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Arc Melter Demonstration
Phase 2 Test Results**

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ABSTRACT

Several U.S. Department of Energy organizations and the U.S. Bureau of Mines have been collaboratively conducting mixed waste treatment process demonstration testing on the near full-scale graphite electrode submerged arc melter system at the Bureau's Albany (Oregon) Research Center. An initial (Phase 1) test series successfully demonstrated arc melter capability for treating surrogate incinerator ash of buried mixed wastes with soil. The conceptual treatment process for that test series assumed that buried waste would be retrieved and incinerated, and that the incinerator ash would be vitrified in an arc melter. This report presents results from a recently completed second series of tests, undertaken to determine the ability of the arc melter system to stably process a wide range of "as-received" heterogeneous solid mixed wastes containing high levels of organics, representative of the wastes buried and stored at the Idaho National Engineering Laboratory (INEL). The Phase 2 demonstration test results indicate that an arc melter system is capable of directly processing these wastes and could enable elimination of an up-front incineration step in the conceptual treatment process.

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EXECUTIVE SUMMARY

Several different U.S. Department of Energy (DOE) organizations and the U.S. Bureau of Mines (USBM) have collaborated to perform process demonstration testing on the capability of 3-phase AC electric arc furnace melting technology to treat materials simulating buried and stored mixed wastes. The USBM furnace is near full-scale for DOE waste treatment applications, and can operate in submerged arc mode (electrode tips submerged in the melt). Tests were conducted at the USBM Albany Research Center in Albany, Oregon, on April 11-14, 1995. Prior to these process demonstration tests, the air pollution control system (APCS) was significantly modified to enable processing of feed materials containing large amounts of organic and halogenated materials. These modifications included installation of a "dry-wet APCS" with a gas-fired thermal oxidizer, a larger baghouse, and a wet scrubber system.

These tests were the second series (Phase 2) in the AC submerged arc melter demonstration test program for buried mixed wastes. The initial (Phase 1) tests, conducted during Fiscal Year (FY) 1993, successfully demonstrated arc melter processing of surrogate incinerator ash and soils typical of INEL buried mixed wastes. The conceptual treatment process for the Phase 1 tests assumed that buried wastes would be retrieved and incinerated, and that the incinerator ash would be vitrified in an arc melter, with varied amounts of soil. The Phase 2 tests were based on the successful results from the Phase 1 tests. The primary objective of the Phase 2 tests was to demonstrate the capability of the graphite electrode arc melter system for directly processing "as-received" heterogeneous solid mixed wastes containing high levels of combustible organics in the heterogeneous mixtures. Varied amounts of soil were also processed with the waste. Successfully demonstrating the arc melter system capability to process widely varying feed materials that contain significant amounts of organics, chlorides, nitrates, and other volatile materials at levels representative of wastes at the Idaho National Engineering Laboratory will enable the elimination of an up-front incineration step in the conceptual treatment process.

Integrated Arc Melter Test Facility

The integrated arc melter test facility includes a continuous feed system, a 3-phase AC electric arc melter, an air pollution control system (APCS), and facility power, water, instrumentation, and controls. The system can process materials at a maximum rate of 2,000 lb/h, depending on the characteristics of the materials. The arc furnace is a stationary, refractory-lined, small industrial-scale (800 kVA), 3-phase electric arc melting furnace that is sealed for atmosphere control. The furnace has three moveable 4-in. diameter solid graphite electrodes. The electrodes are positioned at the apexes of an equilateral triangle 11.25 in. from electrode center to center and extend through ports in the furnace roof. Four water-cooled feed tubes also penetrate the furnace roof for uniform feed distribution and cold top or hot top operation. The furnace roof, sidewalls, and copper slag tapping fixture are water cooled. Slag can be continuously tapped from the side of the furnace through a water cooled copper slag tapping fixture. Metal is tapped (and the hearth is emptied) through a taphole in the bottom center of the hearth. The inside diameter of the furnace is about 46 in. at mid-height. The capacity of the hearth is approximately 5 ft³.

