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INNOVATIVE TECHNOLOGY
Summary Report

Graphite Electrode DC Arc Furnace

Mixed Waste Focus Area

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INNOVATIVE TECHNOLOGY
Summary Report

Graphite Electrode DC Arc Furnace

OST Reference #1652

Mixed Waste Focus Area

MASTER

Demonstrated with
Waste from Pantex,
Texas

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at http://OST.em.doe.gov under "Publications."

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SECTION 1

SUMMARY

Technology Summary

The Graphite Electrode DC Arc Furnace (DC Arc) is a high-temperature thermal process, which has been adapted from a commercial technology, for the treatment of mixed waste. A DC Arc Furnace heats waste to a temperature such that the waste is converted into a molten form that cools into a stable glassy and/or crystalline waste form. Hazardous organics are destroyed through combustion or pyrolysis during the process and the majority of the hazardous metals and radioactive components are incorporated in the molten phase. The DC Arc Furnace chamber temperature is approximately 593 – 704°C and melt temperatures are as high as 1,500°C. The DC Arc system has an air pollution control system (APCS) to remove particulate and volatiles from the offgas. The advantage of the DC Arc is that it is a single, high-temperature thermal process that minimizes the need for multiple treatment systems and for extensive sorting/segregating of large volumes of waste. The DC Arc has the potential to treat a wide range of wastes, minimize the need for sorting, reduce the final waste volumes, produce a leach resistant waste form, and destroy organic contaminants.

Although the DC arc plasma furnace exhibits great promise for treating the types of mixed waste that are commonly present at many DOE sites, several data and technology deficiencies were identified by the Mixed Waste Focus Area (MWFA) regarding this thermal waste processing technique. The technology deficiencies that have been addressed by the current studies include:

- establishing the partitioning behavior of radionuclides, surrogates, and hazardous metals among the product streams (metal, slag, and offgas) as a function of operating parameters, including melt temperature, plenum atmosphere, organic loading, chloride concentration, and particle size;
- demonstrating the efficacy of waste product removal systems for slag and metal phases;
- determining component durability through test runs of extended duration,
- evaluating the effect of feed composition variations on process operating conditions and slag product performance,
- collecting mass balance and operating data to support equipment and instrument design.

These issues were first addressed by a series of bench-scale DC Arc Furnace tests with both nonradioactive and radioactive surrogate feeds. These tests were used to evaluate the processability of a wide range of feeds and operating conditions before committing to engineering-scale tests. A series of both radioactive and nonradioactive engineering-scale furnace (ESF) test campaigns were then completed to address scale-up and operability questions.

A summary of the graphite electrode DC Arc Furnace's demonstrated capabilities and the issues that will affect its implementation by a DOE site is provided in this report to support end users and other interested parties in technology selection.

Demonstration Summary

A series of nonradioactive and radioactive bench-scale tests were completed on Idaho National Engineering and Environmental Laboratory (INEEL) wastes to determine the potential for using the DC Arc Furnace for waste treatment. A second waste stream tested was a simulated ^{238}Plutonium contaminated job control waste from the Savannah River Site (SRS). Waste formulation, metals partitioning, and waste form performance data was generated to evaluate the potential for using the DC Arc technology in treating those waste streams. Bench-scale testing for both waste types showed the potential for the DC Arc furnace technology to be used in treatment. Demonstration testing was then planned on the engineering-scale unit using these waste types.

The first of the ESF test campaigns provided data regarding the effect of process operating conditions on partitioning behavior, as well as the opportunity to shakedown the system and to validate sampling and operating procedures. The second test campaign investigated the effect of variation in feed composition and operating conditions on partitioning; however, damage sustained to the melter during startup operations caused the test to be terminated prematurely.

The actual damage to the DC Arc Furnace incurred during the second melter test was extensive enough to require major repairs before waste processing tests could resume. During this period, the test data were evaluated and the future experimental work redirected. Since numerous bench-scale DC Arc Furnace tests had previously established that offgas partitioning for transuranic waste components was dominated by scale-independent entrainment losses, it was reasoned that additional engineering-scale testing of plutonium bearing soils would provide little additional processing information. Consequently, the DC Arc Furnace project was redirected to evaluate the technology's capability of converting classified hardware containing both hazardous and radioactive materials (Pantex ferroelectric neutron generators) into unclassified, durable waste forms that could be disposed of conventionally in a commercial waste repository. This demonstration was successfully completed and the slag was disposed of as nonclassified, low level waste (LLW) at the Hanford site.

Key Results

- Operating and performance data of the DC Arc technology in treating several waste types: Rocky Flats Pondcrete; INEEL - soils, high metals wastes, organics/oils/solvents, nominal debris type waste; and an SRS 238Pu contaminated debris waste.
- The behavior of ^{238}Pu was found to be identical to that of ^{239}Pu, with the majority of the plutonium partitioning to the glass phase.
- High water content in sludges (30wt%) was found to increase electrode corrosion, cause problems with feeding via the solids auger, and cause water to collect in the offgas system.
- All levels of organic materials appear to be processable in the bench-scale furnace when fed on top of an existing molten pool. However, it should be noted that the bench-scale furnace is a semi-batch system and cannot see effects which might arise from long periods of continuous operation. Although the feeds high in organic materials were successfully processed, several difficulties were encountered. The highest organic contents caused pressurization of the furnace plenum. These occurrences must be addressed in the design of any future system. The elevated levels of organic materials were found to have a significant impact on the slag, causing the formation of crystals, which increased the melt viscosity and electrical resistivity. Changes in the baseline debris formation were made to alleviate this problem and feed with up to 50 wt% organic material was successfully processed.
- Increased cold-cap coverage reduced the carryover of solids into the offgas during submerged arc operation. When the arc was exposed, solids carryover was high regardless of the cold-cap coverage.
- The overall leach rate, determined from the concentration of all elements in the TCLP leachate, shows the leaching of the glass to be very slight, comparable to that of natural basalt, a material of similar composition. No apparent impact of the test operating conditions on the leachability of the glass product was noted.
- The DC Arc technology successfully demilitarized 200 neutron generators.

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SECTION 2

TECHNOLOGY DESCRIPTION

Overall Process Definition

The DC arc plasma furnace, schematically illustrated in Figure 1, is a robust, high-temperature thermal treatment system that was tested in support of the treatment of DOE mixed wastes under the MWFA. In this system, a stable DC arc is created by applying a potential between a graphite electrode and the graphite hearth of the furnace. The thermal energy produced by this arc creates and maintains a molten bath of material (glass/slag and/or metal) in the furnace hearth. Waste materials fed into the system are melted into the bath. Organics are pyrolyzed at the high operating temperatures and may be destroyed in the plenum or in a suitable afterburner. Oxide materials, including many hazardous and radioactive species, are immobilized in the durable glass/slag phase, while metals are converted to a second, more dense, molten-metal phase. The melter's inductively heated bottom drain and resistively heated overflow section are used to periodically transfer molten metal and glass waste products, respectively, to waste receipt canisters. An advantage of this technology is its potential application to waste streams containing a wide range of materials (debris, trash, metals, soil, etc.).

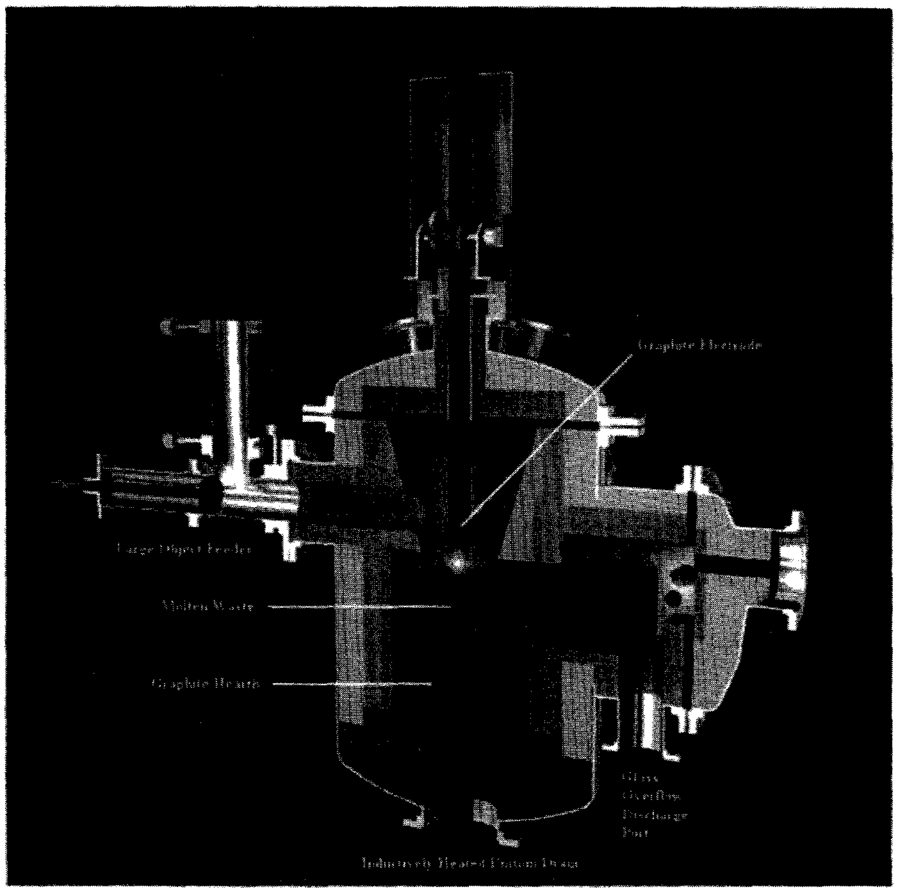

Figure 1. Schematic view of the DC, Plasma-Arc Melter.

