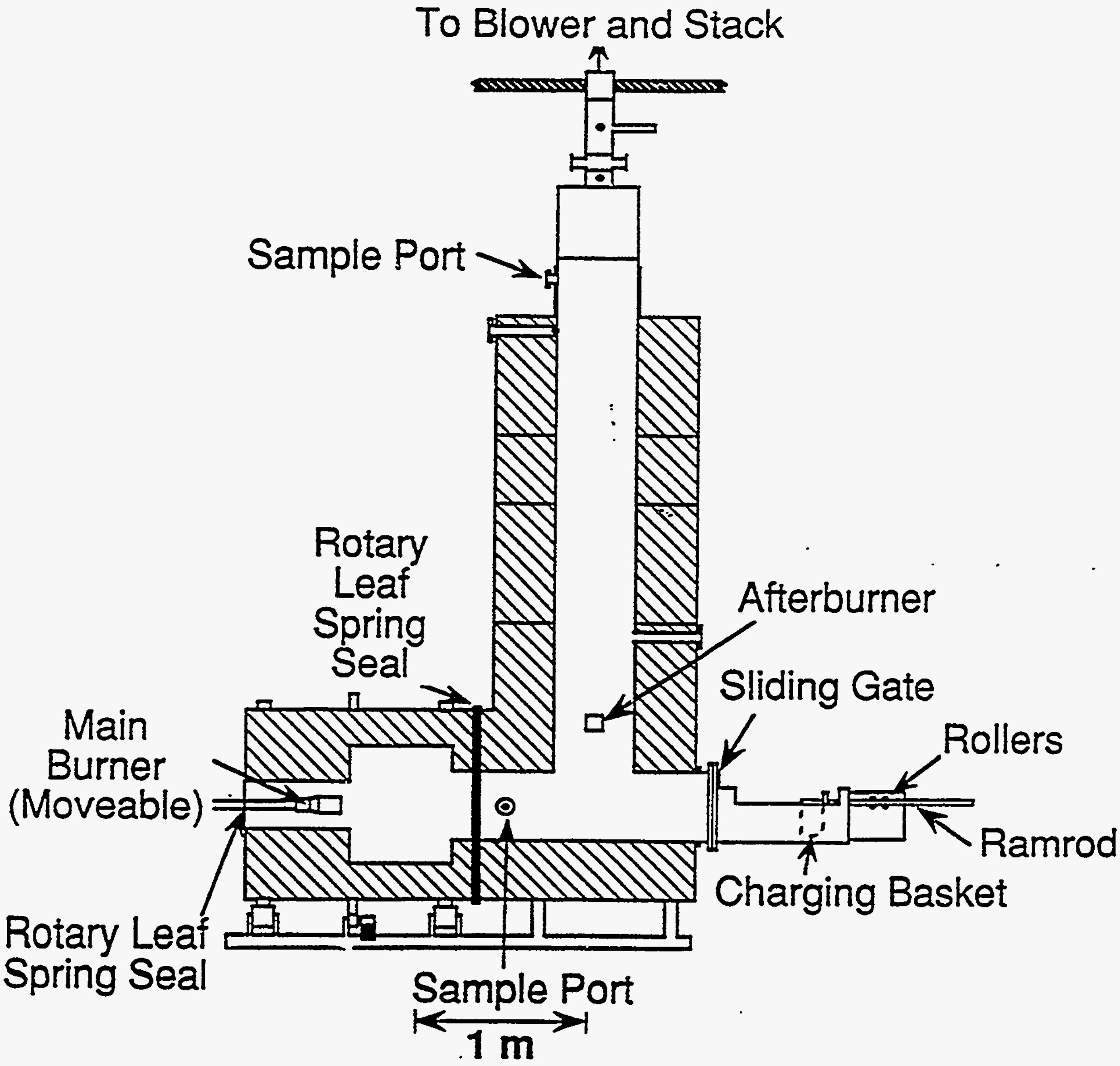


Figure 1. Rotary Kiln Incinerator Simulator

Thermal treatment process: Rollins Environmental Services (RES)

Location: Deer Park, TX

Mode of operation (continuous,batch): continuous

Status: operational

Process description/size/dimensions/materials of construction:

The process described in 1977 consisted of a rotary kiln and a liquid injection burner, both feeding a common afterburner. Total heat release of the system is 110 MBtu/hr (32.2 MW). The kiln is 4.9 m (16 ft) long and 3.2 m (10.5 ft) in diameter. The afterburner, or secondary combustion chamber (SCC), was horizontal and 10.6 m (35 ft) long, 4.0 m (13 ft) high, and 4.3 m (14 ft) wide. Operating temperatures in the kiln and SCC of 2372°F (1300°C) and 2732°F (1500°C), respectively, were reported.

In a 1994 document, the Deer Park facility was described differently. The rotary kiln was 10.7 m (35 ft) long with a diameter of 3.7 m (12 ft). The SCC was 12.2 m (40 ft) high with a diameter of 6.1 m (20 ft). The thermal duty of the kiln was 80 MBtu/hr (23.4 MW) and the duty of the SCC was 100 MBtu/hr (29.3 MW). The average kiln and SCC temperatures performed in 3 trial burns were 2055°F (1124°C) and 2196°F (1202°C).

Waste feed preparation/sorting/sizing requirements:

Air pollution control system components:

In 1977, the APCS contained a venturi scrubber, a wet scrubber using lime to neutralize acid gases, absorption trays, and a mist eliminator before exiting the stack.

In 1994, the APCS consisted of a quench tower, venturi scrubber, packed absorber, and a collision scrubber.

References:

Ackerman D. et al., "Destroying chemical wastes in commercial scale incinerators, Facility report No. 6. Rollins Environmental Services, Inc., Deer Park, Texas", TRW Defense and Space Systems Group, Report No. EPA/SW-122C.5, (1977).

Ho T.C. et al., "Analysis of incinerator performance and metal emissions from recent trial and test burns", *Haz. Waste & Haz. Mat.*, 11(1), 53-70 (1994).

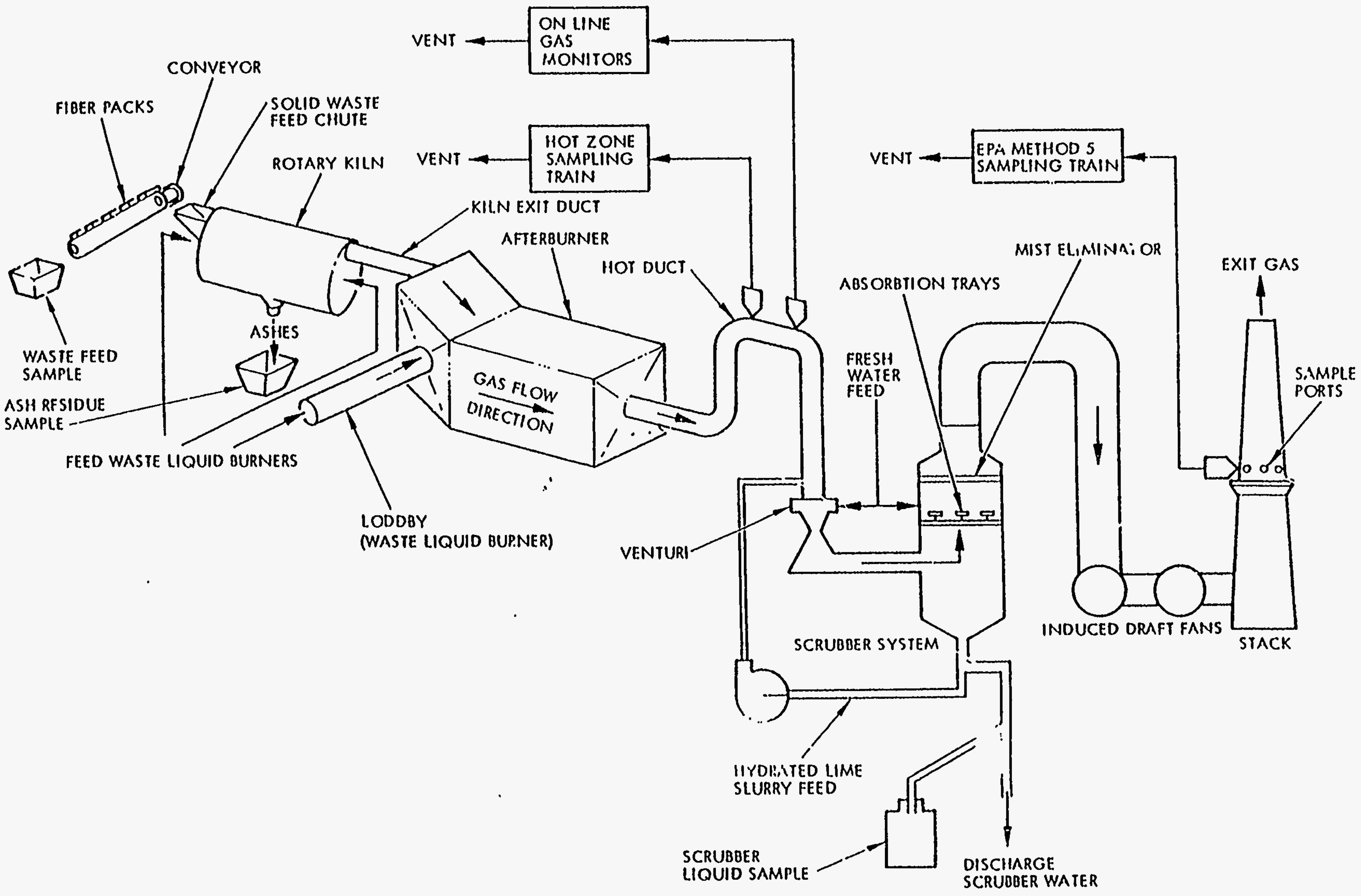


Figure 1. Schematic of Rollins Environmental Services incinerator at Deer Park, TX (1977).

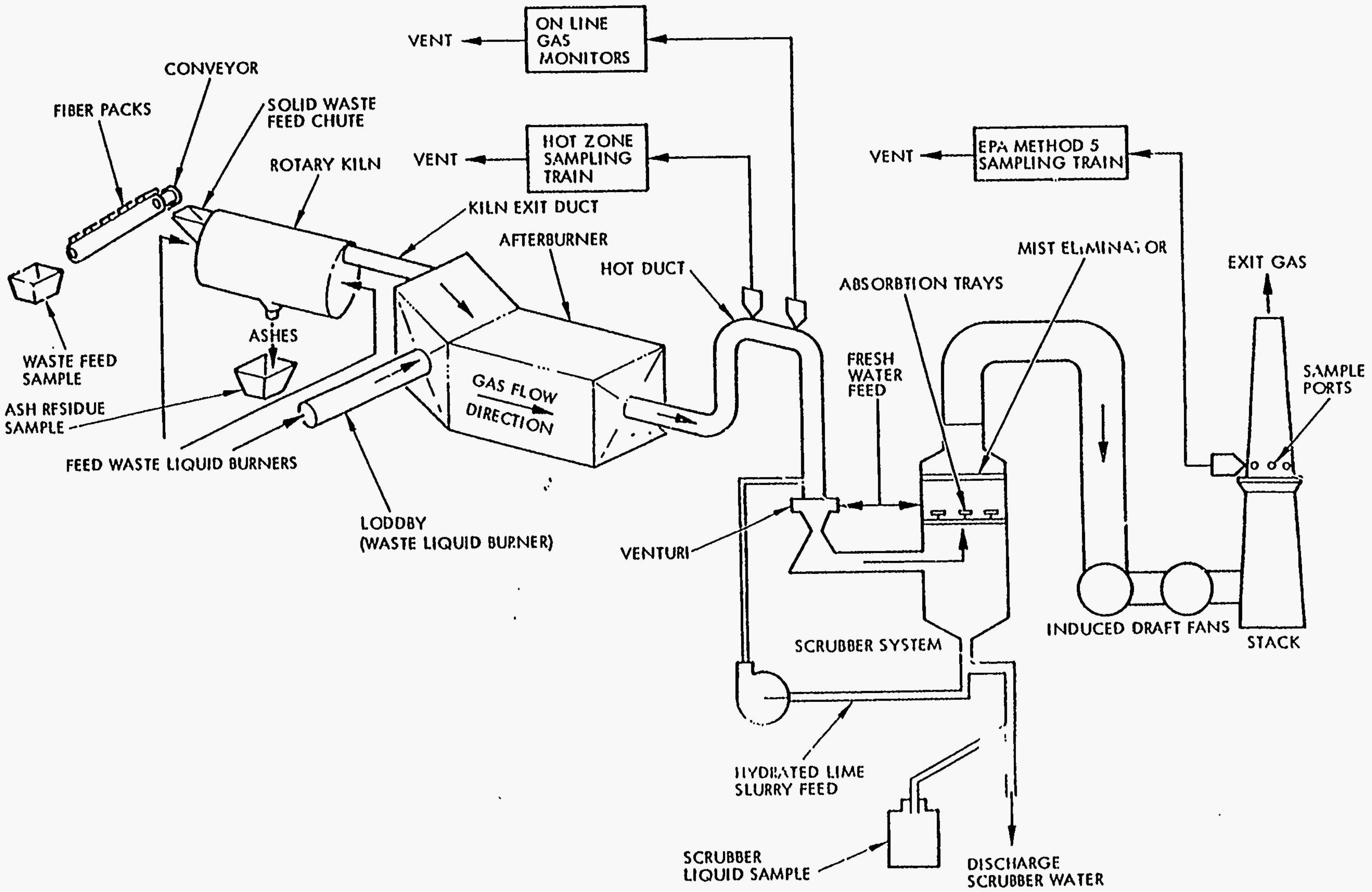


Figure 1. Schematic of Rollins Environmental Services incinerator at Deer Park, TX (1977).

Thermal treatment process: Multi-purpose Incinerating Melter System (MIMS); Oscillating, horizontal kiln

Location: Japan

Mode of operation (continuous,batch): Semi-continuous

Status: Demonstration unit constructed in 1989
Additional test data scheduled to be completed by 1992

Process description/size/dimensions/materials of construction:

The incinerator has two major parts: a cylindrical oscillating kiln and a secondary combustion chamber (SCC). Wastes are fed into the horizontal kiln through a waste feeder and incinerated or melted at a temperature range between 1000°C and 1500°C which is generated by a LPG burner. The kiln is designed to oscillate clockwise and counterclockwise alternatively up to ±90° to stir wastes and molten materials. The kiln seals are conventional mechanical seals attached between oscillating kiln barrel and the stationary members on each end. A specially designed Zr-Cr rich castable refractory is lines the kiln. This material exhibits excellent thermal shock and corrosion resistance from molten materials. On one end of the kiln, there is a wall made of the castable refractory to serve as a dam to hold in wastes and molten materials and provide them with an arbitrary residence time. The kiln is rotated at the appropriate time to bring to discharge the melt through an opening in the dam. The gases, vapors, and particulates in the offgas pass through the SCC designed as a vertical shaft without internal elements.

In a demonstration unit, 10 kg of simulated waste was fed intermittently to the kiln in every batch operation.

Waste feed preparation/sorting/sizing requirements:

The MIMS process accepts a wide variety of wastes without segregation or pretreatment. As a result, it can handle noncombustible as well as combustible materials.

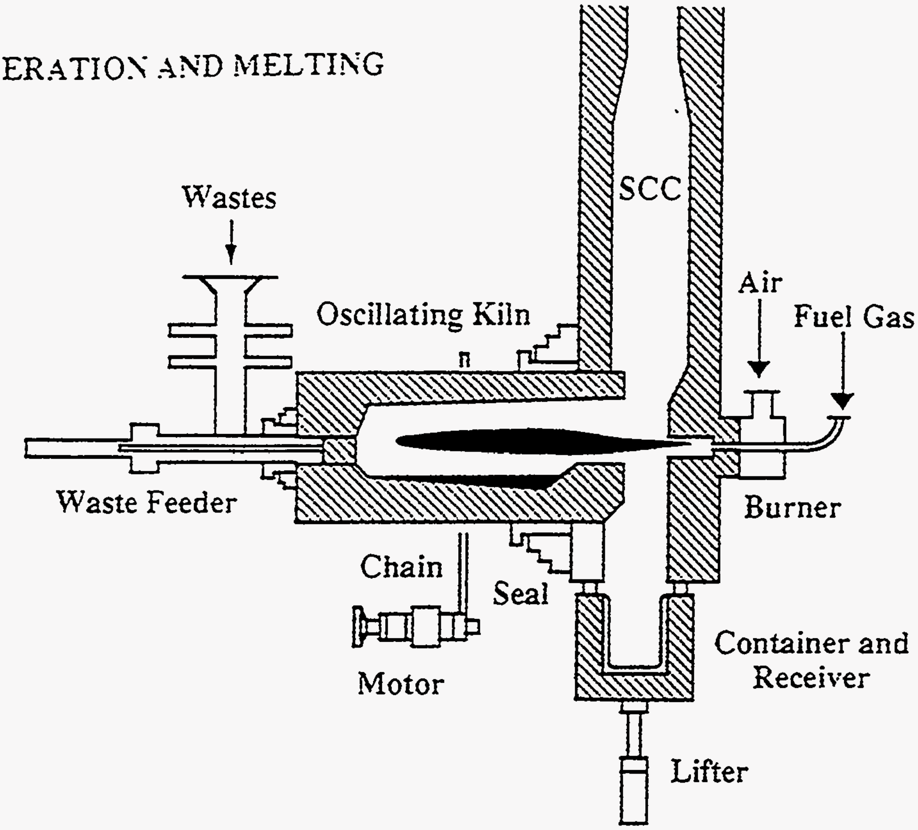
Air pollution control system components:

The offgas treatment train consists of jet-bubbling scrubber, a mist eliminator, a prefilter and a HEPA filter. In the scrubber, gas is directly in contact with scrubbing solution and forms a jet bubbling layer in which most particulates and condensable gases are removed. The noncondensed fraction is cooled and leaves the solution saturated with water vapor at 323 K which is maintained using an external heat exchanger. The scrubber offgas passes through a demister and is reheated to 353 K to prevent condensation in the filters. The offgas then passes through a prefilter and then a HEPA filter before being released into the atmosphere.

References:

H. Miyao et al.,"Demonstration of a new volume reduction technique for a wide variety of wastes", *Proceedings of Waste Management '92*, Tucson, AZ (1992).

INCINERATION AND MELTING



DISCHARGE OF MOLTEN MATERIAL

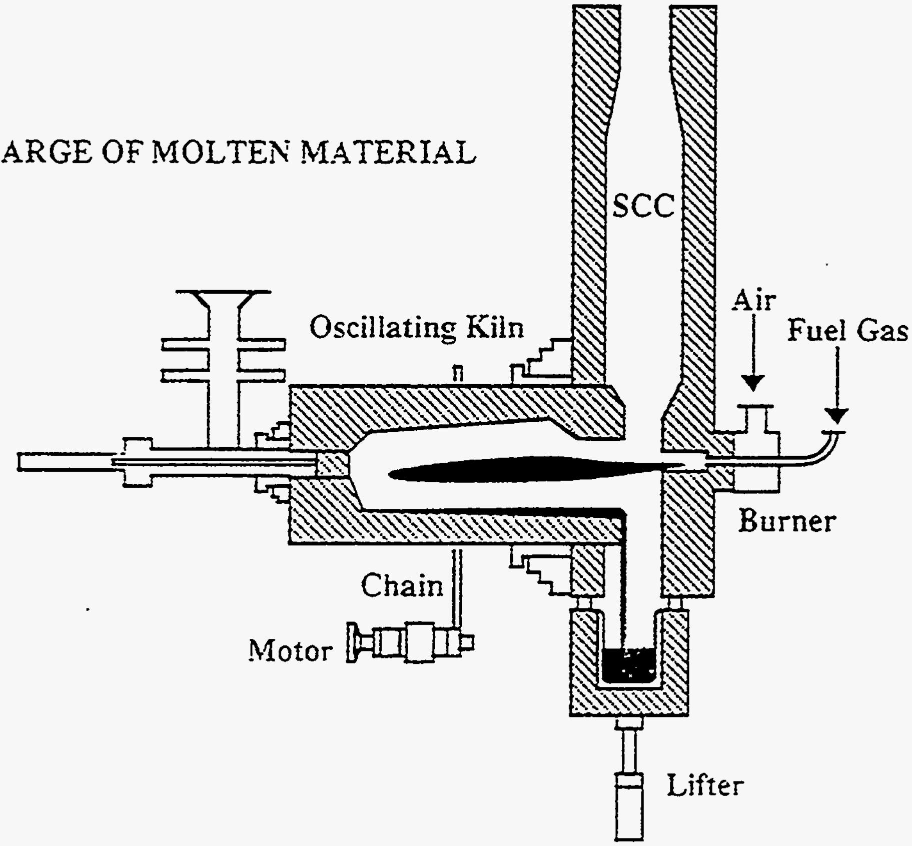


Fig. 1 Schematic drawing of the incinerating melter

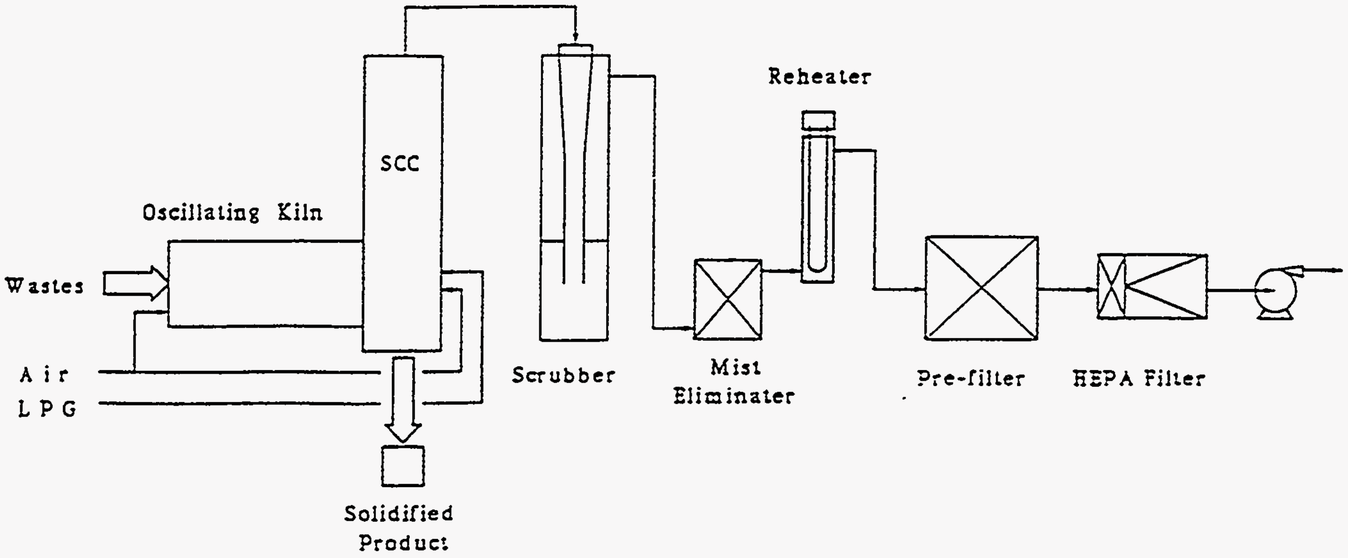


Fig.2 A process flow of the demonstration test unit

Thermal treatment process: APTUS/Rollins HWI (Coffeyville, KS)

Location: Coffeyville, Kansas

Mode of operation (continuous,batch): Continuous

Status: Operational (as of 1989)

Process description/size/dimensions/materials of construction:

The Aptus facility includes a HW horizontal slagging rotary kiln incinerator with a vertical afterburner and air pollution control system. Kiln temperature ranges between 1600-1900°F (870-1040°C). The afterburner temperature 2200°F (1200°C). Solid waste feedrates ranged between 1500-3900 lb/h (680-1770 kg/h). Total heat input is 61.9 MBtu/h (18.1 MW). Solid residence times are between 30-45 minutes. The kiln provides a gas residence time of 0.8 s. Slag discharges from the lower end of the kiln into a quench tank where the slag is removed.

Waste feed preparation/sorting/sizing requirements:

A variety of waste may be fed to the incinerator: PCB liquids, PCB-containing capacitors, contaminated soil, aqueous waste and debris. PCB-containing capacitors may be shredded. A conveyor feeds drummed material to an elevator where the drums are emptied automatically. Solid waste and containerized wastes are fed to the kiln through the solids feed chute. The front wall of the kiln also incorporates a direct-burn waste atomizing nozzle and a sludge lance. Aqueous wastes and blended combustible liquid wastes can be mixed and introduced into the kiln through the nozzle. The sludge lance can be used to introduce sludge suspended wastes into the kiln.

Air pollution control system components:

The APCS consisted of a spray dryer, fabric filter, and a wet scrubber followed by a stack. The spray dryer brine feed rate is approximately 80 gpm. There are no liquid discharges from the wet scrubbing systems. The exiting gas stream temperature is 460°C. The baghouse is a 4-chambered unit with vertically mounted filter sacks in each chamber.

References:

R.G. Rizeq et al.,"Predictions of metals emissions from hazardous waste incinerators and comparison to test results from a full scale facility", *Proceedings of the 1993 Incineration Conference*, Knoxville, TN (1993).

Radian Corp., "A Performance Test on a Spray Dryer, Fabric Filter, and Wet Scrubber System", Draft Test Report, Document Control Number: 89-232-011-034-06, U.S. Environmental Protection Agency, Washington, D.C. (1989).

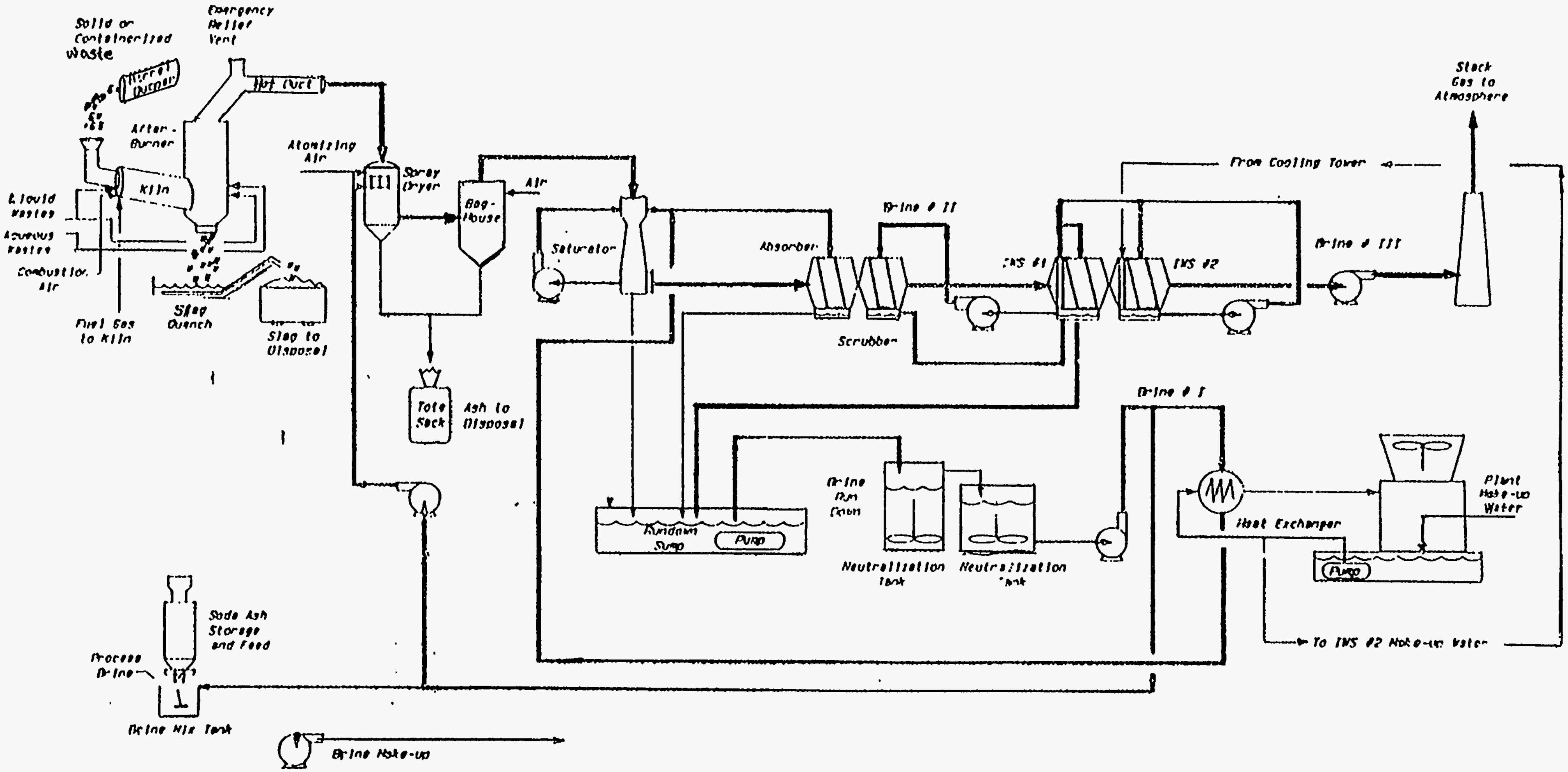


Figure 2-1. APTUS Incineration System
Coffeyville, Kansas

Thermal treatment process: APTUS/Rollins HWI (Aragonite, UT)

Location: Aragonite, UT

Mode of operation (continuous,batch): Continuous

Status: Operational (as of 1993)

Process description/size/dimensions/materials of construction:

The Aptus-Aragonite incineration system consists of a horizontal slagging rotary kiln with an afterburner chamber followed by a gas conditioning and air pollution control train. The system is designed for a nominal heat release of 120 MBtu/h (35.1 MW). The kiln is 4.4 m in diameter and 12 m in length. The kiln and afterburner are constructed of steel and refractory lined with high alumina brick. The waste feed system is capable of handling liquids, solids, and sludges. Both bulk solid waste and containerized waste are fed to the kiln through a feed chute. Liquid wastes and auxiliary fuel are fed to the system through combination burners located on the kiln front wall and in the afterburner. The liquid is air atomized.

Waste feed preparation/sorting/sizing requirements:

Air pollution control system components:

The APCS consisted of a spray dryer, baghouse, saturator, wet scrubber and wet electrostatic precipitator.

References:

F. Murray, H. Lee, and S. Barber, "The experience of a hazardous waste incinerator trial burn", *Proceedings of the 1993 Incineration Conference*, Knoxville, TN (1993).

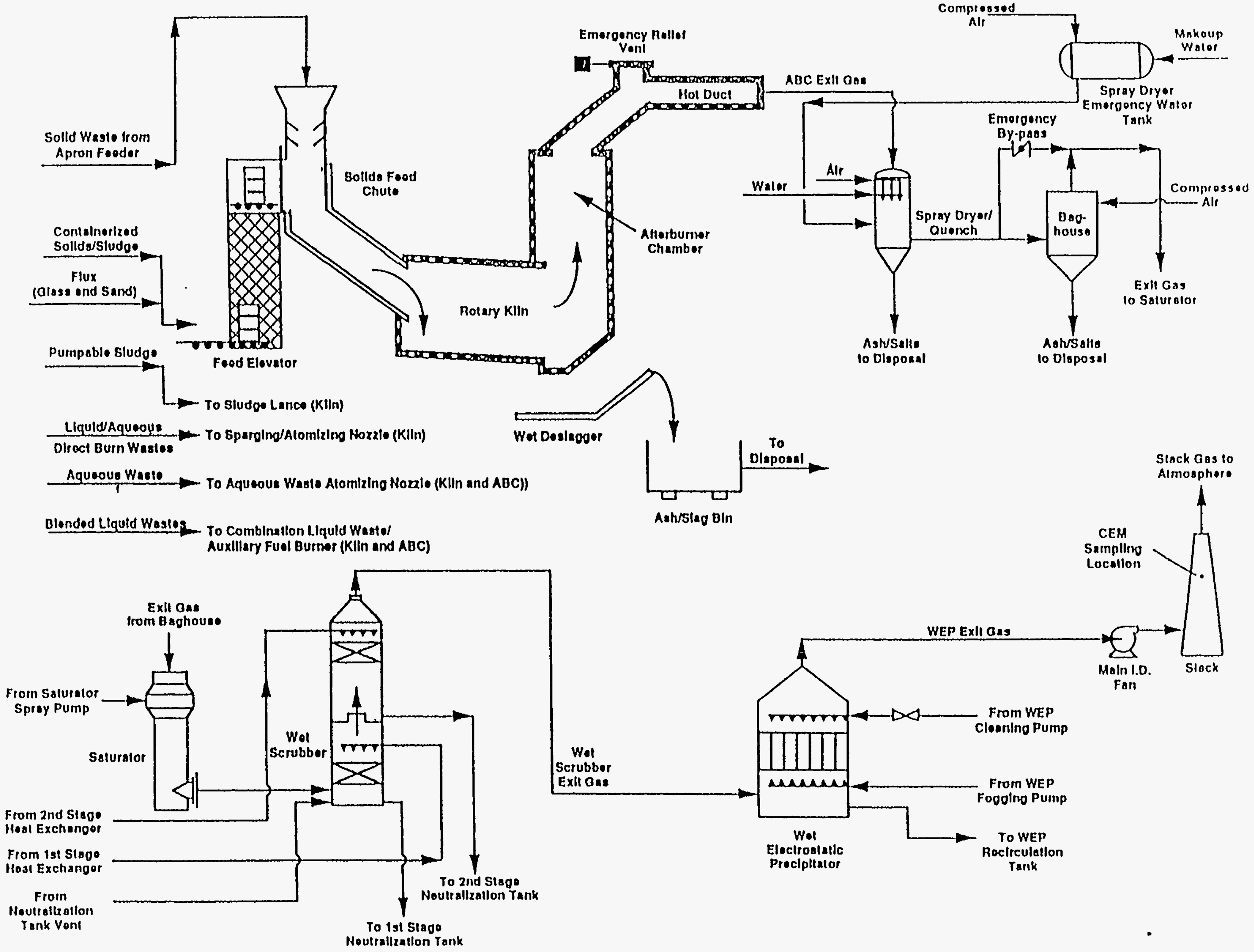


Fig. 1. Incinerator train schematic--APTUS Environmental Services.

Thermal treatment process: Radwaste Treatment RD

Location: Korea

Mode of operation (continuous,batch): Operated on daily basis

Status: Unknown

Process description/size/dimensions/materials of construction:

Incineration plant with a capacity of 20 kg/h consists of 2 incineration chambers and an offgas treatment system. The secondary combustion chamber (SCC) or afterburner incinerated volatiles and particulates that were not incinerated in the PCC. The SCC has a structure that functions as a cyclone to remove some particulate matter in the offgas. Concentrations of hazardous gases, particulates, and radioactivity were monitored at several points in the plant.

Waste feed preparation/sorting/sizing requirements:

Waste was repackaged in cardboard boxes and fed into the incinerator using a set of sliding gates before incineration. Some waste packages without tracer materials were fed into the PCC until the chamber reached a desired temperature.

Air pollution control system components:

The offgas treatment system includes a heat exchanger, an air dilution cooler, a bag filter, a wet scrubber, and HEPA filters. Use of the wet scrubber was optional and was dependent on the acid gas concentrations. The gas exiting the SCC has a temperature exceeding 800°C and is cooled down to 500°C by passing through the heat exchanger. An air dilution mixer was used to lower the temperature below 200°C.

References: H.C. Yang et al., "Behavior of toxic metals and radionuclides in analytical and real thermal conditions", *Proceedings 1995 International Incineration Conference*, Bellevue, WA (1995).

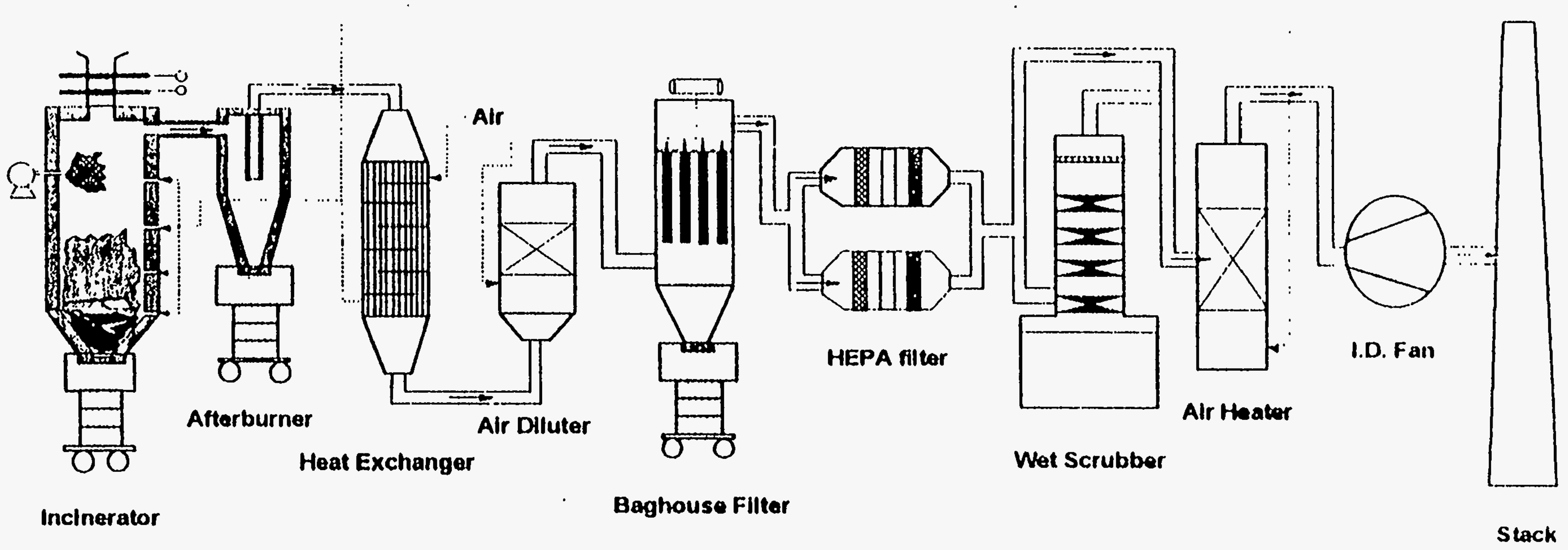


Figure 1. Schematic diagram of demonstration-scale incineration process (1995).

Thermal treatment process: Cogema

Location: SGN's Beaumont-Hague Research Facility, France

Mode of operation (continuous,batch): Continuous

Status: Constructed in November 1992, operational as of 1994.

Process description/size/dimensions/materials of construction:

Pilot-plant facility designed with feed capacity of 10 kg/h of waste with LHV of 25,000 kJ/kg. A conveyor transports boxed waste to an air lock equipped with upper and lower sliding trap doors. All operations are conducted by control system. Waste placed on grates inside the vertical shaft incinerator is burned while ash, dripping plastics, etc. drop through openings in the grates. A parallelpiped-shaped combustion chamber has 2 burners. The lower burner ensures a minimum combustion temperature of 800°C. The other burner heats the flue gas to the required temperature for postcombustion (PC). The PC chamber enables a residence time of 2 s at 1200°C. It is comprised a U-shaped chamber followed by a Y-shaped chamber filled with SiC aggregates. A burner placed between the 2 chambers adjusts the temperature before the gas passes through the SiC. The facility has been operated for nearly 4000 h

Waste feed preparation/sorting/sizing requirements:

Waste is shredded and placed in cardboard boxes (about 1 kg per box).

Air pollution control system components:

At the incineration outlet, a radiation-type flue gas/air cooler lowers the flue gas temperature to 500°C. Flue gas cooling is completed in a 2-stage dilutor. The gases are then routed into the main bag filter and into a bypass circuit used for special tests. The bypass circuit includes a small bag filter and, in some instances, a HEPA filter mounted in series. Both streams are then mixed and treated in a gas scrubber system comprising a venturi, a disengaging vessel, a finishing column packed with Raschig rings and a demister. To ensure complete neutralization of acid gases, a pH-adjusted solution is sprayed into the venturi and cleans the gases by countercurrent scrubbing in the finishing column.

References:

T. Flament et al., "A new pilot waste incineration plant at SGN's Beaumont Hague Research Facility", *Proceedings 1994 International Incineration Conference*, Houston (1994).

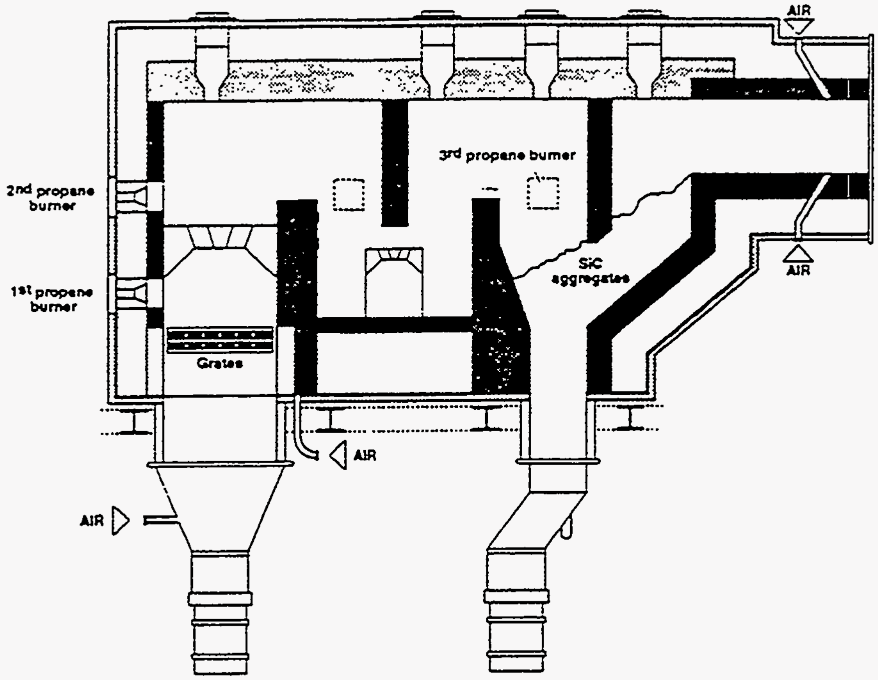


Fig. 1. Incineration pilot plant furnace.

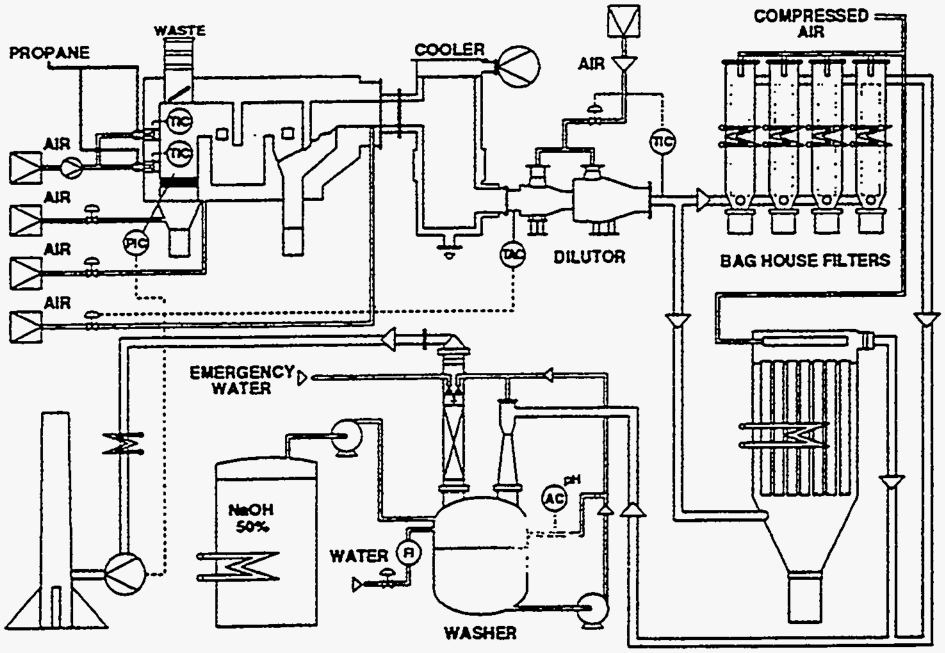


Fig. 2. Incineration pilot plant process diagram.

Thermal treatment process: Karlsruhe Nuclear Research Center (KfK) Incinerator: α solids; β/γ solids; β/γ liquids

Location: Karlsruhe Nuclear Research Center, Karlsruhe, Germany

Mode of operation (continuous,batch): Continuous

Status: Operational

Process description/size/dimensions/materials of construction:

In 1971, radioactive β/γ solid waste (50 kg/h) has been incinerated at Karlsruhe. In 1988, an incinerator for β/γ liquid waste (30 kg/h) began operation. In 1989, a solid α-contaminated waste (50 kg/h) incinerator began operation. In mid-1995, the α-incinerator was shutdown and redesigned. Capacity will be increased to 60-70 kg/h and an improved APCS installed. The incinerator is scheduled to reopen in early 1997. The other incinerators are scheduled for permanent shutdown at end of 1996. The waste feed is supplied to the vertical shaft incinerator automatically and intermittently. The waste is subjected to substoichiometric incineration at 850°C in the lower part of the furnace and to superstoichiometric incineration at 1000°C in the upper section. To attain a homogeneous ash bed temperature, steam is added to the incineration air. The afterburner chamber incinerates combustible flue gases at 1200°C.

Waste feed preparation/sorting/sizing requirements:

The α-contaminated solid burnable residue are delivered in 200-L barrels. For feeding into the furnace, the barrel is coupled to a rotating box. Upon rotating, the barrel contents are conveyed into the shaft.

Air pollution control system components:

1995 system: Downstream from the afterburner, injection of demineralized water and air cools flue gas to less than 850°C. Flue gas purification is accomplished in several stages. In the first stage (hot gas filter), coarse dust is retained. This filter also serves as a second afterburning zone. Service life of the ceramic filter elements varies between 2500 and 3000 h. Before entering the second stage, flue gas temperature is about 250°C. Flue gas scrubbing took place in 2 stages. The first stage was a jet scrubber with pH of 0.5-2.0. The second scrubber was a venturi operating at pH 8-9. The saturated offgas exits at 75°C and is heated to 100°C to prevent condensation. The offgas is then passes through HEPA filters.

1997 system: New afterburning chamber design to ensure gas RT > 2 s at 1200°C. Liquid waste will be incinerated directly in the afterburning chamber. The hot gas filter may be bypassed during liquid incineration to prevent particulate fouling. For reduction of NO_x in the flue gas, the selective noncatalytic reduction gas filter technique will be used. Reduction is achieved by the injection of additives both into the lower part of the afterburning chamber and the pipe located between the chamber and the hot gas filter. The quencher will be removed and offgas at 650°C fed directly into scrubber system. A dioxin filter will be installed downstream from the HEPA filters.

References:

F. Dirks and R. Muller, "Further development of the incineration plant for α-contaminated solid burnable residues", *Proceedings 1995 International Incineration Conference*, Bellevue, WA (1995).

F. Dirks et al., "Further development of the KfK system for radioactive waste incineration", *Proceedings 1992 Incineration Conference*, Albuquerque, NM (1992).

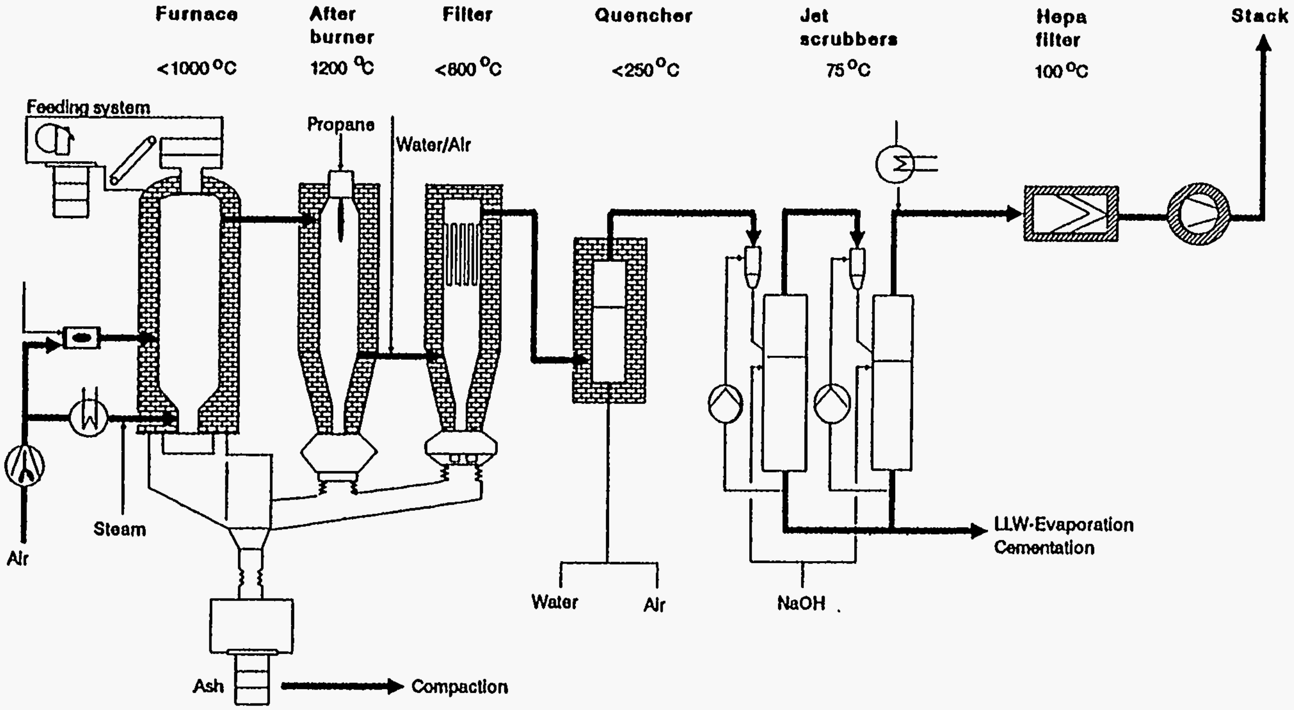


Fig. 1. Alpha-incineration plant, current status 1995.

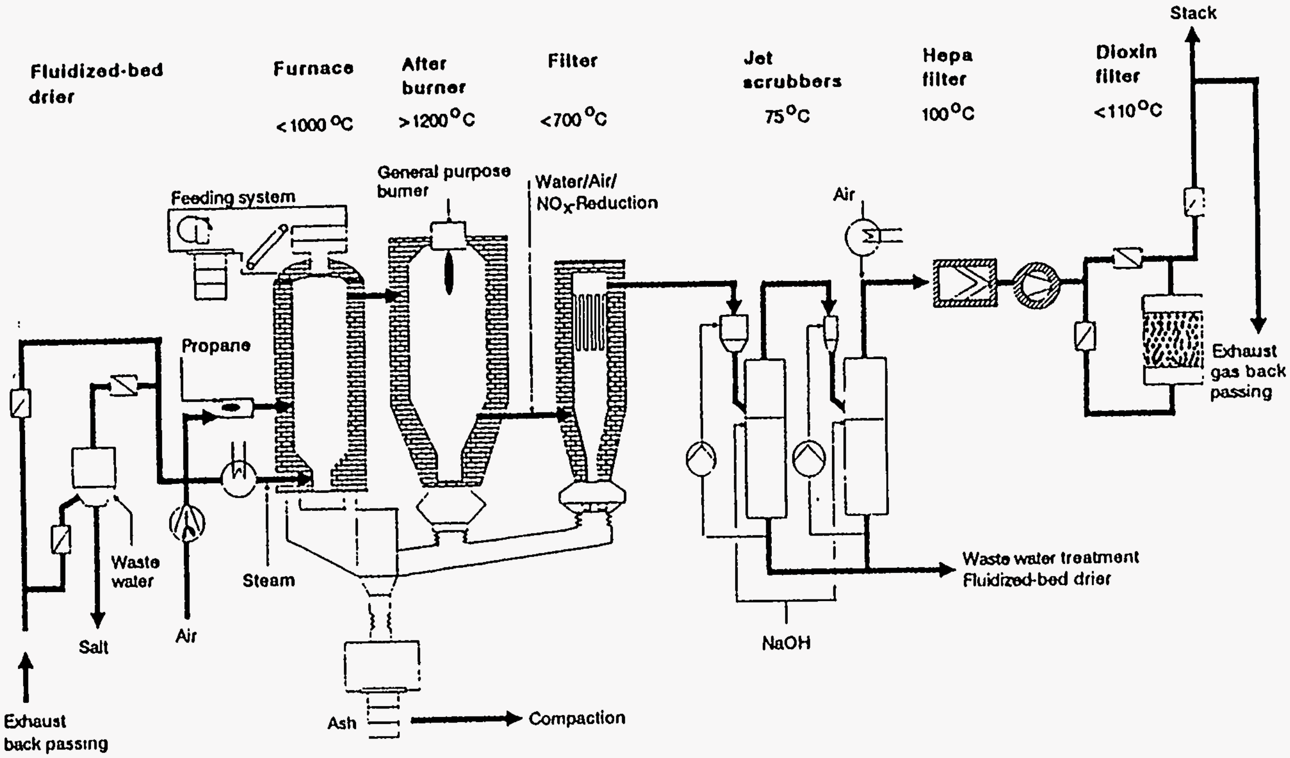


Fig. 2. Status to be achieved by the alpha-plant by December 1996.