A new "dry-wet" APCS was designed, procured, and installed for this test series in order to completely oxidize the arc furnace offgases and control potential emissions of particulate, toxic metals and acid gas. The APCS includes (a) a gas-fired thermal oxidizer, (b) a water spray cooler to rapidly cool the offgas to around 260°C (500°F), (c) an air-dilution temperature quench section to further cool the gas to 150°C (300°F) while remaining above the dewpoint, (d) a cyclone to remove coarse particulate, (e) a pulse-jet baghouse for dry particulate removal, (f) a wet scrubber for acid gas removal, (g) a cooler and condenser for additional gas cooling and removal of condensed water droplets, (h) a reheater to raise the

offgas temperature above the dewpoint, (i) an activated carbon filter for adsorbing any remaining gaseous toxic contaminants, and (j) a high efficiency particulate arrestor (HEPA) filter, rated to remove 99.98% of particulate greater than 0.3 microns.

Test Program

The Phase 2 test program included an APCS shakedown test and the demonstration tests. As a result of the APCS shakedown test, conducted without melter operation and roughly one month prior to the demonstration tests, several minor APCS modifications were made. These are discussed in the body of the report. The demonstration tests were conducted with continuous operation on ten different feed mixtures following two preheat intervals.

The feed mixtures for these tests were nonradioactive surrogates for mixed, alpha-contaminated waste at the Subsurface Disposal Area (SDA) and the Transuranic Storage Area (TSA) located at the INEL Radioactive Waste Management Complex (RWMC). These wastes result from many decades of waste disposal and storage. The wastes are from many different DOE facilities, but the greatest portion of these wastes is from the Rocky Flats Plant. The wastes are very heterogeneous, packaged in many different kinds of containers, and represent a wide variety of different waste materials. By volume, the largest single category is combustible-type wastes, at around 26% of the total TSA waste volume, followed by metals (21%), and sludges (11%).

Surrogate waste feed mixtures were prepared to represent three different types of wastes for this demonstration: (a) a nominal mixture of buried waste and soil, (b) liquid chlorinated and nonchlorinated organics that were absorbed in silica-based absorbents, and (c) solid combustibles such as paper, rags, and plastic. Soil was added to these mixtures in proportions commensurate to the lesser value of either (a) the expected amounts of contaminated soil or (b) the amount needed to produce an acceptable waste form based on earlier modeling. Some lime (CaO) was added to each mixture of surrogate waste and soil to decrease processing slag viscosity and increase the molar basicity of the product slag to 1.0. Cerium oxide, a plutonium oxide surrogate, was also added to each mixture to track process partitioning of plutonium and similar TRU radionuclides. The amount added was sufficient to provide approximately 0.5% CeO_2 in the product slags if all Ce partitioned to the slag as expected.

Various process samples and system operating parameter data were gathered during this program including:

- Automatic, continuous process data acquisition (pressures, temperatures, flowrates, power levels, etc.)
- Manual data collection (feed material weight, cold top depth, furnace parameters, etc.)
- Process sampling of (a) slag from the slag tap, (b) metal samples from the furnace bottom tap, (c) APCS solids collected from the thermal oxidizer base, ductwork, cyclone, and baghouse, and (d) scrubber solutions collected from the acid gas scrubber
- Offgas measurements and sample collection at selected locations in the APCS for (a) gas composition and flowrate, (b) particulate and metals emissions, and (c) dioxin emissions.

Results

The demonstration tests were successfully conducted at the USBM facility on surrogate INEL alpha-contaminated wastes on April 11-14, 1995. This was the first vitrification demonstration of surrogate mixed wastes and soils that included large amounts of combustibles, halocarbons, nitrates, and hydroxides in this type of melter system. All of the planned feed mixtures and three additional feed mixtures were successfully processed. Results from these tests show the potential for processing a wide range of "as-received" buried and mixed wastes and soils in an electric arc melter system without prior incineration.