Technology Description

The DC Arc ESF system consists of the furnace, power control systems, feed systems, offgas system, and a supervisory control and data acquisition system. Figure 2 shows the flowsheet for the ESF system. The furnace and most of the offgas system are located within a walk-in enclosure/hood, while the remainder of the system is located outside this enclosure. The ESF was designed to deliver 50 to 100 kW of arcing power and to operate at bulk glass temperatures in excess of 1,500°C. The offgas system is designed to handle furnace outlet gas temperatures up to 1,000°C laden with submicron particulate and acid gases. The following sections describe the primary components of the ESF system.

Furnace System

Special features in the ESF design include a bottom drain for both metals and glass, an overflow discharge section proven in many PNNL melters, and a graphite glass cavity capable, if ceramically lined, of operating in both oxidizing and reducing environments. A removable furnace roof, which is constructed of stainless steel, supports hangers for the insulating and refractory brick liner. There are eight openings through the furnace wall. Four of these penetrations are for the side busses to the graphite hearth. The other penetrations are present for a large object ram feeder, glass overflow discharge, furnace offgas, and pyrometer access. Both a vacuum-assisted overflow and inductively-heated bottom drain permit molten glass and metal to be poured from the furnace.

The refractory design of the ESF was modified somewhat during the FY 1998 furnace repair. The changes in materials were prompted both by FY 1998 projected flowsheet alterations and from lessons learned during FY 1997 testing. Since these modifications were slight, the original design will be discussed first, followed by a description of FY 1998 alterations.

Vessel and Refractories

The ESF comprises a 3.5-ft diameter by 4-ft high stainless steel vessel that encloses the furnace hearth and contains a discharge section and penetrations for introducing feed, adding electrode, discharging offgases, viewing, and emergency pressure relief. The distribution of refractories in the furnace is shown in Figure 3.

Electrical conductivity for the DC plasma arc is established between a graphite electrode introduced through the furnace lid and a graphite crucible, which forms the hearth. Electrical contact is made to the hearth through four graphite rods, or busses, threaded into the crucible wall. These busses penetrate through 4-in. flanged penetrations in the shell and similar sized openings in the refractory. The walls of the crucible are 2 in. thick and the bottom of the crucible is 4 in. thick. The walls of the graphite crucible are lined with 3 in. of Monofrax K-3 refractory to protect the crucible from oxidizing conditions in the glass and gases above the melt. Immediately below the graphite crucible is a 3-in. layer of porous graphite on top of a 3-in. layer of high density firebrick. A 2-in. layer of Greenlite-28 firebrick surrounds the wall of the graphite crucible. This layer is, in turn, surrounded by a 3-in. layer of Alfrax-66. Both layers are supported on the dense firebrick, BN23000.

To prevent oxygen from attacking the graphite crucible, nitrogen is purged through a 24-in. diameter ring of stainless steel tubing embedded where the Greenlite and high-density firebrick join. The flow rate of nitrogen through this ring is nominally 1 to 2 standard cubic feet per minute (SCFM). An additional nitrogen gas purge of 10–20 SCFM is introduced around the top feeding electrode to reduce oxidation of the graphite.

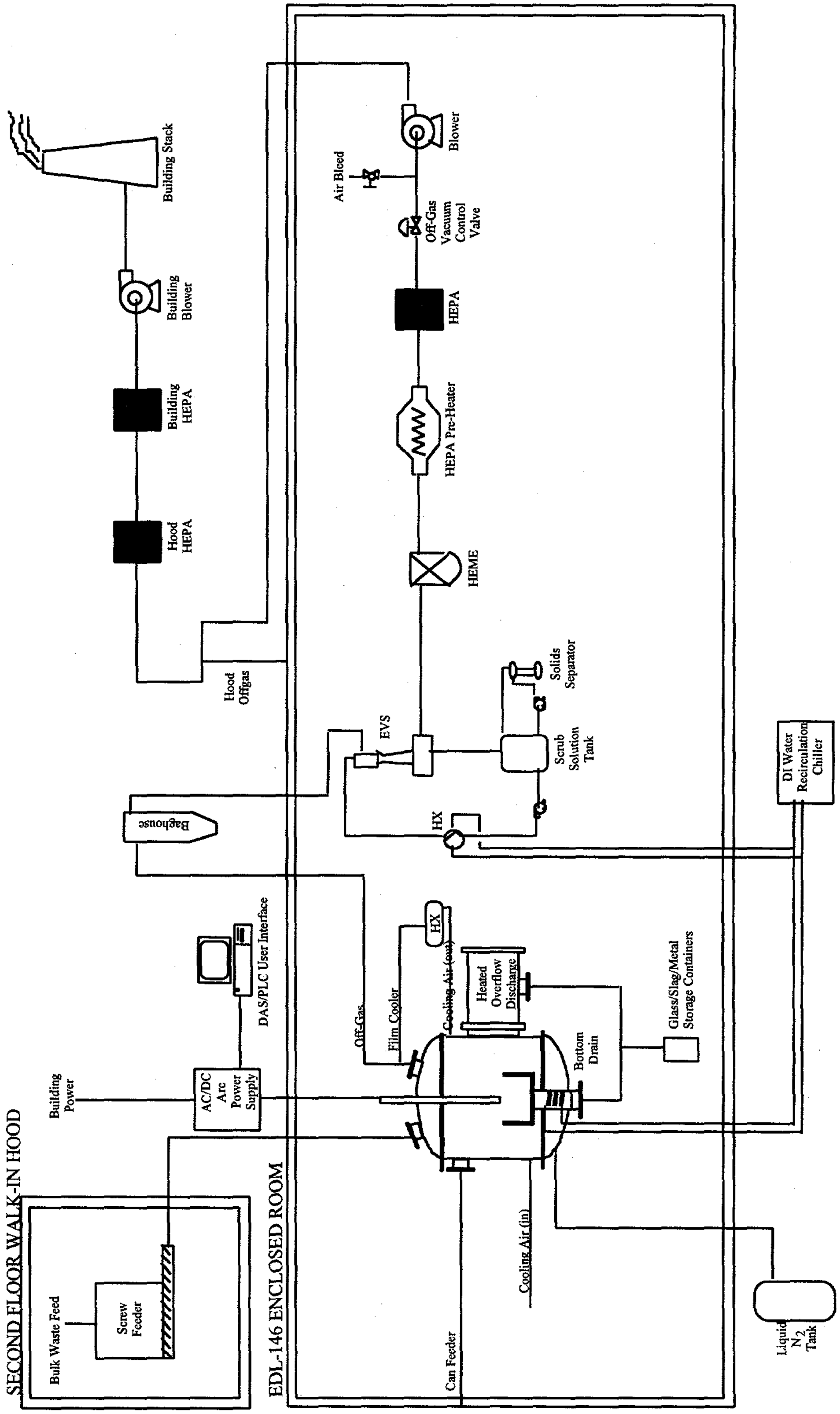

Figure 2. Engineering-scale furnace equipment layout.

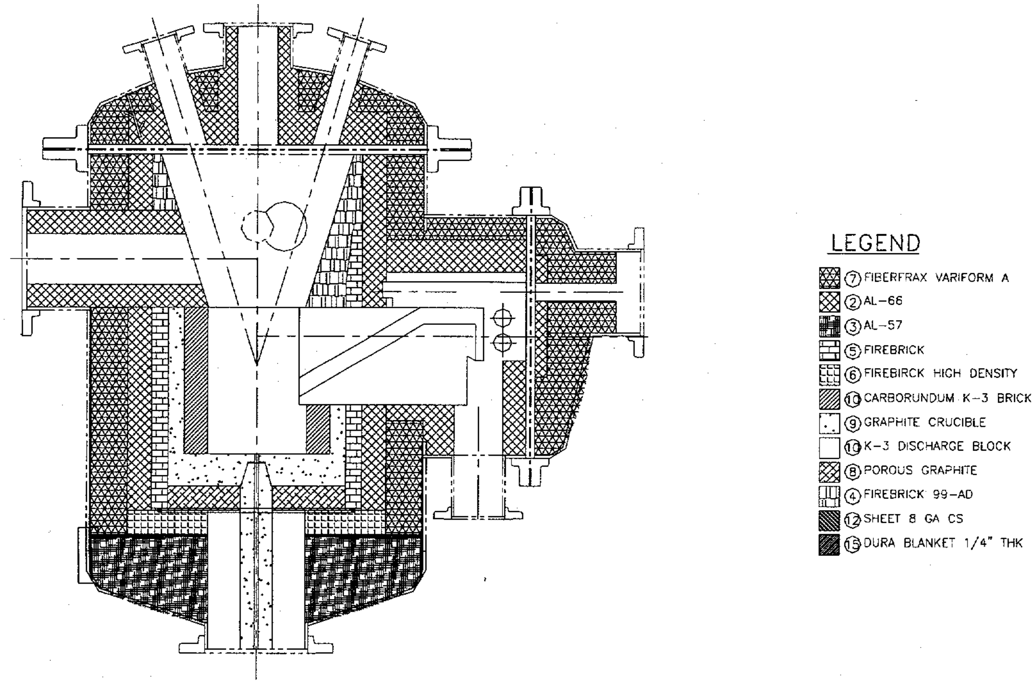

Figure 3. Furnace section showing refractory layers (side view).

The high density firebrick is supported on a layer of Alfrax-57 castable refractory which fills the domed bottom of the vessel. The outermost wall of refractory is formed by Fiberfrax Variform A cast refractory, nominally 4-5/8 in. thick. Firebrick 99-AD is used to line the plenum area of the melter above the K-3 refractory level. Outside of the firebrick are layers of cast Alfrax-66 and Variform A refractories, respectively.

The most significant change to the melter design during FY 1998 was the elimination of the graphite hearth's ceramic liner. This change was prompted by initial technical guidance that the neutron generators to be processed were primarily composed of metallic components that would require reducing process conditions with little formation of glass. Since the Monofrax K-3 refractory liner used during FY 1997 testing was shown to be unsuitable under reducing conditions and its corrosion was believed to be a contributory cause of the FY 1997 melter failure, a search for a more compatible liner refractory was made. However, a suitable substitute with a proven performance record could not be identified for the processing conditions anticipated. Because unlined graphite crucibles are routinely used in electric melters used to smelt metals, and graphite, unlike K-3, cannot dissolve into and change the viscosity characteristics of any slag that might be generated in the projected process, the design of the FY 1998 melt cavity did not include a crucible liner.