Thermal treatment process: DuPont Experimental Station HWI

Location: Wilmington, DE

Mode of operation (continuous,batch): Continuous, periodic maintenance shutdowns

Status: Operational (1993)

Process description/size/dimensions/materials of construction:

A 2-stage system capable of destroying over 40 MBtu/h of solid and hazardous wastes. A Nichols Monohearth incinerator is used as the primary combustion chamber (PCC). Waste is fed to this chamber using a ram feeder for up to 2-yd^3 charges of solid waste, a cylindrical chute for up to 1-gal charges of batched waste material, and a Trane Thermal vortex burner for up to 1600 lb/h liquid waste. The PCC is a vertical cylinder with a support grate at its base and a conical air distributor at the center of the grate. Rotating rabble arms stir the solid waste material on the grate, and air is fed through the grate area to ensure adequate O_2 for combustion. The PCC exhaust gas enters a secondary combustion chamber (SCC) or afterburner equipped with a vortex burner to burn fuel oil as an auxiliary fuel. The SCC is designed to provide a gas residence time up to 2 s.

Waste feed preparation/sorting/sizing requirements:

Synthetic wastes were made up to simulate the various waste types that may be incinerated during normal operations. Synthetic waste feeds included an organic liquid waste, two jug wastes, a ram feed waste. Metals were spiked into both the liquid waste and one of the jug wastes. Spiking of the liquid waste with metals was performed by pumping concentrated aq. solutions of the five test metals into the liquid waste feed line just ahead of an in-line mixer which was near the burner. Due to interactions between compounds, the Pb salt was kept in a separate solution. The organic liquid feed consisted of no.2 fuel oil with varying levels of CCl_4 added as a source of chlorine. Aqueous solutions were added at a low rate that did not affect burner operation. During testing, 4 metals (As,Be,Cd,Cr) were fed at pre-calculated feed rates in the liquid waste. At least 30 min of metal spiking was performed prior to the start of each mini-burn run to precondition and allow for equilibration within the system. During trial burn testing, at least 1-hr preconditioning occurred before each run.

Air pollution control system components:

SCC offgas discharges to an Andersen spray dryer where the elevated temperature of the exhaust gases (> 400°F) are used to evaporate effluent from the wet scrubbing system downstream. The spray dryer is exhausted to a large induced draft (ID) fan which also provides positive pressure to the gas cleaning system downstream from the fan. The fan discharges to a cooler/condenser which lower the gas temperature below the dew point. Then the gas enters a variable throat venturi scrubber which is used to remove particulate matter and some acid gases. The venturi scrubber discharges into a 3-stage baffle absorber in which soda-ash neutralized scrubbing solution is used to absorb acid gases. The exhaust passes through a mist eliminator to the upper stack and then to the atmosphere.

References: G.D. Hinshaw et al., "Parametric testing of metals emissions from the Du Pont Experimental Station Hazardous Waste Incinerator", *Proceedings 1993 Incineration Conference*, Knoxville, TN (1993).

Thermal treatment process: Juelich Incineration Systems

Location: Juelich Nuclear Research Center, Germany
German Fuel Reprocessing Pant, Wackersdorf, Bavaria, Germany

Mode of operation (continuous,batch): Continuous

Status: Juelich NRC (as of 1988) - Third generation incinerator under construction (50 kg/h)
German FRP (as of 1987) - Modified design under construction (100 kg/h)

Process description/size/dimensions/materials of construction:

The Juelich incinerator process is a 2-stage controlled incineration process. The incinerator is a brick-lined vertical duct of rectangular construction. This duct is divided into a treatment and combustion section by a movable grate. Flue gas recycle and primary air are supplied at the treatment level. With the rising temperatures on its path down through the incinerator, the waste is decomposed to form gas and coke which are burnt in the combustion chamber below by a controlled air supply. The afterburning section is a cylindrical, brick-lined pipe section. The flue gas released by the incinerator goes directly into the afterburning section maintained at 1200°C. Frequently handling procedures, such as waste feeding and ash removal, are performed by remote operation.

Waste feed preparation/sorting/sizing requirements:

Unsorted packages are gravity fed through a feed lock into a thermal treatment chamber. In some cases, waste material is delivered in 55-gal waste drums and directly placed into the incinerator with no prior sorting.

Air pollution control system components:

A new, improved APCS was developed for the third generation process. The APCS consists of an afterburner chamber, air-cooled heat exchangers, baghouse filters, wet scrubbers, and HEPA filters. Volatile constituents precipitate to form particulate matter prior to filtration by cooling the flue gas first to 200°C. The gas flow and the dimensions of the downstream APCS are reduced by installing the heat exchangers. Flue gas cooling is ensured by a radiation cooler and 2 identical convection coolers. The baghouse filter is designed as rectangular sheet metal housing. A 2-stage scrubber removes acid gases. The first stage is a jet scrubber and the second stage is a high-efficiency venturi scrubber with an integral demister.

References:

Dietrich H. et al., "Incineration of dry burnable waste from reprocessing plants with the Juelich incineration process", *Proceedings International Conference on Nuclear Fuel Reprocessing and Waste Management- Volume 2*, (1987)

Wurster W. and G. Zapf, "Latest development in the Juelich incineration system, and similarities in the treatment of radioactive and hospital wastes", *Proceedings International Conference on Incineration of Hazardous, Radioactive, and Mixed Waste*, San Francisco (1988).

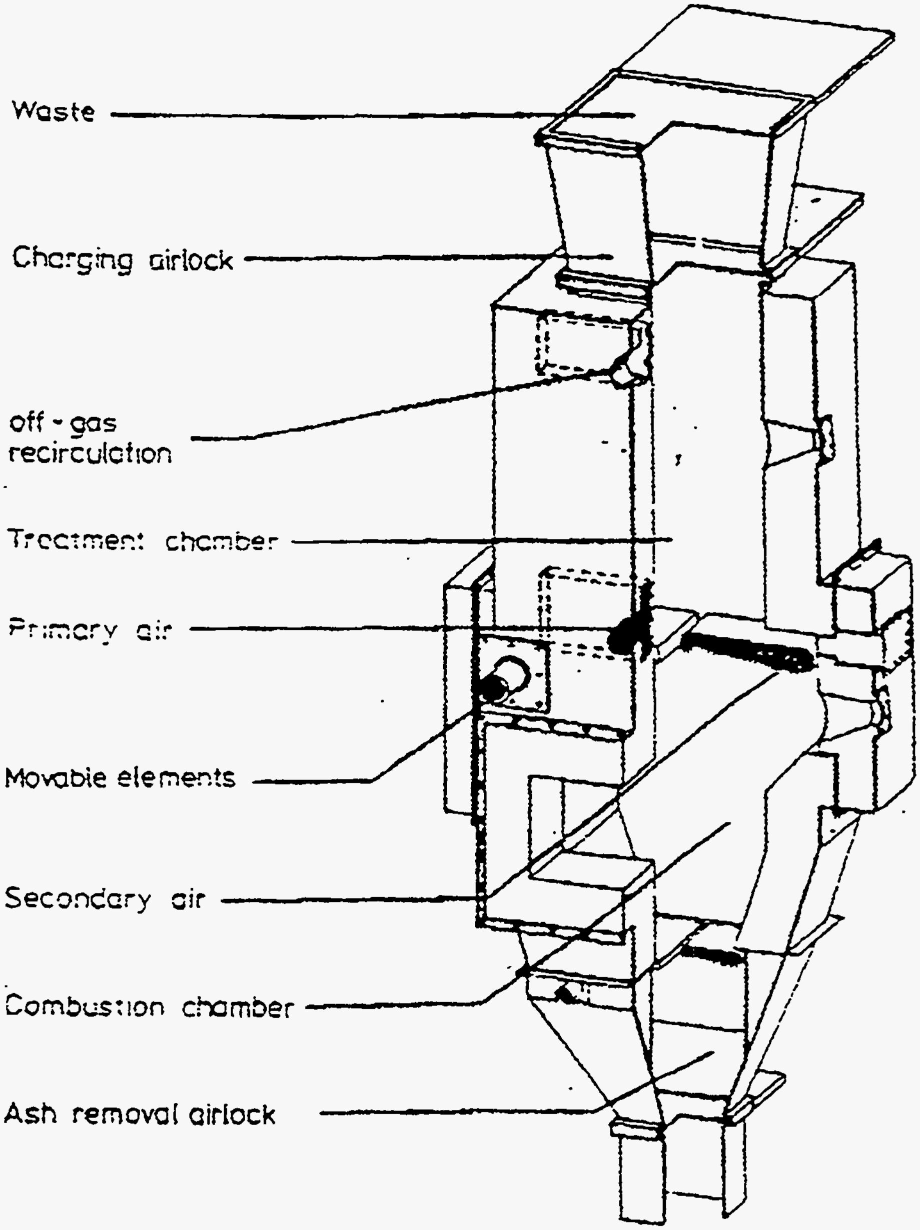
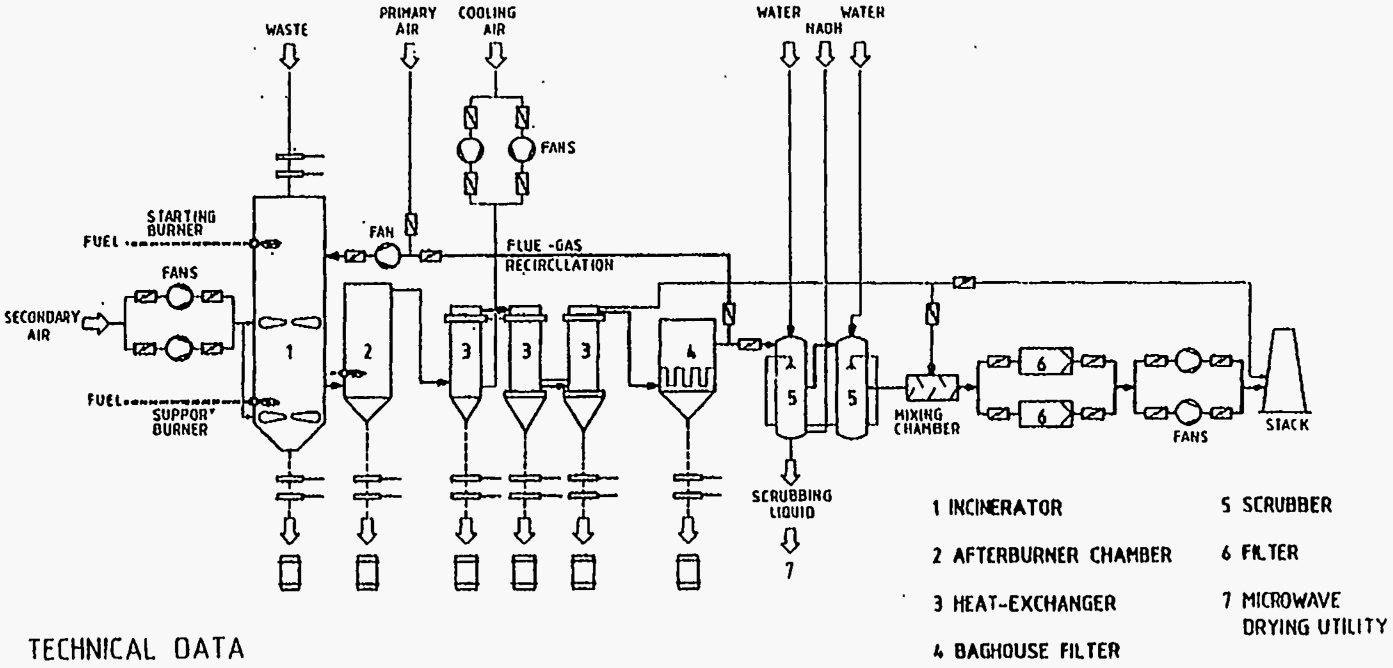


Figure 1. Schematic of Juelich incinerator (1988).



TECHNICAL DATA

-WASTE	LLW
- CAPACITY	100 KG/H
- HEAT-UP MEDIUM	NATURAL GAS
- THERMAL OUTPUT	0.7 MW
- TEMP OF TREATMENT CHAMBER	20-800°C
- TEMP OF COMBUSTION CHAMBERS	850-1000°C,1200°C
- AVERAGE CALORIFIC VALUE OF WASTE	20000 KJ/KG

Figure 2. Process flow diagram of Juelich incineration process in Bavaria, Germany (1987).

Thermal treatment process: SRP LLW Incinerator

Location: Savannah River Plant (SRP)

Mode of operation (continuous,batch): Continuous, periodic maintenance shutdowns

Status: (As of 1992) unit is not operating. Startup status is unknown.

Process description/size/dimensions/materials of construction:

Volume reduction of solid and liquid low-level waste has been demonstrated since January 1985 at the SRP in the Waste Management Beta-Gamma Incinerator (BGI) facility. The BGI uses a two-stage controlled-air incinerator capable of 180 kg/h (400 lb/h) solid waste or 150 L/h (40 gal/h) liquid waste. These wastes are pyrolyzed in a substoichiometric air environment at 900 to 1100°C in the PCC. Products of partial combustion from the primary chamber are oxidized to 950 to 1150 °C in the SCC. Using feedback control, the vacuum set point between 0.2" to 1.0" w.c.. Ash is removed semi-continuously from the primary chamber.

Waste feed preparation/sorting/sizing requirements:

Before being processed in the incinerator, each solid waste box is x-rayed for the presence of metals or liquids as well as assayed to determine isotopic content. Any box that contains detectable amounts of Pu or U are rejected. Boxes are fed into the primary chamber with a hydraulic feed ram.

Primary components of the solvent feed system are a storage tank, a feed tank and four pumps. In regards to phosphate-containing liquid waste, tetrabutyl titanate (TBT) is mixed with spent solvent prior to incineration. As the mixture is incinerated, Ti reacts with P to form a stable ash which can removed in the baghouse. Without phosphorus fixation, a tar-like ash would form, which would blind the baghouse filter bags.

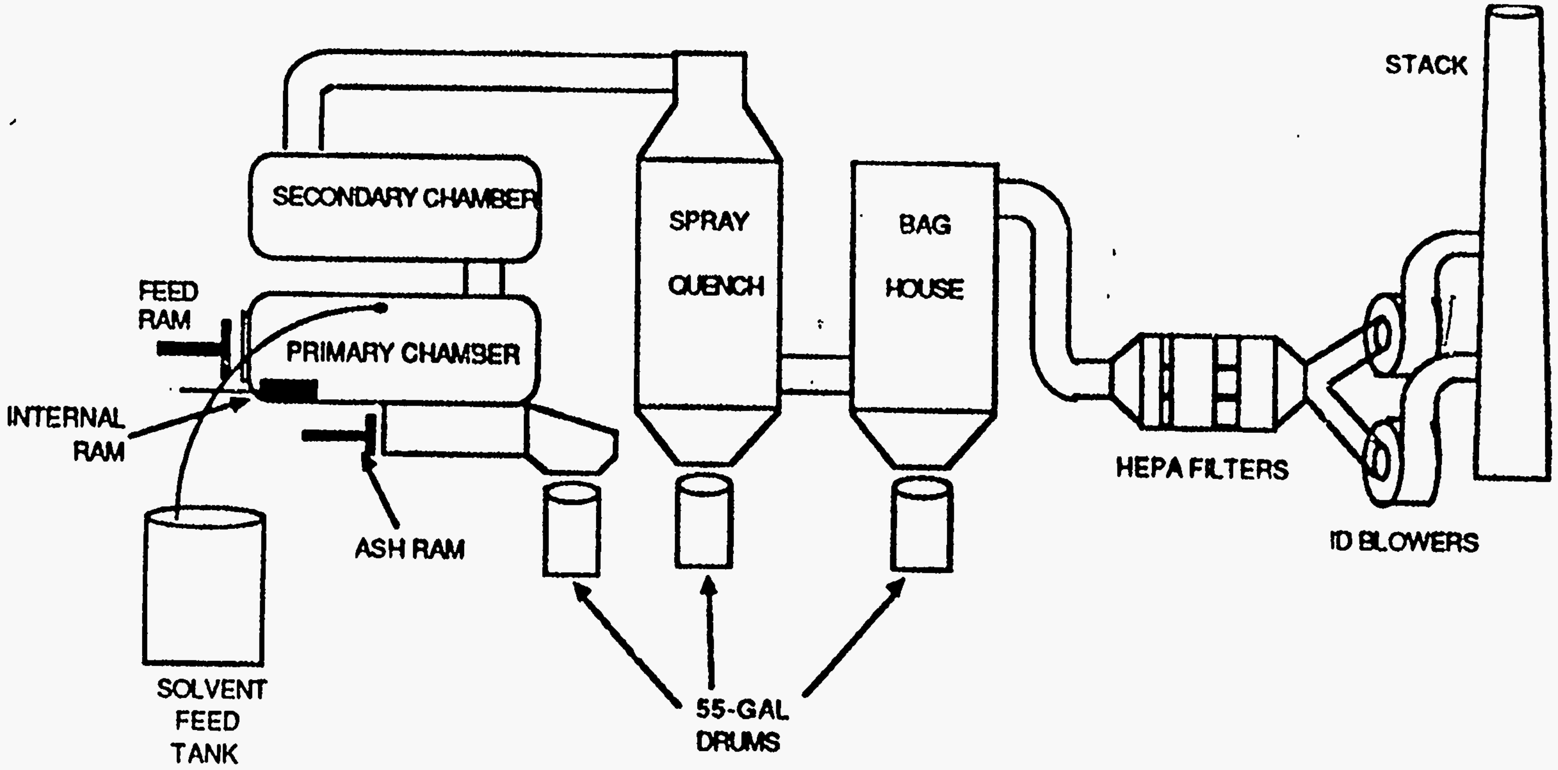
Air pollution control system components:

A spray dryer, baghouse, and HEPA filter unit cool and filter the incinerator offgases. In the spray quench, the offgases from the secondary chamber are cooled from 1000°C to 200°C using an air-atomized water spray. The gases leaving the spray quench are maintained above the dewpoint to minimize corrosion and to avoid generating secondary liquid waste streams. The baghouse contains 135 vertically hanging filter bags. A lime (CaO) precoat is applied to the bags during solvent incineration. The HEPA filters are rated to 260°C. There is a prefilter in front of each HEPA filter to decrease the frequency of HEPA filter changeout. Two 60-hp induced-draft blowers maintain a negative pressure in the process and exhaust the gases to the atmosphere through a 60-ft stack.

References:

M.J. Irujo and J.R. Bucci, "Savannah River Plant low-level waste incinerator", DP-MS--86-186, E.I. du Pont de Nemours Co., SRP, Aiken, SC (1987).

J. Mayberry et al.,"Experience base for radioactive waste thermal processing systems - A preliminary survey", EGG-WTD-10037, EG&G Idaho, Idaho Falls, ID (April 1992).


STACK
SECONDARY CHAMBER
SPRAY
QUENCH
BAG
HOUSE
FEED
RAM
PRIMARY CHAMBER
INTERNAL
RAM
ASH RAM
HEPA FILTERS
ID BLOWERS
SOLVENT
FEED
TANK
55-GAL
DRUMS

Thermal treatment process: SEG Radioactive Waste Incinerator

Location: Oak Ridge, TN

Mode of operation (continuous,batch): Continuous; periodic maintenance shutdowns

Status: Operational

Process description/size/dimensions/materials of construction:

The incinerator is a controlled-air unit rated at 2.89E6 kcal/h (11.44E6 Btu/h). The incinerator has a primary, secondary, and retention chambers, each equipped with a propane burner. The retention chamber is a dual fuel burner and also can be used to burn nonhazardous waste oils at a rate of 265 L/h (70 gal/h). The combined residence time of the SCC and retention chamber is 3 s, and the incinerator is designed to operate at temperatures up to 1,300°C. Throughput capacity of the incinerator is rated at 1000 lb/h solid waste and 30 gal/h liquid waste.

Both secondary and retention combustion chambers have multiple turns to create turbulent mixing with the excess air that is injected. The ash char generated during pyrolysis is mechanically transported to chambers where excess air is provided to completely burnout the carbonaceous material by gently turning and mixing the ash.

Waste feed preparation/sorting/sizing requirements:

Waste packaged in plastic bags are transported in large containers. The bags are loaded onto a conveyor belt to a revolving sorting table. On the sorting table, the waste is segregated by hand according to the process that will be used to treat the waste. During the sorting process, waste to be incinerated is placed in large bags inside metal boxes which, when full, are transported to a conveyor system which automatically feeds waste to the incinerator when it is ready for another charge. As of 1992, the incinerator had not burned mixed waste (no RCRA waste).

Air pollution control system components:

The first step in the flue gas treatment system is a 3-pass boiler which cools the gases to about 170°C (338°F). This boiler is mounted in a vertical position with access plates on the top and hoppers with ash drums on the bottom so that the tubes can be cleaned. After the boiler, the offgas is filtered in a 4-chamber baghouse. This baghouse has a 3.32:1 air-to-cloth ratio when all 4 chambers are in use. Then fine particulate matter is removed in one of two redundant HEPA banks. After filtration, the offgas is quenched and then scrubbed in a packed tower for acid gas removal. Then the offgas is drawn through one of two induced-draft fans. The offgas is then mixed with building exhaust (to eliminate the visible plume) before being sent out the stack.

References: J.D. Dalton and H.W. Arrowsmith, "Radioactive waste incinerator at the Scientific Ecology Group", *Proceedings 1990 Incineration Conference*, San Diego, CA (1990).

J. Mayberry et al.,"Experience base for radioactive waste thermal processing systems - A preliminary survey", EGG-WTD-10037, EG&G Idaho, Idaho Falls, ID (April 1992).

Thermal treatment process: INEL WERF Incinerator

Location: Idaho National Energy Laboratory (INEL)

Mode of operation (continuous,batch): Continuous (5-20 day campaigns)

Status: Operational (Currently, TRU waste only)

Process description/size/dimensions/materials of construction:

The Waste Experimental Reduction Facility (WERF) is a dual-chamber controlled-air system commercially available (model 1000TL) from Joy Energy Systems. The incinerator is lined with a high alumina refractory backed by mineral wool insulation. Incinerator thermal capacity is 5 MBtu/h. Assuming solid waste with heating value of 12,500 Btu/lb, the maximum feed rate is 400 lb/hr. A typical feed rate is about 140 lb/h. Liquid waste can be fed to a maximum of 1.3 MBtu/h. Liquid organics are fed to a liquid burner and aqueous waste is fed to a waste atomizer. Gas residence time in the SCC is rated at 2 s at 5 MBtu/h and 100% excess O_2.

On average, the incinerator is operated approximately 10 days per month. The incinerator has been operated continuously for up to 20 consecutive days before system shutdown is required, usually the result of ash accumulation at the entrance of the heat exchanger causing a significant pressure drop.

Waste feed preparation/sorting/sizing requirements:

Solid waste is packaged in polyethylene-lined 2'x2'x2' cardboard boxes before incineration. Boxes of solid waste are fed to the incinerator by gravity through a top-loading feed assembly mounted on top of the primary chamber. Use of dry offgas system limits the acceptable amount of acid forming chemicals, such as Cl, in the waste feed to minimize corrosion problems.

Air pollution control system components:

The dry offgas handling system consists of a dilution stream, an air-to-air heat exchanger, another dilution stream, and a baghouse and HEPA filter system. The heat exchanger is a shell-and-tube type with cooling air drawn from outside by 2 10-hp blowers in parallel. The HEPA filters are capable of removing 99% of 0.5 μm particles. A spray dryer is partially constructed in the offgas system but is not operational.

References:

J.J. Riedesel and G.L. Tyger, *WERF Safety Analysis Report - Volume 1*, Rev.0, Chg. 2, INEL-95-0487, Lockheed Idaho, Idaho National Engineering Laboratory, (1996).

J. Mayberry et al.,"Experience base for radioactive waste thermal processing systems - A preliminary survey", EGG-WTD-10037, EG&G Idaho, Idaho Falls, ID (April 1992).

D. Christensen, "Fraction of material in bottom and fly ash from incineration campaigns", Engineering Design File Ser. No. WERF-0193, EG&G Idaho, Idaho Falls, ID, November 30, 1992.

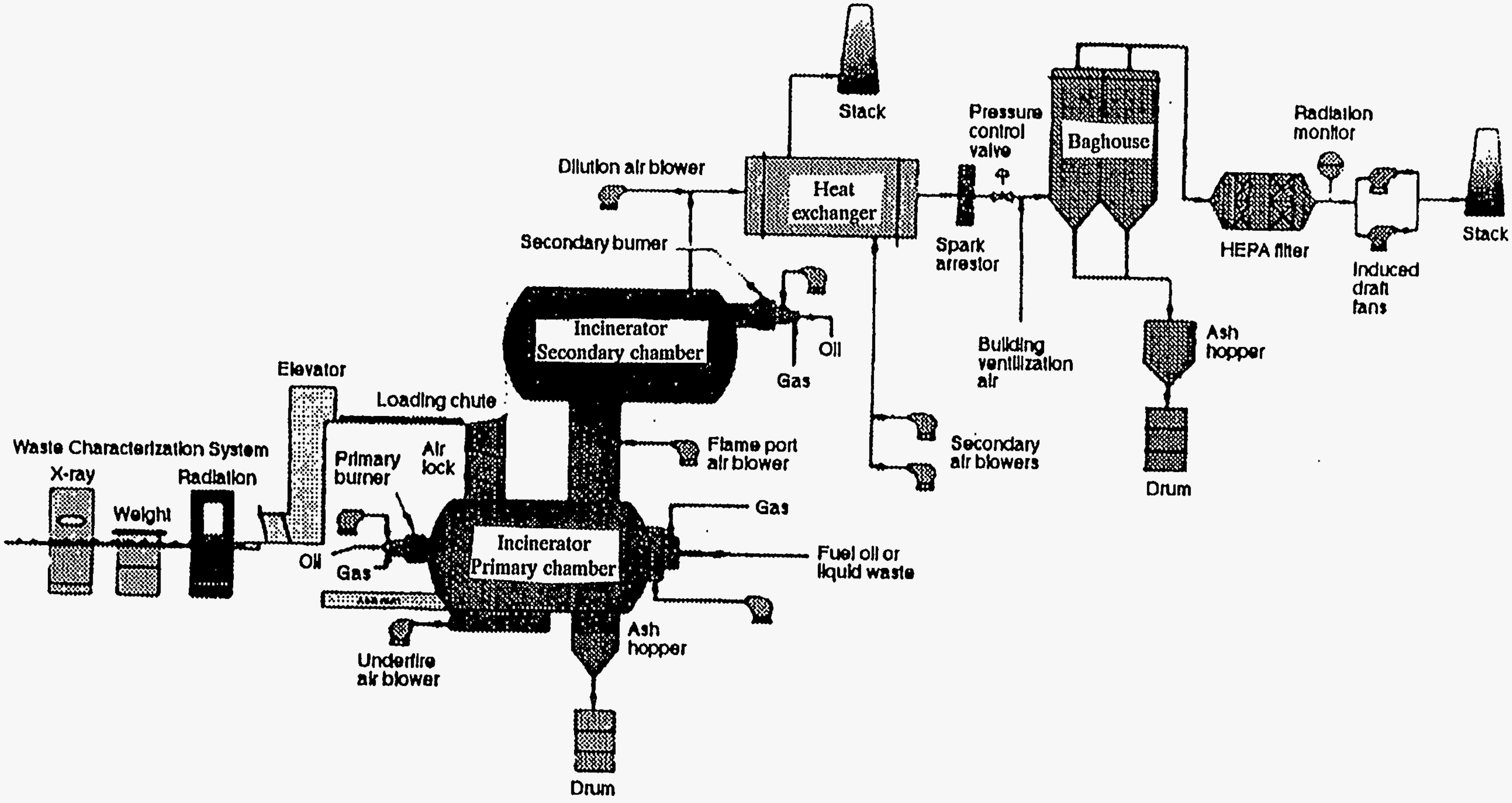


Figure 1. Waste Experimental Reduction Facility (WERF) at the INEL (1992)

Thermal treatment process: Los Alamos CAI

Location: Los Alamos National Laboratory (LANL)

Mode of operation (continuous,batch): Continuous for specific campaigns

Status: CAI was shut down for extensive modifications in 1987.
Not operational - unit decommissioning planned (1996)

Process description/size/dimensions/materials of construction:

The heart of the CAI is a commercially available dual-chamber incinerator. The primary combustion chamber (PCC) is a refractory lined cylinder with an internal diameter of 1.5 m and a length of 1.8 m. The secondary combustion chamber (SCC) has an ID of 1.16 m and is also 1.8m long. The addition of a gravity ash dropout system allows for semi-continuous ash removal from the incinerator hearth while the unit is in operation.

Underfire air is added through ports on the hearth of the PCC to ensure complete burning of solids. Combustion and pyrolysis products pass to the SCC where secondary air and additional heat are added to allow complete combustion of pyrolysis products. Normal operating temperatures within the PCC and SCC are 930°C and 1100°C. respectively.

Waste feed preparation/sorting/sizing requirements:

All solid waste feed is prepackaged in 1'x1'x2' cardboard boxes.

Air pollution control system components:

Combustion gases leave the SCC through a refractory lined crossover duct from which they enter the offgas cleanup system consisting of a water-spray quench column, a high-energy venturi scrubber for particulate removal, a packed-column acid gas absorber, offgas condenser, reheater, HEPA filters, and a carbon bed adsorber. A demister removes entrained water droplets from the absorber tower. An electric preheater adds heat to the gas stream to prevent water from condensing in the HEPA filters that follow. After the carbon bed adsorber, the remaining components downstream are another HEPA filter, the induced draft blower, and the exhaust stack.

The scrub solution is collected from the quench column and adsorber tower, neutralized with NaOH, cooled to remove sensible heat, cleaned with a hydrocyclone, and returned to a sump tank for recycle.

References:

J.M. Newmyer, The controlled-air incinerator at Los Alamos", LA-UR-1056, Los Alamos National Laboratory, Los Alamos, NM (1994).

D.A. Hutchins, Performance assessment of refractory samples in the Los Alamos controlled-air Incinerator, *Proceedings Waste Management '86 Symposium*, Tucson, AZ (1986).

J. Mayberry et al.,"Experience base for radioactive waste thermal processing systems - A preliminary survey", EGG-WTD-10037, EG&G Idaho, Idaho Falls, ID (April 1992).

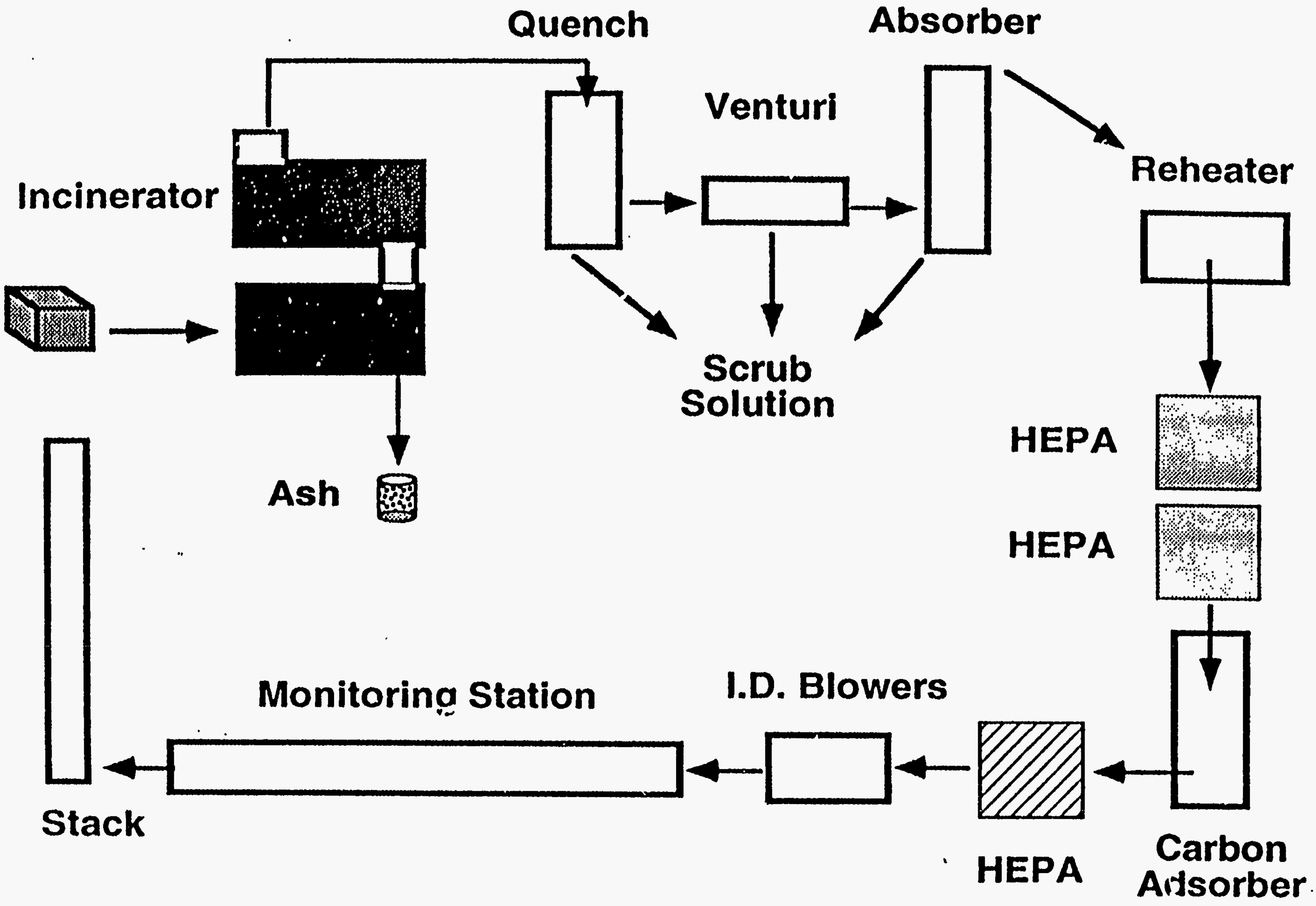


Figure 1. Crude schematic of Los Alamos incineration process (1994).

Thermal treatment process: RFP Fluidized Bed

Location: Rocky Flats (RFP), CO

Mode of operation (continuous,batch): Continuous

Status: Non-operational, halted in 1986 after small fire in demonstration unit

Process description/size/dimensions/materials of construction:

RFP first began work on the fluidized bed incinerator in 1972. A small bench-top unit was built followed by a 9 kg/h pilot plant system. In 1977, a Fluidized Bed Incinerator (FBI) demonstration unit was constructed with a capacity of 82 kg/h. The FBI was a 2-stage system. In the first stage, waste was fed into the bed consisting of sodium carbonate and chromia-alumina catalyst. The sodium carbonate served as a sorbent for *in situ* neutralization of acid gases and the catalyst was used to facilitate destruction of waste at relatively low temperatures of 525-600°C. The first stage was operated at substoichiometric O_2 concentrations. The pyrolytic gases were sent to the second stage containing only the catalyst and excess O_2. The superficial gas velocity through both stages was less than 0.5 m/s. As such, these beds were "bubbling". Beds operating in this regime are characterized by low air flow as well as distinct dense and lean regions. In these beds, there is significant disengagement of solids, so there is minimal entrainment of solids in the offgas.

Air pumps at the exhaust end of the FBI drew air through the system and assured continuous operation under negative pressure. The entire unit was fabricated out of stainless steel without a refractory lining due to the relatively low operation temperature.

Waste feed preparation/sorting/sizing requirements:

Solid wastes are manually sorted to separate combustible wastes from noncombustible wastes in a glovebox. The combustibles are fed to a low-speed, high-torque coarse shredder located beneath the sorting glovebox. The shredded waste falls into a gas stream classifier. A N_2 stream, regulated by a moving vane, separates light and dense particles. Light shredded material is pneumatically transferred to a cyclone separator where coarsely shredded combustibles are sent to a second shredder. The second shredder delivers a finely shredded waste to a hopper that feeds a screw conveyor. The liquid waste feed is pumped into the primary reactor through nozzles.

Air pollution control system components:

Offgas from the 2nd stage entered the exhaust treatment train. The gas initially passed through a sintered metal filter to remove particulates $> 2.8\ \mu m$, and then entered a heat exchanger to reduce its temperature to about 80°C before passing through a HEPA filter. The offgas then passed to the building ventilation system and through an additional bank of four HEPA filters in series before being discharged to the atmosphere. Each HEPA filter was designed to 99.97% of particulates $\geq 0.3\ \mu m$.

References:

G.B. Semones et al.,"A low temperature fluidized bed thermal treatment process for treating mixed waste at the Rocky Flats Plant", *Proceedings 1993 Incineration Conference*, Knoxville, TN (1993).

J. Mayberry et al.,"Experience base for radioactive waste thermal processing systems - A preliminary survey", EGG-WTD-10037, EG&G Idaho, Idaho Falls, ID (April 1992).

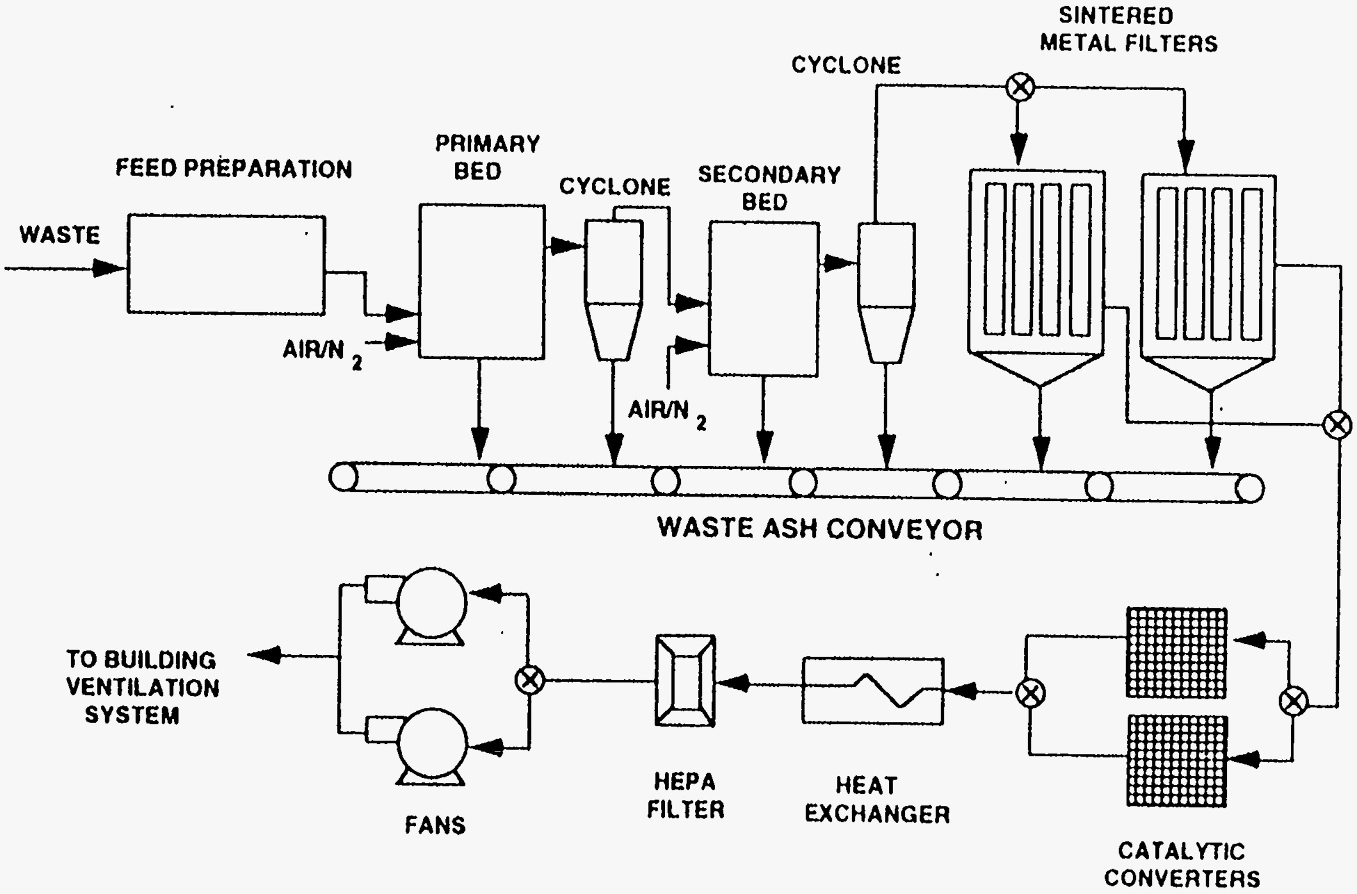


Fig. 1. Design of Rocky Flat's fluidized bed incinerator.

Thermal treatment process: LLNL Transpiration Furnace

Location: Lawrence Livermore National Laboratory (LLNL)

Mode of operation (continuous,batch): Batch operation (sample mass on the order of grams)

Status: Unknown

Process description/size/dimensions/materials of construction:

The transpiration experimental equipment is located inside an air-flow glovebox. The furnace is a Kanthal-heater horizontal clamshell furnace rated to 1200°C in air. It provides a uniform-temperature hot zone about 7 cm long and an overall heated zone about 20 cm long. The furnace tube is silica glass, 26 mm OD by 385 mm long with 35/25 silica glass ball and socket end joints sealed with silicone grease. A 9-mm OD by 12-cm long outlet and collector tube extended from the downstream side of the uniform temperature hot zone and continued through the end cap. The boat used to hold the sample is made of Al_2O_3 or silica glass. The vessel is heated a Glas-col mantle. A water saturator is located upstream of the furnace. Heating tape is wrapped around the lines from the saturator and to the desiccator to heat the lines to ≈150°C to prevent water condensation. Experiment allows for an accurate material balance without fear that some vapors condense onto particulate matter that can not be completely collected in an offgas treatment system.

Waste feed preparation/sorting/sizing requirements:

A known amount of carrier gas is slowly passed over a solid or liquid in the furnace chamber such that any volatile gases produced become entrained in the carrier gas and are swept out of the chamber where the volatilized gas is condensed and analyzed. The carrier gas may also contain reactive gases that contribute to forming the volatilized species. Gas flow rate is adjusted so that the carrier gas becomes saturated with the equilibrium vapor pressure of the volatilizing species.

Air pollution control system components:

Actinide compounds that deposited on the silica tube inner walls were dissolved off using nitric acid or HF. A desiccant cartridge is located downstream of the furnace to collect water vapor. A Precision Flow Devices mass flow controller was located downstream from the desiccator and used to monitor output gas flow rate. A HEPA filter may be added to minimize the release of radionuclides or contaminated particulates into the exhaust stream.

References:

O.H. Krikorian et al.,"Experimental studies and thermodynamic modeling of volatilities of uranium, plutonium, and americium from their oxides and from their oxides interacted with ash", UCRL-ID-114774, Lawrence Livermore National Laboratory, September 1993.

O.H. Krikorian et al.,"Measurement of Pu and Am volatilities under thermal process conditions; Final report", UCRL-ID-112994, Lawrence Livermore National Laboratory, April 1993.

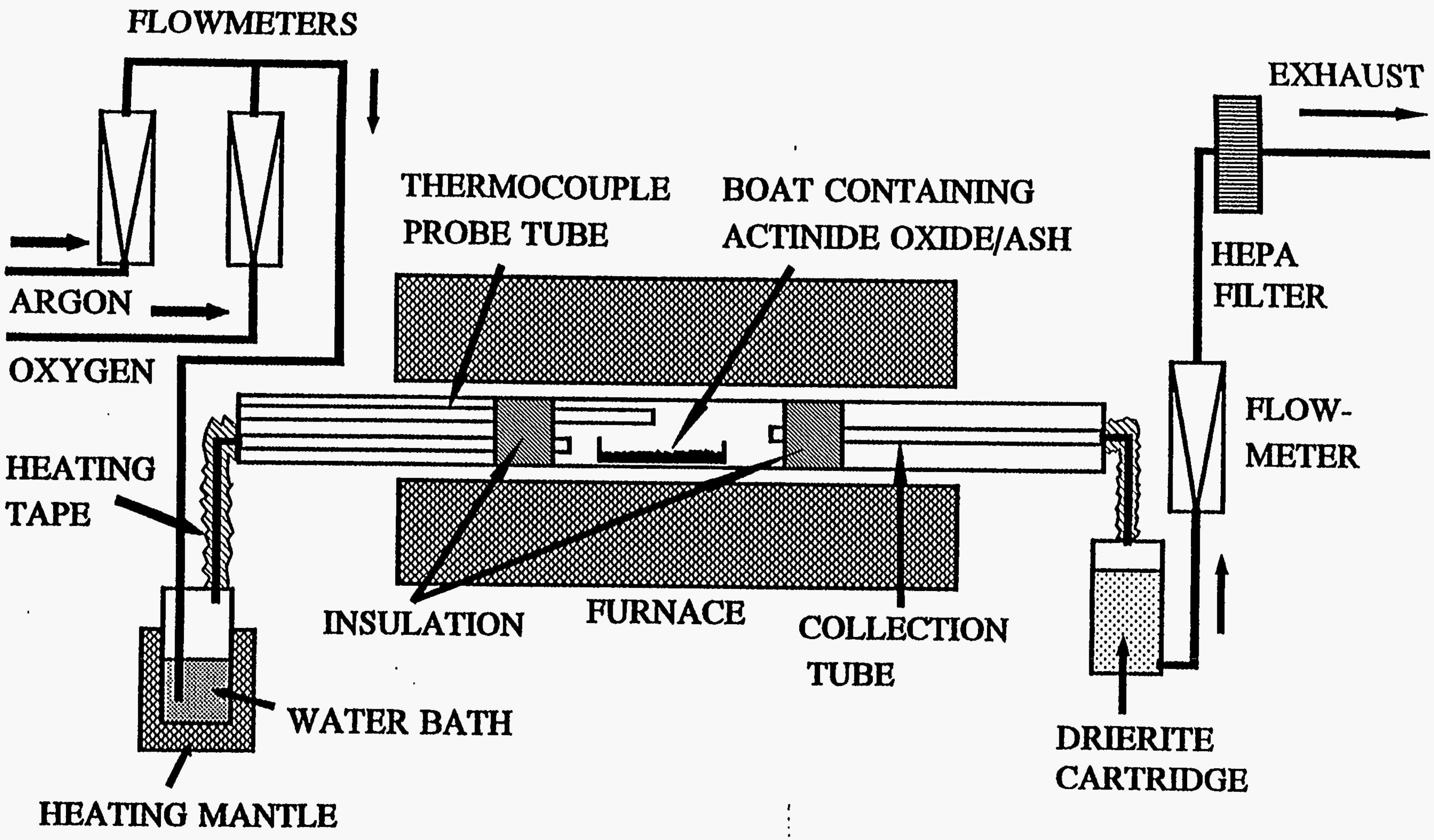


Figure 1. Schematic of LLNL transpiration experimental apparatus (1993).

Thermal treatment process: ACERC Differential Bed Reactor

Location: ACERC, University of Utah

Mode of operation (continuous,batch): Semi-continuous

Status: Unknown

Process description/size/dimensions/materials of construction:

A differential-bed reactor (DBR) was used for the collection of metal vaporization data. A thin bed (0.6 cm thick) of contaminated substrate is contained between 2 stainless steel screens. This bed is placed inside a square ceramic block which is a cast refractory material. Inside the refractory block, there is a Ni/Cr wire that provides direct heat to the bed particles. A gas stream passes through the bed of particles and is cooled upon exiting.

Waste feed preparation/sorting/sizing requirements:

In one case, the contamination method involved mixing an aqueous metals solution with either clay sorbent particles or silica gel particles. Because the sample size for each experiment is small, it is important to avoid hot spots of high concentrations.

Air pollution control system components: None

References:

J.S. Lighty et al., "Rate limiting processes in the rotary-kiln incineration of contaminated solids", *Combust. Sci. and Tech.*, **74**, 31-49 (1990).

E.G. Eddings and J.S. Lighty, "Fundamental studies of metal behavior during solids incineration", *Combust. Sci. and Tech.*, **85**, 375-390 (1992).

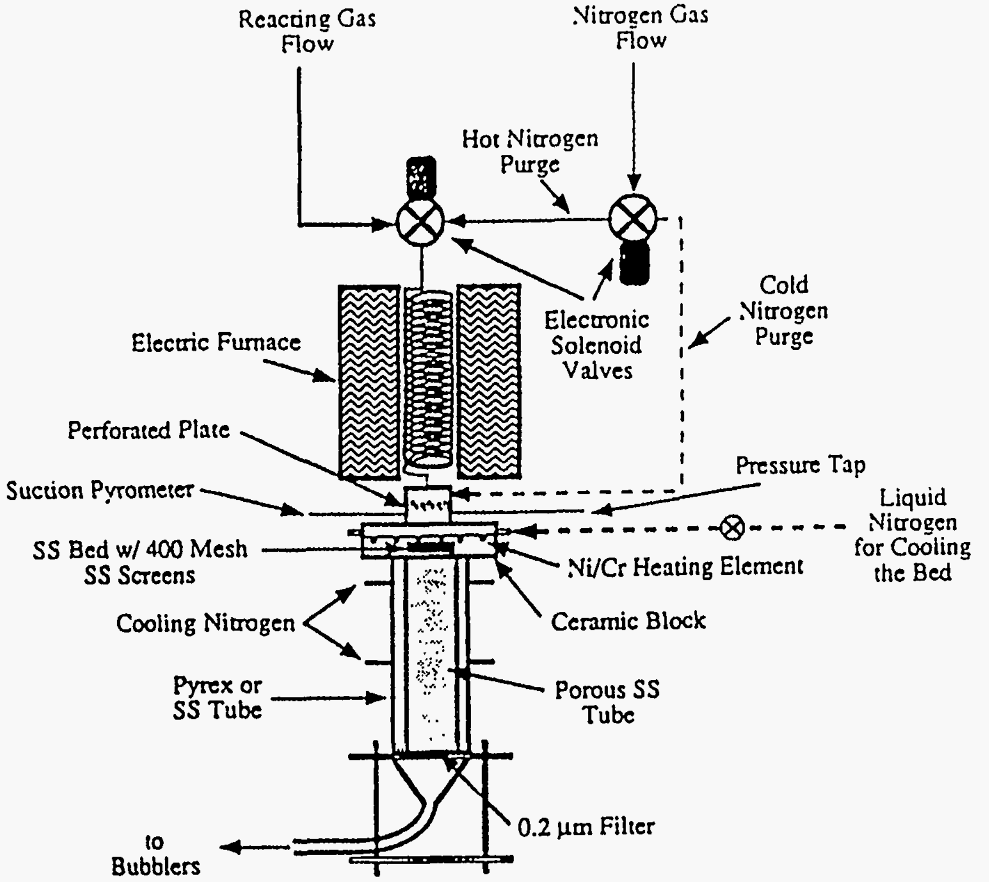


FIGURE 1 Differential-bed reactor (DBR) used for measuring metal vaporization rates

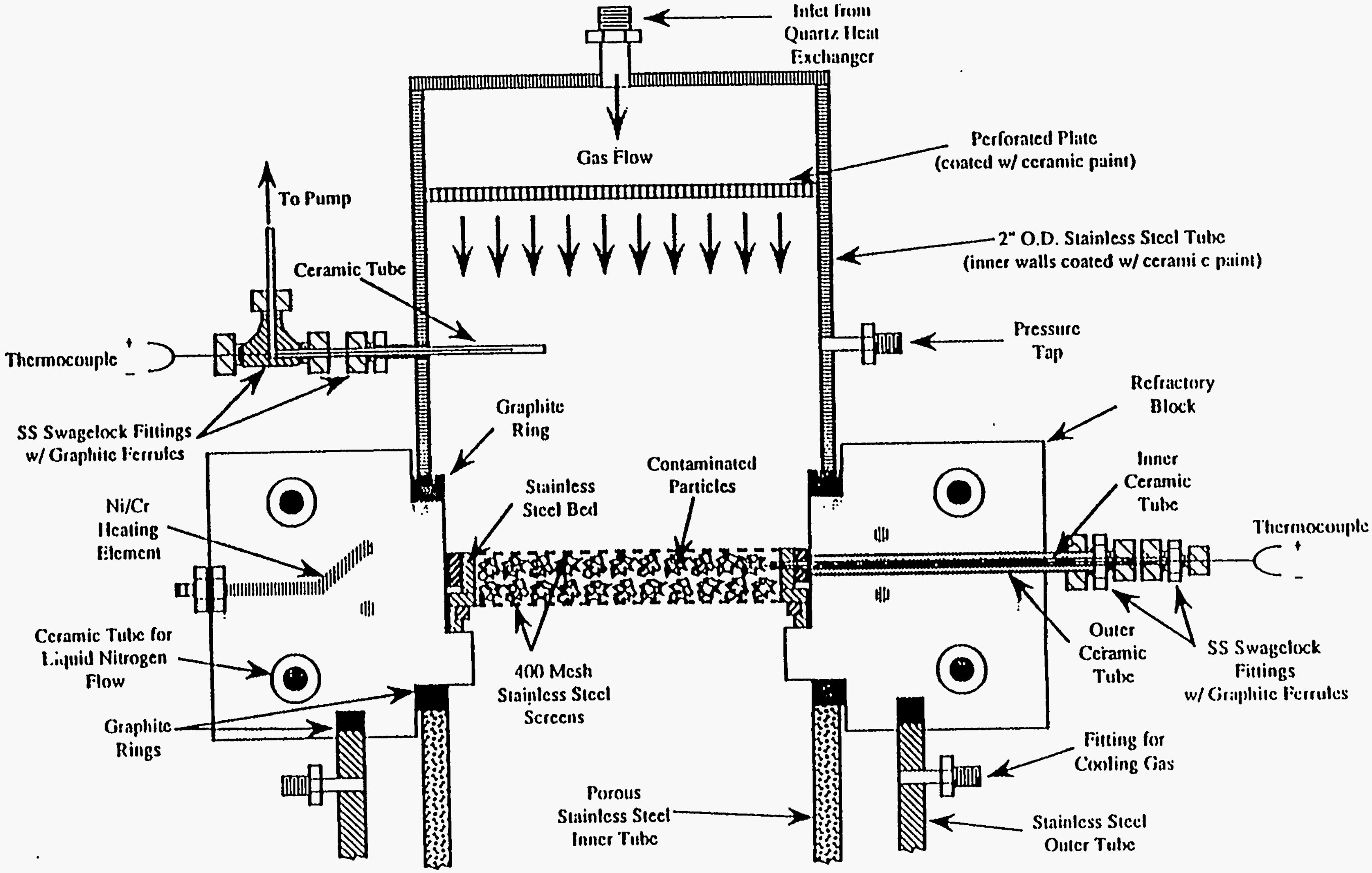


FIGURE 2 Cross-section of the refractory block and the upper transition section of the DBR.