The arc furnace produced process conditions desired for controlled separations, destruction of complex waste compounds, and stabilization of cerium (the TRU surrogate) and some of the toxic metals in the slag product. Feed was processed continuously and slag was tapped semicontinuously as required, depending on the feedrate of slag-forming materials to the furnace. The slag was the primary product material and yielded a homogeneous, durable glass/ceramic product upon cooling that easily passed Toxicity Characterization Leaching Procedure (TCLP) tests and showed low leachability in Product Characterization Test (PCT-A) analyses. A separate, tappable, homogeneous metal alloy product was also produced, and condensed fume and entrained feed particulate in the offgas was successfully captured and retained by the air pollution control system (APCS). Each product material was essentially homogeneous (much more so than the waste feeds), and properties evaluated were generally acceptable.

The melter system was operated continuously for 84 hours of operation, including preheat and cleanout intervals. The arc melter operated very stably and reliably. Twenty-eight thousand (28,000) lb of feed mixtures of varying densities were processed representing (a) a nominal INEL buried mixed waste mixture with 40-90 wt% added soil from the Radioactive Waste Management Complex (RWMC), (b) stored organic sludge wastes with chlorinated and nonchlorinated organics (grease, oils and solvents) absorbed in silica-based absorbents, both without added soil and with 40% soil, and (c) stored solid combustible wastes mixed with 20% and 40% soil. The nominal surrogate waste and soil mixtures contained up to 20% metals, 13% combustibles, 13% silicated organics, and 5% nitrates. The silica-absorbed organic surrogate mixtures contained up to 60% volatile and chlorinated organics that had up to 20% Cl and 35% C. The surrogate solid waste combustibles mixtures had up to 70% combustibles, with up to 39% C, 3.4% Cl, and 3% metal.

Feedrates ranged up to 1,200 lb/h, and the average feedrate was 369 lb/h. Average power levels for different feed intervals ranged from 123-347 kW, resulting in an average energy efficiency of 0.64 kWh/lb. The slag product (over 18,000 lb) was 67% of the initial feed mass, and the metal product (over 1,800 lb) was 6.6% of the initial feed. APCS solids (1,900 lb) were 6.9% of the initial feed mass. The remaining 20% of the feed material was evolved as scrubbed and filtered offgas consisting primarily of N₂, O₂, CO₂, and H₂O.

The global mass balance closure for each of these tests (total furnace output mass including the slag, metal, APCS solids, and offgas, compared to the input mass of total feed material and electrode consumption) was very good at 0.99 (99%). Individual elemental mass balance closure was more variable. While the average elemental mass balance closure for those elements present in large amounts was very good, typically between 90-110%, the mass balance closure for some elements during some feed intervals, especially those present at trace levels deviated well outside the 90-110% range. Such elemental mass balance variations are common, and are often due either to inaccuracies in very low-concentration measurements, samples that are less representative for the sample period, or feed concentration variations over short durations of time (even though the average feed concentrations over larger time periods are very consistent).

The volume reduction factor (initial volume/treated volume) for the surrogate mixtures was 2.3, though the achievable volume reduction factor for the simulated wastes with 20–40% added soil can reach 17 from the combined benefits of reduced solid mass (owing to pyrolysis and oxidation of organics) and production of void-free, homogeneous slag and metal monoliths. A volume reduction factor of 2.3 implies that the final volume of treated material is 43% of the initial volume, while a volume reduction factor of 17 equates to a final treated volume that is only 6% of the initial volume.

Based upon pre- and post-test observations, there was no deterioration of the refractory brick or erosion of the hearth refractory (Ruby ramming mix) in these Phase 2 tests. This was a significant improvement over the results from the Phase 1 melting tests when a magnesia ramming mix was used. The water-cooled components performed within design and showed no signs of degradation.