To minimize the problems of water-based corrosion of graphite melter components that had destroyed the graphite bus-bars in both FY 1997 tests, alternatives for water-containing castable refractories were sought whenever possible. Specifically a dry Duraboard insulator was substituted for castable Fiberfrax Variform A originally used to form the melter's outer-wall refractory. In addition, to further reduce the rate or probability of bus-bar corrosion, each current carrying graphite rod was equipped with a protective ceramic sleeve with its own, independent nitrogen purge.

Overflow Section

The molten slag or glass phase is withdrawn from the furnace through an overflow channel cut into a block of refractory. The overflow tube is approximately 2 inches in diameter and is cut into the block at approximately a 30 degrees upward slope, which seals the overflow section from the furnace hearth when the furnace is filled with molten glass. Glass pours from the overflow section as its level within the furnace increases above the pour spout. Additionally, a small vacuum can be pulled on the overflow section to provide better pouring control and flexibility. The side of the overflow block opposite from the furnace is centered over the discharge port so that glass that flows through and over the block falls down the middle of the 6 in. discharge nozzle into the receiving container. The receiving container is an 8-gallon drum that sits on a transfer dolly and is sealed to the overflow section with a steel bellows. Load cells are used to monitor the drum weight.

The overflow section is heated so that the glass remains molten while pouring. Temperatures as high as 1,500°C are maintained with five silicon carbide bayonet heaters; two entering from opposite sides (face heaters) and three entering through the end of the overflow section (trough heaters). These heaters protrude over the overflow block to keep the glass heated as it is poured from the furnace. The total power rating of the overflow section heaters is 16 kW.

Because of the incompatibilities of the Carborundum K-3 refractory with the anticipated need for strong reducing conditions required by a metal smelting flowsheet, the original design was modified to include a graphite overflow block. The rationale for the choice was similar to that used for eliminating the hearth liner: graphite was compatible with reducing process conditions and would not materially contribute to any slag produced. For similar reasons the FY 1998 design also specified graphite material for the transfer channel linking the melt and overflow chambers. No other substantive changes were made to the overflow design.

Furnace Cooling

The outside walls of the furnace are cooled to preclude unwanted glass migration throughout the refractories and insulation. Molten glass will flow through all of the crevices between the refractories until cooled to a temperature where the viscosity is high enough to prevent flow. The primary means of cooling these regions is a cooling jacket surrounding the furnace. Air flows through this jacket at rates as high as 50 SCFM. This cooling also helps keep the outer jacket temperature below 200°C to minimize safety hazards to the system operators. Special cooling is also provided to prevent glass from flowing around the bottom and sides of the Monfrax K-3 pour block. Two cooling coils are embedded in the Alfrax-66 refractory on each side of and underneath the pour block. The coils are designed to maintain the temperature at the surface of the pour block below the liquidus temperature of the glass. The total designed air flow to these coils is approximately 16 SCFM.

Bottom Drain

The ESF is equipped with an inductively-heated/freeze-valve bottom drain for the tapping of metals and/or slag from the bottom of the furnace. This drain consists of a 4 in. diameter x 24 in. long graphite rod, or udder, that is screwed into the bottom of the furnace hearth. Material is drained from the furnace through a 1/2 in. diameter hole in the center of the udder. A water-cooled induction coil powered by a 50 kW induction power supply surrounds the udder. The induction coil provides the energy to heat the graphite tube when under power, and also provides the cooling to stop the flow of molten material when the power is shut off. Nitrogen is purged into the bottom drain area to protect the graphite from oxidization.

SECTION 3

PERFORMANCE

Demonstration Plan

Initially, scoping studies were done in a series of bench-scale plasma arc furnace tests (48 total, five radioactive) that were especially useful for evaluating the processability of wide ranges of feeds and operating conditions before committing to large scale tests (Freeman, et al. 1995, Freeman and Seiler 1997, Whyatt, et al. 1998). Surrogate waste types used in these tests included: Rocky Flats Pondcrete; INEEL - soils, high metals wastes, organics/oils/solvents, nominal debris type waste; and an SRS 238Pu contaminated debris waste. Based on data collected during these series of tests, engineering-scale furnace test campaigns were planned for FY 1997.

Two ESF tests were conducted at PNNL during FY 1997 (Goles, et al., to be issued September 1998). A primary focus of the initial FY 1997 melter test was to investigate the effect of process operating conditions on the partitioning of hazardous metals and plutonium surrogates. The feed was spiked with heavy metals and plutonium surrogates, and the partitioning of the species to the glass and offgas was determined for several test conditions. The operating conditions varied in this testing included the degree of cold-cap coverage and the position of the electrode. The effect of particle size on entrainment was investigated by adding three different elements, which form nonvolatile, stable oxides in particle sizes ranging from <1 micron to 4 mm in diameter. The second FY 1997 test campaign was initiated several months after the first test campaign. The furnace was shut down in the interim. The objective of the second test campaign was to process a nonradioactive surrogate of SRS debris and assess its performance. This surrogate was tested in the bench-scale DC Arc Furnace, where glass forming additives and amounts were identified.

A failure of the DC Arc Furnace pouring system during the second FY 1997 melter test necessitated a major repair before waste processing tests could commence. Also, at this time the strategy for further testing was reevaluated to focus on obtaining data that would be most useful for technology deployment. Numerous bench-scale DC Arc Furnace tests had already established that offgas partitioning for transuranic waste components was dominated by scale-independent entrainment losses. Thus, it was concluded that additional engineering-scale testing of plutonium bearing soils would provide little additional information. Consequently, testing of the DC Arc Furnace was redirected to evaluate the technology's potential for converting classified hardware containing both hazardous and radioactive materials (Pantex ferroelectric neutron generators) into unclassified, durable waste forms that could be disposed of conventionally in a commercial waste repository.

Treatment Performance

The bench-scale testing is summarized in this section. More detail will be given to the ESF testing summary.

Bench-Scale Testing

Over 30 crucible melts and 48 bench-scale arc furnace tests (5 in the radioactive system and 43 in the non-radioactive system) were completed, not including the tests to support the Pantex demonstration. Highlights of these tests follow:

- Plutonium partitioning data was collected from 50% INEEL debris waste/50% INEEL soil feeds spiked with ^{238}Pu or ^{239}Pu. The behavior of ^{238}Pu was found to be identical to that of ^{239}Pu, with the majority of the plutonium partitioning to the glass phase. The partitioning values of calcium, aluminum, titanium, and plutonium were nearly identical in both the metal phase and the offgas solids, indicating that the likely partitioning mechanism was inclusion of the glass in the metal phase and feed entrainment in the offgas phase.
- Data from surrogate sludge wastes (MWFA sludge recipes) was also collected. Testing showed that glass forming additives were required at a 7:3 sludge to additive ratio to produce a pourable slag at 1400°C. A maximum waste loading of about 20% high-silica sludge (70 wt% silica) can be tolerated

using the baseline soil/lime additive. If a waste loading of 70 wt% sludge is maintained, the maximum level of silica that can be tolerated in the sludge waste is about 30 wt%. The maximum levels of calcium carbonate were not as limited; processable melts were obtained with up to 50 wt% waste loading of the high calcium sludge (60 wt% calcium carbonate). Bench-scale arc furnace tests with the 7:3 sludge-additive blend produced fully melted glasses under stable operating conditions. The high water content of the sludge (30wt%) was found to increase electrode corrosion, cause problems with feeding via the solids auger, and cause water to collect in the offgas system. These problems will need to be addressed in the design of future systems.

- A series of tests were also completed on high organic sludges. Organic contents as high as 50 wt% were fed to the arc furnace. In several tests, large portions of feed remained unmelted in the furnace at the completion of the test. Incorporation of the feed into a slag phase was improved by developing a molten pool in the furnace prior to feeding the high-organic material. This method better represents the conditions of a larger furnace during steady operation. An additional outcome from these tests was the identification of the need for some metal on the furnace hearth during operation. Later tests confirmed that the absence of iron in the feed resulted in large power fluctuations and an inability to control the arc. This behavior is believed to result from the formation of a resistive layer oat the slag/graphite interface.
- A series of tests was then performed on a SRS debris surrogate composition. Like the slags produced from the sludge surrogate, the slags produced using this material were not pourable at 1400°C without glass forming additives. Additive amounts corresponding to a 60 wt% waste loading of the debris were found to be necessary to achieve this pouring criterion. Bench-scale arc furnace testing with this baseline debris formulation showed stable processing behavior and a carryover of solids to the offgas system comparable to previous feed materials. A test performed in which large graphite pieces were added during processing of the baseline debris formulation demonstrated that large graphite pieces, which enter the furnace, will remain intact for significant intervals of time. After these tests, the organic content of the SRS debris was varied and tested the bench-scale furnace. The high–organic debris feeds were added to an existing molten slag pool of the baseline debris feed. Organic contents ranging from 25 wt% to 100 wt% were tested. All levels of organic materials appear to be processable in the bench-scale furnace when fed on top of an existing molten pool. However, it should be noted that the bench-scale furnace is a semi-batch system and cannot see effects which might arise from long periods of continuous operation. Although the feeds high in organic materials were successfully processed, several difficulties were encountered. The highest organic contents caused pressurization of the furnace plenum. These occurrences must be addressed in the design of any future system. The elevated levels of organic materials were found to have a significant impact on the slag, causing the formation of crystals, which increased the melt viscosity and electrical resistivity. Changes in the baseline debris formation were made to alleviate this problem and feed with up to 50 wt% organic material was successfully processed.