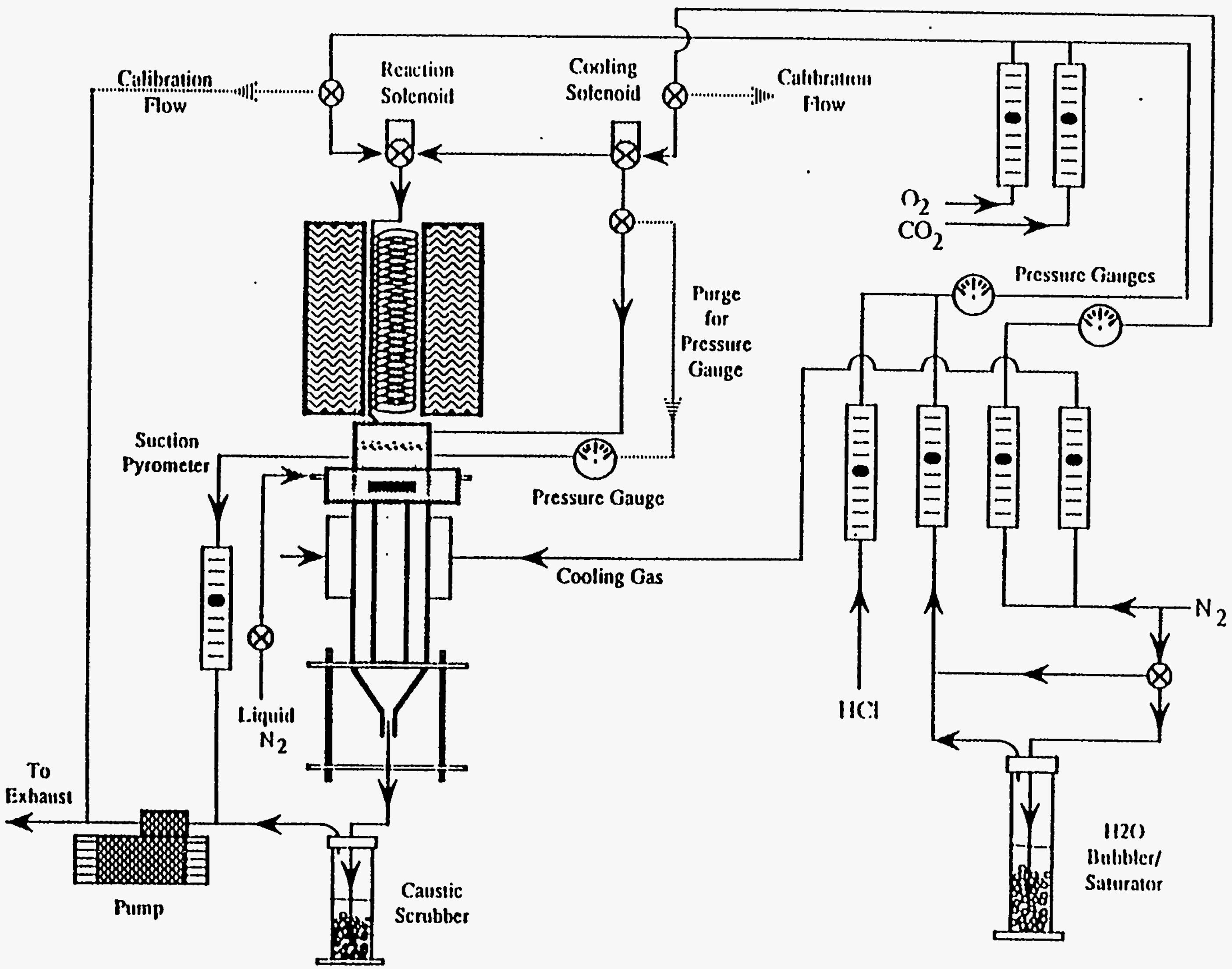


FIGURE 3 Overall flow layout of the DBR.

Thermal treatment process: SCK/CEN High temperature slagging incinerator (HTSI)

Location: Mol, Belgium

Mode of operation (continuous,batch): Continuous

Status: Operational (as of 1986)

Process description/size/dimensions/materials of construction:

The basic process includes a waste handling system, an incinerator, an offgas treatment system, and a slag recuperation and conditioning system. The incineration system is based upon the FLK technology for the conversion of mixed industrial refuse into usable energy by combustion and melting. This system was modified for remote operation and maintenance in an alpha-area. This installation consists of a fixed cylindrical outer shell, with a concentrical suspended inner cylinder, made gas tight by a water seal. This inner cylinder has two concentric cylinders - a rotating outer cylinder providing the distribution and the downwards motion of the waste from the waste inlet to the top of the bottom conus, and a fixed inner cylinder wherein the conical refractory lined flame-chamber is formed. The upper layer of the waste cone is exposed to intense heat from waste combustion and an auxiliary burner. The resulting heat melts the waste residues into a molten slag film at temperatures up to 1600°C. The slag flows along the slope of the chamber through the exit hole into a waterbath where it is quenched and then granulated. The system is designed to process 230 kg/h but usually handles between 25 and 30 kg/h.

Waste feed preparation/sorting/sizing requirements:

No requirements are mentioned but the process diagram shows the waste feed being fed to the incinerator by feedscrew (size unknown) suggesting some sorting and sizing of solid waste feed is necessary.

Air pollution control system components:

The process objective of the offgas treatment system is the removal of semivolatile radioactive components and other noxious or corrosive gases and vapors. The offgas exits the postcombustion chamber at 1000°C and is cooled to 800°C with fresh air. The offgas is then cooled to 200°C by contacting with atomized water in a cooling tower. The gas stream is passed through bagfilters to reduce dust content to less than 2 $mg.Nm^{-3}$. The filtered offgas then is sent through a venturi scrubber and washtower using alkaline solution to remove acid gases. After reheating to 90°C, the gas is finally passed through 3 batteries of HEPA filters in series.

References:

N. Van de Voorde, "High temperature slagging incinerator for alpha-contaminated wastes", *of Seminar Proceedings, Commission of European Communities*, Arnhem, Netherlands (1984).

D.M.J.G. Hennart, "Filtration and releases from the high-temperature slagging incineration pilot-plant at Mol, Belgium", *Proceedings of European Conference on Gaseous Effluent Treatment in Nuclear Installation*, (1985).

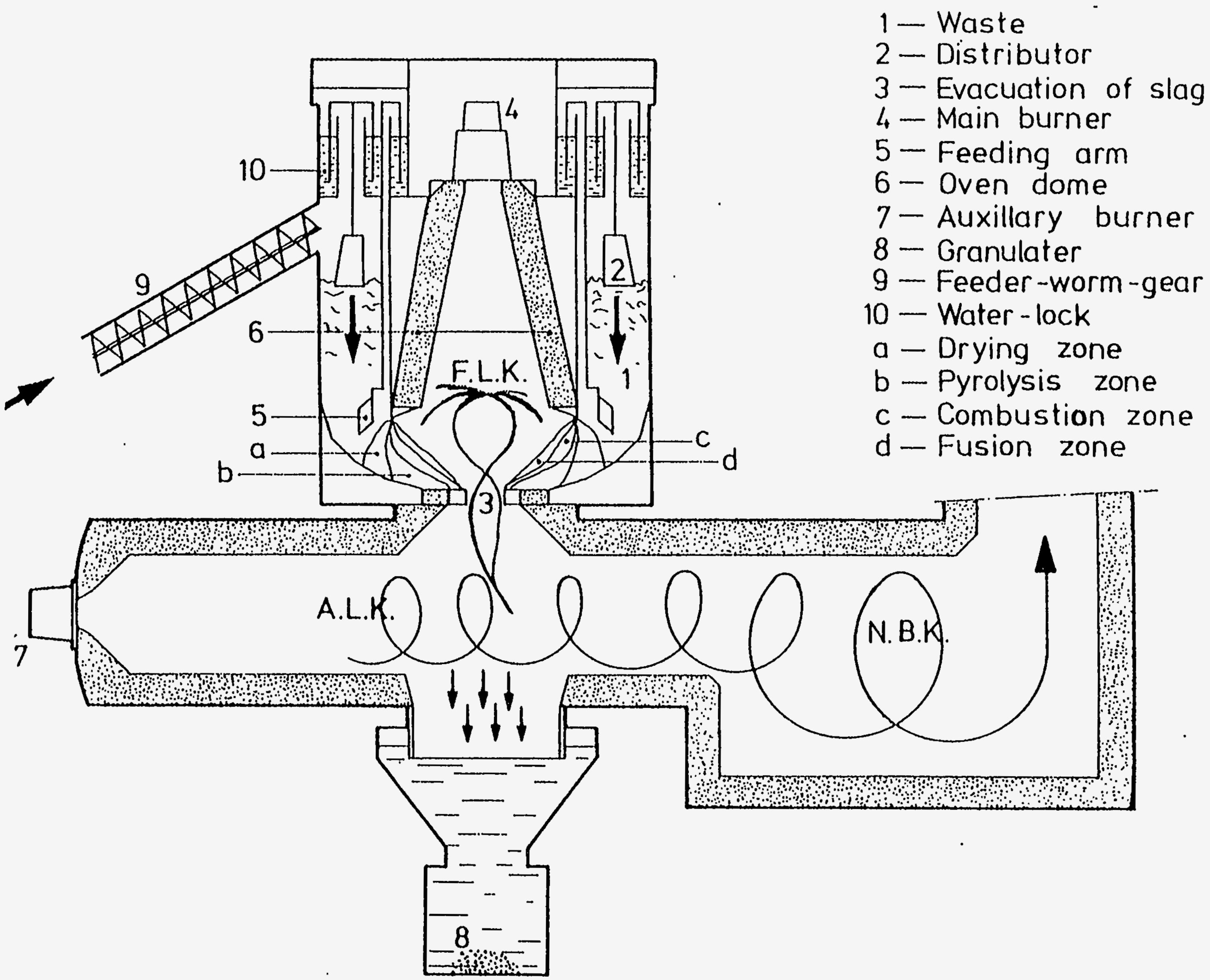


Figure 1. Schematic of FLK-60 high-temperature slagging incinerator. (1984)

Appendix C

Global Summaries of Selected Thermal Treatment Systems

GLOBAL TESTING SUMMARY
Thermal Treatment Process: PNNL Bench scale DC Arc Furnace (Rad)
Location: Pacific Northwest Laboratory, Richland, WA.

Test Series: Plutonium partitioning tests.
Dates/Time Frame: FY-95 and early FY-96
Purpose/Goal: A scoping study to obtain preliminary information on the fate of transuranic radionuclides processed in a graphite electrode DC arc furnace.

Test name or Feed type	Total operating time (hr)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	Avg melt temp (°C)	distribution of feed material to: (kg)				
						Slag/ash	Metal	Unmelted Material	Off gas	Closure (%)
Metals-R	4.60	1.1	0.795	0.480	698	0.368	0.410	0.021		
S-O	1.92	2.0	0.190	0.192	757	0.120	0	0.000		
1 Nom-60	2.17	2.0	0.773	0.726	926	0.452	0.027	0.000		
2 Nom-60 + lead	1.73	2.3	0.569	0.366	921	0.321	0.053	0.017		
3 Nom-60 + iron	2.27	unk	0.795	0.390	1116	0.334	0.237	0.038		
4 Nom-60 + sodium	2.52	2.7	0.793	0.372	886	0.395	0.078	0.035		
5 Nom-60 + chlorine	2.60	2.5	0.797	0.348	1388	0.383	0.085	0.037		
6 Nom-60 + carbon	1.85	1.7	0.745	0.444	885	0.200	0.004	0.485		
7 Nom-60 + oxygen	2.72	2.5	0.683	0.270	1308	0.475	0.082	0.040		
Totals or Averages	22.38	2.1	6.140		987	0.339	0.108	0.074		

Comments: The data for one test with Rocky Flats Pondcrete was not available.
Although CO_2 and O_2 gas volumes were measured, contributions from the melt material vs. other sources is unknown. Using the gas volumes listed in the data source yields mass closures of 200% and much greater.
unk - unknown

Besides using a high metals simulated waste stream (Metals-R) and a simulated organic waste stream (S-0), a nominal waste stream (NOM-60) consisting of a mixture of 60 wt% INEL soil and 40 wt% "average" or nominal waste was parametrically studied by varying specific compounds in the mixes as shown below.

	Nom-60 Minor Component Levels					
Test Number	Lead	Iron	Sodium	Chloride	Carbon	Plenum Oxygen
1	1X	1X	1X	1X	1X	LOW
2	**75X**	1X	1X	1X	1X	LOW
3	1X	**5X**	1X	1X	1X	LOW
4	1X	1X	**2.5X**	1X	1X	LOW
5	1X	1X	1X	**2X**	1X	LOW
6	1X	1X	1X	1X	**5X**	LOW
7	1X	1X	1X	1X	1X	**HIGH**

The compositions of INEL soil and the resulting Nom-60 test mixtures, plus the Metals-R and S-0 compositons are given below. An elemental mass balance for each test which includes plutonium is also given below. Results have been taken from the reference: C. J. Freeman, et. al., "Radioactive Waste Species Partitioning in the Bench-Scale Graphite Electrode DC Arc Furnace," PNNL, Richland, WA., July 1995.

Estimated Composition of INEL Soil

Constituent	wt%	Constituent	wt%	Constituent	wt%
Ag_2O	0.00	CuO	0.01	SO_4	0.05
Al_2O3	12.04	Fe_3O_4	4.75	SeO	0.00
As_2O_3	0.00	HgO	0.00	SiO_2	61.40
BaO	0.12	K_2O	2.32	TiO_2	0.66
$CaCO_3$	9.08	MgO	2.19	ZnO	0.02
CaO	0.24	MnO_2	0.11	ZrO_2	0.02
CdO	0.00	Na_2O	1.59	Cl	0.00
CeO_2	0.01	NiO	0.01	H_2O	5.13
Cr_2O_3	0.01	PO_4	0.24		
Cs_2O	0.00	PbO	0.00		

Elemental Compositions of Wastes Materials (wt %)

Constituents	Rocky Flats Pondcrete	Metals-R	S-O	Nom-60
Majors:				
O	45.0	24.0	19.0	38.0
Si	29.0	15.0	9.0	15.0
Fe	0.8	50.0	0.4	12.0
Ca	14.0	5.8	11.0	13.0
C	0.0	0.0	32.0	7.1
Cl	0.0	0.02	22.0	2.2
Al	2.0	3.4	0.4	4.0
Na	4.3	1.1	0.3	0.9
H	0.0	0.0	4.8	1.7
K	1.6	0.0	0.08	1.3
Mg	1.0	0.8	0.2	0.9
S	1.3	0.0	0.07	0.03
P	1.1	0.07	9.5E-3	0.04
Minors:				
Cr	9.0E-2	3.5E-2	9.7E-4	7.0E-1
Ag	0.0E+0	6.6E-1	8.1E-5	8.9E-5
Ni	1.6E-1	1.0E-2	1.1E-3	3.3E-1
Ti	4.0E-2	2.2E-1	2.0E-2	2.0E-1
Ce	0.0E+0	0.0E+0	1.7E-1	3.0E-1
N	0.0E+0	0.0E+0	9.0E-2	2.3E-1
Zr	0.0E+0	5.3E-3	9.1E-4	3.0E-1
Cu	5.0E-2	2.6E-3	4.0E-4	1.9E-1
Cs	0.0E+0	2.0E-1	1.5E-4	5.5E-4
Cd	1.5E-1	1.0E-2	1.3E-4	1.4E-4
Mn	4.0E-2	3.3E-2	0.0E+0	7.0E-2
Zn	9.0E-2	0.0E+0	1.4E-3	6.6E-3
Ba	3.0E-2	0.0E+0	2.0E-3	5.0E-2
Pb	0.0E+0	1.8E-3	1.0E-2	6.0E-2
Mo	0.0E+0	0.0E+0	0.0E+0	1.0E-2
As	0.0E+0	5.3E-3	3.8E-4	4.1E-4
Total:	100.7	101.4	99.5	98.7

Average Compositions of Nom-60 Test Matrix (wt%)

Elemental Name	Test Number						
	1	2	3	4	5	6	7
Ag	9E-5	8E-5	6E-5	9E-5	9E-5	7E-5	9E-5
Al	3.94	3.77	2.66	3.88	3.85	3.08	3.94
As	4E-4	4E-4	3E-4	4E-4	4E-4	3E-4	4E-4
Ba	0.05	0.05	0.03	0.05	0.05	0.04	0.05
C	7.00	6.70	4.72	6.90	6.85	27.33	7.00
Ca	14.40	13.79	9.72	14.20	14.09	11.25	14.40
Cd	1E-4	1E-4	9E-5	1E-4	1E-4	1E-4	1E-4
Ce	0.30	0.28	0.20	0.29	0.29	0.23	0.30
Cl	2.19	2.10	1.48	2.16	4.28	1.71	2.19
Cr	0.69	0.66	0.47	0.68	0.68	0.54	0.69
Cs	5E-4	5E-4	4E-4	5E-4	5E-4	4E-4	5E-4
Cu	0.19	0.18	0.13	0.19	0.18	0.15	0.19
F	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	12.04	11.54	40.64	11.88	11.79	9.41	12.04
H	1.68	1.61	1.14	1.66	1.65	1.31	1.68
Hf	3E-4	3E-4	2E-4	3E-4	3E-4	2E-4	3E-4
Hg	7E-6	7E-6	5E-6	7E-6	7E-6	5E-6	7E-6
K	1.31	1.25	0.88	1.29	1.28	1.02	1.31
Mg	0.90	0.86	0.61	0.89	0.88	0.70	0.90
Mn	7E-2	7E-2	5E-2	7E-2	7E-2	5E-2	7E-2
Mo	1E-2	9E-3	7E-3	1E-2	1E-2	8E-3	1E-2
N	0.23	0.22	0.15	0.22	0.22	0.18	0.23
Na	0.93	0.89	0.63	2.29	0.91	0.73	0.93
Ni	0.33	0.31	0.22	0.32	0.32	0.26	0.33
O	37.93	36.34	25.60	37.41	37.12	29.64	37.93
P	0.04	0.04	0.03	0.04	0.04	0.03	0.04
Pb	0.06	4.27	0.04	0.06	0.06	0.05	0.06
Pu (nCi/g)	300	300	300	300	300	300	300
S	0.03	0.03	0.02	0.03	0.03	0.02	0.03
Se	9E-5	8E-5	6E-5	9E-5	9E-5	7E-5	9E-5
Si	15.19	14.55	10.25	14.98	14.87	11.87	15.19
Ti	0.20	0.19	0.13	0.20	0.19	0.15	0.20
Zn	7E-3	6E-3	4E-3	6E-3	6E-3	5E-3	7E-3
Zr	0.30	0.28	0.20	0.29	0.29	0.23	0.30
Plenum O2	Low	Low	Low	Low	Low	Low	High

Table 4.2. (Part 1) Mass Balance Results for Bench-Scale DC Arc Testing

Element	Metals-R			S-O		Nom-60		
	Feed Mass Partitioned to Glass	Feed Mass Partitioned to Metal	Feed Mass Partitioned to Off-gas	Feed Mass Partitioned to Glass	Feed Mass Partitioned to Off-gas	Feed Mass Partitioned to Glass	Feed Mass Partitioned to Metal	Feed Mass Partitioned to Off-gas
Ag	39% ± 8%	<DL	0.26% ± 0.04%	59% ± 13%	0.5% ± 0.09%	<DL	<DL	<DL
Al	62% ± 13%	1.4% ± 0.3%	0.07% ± 0.01%	137% ± 30%	1.1% ± 0.18%	107% ± 22%	0.38% ± 0.10%	0.7% ± 0.12%
B	143% ± 30%	25% ± 5%	41% ± 7%	20% ± 4%	18% ± 3%	77% ± 16%	5.8% ± 1.6%	282% ± 47%
Ba	60% ± 13%	3.1% ± 0.6%	0.13% ± 0.02%	82% ± 18%	1.1% ± 0.19%	104% ± 22%	0.62% ± 0.17%	0.43% ± 0.07%
Ca[a]	54% ± 11%	1.8% ± 0.4%	0.6% ± 0.1%	116% ± 25%	1.5% ± 0.2%	97% ± 20%	0.31% ± 0.08%	0.6% ± 0.1%
Cd	44% ± 9%	<DL	0.01% ± 0.00%	78% ± 17%	0.01% ± 0.00%	237% ± 49%	1.6% ± 0.4%	0.16% ± 0.03%
Cr	<DL	<DL	<DL	<DL	<DL	2209% ± 461%	42% ± 12%	2.0% ± 0.3%
Ce	63% ± 13%	32% ± 6%	1.2% ± 0.2%	63% ± 14%	1.3% ± 0.2%	10% ± 2%	1.4% ± 0.4%	2.4% ± 0.4%
Fe	74% ± 15%	1435% ± 285%	0.03% ± 0.01%	58% ± 13%	0.5% ± 0.08%	8% ± 2%	40% ± 11%	0.08% ± 0.01%
K	45% ± 9%	<DL	0.18% ± 0.03%	63% ± 14%	1.0% ± 0.17%	28% ± 6%	<DL	9% ± 1.55%
La	44% ± 9%	<DL	0.04% ± 0.01%	71% ± 16%	<DL	<DL	<DL	<DL
Li	48% ± 10%	<DL	0.15% ± 0.02%	57% ± 12%	1.5% ± 0.25%	<DL	<DL	<DL
Mg[a]	58% ± 12%	1.9% ± 0.4%	1.0% ± 0.2%	63% ± 14%	5.1% ± 0.8%	98% ± 20%	0.27% ± 0.07%	2.4% ± 0.4%
Mn	53% ± 11%	6.4% ± 1.3%	0.05% ± 0.01%	52% ± 11%	1.2% ± 0.20%	127% ± 26%	1.4% ± 0.4%	0.5% ± 0.1%
Mo	<DL	<DL	<DL	<DL	<DL	<DL	36% ± 10%	<DL
Na	NR	0.0% ± 0.0%	0.01% ± 0.00%	NR	0.02% ± 0.00%	NR	0.00% ± 0.00%	0.03% ± 0.01%
Nd	47% ± 10%	13% ± 3%	0.03% ± 0.00%	61% ± 13%	<DL	22% ± 5%	3.1% ± 0.8%	0.23% ± 0.04%
Ni	56% ± 12%	34% ± 7%	0.08% ± 0.01%	45% ± 10%	0.16% ± 0.03%	1312% ± 274%	149% ± 40%	0.15% ± 0.02%
P	43% ± 9%	36% ± 7%	0.13% ± 0.02%	62% ± 14%	1.0% ± 0.17%	<DL	<DL	<DL
Pb[e]	<DL	<DL	<DL	<DL	34.2% ± 6%	<DL	<DL	18.8% ± 3%
Pu[f]	213% ± 142%	2.9% ± 0.5%	0.01% ± 0.00%	429% ± 288%	0.11% ± 0.02%	133% ± 89%	0.43% ± 0.11%	0.21% ± 0.04%
S	<DL	<DL	<DL	65% ± 14%	6.5% ± 1.1%	75% ± 16%	<DL	2.8% ± 0.5%
Si[a]	53% ± 11%	1.7% ± 0.3%	0.00% ± 0.00%	70% ± 15%	0.04% ± 0.01%	100% ± 21%	1.7% ± 0.5%	3.1% ± 0.51%
Sr	55% ± 11%	<DL	0.14% ± 0.02%	97% ± 21%	1.4% ± 0.24%	96% ± 20%	0.33% ± 0.09%	0.39% ± 0.07%
Ti	58% ± 12%	1.2% ± 0.2%	0.01% ± 0.00%	47% ± 10%	0.15% ± 0.03%	108% ± 23%	0.32% ± 0.09%	0.15% ± 0.02%
U	47% ± 10%	<DL	0.00% ± 0.00%	59% ± 13%	± 0.00%	28% ± 6%	1.6% ± 0.4%	<DL
V	45% ± 9%	53% ± 11%	0.05% ± 0.01%	55% ± 12%	0.25% ± 0.04%	50% ± 10%	18% ± 5%	<DL
Zn	<DL	<DL	<DL	<DL	13% ± 2%	26% ± 5%	1.0% ± 0.3%	6% ± 1%
Zr[c]	NR	<DL	0.00% ± 0.00%	NR	<DL	NR	0.76% ± 0.21%	0.16% ± 0.03%

<DL At least one analytical value in calculation was less than its detection limit.
NR At least one analytical value in calculation was not reported.
a. Particulate filter sample values potentially elevated from glass filter contamination.
b. Data from fusions possibly high due to additions of sodium peroxide & hydroxide.
c Data from fused samples possibly elevated from Zr crucible contamination.
d Particulate filter analyses of Ce performed by ICP-MS.
e Feed values were taken from targets as analytical values were below detection levels.
f. Values determined from scintillation counting analyses, a total alpha measurement.

Table 4.2. (Part 2) Mass Balance Results for Bench-Scale DC Arc Testing

Element	Nom-60 with Elevated Lead			Nom-60 with Elevated Iron			Nom-60 with Elevated Sodium		
	Feed Mass Partitioned to Glass	Feed Mass Partitioned to Metal	Feed Mass Partitioned to Off-gas	Feed Mass Partitioned to Glass	Feed Mass Partitioned to Metal	Feed Mass Partitioned to Off-gas	Feed Mass Partitioned to Glass	Feed Mass Partitioned to Metal	Feed Mass Partitioned to Off-gas
Ag	1.7% ± 0.4%	0.85% ± 0.19%	<DL	44% ± 11%	6% ± 2%	0.07% ± 0.01%	<DL	<DL	<DL
Al	35% ± 7%	0.12% ± 0.03%	0.9% ± 0.14%	101% ± 17%	1% ± 0.1%	1.3% ± 0.16%	87% ± 13%	5% ± 0.8%	2.3% ± 0.20%
B	5.9% ± 1.2%	2.1% ± 0.5%	98% ± 16%	40% ± 9%	21% ± 4%	95% ± 17%	<DL	25% ± 10%	451% ± 169%
Ba	30% ± 6%	0.39% ± 0.09%	0.47% ± 0.08%	86% ± 15%	4% ± 0.7%	0.52% ± 0.06%	88% ± 14%	6% ± 0.9%	1.1% ± 0.10%
Ca [a]	31% ± 6%	0.10% ± 0.02%	0.63% ± 0.1%	104% ± 16%	1% ± 0.1%	1.0% ± 0.1%	72% ± 11%	4% ± 0.6%	1.2% ± 0.1%
Ce	25% ± 5%	0.61% ± 0.13%	0.04% ± 0.01%	82% ± 13%	5% ± 1%	0.02% ± 0.00%	244% ± 38%	31% ± 5%	0.2% ± 0.02%
Cr	<DL	<DL	<DL	59% ± 12%	8% ± 2%	0.03% ± 0.0%	822% ± 423%	144% ± 74%	<DL
Co	6.6% ± 1.4%	8.7% ± 1.9%	0.32% ± 0.1%	9% ± 1%	144% ± 21%	0.61% ± 0.1%	30% ± 5%	20% ± 3%	0.9% ± 0.1%
Fe	5.3% ± 1.1%	34% ± 7%	0.06% ± 0.01%	9% ± 1%	77% ± 11%	0.07% ± 0.01%	18% ± 3%	110% ± 18%	0.18% ± 0.02%
K	4.0% ± 0.8%	0.4% ± 0.1%	1.4% ± 0.24%	44% ± 10%	4% ± 1%	0.61% ± 0.11%	<DL	1% ± 0%	3.2% ± 0.40%
La	4.9% ± 1.0%	<DL	<DL	54% ± 12%	5% ± 1%	0.11% ± 0.02%	<DL	<DL	<DL
Li	<DL	<DL	<DL	51% ± 11%	<DL	0.18% ± 0.03%	<DL	<DL	<DL
Mg [a]	28% ± 6%	0.19% ± 0.04%	2.8% ± 0.5%	91% ± 15%	3% ± 0.4%	4.2% ± 0.4%	71% ± 11%	5% ± 0.7%	7.4% ± 0.7%
Mn	39% ± 8%	0.70% ± 0.15%	0.35% ± 0.06%	86% ± 14%	5% ± 0.7%	0.38% ± 0.04%	100% ± 16%	17% ± 2.6%	0.33% ± 0.03%
Mo	3.4% ± 0.7%	23% ± 5%	<DL	<DL	165% ± 30%	0.06% ± 0.01%	47% ± 17%	83% ± 30%	<DL
Na	NR	0.00% ± 0.00%	0.09% ± 0.02%	NR	0% ± 0.0%	0.04% ± 0.00%	NR	0.01% ± 0.0%	0.08% ± 0.01%
Nd	2.0% ± 0.4%	1.3% ± 0.3%	0.44% ± 0.07%	48% ± 10%	9% ± 2%	0.10% ± 0.02%	<DL	8% ± 1%	<DL
Ni	6.3% ± 1.1%	112% ± 25%	0.26% ± 0.04%	9% ± 2%	185% ± 33%	0.06% ± 0.01%	33% ± 12%	535% ± 197%	0.54% ± 0.19%
P	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL
Pb	2.9% ± 0.6%	2.3% ± 0.5%	10.4% ± 2%	<DL	38.6% ± 5%	148% ± 13%	<DL	<DL	6.5% ± 1%
Pu [f]	71% ± 47%	0.39% ± 0.07%	0.49% ± 0.09%	107% ± 72%	0.87% ± 0.17%	0.23% ± 0.04%	113% ± 75%	7.9% ± 1.3%	0.12% ± 0.02%
S	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	2.9% ± 0.3%
Si [a]	36% ± 8%	0.87% ± 0.19%	3.7% ± 0.61%	106% ± 17%	2% ± 0.3%	4.9% ± 0.51%	91% ± 14%	3.5% ± 0.5%	9.6% ± 0.86%
Sr	30% ± 6%	<DL	0.32% ± 0.05%	88% ± 14%	<DL	0.39% ± 0.04%	75% ± 12%	4.0% ± 0.6%	0.50% ± 0.04%
Ti	35% ± 7%	0.12% ± 0.03%	0.12% ± 0.02%	102% ± 17%	1% ± 0.1%	0.16% ± 0.02%	96% ± 15%	6.6% ± 1.0%	0.30% ± 0.03%
U	4.5% ± 0.9%	0.97% ± 0.21%	<DL	50% ± 10%	6% ± 1%	<DL	<DL	<DL	<DL
V	<DL	<DL	<DL	40% ± 8%	19% ± 3%	<DL	<DL	<DL	<DL
Zn	<DL	<DL	<DL	<DL	<DL	<DL	<DL	2.9% ± 0.7%	2.2% ± 0%
Zr [c]	NR	0.22% ± 0.05%	0.20% ± 0.03%	NR	0.11% ± 0.02%	0.02% ± 0.00%	NR	3.37% ± 0.73%	0.28% ± 0.05%

<DL At least one analytical value in calculation was less than its detection limit.

NR At least one analytical value in calculation was not reported.

a. Particulate filter sample values potentially elevated from glass filter contamination.

b. Data from fusions possibly high due to additions of sodium peroxide & hydroxide.

c Data from fused samples possibly elevated from Zr crucible contamination.

d Particulate filter analyses of Ce performed by ICP-MS.

e Feed values were taken from targets as analytical values were below detection levels.

f. Values determined from scintillation counting analyses, a total alpha measurement.

Table 4.2. (Part 3) Mass Balance Results for Bench-Scale DC Arc Testing

Element	Nom-60 with Elevated Chloride			Nom-60 with Elevated Carbon			Nom-60 with Elevated Plenum Oxygen		
	Feed Mass Partitioned to Glass	Feed Mass Partitioned to Metal	Feed Mass Partitioned to Off-gas	Feed Mass Partitioned to Glass	Feed Mass Partitioned to Metal	Feed Mass Partitioned to Off-gas	Feed Mass Partitioned to Glass	Feed Mass Partitioned to Metal	Feed Mass Partitioned to Off-gas
Ag	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL
Al	91% ± 19%	12% ± 0.4%	1.4% ± 0.23%	136% ± 19%	2.02% ± 0.4%	3.7% ± 0.61%	115% ± 24%	3.0% ± 0.6%	2.2% ± 0.36%
B	<DL	33% ± 7%	241% ± 40%	99% ± 16%	4.3% ± 0.9%	448% ± 74%	57% ± 12%	<DL	366% ± 61%
Ba	86% ± 18%	.3% ± 0.5%	1.0% ± 0.17%	120% ± 17%	0.76% ± 0.16%	3.1% ± 0.51%	108% ± 22%	2.8% ± 0.6%	1.0% ± 0.17%
Ca [a]	78% ± 16%	2% ± 0.4%	1.2% ± 0.2%	86% ± 12%	0.49% ± 0.10%	2.6% ± 0.4%	93% ± 19%	1.6% ± 0.3%	1.6% ± 0.3%
Ce [d]	78% ± 16%	<DL	0.23% ± 0.04%	106% ± 15%	3.3% ± 0.7%	0.6% ± 0.10%	191% ± 40%	12% ± 2%	0.33% ± 0.05%
Cr	101% ± 21%	88% ± 18%	0.18% ± 0.0%	2728% ± 392%	328% ± 67%	2.2% ± 0.4%	157% ± 33%	57% ± 12%	0.86% ± 0.1%
Co	31% ± 6%	139% ± 29%	9.5% ± 1.6%	330% ± 48%	44% ± 9%	5.4% ± 0.9%	72% ± 15%	128% ± 27%	10% ± 1.6%
Fe	14% ± 3%	127% ± 26%	0.43% ± 0.07%	400% ± 58%	40% ± 8%	0.9% ± 0.16%	42% ± 9%	518% ± 107%	0.31% ± 0.05%
K	<DL	<DL	20% ± 3.35%	<DL	<DL	18% ± 3.02%	<DL	<DL	19% ± 3.16%
La	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL
Li	<DL	<DL	6.5% ± 1.08%	<DL	<DL	5.3% ± 0.88%	<DL	<DL	2.7% ± 0.46%
Mg [a]	74% ± 15%	2% ± 0.5%	4.3% ± 0.7%	81% ± 12%	0.33% ± 0.07%	17.1% ± 2.8%	83% ± 17%	3.1% ± 0.6%	8.5% ± 1.4%
Mn	77% ± 16%	4% ± 0.8%	1.3% ± 0.22%	282% ± 41%	18.6% ± 3.8%	11.0% ± 1.82%	143% ± 30%	7.4% ± 1.5%	1.5% ± 0.25%
Mo	<DL	22% ± 5%	0.15% ± 0.03%	<DL	<DL	<DL	<DL	18% ± 4%	0.79% ± 0.13%
Na	NR	<DL	0.07% ± 0.01%	NR	0.00% ± 0.00%	0.09% ± 0.01%	NR	0.0% ± 0.0%	0.10% ± 0.02%
Nd	<DL	<DL	<DL	<DL	0.7% ± 0.2%	<DL	<DL	18% ± 4%	<DL
Ni	14% ± 3%	226% ± 47%	0.28% ± 0.05%	759% ± 109%	97% ± 20%	2.2% ± 0.37%	41% ± 9%	110% ± 23%	0.9% ± 0.15%
P	<DL	39% ± 8%	1.1% ± 0.19%	126% ± 23%	3.5% ± 0.7%	2.2% ± 0.36%	<DL	17% ± 4%	1.3% ± 0.22%
Pb	<DL	<DL	64.6% ± 11%	<DL	<DL	25.4% ± 4%	<DL	<DL	31.9% ± 5%
Pu [f]	112% ± 73%	2.28% ± 0.38%	1.01% ± 0.18%	227% ± 151%	14.0% ± 2.4%	3.1% ± 0.55%	141% ± 93%	2.82% ± 0.47%	0.59% ± 0.10%
S	<DL	<DL	4.0% ± 0.7%	48% ± 10%	<DL	1.6% ± 0.3%	<DL	<DL	9% ± 1.5%
Si [a]	90% ± 19%	13% ± 2.6%	3.6% ± 0.59%	163% ± 23%	4.5% ± 0.9%	1.8% ± 0.30%	116% ± 24%	7.9% ± 1.6%	1.6% ± 0.26%
Sr	83% ± 17%	12% ± 0%	0.81% ± 0.13%	86% ± 12%	0.43% ± 0.09%	1.6% ± 0.26%	97% ± 20%	1.8% ± 0.4%	0.78% ± 0.13%
Ti	96% ± 20%	2% ± 0.4%	0.28% ± 0.05%	247% ± 36%	13.9% ± 2.9%	1.4% ± 0.23%	122% ± 25%	2.7% ± 0.5%	0.28% ± 0.05%
U	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL
V	<DL	37% ± 8%	<DL	<DL	10.9% ± 2.2%	<DL	<DL	50% ± 10%	<DL
Zn	<DL	<DL	31% ± 5%	<DL	1.82% ± 0.37%	67% ± 11%	219% ± 46%	9.3% ± 1.9%	30% ± 5%
Zr [c]	NR	0.81% ± 0.17%	0.05% ± 0.01%	NR	0.64% ± 0.13%	0.03% ± 0.00%	NR	0.19% ± 0.04%	0.05% ± 0.01%

<DL At least one analytical value in calculation was less than its detection limit.
NR At least one analytical value in calculation was not reported.
a. Particulate filter sample values potentially elevated from glass filter contamination.
b. Data from fusions possibly high due to additions of sodium peroxide & hydroxide.
c Data from fused samples possibly elevated from Zr crucible contamination.
d Particulate filter analyses of Ce performed by ICP-MS.
e Feed values were taken from targets as analytical values were below detection levels.
f. Values determined from scintillation counting analyses, a total alpha measurement.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: INEL Small Arc Melter
Location: Idaho Research Center, Idaho Falls, ID

Test Series: Small Arc Melter Development Tests (Initial)
Dates/Time Frame: June, 1992
Purpose/Goal: Initial development tests of the small DC arc melter

Test name or Feed type	Total operating time (hr)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	Avg melt temp (°C)	% distribution of feed material to:				
						Slag/ash	Metal	APCS solids	Off gas	Closure
RWMC soil	0	n/a	n/a	n/a	n/a					
RWMC soil	0.25	7	5.8	n/a	unk					
RWMC soil	0.50	32	5.8	n/a	unk					
RWMC soil	0.30	unk	6.7	n/a	unk					
RWMC soil	0.30	20	6.7	n/a	unk					
IEB/A-40	0.95	21	6.7	n/a	1500					
IEB4/A-40	1.08	17	7.4	n/a	1550					
Totals or Averages	3.38	19	39.1		1525					

Comments: First series of development tests. No distribution data available.
The melter was operated only in batch mode. Only the last 2 tests were completely successful.
unk - unknown
n/a - not applicable

Test Series: Small Arc Melter Development Tests (Follow on)
Dates/Time Frame: August & September , 1992
Purpose/Goal: Development tests of the small DC arc melter

Test name or Feed type	Total operating time (hr)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	Avg melt temp (°C)	% distribution of feed material to:				
						Slag/ash	Metal	APCS solids	Off gas	Closure
RWMC soil	1.17	12.5	10.0	n/a	1500					
IEB4/A-40	1.63	16	10.0	n/a	unk					
RWMC soil + H1-0	2.33	25	6.0 + 0.7	unk	(1450)[1]					
RWMC soil + H1-0 + Aluminum	1.27	14	3.0 + 1.3 + 0.3	unk	1695 (1450)[2]					
RWMC soil + steel	1.07	18	6.0 + 2.0	unk	unk					
RWMC soil + steel	1.58	22	6.0 + 2.0	unk	(2200)[1]					
RWMC soil + soil + steel	2.0	35	6.0 + 4.0 + 2.0	unk	1550					
Totals or Averages	11.05	20	59.3		1679					

Comments: Second series of development tests. No distribution data available.
Additional materials were fed in manually through a 1.5 inch diameter ceramic feeder tube extended into the melt chamber.
[1] - single thermocouple reading.
[2] - pyrometer measurement of surface temperature (not included in average)
unk - unknown
n/a - not applicable

Weight percent compositions for feed materials in the initial and follow on arc melter tests.

	SiO_2	Al_2O_3	FeO-Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2
Average Waste	38.0	7.4	34.5	8.3	4.6	4.8	2.4	-
A-40	51.0	10.2	19.5	9.7	3.5	3.2	2.6	0.3
H1-0*	25.2	7.0	29.6	12.9	3.0	15.9	2.6	0.1
RWMC Soil	65.4	13.0	4.5	10.2	2.4	1.7	2.9	0.6

* - plus 3.8 wt% miscellaneous

GLOBAL TESTING SUMMARY
Thermal Treatment Process: Modified (I) INEL Arc Melter
Location: Idaho Research Center, Idaho Falls, ID

Test Series: Small Arc Melter Development Tests
Dates/Time Frame: February and March, 1993
Purpose/Goal: Development tests of the modified small DC arc melter

Test name or Feed type	Total operating time (hr)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	Avg melt temp (°C)	% distribution of feed material to:				
						Slag/ash	Metal	APCS solids	Off gas	Closure
RWMC soil	0.83	25	10.0	n/a	(1300)[2]					
IEB4/A-80	0.50	15	6.0	n/a	(1520)[1]					
IEB4/A-80 + IEB4/A-40 + Alkali mix	2.33	20	6.0 + 2.0 + 2.0	?	(1517)[1]					
IEB4/A-80	1.55	24	6.0	n/a	(1695)[1] (1400)[2]					
Totals or Averages	5.21	21	32.0		1577					

Comments: Initial tests of the modified arc melter. No distribution data available.
Materials were fed using an auger feeder system.
[1] - single thermocouple reading
[2] - pyrometer measurement of surface temperature (not included in average)
unk - unknown
n/a - not applicable

Test Series: Volatilization Testing Program (HVPM's and Surrogates)
Dates/Time Frame: June & July, 1993
Purpose/Goal: Test the volatilization of selected HVPM's and radionuclide surrogates as a function of reducing/oxidizing conditions in the melter.

Test name or Feed type	Total operating time (hr)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	(kWh/kg) Avg melt temp (°C)	% distribution of feed material to:				
						Slag/ash	Metal	APCS solids	Off gas	Closure
IEB4/A-80/H/S + IEB4/A-40/H/S	2.82	16.5	6.0 + 1.0	3.5	1343					
IEB4/A-80 + IEB4/A-40/H/S	2.08	22/31	6.0	4.0	(1650)[1] (1500)[2]					
IEB4/A-80 + IEB4/A-40/H/S	1.63	unk	6.0 + 1.0	4.0	(1900)[1] (1300)[2]					
(remelt of above) + Alkali	1.00	18	(7.0) + 0.7	n/a	unk					
(remelt of above) + IEB4/A-40/H/S + Alkali	2.27	18	(7.7) + 1.5 + 0.9	2.0	1570					
(remelt of above) + IEB4/A-40 IEB4/A-40+H+S	2.40	16/7	(10.1) + 0.5 + 2.0	4.0	1730/1440					
Totals or Averages	12.20	18	25.7	3.5	1605					

Comments: No distribution data available. Materials were fed using an auger feeder system.

[1] - single thermocouple reading

[2] - pyrometer measurement of surface temperature (not included in average)

H - high vapor pressure metals (as oxides) at 1 wt% loading

S - surrogate radionuclides (as oxides) at 1 wt% loading

unk - unknown

n/a - not applicable

Test Series: Volatilization Testing Program (Cold Cap Tests)
Dates/Time Frame: July, 1993
Purpose/Goal: Test the effectiveness of cold cap conditions to reduce volatilization of selected HVPM's and radionuclide surrogates.

Test name or Feed type	Total operating time (hr)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	(kWh/kg) Avg melt temp (°C)	% distribution of feed material to:				
						Slag/ash	Metal	APCS solids	Off gas	Closure
IEB4/A-80 + IEB4/A-40/H/S	1.03	16	6.0 + 7.0	120/6	(2300)[1]					
IEB4/A-80 + IEB4/A-40/H/S	1.87	16/3	6.0 + 3.2	120/6	1340					
IEB4/A-80 + IEB4/A-40/H/S	1.43	17/12	6.0 + 5.7	198/25	1900					
IEB4/A-80	1.03	17	6.0	n/a	unk					
IEB4/A-80 + IEB4/A-40/H/S	1.33	15	6.0 + 4.0	198	2000					
Totals or Averages	6.69	14	49.9	159/12	1885					

Comments: No distribution data available. Materials were fed using an auger feeder system. Dual numbers in feedrate column indicate the high rate used to establish the cold cap and a slow rate needed to maintain it.

[1] - single thermocouple reading

H - high vapor pressure metals (as oxides) at 1 wt% loading

S - surrogate radionuclides (as oxides) at 1 wt% loading

unk - unknown

n/a - not applicable

Test Series:	Volatilization and Redox Program (Redox Tests)
Dates/Time Frame:	July & August, 1993
Purpose/Goal:	Test the overall effect of reducing vs. oxidizing melt conditions on HVPM and surrogate retention in the slag.

Test name or Feed type	Total operating time (hr)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	(kWh/kg) Avg melt temp (°C)	% distribution of feed material to:				
						Slag/ash	Metal	APCS solids	Off gas	Closure
IEB4/A-40/H/S + carbon	1.83	12	6.0/0.08	n/a	1470					
IEB4/A-40/H/S + carbon	1.58	12	6.0/0.32	n/a	1570					
IEB4/A-40/H/S + air	1.92	7	6.0	n/a	1610					
IEB4/A-40/H/S + air	2.08	17/13	6.0	n/a	1700					
IEB4/A-40/H/S + air	1.58	unk	6.0	n/a	1700					
(remelt of above) + air	2.00	18	(6.0)	n/a	1700					
Totals or Averages	11.00	13								

Comments: No distribution data available.
Carbon was added as part of the starting material. Air was introduced by means of a water cooled lance injected into the melt.
Remelts resulted from conditions either that required shutdown of the melter for emergency reasons (water leaks, etc.) or that resulted in test objectives not being fulfilled.

H - high vapor pressure metals (as oxides) at 1 wt% loading
S - surrogate radionuclides (as oxides) at 1 wt% loading
unk - unknown
n/a - not applicable

Test Series: PSPI proof tests
Dates/Time Frame: August & September, 1993.
Purpose/Goal: Prepare specimens for analytical, mechanical and leach testing.

Test name or Feed type	Total operating time (hr)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	(kWh/kg) Avg melt temp (°C)	% distribution of feed material to:				
						Slag/ash	Metal	APCS solids	Off gas	Closure
IEB/A-40/H/S	1.20	14	8.5	n/a	1622[1]					
remelt of above	1.70	14	(8.5)	n/a	1570[1]					
ASG/A-40/H/S	0.72	16	10.0	n/a	1600[1]					
(remelt of above)	1.75	17	(10.0)	n/a	1740[1]					
(remelt of above)	1.13	16	(10.0)	n/a	1600[1]					
IEB4/A-40/H/S	0.47	9	9.0	n/a	unk					
(remelt of above)	2.50	4	(9.0)	n/a	1490[1]					
(remelt of above)	2.25	10	(9.0)	n/a	unk					
IEB4/H1-40/H/S	2.33	14	9.0	n/a	1570					
Totals or Averages	14.05	13	36.5		1600					

Comments: No distribution data available. Remelts in these tests resulted from excess foaming of slag after starting the melt. These conditions may have been the result of a pinhole water leak in the stainless steel water cooled crucible.

[1] - single thermocouple reading
H - high vapor pressure metals (as oxides) at 1 wt% loading
S - surrogate radionuclides (as oxides) at 1 wt% loading
unk - unknown
n/a - not applicable

Test Series: Waste Stream Limits testing series.
Dates/Time Frame: August & September, 1993.
Purpose/Goal: Prepare specimens for analytical, mechanical and leach testing.

Test name or Feed type	Total operating time (hr)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	(kWh/kg) Avg melt temp (°C)	% distribution of feed material to:				
						Slag/ash	Metal	APCS solids	Off gas	Closure
IEB4/H1-0/H/S	1.55	9	6.0	n/a	1205[2]					
remelt of above	1.25	10	(6.0)	n/a	1210[2]					
IEB4/H-20/H/S	1.67	11	6.0	n/a	1103[2]					
(remelt of above)	1.80	8	(6.0)	n/a	1400 1020[2]					
IEB4/H-60/H/S	1.88	11	6.0	n/a	1650[1]					
(remelt of above)	1.25	12	(6.0)	n/a	unk					
IEB4/H-80/H/S	3.25	14	6.0	n/a	1820[1]					
IEB4/H-100/H/S	2.33	10	6.0	n/a	unk					
(remelt of above)	1.75	12	(6.0)	n/a	unk					
Totals or Averages	16.73	11	30.0		1623					

Comments: No distribution data available. Remelts in these tests usually resulted from excess foaming of slag after starting the melt. These conditions may have been the result of a pinhole water leak in the stainless steel water cooled crucible.

[1] - single thermocouple reading
[2] - pyrometer measurement of surface temperature
H - high vapor pressure metals (as oxides) at 1 wt% loading
S - surrogate radionuclides (as oxides) at 1 wt% loading
unk - unknown
n/a - not applicable

Feed compositions for the arc melter tests after it had been modified to accomodate HVPM's. The compositions above labeled with "/H/S" contain 1 wt% each of surrogates, CeO_2 and Sm_2O_3, and 10 wt% TiO_2 and 5 wt% ZrO_2.

Weight percent compositions of the IEB series waste forms.

	SiO_2	Al_2O_3	FeO-Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2
A-0	38.0	7.4	34.5	8.3	4.6	4.8	2.4	-
A-40	51.0	10.2	19.5	9.7	3.5	3.2	2.6	0.3
A-80	60.4	12.0	9.4	9.9	2.8	2.2	2.8	0.5
A-100	65.4	13.0	4.5	10.2	2.4	1.7	2.9	0.6

The H1 waste sludge is produced by treating aqueous process wastes, generated by plutonium recovery operations. The treatment process produces a precipitate of the hydrated oxides of iron, magnesium, aluminum, silicon, etc.