The tapped and naturally cooled glass/ceramic product material was primarily noncrystalline (amorphous glass) with some minor crystalline phases. Glass compositions were typically within the range of aluminosilicate glasses. While the slag product material varied somewhat for the different feed mixtures, the composition averaged about 27–49% SiO₂, 29–57% CaO, 9–14% Al₂O₃, 0.2–3% FeO, 0.1–2% combined K₂O and Na₂O, 0.1–2% MgO, and less than 1% of many other oxides. The relatively high levels of CaO were due largely to lime added to the feed mixtures to reduce the melt viscosity for easier tapping. Temperatures at which a viscosity of 100 poise (a typical target for glass fluidity) was calculated ranged between 1,330–1,370°C for most of the slag products. In this temperature range, the calculated viscosity was relatively sensitive to temperature. As a result, the average melt temperatures (measured optically at the slag taphole during tapping) averaged about 250°C higher, at around 1,600°C. This amount of "superheat" above the calculated 100 poise temperature was necessary to enable tapping through the water-cooled taphole.

Other measured slag properties included leachability and density. Slag leaching tests showed very good durability with low leaching, as expected, under both acidic TCLP and basic PCT-A conditions. TCLP results for the slag samples were virtually all below detection limits for each of the metals. PCT-A results showed that most of the slag samples were high quality glass products. Normalized release rates for most elements were lower than cumulative release rates of 0.1 gm/m² - 7 days, which indicate a high quality final waste form glass in comparison to standard Environmental Assessment glass. The representative slag samples exhibited excellent leach resistance for Ce, the Pu surrogate. With an average specific gravity of 2.7, the glass product had an average density of 173 lb/ft³, much higher than the represented wastes, that range in density from 25 to 82 lb/ft³.

The metal product was an alloy of primarily iron (averaging 85% Fe), with 6.1% Si, 4.8% C, 4.1% Cr, 1.5% Ni, and 1.4% Cu. Many other elements were present at levels of 0.5% or less. The molten metal product was tapped twice during the test program. As expected, metal tapping was an infrequent but necessary operation, owing to the presence of metals (primarily iron) in the feed that were melted but not oxidized into the slag under the relatively reducing conditions in the furnace. While aluminum metal in the feed almost entirely oxidized to alumina and dissolved in the slag, there was a 32% increase in metallic iron (above the amount fed to the furnace) from carbothermic and aluminothermic reduction of iron oxides in the furnace.

Solid material recovered from the APCS was quantitatively recovered from the baghouse and sections of the APCS upstream of the baghouse. Small amounts of material were deposited on the walls of the thermal oxidizer and in the ductwork leading to the thermal oxidizer and could not be recovered. The APCS solids included both entrained feed material fines and material that volatilized from the melt and then condensed in the APCS. The composition of the APCS solids averaged 15% Si, 13% Cl, 11% Ca, 8.3% Na, 4.5% K, 1.9% Al, and 1% or less of many other elements. Differentiation between entrained

and volatilized matter in the APCS solids could not be reliably done without additional analyses such as scanning electron microscopy, microprobe analysis, and other techniques which might provide visual, phase, chemical, or other indicators of volatilized and condensed versus entrained materials. There were relatively large amounts of chlorine in the feed mixtures that may have combined with many elements and increased their volatility as chlorides, especially under the relatively reducing conditions caused by the large amounts of added organic material in the feeds. X-ray diffraction (XRD) results of the APCS solids (lack of crystalline phases in the baghouse samples) suggest that much of the APCS solids are a result of volatilization of the feed materials in the furnace.

The cyclone catch samples each passed the TCLP limits, though not to the degree exhibited by the slag. There were larger concentrations of several metals present in the cyclone catch as compared to the slag samples. Only the post-test baghouse catch sample, which represented a composite of material reporting to the baghouse during all of the feed intervals, failed the TCLP (for Cd and Pb).