ESF FY 1997 Campaign 1

The first test campaign was successfully completed using a soil/lime feed material. This was the first extended operation of the furnace, and served as a final check of the system and the sampling and analytical procedures to be used in subsequent testing on surrogate debris wastes. Approximately 320 kg of feed material was processed over an 86-hour period, producing 275 kg of vitrified product. The feed rate over the duration of the test was about 5 kg/h, and was as high as 10 kg/h during the actual test segments of the run.

System Performance

The system performed as designed, with a few minor problems encountered. The failure of an overflow heater required feeding to be stopped, but the furnace was maintained in an idling condition while the repair was made. Additionally, the can feeder ram failed due to the overheating of rubber seals, resulting in the postponement of the can feeding test segment. The existing ram was replaced with a different model, having higher temperature seals. This new design was evaluated during FY 1998 testing.

Posttest inspection of the hearth busing revealed significant attack on the graphite in that area. The attack was the result of residual water vaporizing from the castable refractories and reacting with the hot graphite as it was drawn into the melter plenum. The corroded regions were repaired and design changes were implemented in FY 1998 that successfully controlled this corrosion-based problem.

The vacuum assisted overflow drain performed well throughout the test, once the repair to the heaters was made. Some wandering of the pour stream occurred, which eventually resulted in a glass plug that had to be broken out of the overflow section outlet. Modification of the pouring procedure and better sealing of the overflow container to the overflow section minimized this problem.

The electrode feeder provided excellent control of the arc, especially during the exposed arc segments when the position of the electrode was critical to maintaining the arc. In several instances when the arc was extinguished, it was readily restarted by simply lowering the electrode into the melt pool and raising the electrode again above the melt surface. Electrode consumption rates were low, as only one additional segment of electrode was required during the weeklong test.

Partitioning

Volatilization and carryover of radionuclides (particularly alpha emitters) and toxic metals is a primary concern with high-temperature systems, because losses from the melt represent potential inventory control, secondary waste, maintenance exposure and permitting issues. To investigate the effect of process operating conditions on the partitioning of hazardous metals and plutonium surrogates, the feed was spiked with heavy metals and plutonium surrogates, and the partitioning of the species to the glass and offgas was determined for several test conditions. The operating conditions included the degree of cold-cap coverage (unmelted, cool material floating on the surface of the melt) and the position of the electrode (submerged in the glass as in a joule-heated melter, or above the surface producing an exposed arc similar to the Plasma Hearth Project design, Reference Plasma Hearth Project ITSR, 1998).

These operating conditions were found to have significant impact on the partitioning of the metals to the offgas. Both overall bulk solids and individual elemental partitioning followed similar trends. A decrease in the cold-cap coverage increased the carryover of solids into the offgas during submerged arc operation. When the arc was exposed, solids carryover was high regardless of the cold-cap coverage. Minimum solids carryover was obtained with a high cold-cap coverage and submerged arc operation.

Volatilization of hazardous, semivolatile metals to the offgas was found to be significant, especially for cadmium and lead. Partitioning followed the same trends as described above for bulk solids; however, low total recovery in the mass balance for these elements weakens these conclusions. Nevertheless, submerged-arc / high-cold-cap operating conditions were found to be important factors in reducing overall process losses of semivolatiles.

The effect of particle size on partitioning was investigated by adding three different elements, which form nonvolatile, stable oxides in particle sizes ranging from <1 micron to 4 mm in diameter ($ZrSiO_4$, <1 µm; Nd_2O_3, <44 µm; and $Y(OH)_3$, <4mm). A measurable partitioning increase relative to bulk entrainment was found for these additives, as well as the lime flux. However, the maximum partitioning to the offgas observed for any of these additives was 4 wt%, or about two times the bulk entrainment value. These data indicate that the offgas partitioning of even submicron particulate remains near the bulk entrainment value in this system, when operating at the conditions of this test. This is an important conclusion for very finely divided materials such as the submicron Pu^{238} contaminated materials at the Savannah River and Los Alamos Sites. It appears that volatization of plutonium is not a significant contributor to partitioning, and a full-scale system should be designed to minimize physical entrainment.

The glass product obtained from this campaign was visually uniform and homogeneous. The vitrified product achieved a 52% reduction in volume compared to the initial soil material. Samples of the vitrified product were subjected to the toxicity characteristic leach procedure (TCLP), and leachate concentrations were well below the regulatory limits for all hazardous metals in the samples. The overall leach rate, determined from the concentration of all elements in the TCLP leachate, shows the leaching of the glass to be very slight, comparable to that of natural basalt, a material of similar composition. No apparent impact of the test operating conditions on the leachability of the glass product was noted. TCLP leachate concentrations from the baghouse solids were found to exceed regulatory standards for lead and chromium, as expected.

ESF FY 1997 Campaign 2

The second FY 1997 test campaign was dedicated to produce data specific to partitioning concerns on the Pu^{238} job-control wastes at the SRS. A nonradioactive surrogate of the SRS debris was used to assess performance. This surrogate was tested in the bench-scale DC Arc Furnace, where glass forming additives and amounts were identified.

System Performance

Operational evidence during the ESF restart indicated that current had fired through a crack or *fissure in* the Monofrax K-3 sidewall instead of the exposed graphite on the bottom of the furnace. Approximately 110 pounds of soil-lime feed, the same material used in the first campaign, was fed to the furnace until glass pouring was reestablished through the overflow. Next, SRS debris surrogate was fed to the furnace. After 120 pounds of this material had been feed to the furnace, with batch pours of glass every half-hour, pouring ceased from the furnace overflow. All attempts to resume pouring from the overflow were unsuccessful, so the system was shut down. Inspection of the furnace during and after the test and analysis of the glass provided indication that the Monofrax K-3 glass contact refractory corroded at higher-than-expected rates, primarily due the furnace restart and the high organic content of the SRS debris surrogate. Visual inspections revealed that part of one Monofrax K-3 side wall (approximately 3 in. by 4 in.) was entirely missing. The corrosion products appear to have increased the alumina and chromia levels in the slag during operation resulting in a viscous, unpourable material. Another possibility is that a piece of the refractory dislodged from the sidewall and physically obstructed the overflow channel. The actual cause or causes of the pour stream failure could not be conclusively established by the existing analytical data.

ESF FY1998 Campaign

The failure of the DC Arc Furnace during the second FY 1997 melter test necessitated a major repair before waste processing tests could commence. During this operational stand-down, Battelle Northwest researchers and MWFA personnel concluded that the data from the bench-scale system and the limited data from the ESF proved fairly conclusively that volatility of plutonium was not a major concern, and that partitioning from the melt was dominated by physical carryover. Consequently, the DC Arc Melter Project testing was redirected to evaluate the technology's capability of converting classified hardware containing both hazardous and radioactive materials (Pantex ferroelectric neutron generators) into unclassified, durable waste forms that could be disposed of conventionally in a commercial waste repository.

Since the repair of the DC arc melter required replacement of most furnace internals, several design changes were made to avoid or minimize operational difficulties encountered during previous FY 1997 testing. These changes included the procurement of a commercial bottom drain induction heating system, eliminating the refractory hearth liner, using a graphite overflow block, minimizing the use of water-bearing castable refractories, and protecting the melter's graphite bus bars with ceramic sheaths.

During the FY 1998 ESF repair, bench-scale furnace scoping tests were carried out to define the chemical additives required to produce a well-behaved baseline waste composition when combined with the neutron generator feed stream. Although the Pantex neutron generators previously described could be melted and/or sintered alone, this material would not be readily removable from the furnace. In order to create a melt that could be easily transferred from the furnace, the feed stream had to be blended with chemical additives designed to reduce the viscosity of the melted material. On the basis of these melter scoping tests, a CaO-Al_2O_3-SiO_2 waste product with ~20% waste loading was chosen that satisfied the requirements for both low viscosity characteristics (<100 poise at 1,300 °C) and high dissolution kinetics for high density alumina.

The FY 1998 ESF test demonstrating the demilitarization of Pantex neutron generators commenced at the conclusion of melter repairs and the subsequent refractory bakeout campaign. After the furnace's arc was struck and a 400°C plenum operating temperature was achieved, glass forming chemicals were fed to the melter (using the ESF's large object feeder) in order to prepare a molten bath into which the neutron generators and their components would be melted and/or dissolved. After 300 lb of target glass was produced, processing of the neutron generators commenced. Radioactive processing continued until all 200 neutron generators were successfully demilitarized by the plasma arc furnace.

System Performance

Several operational problems were encountered during the test that slowed the overall progress of the demonstration. The reliability of the melter's large object, or can feeder, was a major source of operational delays. A significant improvement in processing efficiency was achieved when the automatic can feeder was abandoned in favor of a manual, gravity-fed backup system. The inability to develop a pressure differential between the main melt chamber and the melter's overflow section eliminated the ability to batch-transfer glass from the melter. Consequently, the melter was operated in a continuous overflow mode, which created glass collection problems in the melter's overflow section, and glass receipt canisters. In addition, inadequate temperatures existing below the melter's hearth precluded bottom drain tapping of the ESF's melt chamber.

In spite of these operational difficulties, the processing of neutron generators continued in a more or less continuous manner. During a 21-hour period, 150 neutron generators were successfully processed. At the maximum feeding conditions achieved during this period, a neutron generator was being processed every 6 minutes. This corresponds to a maximum hourly feed rate (generator + glass-formers) of 36 lb/h. The average feeding rate over the 21-hour period when 75% of the neutron generators were processed was 27 lb/h. Note that the project plan for the demonstration was based on only a 25 lb/h processing rate.

Partitioning

The fate and behavior of the elemental constituents of neutron generators were of particular interest during this demonstration. Based on the unclassified bounding value, approximately 85% of the available tritium present in neutron generators was released to the environment through the process stack. The unreleased tritium was primarily collected as tritiated water in the process quench scrubber, which accounted for 15% of the cumulative bounding value. Particulate matter collected by the bag house filter (0.3% of the bounded total) and the melters glass product (0.2% of the bounded total) accounted for the remaining unreleased tritium.