	SiO_2	Al_2O_3	FeO+ Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	misc
H1-0	25.2	7.0	29.6	12.9	3.0	15.9	2.6	0.0	3.8
H1-20	33.2	8.2	24.6	12.4	2.9	13.1	2.6	0.1	3.0
H1-40	41.2	9.4	19.6	11.8	2.8	10.3	2.7	0.2	2.2
H1-60	49.3	10.6	14.5	11.3	2.6	7.4	2.7	0.4	1.5
H1-80	57.3	11.8	9.5	10.7	2.5	4.6	2.8	0.5	0.7
H1-100	65.4	13.0	4.5	10.2	2.4	1.7	2.9	0.6	0.0

GLOBAL TESTING SUMMARY
Thermal Treatment Process: Modified (II) INEL Arc Melter
Location: Idaho Research Center, Idaho Falls, ID

Test Series: Volatilization Testing Program (HVPM's and Surrogates)
Dates/Time Frame: June & July, 1993
Purpose/Goal: Test the volatilization of selected HVPM's and radionuclide surrogates as a function of open melt vs. cold cap conditions.

Test name or Feed type	Total operating time (hr)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	Avg melt temp (°C)	% distribution of feed material to:				
						Slag/ash	Metal	APCS solids	Off gas	Closure
IEB4/A-40/H/S	1.82	19	3.0	1.4	1543	85.0	0.0	3.2	(11.8)	(100)
IEB4/A-40/H/S	1.07	21	4.7	5.9	1746	86.4	0.0	2.4	(11.2)	(100)
IEB4/A-40/H/S	1.25	17	4.5	3.4	1695	86.2	0.0	2.1	(11.7)	(100)
IEB/A-40/H/S	1.07	18	4.8	4.2	1619	86.7	0.0	2.0	(11.3)	(100)
IEB4/A-40/H/S	1.48	20	5.6	5.1	1562	89.1	0.0	1.7	(9.2)	(100)
IEB4/A-40/H/S	0.93	20	5.5	6.9	1683	85.9	0.0	2.7	(11.4)	(100)
Totals or Averages	7.62	19	28.1	4.5	1641	86.5		(2.4)	(11.1)	(100)

Comments: Offgas percentage distribution is calculated assuming 100% closure. Materials were fed using an auger feeder system.
H - high vapor pressure metals (as oxides) at 1 wt% loading
S - surrogate radionuclides (as oxides) at 1 wt% loading

The table below gives the elemental composition of the starting material, IEB4/A-40 with HVPM's and surrogates added. The next table shows the general parameters for each of the six tests. The experiments began with a small amount of the IEB4/A-40 mix, usually 1.5 kg, and a carbon steel ring (about 0.4 kg) to initiate starting. Once the initial charge of material was melted, more mix was added either gradually or at faster rates in order to establish a cold cap. Average feed rates for operation are 94.7 g/min with cold cap and 54.6 g/min without cold cap.

All tests used IEB4/A-40 having 5 wt% each of TiO_2 and ZrO_2 and with HVPM's and surrogates in oxide form at 1 wt% each. Specific materials used were PbO (lead oxide), ZnO (zinc oxide), CdO (cadmium oxide), Cr_2O_3 (chromium oxide) as the HVPM's and Cs_2CO_3 (cesium carbonate), CeO_2 (cerium (IV) oxide), and Sm_2O_3 (samarium oxide) as surrogate radionuclides. The normal coloring of the total mix was black (due to Fe_3O_4), but for the mixes which underwent thermal desorbtion, the color changed to red (Fe_2O_3). For each test about 5.0 kgs of soil mixture was used, therefore, after placing material in the crucible as mentioned above the remaining amount would be placed in the feed hopper.

IEB4/A-40, HVPM's and Surrogates Composition for the FY-94 tests.

Oxide Component	Calculated Oxide Values (wt%)	Calculated Oxide Values (ppm)	Metals Basis Values (wt%)	Metals Basis Values (ppm)
Na2O	2.678	26780	1.987	19870
MgO	2.930	29300	1.767	17670
Al_2O_3	8.537	85370	4.520	45200
SiO_2	42.603	426030	19.881	198810
K_2O	2.176	21760	1.806	18060
CaO	8.119	81190	5.803	58030
TiO_2	4.902	49020	2.939	29390
Cr_2O_3	1.000	10000	0.684	6840
Fe_2O_3	16.405	164050	11.747	117470
ZnO	1.000	10000	0.803	8030
ZrO_2	4.650	46500	3.442	34420
CdO	1.000	10000	0.875	8750
Cs_2CO_3	1.000	10000	0.820	8200
CeO_2	1.000	10000	0.814	8140
Sm_2O_3	1.000	10000	0.862	8620
PbO	1.000	10000	0.928	9280

General parameters and feeding information for the FY-94 HVPM runs.

Test Name	Starting Material Amount (kg)	Type of Run	Feed Rate (g/min)	Feed Duration (mins)	Amount Fed (kg)
ARM082394	0.750 kg IEB4/A-40 + HVPM's + Surrogates	no cold cap, no extension tube	22.6	100	2.257
ARM082694	1.500 kg IEB4/A-40 + H + S	cold cap, no extension tube	97.9	33	3.230
ARM090694	1.500 kg IEB4/A-40 + H + S	no cold cap, extension tube	56.8	52	2.950
ARM090894	1.500 kg IEB4/A-40 + H + S	cold cap, extension tube	70.3	47	3.303
ARM092094	1.500 kg IEB4/A-40 + H + S	no cold cap, extension tube, thermal desorbtion	84.6	48	4.063
ARM092294	1.683 kg IEB4/A-40 + H + S	cold cap, extension tube, thermal desorbtion	115.8	30	3.474

General Mass Balance

A material mass balance of general proportions can be obtained by consideration of the various inputs and outputs of the melter system (see table below). The column labeled "Refractory Liner" is the start weight of the liner plus an extension. The regular refractory liner does not reach up to the top of stainless steel crucible and a refractory liner extension is used to cover the upper portion of the crucible. Small amounts of slag occasionally splash up onto this liner extension. The filters were not in continuous use during any of the runs and therefore some mass was lost as particulate through the bypass exhaust when filters were not in place. The amount of mass collected and time in place of each filter was recorded so that an average particulate flow in the exhaust stream can be calculated. This rate is about 0.3 g/min, but varies for each experiment. Multiplying the rate with the total time of experiment yields the total amount of particulate lost in the exhaust gas stream. This is the figure listed in the "Filters" column. In this way, particulate lost when the filters were not in use can be accounted for. The rest of the columns are self explanatory being dust collected in the other areas of the exhaust system or materials that were added into the melt. Since all the solids have been accounted for, the solid mass loss, listed in the last column is therefore assumed to be made up of material lost in the conversion carbonates and hydrates as solids into gaseous CO_2 and H_2O. This amount ranges from 9-11 wt% of the original mass (IEB4/A-40 plus metal starting ring) and averages 10.7 wt%.

Mass balance information for FY-94 HVPM experiments.

Experiment	Refractory Liner (kgs)	Liner Extension (kgs)	Filters (kgs)	Exhaust Lines (kgs)	Lid (kgs)	Steel Ring (kgs)	Cyclone (kgs)	IEB4/A-40 (kgs)	Solid Mass Loss (kgs)
ARM082394									
Start Weight	7.760	4.361	.000	.000	.000	.424	.000	6.490	
End Weight	10.680	4.368	.022	.018	.061	.000	.002	3.483	
Difference	2.920	.007	.022	.018	.061	-.424	.002	-3.007	-.401
ARM082694									
Start Weight	7.790	4.368	.000	.000	.000	.420	.000	6.137	
End Weight	12.250	4.379	.021	.025	.065	.000	.004	1.407	
Difference	4.450	.011	.021	.025	.065	-.420	.004	-4.730	-.574
ARM090694									
Start Weight	7.662	4.379	.000	.000	.000	.475	.000	5.00	
End Weight	11.907	4.527	.027	.034	.023	.000	.008	.547	
Difference	4.245	.148	.027	.034	.023	-.475	.008	-4.450	-.440

Mass balance information for FY-94 HVPM experiments.

Experiment	Refractory Liner (kgs)	Liner Extension (kgs)	Filters (kgs)	Exhaust Lines (kgs)	Lid (kgs)	Steel Ring (kgs)	Cyclone (kgs)	IEB4/A-40 (kgs)	Solid Mass Mismatch (kgs)
ARM090894									
Start Weight	7.900	4.366	.000	.000	.000	.427	.000	5.000	
End Weight	12.430	4.368	.024	.033	.039	.000	.007	0.197	
Difference	4.530	.002	.024	.033	.039	-.427	.007	-4.803	-.595
ARM092094									
Start Weight	7.930	4.368	.000	.000	.000	.373	.000	5.740	
End Weight	12.788	4.373	.023	.024	.035	.000	.003	0.177	
Difference	4.858	.005	.023	.024	.035	-.373	.003	-5.563	-.988
ARM092294									
Start Weight	7.551	4.373	.000	.000	.000	.337	.000	5.350	
End Weight	12.237	4.384	.035	.038	.056	.000	.005	0.194	
Difference	4.686	.011	.035	.038	.056	-.337	.005	-5.156	-.662

Detailed Mass Balance for HVPM's and Surrogates

The table below contains the necessary information in order to complete a detailed mass balance. Column two contains the total amount of IEB4/A-40 added during the experiment. The total mass (column three) is simply the sum of IEB4/A-40 mass plus the mass of the iron starting ring. The total solids mass measured after the experiment is the sum of the slag mass and the particulate collected within arc melter system. The chamber mass is the sum of masses found in the liner extension and lid. This is total particulate collected in the melt chamber just above the slag. The remaining particulates collected in the exhaust system comprise the sum of material collected in the exhaust lines, filters and the cyclone.

Using the information on concentrations of HVPM's in the slag and particulates, and the information found in the table below listing the mass amounts of slag and particulates, a detailed mass balance can be calculated.

Mass balance information for solid materials in arc melter system.

Experiment	IEB4/A-40 Mass (kg)	Total Mass (kg)	Slag Mass (kg)	Chamber Mass (kg)	Exhaust Mass (kg)	Diff. (kg)
ARM082394	3.007	3.431	2.920	0.068	0.042	0.401
ARM082694	4.730	5.150	4.450	0.076	0.050	0.574
ARM090694	4.450	4.925	4.245	0.033	0.069	0.440
ARM090894	4.803	5.230	4.530	0.041	0.064	0.595
ARM092094	5.563	5.936	4.858	0.040	0.050	0.988
ARM092294	5.156	5.493	4.686	0.067	0.078	0.662

The table below shows the averaged results of the EDX and XRF analyses. The average was taken using both EDX and XRF data. In all cases the majority constituents in the filter particulate is zinc, cadmium, and lead at an average level approaching 20 wt%. Cesium was present at levels of several percent along with silicon, iron, and potassium in most cases. Considering the overall amounts of HVPM's and surrogates, the cold cap tests (ARM082694, ARM090894, and ARM092294) were only somewhat effective in reducing volatilization. In certain cases for specific elements, the data indicates a slight increase in the volatilization in the cold cap test vs. the non-cold cap test.

EDXS and XRF analysis - Average concentrations for HVPM's and surrogates in exhaust filter particulate.

Element	ARM 082394 (ppm)	ARM 082694 (ppm)	ARM 090694 (ppm)	ARM 090894 (ppm)	ARM 092094 (ppm)	ARM 092294 (ppm)
Cr	-	-	3700	1840	2100	1950
Zn	187850	142075	163425	187710	217150	237830
Cd	163575	129225	223975	155100	178750	221425
Cs	72900	17450	53340	52900	19550	18125
Ce	870	578	-	-	-	-
Sm	1440	943	-	-	-	-
Pb	167900	165325	208000	138700	266000	215200

EDX and XRF Analysis of Melter Chamber Particulate.

The table below shows the elemental composition of material removed from the cover of the arc melter chamber. Most of the elements present in the material added to the melter are present in the condensate. Major constituents are cadmium, iron, lead, and zinc. Cerium and samarium are present in measurable amounts. The HVPM's particularly cadmium, are in higher concentrations than in the filter particulate collected downstream in the exhaust system. Data for the last two experiments was not taken.

Table 8.6 EDX and XRF Melter Chamber Condensate/Particulate Analysis.

Element	ARM082394	ARM082694	ARM090694	ARM090894
Na	0	0	0	0
Mg	0	0	0	0
Al	0	0	0	0
Si	26800	13000	7300	10900
K	16200	21000	18800	14900
Ca	26900	17000	20000	20100
Ti	23800	15000	25900	24500
Fe	146200	72600	125200	141300
Zn	155600	175600	190000	161700
Zr	27200	12300	22000	26700
Cd	313000	358400	378300	166200
Cs	18000	15600	31100	12100
Ce	7600	4600	5900	3000
Sm	9900	6700	9200	13500
Pb	230400	199500	219900	161700

Slag compositions for all 1994 runs are presented in the next six tables.

EDX and XRF analysis of ARM082394 slag.

Element	TOP-XRF	TOP-EDX	BOT-XRF	BOT-EDX
Na	0	9900	0	9600
Mg	26400	10300	34300	10000
Al	81200	50900	74000	51400
Si	246000	193700	276000	195000
K	19400	10700	25400	11100
Ca	38300	29900	36300	30600
Ti	24300	23900	30600	24000
Cr	0	3200	0	3200
Fe	152000	127000	126400	121000
Zn	1600	0	1100	0
Zr	15800	35500	15800	32900
Cd	8	0	0	0
Ce	483	2100	728	3400
Cs	557	2100	8800	2400
Sm	1900	1600	6900	0
Pb	2400	0	2500	0

EDX and XRF analysis of ARM-082694 slag.

Element	TOP-XRF	TOP-EDXS	BOT-XRF	BOT-EDXS
Na	0	12300	0	10600
Mg	28000	13100	27400	12300
Al	65100	49700	57600	47600
Si	246300	210800	218600	201600
K	22100	12200	21200	11300
Ca	37300	40200	38100	38800
Ti	29100	26300	29400	25300
Cr	0	3900	0	3700
Fe	118000	120800	129400	123500
Zn	2300	0	2100	0
Zr	15400	101500	17000	108200
Cd	215	0	79	0
Ce	1600	4900	863	3200
Cs	2300	3000	1100	3000
Sm	7100	3700	7300	2400
Pb	7000	0	6100	0

8.10 EDX and XRF analysis of ARM-090694 slag.

Element	TOP-XRF	TOP-EDXS	BOT-XRF	BOT-EDXS
Na	0	13200	0	15200
Mg	32800	13000	48600	14600
Al	57600	43900	48000	45400
Si	57600	43900	222300	200000
K	22800	11200	14800	11900
Ca	45500	42600	37000	42400
Ti	34600	27000	24700	27100
Cr	0	2200	0	3100
Fe	150000	147400	126900	151800
Zn	2100	0	1700	0
Zr	14400	73100	13600	62900
Cd	45	0	32	0
Ce	1400	4300	1300	2400
Cs	1400	2100	1300	2300
Sm	6800	0	5300	1900
Pb	2500	0	2000	0

EDX and XRF analysis of ARM-090894 slag.

Element	TOP-XRF	TOP-EDXS	BOT-XRF	BOT-EDXS
Na	0	14400	0	13900
Mg	26600	14900	34500	14800
Al	57200	47800	61000	47300
Si	265700	202300	263900	199300
K	20900	12700	23900	12200
Ca	41600	43400	45200	42900
Ti	30900	27500	34600	27800
Cr	0	3200	0	2100
Fe	128700	131600	143000	133200
Zn	1800	0	2000	0
Zr	16100	82300	17400	81800
Cd	19	0	20	0
Ce	1400	4700	1300	2300
Cs	1700	3400	1700	3100
Sm	6800	2900	7600	0
Pb	2700	0	2900	0

EDX analysis of ARM-092094 slag.

Element	TOP-EDXS	BOT-EDXS
Na	11700	13600
Mg	14900	15300
Al	46200	48200
Si	194100	201100
K	11000	9900
Ca	46500	46600
Ti	25700	25900
Cr	1900	2200
Fe	124800	123300
Zn	0	0
Zr	84500	89000
Cd	0	0
Ce	2600	4400
Cs	2700	2200
Sm	1500	1800
Pb	0	0

EDX Analysis of ARM-092294 Slag.

Element	TOP-EDXS	BOT-EDXS
Na	10300	13900
Mg	15100	15400
Al	49500	37500
Si	212500	138000
K	13000	4700
Ca	50500	19000
Ti	28200	8000
Cr	3700	40910
Fe	109200	37500
Zn	0	0
Zr	88300	14600
Cd	0	0
Ce	3000	1000
Cs	3400	500
Sm	4100	4800
Pb	0	0

The two tables below list the wt% of each constituent HVPM found in the slag and particulates as determined by EDXS and XRF analysis and in the next column the mass amount of that constituent. In the second to the last column, the masses are added together yielding the total amount of each HVPM found in the slag and particulates. This can be compared with the total mass amount of each HVPM originally introduced into the IEB4/A-40. EDX or XRF spectroscopic analyses were not performed for ARM092094 and ARM092294. The mass balance for chromium cannot be calculated since the particulates were not analyzed for that element.

HVPM mass balance using EDXS and XRF spectroscopic analysis.

Element	Slag (wt%)	Slag Mass (g)	Chamber Particulate (wt%)	Chamber Particulate Mass (g)	Exhaust Filter Particulate (wt%)	Filter Particulate Mass (g)	Total Mass (g)	Introduced Mass (g)
ARM082394								
Cr	0.32	11.7	-		-			25.7
Zn	0.14	5.1	15.56	13.3	18.79	7.9	23.6	30.2
Cd	0.00	0.0	31.30	27.2	16.36	6.9	28.2	32.9
Pb	0.25	9.2	23.04	15.2	16.79	7.1	32.0	34.9
ARM082694								
Cr	0.38	22.6	-		-			42.6
Zn	0.22	13.1	17.56	13.3	14.21	7.1	33.5	50.0
Cd	0.02	1.2	35.84	27.2	12.92	6.5	34.9	54.5
Pb	0.66	39.3	19.95	15.2	16.53	8.3	62.8	57.8
ARM090694								
Cr	0.27	15.9	-		0.38	22.6		40.7
Zn	0.19	11.2	19.00	6.3	16.34	11.3	28.8	47.8
Cd	0.00	0.0	37.83	12.5	22.40	15.5	28.0	52.1
Pb	0.23	13.5	21.99	7.3	20.80	14.4	35.2	55.2

HVPM mass balance using EDXS and XRF spectroscopic analysis.

Element	Slag (wt%)	Slag Mass (g)	Chamber Particulate (wt%)	Chamber Particulate Mass (g)	Exhaust Filter Particulate (wt%)	Filter Particulate Mass (g)	Total Mass (g)	Introduced Mass (g)
ARM090894								
Cr	0.27	16.3	-		0.18	10.7		43.1
Zn	0.19	11.5	16.17	6.6	18.77	12.0	30.1	31.0
Cd	0.00	0.0	16.62	6.8	15.51	9.9	16.7	32.0
Pb	0.28	16.9	16.17	6.6	13.87	8.9	32.4	34.9

ICP Analysis

The table below shows the averaged results of the ICP spectroscopic chemical analyses. FLAA spectroscopy was used to determine cesium concentrations only. In this analysis the filters containing particulate were prepared using microwave digestion then analyzed. Because both the filter and particulate were analyzed, a plain filter sample was also analyzed so the data from this could be subtracted from the filter plus particulate samples, yielding the elemental concentrations for the particulate only. The plain filter sample was composed primarily (98 wt%, metals basis only) of silicon with small amounts sodium, calcium and aluminum plus trace elements.

ICP analysis - Average concentrations for HVPM's and surrogates in exhaust filter particulate.

Element	ARM 082394 (ppm)	ARM 082694 (ppm)	ARM 090694 (ppm)	ARM 090894 (ppm)	ARM 092094 (ppm)	ARM 092294 (ppm)
Cr	2037	3088	2956	3485	2789	2264
Zn	127967	131717	145616	196346	169686	216913
Cd	168800	163598	207667	236484	294578	264437
Cs	39775	45516	68822	65888	46264	40259
Ce	936	1606	1118	1911	287	287
Sm	404	430	218	685	45	41
Pb	215442	206825	192274	196346	201736	2234370

ICP Analysis

The data in the table below for the ICP spectroscopic analysis of HVPM's and surrogates correlates very well with the data using EDXS and XRF analyses, in particular the somewhat higher levels of cadmium than is found in the filter particulates.

ICP analysis - Average concentrations for HVPMs and surrogates for particulate collected from the melter chamber.

Element	ARM 082394 (ppm)	ARM 082694 (ppm)	ARM 090694 (ppm)	ARM 090894 (ppm)	ARM 092094 (ppm)	ARM 092294 (ppm)
Cr	1089	1345	3212	2908	3346	2329
Zn	123941	95776	108560	104802	138395	157266
Cd	262825	243015	240691	246378	279838	238345
Cs	34700	21448	47142	36836	45717	29809
Ce	4458	613	687	1308	1001	623
Sm	5972	193	421	6950	672	507
Pb	238847	285003	162706	148894	176772	178987

The ICP analysis of the slags for the HVPM's and surrogates for each experiment is presented below. FLAA was used to determine cerium concentrations. The results are averaged.

ICP analysis - Average concentrations for HVPMs and surrogates in the slag.

Element	ARM 082394 (ppm)	ARM 082694 (ppm)	ARM 090694 (ppm)	ARM 090894 (ppm)	ARM 092094 (ppm)	ARM 092294 (ppm)
Cr	3557	3301	1599	2258	3257	3404
Zn	2113	8976	6076	2165	3097	1002
Cd	1832	1086	222	111	1289	91
Cs	5082	2732	3216	5060	4325	5319
Ce	2514	1139	1251	2038	1145	1020
Sm	1154	167	794	1041	331	659
Pb	2808	6128	2126	2385	3181	870

HVPM mass balance using ICP spectroscopic analysis.

Element	Slag (wt%)	Slag Mass (g)	Chamber Particulate (wt%)	Chamber Particulate Mass (g)	Exhaust Filter Particulate (wt%)	Filter Particulate Mass (g)	Total Mass (g)	Introduced Mass (g)
ARM082394								
Cr	0.27	9.9	0.13	0.1	0.20	0.1	10.1	25.7
Zn	0.16	5.9	14.68	10.0	12.80	5.4	21.3	30.2
Cd	0.14	5.2	31.13	21.2	16.88	7.1	33.5	32.9
Pb	0.21	7.7	28.29	19.2	21.54	9.1	36.0	34.9
ARM082694								
Cr	0.31	18.5	0.24	0.2	0.31	0.2	18.9	42.6
Zn	0.85	50.6	16.88	12.8	13.17	6.6	70.0	50.0
Cd	0.10	6.0	42.83	32.6	16.36	8.2	30.4	54.5
Pb	0.58	34.5	50.23	38.2	20.68	10.3	83.0	57.8
ARM090694								
Cr	0.18	10.6	0.48	0.2	0.30	0.2	11.0	40.7
Zn	0.68	40.0	16.12	5.3	14.56	10.0	55.3	47.8
Cd	0.02	1.2	35.74	11.8	20.77	14.3	27.3	52.1
Pb	0.24	14.1	24.16	8.0	19.23	13.3	13.3	55.2

HVPM mass balance using ICP spectroscopic analysis.

Element	Slag (wt%)	Slag Mass (g)	Chamber Particulate (wt%)	Chamber Particulate Mass (g)	Exhaust Filter Particulate (wt%)	Filter Particulate Mass (g)	Total Mass (g)	Introduced Mass (g)
ARM090894								
Cr	0.20	12.1	0.21	0.1	0.34	0.2	12.4	43.1
Zn	0.19	11.5	16.90	6.9	19.63	12.6	31.0	48.4
Cd	0.01	0.6	39.73	16.3	23.65	15.1	32.0	52.8
Pb	0.21	12.7	24.01	9.8	19.38	12.4	34.9	56.0
ARM092094								
Cr	0.21	13.4	0.54	0.2	0.28	0.1	13.7	45.0
Zn	0.21	13.4	22.25	8.9	16.97	8.5	30.8	52.8
Cd	0.08	5.1	44.99	18.0	29.46	14.7	37.8	57.6
Pb	0.18	11.4	28.42	11.4	20.17	10.1	32.9	61.1
ARM092294								
Cr	0.31	19.2	0.36	0.2	0.23	0.2	19.6	45.3
Zn	0.13	8.0	24.11	16.2	21.69	16.9	41.1	53.2
Cd	0.01	0.6	36.54	24.5	26.44	20.6	45.7	57.9
Pb	0.07	4.3	27.44	18.4	23.44	18.3	18.3	61.4

Surrogate mass balance for ARM082394. These results are typical for the other experiments.

Element	Slag (wt%)	Slag Mass (g)	Chamber Particulate (wt%)	Chamber Particulate Mass (g)	Exhaust Filter Particulate (wt%)	Filter Particulate Mass (g)	Total Mass (g)	Introduced Mass (g)
ARM082394 - EDX & XRF								
Cs	0.35	12.8	1.80	1.2	7.29	3.1	17.1	30.7
Ce	0.17	6.3	0.76	0.5	0.09	0.1	6.9	30.6
Sm	0.26	9.5	0.99	0.8	0.14	0.1	10.4	32.5
ARM082394 - ICP & FLAA								
Cs	0.38	13.9	4.11	2.8	3.98	1.7	18.4	30.7
Ce	0.19	7.0	0.53	0.4	0.09	0.1	7.5	30.6
Sm	0.08	5.6	0.70	0.5	0.04	0.1	6.2	32.5

GLOBAL TESTING SUMMARY
Thermal Treatment Process: Mark I Furnace
Location: MIT, Cambridge, MA.

Test Series: Technology Evaluation and Demonstration Tests
Dates/Time Frame: FY-92
Purpose/Goal: Determine suitability of the graphite electrode DC arc process for processing INEL buried wastes.

Test name or Feed type	Total operating time (hr)	Total energy used (kWh)	Total material melted (kg)	Average feedrate (kg/h)	Avg melt temp (°C)	% distribution of feed material to:				
						Slag/ash	Metal	APCS solids	Off gas	Closure (%)
1 INEL soil	unk	unk	unk	n/a	unk	87	0			
2 INEL soil	unk	10.3	7.3	n/a	unk	83	0			
3 INEL soil	unk	56	36.3	n/a	unk	76	0			
4 Hosp. incinerator ash	unk	53	unk	n/a	unk	79	0			
5 Hosp. incinerator ash	unk	61	unk	n/a	unk	46	0			
6 Soil + metals	unk	unk	unk	n/a	unk	59	27			
7 Soil + metals	unk	unk	unk	n/a	unk	45	53			
8 Soil + combustibles	2.0	61	unk	n/a	unk	69	0			
9 Soil + 745 sludge	2.0	52	unk	n/a	unk	72	0			
10 Soil + 741/2 sludge	1.5	32	14.9	n/a	unk	73	0			
11 Soil + 743 sludge	1.75	56	unk	n/a	unk	73	0			
12 Soil + Cs & Ce	unk	unk	unk	n/a	unk	85	0			
13 Soil + Cs + Ce	unk	unk	unk	n/a	unk	84	0			
Totals or Averages										

Comments: unk - unknown
n/a - not applicable

Thirteen separate arc furnace runs were carried out to evaluate the processibility of a wide range of waste simulant materials under a variety of operating conditions. These runs can be divided into five categories based on waste simulants. Table 3.1 lists these categories and their corresponding run numbers.

TABLE 3.1. Waste Simulant Categorization

Waste Simulant Category	Run Number	Run Description
Soil	1	INEL Soil - unsubmerged arc
	2	INEL Soil - submerged arc
	3	INEL Soil - submerged arc
Soil and Metals	6	INEL Soil and 25% metal mix
	7	INEL Soil and 50% metal mix
Soil and Combustibles	8	INEL Soil and wood, paper, plastic, cloth, and concrete
	4	Hospital Ash Incinerator
	5	Hospital Ash Incinerator
Soil and RFP Sludges	9	INEL Soil and RFP 745 sludge
	10	INEL Soil and RFP 741/742 sludge
	11	INEL Soil and RFP 743 sludge
Soil and Volatile Metals	12	INEL Soil and ($CsNO_3$ and $Ce(NO_3)_3$) - submerged arc
	13	INEL Soil and ($CsNO_3$ and $Ce(NO_3)_3$) - unsubmerged arc

The composition of the INEL soil used in the experiments.

Oxide	(wt%)
Al_2O_3	12.34
CaO	9.54
Cr_2O_3	0.10
Fe_2O_3	5.41
K_2O	0.00
MgO	2.56
MnO_2	0.10
Na_2O	2.89
NiO	0.10
PbO	0.10
SiO_2	60.77
TiO_2	0.71

The tables on the following pages contain the compositional analysis of the slag materials and where appropriate the metals.

Compositional Phase Analysis of Mark I Runs (Runs 1-3, 12, 13)

Element Analyzed by ICP	Elemental Oxide Formula	Run #1 Oxide Phase (Wt% Oxide)	Run #2 Oxide Phase (Wt% Oxide)	Run #3 Oxide Phase (Wt% Oxide)	Run #12 Oxide Phase (Wt% Oxide)	Run #13 Oxide Phase (Wt% Oxide)
Al	Al2O3	14.6%	12.2%	14.6%	13.4%	13.4%
Ca	CaO	9.4%	8.4%	11.7%	6.1%	5.5%
Cu	CuO	0.0%	0.0%	0.0%	0.0%	0.0%
Cr	Cr2O3	0.0%	0.0%	0.0%	0.0%	0.0%
Fe	FeO	2.8%	2.3%	1.2%	1.6%	1.8%
K	K2O	0.0%	0.0%	0.0%	1.2%	1.2%
Mg	MgO	1.3%	1.2%	1.5%	2.5%	2.4%
Na	Na2O	0.8%	1.1%	0.7%	0.7%	0.8%
Ni	NiO	0.0%	0.0%	0.0%	0.0%	0.0%
Si	SiO2	50.1%	61.2%	54.9%	61.1%	62.9%
Sr	SrO	0.0%	0.0%	0.0%	0.0%	0.0%
Zn	ZnO	0.0%	0.0%	0.0%	0.0%	0.0%
B	B2O3	0.4%	0.5%	0.2%	0.2%	0.3%
Ba	BaO	0.1%	0.1%	0.1%	0.1%	0.1%
Cd	CdO	0.0%	0.0%	0.0%	0.0%	0.0%
Co	Co2O3	0.0%	0.0%	0.0%	0.0%	0.0%
Li	Li2O	0.0%	0.0%	0.0%	0.0%	0.0%
Mn	MnO	0.1%	0.1%	0.0%	0.0%	0.0%
P	P2O5	0.0%	0.0%	0.0%	0.0%	0.0%
Pb	PbO	0.0%	0.0%	0.0%	0.0%	0.0%
Ti	TiO2	0.7%	0.7%	0.6%	0.8%	0.8%
Zr	ZrO2	0.0%	0.0%	0.0%	0.0%	0.0%
Other	--	19.8%	12.2%	14.6%	12.4%	10.7%

Compositional Phase Analysis of Ash Runs

Element Analyzed by ICP	Elemental Oxide Formula	Run #4 Oxide Phase (Wt% Oxide)	Run #4 Metal Phase (Wt% Elem.)	Run #5 Oxide Phase (Wt% Oxide)	Run #8 Oxide Phase (Wt% Oxide)	Run #8 Metal Phase (Wt% Elem.)
Al	Al2O3	35.8%	0.2%	36.5%	13.7%	0.2%
Ca	CaO	22.7%	0.1%	25.1%	6.8%	0.2%
Cu	CuO	0.1%	4.6%	0.0%	0.0%	0.0%
Cr	Cr2O3	0.0%	3.2%	0.0%	0.0%	0.3%
Fe	FeO	0.5%	34.1%	0.1%	1.7%	42.1%
K	K2O	0.0%	0.0%	0.0%	0.0%	0.0%
Mg	MgO	0.9%	0.0%	1.1%	2.5%	1.0%
Na	Na2O	0.1%	0.2%	0.0%	0.8%	0.8%
Ni	NiO	0.0%	0.4%	0.0%	0.0%	0.0%
Si	SiO2	21.5%	9.1%	20.8%	59.2%	32.2%
Sr	SrO	0.1%	0.0%	0.1%	0.0%	0.0%
Zn	ZnO	0.0%	0.0%	0.0%	0.0%	0.0%
B	B2O3	1.4%	0.7%	1.3%	0.3%	0.2%
Ba	BaO	3.2%	0.0%	3.2%	0.1%	0.0%
Cd	CdO	0.0%	0.0%	0.0%	0.0%	0.0%
Co	Co2O3	0.0%	0.0%	0.0%	0.0%	0.0%
Li	Li2O	0.0%	0.0%	0.0%	0.0%	0.0%
Mn	MnO	0.0%	0.7%	0.1%	0.1%	0.3%
P	P2O5	0.0%	0.0%	0.0%	0.0%	0.0%
Pb	PbO	0.0%	0.0%	0.0%	0.0%	0.0%
Ti	TiO2	0.6%	4.6%	0.6%	0.5%	0.9%
Zr	ZrO2	0.0%	0.0%	0.0%	0.1%	0.0%
Other	--	13.0%	42.2%	11.1%	14.2%	21.9%

Compositional Phase Analysis of Mark I Runs 6 and 7

Element Analyzed by ICP	Elemental Oxide Formula	Run #6 Oxide Phase (Wt% Oxide)	Run #6 Metal Phase (Wt% Elem.)	Run #7 Oxide Phase (Wt% Oxide)
Al	Al_2O_3	20.1%	0.4%	21.7%
Ca	CaO	9.4%	0.0%	8.5%
Cu	CuO	0.0%	0.1%	0.0%
Cr	Cr_2O_3	0.0%	2.4%	0.0%
Fe	FeO	1.4%	80.5%	0.4%
K	K_2O	0.0%	0.0%	0.0%
Mg	MgO	2.7%	0.0%	2.4%
Na	Na_2O	0.8%	0.4%	0.6%
Ni	NiO	0.0%	0.6%	0.0%
Si	SiO_2	45.1%	8.4%	39.9%
Sr	SrO	0.0%	0.0%	0.0%
Zn	ZnO	0.0%	0.0%	0.0%
B	B_2O_3	0.3%	0.4%	0.1%
Ba	BaO	0.1%	0.0%	0.1%
Cd	CdO	0.0%	0.0%	0.0%
Co	Co_2O_3	0.0%	0.0%	0.0%
Li	Li_2O	0.0%	0.0%	0.0%
Mn	MnO	0.1%	0.5%	0.1%
P	P_2O_5	0.0%	0.0%	0.0%
Pb	PbO	0.0%	0.0%	0.0%
Ti	TiO_2	0.5%	0.2%	0.5%
Zr	ZrO_2	0.0%	0.0%	0.0%
Other	--	19.4%	6.0%	25.7%

TABLE 3.8. Compositional Phases Analysis of RFP 74 Series Sludge Runs

Element Analyzed by ICP	Elemental Oxide Formula	Run #9 Oxide Phase (Wt% Oxide)	Run #10 Oxide Phase (Wt% Oxide)	Run #11 Oxide Phase (Wt% Oxide)	IEB Tolerance (Range - Wt%)
Al	Al_2O_3	12.3%	8.8%	16.9%	9-20
Ca	CaO	9.0%	11.3%	8.4%	8-20
Cu	CuO	0.0%	0.0%	0.0%	--
Cr	Cr_2O_3	0.0%	0.0%	0.0%	--
Fe	FeO	0.5%	4.4%	0.5%	10-38
K	K_2O	3.0%	3.5%	2.9%	0-8
Mg	MgO	2.4%	5.2%	4.0%	0-10
Na	Na_2O	3.3%	5.5%	0.8%	0-6
Ni	NiO	0.0%	0.0%	0.0%	--
Si	SiO_2	57.5%	49.3%	60.3%	38-57
Sr	SrO	0.0%	0.0%	0.0%	--
Zn	ZnO	0.0%	0.0%	0.0%	--
B	B_2O_3	0.3%	0.2%	0.1%	--
Ba	BaO	0.1%	0.0%	0.1%	--
Cd	CdO	0.0%	0.0%	0.0%	--
Co	Co_2O_3	0.0%	0.0%	0.0%	--
Li	Li_2O	0.0%	0.0%	0.0%	--
Mn	MnO	0.0%	0.0%	0.0%	--
P	P_2O_5	0.0%	0.0%	0.0%	--
Pb	PbO	0.0%	0.0%	0.0%	--
Ti	TiO_2	0.7%	0.3%	0.9%	--
Zr	ZrO_2	0.0%	0.0%	0.0%	0-15
Other	--	10.8%	11.5%	5.1%	--

The percentage of volatilized material for runs #12 and #13 are shown below. The total mass fraction lost to the off-gas was measured to be 0.3 wt% and 0.54 wt% for submerged and nonsubmerged arc operation, respectively, based on all inorganic constituents of the feed material. There was no detectable Ce in either of the off-gas samples.

Volatilized Material (Mass percent) for Run #12

Oxide	Soil (wt%)	Off-gas (wt%)	Soil constituents volatilized into the off-gas (%)
Al_2O_3	12.34	0.87	0.02
CaO	9.54	0.51	0.02
CeO_2	0.26	0.00	0.00
Cs_2O	1.44	4.32	0.88
FeO	5.07	1.18	0.07
K_2O	2.88	3.13	0.32
MgO	2.56	0.51	0.06
Na_2O	1.50	1.79	0.18
SiO_2	60.77	71.69	0.35
B_2O_3	0.06	0.31	1.61

Volatilized Material (Mass percent) for Run #13

Oxide	Soil (wt%)	Off-gas (wt%)	Soil constituents volatilized into the off-gas (%)
Al_2O_3	12.34	0.73	0.03
CaO	9.54	0.47	0.03
CeO_2	0.26	0.00	0.00
Cs_2O	1.44	5.08	1.91
FeO	5.07	0.00	0.00
K_2O	2.88	0.00	0.00
MgO	2.56	0.49	0.10
Na_2O	1.50	3.04	0.55
SiO_2	60.77	73.54	0.69
B_2O_3	0.06	0.32	2.98

GLOBAL TESTING SUMMARY
Thermal Treatment Process: Mark II Furnace
Location: MIT, Cambridge, MA.

Test Series: Mark II operational verification tests.
Dates/Time Frame: Apr 94 - Aug 94
Purpose/Goal: Prove the operability of the Mark II furnace system.

Test name or Feed type	Total operating time (hours)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	Melt temp[†] (°C)	% distribution of feed material to:				
						Slag/ash	Metal	APCS solids	Off gas	Closure (%)
#1 / INEL Soil	264	unk	unk	unk	950					
#2 / INEL Soil	240	unk	unk	unk	2200					
#3 / INEL Soil	120	unk	unk	unk	1450					
#4 / INEL Soil + adds.	24	unk	unk	unk	725					
#5 / INEL Soil + adds.	72	~50	340	65	1640					
#6*										
Totals or Averages	720				1393					

Comments: ref - J. E. Surma, et. al., *FY-94 Summary Report Mark II DC ARC Furnace Testing*, draft PNL report, August, 1994.
unk - unknown
[†] - temperatures listed below are maximum temperatures.
* - test planned for Sep 94, no data in the reference source.

Mark II Feedstock Matrix for Tests

	Composition (%)				
Material	Test 1	Test 2	Test 3	Test 4	Test 5
Soil	100	100	100	60	60
Metals	-	-	-	15	15
Combustibles	-	-	-	10	10
Sludge	-	-	-	15	15

Feedstock was introduced into the Mark II furnace using paper sacks similar to standard cement sacks. Compositions for Metals, Combustibles and Sludge are on the following pages.

The composition of the INEL soil used in the experiments.

Oxide	(wt%)
Al_2O_3	12.34
CaO	9.54
Cr_2O_3	0.10
Fe_2O_3	5.41
K_2O	0.00
MgO	2.56
MnO_2	0.10
Na_2O	2.89
NiO	0.10
PbO	0.10
SiO_2	60.77
TiO_2	0.71

TABLE 3.4. Metals Composition

Metal	Wt%
Carbon Steel	60.5
Stainless Steel	30.5
Aluminum	5.0
Zirconium and Alloys	2.5
Copper	1.5
Lead	0.0
Total	100.0

TABLE 3.5. Combustible Feed Compositions

Material	Wt %
Plastic	22.0
Paper	13.0
Wood	46.0
Rubber	10.0
Sorbent	6.0
Cloth	3.0
Total	100.0

TABLE 3.6. Sludge Waste Surrogates

Material	wt%
741 Series Sludge	
$Al(OH)_2$	11.5
$Ca(OH)_2$	6.6
$Fe(OH)_2$	10.8
KOH	7.4
$Mg(OH)_2$	7.9
Portland Cement	11.6
Water	44.2
743 Series Sludge	
Texaco Regal Oil	38.0
Hydrolic Oil	31.0
Wheel Bearing Grease	7.7
Calcium Silicate	23.3
745 Series Sludge	
$NaNO_3$	60.0
KNO_3	30.0
NaCl	3.4
$NaSO_4$	3.3
NaOH	3.3

GLOBAL TESTING SUMMARY
Thermal Treatment Process: USBM AC, 3-electrode Arc Melter
Location:USBM Albany Research Center (ALRC), Albany, Oregon

Test Series: FY93 Phase 1 (baseline) test program
Dates/Time Frame: July 19-23, 1993
Purpose/Goal: Demonstrate arc melter processing for surrogate incinerator ash for buried mixed wastes, mixed with soil.

Test name or Feed type	Total operating time (h)	Average power (kW)	Total feed material (kg)	Average feedrate (kg/h)	Energy efficiency (kWh/kg)	Average melt temp. (°C)	% distribution of feed material to:				
							Slag/ash	Metal	APCS solids	Offgas	Closure
S60	9.25	544	4448	525.26	1.06	1450-1700	84	0	1	10	96
S60-IV	10.7	422	3753	353.35	1.23		84	0	2	13	99
N80	4.2		2087	496.68	0.926	1550-1600		1	2		
N80-Mod	4.3		1714	398.71	1.01	1550-1650		1	3	16	108
N80-Interval	8.5	462	3801	447.7	0.97	1650-1800	88	1	3		
N80-IV	5.2		2503	481.26	1.102	1450-1550		2	2	18	
N80-IV-Mod	4.25		2262	532.06	1.06			2	3	11	
N80IV-Interval	9.45	540	4765	506.66	1.08	1650-1750	84	2	2	14	101
M60	3.1		1480	477.63	0.88	1550-1590		24	2	11	
M60-Mod	4.6		1544	335.66	1.41			0	2	10	
M60-Interval	7.7	473	3024	406.87	1.17		78	12	2	11	102
Total/Average	45.6	488	19,791.00	450.08	1.08	1450-1800	83.60	9	4.80	22.8	

Comments: The basis for the Phase I tests was the assumption that buried wastes would be retrieved and incinerated, and that the incinerator ash would be vitrified in an arc melter.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: USBM AC, 3-electrode Arc Melter
Location:USBM Albany Research Center (ALRC), Albany, Oregon

Test Series: FY95 Phase 2 test program
Dates/Time Frame: April 10 to April 14, 1995
Purpose/Goal: Determine the ability of the melter system to stably process heterogeneous solid wastes containing high levels of organics.

Test name or Feed type	Total operating time (h)	Average power (kW)	Total feed material (kg)	Average feedrate (kg/h)	Energy efficiency (kWh/kg)	Average melt temp. (°C)	% distribution of feed material to:				
							Slag/ash	Metal	APCS solids	Offgas	Closure
Preheat interval	19.37		3100				82	0	4	6	91
BWID nominal avg.	37.2	197	6331	189	1.08	1562	66	10	9	22	105
IWPF S-40	5.93	196	723	122	1.61					39	
IWPF S-0	10.2	147	498	49	3.0					62	
IWPF C-20	1.67	224	136	82	2.75					72	
IWPF C-40	0.83	123	225	272	0.44	1641	168			54	
Cleanout	8.42		1490.5	177			85	13	2	5	104
IWPF+Cleanout	27		3073				54	6	6	29	94
Totals or Averages	83.62	177	12,510	149	1.41	1602	67	7	7	20	99

Comments: All of the planned feed mixtures and three additional feed mixtures were successfully processed. These tests show the potential for processing a wide range of as-received buried and mixed wastes in an electric arc melter without prior incineration.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: USBM AC, 3-electrode Arc Melter
Location: USBM Albany Research Center (ALRC), Albany, Oregon

Test Series: ASME/USBM municipal waste incinerator ash vitrification test program
Dates/Time Frame: 1992
Purpose/Goal:

Test name or Feed type	Total operating time (h)	Average power (kW)	Total feed material (kg)	Average feedrate (kg/h)	Energy efficiency (kWh/kg)	Average melt temp. (°C)	% distribution of feed material to:				
							Slag/ash	Metal	APCS solids	Offgas	Closure
SSI ash		375	6040	425	0.88		86	1	1	12	100
MSWI ash A		440	4855	438	1.01		83	8	2	8	100
A w/ recycled APCS solids		459	6953	495	0.92		75	6	3	16	100
MSWI ash B		395	3308	290	1.36		83	6	2	9	100
MSWI ash C		344	2770	177	1.94		69	9	4	18	100
RDF APCS solids		308	443	221	1.39		44	2	6	49	100
RDF APCS solids w/ additives		266	472	117	2.27		86	0	9	5	100
Totals or Averages	110	370	24,800	340	1.03		75	5	4	17	100

Comments: SSI=sewage sludge incinerator; MSWI=municipal solid waste incinerator; RDF=refuse derived furnace; Partitioning to the offgas and the global mass balances for the ASME/USBM test program are estimated.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: USBM AC, 3-electrode Arc Melter
Location: USBM Albany Research Center (ALRC), Albany, Oregon

Test Series: WHC low-level tank waste test program
Dates/Time Frame: FY95
Purpose/Goal: Test program for surrogates of absorbed high sodium nitrate wastes

Test name or Feed type	Total operating time (h)	Average power (kW)	Total feed material (kg)	Average feedrate (kg/h)	Energy efficiency (kWh/kg)	Average melt temp. (°C)	% distribution of feed material to:				
							Slag/ash	Metal	APCS solids	Offgas	Closure
WHC1	24	429	5909	339	1.28	1620	85	0	6	9	
WHC2	10	178	3636	180	0.99	1480	88	0	1	11	
WHC3	9	241	3636	255	0.95	1400	89	0	1	10	
Total	42		13,182								
Average		339		285	1.08		87	0	4	10	

Comments:

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N. SOELBERG

Global summary of demonstration test performance.

Feed type	Total Operating hrs	Average power[1] (kW)	Total feed material (lb)	Average feedrate[1] (lb/h)	Energy Efficiency (kWh/lb)	Melt temp. at taphole (°C)	Percent distribution of feed material to: glass/ ceramic	metal	APCS solids	Offgas	Electrode consumption (lb/ MWh	(lb/ton feed material)	Global mass balance closure
FY95 Phase 2 test program for surrogates of mixed, TRU-contaminated wastes:													
Preheat interval			6,818				82	0	4	6			0.91
BWID nominal average		197	13,929	416	0.49	1,562	66	10	9	22			1.05
S-40		196	1,594	269	0.73					39			
S-0		147	1,098	108	1.36					62			
C-20		224	300	180	1.25					72			
C-40		123	497	599	0.20	1,641	168			54			
Cleanout			3,286	390			85	13	2	5			1.04
IWPF + Cleanout			6,775				54	6	6	29			0.94
Totals (for all days)	84		27,522								19	21	
Averages (for all days)		186		369	0.64	1,575	67	7	7	20			0.99
Westinghouse Hanford Company (WHC) test program for surrogates of absorbed high sodium nitrate wastes.													
WHC1	24	429	13,000	745	0.58	1,620	85	0	6	9			
WHC2 (lower input voltage	10	178	8,000	396	0.45	1,480	88	0	1	11			
WHC3 (8-in. electrodes)	9	241	8,000	560	0.43	1,400	89	0	1	10	(retained 88% of boria and 100% of soda in the melt)		
Totals	42		29,000										
Averages		333		627	0.52	1,400-1620	87	0	4	10			
FY93 Phase 1 (baseline) test program for surrogates of ash from pre-incinerated buried wastes:													
RWMC soil & mill scale			7,516	579			80	2	1				NC
CaO + SiO2		356	4,301	589	0.69		100	0					1.00
S60		544	9,806	1,158	0.48	1,450-1,700	84	0	1	10			0.96
S60-IV		422	8,273	779	0.56		84	0	2	13			0.99
N80			4,601	1,095	0.42	1,550-1,600		1	2				
N80-Mod (h)			3,778	879	0.46	1,550-1,650		1	3	16			1.08
		462	8,379	987	0.44	1,650-1,800	88	1	3				
N80-IV			5,518	1,061	0.50	1,450-1,550		2	2	18			1.04
N80-IV-Mod (h)			4,986	1,173	0.48			2	3	11			0.98
		540	10,504	1,117	0.49	1,650-1,750	84	2	2	14			1.01
M60			3,263	1,053	0.40	1,550-1,590		24	2	11			
M60-Mod (h)			3,403	740	0.64			0	2	10			
		473	6,666	897	0.53		78	12	2	11			1.02
						1,550-1,690							
Average (Baseline tests)		483	5,454	992	0.49		84	3	2	13			1.01
Average (for all days)		441	5,545	911	0.51		86	3	2	13			1.00
Subtotal (Baseline tests)			43,628	7,938							12	12	
Totals (for all days)	66		55,445	9,106									
ASME/USBM municipal waste incinerator ash vitrification test program:													
SSI ash		375	13,288	934	0.40		86	1	1	12			1.00
MSW I ash A		440	10,681	964	0.46		83	8	2	8			1.00
A w/ recycled APCS solids		459	15,297	1,090	0.42		75	6	3	16			1.00
MSW I ash B		395	7,278	637	0.62		83	6	2	9			1.00
MSW I ash C		344	6,093	389	0.88		69	9	4	18			1.00
RDF APCS solids		308	974	487	0.63		44	2	6	49			1.00
RDF APCS solids w/ additives		266	1,039	258	1.03		86	0	9	5			1.00
Totals	110		54,650										
Averages		353		749	0.47		75	5	4	17			1.00
Grand totals	302		166,617										

Notes:

1. SSI = sewage sludge incinerator
2. MSWI = municipal solid waste incinerator

RDF = refuse derived furnace

4. Partitioning to the offgas and the global mass balances for the ASME/USBM test program are estimated.

CAPABILITIES OF THE USBM MELTER SYSTEM:

800 kVA power input

Up to 2,000 lb/hr feedrate

Continuous feeding and tapping, with metal tapping as needed

Variety of feed compositions (<3/8 inch particle size):
- metals, slag formers, volatiles, combustibles
- fixed or volatile carbon, hazardous and nonhazardous organics
- hazardous or nonhazardous metals
- manual feed spikes in addition to continuous feeding
- Efficient, state-of-art control of combustion gases, semivolatiles, mercury, and control of particulate

Versatile operation
- with or without cold top
- varying power levels and feedrates
- continuous or noncontinuous day-to-day operation
- Oxidizing or reducing conditions in furnace, with downstream total oxidation of organics
- low NO_x formation even with nitrates in the feeds
- Easy startup and restart following shutdown

Extensive data collection and logging
- Process monitoring over 60 data points
- Product sample collection - glass/ceramic, metal, particulate, offgas
- On-site sample analysis for over 40 elements, Fe ratio, leachability (TCLP and PCT-A), physical structure (XRD, SEM) and properties (hardness, etc), and others
- Offgas system sample locations for velocity, particulate and gaseous measurements
- Continuous gaseous analysis (on-line GC, O_2, CO)

Summary of the feed mixtures tested in the USBM arc melter test facility.