Essentially all of the complex organics present in the feed materials were thermally decomposed in the melter to form simple gas phase hydrocarbons, and these were ultimately efficiently oxidized in the APCS thermal oxidizer to form gaseous CO_2 , H_2O , and smaller amounts of HCl. The concentration of carbon remaining in the slag averaged around 300 mg/kg by weight and was 200–300 mg/kg for most of the test program, but reached as high as 0.34 wt% (3,400 mg/kg) when the feed mixtures contained up to 40% carbon. The amount of carbon remaining in the slag, although very small, rapidly increased as the amount of fixed carbon in the feed increased near the end of the test program. Analyses performed were not sufficient to determine the form of carbon present in the slag product. When present at very small amounts (200–300 ppm) in the slag, the carbon could have been dispersed as a fine elemental soot-type material or carbide in the slag. Higher carbon levels in the slag (e.g., 0.34 wt%) were probably present as silicon carbide or calcium carbide since there were no visible carbon inclusions in the slag monolith.

Carbon in the slag products is not undesirable unless it in any way increases leachability or degradation of the slag monolith over time. The slag leachability tests have shown that all of the slag samples representative of the processed feed mixtures easily passed TCLP and PCT-A tests. Also, none of the representative slag samples had inclusions of carbon, graphite, or other materials that were visible to the unaided eye. Additional analyses such as optical microscopy might provide further data regarding carbon in the slags.

Measured gas-phase levels of CO, CO_2 , and total hydrocarbons (THC) in the furnace plenum ranged from 6,200–110,000 ppm by volume, 0.5–20.5 volume %, and 8,700–120,000 ppm. Measured speciation of the THC using FTIR instrumentation included primarily methane, with smaller amounts of ethylene, benzene, and toluene. Other THC gas species for which the FTIR was not calibrated may have also been present, such as vinyl chloride from gasification of large amounts of added polyvinyl chloride in the feed mixtures. All of those products of incomplete combustion (PICs) that entered the melter were efficiently oxidized in the thermal oxidizer.

An attempt was made to investigate variations in oxidation potential in the furnace by adding combustion air through the feed tubes along with the feed material. There was also a small amount (up to around 2 wt%) of combined sodium and potassium nitrates (solid oxidants) in the nominal buried waste surrogate feed mixture, and some added mill scale (Fe_3O_4). These solid oxidants also contributed oxygen to the melt and/or plenum for oxidation when they were fed to the furnace. No effects of the added primary air or the small amount of nitrates on oxidation of organics were observed. Added mill scale (a solid oxidant) near the end of the demonstration tests, however, had a large positive effect on organics oxidized in the melter. This demonstrated the potential to adjust oxidation conditions in the melt through the use of solid oxidant additives in the feed material.

The APCS operated satisfactorily within design and operating constraints, and efficiently controlled air emissions of particulate, metals, hydrocarbons, dioxins, and acid gases. Hydrocarbon destruction efficiency in the gas-fired thermal oxidizer was measured at 99.999%. The CO and THC levels in the stack gas were within expected regulatory limits and within ranges for good combustion practice at all times when the thermal oxidizer was operated within the design envelope. The HCl scrubbing efficiency was calculated at 98.9% for the S-40 feed interval, which had very high levels of feed Cl. Limited dioxin measurements were also made to evaluate the arc melter APCS potential for controlling dioxin emissions. A very low dioxin emission limit of 0.2 ng/dscm toxicity equivalent (TEQ at 7% O₂) for hazardous waste incineration is included in the proposed Maximum Achievable Control Technology (MACT) rule emission limits. Results of single investigatory dioxin sampling train measurements at the baghouse outlet and at the stack show that (a) baghouse outlet dioxin level was 3.3 times higher than the proposed limit, (b) the stack gas level was 10% lower, and (c) the dioxin control efficiency across the wet scrubber, the charcoal absorber, and the HEPA filters was 73%. These measurements were made during the S-0 feed interval when there were very high levels of chlorine (20%) and carbon (35%) in the melter feed. These results suggest that proposed dioxin limits can be met with the melter and APCS design represented by this test facility. Stack gas dioxin levels may be further reduced, if necessary, by such methods as (a) more rapidly quenching the hot offgas to a lower temperature, (b) using more efficient downstream dioxin removal techniques, or (c) reducing the input amounts of Cl in the feed.