Lead, the major hazardous constituent present in neutron generators, partitioned primarily to the offgas system. Approximately 75% of the available Pb was accounted for in the offgas system's bag house solids. The semivolatile Zn, which was an unidentified neutron generator constituent, was also a dominant component of these solids. Since the lead content of the process glass was quite low (500 ppm), this waste form easily passed TCLP testing. Process operating conditions, driven by glass pour rate concerns, were most likely responsible for the high partitioning of semivolatile feed constituents to the offgas system during the Pantex processing campaign. Previous FY 1997 ESF testing has shown that Pb partitioning to the glass can be strongly enhanced by operating with high cold-cap coverage and a submerged electrode.

Conclusions

The suitability of applying the DC plasma arc technology for the treatment of a wide range of materials containing hazardous and radioactive constituents, including soil-based waste and military hardware, has been successfully demonstrated using both engineering- and bench-scale furnaces. Moreover, the high-temperature capabilities of this plasma arc technology has been shown to be more than sufficient to satisfy demilitarization requirements. Although only first-generation, developmental equipment was used in the present tests, all major technology-based objectives were, nevertheless, successfully demonstrated. Current improvements in plasma-arc technology-design have eliminated important operational problems such as the need for cold-restart.

Key System Parameters

Waste Acceptance Criteria for a DC arc type treatment process will include physical, chemical, and radiological constraints based on regulatory and process capability considerations. However, the DC arc concept has the potential to minimize physical constraints on waste feeds. Essentially any waste matrix containing enough conductive material to maintain the DC current path will be potentially treatable. Physical limitations are related primarily to industrial safety problems, such as volatile liquid or steam pressure excursions. Chemical and radiological constraints are primarily related to regulatory emissions requirements and operations personnel exposures, respectively, though some limiting process considerations are described below. Waste characterization for hazardous constituents, and elements known to affect melt operations (i.e. viscosity, partitioning) will be required to ensure safe, reliable operation within permit requirements.

Limitations/Potential Problems

High-temperature melter systems and their potential application to mixed wastes were conceived based on the theory that with enough energy input all wastes would melt, making possible significant volume reduction. It was also considered feasible that since virtually all materials could be melted, feed characterization requirements could be minimized, thereby reducing overall costs. Enough is known about these systems now, however, to begin to limit these potential advantages. Given a large, homogeneous, noncombustible waste stream, containing limited volatile constituents, vitrification may be possible with only cursory additional characterization, yielding excellent volume reduction. However, for heterogeneous streams with variable conductivity, containing different levels of glass formers, combustibles, and volatile matter; characterization, feed additives, and feed blending will be required.

The DC arc system is now ready for specific applications with well-characterized waste streams, and with additional operating experience, feed additives and blending techniques will broaden applicability. Some of the limitations on waste feeds to be considered for all vitrification systems are:

- Melt resistance must be controlled within design limitations to ensure sufficient power for waste processing.
- The molten glass must be pourable to decant it from the melter. Fluxing materials and glass formers loadings, used to control melt viscosity, must be balanced with desired waste loading in the final product.
- The basic (versus acidic) nature of the melt will affect the durability of the glass-contact refractory, and must therefore be controlled within design limits to yield predictable refractory life.
- Salts do not contribute to the formation of glass, nor do they readily dissolve into the matrix. Thus their content must be limited to maintain the durability of the overall matrix.
- Thermal destruction of organic matter is limited by surface area and contact with oxidants. A secondary combustor may be necessary to meet air emission standards.
- Volatile radionuclides and metals may be significantly vaporized from a molten pool, particularly from very high-temperature processes.

Blending wastes to control these parameters could be advantageous to minimize the use of additives that increase waste volume, however chemical characterization of the waste will be required.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

This section addresses in more detail the types of mixed waste streams that the Graphite Electrode DC Arc Furnace technology is most amenable to. The section also compares the DC Arc technology to other competing thermal treatment technologies and defines its development status, commercial availability, and maturity.

Competing Technologies

The DC arc process is an adaptation of commercial smelting technology. It could potentially compete with any process designed for organic destruction, volume reduction, and final waste stabilization. The most obvious comparable technologies are incineration and direct-fired melters, joule heated melters, and plasma-based melters. All of these technologies have been investigated to some degree by the MWFA and are summarized below.

INCINERATION AND DIRECT FIRED MELTERS

Traditional incinerators operate based on residence time in a well-mixed oxidizing environment. Environmental regulations for incinerator operation are very prescriptive, and with the promulgation of the Maximum Achievable Control Technology (MACT) rule, emission limits for hazardous waste incinerators will drastically limit the operation of many current units. Efficient destruction of organic contaminants relies on raising the material to near the flame temperature, and maintaining these conditions for about two seconds. This is accomplished by a design residence time in a secondary combustion chamber (SCC), based on typical and surge flows leaving the primary combustion chamber where waste is fed. However, incineration processes are continually challenged by short-circuiting through the SCC, pulses of gas caused by rapid release of volatile material, and refractory compounds, all of which contribute to less than desirable destruction removal efficiency (DRE). In addition, organic fragments may recombine in the offgas system, and in the presence of chlorine, form dioxins and furans, emissions of which are tightly controlled. Wastes containing metals such as mercury, cadmium and lead also challenge the APCS.

While all of the emission limits can be met by state-of-the-art APCS design and good engineering practice, many wastes (high mercury, lead, cadmium, or polychlorinated byphenyls [PCBs]) will be limited in feed rate, and may require alternative methods or blending for treatment. Incinerators also produce hearth and fly-ash that must be stabilized to pass TCLP limits. Slagging units operate at high enough temperatures to cause the hearth ash to fuse, but some fly-ash will still require treatment. Rotary kilns are probably the best known design for this purpose, suitable for processing essentially all physical forms and waste matrices, though leakage around kiln seals has proven to be a challenging weakness for radiological applications. On the other end of the range of waste form acceptance are cyclonic combustors, that have been demonstrated to yield very high DRE and durable glassy fused products, but waste feeds must be in the form of finely divided particulate, which limits potential feeds or makes pretreatment very expensive. Fixed and moving hearth designs, and fluidized beds are intermediate in this range of design, and may provide the best performance for radiological applications.

Problematic to any incinerator deployment is the current negative social sentiment towards the technology.

JOULE –HEATED MELTERS

Another adaptation from commercial technology, this time from the glass-making industry, is the family of melter designs based on joule-heating, or resistive heating produced by electrical current passing between opposed submerged electrodes. This heating method is the same as the DC arc concept when operated with the electrode submerged in the melt. The designs differ in that the DC arc unit can be operated with the electrode above the melt striking an exposed arc to produce initial melting from a cold start. A joule-heated melter must be supplemented with a conventional heat source such as a propane torch or radiant heaters for initiating the melt.

A joule-heated melter is limited by all of the constraints listed in Section 3 for the DC arc unit, but is additionally constrained by lower operating temperatures, due to the operating limits of the submerged electrodes. Many metallic electrodes are limited to less than 1150°C.

Joule-heated melters are in use at West Valley, NY and the SRS for immobilization of high-level waste, and have been deployed with varying degrees of success for treatment of wastewater treatment sludges containing RCRA contaminants at the SRS, Fernald, and Oak Ridge Sites. There is also one commercial operation currently in practice for combustible materials, but the glass is not required to meet any particular durability requirements. Treatment of heterogeneous debris is not regarded as feasible because the temperatures are too low, and the waste acceptance criteria would be impractical.

PLASMA-BASED MELTERS

Plasma-based units are similar to the DC-arc in most ways regarding waste acceptance criteria and feed applicability, differing primarily in how heat is generated. The plasma units require creating an electrical arc in a gas stream to ionize the gas producing a plasma. The plasma can then be physically distorted by the force of the gas flow to transfer heat to the waste. Once generated, the plasma can be used in a transferred, or nontransferred mode depending on whether the waste acts as one electrode (transferred), or both electrodes are external to the melt (nontransferred). A plasma unit has an inherent advantage in that totally nonconductive materials can be melted in the nontransferred mode. This is particularly useful during startup. Conversely, the DC arc technology has a significant advantage in operating in the completely submerged mode with a cold cap, which has proven to minimize physical entrainment and volatility. This mode of operation also minimizes plenum temperatures, which should reduce heat loss and wear on refractory materials. Both stationary and rotary hearth designs have been tested in plasma based systems. None are known to be operational at this time with radioactive wastes, though a DC arc unit is currently in the permitting process for treatment of mixed wastes at Hanford.

Technology Applicability

The MWFA funded the development and demonstration of high-temperature melter technologies in an effort to minimize waste characterization requirements for hazardous and radioactive waste treatment. The DC arc concept was one of two technologies selected by the MWFA (out of a field of approximately 13 technologies) as potentially applicable to treatment of heterogeneous debris mixed wastes (including transuranic). The selection process reviewed available technologies against their potential abilities to address the highest risk problems and largest volumes of wastes, and their stage of development. A technical peer review was held in FY-96 to aid the DOE in making this decision. Unique to this review was the fact that both an internal users and stakeholders panel, and an external experts panel were used to evaluate the technology presentations.

The MWFA then worked with potential end-users in deriving the test requirements and objectives. The original target wastes for the DC arc process were the stored mixed wastes at the INEEL's Radioactive Waste Storage Complex. These stored wastes include aqueous and organic sludges, dirt and construction debris, and other miscellaneous materials. The wastes have been accumulated since 1970, coming predominantly from weapons-production operations at the DOE's Rocky Flats Plant. Comparable materials exist throughout the DOE complex, as well as their nonradioactive counterparts throughout industry. The DC arc melter concept could be applicable to any waste treated by incineration, joule-heated melters, or plasma units, particularly heterogeneous debris. Limitations due to waste chemistry or emission requirements are provided above.