Feed Mixtures	Description of represented actual waste stream
FY95 Phase 2 test program for surrogates of mixed, TRU-contaminated wastes	
BWID nominal average	Average, nominal composition (metals, combustibles, absorbed organic liquids, nitrates, and hydroxides) of mixed, TRU-contaminated wastes buried at the INEL Subsurface Disposal Area; 6 different feed mixtures with 40-90% added INEL soil
Silicated organics	Chlorinated and non-chlorinated organic liquids absorbed on Micro-Cel E (expanded $CaSiO_3$) and Oil-Dri (calcined diatomite, SiO_2), stored at the INEL Transuranic Storage Area; two different feed mixtures without soil and with 40% added soil
Combustible	Solid combustible wastes (plastics, paper, wood, cloth, etc with some non-combustible inerts) stored at the INEL Transuranic Storage Area; two different feed mixtures with 20 and 40% added soil
FY95 WHC LL tank waste test program	
WHC A and B	High sodium nitrate, low-level radioactive tank waste from Hanford. Both feed mixtures were formulated to produce LD6-5510 glass with 25% waste loading, one of the five preapproved formulations developed by Pacific Northwest Laboratory. The WHC A surrogate feed mixture was prepared by absorbing the liquid LLW surrogates into previously prepared pellets containing solid reductants (powdered sugar and activated carbon) and industrially-obtained glassformer oxides. The absorbed pellets were then heated to remove moisture and induce reaction between the reductants and the nitrates/nitrites. The WHC B surrogate feed mixture was similar to WHC A but was prepared in fewer steps by mixing the solid reductants, glassformers, and the liquid LLW surrogate at the same time, producing agglomerated pellets, and followed by heating to remove moisture and reduce the nitrates/nitrates.
FY93 Phase 1 (baseline) test program for surrogates of ash from pre-incinerated buried wastes	
Silicated organic ash/soil	Ash from chlorinated and non-chlorinated organic liquids absorbed on Micro-Cel E and Oil-Dri, with 60% added soil; two different feed mixtures with and without added titanium and zirconium oxides to from an iron-enriched basalt waste form
Nitrate waste ash/soil	Ash from evaporator salts that contain sodium and potassium nitrates, buried at the INEL Subsurface Disposal Area, with added 80% INEL soil; two different feed mixtures with and without added titanium and zirconium oxides to from an iron-enriched basalt waste form
Metals waste ash/soil	Ash from scrap metal wastes buried at the INEL Subsurface Disposal Area, with 80% added soil
ASME/USBM municipal waste incinerator ash vitrification test program	
A, B, and C	Combined bottom ash, fly ash, and acid gas scrubber residues from three different municipal solid waste incinerators, each of a different design
D	Ash from a multiple hearth dewatered sewage sludge incinerator at a regional waste water treatment facility
E	Fly ash and acid gas scrubber residues from a large refuse derived furnace

Compositions of the feed mixtures tested in the USBM arc melter test facility.

Feed Mixtures	Composition of the feed mixtures, weight %										
	SiO_2	CaO	Al_2O_3	Na & K	Total metals	Pb	Cr	Total volatiles	C	Cl & S	Nitrates
FY95 Phase 2 test program for surrogates of mixed, TRU-contaminated wastes											
BWID Nom. average	25-42	13-23	4-8	2	3-20	0.01-0.1	0.2-1	14-31	1-11	1-11	0.3-2
Silicated organics	19-31	17	0.8-4	0.5	---	---	---	39-62	19-34	11-20	---
Combustible	13-19	5-10	3	1	3	0.03	0.03	62-82	28-39	2-3	---
FY93 Phase 1 (baseline) test program for surrogates of ash from pre-incinerated buried wastes											
Silicated organic ash/soil	42	3	8	2-3	---	---	0.04	16	0.9	3	---
Nitrate waste ash/soil	38	4	7	9-10	---	---	0.03	15	3	0.05	---
Metals waste ash/soil	38	1	8	2	32	0.7	2	9	1	0.03	---
ASME/USBM municipal waste incinerator ash vitrification test program											
A, B, and C (MWI ashes)	44	8	10	3.7	>7	0.3	0.03	7	4	2	---
D (SSI ash)	23	13	6	2	>0.7	0.02	0.1	2	1	0.03	---
E-1, E-2 (RDF baghouse ash and scrubber residues	27	18	7	2	0	0.2	0.02	25	4	16	---

Notes:

1 The ASME/USBM metals content was based on the amount of metal product produced from the tests. Allowing for some Fe reduction in the reducing conditions, the metal was probably less than the reported metals product.

2. The ASME/USBM SIO2, CaO, and Al2O3 contents were calculated from the elemental Si, Ca, and Al contents assuming that only the oxide forms were present in the feeds, and that all of the analyses total 100%.

3. The ASME/USBM total volatiles is calculated as the sum of (a) LOI tests, at 1,000 C, that include moisture, CO2 from carbonates, etc., but not fixed C, (b) total C, and (c) Cl. Relatively close agreement is seen between these calculated values and the values for "other" in the product distribution tables.

4. ASME/USBM E-1 is E without additives. E2 is E with 22.7% added Fe3O4 and 20.1% added SiO2.

5. Some of the values are average values for several feed mixtures, where the average value is not significantly different from the values of the individual mixtures.

Key melter system design or operating lessons learned, problems, and resolutions.		
Issue or problem	Potential or implemented resolutions	Implemented?
Tolerance of the feed system to large particles or aspect-ratio particles.	Change the feed system equipment from the auger-based system (designed for feeding and accurately metering fine incinerator ash and fine aggregate) to an Archimedes screw or Komar-type feed system.	Not yet. Surrogate feeds have been designed to avoid large particles.
Plugging of the furnace offgas outlet duct with particulate deposits. The deposits have been primarily aggregations of entrained particulate embedded in solidified deposits of condensed alkali salts (NaCl, KCl), organics, and condensed species. The material condenses on water-cooled sections of the relatively small-diameter furnace outlet duct.	1. Install a mechanical scraper to periodically scrap away deposits. 2. Eliminate cooled surfaces, tortuous gas paths, and increase duct diameters.	1. Used with success during the Phase 1 tests. 2. Physical layout of melter in facility prevents this implementation.
Offgas solids deposition in offgas system, especially in the thermal oxidizer (as molten slag in bottom of thermal oxidizer), and in all horizontal sections.	1. Recover quantitatively all offgas solids for mass balance determinations and elemental analysis. 2. Include capability to remove solids from key locations such as the base of the thermal oxidizer in a treatment system design. 3. Eliminate or at least minimize horizontal sections of ductwork in a treatment system design.	1. Used in every test program. 2 & 3. Will be done in designs resulting from the INEL/USBM research.
Control of feed material entrainment.	1. Implement water-cooled feed tubes that penetrate the furnace roof to about 18 inches above the melt. 2. Use larger particle-sized (larger than 1/8-inch, but less than 3/8-inch) surrogate feed mixture components where possible.	1. Used successfully during the Phase 1 and Phase 2 tests. 2. Used successfully during the Phase 2 tests.

Key melter system design or operating lessons learned, problems, and resolutions.		
Issue or problem	Potential or implemented resolutions	Implemented?
Control of material volatilization from the melt.	1. Use cold top of unmelted feed material to reflux volatilized materials back to melt and to reduce furnace plenum temperatures. 2. Reduce power density in region of electrodes by reducing voltage and power input to furnace, to better match feedrate and melting rate 3. Reduce power density in region of electrodes by increasing diameter of electrodes. 4. Reduce need for superheating melt by modifying slag tapping equipment. 5. Increase the throughput of slagformers and reduce the residence in the melt for volatile species.	1. Used with uncertain success due to difficulty in measuring cold top and the potential for significant volatilization from the high temperature, uncovered region near the electrodes 2. Successfully demonstrated in the WHC2-1995 test. 3. Successfully demonstrated in the WHC3-1995 test. 4. Not yet implemented, but tested a graphite tapping fixture, and have installed tapping area slag heaters. 5. May be done be minimizing "idle" operation with power on but no feeding, as shown in WHC and Phase 2 tests.
Dissolution of cast MgO refractory hearth in the high silica molten slag bath.	Changed the cast refractory to a material (high alumina Ruby) that tolerates high temperatures and is more chemically resistant to the high silica slag.	Ruby refractory used in the Phase 2 tests worked very well.
Tapping difficulties with viscous, high silica slags through the 10 inch long water-cooled tapping fixture.	1. Increased the diameter of the tapping fixture from 3/8 inch to 1 inch. 2. Increased melt temperatures beyond the melting points to achieve slag melt viscosities of ~100 poise. 3. Added typically small amounts (10% or less) of melt fluidizers CaO or Fe_2O_3. 4. Change taphole to provide shorter length (to reduce heat losses) and to eliminate water cooling by changing to other material. 5. Add small heater electrodes to locally heat the slag melt near the taphole.	1, 2, and 3. Used successfully during all test programs. 4. Tested briefly prior to Phase 2 tests, but not implemented. 5. Installed following the Phase 2 tests.

Key melter system design or operating lessons learned, problems, and resolutions.		
Issue or problem	Potential or implemented resolutions	Implemented?
Optimizing feedrate for mixtures that contain large proportions of combustibles and small proportions of slagformers. An excessively slow slagformer feedrate results in higher melt residence time and increased volatilization of some species (Na, Pb, Zn), while an excessively high feedrate of combustible materials exceeds the thermal oxidizer combustion air capacity and high temperature limit.	1. Increase the physical size of the thermal oxidizer, increase the secondary air capacity, and enable addition of recycled offgas for cooling. 2. Increase non-combustible additives such soil to reduce the proportion of combustibles and increase the proportion of slagformers.	1. Not yet implemented. 2. Used with success during the Phase 2 tests.
Varying composition of slag products. CaO additives in the Phase 2 test results, together with small proportions of slagformers in the feed mixtures, resulted in a questionable glass product containing non-durable larnite. (Even with varying slag product compositions, all products have easily passed TCLP leachability tests, and Phase 2 products have easily met PCT-A leachability objectives.)	Reduce the need for CaO additive by using other resolutions to the tapping issue.	Not yet implemented.
Electrode consumption. (This is relatively a very minor operating cost).	1. Coat electrodes with oxidation-resistant material such as silicon carbide or aluminum. 2. Operate with less idle time, without power levels and feed optimized.	1. Small-scale tests have been done. 2. Implemented where possible, within the scope and critical objectives of the test programs.

Glass/ceramic product characteristics.

Characteristic	Phase 2 (as received mixed waste surrogates)	WHC (absorbed high sodium nitrate surrogates)	Phase 1 (pre-incinerated mixed waste surrogates)	ASME/USBM Incinerator ash
Composition (wt %)				
SiO_2	27-49		28-51	24-53
CaO	29-57		3-18	15-22
Al_2O_3	9-14		6-9	7-18
MgO	0.1-2		2-16	2-34
K_2O & Na_2O	0.1-2	16-18% Na_2O	1-14	0.5-5
B_2O_3		3-4		
FeO	0.2-3			
Fe_2O_3	0-2.4			
Fe_3O_4	0.2-2.6		12-23	2-23
TiO_2	0.1-1		1-8	1-3
CeO_2	0.3-0.6		0.2-0.5	>0.01-0.02
ZrO_2	0.01-1		0.02-3	
Cr_2O_3	0.01-0.1		0.04-0.1	0.07-0.3
C	0.02-0.3			0.01-0.05
Cl	0.002-0.02		0.001-0.02	0.001-1
TCLP Leachability	Very acceptable		Very acceptable	Very acceptable
Crystalline phases	Primarily noncrystalline except for one sample that was primarily Ca_2SiO_4 (larnite); trace (1-10%) levels of alpha Fe and unidentified compounds	Noncrystalline	Primarily noncrystalline; trace (1-10%) levels of alpha Fe, Fe_3O_4, MgO, and unidentified compounds	Primarily noncrystalline except for the sewage sludge incinerator ash, that contained around ½ as much silica (24% SiO_2) and much higher Fe_3O_4 (23%) than most of the other slags
Specific gravity	2.8		3.1	

Elemental partitioning (wt % to the furnace products).

Element	Phase 2 (as received mixed waste surrogates) feed mixtures		Phase 1 (pre-incinerated mixed waste surrogates, metal feed mixture only)	ASME/USBM Incinerator ash	Comments
	BWID nominal	Silicated organics and combustibles			
To the glass/ceramic products					
Ag	0-69			2-78	Present only as a trace element in the feeds.
Al	96	88	99		Present as a metal in the Phase 2 BWID nominal and the Phase 1 metal feed mixtures.
As	26		4.6	3-58	Present only as a trace element in the soil, so data quality is low, near or below detection limits.
Ba	89	37	96	95-99	Present only as a trace element in the soil, so data quality is low (somewhat higher levels in the incinerator ashes).
C	0.3	0.3			Present in large amounts in the Phase 2 tests, and percent level amounts in the other tests except the Phase 1 metals feed. Most C went to the offgas.
Ca	94	88	98		
Cd	0-1			6-82	Present only as a trace element in the soil, so data quality is low.
Ce	99.7	99.4	97		Added as a surrogate for Pu.
Cl	0.2	0.04		0-7	Present in large amounts in all tests except the Phase 1 metals feed. Most Cl went to the offgas.
Cr	3.2	0.4	65	56-99	Present as a metal in significant amounts only in the BWID nominal and the Phase 1 metal feed mixtures.
Cs	2.9	0	62		Present only as a trace element in the soil, so data quality is low.
Cu	1.4	5.9	4.3	2-73	Present as a metal in significant amounts only in the BWID nominal and the Phase 1 metal feed mixtures, but present in the incinerator ashes.
F	5.1	1.8			Present only in small amounts BWID nominal and the combustibles feed mixtures.
Fe	9.5	19	14	27-96	Present as a metal in significant amounts only in the BWID nominal and the Phase 1 metal feed mixtures, but present as oxide in all tests.

Element	Phase 2 (as received mixed waste surrogates) feed mixtures		Phase 1 (pre-incinerated mixed waste surrogates, metal feed mixture only)	ASME/U SBM Incinerator ash	Comments
	BWID nominal	Silicated organics and combustibles			
K	50	0.3	96		
Mg	90	23	99		
Na	28.3	5.1	94		
Ni	0.3	1.3	8.4		Present as a metal in significant amounts only in the BWID nominal and the Phase 1 metal feed mixtures (only small amounts in the incinerator ashes).
P	11-90	14	1.7	25-97	Present only as a trace element in the soil (somewhat larger amounts in the incinerator ashes).
Pb	0.2		47	1-82	Present as a metal in significant amounts only in the BWID nominal and the Phase 1 metal feed mixtures, and present in the incinerator ash tests.
S	10			4-31	Most S went to the offgas.
Se	0-15			0-22	Present only as a trace element in the soil.
Si	90	64	95		
Ti	86	46	99		
Zn	5.7	1.5	38	3-90	Present in the Phase 1 metals test and in the incinerator ashes.
Zr	99	98	95		
To the metal and matte (matte occurred only during the incinerator ash tests) products. One of the feed intervals (the fly ash with acid gas scrubber residue (E) with additives) had no metal or matte product.					
Ag	0-8	3.9		0-91	Th e matte from the incinerator ash tests had concentrated S.
Al	0.03	0.005	0.6		
As	59-77	18	92	0-92	
Ba	0.6	0.1	0.7	0-1	
C	3.5	0			
Ca			0.3		
Cd	0-0.1			0-28	
Ce	0-0.003				

Elemental partitioning (wt % to the furnace products) (Continued).

	Phase 2 (as received mixed waste surrogates) feed mixtures		Phase 1 (pre-incinerated mixed waste surrogates, metal feed mixture only)	ASME/U SBM Incinerator ash	Comments
Element	BWID nominal	Silicated organics and combustibles			
Cl					
Cr	97	94	35	0-39	
Cs	0-0.3				
Cu	97	71	96	0-96	
F					
Fe	89	63	86	0--72	
K			0.1		
Mg	62		0.5		
Na			0.6		
Ni	99.5	94	92		
P	72	14	95	0-72	
Pb	7.6	0.6	34	0-36	
S	2			0-49	The matte from the incinerator ash tests had concentrated S
Se	0-1.6		0.002	0-97	
Si	1.8	0.5	3.8		
Ti	10	6	1.1		
Zn			5.7	0-6	
Zr	0.7	0.6	0.4		
To the offgas solids					
Ag	23-100	96	100	1-78	Partitioning to offgas solids for the incinerator ash tests was high only for the baghouse ash/scrubber residue feeds (E) that contained moderate C levels (2.6-4.6%) and high Cl levels (12-20%), resulting in more reducing conditions in melt with potential for forming metal chlorides.
Al	3.5	13	0.6		
As	15-20	83	3	7-76	Partitioning to offgas solids for the incinerator ash tests was high only for the baghouse ash/scrubber residue feeds (E)
Ba	11	63	3	1-5	

Elemental partitioning (wt % to the furnace products) (Continued).

Element	Phase 2 (as received mixed waste surrogates) feed mixtures		Phase 1 (pre-incinerated mixed waste surrogates, metal feed mixture only)	ASME/USBM Incinerator ash	Comments
	BWID nominal	Silicated organics and combustibles			
C	1.3	0.2			
Ca	6.5	12	1.5		
Cd	99-100	100	100	14-98	
Ce	0.3	0.6	2.9		
Cl	68	2.2		6-21	
Cr	0.3	5.7	0.09	0.2-3	
Cs	97	100	38		
Cu	2	23	0.2	1-48	
F		98			
Fe	1.2	18	0.14	0.3-4	
K	51	99.7	3.8		
Mg	10	77	1		
Na	61	95	4.9		
Ni	0.2	5	0.09		
P	17	72	3.2	2-50	Partitioning to offgas solids for the incinerator ash tests was high only for the baghouse ash/scrubber residue feeds (E)
Pb	92	99	20	8-96	Partitioning to offgas solids for the incinerator ash tests was high only for the baghouse ash/scrubber residue feeds (E) and one MSW ash feed (A)
S	35			1-19	
Se	84-100	100	10	1-49	Partitioning to offgas solids for the incinerator ash tests was high only for the baghouse ash/scrubber residue feeds (E)
Si	8.2	35	1		
Ti	3.6	48	0.4		
Zn	94	98.5	56	10-96	
Zr	0.2	1	4.3		

AREAS OF FURTHER OPTIMIZATION, DEMONSTRATION, OR OTHER RESEARCH

Controlling metals volatilization
  Lower power density
  Lower bulk melt temperatures (lower melt superheat above melting temperature)
  More extensive and conclusive old top evaluations
  Lower melt residence time
  Empirical/theoretical volatility models

Controlling metals entrainment
  Reduce melter plenum gas flows and turbulence in melter by reducing total added combustion gas, and using oxygen, oxygen-enriched air, steam, or solid oxidants instead of air

  Eliminate or reduce fine feed materials by adding moisture, pelletizing, or containerizing (plastic bags, for example)

Pyrolysis and oxidation of feed materials
  Sequential operation-- pyrolysis to synthesis gas, gas cleanup, then oxidation (can reduce gas flowrates through control equipment, increase offgas control efficiencies, and reduce undesirable offgas system conditions including metals volatilization in high temperature oxidation zones, slagging, and catalytic formation of dioxins.

  Evaluation of stoichiometry and alternative oxidation choices - air, oxygen, oxygen-enriched air, steam, and solid oxidants, and effects on system performance, safety, pyrolysis/oxidation of volatile and fixed carbon, and melter system solid and gaseous products.

Melter system product evaluations
  Final waste form characterization, geometry, packaging, transportation, disposal
  Handling and immobilization of secondary waste streams from the offgas system
    Alternatives of dry vs wet secondary streams that will drive offgas system design and operation depending on transportation and disposal site acceptance criteria

    Characterization

    Recyclability to the melter or to a melter designed for lower volatilization and entrainment

    Immobilizability using sulfur polymer cement, portland cement, sol gels, etc

    Recyclability/reuse of metal product

    Empirical/theoretical models validated with data to predict final waste form and secondary waste properties

Diagnostics and instrumentation development and demonstration
  Continuous temperature sensors capable of remote operation, oxidizing/reducing conditions, low maintenance, sense solid, liquid and gas temperatures in smoky, dusty environment, at temperatures up to 2,000 C

  Continuous melt depth sensors capable of remote operation, oxidizing/reducing conditions, low maintenance, sense solid, liquid and gas temperatures in smoky, dusty environment, at temperatures up to 2,000 C

  - Continuous particulate, metals, organic gases, acid gases, and radionuclide emission monitors capable of remote operation, oxidizing/reducing conditions, low maintenance, sense solid, liquid and gas phases, for the offgas, final waste forms, and secondary streams

Peripheral systems development and demonstrations
  - Feed system (receiving, characterization, sizing, separation, transport to melter, containment, safety, etc)
  - Tapping (side vs bottom taps, no tap (batch operation), tapping designs, reliability, containment, safety, etc)
  - Radiation and contamination containment
  - Ability to reliably, remotely operate and minimize hands-on worker maintenance

Operating choices/conditions
  - Oxidize metals or tap metals?
  - Limits on Cl, C, crystallinity, etc. for final waste form
  - Criticality control
  - Waste stream limits -- mixing/blending feeds vs as-received

Melter and offgas system optimization and analysis
  - Design and operation for individual subsystems (such as the feed sizing, segregation, characterization, and delivery subsystems, or the furnace, offgas control, secondary stream, and final waste form subsystems), and for the entire system

  - Secondary streams

  - Detailed feasibility studies and cost estimates/comparisons

  - Prevention of particulate slagging/fouling in the offgas system

  - Testing using radioactive feed materials to validate models and surrogate tests and demonstrate containment and remote operation

  - Criticality control

REPORTS AND PAPERS BASED ON OR USED IN THE INEL/USBM ARC MELTER SYSTEM TEST PROGRAMS

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Soelberg, N. R., and W. J. Quapp, "Size Reducing Radioactive Wastes for Treatment Processes", Spectrum '94

Nuclear and Hazardous Waste Management International Topical Meeting, Atlanta, GA, August 14-18, 1994.

Soelberg, N. R., D. M. Ginosar, G. L. Anderson, and W. K. O'Connor, " Fate of Metals and TRU Surrogates During Arc Melter Vitrification", Spectrum '94 Nuclear and Hazardous Waste Management International Topical Meeting, Atlanta, GA, August 14-18, 1994.

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GLOBAL TESTING SUMMARY
Thermal Treatment Process: Plasma Hearth Process (Proof of Principle Unit)
Location: Retech, Inc., Ukiah, CA.

Test Series: PHP Mixed Waste Treatment Applications Demonstration (Proof of Principle Tests)
Dates/Time Frame: January 1994
Purpose/Goal: Determine treatability of three types of surrogate wastes and collect process-development data.

Test name or Feed type	Total operating time (hr)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	Avg melt temp (°C)	% distribution of feed material to: (kg/hr)				
						Slag/ash	Metal	APCS solids	Off gas	Closure (%)
M-1/Inorganic Sludge	unk	827	unk	163	unk	71•		4	881	81
M-2/Inorganic Sludge	unk	784	unk	85	unk	51•		2	1115	118
M-3/Heterogen. Debris	unk	668	unk	58	unk	37•		2	1396	120
M-4/Heterogen. Debris	unk	811	unk	54	unk	40•		2	1421	132
M-5/Organic Sludge	unk	747	unk	69	unk	38•		5	1784	116
M-6/Organic Sludge	unk	728	unk	97	unk	42•		4	1991	108
Totals or Averages		761		88		47•		4	1431	112

Comments: unk - unknown
n/a - not applicable
• - includes metals

References: G. R. Hassel, et. al., *Evaluation of the Test Results from the Plasma Hearth Process Mixed Waste Treatment Applications Demonstration,* Science Applications International Corp., Report No.SAIC-94/1095, October 1994.

The Proof of Principle (POP) Tests consisted of six tests using 3 surrogate waste formulations. Bulk ingredients were loaded into 30-gallon steel drums. The waste streams and the recipes for them are listed below in the table.

Surrogate waste formulations for the POP tests.

Surrogate Waste Components	Inorganic Sludge Tests M1,M2 (wt%)	Heterogeneous Debris Tests M3,M4 (wt%)	Organic Sludge Tests M5,M6 (wt%)
BULK INGREDIENTS			
Activated carbon	3.5	5	10
Cationic exchange resin	3.5	5	5
Tap water	40	10	15
Vermiculite	10		10
Iron oxide	14		10
Hydrated lime	10.5		10
Bulk alumina refractory		10	
Alumina blasting grit	7		5
Sodium nitrate	7		
Magnesium oxide	3.5		
Ethylene glycol			10
Lathe cutting oil			10
Mineral oil			7
Scrap wood		16	
PVC gloves		5	
Latex gloves		10	
Scrap mild steel		10	
Glass bottles		10	
Bulk concrete		8	
Diatomaceous earth		10	
RCRA METALS			
Cadmium nitrate	0.1	0.1	0.1
Chromium nitrate	0.1	0.1	0.1
Lead nitrate	0.1	0.1	0.1
Nickel nitrate	0.1	0.1	0.1
RCRA ORGANICS			
Naphthalene			3.5
1,2-Dichlorobenzene			3.5
RADIONUCLIDE SURROGATES			
Cerium (IV) oxide	0.3	0.3	0.3
Cesium chloride	0.3	0.3	0.3

The average elemental composition of the slag is given below in the table. The selected analytes accout for 90 to 96 wt% of the overall composition of the slag matrix. The compositions of all the slags were outside of typically accepted glass-forming compositions. The compositions for the baghouse dust are in the next table.

Slag compositions for POP Tests (%).

Element	Inorganic Sludge		Heterogeneous Debris		Organic Sludge	
	M-1	M-2	M-1	M-2	M-1	M-2
MATRIX ELEMENTS						
Aluminum	5	5	7	8	6	8
Calcium	5	5	2	3	7	9
Iron	24	24	9	2	6	4
Magnesium	20	20	20	19	28	23
Oxygen	na	34	38	42	na	34
Silicon	7	6	13	17	9	11
Sodium	0.8	1	0.6	0.9	0.04	0.1
TRACE ELEMENTS						
Carbon	0.08	0.04	0.05	0.04	0.07	0.07
Chlorine	na	<0.03	0.03	0.03	na	<0.03
Manganese	0.3	0.2	0.3	0.3	0.2	0.3
Nitrogen	0.09	0.09	0.09	0.08	0.06	0.08
Phosphorus	0.01	0.01	0.01	0.003	0.009	0.009
Potassium	0.1	0.1	0.1	0.1	0.01	0.05
Sulfer	0.3	0.09	0.3	0.3	0.1	0.1
Titanium	0.1	0.1	0.1	0.06	0.2	0.2
Zinc	0.001	<0.001	0.001	0.001	0.001	0.006
SPIKED METALS						
Cadmium	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cerium	0.2	0.02	0.12	0.02	0.3	0.3
Cesium	0.01	0.01	<0.01	0.04	<0.01	<0.01
Chromium	0.04	0.04	0.04	0.03	0.03	0.03
Lead	0.004	0.004	0.003	0.003	0.004	0.01
Nickel	0.03	0.02	0.004	0.006	0.006	0.01
TOTAL						
without oxygen	63	62	53	51	57	56
with oxygen	NA	96	91	93	NA	90

Baghouse dust compositions for POP Tests (%).

Element	Inorganic Sludge		Heterogeneous Debris		Organic Sludge	
	M-1	M-2	M-1	M-2	M-1	M-2
MATRIX ELEMENTS						
Aluminum	15	16	16	15	12	14
Calcium	0.5	0.3	0.3	0.3	1	1
Iron	5	3	5	5	10	6
Magnesium	0.4	0.3	0.6	0.6	2	1
Potassium	1	1	1	0.7	3	3
Silicon	21	21	22	22	16	19
Sodium	3	3	3	3	4	3
TRACE ELEMENTS						
Carbon	0.6	0.3	0.2	0.3	0.9	1
Carbon (total organic)	0.4	0.2	0.2	0.3	0.9	1
Chloride (total)	0.6	0.6	3	4	10	8
Cyanide (total)	na	<0.0	<0.00005	na	<0.0	na
Manganese	0.1	0.05	0.1	0.1	0.005	0.2
Nitrogen	0.2	0.05	0.08	0.06	0.3	0.04
Phosphorus	0.06	0.2	0.05	0.04	0.04	0.03
Sulfer	2	0.05	1	0.6	0.04	0.6
Titanium	0.5	2	0.6	0.6	0.6	0.5
Zinc	1	0.6	0.9	0.4	0.4	0.2
SPIKED METALS						
Cadmium	0.1	0.2	0.1	0.1	0.3	0.3
Cerium	0.008	0.008	0.04	0.06	0.05	0.04
Cesium	1	2	1	1	3	3
Chromium	0.04	0.04	0.04	0.03	0.03	0.03
Lead	0.4	0.4	0.3	0.3	0.6	0.5
Nickel	0.02	0.01	0.02	0.02	0.04	0.03

The two tables below present an overall mass balance for each of the six tests. All of the input and output flows represent averaged flows during the drum processing period. The mass balance error is the difference between the input and output values divided by the input value.

TEST	INPUT MASS FLOWS (kg/h)								TOTAL INPUT
	Feed Mateial	Plasma Torch	Air to PPC	Feeder Purge gas	Fuel and Air to	Air to SPC	Evap. Cooler	Evap Cooler	
M-1	163	88	88	27	232	277	112	189	1177
M-2	85	79	88	27	232	167	112	202	992
M-3	58	76	250	27	232	225	94	230	1193
M-4	54	73	263	27	232	119	77	264	1109
M-5	69	74	263	27	276	445	67	348	1569
M-6	97	76	263	27	276	736	70	339	1883
Ave.	88	78	202	27	247	328	89	262	1321

TEST	OUTPUT MASS FLOWS (kg/h)				
	Slag & Metal	Fly Ash	Stack Offgas	Total Output	Error
M-1	71	4	881	956	19%
M-2	51	2	1115	1169	-18%
M-3	37	2	1396	1436	-20%
M-4	40	2	1421	1463	-32%
M-5	38	5	1784	1827	-16%
M-6	42	4	1991	2037	-8%
Ave.	47	4	1431	1481	-12%

Mass balances were performed for the spicked RCRA and surrogate radionuclide metals to determine closure based on the quantities recovered in the process exit streams (slag, metal, baghouse dust, and stack gas) versus the quantity in the feed. The mass balnace closure values partitioning values were not unusual and show excellent agreement between the duplicate tests for each of the three feed types. Chlorine concentration did not appear to impact the recovery of the surrogate metals. Recoveries were fairly consistent between the inorganic sludge and the heterogeneous debris tests. Recoveries changed significantly with the organic sludge tests, increasing for cadmium, cesium and lead, while decreasing for chromium and nickel.

Partitioning to the stack gas was less than 1% for all of the metals. The cerium partitioned primarily (94% - 98%) to the slag while only 1% to 2% partitioned to the metal. Cerium was the least volatile of the spiked metals, as only *% or less partitioned to the offgas solids.

Metals partitioning, %, based on amounts recovered.

Metal	Slag	Metal	Bag-house Dust	Stack Gas	Mass Balance Closure	Slag	Metal	Bag-house Dust	Stack Gas	Mass Balance Closure
	INORGANIC SLUDGE									
	M-1					M-2				
Cadmium	3	1	96	0.02	45	3	2	95	0.01	52
Cerium	97	2	1	0.01	43	98	1	1	0.01	42
Cesium	3	5	92	0.01	63	3	4	94	0.004	82
Chromium	81	2	16	0.1	246	89	2	9	0.1	224
Lead	5	2	93	0.04	81	5	2	93	0.02	80
Nickel	60	31	9	0.05	146	44	52	4	0.1	141
	HETEROGENEOUS DEBRIS									
	M-3					M-4				
Cadmium	9	4	87	0.02	25	5	2	93	0.1	48
Cerium	91	2	8	0.03	46	91	2	7	0.01	49
Cesium	4	9	87	0.01	91	14	9	77	0.05	91
Chromium	84	4	12	0.1	279	54	35	11	0.3	308
Lead	4	4	92	0.02	94	5	3	93	0.05	72
Nickel	11	77	11	0.1	178	12	75	12	0.4	160
	ORGANIC SLUDGE									
	M-5					M-6				
Cadmium	1	0.4	99	0.003	128	1	1	98	0.004	102
Cerium	94	1	5	0.01	59	96	1	4	0.001	57
Cesium	1	2	97	0.001	198	1	2	97	0.002	152
Chromium	83	3	14	0.1	144	82	4	14	0.8	147
Lead	3	2	95	0.0001	148	7	0.5	93	0.01	117
Nickel	11	66	22	0.5	113	21	68	10	0.7	119

The most striking feature of the partitioning data is that partitioning to the stack gas (emissions) was less than 1% for all of the metals. These data indicate that metals of concern can be captured at high efficiencies, thereby preventing significant stack emissions. These results are especially encouraging since it can be argued that the metals were added to the feed in a manner

GLOBAL TESTING SUMMARY
Thermal Treatment Process: Plasma Energy Applied Tech. (PEAT) Thermal Destruction and Recovery (TDR) system
Location: Plasma Energy Applied Technology, Inc. (PEAT), Huntsville, AL

Test Series:
Dates/Time Frame:
Purpose/Goal:

Test name or Feed type	Total operating time (hr)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	Avg melt temp† (°C)	% distribution of feed material to: (kg/hr)				
						Slag/ash	Metal	APCS solids	Off gas	Closure (%)
Totals or Averages					1393					

Comments: **NO TESTING DATA AVAILABLE**

List of Materials Tested by PEAT

Contaminated Soils (Demonstration only)

Solid and Liquid Organic Wastes

Oxidant with Hydrocarbons

Small Arms Ammunition

Coal ash

Wastes with Suspended Volatile Metals

Thermal Batteries

Controlled Substances (Demonstration Only)

Municipal Waste Incinerator Fly Ash

Weapons Components

Microbiological Challenge

Medical Waste (Permit Validation)

Weapon Components with Imbedded Explosives

Emission Inventory

Based on independent sampling and analytical results, the following emissions data were used to conduct a comprehensive health risk assessment as part of an application to construct a TDR system to process 1000 pounds per hour of general hospital waste (including infectious waste) at a hospital in San Diego (Table 1).

Table 1. Emission Inventory, TDR Process for 1000 lbs/hr Medical Waste

Pollutant	Emission (g/sec)
Particulate	7.3E-02
HCl	1.01E-02
HF	5.05E-04
Aldehydes/Ketones	
Formaldehyde	1.08E-03
Acetaldehyde	5.42E-03
Butyraldehyde	4.19E-04
CO	3.8E-02
NOx	
SOx	1.20E-02
SVOC And PAH	
Phenol	4.21E-06
Acetophenone	8.88E-06
Benzoic Acid	1.15E-03
Naphthalene	1.33E-05
Diethyl Phthalate	4.59E-06
Di-n-Butyl Phthalate	1.01E-04
Butylbenzyl Phthalate	1.78E-05
bis(2-Ethylhexyl) Phthalate	4.29E-05
Dioxins/Furans	
Octachlorodibenzo-p-dioxin (OCDD)	1.01E-10
2,3,7,8-Tetrachlorodibenzofuran (TCDF)	5.32E-12
Octachlorodibenzofuran (OCDF)	4.79E-11
Total Tetrachlorodibenzofuran	4.04E-11
Metals	
Cadmium	1.24E-05
Copper	9.06E-05
Lead	1.41E-04
Nickel	3.13E-05
Zinc	4.89E-04

GLOBAL TESTING SUMMARY

Thermal Treatment Process: Rotating Hearth Furnace (PACT-1)
Location: TREAT Facility, ANL-W

Test Series: Volatility studies on a rotating hearth furnace.
Dates/Time Frame: August and November 1993
Purpose/Goal: Test the volatility and partitioning behavior of Ce and Pu .

Test name or Feed type	Total operating time (hr)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	Avg melt temp (°C)	Distribution of feed material to: (kg)				
						Slag/ash	Metal	APCS solids	Off gas	Closure (%)
Test 1 INEL Soil+CeO$_2$	unk	unk	4.754	unk	unk	3.625	0	(0.010)*		
Test 2 INEL Soil+PVC+CeO$_2$	unk	unk	5.777	unk	unk	3.815	0.702	(0.023)*		
Test 3 INEL Soil+(Pu)	unk	unk	5.081	unk	unk	4074	0	unk		
Test 4 INEL Soil+PVC+(Pu)	unk	unk	6.951	unk	unk	5183	unk	unk		
Totals or Averages			22.563	unk	unk					

Comments: unk - unknown
n/a - not applicable

References: T. F. Yeast, et. al., "Volatility Studies in a Rotating Hearth Furnace," *1994 American Nuclear Society Meeting, November 13, 1994, Washington, D.C.*

Test Recipes for Surrogate Tests (conducted at Ukiah, CA)

Test 1: Hearth Charge		Feeder Charge	
Dry INEL Soil	2250 gm	Dry INEL Soil	2218 gm
Water	350 gm	Water	391 gm
		CeO_2	53 gm
Total	2600 gm	Total	2662 gm

Test 2: Hearth Charge		Feeder Charge	
Dry INEL Soil	2517 gm	Dry INEL Soil	2166 gm
Water	243 gm	Water	324 gm
Iron	839 gm	PVC	94 gm
		CeO_2	69 gm
Total	3599 gm	Total	2653 gm

Test Recipes for Plutonium Tests (conducted at TREAT Facility, ANLW)

Test 3: Hearth Charge		Feeder Charge	
INEL Soil	2600 gm	INEL Soil	2595 gm
		(Pu 5660 nCi)	
Total	2600 gm	Total	2595 gm

Test 4: Hearth Charge		Feeder Charge	
INEL Soil	2400 gm	INEL Soil	3595 gm
Iron	1200 gm	PVC	106 gm
		(Pu 7660 nCi)	
Total	3600 gm	Total	3621 gm

Plutonium Distribution Data

IN	Source	Test 3 Plutonium (µCi)	Test 4 Plutonium (µCi)
	In Feeder	5.66	7.66
	Less Feeder/Residual	0.175±0.013	0.279±0.018
	Net Input	5.5±0.9	7.4±1.3

OUT	Source	Test 3 Plutonium (µCi)	Test 4 Plutonium (µCi)
	Slag	6.64±1.1	8.6±0.6
	Hearth Refractory	< MDA	0.03
	Torch Refractory	0.001	0.001
	Chamber / Spill	0.0008	0.0004
	Torch Ram / Ball	0.0002	0.0001
	Cold Finger / Spill	0.0009	0.0004
	System Piping	< MDA	< MDA
	HEPA Filter	0.0011	0.0021
	Total Out	116±26%	116±19%

Conclusion:

Although closure of the material balance is less than perfect, the evidence suggests that plasma melting does not cause substantial volatilization of plutonium.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: RETECH Plasma Arc Centrifugal Treatment (PACT-2)
Location: Ukiah, CA

Test Series: Minimum Additive Waste Stabilization (MAWS) Program
Dates/Time Frame: August-September 1993
Purpose/Goal: Demonstrate technology and characterize stack gas emissions/process flows

Test name or Feed type	Total operating time (h)	Average power (kW)	Total feed material (kg)	Average feedrate (kg/h)	Energy efficiency (kWh/kg)	Average melt temp. (°C)	% distribution of feed material to:				
							Slag/ash	Metal	APCS solids	Offgas	Closure
MAWS		160		2.3-4.5[a]		2500-3000[b]					

Comments:
a. Feed range; feed is fed in a batch-like mode
b. Estimated temperature range

All data listed in this global summary are from:

Test Results of Screening High-Metal-Content Wastes in a Plasma Centrifugal Furnace under the Minimum Additive Waste Stabilization Program, MSE, Inc., Butte, MT (1994).

Tests performed in the PACT-2 (or PCF-1.5) rotating hearth melter are designated by the notation MAWS (for Minimum Additive Waste Stabilization). Eight different test series were investigated and designated as MAWS-1 through MAWS-8. The waste formulations for tests performed are listed in Table 3. Additional tests within a series were indicated by a letter notation (MAWS-2A, MAWS-2B, etc.). Apparent complete melting and oxidation of feed material was achieved during tests MAWS-1, MAWS-2C, MAWS-4A, MAWS-5A, and MAWS-8A. Typical process conditions for successful tests (as indicated by complete melting/oxidation) and unsuccessful tests are listed in Tables 4 and 5, respectively. General test comments are summarized in Table 6.

Test feed and slag characterization

Measured metal concentrations for the MAWS PCF-1.5 feed components and product slags are shown in Table B-3. The compositions of feed soil and product slag compositions, expressed as the oxide are shown in Table B-4. The range of measured slag compositions is also shown in Table B-4.

Tables 9 and 10 show a comparison of expected and measured slag compositions for five apparently fully oxidized test series. The expected slag composition on an oxide basis is listed in Table B-5.

Notes:

The authors of the report do not elaborate on the method used to estimate the expected metal concentrations in the slag.

No material balance calculations were made on PACT-2 tests since this was not the primary purpose of the tests.

Table 3. Waste formulations selected for PCF testing (wt%).

Feed	Carbon Steel wt%	Stainless Steel wt%	Soil wt%	$FeCl_3$ wt%	Pb wt%	CeO_2 wt%
MAWS-1 (ANL-M5)	50.0		49.0			1.0
MAWS-2 (ANL-M16)	70.0		29.0			1.0
MAWS-3 (ANL-M14)		10.0	89.0			1.0
MAWS-4 (ANL-M4)		29.0	70.0			1.0
MAWS-5 (ANL-M10)	45.0	10.0	44.0			1.0
MAWS-6 (ANL-M11)	43.0	10.0	44.0		2.0	1.0
MAWS-7 (ANL-M12)	44.0	10.0	44.0	3.0		1.0
MAWS-8 (ANL-M7)	50.0	20.0	29.0			1.0

Table 4. Typical process parameters for successful tests.

	MAWS-1	MAWS-2C	MAWS-4A	MAWS-5A
Torch Gas	N_2 w/5% O_2	N_2 w/5% O_2	N_2 w/5% O_2	N_2 w/5% O_2
Torch Voltage (V)	550	410	410	410
Torch Amperage (Amp)	500	360	410	410
Chamber Vacuum (in H_2O)	8	10.75	10.75	10.75
Chamber Temperature (°F)	1900	1775	1800	1750
Kw Supplied	N/A	155	180	170
Kw Removed	N/A	130	150	160
Chamber RPM	24	26	22	23
Stack Gas O_2%	< 15	Not Measured	Not Measured	Not Measured

Table 5. Typical process parameters for failed tests.

	MAWS-2A	MAWS-4	MAWS-5
Torch Gas	N_2 w/5% O_2	N_2 w/5% O_2	N_2 w/5% O_2
Torch Voltage (V)	380	400	360
Torch Amperage (Amp)	400	380	370
Chamber Vacuum (in H_2O)	6.2	< 10.0	6.0
Chamber Temperature (°F)	1650	1800	1700
Kw Supplied	145	150	130
Kw Removed	155	150	130
Chamber RPM	20	32	31
Stack Gas O_2%	15	20	15

Table 6. MAWS PCF-1.5 test series summary.

PCF Test	Feed Material Oxidation/Mixing
93-MAWS-1	Feed material appeared to be fully melted and oxidized at the end of the test. No unoxidized metals were evident in the slag product.
93-MAWS-2A	At the end of the test a 4.07 lb metal ring was found under the product slag.
93-MAWS-2B+C	Melting/oxidation was incomplete after the initial test run (designated 2B). The contents of the primary chamber were reheated and the final slag product appeared to be fully melted and oxidized with no evidence of unmelted/unoxidized feed material.
93-MAWS-3A	Unmelted metal and soil was found in the final slag product.
93-MAWS-4	A 7.23 lb metal ring was found under the final slag product.
93-MAWS-4A	Feed material appeared to be fully melted and oxidized at the end of the test. No unoxidized metals were evident in the slag product.
93-MAWS-5	A 12.5 lb metal ring was found under the final slag product.
93-MAWS-5A	Feed material appeared to be fully melted and oxidized at the end of the test. No unoxidized metals were evident in the slag product.
93-MAWS-6	A 12.6 lb metal ring was found under the final slag product.
93-MAWS-7	A 12.3 lb metal ring was found under the final slag product.
93-MAWS-8	A 16.45 lb metal ring was found under the final slag product.
93-MAWS-8A	Feed material appeared to be fully melted and oxidized at the end of the test. No unoxidized metals were evident in the slag product.

Table B-3. Measured total metals analysis (mg/kg) for feed/slag samples for the MAWS PCF 1.5 test series.

PCF Test	93-MAWS Series		93-MAWS Series		93-MAWS Series		93-MAWS Series		93-MAWS Series		93-MAWS 4	
Matrix	C. Steel		S. Steel		C. Steel		S. Steel		Soil		Soil/Ce	
Al	22.7	U	28.3	U	225		38.2		60500		61300	
Sb	42.2	U	52.8	U	52.8	U	50.6		57.6	U	61.5	U
As	144		39.9	U	76		34.2	U	90.9		71.8	
Ba	5.7		3.5		1.8	U	1.9		822		821	
Be	1.2	U	1.5	U	1.5	U	2		1.6	U	1.7	U
Cd	6.1	U	7.6	U	7.6	U	6.6	U	8.3	U	8.9	U
Ca	346		189		12.3	U	103		11600		11400	
Cr	989		155000		624		137000		125		113	
Co	78.3		330		52.8		1220		9.1	U	9.7	U
Cu	3580		1190		1100		3640		105		42.7	
Fe	1130000		593000		842000		510000		33000		33000	
Pb	341		54.7	U	54.7	U	46.9	U	61.8		69.9	
Mg	19.3	U	24.1	U	24.1	U	20.6	U	9120		9180	
Mn	5430		13900		10200		13100		722		705	
Hg	0.03		0.04		0.04		0	U	0.06		0.06	
Ni	948		72500		607		62500		61.8		66	
K	35.2	U	44	U	44	U	37.7	U	20300		21100	
Se	60.9	U	972		76.1	U	1210		83	U	88.7	U
Ag	3.6		3.4	U	8.2		5.4		3.7	U	4	U
Na	57.3		330		99.6		25.2		9510		9640	
Tl	43	U	77.2		53.8	U	46.1	U	58.7	U	62.7	U
V	41		647		43.8		654		107		107	
Zn	403		373		137		252		140		120	
Si	1290		2690		2180		2330		313000		324000	
Ti	9.1		8.1		38.8		5.3		4460		4280	
Ce	47.2	U	59	U	59	U	50.6	U	64.3	U	3810	
Mo	186		1660		86.5		1390		25.5		15.5	
Total (%)	114.4		84.3		85.8		73.4		46.4		48.0	

U = Not detected.

93-MAWS-4 Soil/Ce sample was taken after mixing ceric oxide with the feed soil. Feed materials for 2B+C and appeared to be fully melted and oxidized, while slags for other tests were not.

Table B-3. (Continued).

PCF Test	93-MAWS 1		93-MAWS 2A		93-MAWS 2B+C		93-MAWS 3A		93-MAWS 4		93-MAWS 4A	
Matrix	Slag		Slag		Slag		Slag		Slag		Slag	
Al	92900		75000		99400		60700		57900		165000	
Sb	61.5	U	61.5	U	62.7	U	62.7	U	62.1	U	59.7	U
As	58.3		71.8		65.3		47.4	U	80.4		49.1	
Ba	293		165		584		761		698		294	
Be	1.7	U	1.7	U	1.8	U	1.8	U	1.7	U	1.7	U
Cd	8.9	U	8.9	U	9.1	U	9.1	U	9	U	8.7	U
Ca	5990		2880		13600		13200		12800		6590	
Cr	12700		16100		11800		20600		12900		47600	
Co	17.5		9.7	U	9.9	U	9.9	U	19.6		192	
Cu	1730		1400		1900		1130		1550		3050	
Fe	360000		453000		110000		49600		105000		143000	
Pb	181		63.7	U	65	U	123		82.4		92.5	
Mg	3060		1540		6820		8360		7660		3230	
Mn	1940		2290		709		7620		2770		4030	
Hg	0.03	U	0.02	U	0.04		0.03	U	0.03		0.05	
Ni	476		144		263		705		1250		8320	
K	6560		3600		12900		17300		14800		5850	
Se	150		155		90.4		343		151		813	
Ag	11.7		4	U	4.1	U	4.1	U	4	U	3.9	U
Na	4300		2830		8550		8000		6870		4590	
Tl	68		73.8		63.9	U	63.9	U	63.3	U	60.9	U
V	79.6		40.8		83.2		192		133		174	
Zn	287		68		87.1		87.1		88.2		83	
Si	109000		63400		206000		283000		256000		116000	
Ti	1640		887		3250		4030		37600		16000	
Ce	3630		4810		70.1	U	10800		7460		3670	
Mo	81.6		75.7		27.7		29.7		45.1		240	
Total (%)	60.5		62.9		47.6		48.7		52.6		52.9	

Table B-3. (Continued).

PCF Test	93-MAWS 5		93-MAWS 5A		93-MAWS 6		93-MAWS 7		93-MAWS 8		93-MAWS 8A	
Matrix	Slag		Slag		Slag		Slag		Slag		Slag	
Al	41100		193000		61500		53300		47900		179000	
Sb	62.7	U	58.6	U	60.3	U	59.2	U	57.6	U	61.5	U
As	91.1		88.9		72.4		84.1		43.5	U	46.5	U
Ba	481		185		505		654		427		99	
Be	1.8	U	1.6	U	1.7	U	1.7	U	1.6	U	1.9	
Cd	9.1	U	8.5	U	8.7	U	8.6	U	8.3	U	8.9	U
Ca	10400		4090		10500		12800		7510		2030	
Cr	19700		38900		23400		19200		38400		41700	
Co	9.9	U	46.3		9.5	U	9.3	U	9.1	U	117	
Cu	1330		2210		596		460		536		1060	
Fe	188000		177000		223000		197000		261000		262000	
Pb	259		77.8		4440		555		70.9		63.7	U
Mg	5570		2180		5360		6680		4470		930	
Mn	6120		2810		5230		6820		9450		2520	
Hg	0.03	U	0.03		0.03	U	0.03	U	0.02	U	0.03	U
Ni	665		4160		510		206		1890		6790	
K	10900		4360		11200		12200		9520		1460	
Se	295		630		316		136		629		781	
Ag	4.1	U	3.8	U	3.9	U	3.9	U	3.7	U	4	U
Na	540		5210		5650		6300		4490		1860	
Tl	63.9	U	59.8	U	61.5	U	336		69.1		62.7	U
V	145		98.1		137		155		229		951	
Zn	661		92.6		135		107		96.4		73.8	
Si	189000		73500		201000		244000		165000		37500	
Ti	2740		930		2720		3530		2260		474	
Ce	11100		2890		10200		13100		13100		5360	
Mo	29.7		104		38.1		22.4		74.5		56.3	
Total (%)	48.9		51.3		56.7		57.8		56.7		54.5	

Table B-4. Measured Total metals analysis, expressed as the oxide (% w/w), for MAWS PCF 1.5 test series feed soil, feed soil and ceric oxide mixture, and slag samples.

PCF Test	MAWS Series		93-MAWS 4		93-MAWS 1		93-MAWS 2A		93-MAWS 2B+C	
Matrix	Soil		Soil/Ce		Slag		Slag		Slag	
Al_2O_3	11.4		11.6		17.6		14.2		18.8	
Sb_2O_5	0.008	U	0.008		0.008	U	0.008	U	0.008	U
As_2O_5	0.014		0.011		0.009		0.011		0.010	
BaO	0.0917		0.0916		0.0327		0.0184		0.0652	
BeO	0.0004	U	0.0005		0.0005	U	0.0005	U	0.0005	U
CdO	0.0009	U	0.0010		0.0010	U	0.0010	U	0.0010	U
CaO	1.62		1.60		0.84		0.40		1.90	
Cr_3O_3	0.018		0.017		1.857		2.354		1.725	
Co_2O_3	0.001	U	0.001		0.002		0.001	U	0.001	U
CuO	0.013		0.005		0.217		0.175		0.238	
Fe_3O_4	4.56		4.56		49.75		62.60		15.20	
PbO	0.007		0.008		0.019		0.007	U	0.007	U
MgO	1.51		1.52		0.51		0.26		1.13	
Mn_3O_4	0.100		0.098		0.269		0.318		0.098	
HgO	6E-06		6E-06		3E-06	U	2E-06	U	4E-06	
NiO	0.008		0.008		0.061		0.018		0.033	
K_2O	2.45		2.54		0.79		0.43		1.55	
SeO_2	0.01	U	0.01		0.02		0.02		0.01	
Ag_2O	0.0004	U	0.0004		0.0013		0.0004	U	0.0004	U
Na_2O	1.28		1.30		0.58		0.38		1.15	
Tl_2O	0.006	U	0.007		0.007		0.008		0.007	U
V_2O_5	0.019		0.019		0.014		0.007		0.015	
ZnO	0.0174		0.0149		0.0357		0.0085		0.0108	
SiO_2	67.0		69.3		23.3		13.6		44.1	
TiO_2	0.744		0.714		0.274		0.148		0.542	
CeO_2	0.008	U	0.468		0.446		0.591		0.009	U
MoO_3	0.0038		0.0023		0.0122		0.0114		0.0042	
Totals	90.9		93.9		96.6		95.5		86.6	

U = Not detected. NA = Not applicable.
High and low concentrations for the series are shown in the last two columns of the table.

Table B-4. (Continued).