Essentially all (99.6%) of the cerium additive used as a surrogate for plutonium in the feeds distributed to the durable vitrified slag product. This indicates that the treatment processing objective of immobilizing long-lived TRU elements such as plutonium in a very long-lived, essentially nonleaching final waste form can be achieved by processing the wastes in an arc melter.

Partitioning results for toxic metals and other elements were more variable. Elements that distributed primarily (over 50%) to the slag product were Al, Ba, Ca, Ce, Si, Mg, Na, and K. Elements that distributed over 50% to the metal product were Fe, As, Cr, Cu, and Ni. Elements that distributed over 50% to the APCS solids included Cd, Pb, Se, Hg, Zn, and Cs.

Elements in the feed mixtures that partitioned primarily to the offgas, as expected, are C, H, Cl, N, and S. Ninety-five percent of the C and 64% of the Cl in the feed mixtures partitioned to the offgas. An average of just under 4% of the C partitioned to the metal product. Just under 1% of the C partitioned to the APCS solids. Only 0.2% of the C and 0.1% of the Cl present in the feed partitioned to the slag.

Distribution of Cl between the offgas and the APCS solids depended on the amount of Cl present and other factors such as the amount of Ca, Na, and K in the APCS solids. When the concentration of Cl in the feed during the BWID interval averaged about 1.8%, the Cl distribution to the offgas was only 32%, and Cl distribution to the baghouse was 68%. A relatively large fraction of the Cl reacted with Ca, Na, and K species to form chlorides that were filtered in the baghouse.

Most of the test series was conducted with a cold top of unmelted feed material on top of the molten melt in the furnace. The cold top is thought to reduce toxic metals volatilization from the melt and reduce plenum gas temperatures, and act as a buffer between the feeding and melting rates. When the melting rate is less than the feeding rate, the cold top thickness will increase. When the melting rate is greater than the feeding rate, the cold top will become thin or even entirely dissolve into the melt. Most of the offgas measurements were made when a cold top was present, but some measurements were also made without a cold top in order to evaluate the effects of the cold top on metals volatilization and furnace plenum temperatures. Since the cold top presence and thickness were inferred from measurements from plumb bob readings of feed burden height directly beneath the feed tubes, there may have been less or no cold top in the higher temperature triangular region of the slag pool surrounded by the 3 electrodes.

The total particulate in the offgas includes (a) feed dust entrained in the furnace gas, (b) material volatilized from the hot melt that has or will condense as particles or droplets (also termed fume) in the cooler offgas sections or in the atmosphere, and (c) material ejected from the melt as fine droplets due to turbulence or gaseous emissions from the melt. The volatilized material can condense on the surfaces of entrained feed material or ejected melt material (heterogeneous nucleation) and also form very small fume particles (homogeneous nucleation) that may grow in size with continued condensation or agglomeration. The entrained feed particles, having possibly bypassed higher temperatures in the furnace, can have the same appearance, mineral content, and composition as particles of the same size in the feed mixtures, but may also be enriched with volatilized materials such as toxic metals that have condensed on the entrained particles. The condensed fume particles are also enriched with materials volatilized from the melt. The particles of ejected melt material are similar in composition to the melt, but they may be enriched with condensed material on the surface.

Results of a very limited number of modified Method 29 sampling runs made at the furnace outlet for metals and particulate emission measurements are in reasonably good agreement with furnace outlet particulate mass emission rates calculated from the APCS solids collected. The Method 29 measurements agreed to within 50% for individual sampling runs, and within 0.5% for the average of the sampling runs. The Method 29 results also show that metals and particulate emissions from the furnace were highest when there was a cold top of unmelted feed material in the furnace, with or without added primary air. Metals and particulate emissions were lowest when there was not a cold top. These findings may occur when the majority of the total particulate in the offgas is actually entrained feed material, rather than volatilized feed materials or ejected melt particles. However, high dust entrainment is not consistent with the XRD results for the APCS solids (which suggests that most of the APCS solids were amorphous, and therefore condensed fume or solidified melt ejecta, not entrained dust). Also, there are areas of the furnace such as the high temperature arc zone near the electrodes that may not be covered with cold top even when the rest of the melt is covered. Volatilization and melt ejection may occur in this very high temperature, turbulent, reducing (oxygen-lean) area, regardless of the presence of cold top on the rest of the melt.