Technology Status and Maturity

The DC arc concept has been successfully demonstrated at the engineering-scale on radioactive feeds, and the base technology is an adaptation from commercial practice, so further development of the concept is not believed necessary. What is now needed is additional operating experience to better define the operating envelope for reliable operation in a radioactive environment where maintenance is extremely expensive and made complex by radiation fields.

Patents/Commercialization/Sponsor

Electro-Pyrolysis, Inc. in Wayne, PA holds the patents and markets the original DC arc technology used in this program. The patent number is 5673285 and is titled "Concentric electrode DC arc systems and their use in processing waste materials". The patent was filed June 27, 1994 and was issued September 30, 1997. This technology is available to treat a wide variety of waste materials.

The knowledge gained from the DC Arc program has been applied and the design improved upon to develop a second-generation plasma-assisted joule-heated melter technology commercialized by Integrated Environmental Technologies. Two units have been sold to Allied Technology Group, Inc. for use in the Richland Environmental Technology Center in Richland, WA. One unit will be used to augment existing technology for producing a glass waste form from combustible low level waste, and the other is for a planned mixed waste treatment facility. The company is also marketing the technology for nonradiological applications.

SECTION 5

COST

Methodology

The cost estimates summarized in this section are at the planning estimate level, and are based on information received from, and discussions with, the Principal Investigator. The cost and contingency application methods used in this section follow the Good Practice Guide on Life Cycle Cost and multiple Cost Estimating Guides.

The referenced discussion identified these assumptions:

- New facility will be constructed to house the DC Arc melter and associated equipment
- New DC Arc melter and associated equipment will be purchased
- Facility throughput will be 10 tons per day
- Facility life will be 15 years.

These other assumptions were included in this estimate:

- Drum equivalent is estimated at 300 pounds per drum
- It will take one year to design and permit the facility
- It will take one to two years to construct and startup the facility
- Facility will treat 17,000 cubic meters of waste over five years
- It will take one year to decommission the facility.

The referenced discussion then addressed collecting detailed cost data on:

- Cost to purchase furnace system, off gas system, and secondary combustion chamber
- Cost to design facility
- Cost to prepare site
- Cost to construct and outfit facility
- Cost to permit facility
- Cost to operate facility (labor cost, utilities cost)
- Cost to maintain facility (equipment replacement cost, consumables cost)
- Cost to dispose of secondary waste
- Cost to dispose of primary waste product.

Some of the cost data were based on the testing during the development and demonstration phases; other cost data were based on past melter installations.

Cost Analysis

Capital costs have been estimated at $50 to $86 million for the production facility construction and outfitting. Operations budget funded activities are estimated at $12 to $18 million through the startup period. Operations and maintenance costs are estimated at $48 to $62 million for a five-year operating period. Decontamination and decommissioning costs are estimated at $4 to $8 million for a one-year decommissioning period. Product disposal costs are estimated at $10 million. The total life cycle costs are estimated at $124 to $184 million.

Conclusions

End-users should examine the assumptions used in this analysis before applying the cost estimates as their site-specific solution. Using a DC Arc Melter to treat about 17,000 cubic meters, the treatment and disposal costs are projected at $7400 to $10,800 per cubic meter.

SECTION 6

REGULATORY AND POLICY ISSUES

This section presents current and anticipated regulatory requirements that an end user of a high-temperature melter technology would have to meet before mixed waste treatment and during any development phases. The specific regulatory requirements and their associated issues that pertained to the DC Arc Furnace development effort are also described.

This section also presents an analysis performed by the MWFA that assesses the various risks involved with deployment of the DC Arc Furnace and pertinent stakeholder responses to the siting of a mixed waste thermal treatment facility in a given community.

Regulatory Considerations

The objective of using the DC Arc Furnace was to treat mixed waste to produce a waste form that could meet applicable Land Disposal Restriction (LDR) treatment standards for organics and metals. Small amounts of metals/radionuclides are expected to volatilize to the offgas or be entrained in the offgas during processing of wastes. A highly efficient, state-of-the-art air pollution control system (APCS) is required to remove particulate, acid gases, and any volatilized toxic metals or radionuclides. The APCS used in the engineering-scale tests, included an evaporative cooler, a baghouse, high efficiency particulate air (HEPA) filters, and a full quench/packed bed scrubber. Feed control was also to be used to assist in controlling potential emissions. Additional controls for mercury emissions may be needed, depending on the mercury content of the feed.

Major regulatory requirements, including permit/license requirements, for implementation of this technology to treat RCRA LDR mixed wastes and possibly PCB mixed wastes, are expected to include:

- National Environmental Policy Act (NEPA) review for implementation at federal facilities (categorical exclusion is likely to apply for treatability studies). At DOE facilities, this includes an initial environmental checklist that is used to assist in determining if a more detailed environmental assessment or environmental impact statement is required.
- A radioactive material license for NRC or its applicable agreement state for non-DOE facilities.
- RCRA notifications or applications submitted to the regulatory agency based on the scale and purpose of the process and the capability of the process to achieve the required treatment of LDR wastes and meet applicable (state or EPA) requirements for treatability studies:
  - Notification to applicable regulatory agency (state of EPA) for treatability studies.
  - Variance or Determination of Equivalent Treatment to allow disposal of treated wastes and residues if, for example, the waste is subject to a specific technology based LDR treatment standard (such as INCIN).
  - Waste Analysis and Treatment plans for wastes treated by generator under 40 CFR 262.34 or under 40 CFR 264 or 265 for wastes to be treated at permitted facilities.
  - Submittal of a permit application or modification to applicable regulatory agency (state or EPA) for review and approval of treatments that are not treatability studies. Currently, risk assessment for emissions and effluents is required for this.
- Clean Air Act Permitting
  - NESHAPs (National Environmental Standards for Hazardous Air Pollutants) applicability review to determine need for NESHAPS permitting or air/emissions monitoring for any operation that involves potential releases of particulates, gases, or vapors that may contain radionuclides or other regulated hazardous air pollutants. Forthcoming (ca. early 1999) MACT based NESHAPs (including standards for dioxin, mercury, particulate matter, CO, hydrocarbons, and HCl) and associated requirements for continuous emissions monitoring may be applied by state regulatory agencies to thermal mixed waste treatment technologies via the RCRA permitting "omnibus" provision.
  - National Ambient Air Quality Standards (NAAQS) and New Source Performance Standards (NSPS) applicability evaluation and PSD review to determine need for Permit to Construct application or air permit modification as applicable.
  - Liquid effluent/wastewater (such as scrubber blowdown) treatment needed to meet NPDES, POTW, or other applicable wastewater disposal requirements.

- Treatment and disposal requirements for other secondary waste streams, e.g.,
  - Spent pre-HEPA and HEPA filters from offgas system
  - Spent baghouse filters
  - Spent refractory
  - Excess fly ash
  - Dry PBS blowdown salts
  - Miscellaneous maintenance, repair, and operations wastes.
- TSCA (Toxic Substance Control Act) permit if subject PCB wastes are to be treated and variance for alternative treatment of any PCB wastes that require incineration.
- State- or locality-specific requirements, e.g., siting, zoning, historic preservation, and other laws and regulations, that may require additional permits and licenses.

Treatment of hazardous waste or mixed waste must meet the applicable RCRA 40 CFR 268.40 LDR treatment standards for wastewaters or nonwastewaters, including treatment of underlying hazardous constituents to universal treatment standards, as applicable. NRC waste form testing requirements may also need to be met for disposal in NRC licensed sites. Individual commercial and DOE disposal sites may have site-specific requirements, including specific radionuclide limitations that may affect qualification of the final waste form.

The regulatory activities conducted for the experimental DC Arc systems include:

- Application for and receipt of an approved Notice of Construction (NOC), approved by the Washington State Department's of Ecology and Health (WDOE and WDOH) on 5/20/98 and 4/18/96, respectively, letter references NWP-96-1, AIR-96-403, respectively for the engineering scale DC Arc system's air emissions. The NOC covered all state approvals required for hazardous air pollutant and PSD criteria pollutant emissions. An application to modify the NOC to include the release of up to 20 Ci of tritium was verbally submitted to the WDOH on 6/19/97, and approval was subsequently granted without the need for NOC revision. Bench-scale studies were performed under the corresponding existing state approval of R&D emissions after an internal air permitting review was performed.
- Estimated (modeled) radionuclide emissions were reviewed versus the radionuclide emissions allowed under the existing approved NESHAPs documentation. The original NESHAPs documentation was approved by EPA on 4/3/96, Reference 96-PCA-149. ESF radioactive processing was limited to the FY98 neutron generator processing campaign. Since total tritium inventory release was anticipated and permitted by WDOH, no emission measurements were necessary.
- An environmental checklist for the radioactive bench scale treatability study was submitted. It was determined that the project met the requirements of a categorical exclusion under NEPA Regulation, 10 CFR Part 1021.400, Subpart D, Section B3.10.
- A TSCA permit application was drafted for full operation of the ESF, but not submitted when a decision was made to exclude PCB wastes for the DC Arc system feed. The Battelle DC Arc bench-scale system received a TSCA demonstration permit in 1995 to test treatment of waste generated from ship decontamination.

Regulatory Issues

This demonstration stage project experienced no unusual regulatory issues that would be expected to affect construction and use of a DC Arc system at this or another facility. Although the relatively high temperatures and nature of the process can be expected to volatilize and entrain into the offgas, a small portion of the chemical species present in the waste feed, low DC Arc offgas flow rated combined with a state-of-the-art offgas control system could be expected to minimize issues associated with emissions to air. Bench-scale tests demonstrated that transuranics (Pu, Am, Np) offgas partitioning was limited to physical entrainment losses which is the minimum design basis. There is still a potential, however, that associated air emissions control issues could vary significantly depending of the states and individual regulators involved in approval of a DC Arc process. For example, the engineering-scale facility demonstration included destruction of classified, mixed waste containing tritium. During this part of the project, tritium releases, although within allowable limits, were the subject of regulatory concern and adverse publicity when a tritium monitor was turned off for security reasons.