PCF Test	93-MAWS 3A		93-MAWS 4		93-MAWS 4A		93-MAWS 5		93-MAWS 5A	
Matrix	Slag		Slag		Slag		Slag		Slag	
Al_2O_3	11.5		10.9		31.2		7.8		36.5	
Sb_2O_5	0.008	U	0.008	U	0.008	U	0.008	U	0.008	U
As_2O_5	0.007	U	0.012		0.008		0.014		0.014	
BaO	0.0849		0.0779		0.0328		0.0537		0.0206	
BeO	0.0005	U	0.0005	U	0.0005	U	0.0005	U	0.0004	U
CdO	0.0010	U	0.0010	U	0.0010	U	0.0010	U	0.0010	U
CaO	1.85		1.79		0.92		1.46		0.57	
Cr_2O_3	3.012		1.886		6.959		2.880		5.687	
Co_2O_3	0.001	U	0.002		0.024		0.001	U	0.006	
CuO	0.141		0.194		0.382		0.167		0.277	
Fe_3O_4	6.85		14.51		19.76		25.98		24.46	
PbO	0.013		0.009		0.010		0.028		0.008	
MgO	1.39		1.27		0.54		0.92		0.36	
Mn_3O_4	1.058		0.384		0.559		0.849		0.390	
HgO	3E-06	U	3E-06		5E-06		3E-06	U	3E-06	
NiO	0.090		0.159		1.058		0.085		0.529	
K_2O	2.08		1.78		0.70		1.31		0.53	
SeO_2	0.05		0.02		0.11		0.04		0.09	
Ag_2O	0.0004	U	0.0004	U	0.0004	U	0.0004	U	0.0004	U
Na_2O	1.08		0.93		0.62		0.07		0.70	
Tl_2O	0.007	U	0.007	U	0.006	U	0.007	U	0.006	U
V_2O_5	0.034		0.024		0.031		0.026		0.018	
ZnO	0.0108		0.0110		0.0103		0.0823		0.0115	
SiO_2	60.5		54.8		24.8		40.4		15.7	
TiO_2	0.672		6.272		2.669		0.457		0.155	
CeO_2	1.326		0.916		0.451		1.363		0.355	
MoO_3	0.0045		0.0068		0.0360		0.0045		0.0156	
Totals	91.8		96.0		90.9		84.0		86.4	

Table B-4. (Continued).

PCF Test	93-MAWS 6		93-MAWS 7		93-MAWS 8		93-MAWS 8A		MAWS Series		MAWS Series	
Matrix	Slag		Slag		Slag		Slag		Low		High	
Al_2O_3	11.6		10.1		9.1		33.8		7.8		36.5	
Sb_2O_5	0.008	U	0.008	U	0.008	U	0.008	U	0.008	U	0.008	U
As_2O_5	0.011		0.013		0.007	U	0.007	U	0.007	U	0.014	
BaO	0.0564		0.0730		0.0477		0.0110		0.0110		0.0849	
BeO	0.0005	U	0.0005	U	0.0004	U	0.0005		0.0004	U	0.0005	
CdO	0.0010	U	0.0010	U	0.0009	U	0.0010	U	0.0009	U	0.0010	
CaO	1.47		1.79		1.05		0.28		0.28		1.90	
Cr_2O_3	3.421		2.807		5.614		6.097		1.725		6.959	
Co_2O_3	0.001	U	0.001	U	0.001	U	0.015		0.001	U	0.024	
CuO	0.075		0.058		0.067		0.133		0.058		0.382	
Fe_3O_4	30.82		27.23		36.07		36.21		6.85		62.60	
PbO	0.478		0.060		0.008		0.007	U	0.007	U	0.478	
MgO	0.89		1.11		0.74		0.15		0.15		1.39	
Mn_3O_4	0.726		0.947		1.312		0.350		0.098		1.312	
HgO	3E-06	U	3E-06	U	2E-06	U	3E-06	U	2E-06	U	5E-06	
NiO	0.065		0.026		0.240		0.864		0.018		1.058	
K_2O	1.35		1.47		1.15		0.18		0.18		2.08	
SeO_2	0.04		0.02		0.09		0.11		0.01		0.11	
Ag_2O	0.0004	U	0.0004	U	0.0004	U	0.0004	U	0.0004	U	0.0013	
Na_2O	0.76		0.85		0.61		0.25		0.07		1.15	
Tl_2O	0.006	U	0.035		0.007		0.007	U	0.006	U	0.035	
V_2O_5	0.024		0.028		0.041		0.170		0.007		0.170	
ZnO	0.0168		0.0133		0.0120		0.0092		0.0085		0.0823	
SiO_2	43.0		52.2		35.3		8.0		8.0		60.5	
TiO_2	0.454		0.589		0.377		0.079		0.079		6.272	
CeO_2	1.253		1.609		1.609		0.658		0.009	U	1.609	
MoO_3	0.0057		0.0034		0.0112		0.0084		0.0034		0.0360	
Totals	96.6		101.0		93.4		87.5		NA		NA	

Table 9. Expected and measured concentrations for MAWS PCF-1.5 slags for which feed materials appeared to be completely melted and oxidized.

Element	Expected concentration (mg/kg)										Measured concentration (mg/kg)									
	1		2B		4A		5A		8A		1		2B		4A		5A		8A	
Al	20027		11263		35676		18689		11248		92900		99400		165000		193000		179000	
Sb	19	U	11	U	34	U	18	U	11	U	61.5	U	62.7	U	59.7	U	58.6	U	61.5	U
As	30		17		54		28		17		58.3		65.3		49.1		88.9		46.5	U
Ba	272		153		485		254		153		293		584		294		185		99	
Be	0.5	U	0.3	U	0.9	U	0.5	U	0.3	U	1.7	U	1.8	U	1.7	U	1.6	U	1.9	
Cd	2.7	U	1.5	U	4.9	U	2.6	U	1.5	U	8.9	U	9.1	U	8.7	U	8.5	U	8.9	U
Ca	3840		2159		6840		3583		2157		5990		13600		6590		4090		2030	
Cr	41		23		58819		16804		30684		12700		11800		47600		38900		41700	
Co	3	U	2	U	5	U	3	U	2	U	17.5		9.9	U	192		46.3		117	
Cu	35		20		62		32		20		1730		1900		3050		2210		1060	
Fe	510309		601133		260969		499244		556366		360000		110000		143000		177000		262000	
Pb	20		12		36		19		11		181		65	U	92.5		77.8		63.7	U
Mg	3019		1698		5378		2817		1696		3060		6820		3230		2180		930	
Mn	239		134		426		223		134		1940		709		4030		2810		2520	
Hg	0.02		0.01		0.04		0.02		0.01		0.03	U	0.04		0.05		0.03		0.03	U
Ni	20		12		26146		7470		13638		476		263		8320		4160		6790	
K	6720		3779		11971		6271		3774		6560		12900		5850		4360		1460	
Se	27	U	15	U	49	U	26	U	15	U	150		90.4		813		630		781	
Ag	1.2	U	0.7	U	2.2	U	1.1	U	0.7	U	11.7		4.1	U	3.9	U	3.8	U	4	U
Na	3148		1770		5608		2938		1768		4300		8550		4590		5210		1860	
Tl	19	U	11	U	35	U	18	U	11	U	68		63.9	U	60.9	U	59.8	U	62.7	U
V	35		20		63		33		20		79.6		83.2		174		98.1		951	
Zn	46		26		83		43		26		287		87.1		83		92.6		73.8	
Si	103612		58269		184570		96691		58194		109000		206000		116000		73500		37500	
Ti	1476		830		2630		1378		829		1640		3250		16000		930		474	
Ce	7352		6962		9176		7670		6892		3630		70.1	U	3670		2890		5360	
Mo	8.4		4.7		15.0		7.9		4.7		81.6		27.7		240		104		56.3	

U = Below detection limits, detection limit displayed

Table 10. Ratio of observed to expected concentrations in product slag for PCF-1.5 tests for which feed material appeared to be completely melted and oxidized.

Element	**MAWS PCF-1.5 Test Designation**											
	1		**2B**		**4A**		**5A**		**8A**		**Avg**	
Al	5		9		5		10		16		9	
Sb	3.23	U	5.85	U	1.76	U	3.29	U	5.74	U	3.97	U
As	1.94		3.86		0.92		3.17		2.75	U	2.53	
Ba	1.08		3.82		0.61		0.73		0.65		1.38	
Be	3.21	U	6.04	U	1.80	U	3.24	U	6.39	U	4.14	U
Cd	3.24	U	5.89	U	1.78	U	3.32	U	5.77	U	4.00	U
Ca	1.56		6.30		0.96		1.14		0.94		2.18	
Cr	306		507		0.81		2.31		1.36		163	
Co	5.81	U	5.84	U	35.78	U	16.47	U	69.15	U	26.61	U
Cu	49.8		97.2		49.2		68.1		54.3		63.7	
Fe	0.71		0.18		0.55		0.35		0.47		0.45	
Pb	8.85		5.65	U	2.54		4.08		5.54	U	5.33	
Mg	1.01		4.02		0.60		0.77		0.55		1.39	
Mn	8.12		5.27		9.47		12.60		18.77		10.85	
Hg	1.51		3.58		1.41		1.62		2.69		2.16	
Ni	23.27		22.86		0.32		0.56		0.50		9.50	
K	0.98		3.41		0.49		0.70		0.39		1.19	
Se	5.46	U	5.85	U	16.61	U	24.57	U	50.61	U	20.62	U
Ag	9.55	U	5.95	U	1.79	U	3.32	U	5.81	U	5.29	U
Na	1.37		4.83		0.82		1.77		1.05		1.97	
Tl	3.5	U	5.85	U	1.76	U	3.30	U	5.75	U	4.03	U
V	2.25		4.18		2.76		2.97		47.80		11.99	
Zn	6.19		3.34		1.01		2.14		2.84		3.10	
Si	1.05		3.54		0.63		0.76		0.64		1.32	
Ti	1.11		3.91		6.08		0.68		0.57		2.47	
Ce	0.49		0.01	U	0.40		0.38		0.78		0.41	
Mo	9.67		5.84		15.96		13.20		11.87		11.31	

U = Below detection limits. detection limit displayed

Table B-5. Expected slag compositions for the MAWS PCF1.5 tests for which feed material appeared to be completely melted and oxidized.

Element as Oxide	MAWS PCF 1.5 Test Designation									
	1		**2B**		**4A**		**5A**		**8A**	
Al2O3	37852		21287		67427		35323		21260	
Sb2O5	25	U	14	U	45	U	24	U	14	U
As2O5	46		26		82		43		26	
BaO	304		171		541		283		171	
BeO	1.5	U	0.8	U	2.6	U	1.4	U	0.8	U
CdO	3.1	U	1.8	U	5.6	U	2.9	U	1.8	U
CaO	5376		3023		9576		5017		3019	
Cr2O3	60		34		85994		24567		44860	
Co2O3	4	U	2	U	7	U	4	U	2	U
CuO	44		24		78		41		24	
Fe3O4	705248		830766		360659		689955		768898	
PbO	22		12		39		21		12	
MgO	5005		2815		8917		4671		2811	
Mn3O4	332		187		591		310		186	
HgO	0.02		0.01		0.04		0.02		0.01	
NiO	26		15		33257		9502		17348	
K2O	8097		4554		14424		7557		4548	
SeO2	39	U	22	U	69	U	36	U	22	U
Ag2O	1.3	U	0.7	U	2.3	U	1.2	U	0.7	U
Na2O	4244		2387		7559		3960		2383	
Tl2O	20	U	11	U	36	U	19	U	11	U
V2O5	63		36		113		59		36	
ZnO	58		32		103		54		32	
SiO2	221626		124638		394795		206821		124478	
TiO2	2463		1385		4387		2298		1383	
CeO2	9028		8549		11268		9419		8463	
MoO3	12.7		7.1		22.6		11.8		7.1	

U = Not detected.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: Plasma Arc Centrifugal Treatment Furnace (PACT-6)
Location: Western Environmental Technology Office (WETO), Butte, MT.

Test Series: Cerium Test Series
Dates/Time Frame: August - November, 1992
Purpose/Goal: Determine partitioning behavior of cerium in the PCT-6 processing system.

Test name or Feed type	Total operating time (hr)	Average power (kW)	Total material (kg)	Average feedrate (kg/h)	Avg melt temp (°C)	% distribution of feed material to: (kg/hr)				
						Slag/ash	Metal	APCS solids	Off gas	Closure (%)
92-BWID-1	11	unk	245	unk	unk	290*				
92-BWID-2	9	unk	227	unk	unk	375*				
93-BWID-1	10	unk	340	unk	unk	475*				
93-BWID-2	8	unk	336	unk	unk	825*				
Totals or Averages	38		1148			1965*				

Comments: unk - unknown
n/a - not applicable
* - Accounts only for poured slag and slag removed from pour throat. (See text below for additional details).

References: G. R. Hassel, et. al., *Evaluation of the Test Results from the Plasma Hearth Process Mixed Waste Treatment Applications Demonstration,* Science Applications International Corp., Report No.SAIC-94/1095, October 1994.

The cerium series tests were conducted between August and November 1992. The first test processed only clean INEL soil to purge the PCF primary chamber of residual material from previous tests. A cerium mass balance was performed during the three following tests which used 1.25 wt% Ce. The simulated waste feed composition is shown below in the table.

Cerium series feed formulations.

Test Name	Component	weight%
92-BWID-1	INEL Soil	100
92-BWID-2	INEL Soil	60.25
	CeO_2	1.25
93-BWID-1	TCA ($H_3C_2Cl_3$)	0.50
	Wood	18.00
	Stainless Steel	3.00
93-BWID-2	Carbon Steel	15.00
	Lead	1.00
	Aluminum	1.00

Mass balance calculations on this type of system is difficult since it is a continuous process system which leaves residual material in the rotating hearth to protect the refractory. The residual material or "skull" is large compared to the material processed during a single test. Thus, a mass balance for a single test is very difficult and results in large uncertainties.
Typical residual skull weights were in the range of 5,000 pounds while the pour weights all below 1000 pounds. It is difficult to distinguish between the previous skull and the skull remaining after a test. Also the Ce concentrations varied significantly throughout the skull. This was the largest source of error in the mass balance calculations.

Three methods were used to calculate the Ce mass balance. Method 1 was based on total weight and average skull Ce conentrations and yielded a cumulative Ce recovery of 120.4%. Method 2 attempted to isolate exchangeaable regions in the skull and yielded a cumulative recovery of 66%. Method 3 minimized errors in determining skull Ce concentration by using Ce concentration results from the previous test. Tables containing the Ce mass balance information can be seen below.

Less than 0.1% of the input Ce was found in the APCS indicating that Ce volatilization was minimal. There was no direct indications that Ce selectively concetrated in the primary processing chamber.

Methodology #1 cerium balance summary.

				92-BWID-1	92-BWID-2	93-BWID-1	93-BWID-3	
				Test	**Test**	**Test**	**Test**	**Cumulative**
Inputs	Feed	Ce wt.	grams	0.0	2461.8	3692.7	3692.7	9847.2
	Skull	Tot. wt.	lb	4742.7	4585.8	4482.7	4856.6	4742.7
		Ce conc.	mg/kg	660.0	371.5	2492.4	1209.3	660.0
		Ce wt.	grams	1419.6	772.6	5066.9	2663.5	1419.6
	Total in	Ce wt.	grams	1419.6	3234.4	8759.6	6356.2	11266.8
Outputs	Slag	Tot. wt.	lb	289.0	380.0	472.0	825.0	1966.0
		Ce conc.	mg/kg	607.0	6314.0	9445.0	8038.0	6950.2
		Ce wt.	grams	79.6	1088.1	2021.8	3007.4	6196.9
	Skull	Tot. wt.	lb	4585.8	4482.7	4856.6	4412.4	4412.4
		Ce conc.	mg/kg	371.5	2492.4	1209.3	3683.0	3683.0
		Ce wt.	grams	772.6	5066.9	2663.5	7370.0	7370.0
Total out		Ce wt.	grams	852.2	6155.1	4685.3	10377.4	13566.9
Ce recovery (%)				60.0	190.3	53.5	163.3	120.4

Methodology #2 cerium balance summary.

				92-BWID-1	92-BWID-2	93-BWID-1	93-BWID-3	
				Test	Test	Test	Test	Cumulative
Inputs	Feed	Ce wt.	grams	0.0	2461.8	3692.7	3692.7	9847.2
	Skull bottom	Tot. wt.	lb	190.5	189.8	191.7	191.2	190.5
		Ce conc.	mg/kg	1010.0	514.0	7187.0	9445.0	1010.0
		Ce wt.	grams	87.3	44.2	624.8	819.0	87.3
	Total in	Ce wt.	grams	87.3	2506.0	4317.5	4511.7	9934.5
Outputs	Slag	Tot. wt.	lb	289.0	380.0	472.0	825.0	1966.0
		Ce conc.	mg/kg	607.0	6314.0	9445.0	8038.0	6950.2
		Ce wt.	grams	79.6	1088.1	2021.8	3007.4	6196.9
	Skull bottom	Tot. wt.	lb	189.8	191.7	191.2	127.6	127.6
		Ce conc.	mg/kg	514.0	7187.0	9445.0	8038.0	8038.0
		Ce wt.	grams	44.2	624.8	819.0	465.1	465.1
	Skull lower	Tot. wt.	lb	15.0	-305.3	542.1	-387.0	-387.0
	sidewall	Ce conc.	mg/kg	1364.0	524.0	9445.0	176.0	176.0
		Ce wt.	grams	9.3	-72.6	2322.1	-30.9	-30.9
	Skull upper	Tot. wt.	lb	-170.5	197.9	-198.6	-26.8	-26.8
	sidewall	Ce conc.	mg/kg	1182.0	1583.5	1583.5	6372.0	6372.0
		Ce wt.	grams	-91.4	142.1	-142.6	-77.4	-77.4
	Total out	Ce wt.	grams	41.7	1782.5	5020.2	3364.2	6553.7
Ce recovery (%)				47.8	71.1	116.3	74.6	66.0

Methodology #3 cerium balance summary.

			92-BWID-1	92-BWID-2		93-BWID-1		93-BWID-3	BWID
Inputs			Test	Test	Cumulative	Test	Cumulative	Test	Total
Feed	Ce wt.	grams	0.0	2461.8	2461.8	3692.7	6154.5	3692.7	9847.2
Skull bottom	Tot. wt.	lb	1222.0	N/A	N/A	N/A	N/A	N/A	N/A
	Ce conc.	mg/kg	1010.0	N/A		N/A		N/A	
	Ce wt.	grams	559.7	0.0	559.7	0.0	559.7	0.0	559.7
Total in	Ce wt.	grams	559.7		3021.5		6714.2		10406.9
Outputs									
Slag	Tot. wt.	lb	289.0	380.0	669.0	472.0	1141.0	825.0	1966.0
	Ce conc.	mg/kg	607.0	6314.0		9445.0		8038.0	
Total out	Ce wt.	grams	79.6	1088.1	1167.7	2021.8	3189.5	3007.4	6196.9
Ce recovery (%)					38.6		47.5		59.5
Pretest skull assumed to be exchange zone only (0-2 inches)									

Methodology #3 cerium balance summary (cont'd).

			BWID	93-DEMO-3		93-ARII-1		93-SAFE-2		93-SLDG-3D	
Inputs			Total	Test	Cumulative	Test	Cumulative	Test	Cumulative	Test	Final
Feed	Ce wt.	grams	9847.2	0.0	9847.2	0.0	9847.2	0.0	9847.2	0.0	9847.2
Skull bottom	Tot. wt.	lbs	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Ce conc.	mg/kg		N/A		N/A		N/A		N/A	
	Ce wt.	grams	559.7	0.0	559.7	0.0	559.7	0.0	559.7	0.0	559.7
Total in	Ce wt.	grams	10406.9		10406.9		10406.9		10406.9		10406.9
Outputs											
Slag	Tot. wt.	lbs	1966.0	360.0	2326.0	822.0	3148.0	743.0	743.0	304.0	1047.0
	Ce conc.	mg/kg		2115.0		1995.0		825.3		161.0	
Total out	Ce wt.	grams	6196.9	345.3	6542.2	743.7	7285.9	278.1	7564.0	22.2	7586.2
Ce recovery (%)			59.5		62.9		70.0		72.7		72.9

Pretest skull assumed to be exchange zone only (0-2 inches)

Cerium distribution in off-gas system.

	Ce in post-water (grams)	Ce in blower dust (grams)	Ce in filters (grams)	Ce in stack particulate (grams)	Ce in stack vapor (grams)	Test total (grams)
92-BWID-1	0.04	0.00	0.00	N/A	undec	0.04
92-BWID-2	1.33	0.02	0.14	3.98	undec	5.47
93-BWID-1	1.16	0.07	0.22	4.44	N/A	5.89
93-BWID-3	1.32	0.08	0.37	1.40	undec	3.18
Totals	3.85	0.18	0.74	9.82	0.00	14.58
N/A = Not Analyzed						
undec = Undetectable						

GLOBAL TESTING SUMMARY
Thermal Treatment Process: Molten Metals Technology (MMT) Melter-Catalytic Extraction Processing (CEP)
Location: R&D Facility: Fall River, MA
Quantum-CEP: Scientific Ecology Group (SEG), Oak Ridge, TN

Test Series:
Dates/Time Frame:
Purpose/Goal:

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure

Comments:
a. PCC - primary combustion chamber
b. SCC - secondary combustion chamber

Thermal treatment process: MMT Quantum-Catalytic Extraction Processing (CEP)

Experimental Observations and Discussion

Reference: C.A. Herbst et al.,"Quantum-Catalytic Extraction Process application to mixed waste processing",*Proceedings Spectrum'94 Nuclear and Waste Management Meeting*, Atlanta (1994).

Falls River, MA facility (CEP)
Molten Metal Technology (MMT) designed a series of bench-scale experiments using radioactive surrogate materials to demonstrate the oxidation and partitioning of the radionuclides between the metal and vitreous phases and to identify and optimize the effect of operating conditions on partitioning.

Hafnium (Hf) was selected as the radioactive surrogate material due to its similarities in thermodynamic behavior and physical properties to uranium (U). The experimental design parameters evaluated were metal system, gas environment and ceramic phase composition. Radioactive surrogate partitioning was measured using neutron activation analysis (NAA) for non-destructive trace analysis. The hafnium lower detection limits were 0.2 ppm in Fe and 2 ppm in Ni.

Metal samples were taken from different locations in the metal bath to ensure uniform concentration. The objective was to demonstrate uniform metal decontamination above 98%. The average decontamination of the metal exceeded this objective in all experimental trials with the detection of any trace amounts limited by the LDL. Three cases were investigated and the percent decontamination are summarized below with the vitreous phase indicated in parentheses.

Iron (V1): ≥ 99.62%
Nickel (V1): ≥ 99.76%
Iron (V2): ≥ 99.08%

V1 refers to an aluminosilicate vitreous composition
V2 refers to a borosilicate vitreous composition
Exact details of the optimum vitreous phase composition are considered proprietary and are not specified.

Oak Ridge, TN (Quantum-CEP)
MMT used Quantum-CEP to process ion exchange resin. Preliminary results were presented.

Experimental demonstrations on both surrogate and contaminated ion exchange resins indicate complete capture of the cobalt in the molten metal bath with negligible, if any, dust carryover. Because cesium (Cs) is highly volatile, MMT designed and tested a proprietary Cs capture system. Experimental results were expressed in terms of "decontamination factors" or DF

DF = (Activity In) / (Activity Out)

Values were reported for 4 nuclides

Co-60	DF≥ 169,500
Cs-137	DF≥ 138,300
Mn-54	DF≥ 162,700
Zn-65	DF≥ 190,800

GLOBAL TESTING SUMMARY
Thermal Treatment Process: ACERC Bench-scale Rotary Kiln Reactor
Location: University of Utah

Test Series: Parametric study of vaporization of metal species from solids
Dates/Time Frame: *Proceedings 1993 Incineration Conference*, Knoxville, TN **(CASE 1)**
Purpose/Goal: Investigate behavior of Pb, Cd, Cr, and Ni during heating of synthetic waste sludge

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure
Test 1					815						
Test 2					815						
Test 3					815						
Test 4					815						
Test 5					815						
Test 6					815						
Test 7					980						

Comments:
a. PCC - primary combustion chamber or bench-scale rotary kiln
b. No secondary combustion chamber was present in experimental setup.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: ACERC Bench-scale Rotary Kiln Reactor
Location: University of Utah

Test Series: Parametric study of vaporization of metal species from solids
Dates/Time Frame: *Proceedings 1994 International Incineration Conference*, Houston, TX (**CASE 2**)
Purpose/Goal: Investigate behavior metals and radioactive surrogates during heating of synthetic soil

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC^a Gas Temp. (°C)	Average SCC^b Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure
Series 1, No Cl, HVPM^c	>0.5		0.06		315						
Series 1, Cl salts, HVPM	>0.5		0.06		315						
Series 1, Cl salts, No HVPM	>0.5		0.06		315						
Series 1, Organic Cl, HVPM	>0.5		0.06		315						
Series 1, No Cl, HVPM	>0.5		0.06		925						
Series 1, Cl salts, HVPM	>0.5		0.06		925						
Series 1, Cl salts, No HVPM	>0.5		0.06		925						
Series 1, Organic Cl, HVPM	>0.5		0.06		925						
Series 2, No Cl, HVPM	>0.5		0.06		315						
Series 2, Cl salts, HVPM	>0.5		0.06		315						
Series 2, No Cl, HVPM	>0.5		0.06		925						
Series 2, Cl salts, HVPM	>0.5		0.06		925						

Comments:
a. PCC - primary combustion chamber or bench-scale rotary kiln
b. No secondary combustion chamber was present in experimental setup.
c. HVPM - high vapor pressure metals (cadmium, zinc, lead)

GLOBAL TESTING SUMMARY
Thermal Treatment Process: ACERC Bench-scale Rotary Kiln Reactor
Location: University of Utah

Test Series: Parametric study of vaporization of metal species from solids
Dates/Time Frame: "Constituent interaction during thermal treatment of INEL soils", Report No. G34112210, December 1994 **(CASE 3)**
Purpose/Goal: Investigate behavior metals and radioactive surrogates during heating of synthetic soil

Test name or Feed type	Total operating time (h)	Total heat (kW)	Total feed (kg)	Average feedrate (kg/h)	Avg PCC[a] Gas Temp. (°C)	Avg SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure
1. A-40, no Cl	0.5		0.08		470						
2. A-40, no Cl	0.5		0.08		620						
3. A-40, no Cl	0.5		0.08		775						
4. A-40, 5% Cl(inorganic)	0.5		0.08		470						
5. A-40, 5% Cl(inorganic)	0.5		0.08		620						
6. A-40, 5% Cl(inorganic)	0.5		0.08		775						
7. A-40, 5% Cl(inorganic)	0.5		0.08		870						
8. A-40, 5% Cl(inorganic)	0.5		0.08		925						

Comments:
a. PCC - primary combustion chamber or bench-scale rotary kiln
b. No secondary combustion chamber was present in experimental setup.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: ACERC Bench-scale Rotary Kiln Reactor
Location: University of Utah

Test Series: Parametric study of vaporization of metal species from solids
Dates/Time Frame: "Constituent interaction during thermal treatment of INEL soils", Report No. G34112210, December 1994 (**CASE 3**)
Purpose/Goal: Investigate behavior metals and radioactive surrogates during heating of synthetic soil

Test name or Feed type	Total operating time (h)	Total heat (kW)	Total feed (kg)	Average feedrate (kg/h)	Avg PCC[a] Gas Temp. (°C)	Avg SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure
9. A-40, 0.5% Cl(inorganic)	0.5		0.08		925						
10. A-40, 0.5% Cl(inorganic)	0.5		0.08		925						
11. SiO_2, 5% Cl(inorganic)	0.5		0.08		925						
12. Al_2O_3, 5% Cl(inorganic)	0.5		0.08		925						
13. Fe_3O_4, 5% Cl(inorganic)	0.5		0.08		925						
14. CaO, 5% Cl(inorganic)	0.5		0.08		925						
15. A-40, 5% KNO_3	0.5		0.08		925						

Comments:
a. PCC - primary combustion chamber or bench-scale rotary kiln
b. No secondary combustion chamber was present in experimental setup.
c. SM-# - Spiking method number 1: Oxides; 2: Oxides; 3: Nitrates

CASE 1 - Feed descriptions:

A synthetic mixture designed to simulate the behavior of industrial wastewater treatment sludges have been developed at the University of Utah. The bulk composition in g/g peat (% concentration) were: peat, 1.00 (12%); water, 6.13 (71%); iron (II) sulfate, 0.48 (6%), and calcium (Ca) carbonate, 1.06 (12%). An ultimate analysis revealed that the synthetic waste consisted of moisture 73.75% , carbon 8.40%, hydrogen 0.86%, nitrogen 0.18%, sulfur 1.08%, chlorine < 0.01%, oxygen 6.11%, and ash 9.62%.

Two types of surrogate were used. In Surrogate A, a large quantity of material containing all the components of the surrogate except for the toxic metals were prepared prior to testing. The calcium compounds tended to form balls during mixing which made the surrogate inhomogeneous. Aliquots were extracted from this mixture prior to each test. The Ca/peat ratio varied by as much as 50% from aliquot to aliquot. The toxic metals were added to the aliquots as aqueous solutions. The spiking solution contained nitrates of cadmium (Cd), chromium (Cr), lead (Pb), and nickel (Ni). Sufficient quantities of each metal was added to produce a concentration of approximately 1000 ppm in the final surrogate. When called for in the test matrix, chlorine (Cl)-containing compounds were also added to the aliquot just prior to a test.

The second surrogate, Surrogate B, was prepared in which the Ca was not added during the initial preparation. The metals were added in an aqueous solution to dry peat. The mixture was dried before adding the other surrogate compounds. Aliquots were extracted for each test. Calcium carbonate was added prior to testing. This ensured a consistent Ca concentration.

Metal concentrations in spiking solution:

$Cd(NO_3)_2 \cdot 4\,H_2O$	1,895 ppm
$Cr(NO_3)_3 \cdot 9\,H_2O$	1,720 ppm
$Pb(NO_3)_2$	4,752 ppm
$Ni(NO_3)_2 \cdot 6\,H_2O$	1,905 ppm

CASE 2 - Feed descriptions:

The soil used in this study was selected based on a previous study of soils within INEL waste inventory and is designated "A-40". The following high vapor pressure metals (HVPMs) were added to the base soil as dry oxides to a concentration of 1000 ppm: cadmium, lead, and zinc. The nonradioactive surrogates representing radionuclides of interest were also added as dry oxide powders and were added to a concentration of 1000 ppm. The surrogate metals added were: cerium (Ce), cesium (Cs), gadolinium (Gd), neodymium (Nd), and samarium (Sm).

During selected tests, inorganic chlorine was added to the soil mixture in the form of the salts NaCl and KCl. Sufficient quantities of salts were added to brine the Cl concentration to 1% by weight. The salts were added in a 1:1 molar ratio to each other.

During one test at each temperature, an organic chlorine-containing compound was added to the soil mixture. Tetrachloroethylene was added to bring Cl concentration up to 1% by weight.

In the Series 1 tests, the metals were mixed in bulk and separated into sample aliquots for use in the bench-scale rotary kiln. In the Series 2 tests, the soil mixture was divided into sample aliquots and then dry metal oxides were added to each aliquot to ensure that the amount of metal in each sample was known.

CASE 3- Feed descriptions:

The synthetic soil mixture was based on the results of previous studies of soil in INEL waste. The composition of the synthetic waste, A-40, consists of:

SiO_2	49.0 wt%	MgO	3.7%
Al_2O_3	9.5%	NaO	3.5%
Fe_2O_3	1.8%	K_2O	2.6%
F_3O_4	20.6%	TiO_2	0.2%
CaO	9.1%		

The following high vapor-pressure metals (HVPMs) were added to the base soil to a metal concentration of 1000 ppm: Cd, Cr, Pb, and Zn.

The nonradioactive surrogates representing radionuclides of interest were also added to a concentration of 1000 ppm each: Ce, Cs, Gd, Nd, and Sm.

To ensure that the spiked metals were uniformly distributed in the waste matrix, the metal compounds were dissolved in a mild nitric acid solution. When possible, metal nitrates were used. However, nitrates of some of the surrogate metals were not available and oxides were used. The oxides of these metals were soluble. The metal solution is add to the waste matrix to obtain the needed concentration. Excess water is added to saturate the solution and evenly distribute the metals. The matrix is then dried. A sample aliquot is taken and any Cl-containing compounds are added.

Metal compounds used in spiking solution

Cadmium	$Cd(NO_3)_2{\cdot}4H_2O$
Chromium	$Cr(NO_3)_3{\cdot}9H_2O$
Lead	$Pb(NO_3)_2$
Zinc	$Zn(NO_3)_2{\cdot}6H_2O$
Cerium	$Ce(NO_3)_3$
Cesium	$Cs(NO_3)_3$
Gadolinium	Gd_2O_3
Neodymium	Nd_2O_3
Samarium	Sm_2O_3

Test Matrix **(CASE 1)**

Test Number	Compositional Variables						Operational Variables			
	Calcium			Chlorine			Purge Gas Composition		Maximum Temperature	
	0%	5%	10%	0%	5% as PVC	5% as NaCl	Ambient	1% CO	815°C	980°C
1		✓		✓			✓		✓	
2	✓			✓			✓		✓	
3			✓	✓			✓		✓	
4		✓				✓	✓		✓	
5		✓			✓		✓		✓	
6		✓		✓				✓	✓	
7		✓		✓			✓			✓

Elemental partitioning (**CASE 1**)

	Baseline **(No Cl)** Test 1	**5% Cl** **(NaCl)** Test 4	**5% Cl** **(PVC)** Test 5
Weight % metal in Ash			
Cr	≈ 58%	≈ 50%	≈ 30%
Pb	≈ 62%	≈ 48%	≈ 38%

Wt ratios >	**Ca/peat=0.0** Test 2	**Ca/peat=0.3** Test 1	**Ca/peat=0.5** Test 3
Weight % metal in Ash			
Cr	≈ 25%	≈ 58%	≈ 45%
Cd (Surr. B)	≈ 10%	≈ 18%	≈ 30%
Cd (Surr. A, Ca/peat≈0.28)	≈ 42%		
Cd (Surr. A, Ca/peat≈0.45)	≈ 80%		

	815°C Test 6	**980°C** Test 7
Weight % metal in Ash		
Cd	≈ 45%	≈ 20%
Pb	≈ 47%	≈ 22%

CASE 1 - Experimental observations and discussion:

- Metal partitioning in the ash as a function of chlorine in waste feed

A slight decrease in the fraction of Cr observed in the ash occurred when NaCl was added to the surrogate. A much greater fraction left the reactor when PVC was added to the surrogate. These observations agree qualitatively with modeling predictions and previous experimental data. The fraction of Ni and Cd in the ash did not appear to change with the addition of organic or inorganic chlorine. Equilibrium calculations that Ni and Cd do not form volatile metal chlorides at these conditions.

- Metal partitioning in the ash as a function of calcium present in waste feed

The response of cadmium to calcium depended on the method used to formulate the surrogate. For Surrogate B, in which the Ca is added last, the impact of Ca is weak. However, in Surrogate A, in which metals are added last, the Ca has a strong impact on the partitioning of Cd. This is attributed to more intimate mixing of metals and Ca when the metal solution is added than when a solid Ca compound is added to a mixture containing absorbed metal solution. Inhomogeneities (small and large scale) in the waste may prevent potentially reactive materials from coming in contact

The effect of Ca on the partitioning of Cr is less clear. There appears to be an initial increase in the amount of Cd in the ash followed by a decrease with increasing Ca content. While this appears to agree with preliminary observations reported elsewhere, the authors conclude that this phenomenon requires further investigation.

- Metal partitioning in the ash as a function of the purge atmosphere

Because the authors assumed that the peak bed temperature in an incinerator may in fact occur in regions containing reducing atmospheres, tests were conducted with a purge gas containing 1% CO in N_2. The reducing atmosphere did not appear to alter the partitioning of the metals studied.

- Metal partitioning as a function of temperature

As expected, the fraction of metal retained in the ash decreases with increasing temperature for Cd and Pb. However, at both temperatures the fraction retained was greater than would be predicted based on equilibrium considerations. This may be attributed to interactions with the waste matrix which result in the formation of species not included in current thermodynamic databases or to physical interactions which prevent vaporization, such as encapsulation.

CASE 2 - Experimental results and observations

- Material balance on metals

The values of Pb and Cd recovery were similar and ranged from 0.38 to 1.23. The poor recoveries (less than 0.8) occurred during high temperature tests in which no chlorine was added and during the high-temperature test in which tetrachloroethylene was added. The low recoveries are probably the result of either the formation of indigestible complexes or a failure of the multiple metals train to capture all metal vapors. In all tests, none of the metals of interest were found on the impingers. All of the metals found were on the filter or in the sampling probe.

Zinc recovery was not affected by operating temperature or matrix composition but recoveries still varied between 0.5 and 0.9 with the metal retained primarily in the ash.

- Surrogate radioactive metal behavior

All surrogates exhibited similar partitioning behavior except for cesium. The fractional recoveries were significantly lower at the higher temperature. No other change in the behavior of these metals was observed at any of the test conditions. Cesium behaved much like cadmium and lead, and this is consistent with cesium's classification as a HVPM.

- Method of sample preparation

Initial Series 1 test results suggested that waste feed segregation problems may have occurred. This nonuniformity could have resulted in the concentrations of the metals in the feed material used in each test. The method of sample preparation used for Series 2 tests was especially developed to address this concern. Experimental results show no clear cut difference in fraction of metal recovered. This suggests that the eror associated with the assumed metal concentrations in the Series 1 sample aliquots is random.

- Conclusions

It is difficult to draw any significant conclusions from these experiments in light of the poor material balance data collected. It is suspected that organic compound is driven off during heating diminishing the extent of reactions between Cl and any metals that form chlorides.

CASE 3 - Experimental results and discussion

- Element recoveries

Using the oxide powders, recoveries ranged between 20% to 150%. For the nitrate tests, the majority of recoveries were between 80% to 120%. The nitrate tests where recoveries were poor were where SiO_2 and Al_2O_3 were used as the primary matrix. It was suggested that the poor recoveries was attributed to the sample analysis method that was unable to completely digest the sample.

- Cd partitioning

The fraction vaporized increased in the presence of NaCl and KCl. There was a slight increase in the fraction vaporized in the presence of KNO_3. This test was conducted to determine if vaporization resulted from the inorganic Cl or the preferential sorption of K by active sites in the A-40 mixture. This preferential binding had been observed in earlier studies. This study suggests that some vaporization can be attributed to the presence of K. The CaO melt retained Cd to a much greater degree than the other metals.

- Cr, Gd partitioning

Chromium was relatively refractory, remaining in the solid at all conditions studied except in the case of CaO matrix with inorganic Cl. Even then, fraction vaporized was only 20%. Gadolinium behaved much like Cr.

- Pb, Cs partitioning

Lead behaved liked Cd with exception of the CaO/inorganic Cl test. Whereas the fraction vaporized increased in all systems in the presence of inorganic Cl, this was not the case with CaO. Cesium behaved much like Pb.

- Zn partitioning

Zinc showed increased vaporization in the presence of inorganic Cl only under the conditions of separate matrix species (Si, Al, Ca). No effect was observed for the A-40 soil matrix. A small increase in vaporization was observed in soil/KNO_3 tests.

- Surrogate partitioning

All appeared to be refractory under the conditions studied as did Cr and Zn.

- Effect of organic matter on volatilization of metals

The fraction of vaporization, F_v, of metal uniformly dispersed throughout an organic waste feed was determined as a function of the organic matter concentration, C_m. This was done for Cd, Cr, Pb, and Ni. The equation $F_v = 0.28\ C_m$ was found to best describe the relationship. This relationship is not valid when metal is not uniformly dispersed through the organic material.

- Fraction vaporized and waste type

If each solid is assumed have a variety of adsorption sites available, the strength of the bonding associated with each site varies with temperature so that sufficient energy is available to break the bonds associated with some sites and not others. Kinetic theory is used to describe the fraction not vaporized by the Arrhenius equation. The pre-exponential factor and the activation energy term must be determined for each waste form.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: SWIFT Pilot Scale RKS
Location: Energy and Environmental Research, Santa Ana, CA

Test Series:
Dates/Time Frame: Final Report: CIF Metals Partitioning Test (U), WSRC-TR-93-623, August 31, 1993
Purpose/Goal: Test burns using surrogate CIF wastes spiked with hazardous metals and organics

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure
Run 1, Waste Type E	1.5			6.7	1000	1100					
Run 2, Waste Type E	1.0			6.5	1000	1100					
Run 3, Waste Type E	1.5			6.5	1000	1100					
Run 4, Waste Type F	1.5			6.5	1000	1100					
Run 5, Waste Type E	1.5			6.5	870	980					
Run 6, Waste Type F	1.5			6.5	870	980					
Run 7, Waste Type G			21.7		1000	1100					
Run 8, Waste Type G			16.8		870	980					
Run 9, Waste Type E	1.5			6.5	760	870					

Comments:
a. PCC - primary combustion chamber
b. SCC - secondary combustion chamber

Feed description

Waste Type E (Solid Waste Mix):
Paper [$C_6H_{10}O_2$] - 45%
Polyethylene [C_2H_2] - 25%
Latex [$(C_5H_8)_{23}S$] - 20%
PVC [C_2H_3Cl] - 10%

Waste Type F (No PVC Solid Waste Mix):
Paper [$C_6H_{10}O_2$] - 55%
Polyethylene [C_2H_2] - 25%
Latex [$(C_5H_8)_{23}S$] - 20%

Waste Type G (Liquid Waste)
Benzene [C_6H_6] - 95%
Chlorobenzene [C_6H_5Cl]- 5%

Average Metal Concentrations in Waste Feed (mg metal/kg waste feed)

Metal Compound	Solid Waste (Type E & F)	Liquid Waste (Type G)
Antimony, $C_4H_4KO_7Sb$	538	0
Arsenic, $Na_2HAsO_4\bullet7H_2O$	38	0
Barium, $Ba(C_2H_3O_2)_2\bullet H_2O$	85,741	0
Cadmium, $Cd(NO_3)_2\bullet4H_2O$	9	10
Chromium, $Cr(NO_3)\bullet9H_2O$	1,860	2,267
Lead, $Pb(NO_3)_2$	7,426	9,114
Mercury, $Hg(NO_3)_2\bullet H_2O$	446	542
Nickel, $Ni(NO_3)\bullet6H_2O$	7,297	8,963
Silver, $AgNO_3$	5,435	6,663
Thallium, $TlC_2H_3O_2$	545	663

Metals partitioning - All data was normalized by the total mass balance closure achieved. For these tests, metals mass balance closure ranged rom 25% to 156%. In general, mass balance closures were better for nonvolatile metals averaging about 80%. The volatile and semivolatile metals mass balances averaged about 40%.

Table 1. Percent distribution of feed metal in incineration process, Run 1.

Metal	Kiln ash	APCS Solids	Stack gas
Pb	21	60	19
Hg	0	53	47
Cd	8	71	21
Cr	96	4	0
Ni	98	2	0
Ag	70	20	0
Sb	96	4	0
As	94	5	1
Ba	98	2	0
Tl	13	70	17

Table 2. Percent distribution of feed metal in incineration process, Run 2.

Metal	Kiln ash	APCS Solids	Stack gas
Pb	13	65	22
Hg	0	59	41
Cd	10	69	21
Cr	96	4	0
Ni	98	2	0
Ag	24	75	1
Sb	98	2	0
As	99	0	1
Ba	98	2	0
Tl	15	64	20

Table 3. Percent distribution of feed metal in incineration process, Run 3.

Metal	Kiln ash	APCS Solids	Stack gas
Pb	23	52	25
Hg	0	52	48
Cd	10	31	27
Cr	99	1	0
Ni	99	1	0
Ag	70	30	0
Sb	99	0	0
As	99	0	1
Ba	99	1	0
Tl	29	49	22

Table 4. Percent distribution of feed metal in incineration process, Run 4.

Metal	Kiln ash	APCS Solids	Stack gas
Pb	51	30	20
Hg	0	100	0
Cd	34	48	18
Cr	97	3	0
Ni	98	2	0
Ag	70	21	9
Sb	99	1	0
As	80	2	17
Ba	98	2	0
Tl	18	60	22

Table 5. Percent distribution of feed metal in incineration process, Run 5.

Metal	Kiln ash	APCS Solids	Stack gas
Pb	40	45	15
Hg	0	95	5
Cd	13	70	17
Cr	97	3	0
Ni	99	1	0
Ag	82	18	0
Sb	99	1	0
As	92	7	1
Ba	99	1	0
Tl	18	69	17

Table 6. Percent distribution of feed metal in incineration process, Run 6.

Metal	Kiln ash	APCS Solids	Stack gas
Pb	62	25	13
Hg	0	55	45
Cd	26	57	16
Cr	96	4	0
Ni	98	2	0
Ag	92	8	0
Sb	99	0	0
As	99	0	1
Ba	98	2	0
Tl	13	70	17

Table 7. Percent distribution of feed metal in incineration process, Run 7.

Metal	Kiln ash	APCS Solids	Stack gas
Pb	0	53	47
Hg	0	44	56
Cd	0	60	40
Cr	0	71	29
Ni	0	84	16
Ag	0	100	0
Sb	0	65	35
As	0	50	50
Ba	0	98	2
Tl	0	53	47

Table 8. Percent distribution of feed metal in incineration process, Run 8.

Metal	Kiln ash	APCS Solids	Stack gas
Pb	0	89	11
Hg	0	71	29
Cd	0	94	6
Cr	0	94	6
Ni	0	97	3
Ag	0	100	0
Sb	0	72	28
As	0	86	14
Ba	0	99	1
Tl	0	91	9

Table 9. Percent distribution of feed metal in incineration process, Run 9.

Metal	Kiln ash	APCS Solids	Stack gas
Pb	62	31	6
Hg	N/A	N/A	N/A
Cd	8	79	13
Cr	97	2	0
Ni	98	2	0
Ag	93	7	0
Sb	100	0	0
As	95	3	2
Ba	98	2	0
Tl	29	63	8

Particulate Concentrations and Particle Size Distributions

Run	Waste Type	Kiln Temp, °C	Kiln Gas Particulate Concentration (gr/dscf@7% O_2)	Cumulative wt% < 1 µm diameter	Cumulative wt% < 10 µm diameter
1	E	1000	0.077	66	95
2	E	1000	0.056	76	90
3	E	1000	0.11	64	96
4	F	1000	0.033	48	92
5	E	870	0.10	60	90
6	F	870	0.09	26	60
7	G	1000	0.16	70	98
8	G	870	0.14	54	92
9	E	760	0.13	44	84

Experimental results and observations

- Effect of Cl concentration on metal partitioning

Waste Type E (with 10% PVC) contains about 6 wt% Cl and Waste Type F (with 0% PVC) contains about 1.5 wt% Cl. Test data clearly shows a chloride effect on metal partition for 3 spiked metals (Pb, Hg, and Cd). Four metals (Ni, Ag, Tl, and Pb) have lower calculated volatility temperatures in the presence of chlorides, yet only Pb exhibited a significant chloride effect. The chloride effect for Ag and Tl was not clearly discernible due to data scatter. The volatility temperature for the nickel chloride was higher than the operating temperatures in this study.

Two metals (Cd and Hg) exhibited significant chloride effects at high primary combustion chamber (PCC) temperatures although chlorides did not lower the calculated volatility temperature. This data suggests that volatile metal chloride compounds appear to be forming that are not included in the equilibrium code used to calculate the metal volatility temperature. At lower PCC temperatures, the chloride effect as significantly reduced.

No chloride effect was observed for Cr, As, and Ba.

- Effect of waste form

In general, since no kiln ash was formed during incineration of liquid waste, the percentage of feed metal exiting in the stack gas was greater for liquid waste than for solid waste.

- Offgas particulate concentration (total and submicron)

Total particulate and submicron particulate concentration was measured at both the SCC outlet and stack. Extensive graphical analysis of the test data did not reveal a consistent correlation between metals partition and kiln offgas particulate concentration, total or submicron. Although uncontrolled particulate concentration ranged from 0.015 gr/dscf to 0.070 gr/dscf while burning solid wastes, there was no consistent metals partitioning trend observed for any metal. Reasons for no correlation include changes in waste Cl composition and kiln temperature.

- Metals mass balance

For these tests, metals mass balance closure ranged rom 25% to 156%. In general, mass balance closures were better for nonvolatile metals averaging about 80%. The volatile and semivolatile metals mass balances averaged about 40%. The analytical methods were determined be accurate in metal recovery except for Cd in the blowdown analysis and Hg on the offgas analysis.

- Offgas particulate characterization

The kiln offgas particulate concentration and size distribution was measured as a function of waste type and kiln operating conditions. Particulate collection occurred downstream from the afterburner but before the scrubber. Degree of variability in kiln offgas particulate concentration is quite high. Particulate concentrations generally increased during burning of solid waste as the kiln temperature decreased. There was no clear relationship between offgas particulate concentration and the measured offgas velocity although the fraction of entrained particles is relatively small because of low gas velocities in the kiln (0.8-2.1 ft/s). Kiln exit gas velocities for the CIF are expected to be nearly an order of magnitude greater hence greater ash entrainment is expected. Analysis of the kiln offgas particulate size distribution indicates two distinct modes - one mode centered about particulates with an average diameter of 0.5 μm and the other mode centered around 10 µm. The smaller particles are assumed to be formed by homogeneous vapor condensation and the larger particles indicative of ash entrainment. Because of the low gas velocities (and low ash entrainment), a large fraction of particles are submicron in size. None of the tested process variables (waste type, temperature, chloride concentration) showed a significant effect on the bimodal distribution.

It was observed that a decrease in the fraction of submicron particles in the particulate stream coincided with a decrease in the chloride concentration in the solid waste. I suggest this may be related to the generation of more volatile metal chlorides that do not condense until a significant decrease in offgas temperature is achieved. Submicron particulate fraction also decreased with decreasing kiln operating temperature. This is attributed to increased ash entrainment (less efficient incineration) at the lower temperatures. Other possible reasons included decreased vapor generation, smaller temperature gradients in the kiln (hence, less self-condensing), and increased vapor condensation on larger particles.

Scrubber particulate removal efficiencies were also calculated. Scrubber particulate capture efficiencies were lower than expected because of the low particulate concentration exiting the kiln, significantly less than expected for the CIF due to scale.