These results should be considered cautiously since they are a result of single offgas measurements at each operating condition, and sampling procedures were modified (nonisokinetic sampling, abbreviated sample times and volumes) to enable sample collection in the highly particulate-laden, high temperature, non-ideal sample location. Additional, more detailed testing and comparisons with other related test programs must be done before conclusions about relationships between furnace plenum gas flowrates, cold top operation, and volatilization can be made.

A few issues with respect to furnace and APCS operations, operating limits, test procedure limits, or to the facility and test program were also identified and are discussed in more detail in the results. These include (a) rapid feed mixture changes that caused mingling of melted material from different feed intervals in the furnace, and infrequent tapping for some feed intervals, which affected sample concentrations and mass balances, (b) difficulty in controlling the feed input rates of slag-forming materials and volatile materials with respect to melt residence times in the furnace, minimum taprates, and maximum offgas rates, (c) ineffectiveness of the primary air in oxidizing feed material, (d) controlling the deposition of condensed and entrained material on the cool duct surface at the furnace outlet, (e) insufficient secondary combustion air for high melter feedrates of organic-containing materials, and (f) inability to continuously remove APCS solids collected in the cyclone and baghouse. While these issues require further engineering design, optimization, and testing for satisfactory resolution in a production system implementation, they are not indicative of melter technology problems, but are simply artifacts of the specific test facility design in which the tests were conducted. Potential engineering solutions for all of these operating issues have been identified.

Conclusions and Recommendations

The graphite electrode arc melter technology should be considered a viable and near-term available processing alternative for treating alpha-contaminated mixed wastes and soils. This type of furnace has many decades of reliable industrial operating experience in the metals and heterogeneous ore smelting industries. Industrial versions of this technology are commercially available from many vendors. Engineering design optimization for radioactive feed materials processing is needed, but possible.

The primary objective of the test series, to evaluate and demonstrate the application of existing industrial arc melter processing technology for treating buried and stored mixed wastes and soils, was accomplished. It can be concluded that the arc furnace is capable of treating as-received buried and mixed wastes without preincineration, as well as treating ash residuals from a preincinerator step. These tests have demonstrated that this type of arc melter system can satisfactorily process very heterogeneous feed materials that contain wide compositional extremes. Intermediate levels of metals, combustibles, chlorides, and other waste-type materials were successfully processed in feed mixtures that included varied proportions of added INEL soil. The feed mixtures spanned a range of metal, combustible, and organic waste materials representative of those stored and buried at the INEL TSA and SDA.

Stable, relatively steady-state furnace feed processing operation was achieved for most test conditions and would be achievable in production operations. The melter waste processing system products satisfied treatment objectives for (a) immobilizing transuranics and toxic metals that distributed to the glass/ceramic (slag) product (surpassing all leachability requirements), (b) eliminating/destroying organic material, (c) reducing volume with respect to the feed materials, and (d) product homogeneity relative to the feed materials (for easier and less costly characterization, packaging, shipping, and disposal).

The arc melter technology is capable of reliable production operation for this application. Furnace operating parameters were generally within expected values and typical of reliable industrial arc furnace practice norms. Electrode consumption was low, at around 1% of the input feed material (21 lb/ton of feed material), although no efforts were made to minimize electrode consumption by coating the electrodes or optimizing the power levels and feedrates. Electrode consumption at this rate is not a significant operating or cost issue in mixed waste treatment processes, because the graphite electrodes are relatively inexpensive and can be continuously fed to the furnace. Energy efficiency varied during the test program due to significant variations in power levels and feedrates, but energy use as low as 0.20 kWh/lb was observed. The arc melter system processed 28,000 lb of surrogate heterogeneous materials during an 84-h test period essentially without failure (unplanned downtime) except for several short-duration shutdowns for removing deposited material from the furnace outlet duct. This pluggage can be avoided by optimizing the APCS design.