The ability of the final DC Arc waste form to meet all applicable LDR Treatment Standards in 40 CFR 260.40, including applicable Universal Treatment Standards (40 CFR 260.40) for Underlying Hazardous

Constituents, and any replacement treatment standards assigned via a Determination of Equivalent Treatment or Variance, would need to be verified for specific DC Arc installations and feeds.

Safety, Risks, Benefits, and Community Reaction

Eight risk areas were evaluated and assessed independently. These risk values for MWFA developed technologies have been derived from the eight top-level requirements defined in the MWFA Systems Requirements Document (INEL 1997). The eight areas evaluated for level of risk are: (1) ease of permitting, (2) technical correctness, (3) level of safe operability, (4) technical completeness (i.e., ready to use), (5) timely to meet treatment schedules, (6) acceptability to stakeholders, (7) cost-effectiveness to use, and (8) committed sponsorship. A complete description of the methodology and a detailed definition of each risk element, the event scenario, and the basis for assigning consequences and probability factors are included in Appendix C.

Permittable: The risk category is rated as high and unlikely that a permit application will be rejected. The process is highly complex and it is anticipated that the permit process will be lengthy. However, the developers have maintained interaction with state regulators throughout the development process and have obtained feedback on permitting such a process. In addition, an improved DC Arc Furnace will be part of a process to treat Hanford mixed wastes (through a privatization effort). Permitting issues associated with a DC Arc Furnace will surface within the next year.

Complete: The risk category is rated as high and likely that additional engineering is required to allow the instrument to be incorporated into a system to treat heterogeneous wastes.

Acceptable: The risk category for acceptable is rated as medium and unlikely that a Native American Tribe or public interest group would resist the implementation of the DC Arc technology at a DOE site. An improved DC Arc Furnace will be part of a process to treat Hanford mixed wastes (through a privatization effort) and stakeholder acceptability of the process can be better quantified in the next year.

Timely: This category is listed as not applicable since there is currently no end user identified within DOE Environmental Management (EM).

Cost: The risk category is rated as high and likely that the operational costs will be higher than expected. The cost analysis is based on the characterization of a large volume of waste. Even a minor difference in cost could affect a site if large quantities of waste were targeted.

Sponsored: This category is listed as medium and unlikely that no end user or commercial entity selects the technology for implementation. The DC Arc Furnace technology will be the basis for a mixed waste treatment effort at Hanford. This contractor is working closely with the State of Washington in obtaining the appropriate permits.

Correct: This category is listed as high and unlikely that the technology will not be applicable to the target waste. Multiple waste type surrogates were used in experimental testing, but a real waste demonstration was only completed on one waste type.

Safe: This category is listed as low and likely that system failure will adversely impact the health and/or safety of a collocated worker, the environment, or a member of the public. Hazardous materials will not be added to facilitate the treatment process. There is, however, a potential to generate dioxins and furans due to the presence of organics in the feed. Dioxins and furans released to the environment will be controlled through the use of a secondary combustion chamber. Since this is a highly complex and energetic system (operating temperatures are estimated at 1,149 – 1,538°C), the likelihood of a system failure was high.

The MWFA Tribal and Public Involvement Resource Team reviewed stakeholder issues and concerns related to the treatment of mixed wastes. The issues of concern to the public are listed below:

Worker Safety Issues

- The DC arc plasma furnace exhibits hazards typical of high temperature thermal processes.
- This process requires the use of high voltage and has emits an offgas stream.

- Large gas volumes could conceivably contain a significant quantity of contaminants. However, the volume of offgas, during treatment in this process, is lower than incinerators.
- This technology will be set up with engineered barriers to prevent worker exposure to high temperatures.
- A potential for leakage, associated with any high-temperature process, exists.
- Proper design and the use of established procedures should mitigate these risks.

Community Perceptions

It is expected that the stakeholder community will perceive this technology as solving an important problem, but that it would have a negative impact on their quality of life for those residents near the operating facility. Stakeholders may be concerned about the type, toxicity, and amount of emissions to be discharged to the atmosphere and the final disposition site for slag and metal waste forms. This technology has a wide range of applications and may reduce front-end handling. In addition, this technology is favorable because it creates a low volume waste form that is durable and can meet RCRA regulations. General concerns from the stakeholder community will focus on the following:

- high temperature of the system,
- high complexity of the system,
- potential for accidents – explosion, cooling system failure, and process abnormalities;
- potential to impact worker safety due to operating conditions,
- air emissions – no "real time" monitoring devices, release of volatile contaminants, incomplete combustion, dioxin/furan formation;
- ability to remediate all contaminants encountered.

The MWFA Technical Requirements Working Group, a stakeholder group formed to assist the MWFA, reviewed and provided recommendations on changes to the Radionuclide Partitioning Technology Development Requirements Document (MWFA 1997). This document establishes the end-user performance for a technology. Their comments were reviewed and incorporated into the document.

SECTION 7

LESSONS LEARNED

Implementation Considerations

The DC arc technology was developed for rendering debris waste into a glassy slag for disposal. However, other technologies including both those directly competing such as the Plasma Hearth Process (PHP) and other high-temperature plasma and joule-heated melters, as well as low temperature technologies such as macroencapsulation using grouts, plastics, or specially designed containers may also meet the regulatory requirements for disposal. Though the low-temperature processes do not have the potential to incinerate combustibles and melt the noncombustibles into a high-density slag, engineering analysis has shown that this may not be the cost-effective path for some waste types (Schwinkendorf and Cooley, 1998). Shipping regulations and costs, and facility availability may be significant factors in selecting technology.

Other factors that should be considered by the end user when choosing a technology include: long-term storage and disposal costs, capital and operating costs of a treatment system, required additional development costs, ease of permitting, extent of volume reduction, ease of operation, availability of equipment, and stakeholder acceptability.

Design Issues

The engineering-scale unit demonstrated at PNNL proved the concept for potential application to some DOE mixed waste debris, and some unique wastes such as neutron generators requiring destruction to remove a security classification. However, as is typical for prototype testing, some design issues remained outstanding at the conclusion of the project. These issues are summarized below. Since the conclusion of the MWFA project support, commercial entities have undertaken to improve on the DC Arc design. Those improvements are summarized with the issues.

- An electrical bypass was demonstrated to provide an alternate conduction path when the hearth is covered with glass. Although this equipment was not used for restart during the first test campaign, it was used for the restart of the second test campaign. It is suspected, however, that this restart technique may have resulted in short circuiting through a crack or fissure in the furnace side wall. This may have subsequently caused preferential corrosion in that area of the furnace, contributing to the plugging of the furnace overflow section. Since these tests, a hybrid design in 2nd generation plasma arc furnaces has provided for Joule-heated idling of the melter, which obviates the need for and risks of cold melter restarts.

- Post test examination during both test FY 97 campaigns found damage to the graphite rod buses and the hearth from attack by water vapor that was driven off from the incompletely baked-out refractory. Design changes implemented in FY98 mitigated the corrosive affects of residual water in melter refractories. However, total melter immersion in the bake-out oven will effectively cure water-bearing refractories and completely eliminate the threat of water-based corrosion of graphite components.

- Particle size appears to have some impact on partitioning to the offgas; however, the effect appears to be minor. The partitioning of finer particle additives (including particles <1 micron) was measured to be within a factor of two of the bulk entrainment value at all test conditions, indicating that even submicron particulate entrainment is low in this system at the operating conditions of this test. Sweep gas rate across the melt surface is likely to be a significant factor in particle carryover; this parameter should be minimized in full-scale design.

- Operating with a high cold-cap coverage of feed on the glass and with a submerged arc reduced volatility of cadmium and lead to the offgas by a factor of two to three. When feeding volatile and semivolatile species, the system should be operated to maximize the cold-cap coverage and to minimize plasma arc exposure.

- Lead is readily leached (by the TCLP) from the offgas solids from the neutron-generator tests. All the offgas solids are characteristically hazardous because of lead and in some samples, chrome and cadmium. The melter should be designed for recycle of the offgas solids, and provisions should be made for alternate means of stabilization for materials that cannot be held in the melt.

- Lead partitioned mainly to the offgas system in the neutron-generator testing. Designs for processing with high lead and mercury wastes must account for these materials partitioning to the APCS with potential buildup in filters and the scrub system.

- Containerized feeding in the FY-98 testing appeared to reduce physical entrainment of feed stream materials when compared to FY-97 bulk feeding results. Design of the feed system to accomodate prepackaged feeds may be advisable. However, the containers used in the testing added substantial organic material to the process flowsheet and increased offgas loadings of condensable debris. An afterburner used to oxidize organic material exiting the melter could significantly mitigate this offgas system buildup of pyrolyzed material.

- Insufficient temperatures below the melt cavity prevented bottom drain tapping of the melter's molten metal phase in the neutron-generator testing. Although the bottom drain's induction heater did appear to provide adequate heating to the melter's external freeze valve, the plasma arc's power density at the bottom of the unlined crucible was apparently insufficient to achieve expected temperature conditions at the bottom of the melter. An alternative design with better thermal efficiency may be required to ensure reliable operation.

Technology Limitations and Needs for Future Development

Issues that will need to be addressed, for successful deployment of a system to treat mixed wastes, include:

- The processing rates during the engineering-scale submerged arc tests were comparable to those reported for solids feeding of joule-heated melters. However, no attempt was made to maximize these rates during exposed arc operation. This is not a limitation, rather an area in which greater operating knowledge will be necessary to fully define the operating range of the system.

- The bottom drain design concept used in the ESF should be capable of preferentially draining the discrete metal phase from the melter. However, thermal design issues involving the melter and possibly its freeze valve have to be resolved before the concept can be fully demonstrated.

- The relative behavior of metals versus oxides of actinides needs to be established to support operational decisions (reducing versus oxidizing) and permitting needs. This pertains to both actual actinides and surrogate actinides.