- Kiln offgas HCl concentration

The measured HCl concentrations in the offgas were measured. These values were compared to theoretical HCl gas formation if all Cl was converted to HCl. Measured values ranged from 63% to 1% of the theoretical values. Samples did not collected entrained Cl-containing particles nor chlorinated condensed vapors that did not dissociate from the metal during analysis.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: Toxic Substances Control Act (TSCA) Mixed Waste Incinerator
Location: K-25 Site in Oak Ridge, TN

Test Series: CASE 1
Dates/Time Frame: August 27, 1990
Purpose/Goal: Special emissions test to character stack emissions

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure
	6			163	1010	1191					

Comments:
a. PCC - primary combustion chamber
b. SCC - secondary combustion chamber

GLOBAL TESTING SUMMARY
Thermal Treatment Process: Toxic Substances Control Act (TSCA) Mixed Waste Incinerator
Location: K-25 Site, Oak Ridge, TN

Test Series: CASE 2
Dates/Time Frame: December 11, 1991
Purpose/Goal: Determine uranium partitioning to the stack, scrubber waters, and bottom ash

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure
	5			319[c]	993	1217					

Comments:
a. PCC - primary combustion chamber
b. SCC - secondary combustion chamber
c. 138 kg/h aqueous waste fed to PCC and 181 kg/h liquid organic waste fed to SCC.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: Toxic Substances Control Act (TSCA) Incinerator
Location: K-25 Site in Oak Ridge, TN

Test Series: CASE 3
Dates/Time Frame: December 15-17, 1993
Purpose/Goal: Study isotope/metal partitioning in incinerator process

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure
Period 1	6			217	1011	1221					
Period 2	3			309	1011	1221					
Period 3	3			334	1010	1221					
Period 4	3			343	1011	1221					
Period 5	3			337	1013	1221					

Comments:
a. PCC - primary combustion chamber
b. SCC - secondary combustion chamber

Waste Feed Characterization - CASE 1

	Primary Feed			Aqueous Feed		
Analysis	Units	Predicted Value[a]	Feed Analysis[b]	Units	Predicted Value[a]	Feed Analysis[b]
Al	μg/g	28	22	mg/L	0.21	21
Ba	μg/g	5.8	5.4	mg/L	0.11	0.54
Be	μg/g	0.27	0.31	mg/L	< 0.003	< 0.03
Cd	μg/g	0.30	< 0.3	mg/L	< 0.03	< 0.29
Cl	μg/g	17,500	22,000	mg/L	2.7	1370
Cr	μg/g	257.5	440	mg/L	0.15	43
Cu	μg/g	13	33	mg/L	0.26	8.7
Fe	μg/g	1580	1800	mg/L	170	1100
Hg	μg/g	0.5	< 0.5	mg/L		< 0.5
Mn	μg/g	49	91	mg/L	0.40	22
Na	μg/g	75	42	mg/L	440	440
Ni	μg/g	430	640	mg/L	0.69	25
P	μg/g	6950	5100	mg/L	4.5	120
Pb	μg/g	17	23	mg/L	426	160
Zn	μg/g	50.8	61	mg/L	1.6	58
Alpha activity	pCi/g	548 (±13)	280 (±5)	pCi/g	NR[c]	6.8 (±0.8)
Beta activity	pCi/g	918 (±17)	560 (±6.5)	pCi/g	NR	14 (±1.1)
Np-237	pCi/g	-0.225 (±0.88)	0.12 (±0.18)	pCi/g	NR	0.03 (0.11)
Pa-234m	pCi/g	418 (±11)	560 (±30)			
Tc-99	pCi/g	180 (±140)	270 (±110)	pCi/g	NR	9.5 (±7.8)
Th-234	pCi/g	268 (±1.8)	360 (±5.2)			
U alpha	pCi/g	635 (±20)	380 (±8)	pCi/g	NR	0.37 (±0.75)
U (polar)	μg/g	813	918	μg/g	NR	1.5
U-235	wt%[d]	0.42	0.41 (±0.02)	wt%[d]	NR	0.92
U-235	pCi/g		2.58 (±0.28)	pCi/g	NR	0.35 (±0.75)

a. Average values of samples collected from blend tank prior to burn.

b. Composite samples taken from feed line during burn campaign.

c. Not recorded.

d. Isotopic

Waste Feed Characterization - CASE 2

	Tank 307A (aqueous waste)	Tank 305B (organic feed)
Uranium (ppm)	229 (prerun analysis) 118 (online analysis)	336 (online analysis)
Heat content (Btu/lb)	< 50	11,300
Phosphorus (ppm)	2,500	7,510
Sulfur (ppm)	< 500	4,753
Chlorine (ppm)	< 500	10.475% (organic)
PCB content (ppm)	4.1	3,000
Ash, %	0.10	1.81
Density, g cm^{-3}	0.98	0.960
Viscosity, cp	4.81	63.5
U, µCi/g	3.42×10^{-3}	1.83×10^{-4}

Waste Feed Characterization - CASE 3

1. Sr- and Cs-Spiked Liquid Wastes

Nonradioactive and nonhazardous isotopes of strontium chloride ($SrCl_2$) and cesium chloride (CsCl) were used to spike an aqueous feed. The total quantities used were 5 kg of $SrCl_2$-$6H_2O$ and 1 kg of CsCl in approximately 15,000 L of aqueous feed. A Sr concentration of 108 µg/g and a Cs concentration of 52 µg/g were anticipated from the chemical weighings. Although the ORNL wastes are anticipated to have an organic matrix, aqueous feed was spiked instead of the organic feed to simplify batch mixing. It was additionally concluded that introduction of the Sr and Cs not through an autogenous flame would conservatively promote partitioning to the scrubber effluent, the focal point of needed design information. Initial characterization of the partitioning study feeds is presented in Table 1. The primary and secondary organic feeds were essentially contaminated oils. The aqueous feed was essentially water with trace organic contamination. The reported PCB concentration of 34 µg/g in the aqueous waste is probably indicative of a separate phase in the analyzed sample. It is significant to note that organic Cl in the feeds was near or below 0.1 wt% and ash content was less than 0.5 wt%. Replicate analyses for Pb, Be, and Hg are routinely performed to enable calculation of statistical tolerance intervals.

Table 1. Initial characterization of partitioning study feeds.

Parameter	Primary organic	Secondary Organic	Aqueous feed
Density (g/mL)	0.855	0.862	1.00
Heating value (kJ/kg)	40,662	43,557	< 112
Ash content (wt%)	0.42	0.08	< 0.02
Chlorine (wt%)	< 0.1	0.1089	< 0.1
Fluorine (wt%)	0.0072	0.0046	0.0005
Sulfur (wt%)	0.3531	0.3515	< 0.1
Viscosity (Pas)	0.07497	0.05518	0.00138
Lead (µg/g)	18, 21, 24	< 8.1, < 8.1, < 8.2	< 7.3, < 7.4, < 7.4
Beryllium (µg/g)	3.7, 4.0, 4.2	0.99, 1.1, 1.2	< 0.044, < 0.044, < 0.045
Mercury (µg/g)	2.0, 2.0, 2.0	0.67, 0.70, 0.71	< 0.08, < 0.08, < 0.08
PCB (µg/g)	100	92	34
Strontium (µg/g)	NA	NA	110
Cesium (µg/g)	NA	NA	57
Uranium (µg/g)	23.9 ± 0.74	5.96 ± 0.35	0.0070 ± 0.024

Experimental Results and Discussion - CASE 1

During the test, 60.1 dscf of incinerator offgas was pulled through an isokinetic gas sampling train. a total of 364 µg U was collected, all of this as particulate material on the inner walls of the probe or on the filter. Thus, the U concentration was 6.06 µg/dscf. The flow rate of offgas from the incinerator was 467,000 dscf/h. Therefore, the discharge rate of U during the test was 2.83 g/h. From the feed analysis and the feed rate data, the average feed rate of U to the incinerator was 96.6 g/h. Thus, the U stack emission was about 2.9% of the total amount fed. This value is consistent with an estimate of 4% or less.

The radioactivity in the offgas sampling system was analyzed to estimate the emission rates for radionuclides; this data is summarized below. During this test, the only statistically significant radioactivity in the air emission was alpha radiation from U and beta radiation from short-lived daughter products.

Contaminant	Stack emission rate (µCi/h)
Alpha activity	9.17 ± 1.54
Beta activity	14.2 ± 22.7
Tc-99	27.4 ± 20.8
Cs-137	2.11 ± 2.80
Th-234	7.36 ± 4.35
Pa-234	75.7 ± 175

The actual air emission rates for other metals were not determined for the August 27, 1990 test. The aqueous feed was a lead nitrate solution left over from a Pb and Be air emissions test performed June 19-21, 1990. This earlier test was performed with the PCC at 1600°F and the SCC at 1900°F. The partitioning of the total Be fed to the incinerator was determined to be (0.70 ± 0.11)% to air emissions and (6.2 ± 6.3)% to the aqueous blowdown, whereas the corresponding partition of the total lead fed to the incinerator was (0.94 ± 0.05)% to air emissions and (12.5 ± 0.9)% to the aqueous blowdown. Based on mass balance considerations, it may be inferred that greater than 80 to 90% of Be and Pb were concentrated to the ash waste or residual slag.

The aqueous effluent from the incinerator results from the use of wet scrubbers to remove contaminants (especially acid gases) from the combustion gases produced in the thermal destruction of hazardous and toxic wastes. The scrubber fluid is recirculated, concentrating soluble constituents and entrained particulates. A portion of the scrubber fluid (blowdown) is removed, and fresh scrubber fluid (makeup) is added.

CASE 2. Uranium offgas

Comparison of uranium and chlorine feeds with stack emissions

	Uranium in stack gas		Uranium in feed (g/h)			Feed Cl
Test date	g/h	% of feed	PCC	SCC	Total	g/h
8/27/90	2.83	2.9	96.6	0	96.6	2,400
1/18/91	0.136	0.39	24.8	9.9	34.7	3,755
12/11/91	6.11	7.94	16.3	60.7	77.0	19,000

Results of aqueous scrubber emissions

	U (ppm)	Total dissolved solids (g/L)	U partitioning (%)			
Test date>	12/11/91	12/11/91	12/11/91	01/18/91	01/16/91	08/27/90
Quench[a]	4.9	3.5	38	29.7	35.5	1.4
IWS[a]	4.1	1.5	25[c]			

a. Quench tower
b. Ionizing wet scrubber
c. Limited data

Particle size data were obtained on the quench and IWS recycle systems to assess the scrubber performance. Electron micrographs were made of the specially centrifuged and washed solids from the purge samples. The cross-section of the particles seen in the micrographs were measured and the PSD produced, assuming spherical particles. The spherical particles seen in the micrograph suggests that for some time during combustion the ash was in a molten form. The median Waddel diameters for the particles were 0.31 μm in the IWS and 0.37 μm in the quench tower. These particle sizes are similar but smaller than the median values of 0.75 μm (IWS) and 1.2 μm (quench) recorded for January 18, 1991 tests.

Elemental analysis was quantitatively measured by energy dispersive x-ray spectroscopy (EDX). It is revealed the presence of Ti much more prominently than in the past experiments. Ti is a very refractory metal, except in the presence in its chloride forms. Its penetration to the IWS may be consistent with the volatilization condensation particulate formation mechanism and the high Cl feed concentration. Also, it could have resulted from a slightly higher feed concentration of Ti during this run and therefore be the result of entrainment and have no special significance.

Case 3. **Sr- and Cs-Spiked Liquid Wastes**

There were five test periods

Period 1: 11:30-17:30, Dec 15, 1991
Period 2: 10:30-12:00 and 12:30-14:00, Dec 16, 1991
Period 3: 14:40-16:10 and 17:00-18:30, Dec 16, 1991
Period 4: 8:00-9:30 and 10:00-11:30, Dec 17, 1991
Period 5: 13:40-15:10 and 15:35-17:05, Dec 17, 1991

Partitioning Summary (% of measured incinerator feed)

	Period 2		Period 3		Period 4		Period 5	
Element	Scrubber	Stack	Scrubber	Stack	Scrubber	Stack	Scrubber	Stack
Be	64	1	69	1	47	2	35	1
Cs	72	2	80	2	58	3	45	2
Cr	137	4	103	2	92	5	86	2
Pb	94	5	106	4	57	6	41	4
Mo	146	4	137	3	118	5	76	3
Ag	56	5	50	5	39	10	43	5
Sr	89	1	85	2	66	2	60	3
U	74	4	78	3	46	6	33	4

Period 1 data was transient and was not reported.

Analysis methods

Composite samples of aqueous blowdown slurry were filtered through 0.2-μ pore polycarbonate membrane filters. After filtration, the particulates collected on the membrane were examined by scanning electron microscopy (SEM) instrumentation equipped with energy-dispersive X-ray spectroscopic (EDS) and image analysis capabilities. These analytical techniques were used to gain insight into the size, chemical associations, and morphological structures of the insoluble particulate phases. Image analysis with the EDS technique allows elemental determinations to be made on either "bulk" samples (large field) or on individual particles at higher magnification.

Major elements identified in the bulk phase of the scrubber solids included P, Si, Ca, Fe, Al, U, and TI (presumably as oxides) with trace levels of Zn, Mg, Cu, and Sr.

Uranium-containing particulates from the quench recycle were also examined (easily identified by backscatter electron imaging). Typical morphology was 10-30 μm spheres with U as the primary component. Filter media was potted in epoxy resin to prepare a polished cross-section which revealed that predominantly-U particulate was cenospheric (thin-walled hollow spheres). This suggests particles were formed by bubble nucleation and growth in a melt of critical viscosity. Estimated wall thickness was only a few microns.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: EPA Incineration Research Facility
Location: Jefferson, AK

Test Series: Rotary kiln Incinerator with a Venturi/Packed Column Scrubber
Dates/Time Frame: August 25-September 22, 1988
Purpose/Goal: Identify fate of trace metals

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solids[c]	Offgas[d]	Closure[d]
Test 4				59.4	874	1,093	58	–	(13)	(29)	(100)
Test 5				63.5	825	1,071	60	–	(11)	(29)	(100)
Test 6				62.6	928	1,092	54	–	(14)	(32)	(100)
Test 7				63.4	878	1,088	60	–	(9)	(31)	(100)
Test 8				63.4	871	1,196	60	–	(11)	(29)	(100)
Test 9				62.5	875	983	64	–	(9)	(27)	(100)
Test 10				62.8	873	1,094	55	–	(10)	(35)	(100)
Test 11				63.5	870	1,092	54	–	(12)	(34)	(100)

Comments: In all tests, waste feed consisted of a mixture of organic liquids added to a clay absorbent material. Trace metals were incorporated by spiking an aqueous mixture of the metals of interest onto the organic-liquid containing solid material.

a. PCC - primary combustion chamber (rotary kiln)
b. SCC - secondary combustion chamber (afterburner)
c. Solids carryover in the air pollution control system was assumed to be residual clay unaccounted for by kiln ash (100% clay) and assumed 7% water in original feed clay. Aqueous metal solution was added to waste feed at rate of 0.5 to 1.0 kg/h but not accounted for in total waste feed rate.
d. Offgas fraction assumed to equal 100 - % Feed in Kiln Ash - % Feed in APCS Solids

GLOBAL TESTING SUMMARY
Thermal Treatment Process: EPA Incineration Research Facility
Location: Jefferson, AK

Test Series: Rotary kiln Incinerator with a single-stage Ionizing Wet Scrubber
Dates/Time Frame: July 28-August 17, 1989
Purpose/Goal: Identify fate of trace metals

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solids[c]	Offgas[d]	Closure[d]
Test 1	4.9	287	323	65.9	900	1,088	65	--	(4)	(31)	(100)
Test 2	8.4	235	465	55.4	819	1,095	67	--	(2)	(31)	(100)
Test 3	3.4	367	218	64.1	929	1,092	67	--	(1)	(32)	(100)
Test 4	5.1	301	248	48.6	877	1,096	67	--	(1)	(32)	(100)
Test 5	4.7	278	313	66.6	885	1,163	65	--	(4)	(31)	(100)
Test 6	5.1	293	338	66.3	887	1,107	64	--	(5)	(31)	(100)
Test 7	4.4	285	265	60.2	881	1,103	64	--	(4)	(32)	(100)
Test 8	4.7	288	309	65.7	879	1,097	67	--	(1)	(32)	(100)
Test 9	6.7	309	315	47.0	881	1,087	67	--	(2)	(31)	(100)

Comments: In all tests, waste feed consisted of a mixture of organic liquids added to a clay absorbent material. Trace metals were incorporated by spiking an aqueous mixture of the metals of interest onto the organic-liquid containing solid material.

a. PCC - primary combustion chamber (rotary kiln)
b. SCC - secondary combustion chamber (afterburner)
c. Solids carryover in the air pollution control system was assumed to be residual clay unaccounted for by kiln ash (100% clay) and assumed 7% water in original feed clay (excluding water added in aqueous metal solution)
d. Offgas fraction assumed to equal 100 - % Feed in Kiln Ash - % Feed in APCS Solids

GLOBAL TESTING SUMMARY
Thermal Treatment Process: EPA Incineration Research Facility (Rotary kiln)
Location: Jefferson, AK

Test Series: Contaminated soils from Drake Chemical Superfund Site
Dates/Time Frame: January-February 1991
Purpose/Goal: Fate of trace metals and effect of kiln temperature on metal partitioning

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure
Test 1 (Soil M-2)			240	55[c]	826	1093	72				
Test 2 (Soil M-5D)			232	55	823	1093	76				
Test 3a (Soil O-1)			112	55	829	1093	66				
Test 3b (Soil O-1)			113	55	546	1093	73				
Test 6 (Soil L-2)			240	55	822	1093	78				
Test 7 (Soil O-2)			209	55	553	1093	88				

Comments:
a. PCC - primary combustion chamber
b. SCC - secondary combustion chamber

GLOBAL TESTING SUMMARY
Thermal Treatment Process: EPA Incineration Rersearch Facility Rotary Kiln
Location: Jefferson, AK

Test Series: Incineration of Contaminated Soil from Chemical Insecticide Corporation (CIC) Superfund Site
Dates/Time Frame: August 1991
Purpose/Goal: Investigate arsenic and other trace metal flue gas emissions

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure
Test 1				55.7	982	1204					
Test 2				55.5	982	1204					
Test 3				54.2	982	1204					
Test 4				57.0	982	1204					

Comments:
a. PCC - primary combustion chamber
b. SCC - secondary combustion chamber

Test Conditions

Test Series 1: *RK Incinerator with Venturi/PC Scrubber*
Reference: D.J. Fournier et al.,"The fate of trace metals in a rotary kiln incinerator with a venturi/packed column scrubber - Volume 1", Report No. EPA/600/2-90/043a (Sept 1990).

Test program consisted of a 8-test parametric metals series. The test variables were feed chlorine content, kiln temperature, and afterburner temperature. Waste feed Cl concentration ranged from 0 to 8%, kiln temperature ranged from 760° to 1000°C, and afterburner temperature ranged from 870° to 1100°C. All tests were designed for the same nominal excess air levels - 11.5% O_2 in the kiln exit flue gas and 7.5% O_2 in the afterburner exit flue gas. The synthetic waste was composed of a mixture of organic liquids added to a clay absorbent material to yield a mixture containing about 30 wt% organic liquid. Trace metals were incorporated by spiking aqueous mixtures of metals of interest onto the organic liquid-containing solid material. The synthetic waste was fed to the rotary kiln via a screw feeder at a nominal rate of 63 kg/h (140 lb/h). Flue gas at the afterburner exit was sampled with a sampling train designed to collect a large sample of particulate in order to be size fractionated and trace metal concentrations as a function of particle size could be determined.

Test Series 2: *RK Incinerator with a single-stage IWS*
Reference: D.J. Fournier et al.,"The fate of trace metals in a rotary kiln incinerator with a single-stage ionizing wet scrubber - Volume 1", Report No. EPA/600/2-91/032a (July 1991).

The synthetic waste was composed of a mixture of organic liquids added to a clay absorbent material to yield a mixture containing about 30 wt% organic liquid. Trace metals (except Cr and Mg) were incorporated by spiking aqueous mixtures of metals of interest onto the organic liquid-containing solid material. Chromium and magnesium were present in the initial clay material. The synthetic waste was fed to the rotary kiln via a screw feeder at a nominal rate of 63 kg/h (140 lb/h) of which 18 kg/h (40 lb/h) was the organic liquid matrix. The test variables were feed chlorine content, kiln temperature, and afterburner temperature. Waste feed Cl concentration ranged from 0 to 6.9%, kiln temperature ranged from 815° to 930°C, and afterburner temperature ranged from 980° to 1205°C. All tests were designed for the same nominal excess air levels - 11.5% O_2 in the kiln exit flue gas and 8.0% O_2 in the afterburner exit flue gas. Flue gas at the afterburner exit was sampled with a sampling train designed to collect a large sample of particulate in order to be size fractionated and trace metal concentrations as a function of particle size could be determined.

Test Series 3: *Contaminated Soils from the Drake Chemical Superfund Site*
Reference: C. King, J.W. Lee, and L.R. Waterland, "Pilot-scale incineration of contaminated soils from the Drake Chemical Superfund Site", EPA/600/SR-93/047, May 1993.

Contaminated soil from the Drake Chemical Superfund Site was shipped to the EPA IRF for use in incineration tests. Test soils were fed to the kiln via fiberpack drum ram feeder system. Each fiberpack contained 4.5 kg of soil. One fiberpack was charged into the kiln every 5 minutes. The primary air pollution control system used with the rotary kiln system was a venturi scrubber followed by a packed-bed scrubber. Tests 1, 2, 3a, and 3b were designed to study the fate of trace metals. Test 1 and 2 studied the distribution of trace metal contaminants throughout the incinerator system. Tests 3a and 3b determined the effects of kiln temperature on trace metal concentrations in the kiln ash and scrubber liquor streams. Tests 6 and 7 were designed to study the destruction of organic contaminants.

Test Series 4: *Incineration of Contaminated Soil from Chemical Insecticide Corporation (CIC) Superfund Site*
Reference: A. Siag, D.J. Fournier, Jr., and L.R. Waterland, "Pilot-scale incineration of contaminated soil from the Chemical Insecticide Corporation Superfund Site", EPA/600/SR-93//036, April 1993.

The objectives of the test plan were demonstrate that a conventional rotary kiln was capable of destroying organochlorine pesticide and, with a high-efficiency scrubber, capable of achieving arsenic removal efficiency greater than 99.96%. A series of 4 tests was performed using the EPA IRF rotary kiln system (RKS) with a Calvert Flux Force/Condensation scrubber for air pollution control. In 3 tests, raw soil was packaged into 1.5-gal fiberpacks and fed to the RKS kiln via the system ram feeder. In the fourth test, raw soil was mixed with lime at a blend ratio of 0.5 kg of lime per 10 kg soil before being packaged.

Waste Feed Metal Concentration

Table 1a. Integrated feed metal concentrations for Test Series 1.

	Metal concentration (ppm)							
Metal	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11
Arsenic (As)	25	23	23	24	19	19	32	33
Barium (Ba)	36	33	33	39	36	36	36	37
Bismuth (Bi)	98	75	95	84	85	99	110	120
Cadmium (Cd)	5	4	4	5	4	4	6	5
Chromium (Cr)	68	64	61	68	66	66	66	67
Copper (Cu)	260	230	240	310	260	260	270	310
Lead (Pb)	33	26	26	34	28	28	33	32
Magnesium (Mg)	17,700	17,700	16,700	17,000	17,700	17,900	16,100	16,500
Strontium (Sr)	190	140	140	170	150	160	200	200

Table 2a. Integrated feed metal concentrations for Test Series 2.

	Metal concentration (ppm)								
Metal	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Arsenic (As)	41	56	53	46	51	44	49	36	52
Barium (Ba)	335	460	450	390	395	375	395	295	430
Bismuth (Bi)	280	400	390	340	340	330	265	260	390
Cadmium (Cd)	9	12	12	10	11	10	10	8	12
Chromium (Cr)	45	38	38	38	42	39	42	42	37
Copper (Cu)	325	445	430	380	380	365	385	290	425
Lead (Pb)	39	50	48	42	45	40	46	44	47
Magnesium (Mg)	18,800	18,800	19,050	19,900	18,100	18,400	19,100	18,900	18,500
Strontium (Sr)	350	480	470	410	415	395	415	315	455

Table 3a. Feed metal concentrations for Test Series 3.

	Metal concentration (ppm)		
Metal	Test 1	Test 2	Test 3
Arsenic (As)	16	62	11
Barium (Ba)	167	57	194
Cadmium (Cd)	1.1	2.0	< 1.0
Chromium (Cr)	18	12	20
Copper (Cu)	49	43	35
Lead (Pb)	439	77	443
Mercury (Hg)	0.1	0.3	0.2
Nickel (Ni)	17	15	12
Selenium (Se)	< 10	< 10	< 10
Silver (Ag)	< 2	< 2	< 2
Zinc (Zn)	302	251	272

Table 4a. Feed metal concentrations for Test Series 4.

	Metal concentration (ppm)			
Metal	Test 1	Test 2	Test 3	Test 4
Arsenic (As)	1040	1040	794	803
Barium (Ba)	56	66	48	43
Cadmium (Cd)	1.7	1.1	0.86	0.97
Chromium (Cr)	16	19	17	13
Lead (Pb)	120	118	104	86
Mercury (Hg)	10	5.8	5.4	6.2

Flue gas flowrates and particulate data

Table 1b. Average flue gas flowrates and particulate data for Test Series 1.

	Kiln	Afterburner		Scrubber Exit		Stack	
Trial	Flue gas flowrate, scm/h	Flue gas flowrate, scm/h	Particulate Conc., mg/dscm @7% O_2	Flue gas flowrate, scm/h	Particulate Conc., mg/dscm @7% O_2	Flue gas flowrate, scm/h	Particulate Conc., mg/dscm @7% O_2
Test 4	173	540	273		7		44
Test 5	157	540	360		7		31
Test 6	274	540	162		31		27
Test 7	246	540	146		23		29
Test 8	245	451	50		40		40
Test 9	213	540	152		12		33
Test 10	233	540	414		21		47
Test 11	271	540	240		51		38

Table 2b. Average flue gas flowrates and particulate data for Test Series 2.

	Kiln	Afterburner		Scrubber Exit		Stack	
Trial	Flue gas flowrate, scm/h	Flue gas flowrate, scm/h	Particulate Conc., mg/dscm @7% O_2	Flue gas flowrate, scm/h	Particulate Conc., mg/dscm @7% O_2	Flue gas flowrate, scm/h	Particulate Conc., mg/dscm @7% O_2
Test 1	713	1,090	117	2,310	17	2,300	43
Test 2	491	1,000	70	1,580	28	1,710	28
Test 3	723	1,030	143	1,890	35	1,940	35
Test 4	593	1,030	84	1,790	75	1,800	37
Test 5	567	1,090	77	2,230	59	2,310	54
Test 6	583	1,060	144	1,790	42	1,880	151
Test 7	617	1,040	101	1,780	36	1,800	28
Test 8	622	817	116	1,830	81	1,910	45
Test 9	884	940	126	1,520	62	1,660	55

Elemental distribution in kiln ash and afterburner exit flue gas - Test Series 1

Table 1c. Summary of metal discharge distributions in kiln ash for Test Series 1.

	Distribution (wt% of metal fed)			Normalized distribution (wt% of total measured)		
Metal	Low	High	Average	Low	High	Average
Cd	<9.7	<17.1	<12.7	<13.7	<43.6	<28.9
Pb	4.7	12.6	8.3	9.5	61.7	35.5
Bi	8.4	24.4	16.2	53.4	89.6	70.0
Cu	34.8	64.2	49.0	63.6	94.1	84.8
Ba	39.2	127.7	67.0	83.3	96.7	88.6
As	36.3	72.0	54.8	88.1	97.4	94.6
Sr	25.5	64.5	43.2	99.5	99.8	99.7
Mg	69.2	133.1	91.7	99.7	99.9	99.8

Table 1d. Summary of metal discharge distributions in afterburner exit flue gas for Test Series 1.

	Distribution (wt% of metal fed)			Normalized distribution (wt% of total measured)		
Metal	Low	High	Average	Low	High	Average
Cd	14.2	70.9	29.6	56.4	86.3	71.1
Pb	5.7	55.1	22.9	38.3	90.5	64.5
Bi	2.5	19.3	6.2	10.4	46.6	30.0
Cu	2.8	19.5	6.6	5.9	36.4	15.2
Ba	1.4	15.4	7.3	3.3	16.7	11.4
As	1.6	5.5	2.1	2.6	11.9	5.4
Sr	0.07	0.3	0.2	0.2	0.5	0.3
Mg	0.1	0.3	0.2	0.1	0.3	0.2

Specific test results of elemental distribution in the kiln ash and afterburner exit flue gas are reported in "The fate of trace metals in a rotary kiln incinerator with a venturi/packed column scrubber - Volume 1", Report No. EPA/600/2-90/043a, September 1990.

Elemental distribution in kiln ash and afterburner exit flue gas - Test Series 2

Table 2c. Summary of metal discharge distributions in kiln ash for Test Series 2.

	Distribution (wt% of metal fed)			Normalized distribution (wt% of total measured)		
Metal	Low	High	Average	Low	High	Average
Cd	3	32	13	7	75	46
Pb	43	148	90	77	98	94
Bi	5	41	21	25	87	72
Cu	23	75	44	83	96	91
Ba	17	60	26	92	99.6	97
As	38	90	59	89	96	93
Sr	15	60	27	98.4	99.9	99.4
Mg	62	123	99	99.8	99.97	99.93

Table 2d. Summary of metal discharge distributions in afterburner exit flue gas for Test Series 2.

	Distribution (wt% of metal fed)			Normalized distribution (wt% of total measured)		
Metal	Low	High	Average	Low	High	Average
Cd	7	73	15	25	93	54
Pb	2	13	5	2	23	6
Bi	3	48	9	13	75	28
Cu	2	11	5	4	17	9
Ba	0.1	1.5	0.6	0.4	8	3
As	3	10	5	4	11	7
Sr	0.05	0.29	0.13	0.1	1.6	0.6
Mg	0.03	0.13	0.06	0.03	0.2	0.07

Specific test results of elemental distribution in the kiln ash and afterburner exit flue gas are reported in "The fate of trace metals in a rotary kiln incinerator with a single-stage ionizing wet scrubber - Volume 1",
Report No. EPA/600/2-91/032a, July 1991.

Table 3c. Summary of metal discharge distributions in kiln ash and afterburner flue gas for Test Series 3.

	Distribution, wt% of metal fed					
	Test 1		Test 2		Test 3a	Test 3b
Metal	Kiln ash	Flue Gas	Kiln ash	Flue Gas	Kiln ash	Kiln ash
As	56	0.7-3	20	6	(a)	(a)
Ba	90	2	65	4	69	70
Cd	71	7	65	9	(b)	(b)
Cr	88	11	61	28	83	69
Cu	61	0.6	37	2	75	88
Pb	66	0.6	38	4	52	68
Hg	<71	150-160	<2.5	68-71	<31	<35
Ni	91	12	45	19	129	108
Zn	55	0.9	35	2	48	81

a. Arsenic present in Test 3 soil but just at the practical quantitation limit, not detected in any residual sample.

b. Cadmium not detected in Test 3 soil.

Table 4c. Trace metal distribution by weight percent of metal fed during Test Series 4

	Test 1		Test 2		Test 3		Test 4	
	Kiln Ash	Scrubber Liquor	Kiln Ash	Scrubber Liquor	Kiln Ash	Scrubber Liquor	Kiln Ash	Scrubber Liquor
Ba	71	6	63	6	84	7	115	10
Cd	20	69	27	36	50	34	59	19
Cr	40	19	42	8	40	7	69	7
Pb	41	4	34	4	37	5	64	5
Hg	<7	<1	<12	<1	<12	<1	<11	<1

Table 4d. Arsenic distributions of metal fed during Test Series 4.

	Test 1		Test 2		Test 3		Test 4	
Sample	Wt%	Normalized wt%	Wt%	Normalized Wt%	Wt%	Normalized Wt%	Wt%	Normalized Wt%
Kiln Ash	42	70.2	42	68.3	49	69.3	91	87.8
Scrubber Liquor	18	29.6	19	31.7	22	30.7	13	12.2
Scrubber exit flue gas	0.1	0.17	0.01	0.01	0.01	0.01	0.01	0.01

Experimental observations and discussion - Test Series 1

- **Metal partitioning (general observations)** Cadmium, Pb, and Bi tend to be relatively volatile and are not found in the kiln ash to a great degree. The other metals (Ba, Cu, Sr, As, Cr, and Mg) were found to be more refractory and as such were found in the kiln ash in higher concentrations. Arsenic was expected to be the most volatile element (as As_2O_3) but instead As remained largely in the ash. This suggests a more refractory compound was formed during incineration possibly interacting with the clay.

- **Metal mass balance** Almost all achieved mass balance closures were less than 100%. The most likely explanation for this is that some quantity of metal fed was deposited as slag buildup in the afterburner. A gradual accumulation of slag was observed over the duration of the test program. The authors still claimed that the average mass balance closure of 65% was considered good.

- **Cd, Pb, Bi partitioning** The kiln ash Cd is greater when no Cl is in the feed than when Cl is present. There is no clear trend in Cd partitioning as a function of the afterburner temperature. Data suggest that the kiln ash fraction decreases slightly with increasing kiln temperature. Lead behaved similarly to Cd as a function of kiln temperature and Cl content. Bismuth partitioning behaved similarly to Cd and Pb as a function of Cl content in the feed. Kiln and afterburner temperatures appeared to have little effect on Bi partitioning.

- **Cu partitioning** Neither kiln nor afterburner temperatures had measurable effects on Cu discharge distributions. However, Cu kiln ash decreased monotonically with increasing feed Cl content.

- **Sr partitioning** Neither kiln temperature nor feed Cl content affected Sr partitioning.

- **As partitioning** A slight increase in kiln ash fraction with increasing kiln temperature was observed. No partitioning effect of varying feed Cl content was observed.

- **Cr, Mg partitioning** Data showed that no test variable measurably affected Cr or Mg discharge distributions.

- **Afterburner exit particle size distribution (PSD)** The log-probability plot of the total particulate PSD data for 6 tests for which size fractionation was performed indicates that the PSDs for all tests were approximately log normal. The PSDs were comparable for 5 tests in which the waste feed contained Cl. The PSD in the one test with no feed Cl was shifted to a larger particle size. This would be expected where the presence of Cl is suspected to increase the amount of volatile metal compounds and consequently increase the quantity of fine particles formed by vapor nucleation.

Analysis for trace metal concentrations by particle size indicated that the size distributions of the less volatile metals (Cr, Cu, Mg, and Sr) were coarser (less fines) than the overall average PSD. The size distribution for the relatively more volatile metals (Ba and Bi) were finer than the overall average PSD.

Experimental observations and discussion -Test Series 2

- **Metal partitioning (general observations)** Cadmium and Bi tend to be relatively volatile and are not found in the kiln ash to a great degree. The other metals (Ba, Cu, Sr, As, Cr, Pb, and Mg) were found in the kiln ash in higher concentrations. Arsenic was expected to be the most volatile element (as As_2O_3) but instead As remained largely in the ash. This suggests a more refractory compound was formed during incineration possibly interacting with the clay.

- **Metal mass balance** Almost all achieved mass balance closures were less than 100%. This was attributed to material accumulation in the process. Examples include slag deposits in the afterburner, particulate accumulation in the connecting ductwork, and sludge accumulation in the bottom of the scrubber. The inability of the analytical method to completely dissolve particulate material was also blamed for less than accurate measurements of metal concentrations.

- **General effect of waste feed Cl on metals partitioning** With the exception of Cd and Bi, *metal distributions in the kiln ash represented as the fraction of metal feed increased significantly when waste feed Cl content increased from a nominal 4% to 8%. The same is true for Cr, Pb, and Mg when the waste feed Cl content increased from 0 to 4%. This is not unexpected behavior. Generally, increased volatility evidenced by lower ash fractions is expected during incineration in the presence of Cl. The authors suggest the compounds generated at kiln temperatures in the presence of Cl generates compounds that are more soluble and more recoverable during sample digestion.*

- **Cd, Bi partitioning** Volatility of Cd and Bi increase significantly with increased kiln temperature. These metals show no conclusive partitioning behavior with variations in Cl content of the waste feed.

- **Pb partitioning** Lead volatility increased significantly with increasing kiln temperature, although Pb remained relatively refractory and was found primarily in the kiln ash.

- **Cu partitioning** Neither kiln nor afterburner temperatures had measurable effects on Cu discharge distributions.

- **Ba, Sr partitioning** A small decrease in the Sr and Ba kiln ash fraction was observed with increased kiln temperature. There were no clear effects of afterburner temperature or chlorine content on Sr or Ba partitioning.

- **As partitioning** Neither changes in the kiln or afterburner temperatures influenced As partitioning within the limits of data variability. Arsenic was expected to be a more volatile metal, instead As behaved as a relatively refractory metal in the kiln.

- **Cr partitioning** Neither changes in the kiln or afterburner temperatures influenced Cr partitioning within the limits of data variability.

- **Mg partitioning** A slight decrease in the kiln ash fraction of Mg with increasing kiln temperature. The afterburner temperature exhibited no effect on partitioning.

- **Metal distribution among flue gas particulate by particle size in the afterburner exit** Metal distributions identifying the cumulative percent of particles less than 4 µm, less than 10 µm, and greater than 30 µm. The data show a relationship between the relative volatility of each metal and its propensity for redistribution to finer particulate. This behavior is as expected although As behaves slightly differently. In the kiln, As behaves a refractory material with most of the material remaining in the ash. But As swept out of the kiln as entrained ash is exposed to higher temperatures in the afterburner where the As volatizes and later condensed into fine particles that are typical of metals with low volatility temperatures.

At the lower kiln temperature (815°C), the metal distribution as a function of particle size was similar to the overall particle. For example, about 10% of the total particle sample were less than 4 μm and for most metals approximately 10% of each metal were found in these particles. This suggests that most of the particles exiting the afterburner were the result of entrainment and not vaporization and nucleation.

Increasing the kiln temperature to 870°C did not significantly increasing the metal composition of particles less than 4 μm but it did significantly increase the metal concentration of particles less than 10 μm. This was attributed to increased ash entrainment from the kiln as the result of increase flue gas velocity. The significant increase of available surface area promotes vapor condensation on existing particles at the expense of fines formation by vapor nucleation.

Increasing the kiln temperature to 930°C, the afterburner exit flue gas particulate increased suggesting additional entrainment with increasing kiln exit flue gas velocity. The particle size distribution of the total sample did not change significantly. However, with the increased kiln temperature, a significant redistribution of all metals to particulate less than 4 μm is observed. More volatile metals were redistributed to a greater extent in the fines.

Variations in the afterburner temperature also appeared to affect both the distribution of flue gas particulate and the distribution of metals in the particles. With increased temperature, particulate loading decreased on a mg/m_3 basis. The overall PSD shifted to coarse particulate as the temperature increased, particularly when increased to 1205°C. This shift is probably due to the elimination of finer particulate through melting/softening and subsequent coalescing into larger particles. *I raise the possibility that the volatile metals may still be in the vapor phase and have not yet condensed to form fine particulate, although the authors noted that scrubber efficiency was not influenced by the afterburner temperature.*

The effects of waste feed Cl on total particle and metal-specific size distribution were considered significant when the metal distributions shifted more than total particulate sample distribution. Chlorine had a pronounced effect on the PSD of Cr, Cd, Cu, and Pb. For Cd, Cu, and Pb, the shift to finer particles occurred with the initial feed Cl content increase from 0 to 4%. The distribution of these metals in particulate less than 10 μm increased from 20 to 55%. No additional redistribution occurred with further increased of the Cl content to 8%. Chromium distributions in particulate less than 10 μm increased with Cl content increases from 2 to 20 to 50% with chlorine increased from 0 to 4 to 8%, respectively. Chromium is the least volatile metal but is suspected of forming CrO_2Cl_2 which is quite volatile. If the formation of chromyl chloride is increasingly favored as feed Cl content increases, Cr redistribution to finer particulate would be expected.

Experimental results and observations - Test Series 3

- **Sampling methods** Several sampling procedures were performed for all tests. Composite samples were obtained from the soil feed before being packaged in a fiberpack container, from the kiln ash sample, and from the scrubber liquor.

- **Metal concentrations in particulate** The metal concentrations in the afterburner exit flue gas particulate were significantly greater than in the coresponding soil feed and kiln ash concentrations for all metals.

- **Effect of kiln temperature** Results from tests performed at kiln operating temperature 546°C and 824°C showed no significant differences in trace metal contents of the kiln ash.

- **Overall metal distribution** The kiln discharge accounted for the predominant fraction of all trace metals introduced in the soil feed with the exception of mercury, which appeared to be completely accounted for in the flue discharges. The scrubber exit flue gas accounted for a minor fraction of the trace metals fed with the exception of Hg, Cd, and possibly As. The scrubber liquor accounted for less than 10% of the trace metals fed with the exception of Cu.

Experimental results and observations - Test Series 4

- **Arsenic distribution** Nominally 70% of the As exiting the incinerator was in the kiln ash for tests in which soil alone was fed. In the test in which lime was added to the soil, the kiln ash As fraction increased to about 90%. It was also noted that the leachability of As in the kiln ash from the test using lime was significantly reduced.

- **Other trace metal distributions** The kiln ash discharge accounted for most of the Ba and Pb fed in all tests. The kiln ash also accounted for the predominant fraction of Cr fed in all tests. The behavior of Cd was inconsistent from test to test. No Hg was found in the kiln ash or scrubber liquor. The "less than" fractions noted in Table 4c correspond to sample analysis practical quantitation limits.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: Rotary kiln, Rollins Environmental Services (RES)
Location: Deer Park , TX

Test Series: PCB-containing capacitors
Dates/Time Frame: 1977
Purpose/Goal: Investigate PCB destruction at maximum temperatures, residence times

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure
Test I (No. 2 oil)	2-3			3200[c]	1306	1308					
Test II	2-3			210[d]	1252	1339					
Test III	2-3			360	1331	1332					

Comments:
a. PCC - primary combustion chamber
b. SCC - secondary combustion chamber
c. Oil volumetric flow rate, L/h
d. Feed rate of capacitors excluding fiber drums. If drums included, feedrate is 330 kg/h.

GLOBAL TESTING SUMMARY

Thermal Treatment Process: Rotary kiln, Rollins Environmental Service (RES)
Location: Deer Park, TX

Test Series: NCB burns
Dates/Time Frame: 1977
Purpose/Goal: Investigate destruction of liquid waste from nitrochlorobenzene production

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure
R1 (Fuel oil, background)					-	1258					
R3				404[c]	-	1307					
R4				350[c]	-	1332					

Comments:
a. PCC - primary combustion chamber (not used in these tests)
b. SCC - secondary combustion chamber
c. Liquid waste flowrates, L/h

Experimental results and discussion

The tests were designed primarily to characterize the extent of organic and PCB destruction. Measurements were also made concerning particulate carryover from the system and metal constituents on offgas exiting the incinerator and the stack. There was no specific characterization of the waste feed to provide information about metal partitioning.

During the PCB tests, the predominant metals observed in the combustion and stack flue gases were copper, iron, lead, tin, and cadmium. The residual solids were analyzed to determined if any hazardous components remained that would interfere with its disposal. The major inorganic components identified in the residue were aluminum, silicon, copper, tin, lead, zinc, and phosphorus; all of which were found to predominate from other areas in the kiln system.

In one reference (Ho et al., 1994), overall metal emission rates were presented for the Deer Park, TX facility operated in 1993. Again, the partitioning of the metals between the kiln and the different components of the APCS was not identified.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: APTUS/Rollins HWI
Location: Coffeyville, KS

Test Series: Condition 1
Dates/Time Frame: April 25-26, 1989
Purpose/Goal: Evaluate effect of approximately 10% Cl in waste feed on metal partitioning

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure
Run 1	2			3,087	928	1,231					
Run 2	2			3,862	892	1,198					
Run 3	2			3,008	956	1,178					

Comments:
a. PCC - primary combustion chamber
b. SCC - secondary combustion chamber or afterburner

GLOBAL TESTING SUMMARY
Thermal Treatment Process: APTUS/Rollins HWI
Location: Coffeyville, KS

Test Series: Condition 2
Dates/Time Frame: April 26-27, 1989
Purpose/Goal: Evaluate effect of approximately 20% Cl in waste feed on metal partitioning

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure
Run 1	2			3,656	938	1,215					
Run 2	1.6			3,454	921	1,197					
Run 3	1.8			3,588	920	1,245					

Comments:
a. PCC - primary combustion chamber
b. SCC - secondary combustion chamber or afterburner

Summary of Waste Feed Rates (lb/h)

	Condition 1			Condition 2		
Waste Components	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Contaminated Soil	387	495	580	0	0	0
Contaminated Soil/ Latex Paint	0	0	0	845	564	637
Capacitors	2,659	2,722	2,809	1,142	904	1,116
Debris	155	170	200	77	62	58
Surrogate Metals Mixture	42	44	47	47	38	42
Mercury	1.8	2.0	2.1	2.1	1.6	1.9
Caustic Slag	14	14.7	15.6	0	0	0
Tellurium	0	0	0	7.9	6.9	7.1
Total Solid Waste	3,259	3,448	3,654	2,121	1,576	1,862
PCB Liquid	2,123	3,059	2,115	4,146	4,250	4,272
Aqueous Waste	1,410	1,990	848	1,778	1,773	1,760
Total Liquid Waste	3,533	5,049	2,963	5,924	6,023	6,032
Total Feed	6,792	8,497	6,617	8,045	7,599	7,894
Total Chlorine in Feed	656	760	681	1,848	1,851	1,865
% Chlorine in Feed	9.7	8.9	10.3	23.0	24.4	23.6

Waste Profile

Waste	H_2O, wt%	Ash, wt%	Cl, wt%	PCB, wt%	Heat value, Btu/lb
Contaminated Soil	2.0	45	0.2	0.2	2,100
Capacitors	0	28	16.7	21.0	6,657
Debris	8	5	0.1	0	10,000
Latex Paint	48	11.5	0.2	0	2,640
Oil-based Paint	3.6	11.7	0.2	0	14,700
Paint Filters	0	5.4	0	0	5,300
Aqueous Waste	98	2	0	0	0
PCB Liquid Run 1	0	0.5	10.0	12	17,124
PCB Liquid Run 2	0	0.5	40.0	25	10,266

Summary of Waste Feed Metal Concentrations (ppm/w) for Condition 1

Parameter	Soil	Debris	Capacitors	Liquid Feed	Caustic Slag	Bismuth Spike	Strontium Spike	Magnesium Spike	Mercury Spike
Silver (Ag)	< 0.01	0.10		< 0.005	190.32	1.82	0.62	2.89	
Arsenic (As)	2.37	< 0.06		9.330	94195.16	6.88	6.88	6.88	
Barium (Ba)	169.97	879.16		0.680	2.50	2.77	44565.82	3.71	
Beryllium (Be)	57.46	< 0.01		< 0.005	0.50	0.63	0.63	0.63	
Cadmium (Cd)	2.70	0.07		< 0.005	12.10	0.63	0.63	0.63	
Chromium (Cr)	90.29	8.09	18000[a]	< 0.005	42.74	12156.16	161.54	2.08	
Copper (Cu)	419.56	4.50	9000[b]	1.190	1471.77	1.88	15.34	1.88	
Mercury (Hg)	3.09	0.64		0.070	5.00	95.32	8.75	27.67	1000000.0
Manganese (Mn)	295.68	253.82		0.300	5.65	0.63	14.79	178.28	
Nickel (Ni)	13.21	2.19		< 0.010	183.07	1.25	1.25	1.25	
Lead (Pb)	51.34	15.87	12000	1.250	327512.90	5.00	48.55	5.00	
Antimony (Sb)	< 0.11	< 0.11	500	< 0.011	34468.55	13.75	56.38	13.75	
Selenium (Se)	< 0.05	0.06		< 0.050	79.84	6.25	6.25	6.25	
Thallium (Tl)	41.87	2.63		1.400	20.00	23.75	23.75	23.75	
Zinc (Zn)	276.73	423.61	1000	3.270	59285.41	3.13	148.08	24.05	
Bismuth (Bi)					125.00	392691.60	8870.89	1766.67	
Calcium (Ca)					704.84	9.84	592.71	439444.70	
Magnesium (Mg)					292.08	168.39	6134.55	3580.27	
Strontium (Sr)					2.50	32.10	473288.55	325.33	
Tellurium (Te)					642.97	5.00	50.00	50.00	

a. Assume stainless steel casing contains 18,000 ppm Cr.
b. Assuming all aluminum winding.

Summary of Waste Feed Metal Concentrations (ppm/w) for Condition 2

Parameter	Soil	Paint	Paint & Soil	Debris	Capacitors	Liquid Feed	Tellurium Spike	Bismuth Spike	Strontium Spike	Magnesium Spike	Mercury Spike
Silver (Ag)	< 0.01	0.06	< 0.01	0.11		< 0.005	16.44	1.82	0.62	2.89	
Arsenic (As)	8.95	0.06	< 0.05	0.08		2.860	1370.65	6.88	6.88	6.88	
Barium (Ba)	218.32	461.32	555.70	1713.33		0.770	2.50	2.77	44565.82	3.71	
Beryllium (Be)	0.73	< 0.02	< 0.01	0.01		< 0.005	0.50	0.63	0.63	0.63	
Cadmium (Cd)	2.55	1.04	0.70	0.13		< 0.005	33.07	0.63	0.63	0.63	
Chromium (Cr)	806.90	12.50	28.37	127.42	18000[a]	0.590	7.63	12156.16	161.54	2.08	
Copper (Cu)	154.60	6.79	6.42	8.04	9000[b]	0.630	5085.13	1.88	15.34	1.88	
Mercury (Hg)	1.24	19.14	15.52	0.89		< 0.070	2.50	95.32	8.75	27.67	1000000
Manganese (Mn)	209.80	30.52	31.40	306.01		0.560	5.48	0.63	14.79	178.28	
Nickel (Ni)	11.32	5.10	2.43	5.22		< 0.010	13832.29	1.25	1.25	1.25	
Lead (Pb)	64.52	37.96	140.14	1499.00	12000	3.910	114831.70	5.00	48.55	5.00	
Antimony (Sb)	< 0.11	< 0.11	< 0.11	0.16	500	< 0.110	147509.79	13.75	56.38	13.75	
Selenium (Se)	< 0.11	< 0.05	< 0.05	0.07		< 0.050	2945.01	6.25	6.25	6.25	
Thallium (Tl)	34.91	11.99	15.81	2.68		< 0.190	20.00	23.75	23.75	23.75	
Zinc (Zn)	245.79	1588.19	1914.58	6621.49	1000	6.880	10863.01	3.13	148.08	24.05	
Bismuth (Bi)							150.00	392691.60	8870.89	1766.67	
Calcium (Ca)							865.81	9.84	592.71	439444.70	
Magnesium (Mg)							308.52	168.39	6134.55	3580.27	
Strontium (Sr)							13.82	32.10	473288.55	325.33	
Tellurium (Te)							77399.91	5.00	50.00	50.00	

a. Assume stainless steel casing contains 18,000 ppm Cr.
b. Assuming all aluminum winding.

Other Operational Process Parameters

Condition 1:

Parameter	Run 1	Run 2	Run 3
Kiln Rotational Speed, rpm	3.5 ± 0.9[a]	3.4 ± 2.0	3.0 ± 0.0
Kiln O_2, High value, %	11.4 ± 1.1	13.2 ± 2.5	11.4 ± 2.7
Kiln O_2, Low value, %	5.0 ± 0.3	2.9 ± 0.5	2.9 ± 1.7
Afterburner O_2, %	10.4 ± 5.7	8.8 ± 0.3	6.9 ± 1.7
Stack Gas Flow, acfm	28560 ± 2985	32421 ± 847	31396 ± 141
Stack Temperature, °F	141.0 ± 1.9	148.6 ± 3.3	146.3 ± 1.6

a. Standard deviation

Condition 2:

Parameter	Run 1	Run 2	Run 3
Kiln Rotational Speed, rpm	5.8 ± 1.3[a]	4.0 ± 1.0	5.0 ± 0.0
Kiln O_2, High value, %	9.7 ± 0.5	11.4 ± 1.3	9.6 ± 1.9
Kiln O_2, Low value, %	3.9 ± 0.7	3.9 ± 0.7	5.1 ± 1.1
Afterburner O_2, %	10.0 ± 6.1	6.7 ± 1.4	6.8 ± 1.4
Stack Gas Flow, acfm	32546 ± 613	31586 ± 135	30953 ± 2870
Stack Temperature, °F	145.5 ± 0.9	147.7 ± 2.3	147.2 ± 2.5

a. Standard deviation

Average Normalized Metals Partitioning Mass Percentages

	Condition 1		Condition 2	
Element	Kiln Slag	APCS Solids/Gas	Kiln Slag	APCS Solids/Gas
Antimony (Sb)	46.19	53.81	52.97	47.03
Arsenic (As)	23.82	77.18	74.73	25.27
Barium (Ba)	97.56	2.44	97.45	2.55
Beryllium (Be)	99.69	0.31	99.83	0.17
Cadmium (Cd)	81.68	18.32	93.60	6.40
Chromium (Cr)	99.27	0.73	99.85	0.15
Copper (Cu)	92.95	8.05	88.56	11.44
Lead (Pb)	18.32	81.68	17.71	82.29
Mercury (Hg)	27.19	72.81	16.06	83.94
Manganese (Mn)	98.57	1.43	99.07	0.93
Nickel (Ni)	99.38	0.62	99.26	0.74
Selenium (Se)	99.58	0.42	93.11	6.89
Silver (Ag)	90.59	9.41	95.85	4.15
Tellurium (Te)	100.00	0.00	100.00	0.00
Thallium (Tl)	98.37	1.63	30.69	69.31
Zinc (Zn)	15.03	84.97	37.10	62.90
Bismuth (Bi)	98.20	1.80	99.09	0.91
Calcium (Ca)	100.00	0.00	0.00	100.00
Magnesium (Mg)	99.70	0.30	99.57	0.43
Strontium (Sr)	80.55	19.45	87.10	12.90

Experimental results and discussion

The majority of the data reported above was found in the 1989 Radian report which documented experimental test results investigating offgas treatment equipment. Test results were geared to characterizing the efficiencies of a spray dryer, baghouse filter, and wet scrubber system.

- **Particulate generation** Particulate concentrations measured for the afterburner outlet indicate no significant difference between conditions. The average concentration for Condition 1 was 2.45 gr/dscf @ 7% O_2 and for Condition 2 was 2.08 gr/dscf @ 7% O_2.

- **Metal partitioning during Condition 1** Arsenic was only present in significant quantity during Condition 1. Partitioning indicated was 25% slag and 75% to the APCS. This calculation was based on the assumption that the actual concentration in the slag is one-half the detection limit. Using the full range of possible concentrations represented by the detection limit, the capture of As in the slag could range between 0 and 40% of the mass feed rate. The value of 40% yields a nearly complete material balance. Nearly all Cr was removed in the slag (99.32%). Lead and zinc are primarily removed in the baghouse (dry scrubber) ash stream.

The calculation that 28.65% of feed Hg was in the slag is suspect since it is based on the assumption that Hg in the slag is one-half of the lower detection limit. Partitioning data revealed that the spray dryer/baghouse combination is not highly effective in removing Hg at the current operating temperatures. However, the wet scrubber was quite effective in preventing most Hg from exiting the stack.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: SEG Radioactive Waste Incinerator
Location: Oak Ridge, TN

Test Series:
Dates/Time Frame:
Purpose/Goal:

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure

Comments:
a. PCC - primary combustion chamber
b. SCC - secondary combustion chamber

Experimental observations and discussion - SEG Incinerator

J. D. Dalton and H. W. Arrowsmith, "Radioactive waste incinerator at the Scientific Ecology Group, Inc.", *Proceedings of 1990 Incineration Conference*, San Diego, CA (1990).

SEG began operation of the first commercial low-level radioactive waste incinerator in the US. This incinerator is an Envikraft EK 980 NC multi-stage, partial pyrolysis, controlled-air unit equipped with an offgas train that includes a boiler, baghouse, HEPA bank, and wet scrubber. The incinerator is operated on a continuous basis, processing up to 725 kg/hr (1,600 lb/hr) of solid waste while achieving a volume reduction exceeding 300:1.

For permitting purposes, it was assumed that the total nuclide release up the stack was 0.0001 of each nongaseous nuclide present in the waste. These arbitrary limits are far below the existing regulatory requirements. Measured nuclide releases reported as a fraction of the estimated release are summarized in the table below.

Nuclide release as a percentage of predicted average releases.[a]

Nuclide	**Jan 90**	**Feb 90**	**Mar 90**
Cr-51	13	7	5
Mn-54	0.7	0.6	0.5
Co-58	0.01	0.3	0.2
Fe-59	3	5	4
Co-60	0.6	0.4	0.1
Nb-95	0.3	2	2
Sb-125	28	50	13
Cs-134	3	3	0.6
Cs-137	5	3	0.3

a. Actual nuclide release percentages include lower detection limit values when measured nuclide activities re below detection limits.

GLOBAL TESTING SUMMARY
Thermal Treatment Process: Waste Experimental Reduction Facility (WERF) Incinerator
Location: Idaho National Engineering Laboratory

Test Series:
Dates/Time Frame:
Purpose/Goal:

Test name or Feed type	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC[a] Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure

Comments:
a. PCC - primary combustion chamber
b. SCC - secondary combustion chamber

Experimental observations - WERF Incinerator

There has never been an explicit partitioning study where the known amounts of metals and radionuclides are in the waste feed and the exit streams (bottoms ash, flyash, offgas). However, there are examples of different studies that provide some qualitative insight to the nature of metal and radionuclide partitioning.

- In the engineering design file (EDF) written by D. Christensen, it was reported that of all the ash collected inside the WERF process over the course of 24 burn campaigns 85% of the ash was collected from the primary chamber ashpit and 15% of the ash was fly ash collected in the baghouse.

A record of the total mass incinerated during each campaign indicated that a total of 634,423 lbs was incinerated between campaigns 33 through 56. A total of 26,331 lb (4.15% of waste fed) was captured as bottoms ash and 4,785 lbs (0.75% of waste fed) was captured as flyash in the baghouse and HEPA filters. This provides some evidence of the nature of ash carryover. There was no detailed description of waste type fed during each campaign. One campaign was reported to incinerate the flyash captured in the baghouse and HEPA filters. This was done in order to collect the majority of this material in the bottoms ash so it can be solidified and shipped out as rad waste. Typical WERF waste feed is assumed to contain 60 wt% cellulose, 35% polyethylene, and 5% rubber. Cellulose is assumed to contain 10% fixed carbon and 3% ash. Polyethylene and rubber are assumed to have negligible ash content. Using this composition as typical, the lower and upper limits for solids removed as bottoms ash and flyash can be calculated assuming cellulose ash only (11,420 lbs) and cellulose ash and fixed carbon (49,485 lbs). The total ash collected (31,116 lbs) falls between these limits.

- A conversation with the incinerator engineer stated that current practice is to send any air through the inlet lines because sufficient air enters the chamber as the result of leaks. A process flow diagram described air flow into the primary chamber to be 1600 scfm. How this number was arrived at is not clear. There is no control of the air flow other than the vacuum created by the induction draft fan. The absence of air flow through inlet pipes would eliminate potential high velocity regions that could increase ash carryover. In the discussion in the preceding paragraph only 0.75% of waste was carried over as flyash.

- Reference: G.R. Smolik and J.D. Dalton, "Materials evaluation in the WERF low-level radioactive waste incinerator off-gas system", EGG-WM-8181, EG&G Idaho, Inc., August 1988.

Ash particulate that had collected on the face of the heat exchanger downstream from the secondary combustion chamber was analyzed to determine the elemental composition of the ash. The composition identified by the analysis is listed below.

Element	Concentration, wt%
Zn	15.2
S	8.0
Ca	2.1
Pb	1.4
Fe	1.2
Cd	0.37
Cu	0.26
Sb	0.18
P	0.17
Ni	0.16
C	0.07
Cr	0.05
Na	0.04
Cl[a]	0.02

[a] Average chloride content of waste was approximately 0.6 wt%.

The majority of the material mass not accounted was believed to be oxygen in the form of oxides. Other than the Cl content is no other definitive characterization of the waste feed and its chemical composition. The temperature at the entrance of the heat was approximately 1200°F.

- Some fly ash and bottoms ash analysis for metal content has been performed.

Fly ash and bottoms ash sample were collected from the WERF incineration process. There were several limitations to the usefulness of the data collected. First, the flyash collected was over the course of many burn campaigns. The bottoms ash is more segreated but still any sample collected for a specific burn campaign can be expected to be a blend of ash from burn campaigns performed before and after it. Secondly, there was no detailed characterization of the waste feed incinerated, particularly for metals. Finally, although the flyash metal concentration was determined as a weight fraction, only the quantity of the leachable metals from bottoms ash was reported. This a TCLP test and it is difficult to relate these results to the actual metal content of the bottoms ash. All these results provide some qualitative information.

Element	Average fly ash metal concentration, ppm
Al	1,760
Sb	3,780
As	59
Ba	191
Be	0.13
Cd	890
Ca	8,480
Cr	560
Co	26.6
Cu	1,470
Fe	14,800
Pb	44,000
Mg	1,010
Mn	510
Hg	0.30
Ni	700
K	63,000
Se	8.6
Ag	140
Na	25,200
Tl	3.4
V	10.1
Zn	192,000

Without having any knowledge of the elemental composition of the waste feed, the data above suggest that lead, iron, zinc, and silver may end up in the fly ash as the result of volatilization and subsequent condensation. The high sodium and potassium concentration may be indicative of ash carryover from the primary combustion chamber. The source of each of the elements is not certain and may originate in the waste packaging instead of the waste feed.

The bottoms ash underwent a TCLP test to identify leachability of the ash. The results can indicate the soluble compounds present but not elements bound as insoluble compounds. The results are expressed in terms of maximum concentration (μg/L) measured in the leachate during 3 different burn campaigns

Element	Leachate concentration (μg/L)		
	Burn 69	Burn 71	Burn 73
Sb	212	255	---
As	60.8U	56.4	44.6
Ba	256	1,010	700
Be	0.4U	0.2U	1.6
Cd	11.4	3.1U	3.4U
Cr	3,730	6,770	6,870
Pb	64.6	29.4U	25.9U
Hg	199	0.1U	0.35
Ni	33.8	6.5U	14.9U
Se	90.8U	35.3U	74.8U
Ag	6.1U	6.5	4.4U
Tl	28.7U	31.2U	111

U - undetected at the lower detection limit indicated

GLOBAL TESTING SUMMARY
Thermal Treatment Process: LLNL Transpiration Furnace
Location: Lawrence Livermore National Laboratory (LLNL)

Test Series: Evaluation of actinide volatilities in mixed waste
Dates/Time Frame: tests performed before August 1992 (**CASE 1**)
Purpose/Goal: Measure U, Pu, and Am volatilities in mixed waste

Test name or Feed type[a]	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure

Comments:
a. Feed type and test conditions summarized in Table 1.
b. No secondary combustion chamber used in lab-scale experiments

GLOBAL TESTING SUMMARY
Thermal Treatment Process: LLNL Transpiration Furnace
Location: Lawrence Livermore National Laboratory (LLNL)

Test Series: Evaluation of actinide volatilities in mixed waste
Dates/Time Frame: tests performed before April 1993 (**CASE 2**)
Purpose/Goal: Measure Pu and Am volatilities in mixed waste

Test name or Feed type[a]	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure

Comments:
a. Feed type and test conditions summarized in Table 2.
b. No secondary combustion chamber used in lab-scale experiments

GLOBAL TESTING SUMMARY
Thermal Treatment Process: LLNL Transpiration Furnace
Location: Lawrence Livermore National Laboratory (LLNL)

Test Series: Evaluation of actinide volatilities in mixed waste
Dates/Time Frame: tests performed before September 1993. **(CASE 3)**
Purpose/Goal: Measure U, Pu, and Am volatilities in mixed waste

Test name or Feed type[a]	Total operating time (h)	Total heat input (kW)	Total feed material (kg)	Average feedrate (kg/h)	Average PCC Gas Temp. (°C)	Average SCC[b] Gas Temp. (°C)	% distribution of feed material to:				
							Ash	Metal	APCS solid	Offgas	Closure

Comments:
a. Feed type and test conditions summarized in Tables 4, 5, and 7.
b. No secondary combustion chamber used in lab-scale experiments

CASE 1
O. H. Krikorian et al., "Evaluation of actinide volatilities in mixed waste processor: Interim report", UCRL-ID-111352, Lawrence Livermore National Laboratory, (August 1992).

Abstract: This report is an interim status report on a study of U, Pu, and Am volatilities in mixed waste oxidation processors. Both thermodynamic modeling methods and experimental measurements are being used to assess actinide volatilities. The volatile species of greatest importance is expected to be the actinide oxyhydroxide $MO_2(OH)_2(g)$ (M=actinide). Based on early measurements, the volatility of $PuO_2(OH)_2(g)$ from $PUO_2(s)$ in the presence of 0.9 atm O_2 and 0.1 atm H_2O at 1330 K (1935°F) was 4×10^{-10} atm. Interactions of the actinide oxides with the incinerator ash during the MW combustion process are expected to lower the actinide oxide activities and result in lower $MO_2(OH)_2(g)$ volatilities as compared with volatilities over the pure actinide oxides.

CASE 2
O. H. Krikorian et al., "Measurement of plutonium and americium volatilities under thermal process conditions: Final report", UCRL-ID-112994, Lawrence Livermore National Laboratory, (April 1993).

Abstract: This study has been performed in support of the RFP fluidized bed unit development. The objective of the study has been to conduct experiments to identify the types and amounts of volatile gaseous species of Pu and Am that are produced in the offgases of MW oxidation processes. The transpiration method was used to measure volatilities of Pu and Am from $PuO_2(s)$ and $PuO_2/2\%AmO_2(s)$ in the presence of steam and O_2 at temperatures of 1230-1430 K. The species of $PuO_2(OH)_2(g)$ and AmO2(OH)2(g) at vapor pressures on the order of 10^{-10} atm and 10^{-12} atm, respectively, were found under measurement conditions. These results were applied to the RFP FBU to assess the quantity of volatile Pu and Am produced from the secondary combustor chamber. Assuming a SCC temperature of 550°C, 40 kmol/h of total gas flow at 1 atm, 0.1 atm $O_2(g)$, 0.05 atm $H_2O(g)$, $PuO_2(s)$ containing 200 ppm AmO_2 in the bed, and 6000 h of operating time per year, yields volatilization rates of 7×10^{-6} g Pu/y and 4×10^{-9} g Am/y.

CASE 3
O. H. Krikorian, "Experimental studies and thermodynamic modeling of volatilities of uranium, plutonium, and americium from their oxides and from their oxides interacted with ash", UCRL-ID-114774, Lawrence Livermore National Laboratory, (Sept 15, 1993).

Abstract: The purpose of this study is to identify the types and amounts of volatile gaseous species of U, Pu, and Am that are produced in the combustion chamber offgases of mixed waste oxidation processors (with primary emphasis on the RFP FBU). Transpiration experiments were carried out on $U_3O_8(s)$ (w/ and w/o ash material), $PuO_2(s)$ (w/ and w/o ash material), and on a $3\%PuO_2/0.06\%AmO_2$/ash material - all in the presence of steam and oxygen, and at temperatures in the vicinity of 1300 K. $UO_3(g)$ and $UO_2(OH)_2(g)$ have been identified as the uranium volatile species and thermodynamic data established for them. Pu and Am were found to have very low volatilities, and carryover of Pu and Am as fine dust particulates is found to dominate over vapor transport. Very little lowering of U volatility was found for U_3O_8 interacted with typical ashes. However, ashes high in Na_2O (6.4 wt%) or in CaO (25 wt%) showed an order of magnitude reduction in U volatility.

Thermodynamic modeling studies were carried out that showed that for aluminosilicate ash materials, it is the presence of group I (Na, K) and group II (Ca) oxides that reduces the activity of the actinide oxides. K_2O was the most effective followed by Na_2O and CaO for common ash constituents. A more major effect in actinide activity lowering could be achieved by adding excess group I or group II oxides to exceed their interaction with ash, resulting in direct formation of alkali or alkaline earth uranates, plutonates, and americates. This report includes interim results reported by O. H. Krikorian et al., "Evaluation of actinide volatilities in mixed waste processor: Interim report", UCRL-ID-111352, Lawrence Livermore National Laboratory, (August 1992).

Operating Conditions and Test Results - CASE 1

Table 1. Summary of interim results of $PuO_2(OH)_2$ volatility data by transpiration measurements

Run #	T, K	Time, min	Moles gas	p_{O2}, atm	p_{Ar}, atm	p_{H2O}, atm	Pu mass, μg	$p_{PuO2(OH)2}$, atm
4	1312	60	1.743	0.356	0.356	0.283	0.22	5.3×10^{-10}
6	1413	60	1.351	0.459	0.459	0.083	0.98	3.0×10^{-9}
8	1413	60	1.365	0.454	0.454	0.092	1.3	4.0×10^{-9}
9	1413	120	2.727	0.909	--	0.091	0.26	4.0×10^{-10}
11	811	120	2.695	0.920	--	0.080	0.02	3.1×10^{-11}
23	1215	250	5.640	0.916	--	0.084	0.18	1.3×10^{-10}
24	1331	125	2.582	0.917	--	0.083	0.25	3.7×10^{-10}
25	1433	65	1.462	0.918	--	0.082	0.09	2.6×10^{-10}

- Data in the table above was intepreted on the basis of the reaction

$$PuO_2(s) + 1/2\ O_2(g) + H_2O = Pu_2(OH)_2(g)$$

The amount of Pu collected during Run 11 at 811 K was near or at the background level for sample contamination, hence the value reported for the partial pressure of $Pu_2(OH)_2(g)$ was considered the upper limit of that run. The carrier flow rates used in the runs above were fairly rapid at 500 cm^3/min (STP). While this gives a linear velocity of about 10 cm/s in the furnace chamber which is not much different than can be expected in an incinerator, the investigators believe these volatility results may be somewhat lower than equilibrium volatility values.

- Two tests were performed to measure the volatility of $Pu_2(OH)_2(g)$ from PuO_2/ash mixtures. The first test used a mixture containing 3.7% PuO_2 in NIST coal fly ash SRM 2691. The test was made at 1331 K for 630 min using an O_2 gas flow of 500 cm^3/min with 13.013 moles O_2 and 1.413 moles H_2O passed, 0.902 atm O_2 and 0.098 atm H_2O partial pressures, and 1.43 mg Pu collected. The pressure of $Pu_2(OH)_2(g)$ was calculated from these data to be 4.1×10^{-10} atm. This value was surprisingly close for PuO_2 run without ash for the same conditions. This suggests PuO_2 did not interact chemically with the ash. A better blending procedure of ash and oxide was suggested.The second test was made to simulate the RFP fluidized bed incinerator (FBI) conditions. The PuO_2/ash sample used in test 1 was blended with appropriate amounts of salts and Cr_2O_3/Al_2O_3 catalyst. The sample contained the following: 0.0142 g PuO_2, 0.3658 g SRM 2691, 0.0649 g Na_2CO_3, 0.2262 g NaCl, 0.459 g Na_2SO_4, 0.3632 g of 20% Cr_2O_3/80% Al_2O_3. PuO_2 represented 1.3 wt% of the sample. The test was made at 827 K for 610 min using an O_2 gas flow of 500 cm^3/min with 12.600 moles O_2 and 1.139 moles H_2O passed, 0.917 atm O_2 and 0.083 atm H_2O partial pressures, and 0.125 mg Pu collected. The pressure of $Pu_2(OH)_2(g)$ was calculated from these data to be 3.8×10^{-11} atm. This value was higher than expected. The amount of Pu collected is above the background level associated with glovebox contamination,; however, the dust filter was inadvertently left off and dust carryover most likely occurred increasingly the amount of Pu collected.

Weight composition of major constituents in NIST standard reference material coal fly ash SRM 2691

Na_2O	1.47	MgO	5.17	Al_2O_3	18.54	SiO_2	36.00	SO_3	2.07
K_2O	0.41	CaO	25.82	TiO_2	1.50	Fe_2O_3	6.32		

Table 2. Summary of transpiration experiments on $PuO_2(s)$ and $PuO_2/2\%AmO_2$ (CASE 2).

Run	Sample	T, K	O_2 flow cm^3/min	Ar flow cm^3/min	Time min	O_2, moles	H_2O, moles	Ar, moles	Total moles	$p(O_2)$ atm	$p(H_2O)$ atm	Pu µg	Am µg	$p(Pu_{tot})$ atm	$p(Am_{tot})$ atm
2	$^{239}PuO_2$	1322	500	500	120	2.479	2.349	2.479	7.307	0.339	0.321	14.2^a	0.0075^a		
4	$^{239}PuO_2$	1341	250	250	120	1.239	0.503	1.239	2.981	0.416	0.169	0.22		3.09×10^{-10}	
5	$^{239}PuO_2$	1413	250	250	60	0.620	0.249	0.620	1.489	0.416	0.167	24.9		7.00×10^{-8}	
6	$^{239}PuO_2$	1414	250	250	60	0.620	0.112	0.620	1.352	0.459	0.0828	0.975		3.02×10^{-9}	
8	$^{239}PuO_2$	1413	250	250	60	0.620	0.125	0.620	1.365	0.454	0.0916	1.3		3.98×10^{-9}	
9	$^{239}PuO_2$	1316	500		120	2.479	0.249		2.728	0.909	0.0913	0.26		3.99×10^{-10}	
11	$^{239}PuO_2$	811	500		120	2.479	0.217		2.696	0.920	0.0804	0.02		3.10×10^{-11}	
19	$^{239}PuO_2$	1216	500		240	4.957	0.468		5.425	0.914	0.0863	0.02		1.54×10^{-11}	
20	$^{239}PuO_2$	1317	500		120	2.479	0.225		2.704	0.917	0.0832	0.04		6.19×10^{-11}	
21	$^{239}PuO_2$	1415	500		65	1.343	0.122		1.465	0.917	0.0828	0.01		2.86×10^{-11}	
23	$^{239}PuO_2/2\%AmO_2$	1218	500		250	5.164	0.476		5.640	0.916	0.0844	0.178	0.016	1.32×10^{-10}	1.2×10^{-11}
24	$^{239}PuO_2/2\%AmO_2$	1331	500		125	2.582	0.233		2.815	0.917	0.0828	0.247	0.003	3.67×10^{-10}	4.4×10^{-12}
25	$^{239}PuO_2/2\%AmO_2$	1433	500		65	1.343	0.119		1.462	0.919	0.0814	0.089	0.003	2.55×10^{-10}	8.5×10^{-12}
28	$^{239}PuO_2/2\%AmO_2$	1432	1000		125	5.164			5.164	1.000		0.09	0.002	7.29×10^{-11}	1.6×10^{-12}
32	$^{239}PuO_2/2\%AmO_2$	1434	100		300	1.239	1.049		2.288	0.542	0.458	0.037	0.001	6.77×10^{-11}	1.8×10^{-12}
33	$^{239}PuO_2/2\%AmO_2$	1434	50		180	0.372	0.339		0.711	0.523	0.477	0.214	0.004	1.26×10^{-9}	2.3×10^{-11}
34	$^{239}PuO_2/2\%AmO_2$	1334	50		300	0.620	0.770		1.390	0.446	0.554	0.081	0.001	2.44×10^{-10}	3.0×10^{-12}
36	$^{239}PuO_2/2\%AmO_2$	1229	50		600	1.239	1.885		3.124	0.397	0.603	0.177	<0.001	2.37×10^{-10}	$<1.3\times10^{-12}$
37	$^{239}PuO_2/2\%AmO_2$	825	50		600	1.239	1.545		2.784	0.445	0.555	0.073	<0.001	1.10×10^{-10}	$<1.5\times10^{-12}$
44	$^{239}PuO_2/2\%AmO_2$	1431	50		600	1.239	1.242		2.481	0.499	0.501	0.44	0.0088	7.42×10^{-10}	1.5×10^{-11}
73	$^{238}PuO_2$	823	50		900	1.859	1.670		3.529	0.527	0.473	0.0032		3.86×10^{-12}	

a. Plutonium and americium present on dust filter.

Table 3. Mass ratio of plutonium to americium in volatilized samples at various temperatures. (CASE 2)

Run #	T, K	Pu/Am ratio
23	1218	11
24	1331	82
25	1433	30
28	1432	45
32	1434	37
33	1434	54
34	1334	81
36	1229	> 177
37	825	> 73
44	1431	50

Experimental observations and discussions - CASE 2

- The measured Pu volatilities were considerably lower than was predicted. Run #5 was rejected because of background contamination. Runs #4, 6, and 8 where high gas flow rates and a fine particulate sample were used, some dust transport of PuO_2 may have occurred resulting in higher measured volatilities. Extensive sintering had occurred in the source samples used in runs #19, 20, 21, and 32, thus reducing the sample surface area and making it difficult to obtain equilibration between the carrier gas and the sample. These runs were rejeccted. Runs #25, 33, 34, and 44 also showed evidence of sintering effects and these volatilities appear to be on the low side. Some cross contamination may have also occurred because the furnace tubes were reused for most of the runs. Runs #11, 37, and 73 that were run near 820K are considered to only provide an upper bound of the volatilities and give a representation of the level of contamination to be expected in handling the collection samples in the glovebox. Considering the uncertainties in the selected runs, it is estimated that the volatility values fall within the range of 1/3 to 3 times the measured values. For the measurement of Am volatilities, the same uncertainties apply plus the uncertainty due to surface depletion. We estimate the accuracy of the measured Am equilibrium to be accurate within a range of 1/5 to 15 times the selected values.

The experience gained performing these tests was useful in identifying areas of improvement in accurately measuring the Pu volatilities. Using $^{238}PuO_2$ instead of $^{239}PuO_2$ as the sample material would improve the senstivity of detection by alpha counting by a factor of 275 because of the higher specific activity pf ^{238}Pu. Temperatures could be held low enough to avoid sintering effect on equilibriation and collection tubes could be used instead of glass wool to obtain more complete collection of the volatilized samples.

Operating Conditions and Test Results - CASE 3

Table 4. Composition of simulated incinerator ash in weight percent of constituent oxides

Oxide	Mix A	Mix B	Mix C	Mix D	Mix E	Mix F	Mix G	Mix H	Mix I	Mix J	Mix K	Mix L
Na_2O	0.23	0.31	1.40	0.24	0.35	0.32	1.47	13.10	6.37	1.43	1.47	0.24
K_2O	2.23	1.19	0.39	2.34	2.69	1.25	0.41	2.33	2.53	0.40	0.41	2.35
MgO	0.74	2.43	4.92	0.78	1.03	2.55	5.17	0.91	0.96	5.04	5.16	0.78
CaO	1.53	7.63	24.59	1.60	3.10	8.01	25.80	2.76	2.91	25.16	25.78	1.61
SrO	0.10	0.23	0.30	0.10	0.08	0.24	0.32	0.07	0.08	0.31	0.32	0.10
BaO	0.17	0.70	0.70	0.18	0.09	0.73	0.74	0.09	0.09	0.72	0.74	0.18
MnO	0.02	0.04	0.03	0.02	0.04	0.04	0.03	0.04	0.04	0.03	0.03	0.02
Al_2O_3	26.60	22.28	17.65	27.97	24.82	23.38	18.53	21.62	23.32	18.06	18.51	28.11
Fe_2O_3	13.23	4.87	6.02	13.91	13.53	5.11	6.32	11.69	12.72	6.16	6.31	13.98
SiO_2	48.03	52.80	34.28	50.50	52.26	55.43	35.98	45.58	49.10	35.07	35.95	50.74
TiO_2	1.31	0.83	1.43	1.38	1.27	0.87	1.50	1.10	1.19	1.46	1.50	1.38
SO_3	0.44	0.35	1.97	0.47	–	0.37	2.07	–	–	2.02	2.07	0.47
P_2O_5	–	1.14	1.11	–			1.17			1.14	1.17	–
U_3O_8	5.38	5.21	5.20	0.520	0.510	0.503	0.502	0.504	0.479	0.10	0.02	–
PuO_2	–	–	–	–	–	–	–	–	–	2.9	0.57	3.0
AmO_2	–	–	–	–	–	–	–	–	–	–	–	0.6

Mix A - 5%$UO_{2.67}$/1633a
Mix B - 5%$UO_{2.67}$/2690
Mix C - 5%$UO_{2.67}$/2691
Mix D - 0.5%$UO_{2.67}$/1633a
Mix E - 0.5%$UO_{2.67}$/2689
Mix F - 0.5%$UO_{2.67}$/2690
Mix G - 0.5%$UO_{2.67}$/2691
Mix H - 0.5%$UO_{2.67}$/Ash1
Mix I - 0.5%$UO_{2.67}$/Ash2
Mix J - 3%PuO_2/2691
Mix K - 0.6%PuO_2/2691
Mix L - 3%PuO_2/0.6%AmO_2/1633a

Table 5. Summary of uranium transpiration experiments on U_3O_8 and U_3O_8/ash samples (Case 3).

Run	Sample	T, K	O_2 flow cm³/min	Ar flow cm³/min	Time, min	H_2O,g	O_2, moles	H_2O, . moles	Ar, moles	Total moles	p(O_2) atm	p(H_2O) atm	U µg	p(U_{tot}) atm
1	5%$UO_{2.67}$/2690	1330	50		240	6.86	0.495	0.381		0.876	0.565	0.435	5.3	2.54×10^{-8}
7	U_3O_8(s)	1323	50		180	8.51	0.370	0.472		0.843	0.440	0.560	19.3	9.62×10^{-8}
8	U_3O_8(s)	1323	25		180	4.07	0.185	0.226		0.411	0.451	0.549	9.63	9.84×10^{-8}
9	U_3O_8(s)	1323	15		180	4.25	0.111	0.236		0.347	0.320	0.679	9.52	1.15×10^{-7}
10	U_3O_8(s)	1323	25	30.5	180		0.185		0.226	0.411	0.450		7.23	7.38×10^{-8}
11	U_3O_8(s)	1323	6		180	6.21	0.0445	0.345		0.389	0.114	0.886	12.4	1.34×10^{-7}
12	U_3O_8(s)	1323	25	30	180		0.185		0.222	0.408	0.455		3.03	3.12×10^{-8}
13	U_3O_8(s)	1473		25	180	4.99		0.277	0.185	0.462		0.599	70.4	6.40×10^{-7}
14	U_3O_8(s)	1323	25	25	180	8.88	0.185	0.493	0.185	0.864	0.215	0.571	13.96	6.79×10^{-8}
15	U_3O_8(s)	1223	30.5	25	1200		1.507		1.235	2.742	0.550		1.54	2.36×10^{-9}
17	U_3O_8(s)	1473	50		120	6.17	0.247	0.342		0.590	0.419	0.581	250.9	1.79×10^{-6}
18	U_3O_8(s)	1323	9		120	2.49	0.0445	0.138		0.183	0.244	0.756	6.86	1.58×10^{-7}
19	U_3O_8(s)	1323	25	30	180		0.185		0.222	0.408	0.455		2.97	3.06×10^{-8}
20	U_3O_8(s)	1373	100		120	11.71	0.494	0.650		1.144	0.432	0.568	72.4	2.66×10^{-7}
21	U_3O_8(s)	1223	30		1440	25.89	1.808	1.437		3.245	0.557	0.443	5.9	7.64×10^{-9}
22	U_3O_8(s)	1373	10		180	1.39	0.0741	0.0880		0.162	0.457	0.543	10.4	2.70×10^{-7}
24	U_3O_8(s)	1373	30		180	(5.38)	0.222	0.299		0.521	0.427	0.573	29.43	2.37×10^{-7}
25	U_3O_8(s)	1373	300		120	39.76	1.482	2.207		3.689	0.402	0.598	183	2.08×10^{-7}
26	U_3O_8(s)	1323	50		180	4.52	0.370	0.251		0.621	0.596	0.404	9.03	6.10×10^{-8}
27	U_3O_8(s)	1323	50		180	1.51	0.370	0.0838		0.454	0.816	0.184	5.2	4.81×10^{-8}
31	U_3O_8(s)	1573	120		60	7.95	0.296	0.441		0.738	0.402	0.598	1980	1.13×10^{-5}
32	U_3O_8(s)	1573	120		60	32.38	0.296	1.797		2.094	0.142	0.858	3150	6.32×10^{-6}
33	U_3O_8(s)	1573	50		180	5.61	0.370	0.311		0.682	0.543	0.457	2080	1.28×10^{-5}

Table 5. Summary of uranium transpiration experiments on U_3O_8 and U_3O_8/ash samples (Case 3).

Run	Sample	T, K	O_2 flow cm^3/min	Ar flow cm^3/min	Time, min	H_2O,g	O_2, moles	H_2O, . moles	Ar, moles	Total moles	p(O_2) atm	p(H_2O) atm	U µg	p(U_{tot}) atm
34	U_3O_8(s)	1573	50		180		0.370			0.370	1.000		2480	$2.81x10^{-5}$
35	5%$UO_{2.67}$/2690	1323	55		360		0.370		0.445	0.815	0.454		4.71	$2.43x10^{-8}$
36	5%$UO_{2.67}$/2690	1323	25		361	9.05	0.372	0.502		0.874	0.425	0.575	15.28	$7.34x10^{-8}$
37	5%$UO_{2.67}$/2691	1323	55		360		0.370		0.445	0.815	0.454		0.95	$4.90x10^{-8}$
39	5%$UO_{2.67}$/1633a	1323	55		360		0.370		0.445	0.815	0.454		3.62	$1.87x10^{-8}$
41	5%$UO_{2.67}$/1633a	1323	55		330		0.747			0.747	1.000		5.45	$3.06x10^{-8}$
42	5%$UO_{2.67}$/2691	1323	25		421	47.8	0.433	2.653		3.087	0.140	0.860	14.37	$1.96x10^{-8}$
43	5%$UO_{2.67}$/2691	1323	25		420	11.01	0.432	0.611		1.044	0.414	0.586	4.18	$1.87x10^{-8}$
44	5%$UO_{2.67}$/2690	1323	25		360	31.03	0.370	1.722		2.093	0.177	0.823	37.26	$7.48x10^{-8}$
45	1.7%$UO_{2.67}$/2690/ salts/catalyst	827	50		4740	243.77	9.757	13.53		23.29	0.419	0.581	0.053	$9.56x10^{-12}$
46	U_3O_8(s)	1373	50		540		1.112			1.112	1.000		13.93	$5.26x10^{-8}$
47	U_3O_8(s)	1373	200		120	26.78	0.988	1.486		2.475	0.399	0.601	162.7	$2.76x10^{-7}$
48	1.7%$UO_{2.67}$/1633a/salts/catalyst	826	50		2915	153.71	6.001	8.532		14.53	0.413	0.587	0.207	$5.98x10^{-11}$
49	U_3O_8(s)	1473	30		240		0.296			0.296	1.000		180	$2.55x10^{-6}$
50	U_3O_8(s)	1273	30		480		0.593			0.593	1.000		3.02	$2.14x10^{-8}$
51	5%$UO_{2.67}$/2690	1323	30		390		0.482			0.482	1.000		3.28	$2.86x10^{-8}$
52	5%$UO_{2.67}$/2690	1323	30		420	10.98	0.519	0.610		1.128	0.460	0.540	20.85	$7.76x10^{-8}$
. 53	5%$UO_{2.67}$/2690	1323	21		420	9.02	0.363	0.501		0.864	0.420	0.580	19.05	$9.26x10^{-8}$
54	5%$UO_{2.67}$/2690	1323	39		420	5.13	0.674	0.285		0.959	0.703	0.297	13.6	$5.96x10^{-8}$
55	U_3O_8(s)	1173	25		1950	55.04	2.007	3.055		5.062	0.397	0.603	2.38	$1.98x10^{-9}$
56	U_3O_8(s)	1373	6		480	3.05	0.119	0.169		0.288	0.412	0.588	30.3	$4.42x10^{-7}$
58	U_3O_8(s)	1373	20		440	9.81	0.362	0.544		0.907	0.400	0.600	67.4	$3.12x10^{-7}$

Table 5. Summary of uranium transpiration experiments on U_3O_8 and U_3O_8/ash samples (Case 3).

Run	Sample	T, K	O_2 flow cm³/min	Ar flow cm³/min	Time, min	H_2O,g	O_2, moles	H_2O, moles	Ar, moles	Total moles	p(O_2) atm	p(H_2O) atm	U µg	p(U_{tot}) atm
59	U_3O_8(s)	1173	25		540		0.556			0.556	1.000		1.31	9.90×10^{-9}
60	U_3O_8(s)	1373	50		510	27.0	1.050	1.499		2.549	0.412	0.588	148	2.44×10^{-7}
61	5%$UO_{2.67}$/2690	1323	21		405	16.22	0.350	0.900		1.251	0.280	0.720	21.9	7.36×10^{-8}
63	5%$UO_{2.67}$/2691	1323	25		420	11.70	0.432	0.650		1.082	0.400	0.600	3.13	1.22×10^{-8}
64	5%$UO_{2.67}$/2691	1323	21		450	19.77	0.389	1.097		1.487	0.262	0.738	5.40	1.53×10^{-8}
65	5%$UO_{2.67}$/1633a	1323	35		1755		2.529			2.529	1.000		21.1	3.50×10^{-8}
66	5%$UO_{2.67}$/1633a	1323	25		450	11.70	0.463	0.650		1.113	0.416	0.584	20.6	7.78×10^{-8}
67	0.5%$UO_{2.67}$/1633a	1323	21		465	19.74	0.402	1.096		1.498	0.268	0.732	20.5	5.75×10^{-8}
68	0.5%$UO_{2.67}$/1633a	1323	25		495	12.36	0.510	0.686		1.196	0.426	0.574	14.20	4.99×10^{-8}
69	0.5%$UO_{2.67}$/1633a	1323	39		450	8.32	0.722	0.462		1.184	0.610	0.390	16.05	5.69×10^{-8}
70	0.5%$UO_{2.67}$/1633a	1323	50		510		1.050			1.050	1.000		6.08	2.43×10^{-8}
71	0.5%$UO_{2.67}$/2690	1323	50		462		0.951			0.951	1.000		5.73	2.53×10^{-8}
72	0.5%$UO_{2.67}$/2690	1323	39		435	8.96	0.698	0.497		1.196	0.584	0.416	11.93	4.19×10^{-8}
73	0.5%$UO_{2.67}$/2690	1323	25		475	13.17	0.489	0.731		1.220	0.820	0.180	16.19	5.58×10^{-8}
74	0.5%$UO_{2.67}$/2690	1323	21		460	17.20	0.398	0.955		1.352	0.294	0.706	20.55	6.38×10^{-8}
75	0.5%$UO_{2.67}$/Ash1	1323	50		1755		3.613			3.613	1.000		1.66	1.93×10^{-9}
76	U_3O_8(s)	1273	21		440	17.11	0.380	0.950		1.330	0.286	0.714	5.71	1.80×10^{-8}
77	0.5%$UO_{2.67}$/2691	1323	50		1695		3.489			3.489	1.000		2.05	2.47×10^{-9}
78	U_3O_8(s)	1323	45		480	4.28	0.889	0.238		1.127	0.789	0.211	9.27	3.46×10^{-8}
79	U_3O_8(s)	1223	21		1890	68.86	1.634	3.822		5.456	0.300	0.700	10.57	8.14×10^{-9}
80	0.5%$UO_{2.67}$/2691	1323	39		435	8.56	0.698	0.475		1.174	0.595	0.405	1.22	4.37×10^{-9}
83	0.5%$UO_{2.67}$/2691	1323	21		490	20.49	0.424	1.137		1.561	0.271	0.729	1.53	4.12×10^{-9}
84	0.5%$UO_{2.67}$/2691	1323	25		440	11.11	0.453	0.617		1.070	0.423	0.577	0.94	3.69×10^{-9}

Table 5. Summary of uranium transpiration experiments on U_3O_8 and U_3O_8/ash samples (Case 3).

Run	Sample	T, K	O_2 flow cm^3/min	Ar flow cm^3/min	Time, min	H_2O,g	O_2, moles	H_2O, . moles	Ar, moles	Total moles	p(O_2) atm	p(H_2O) atm	U µg	p(U_{tot}) atm
85	U_3O_8(s)	1223	35		1810	13.21	2.608	0.733		3.342	0.780	0.220	0.68	8.55×10^{-10}
86	U_3O_8(s)	1223	40		1890		3.112			3.112	1.000		0.31	4.18×10^{-10}
87	0.5%$UO_{2.67}$/2691	1223	20		1890	41.53	1.556	2.305		3.862	0.403	0.597	0.27	2.94×10^{-10}
88	U_3O_8(s)	1323	18		515	45.86	0.382	2.546		2.927	0.130	0.870	39.53	5.67×10^{-8}
89	0.5%$UO_{2.67}$/2691	1223	45		1870		3.464			3.464	1.000		1.92	2.33×10^{-9}
90	U_3O_8(s)	1323	21		475	18.44	0.411	1.024		1.434	0.286	0.714	23.63	6.92×10^{-8}
91	U_3O_8(s)	1223	15		1680	103.51	1.038	5.746		6.783	0.153	0.847	13.78	8.54×10^{-9}
92	0.5%$UO_{2.67}$/Ash2	1323	50		455		0.937			0.937	1.000		0.46	2.06×10^{-9}
93	0.5%$UO_{2.67}$/Ash2	1323	21		425	6.35	0.367	0.352		0.720	0.510	0.490	3.68	2.15×10^{-8}
94	U_3O_8(s)	826	20		5785	132.34	4.763	7.346		12.11	0.393	0.607	0.08	2.78×10^{-11}
95	0.5%$UO_{2.67}$/Ash2	1323	25		495	13.06	0.510	0.725		1.234	0.413	0.587	4.12	1.40×10^{-8}
96	0.5%$UO_{2.67}$/Ash2	1323	39		450	8.43	0.722	0.468		1.190	0.607	0.393	4.47	1.58×10^{-8}
97	0.5%$UO_{2.67}$/Ash2	1223	25		1560	43.76	1.606	2.429		4.035	0.398	0.602	2.26	2.35×10^{-9}
98	0.5%$UO_{2.67}$/Ash2	1223	50		1500		3.088			3.088	1.000		0.37	5.03×10^{-10}

Table 6. Total pressures of uranium corrected for $UO_3(g)$ to give pressures of $UO_2(OH)_2(g)$ (CASE 3)

Run #	T, K	Measured $p_{U,total}$ atm	Calculated p_{UO3} atm	$p_{UO2(OH)2}{}^a$ atm
7	1323	$9.619x10^{-8}$	$4.861x10^{-8}$	$4.758x10^{-8}$
8	1323	$9.839x10^{-8}$	$4.882x10^{-8}$	$4.957x10^{-8}$
9	1323	$1.152x10^{-7}$	$4.612x10^{-8}$	$6.908x10^{-8}$
11	1323	$1.340x10^{-7}$	$3.884x10^{-8}$	$9.516x10^{-8}$
14	1323	$6.792x10^{-8}$	$4.314x10^{-8}$	$2.478x10^{-8}$
18	1323	$1.578x10^{-7}$	$4.406x10^{-8}$	$1.137x10^{-7}$
20	1373	$2.659x10^{-7}$	$1.845x10^{-7}$	$8.140x10^{-8}$
21	1223	$7.638x10^{-9}$	$2.502x10^{-9}$	$5.136x10^{-9}$
22	1373	$2.695x10^{-7}$	$1.863x10^{-7}$	$8.320x10^{-8}$
24	1373	$2.374x10^{-7}$	$1.842x10^{-7}$	$5.320x10^{-8}$
26	1323	$6.105x10^{-8}$	$5.115x10^{-8}$	$9.900x10^{-9}$
27	1323	$4.809x10^{-8}$	$5.389x10^{-8}$	---
47	1373	$2.762x10^{-7}$	$1.821x10^{-7}$	$9.410x10^{-8}$
55	1173	$1.975x10^{-9}$	$4.328x10^{-10}$	$1.542x10^{-9}$
58	1373	$3.123x10^{-7}$	$1.821x10^{-7}$	$1.302x10^{-7}$
60	1373	$2.440x10^{-7}$	$1.831x10^{-7}$	$6.090x10^{-8}$
76	1273	$1.803x10^{-8}$	$1.069x10^{-8}$	$7.340x10^{-9}$
78	1323	$3.456x10^{-8}$	$5.360x10^{-8}$	---
79	1223	$8.138x10^{-9}$	$2.256x10^{-9}$	$5.882x10^{-9}$
85	1223	$8.549x10^{-10}$	$2.647x10^{-9}$	---
88	1323	$5.673x10^{-8}$	$3.970x10^{-8}$	$1.667x10^{-8}$
90	1323	$6.921x10^{-8}$	$4.526x10^{-8}$	$2.395x10^{-8}$
91	1223	$8.535x10^{-9}$	$2.017x10^{-9}$	$6.518x10^{-9}$

a. Difference of total uranium partial pressure and calculated partial pressure of UO_3

Table 7. Summary of plutonium transpiration experiments on PuO_2, PuO_2/ash, and PuO_2/AmO_2/ash samples (Case 3).

Run	Sample	T, K	O_2 flow cm^3/min	Ar flow cm^3/min	Time, min	H_2O,g	O_2, moles	H_2O, moles	Ar, moles	Total moles	p(O_2) atm	p(H_2O) atm	Pu ng	p(Pu_{tot}) atm
46	3%$^{238}PuO_2$/2691	1228	50.0		600	21.07	1.239	1.170		2.409	0.515	0.485	0.0900	1.57×10^{-13}
47	3%$^{238}PuO_2$/2691	1330	50.0		600	22.10	1.239	1.227		2.466	0.503	0.497	4.84	8.24×10^{-12}
52	3%$^{238}PuO_2$/2691	1330	50.0		600	67.61	1.239	3.753		4.992	0.248	0.752	3.75	3.16×10^{-12}
53	3%$^{238}PuO_2$/2691	1279	50.0		870	93.14	1.797	5.170		6.967	0.258	0.742	1.20	7.23×10^{-13}
54	3%$^{238}PuO_2$/2691	1355	50.0		600	110.36	1.239	6.126		7.365	0.168	0.832	39.75	2.27×10^{-11}
55	1.1%$^{238}PuO_2$/2691 /salts/catalyst	829	50.0		1100	51.29	2.293	2.847		5.140	0.446	0.554	0.256	2.10×10^{-13}
63	0.6%$^{238}PuO_2$/2691	1228	50.0		630	34.45	1.301	1.912		3.214	0.405	0.595	0.0765	1.00×10^{-13}
64	0.6%$^{238}PuO_2$/2691	1280	50.0		600	34.61	1.239	1.921		3.160	0.392	0.608	0.238	3.16×10^{-13}
65	0.6%$^{238}PuO_2$/2691	1330	50.0		600	32.95	1.239	1.829		3.068	0.404	0.596	1.148	1.57×10^{-12}
66	0.6%$^{238}PuO_2$/2691	1179	50.0		600	32.21	1.239	1.788		3.027	0.409	0.591	2.23	3.09×10^{-12}
67	0.6%$^{238}PuO_2$/2691	1381	50.0		540	20.77	1.115	1.153		2.268	0.492	0.508	3.65	6.76×10^{-12}
69	3%$^{239}PuO_2$/0.06% $^{241}AmO_2$/1633a	1228	50.0		600	22.81	1.239	1.266		2.505	0.495	0.505	<0.0034[a]	$< 5.7 \times 10^{-15}$ [a]
70	3%$^{239}PuO_2$/0.06% $^{241}AmO_2$/1633a	1178	50.0		600	22.07	1.239	1.225		2.464	0.503	0.497	2.20[b]	3.74×10^{-12} [b]
71	3%$^{239}PuO_2$/0.06% $^{241}AmO_2$/1633a	1279	50.0		600	22.77	1.239	1.264		2.503	0.495	0.505	7.59[c]	1.27×10^{-11} [c]
72	3%$^{239}PuO_2$/0.06% $^{241}AmO_2$/1633a	1329	50.0		600	23.23	1.239	1.290		2.529	0.490	0.510	0.31[d]	5.13×10^{-13} [d]

a. 2.6 pg Am, $p(Am_{tot}) = 4.31 \times 10^{-15}$
b. 64 pg Am, $p(Am_{tot}) = 1.08 \times 10^{-13}$
c. 176 pg Am, $p(Am_{tot}) = 2.92 \times 10^{-13}$
d. 8.4 pg Am, $p(Am_{tot}) = 1.38 \times 10^{-14}$

Table 7. Summary of plutonium transpiration experiments on PuO_2, PuO_2/ash, and PuO_2/AmO_2/ash samples (Case 3).

Run	Sample	T, K	O_2 flow cm^3/min	Ar flow cm^3/min	Time, min	H_2O,g	O_2, moles	H_2O, moles	Ar, moles	Total moles	$p(O_2)$ atm	$p(H_2O)$ atm	Pu ng	$p(Pu_{tot})$ atm
73	$^{238}PuO_2$	824	50.0		900	30.09	1.859	1.670		3.529	0.527	0.473	4.05	4.82×10^{-12}
74	$^{238}PuO_2$	1076	50.0		1030	37.30	2.128	2.071		4.199	0.507	0.493	0.0076	7.65×10^{-15}
75	$^{238}PuO_2$	1177	50.0		600	23.42	1.239	1.300		2.539	0.488	0.512	0.163	2.69×10^{-13}
76	$^{238}PuO_2$	1277	50.0		540	21.14	1.115	1.173		2.288	0.487	0.513	0.0082	1.50×10^{-14}
77	$^{238}PuO_2$	1327	50.0		600	25.32	1.239	1.406		2.645	0.469	0.531	0.0348	5.52×10^{-14}
78	$^{238}PuO_2$	1325	50.0		600		1.239			1.239	1.000		0.0313	1.06×10^{-13}
79	$^{238}PuO_2$	1327	25.0	24.9	840		0.868		0.864	1.732	0.501		0.0006	1.52×10^{-15}
80	$^{238}PuO_2$	1326	12.5	37.5	1050		0.542		1.627	2.169	0.250		0.0035	6.83×10^{-15}
81	$^{238}PuO_2$	824	50.0		900	31.26	1.859	1.735		3.594	0.517	0.483	0.0895	1.05×10^{-13}
82	$^{238}PuO_2$	1076	50.0		1010	39.24	2.086	2.178		4.264	0.489	0.511	0.0076	7.49×10^{-15}
83	$^{238}PuO_2$	1176	50.0		600	24.02	1.239	1.333		2.572	0.482	0.518	1.92	3.14×10^{-12}
84	$^{238}PuO_2$	1277	50.0		590	25.92	1.219	1.439		2.658	0.459	0.541	0.0003	4.90×10^{-16}
85	$^{238}PuO_2$	1326	50.0		480	20.44	0.991	1.135		2.126	0.466	0.534	0.0159	3.14×10^{-14}
86	$^{238}PuO_2$	1326	50.0		600		1.239			1.239	1.000		0.0022	7.42×10^{-15}
87	$^{238}PuO_2$	1326	25.0	24.9	890		0.919		0.916	1.835	0.501		0.0007	1.65×10^{-15}
88	$^{238}PuO_2$	1325	12.5	37.5	860		0.444		1.332	1.776	0.250		0.173	4.08×10^{-13}
89	$^{238}PuO_2$	824	50.0		600	23.18	1.239	1.287		2.526	0.491	0.509	< 0.0006	$< 9 \times 10^{-16}$
90	$^{238}PuO_2$	1176	50.0		480	20.17	0.991	1.120		2.111	0.470	0.530	0.0004	8.11×10^{-16}

Experimental Observations and Discussion - CASE 3

- **Volatility of $UO_3(g)$ and $UO_2(OH)_2(g)$ from $U_3O_8(s)$** The effect of water vapor on U species formation was investigated. The formation of total gaseous U species is expected to increase linearly with increasing water vapor pressure. This appears to be confirmed experimentally.

- **Volatility of $UO_3(g)$ and $UO_2(OH)_2(g)$ from U_3O_8/Ash** The effect of water vapor on total U volatility is apparent in the U_3O_8/ash samples as was the case of $U_3O_8(s)$. The extent of U volatility lowering by the 1633a and 2690 ashes is small, while the Na_2O ash (ash 1) and the high CaO ash (2691) both show considerable lowering of the volatility. To analyze the U_3O_8/ash volatility data, it would be desirable to define the chemical form of the uranium. However, the systems are very complex. The characterization studies indicate that uranium is present both in the glass and in the crystalline phases, but a complete definitive description is not available. For convenience in analyzing the data, a solution model is used. It is assumed that U is dissolved in the host matrix as the oxide U_3O_8 represented as $UO_{2.67}$.

- Two trials were performed involving a mixture of $UO_{2.67}$, ash, salts, and catalysts at 826 K. The total U partial pressure in both cases was on the order of 10^{-11} atm. These values were considered too high and probably the result of dust carryover or contamination during handling of the collector tubes.

- **Volatility of $PuO_3(g)$ and $PuO_2(OH)_2(g)$ from PuO_2/Ash** In earlier work with $^{239}PuO_2(s)$, because of the low levels of Pu volatilized, it was found that the results were complicated by problems of PuO_2 dust transport, collection of volatilized samples on quartz wool plugs, cross-contamination of collection samples, and background contamination from the glovebox environment during sampling handling. In addition, it was thought that maybe sintering of the samples inhibited the approach to equilibrium. Upon reviewing current results, dust transport and sample contamination are believed to be the main problems. Trials 4, 6, 8, and 9 results were believed to effected by dust transport resulting from high gas flow rates. A number of steps were taken to avoid or reduce the problems encountered in the earlier work. ^{238}Pu was used because of greater sensitivity of detection. Temperatures were kept below 1330 K to avoid extensive sintering. A collection tube was used instead of quartz wool for sample collection. Solvent was added to only the inside of the collection tubes to leach out the Pu deposit for analysis, thus avoiding any contamination picked up on the outside of the tubes.

Using alpha counting for ^{238}Pu analysis, the Pu volatilities were somewhat higher. However, a check on alpha peaks using pulse height analysis showed that the alpha counts came primarily from a 4.75 MeV peak corresponding to either ^{234}U, ^{237}Np, or ^{233}U. All runs using ^{238}Pu were reanalyzed by pulse height analysis to obtain both ^{238}Pu and ^{234}U values. The ^{238}Pu values were corrected to total Pu based on the isotopic mix. Examination of the Pu volatility data from the PuO_2/ash tests show Pu volatilities that exceed those observed from pure $^{238}PuO_2(s)$. This is not reasonable. If anything, interaction with the ash is expected to lower the Pu volatility. Again, these results are attributed to dust carryover.

- **Interactions of Actinides with Oxides** The addition of Na_2O and CaO to ash lowered the U volatility as the result of interactions between U and group I and group II constituents in the ash. No data was available to suggest how Pu and Am oxides would interact with the ash components. For the U_3O_8/ash interactions, the activity lowering is calculated to be greater at higher temperatures and smaller at lower temperatures. Model calculations indicate qualitatively that group I oxides interact stronger with the actinides than does group II oxides. Also, group I and II oxides interact stronger with $UO_{2.67}$ than with PuO_2, PuO_2 interacting stronger than AmO_2. However, very little can be said quantitatively about the amount of volatility reduction that will occur when large amounts of ash are present because group I and II oxides may react with other oxides in the ash instead of with the actinide oxides.