- Treatability studies with all new waste types will be necessary before operation, including very high organic content materials, salts, and refractory materials (brick, mortar).

The DC arc technology is primarily in need of operating data. No substantial questions remain on whether the technology can be implemented, only which waste types can be cost-effectively treated using the technology, and whether the scope is large enough to support the capital investment for such a process.

APPENDIX A

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APPENDIX C

RISK ASSESSMENT METHODOLOGY

Risk has been measured for eight of the system requirements as defined in the MWFA Systems Requirements Document.

Technically Correct (**Correct**)
The MWFA shall deliver treatment technologies that are technically correct. Operable treatment systems shall be able to: (1) treat target waste streams identified in Federal Facility Compliance Act (FFCA) Site Treatment Plans (STPs) and (2) treat wastes to meet EPA treatment standards (and TSCA or state-regulated treatment standards, where applicable) and comply with the disposal facility Waste Acceptance Criteria.

Technically Complete (**Complete**)
Treatment technologies delivered by the MWFA shall be demonstrated to function as described, and shall be described in sufficient detail so that they may be incorporated into a detailed system design of a mixed low-level or mixed transuranic waste treatment system without further development.

Acceptable to Stakeholders (**Acceptable**)
The MWFA shall deliver mixed waste treatment technologies that are acceptable to the stakeholders.

> Note: The term "stakeholders" means all those who have an interest in the outcome of the MWFA program except the DOE and DOE contractors who have a direct and immediate interest or involvement in the MWFA. Stakeholders include: tribal governments, members of the public, federal, state, and local agencies, universities, and industry.

Acceptable to an End User (**Sponsored**)
The MWFA shall deliver mixed waste treatment technologies to users committed to pursuing the use of those treatment technologies in mixed waste treatment systems.

Permittable
The MWFA shall deliver mixed waste treatment technologies along with sufficient data to show that there are no probable technical reasons to prevent receiving a permit to implement the technology in an operational treatment system. The permit process will be facilitated by involvement with national regulatory organizations such as the National Technical Workgroup (NTW) on Mixed Waste Treatment and Interstate Technology and Regulatory Cooperation Subgroup (ITRC). This will include working with the regulators to improve technologies and/or a facility's ability to obtain a permit.

Safe
The MWFA shall deliver mixed waste treatment technologies that can be incorporated into a treatment system and safely operated.

Timely
The MWFA shall deliver mixed waste treatment technologies to enable treatment systems to be designed, built, and operated in time to meet treatment schedules in the FFCA STPs and negotiated in Consent Orders.

Cost
The "delta" refers to the cost of implementation by an end user when compared to the cost analysis included in the ITSR. The more closely the cost of implementation compares with cost as reported in the ITSRs, the smaller the consequence to the end user of the technology.

Each of the eight system requirements will be addressed independently. Events that can lead to negative consequences relative to implementation of a technology will be identified and assigned to each system requirement. These events will be referred to as "risk factors." Each technology will be evaluated independently and relative values for consequences and probability will be assigned to each of the events. Criteria have been defined for each risk category to allow the user to, as quantitatively as possible, determine the probability and consequence measures to be applied for determination of risk.

Permittable
Permit application is rejected based on regulations that became effective after development of the technology.

The consequences of this scenario will be:

Low if	Treatment process is simple.
Medium if	Treatment process is complex.
High if	Treatment process is highly complex.

The probability of this scenario occurring will be:

Improbable if	An applicable permit has been received.
Unlikely if	Regulators have maintained interaction with developers on this technology during development and demonstration.
Likely if	A permit application has already been rejected for this technology.

Complete
Technology is insufficiently mature to incorporate into a system without additional engineering data.

The consequences of this scenario will be:

Low if	Technology can be deployed without the need for additional testing.
Medium if	Technology can be deployed with limited additional testing and documentation.
High if	Technology requires significant additional development and/or testing to deploy.

The probability of this scenario occurring will be:

Improbable if	Technology successfully meets Stage 5 requirements for full system functionality and has successfully conducted a treatability study.
Unlikely if	Technology successfully meets Stage 5 requirements for full system functionality and has conducted successful demonstration(s) with surrogate wastes.
Likely if	Technology successfully meets Stage 5 requirements for full system functionality but demonstration/testing program is incomplete.

Acceptable
Native American Tribes and/or public interest groups resist implementation of the technology at DOE sites.

The consequences of this scenario will be:

Low if	Concerns can be addressed by providing additional information about the technology's performance.
Medium if	Concerns center on the performance of the technology; relatively minor modifications to the technology can address the needs and concerns.
High if	Major modifications to the technology are required to address concerns about the performance and ability to solve the problem.

The probability of this scenario will be:

Improbable if — The affected Tribes and public perceive implementation of the technology as resolving an important problem at their site with minimal or no impact to their quality of life, or have not expressed any concerns.

Unlikely if — The affected Tribes and public perceive implementation of the technology as solving an important problem but having a negative impact on the quality of life.

Likely if — The affected Tribes and public perceive implementation of the technology will not solve an important problem at the site and is perceived to have significant negative impact on the quality of life.

Timely
The technology is not available for implementation by the STP or Consent Order date.

The consequences of this scenario will be:

Low if — Delay in the availability of the technology will not result in missing a milestone in a Consent Order.

Medium if — Need dates for the Consent Order can be renegotiated to accommodate the delay in availability of the technology.

High if — Unavailability of the technology results in missing key milestones in Consent Orders at multiple sites.

The probability of this scenario will be:

Improbable if — Technology development/implementation activities are completed within end-user schedules.

Unlikely if — Need dates identified accommodate any minor delays in technology development activities.

Likely if — Technology does not meet end-user schedules.

Cost
Operational costs are higher than projected.

The consequences of this scenario will be:

Low if — Volume of the targeted waste is low.

Medium if — Volume of the targeted waste is fairly small.

High if — Volume of the targeted waste is very large.

The probability of this scenario will be:

Improbable if — Projections of the technology's cost is based on data from multiple campaigns.

Unlikely if — Projections of the technology's cost is based on data from only one campaign.

Likely if — No actual cost data for the technology on the targeted waste exists.

Sponsored
No end user or commercial entity selects the technology for implementation.

The consequences of this scenario will be:

Low if	Multiple data sets detailing the technology's performance on targeted waste are available.
Medium if	Only limited data are available detailing the technology's performance on targeted waste.
High if	Data are not available detailing the technology's performance on the targeted waste.

The probability of this scenario will be:

Improbable if	Multiple licensing agreements or financial commitments have been made.
Unlikely if	A single licensing agreement or financial commitment for the technology has been made.
Likely if	No commitments have been made or interest shown in the use of the technology.

Correct
Operable treatment systems, which incorporate this technology, are not applicable to target wastes.

The consequences of this scenario will be:

Low if	Volume of targeted waste to be treated is low.
Medium if	Volume of targeted waste to be treated is fairly small.
High if	Volume of targeted waste to be treated is very large.

The probability of this scenario will be:

Improbable if	Technology developed was tested against multiple waste types.
Unlikely if	Technology developed was tested against only one waste type.
Likely if	Technology developed was not tested against targeted waste type.

Safe
System failure adversely impacts the health and/or safety of a collocated worker, the environment, or a member of the public.

The consequences of this scenario will be:

Low if	Hazardous constituents added or generated by the system are less than the reportable quantities shown in 40 CFR 302.4 and 40 CFR 355, Appendix A.
Medium if	Nominal reportable quantities of hazardous constituents shown in 40 CFR 302.4 and 40 CFR 355, Appendix A, are added or generated by the system.
High if	Hazardous constituents in quantities 10 times or greater than those listed in 40 CFR 302.4 and 40 CFR 355, Appendix A, are added or generated by the system.

The probability of this scenario will be:

Improbable if	System is a benign process, difficult to combust with no natural gas or fuel sources present.
Unlikely if	System is a moderately energetic process with natural gas or fuel sources present.
Likely if	System is an energetic system (high temperature and/or pressure); large amounts of flammables or pyrophorics.

APPENDIX D

ACRONYMS

APCS	air pollution control system
DC Arc	Graphite Electrode DC Arc Furnace
DOE	Department of Energy
DRE	destruction removal efficiency
EM	Environmental Management
EPA	Environmental Protection Agency
ESF	engineering-scale furnace
FFCA	Federal Facility Compliance Act
FY	Fiscal Year
HEPA	high-efficiency particulate air
INEEL	Idaho National Engineering and Environmental Laboratory
ITSR	Innovative Technology Summary Report
LDR	Land Disposal Restrictions
LLW	low-level waste
LMITCO	Lockheed Martin Idaho Technologies Company
MACT	Maximum Achievable Control Technology
MLLW	mixed low-level waste
MTRU	mixed transuranic waste
MWFA	Mixed Waste Focus Area
NAAQS	National Ambient Air Quality Standards
NEPA	National Environmental Policy Act
NESHAPs	National Environmental Standards for Hazardous Air Pollutants
NOC	Notice of Construction
NPDES	National Pollutant Discharge Elimination System
NSPS	New Source Performance Standards
NRC	Nuclear Regulatory Commission
NTW	National Technical Workgroup
OST	Office of Science and Technology
PCB	polychlorinated byphenyl
PHP	Plasma Hearth Process
PNNL	Pacific Northwest National Laboratory
POTW	publicly owned treatment works
PSD	Prevention of Significant Deterioration
RCRA	Resource Conservation and Recovery Act
RWMC	Radioactive Waste Management Complex
SCC	secondary combustion chamber
SCFM	standard cubic feet per minute
SRS	Savannah River Site
STP	Site Treatment Plan
TCLP	toxicity characteristic leaching procedure
TDRD	Technology Development Requirements Document
TRU	transuranic
TSCA	Toxic Substance Control Act
WDOE	Washington Department of Ecology
WDOH	Washington Department of Health