In the existing configuration superheating of the slag is necessary to enable tapping. Slag tap temperatures measured in the tests and the calculated viscosities of the product slags indicate that superheating of the slag was necessary to enable slag tapping. Superheating of the slag up to 250°C above the calculated 100 poise temperature was necessary to achieve sufficient slag fluidity at the taphole. Engineering design corrective actions that may reduce the amount of required slag superheat (and potentially reduce metals volatilization) should be pursued including (a) positioning the slag tap nearer to one of the electrodes to permit a hotter portion of the bath to intersect the slag tap face, (b) replacing the water-cooled tapping fixture with uncooled tapping designs, and (c) adding local heating capability for melt in the region of the taphole. Maintaining reasonably high feedrates of slag-forming materials will also improve tapping conditions. Test results show that continuous tapping requires feedrates of slag-forming materials in excess of 1,000 lb/h for the taphole configuration that existed during the tests. Semicontinuous tapping was also acceptable, with slag-former feedrates of less than 1,000 lb/hr.

Slag temperatures in this Phase 2 test series were only measured at the tap hole exit using an optical pyrometer. No bulk melt slag "in-furnace" temperatures were attempted using sacrificial thermocouples (TCs), which procedure was conducted in the Phase 1 tests for a few conditions. The TC measurements were not considered reliable because of uncertainty that they reached steady-state. Pool melt bulk and local "near-electrode" temperatures are inferred to be several hundred degrees higher using calculational models. The modeling tools need further development, as do "in pool" slag temperature measuring devices.

It can be concluded that heavy metal radionuclides, particularly plutonium, will be distributed essentially entirely to the slag phase as desired. Cerium (the TRU surrogate) distributed primarily (99.6%) to the slag, and 0.4% to the APCS solids. There was none detected in the metal product. The small amount of Ce that appeared in the APCS solids was probably because of entrainment of some fines from the CeO_2 added to the feed mixtures, or small amounts of ejected melt particles. These results show that the metal product from treating alpha-contaminated mixed wastes will have very little if any measurable Pu contamination, assuming that Pu behaves similarly to Ce. The APCS solids will also be relatively decontaminated, with about two orders of magnitude lower Pu contamination than the slag. The high degree of separation of Ce into the slag implies that recycling the APCS solids containing entrained Pu would allow even more of the Pu to be effectively distributed in the slag and, therefore, the glass/ceramic product.

Because about 90–100% of the Cd, Cs, Se, Pb and Zn in the feed distributed to the APCS solids under the test conditions, the potential for recycling the APCS solids back to the melter to collect these metals in the slag or metal phases is limited but still may be possible. For example, recycling one-half of the APCS solids to the melter would reduce by one-half the amount of the APCS solids secondary waste stream, but would result in approximately doubling the concentrations of these elements in the APCS solids. With the feed operating conditions that prevailed during these tests, this would increase the Pb and Cs concentrations in the APCS solids to about 1% and 0.2%, respectively. The chloride concentration would also double to around 26%. The acceptability of these levels depends on such factors as the methods used for immobilizing the APCS solids for disposal, the disposal site criteria, and radiation potential from the small amounts of radioactive Cs or other gamma emitters in the actual waste.

It can be concluded that feed compositions high in carbon and chlorides appear likely to increase carryover of materials to the APCS system in comparison to highly oxidized (preincinerated) feeds. The levels of APCS solids, at around 6.9% of the feed material fed to the furnace, were much higher than the 2% level observed during the baseline (Phase 1) tests. The dominant mechanisms are not, however, clear. The increased APCS solids may have been caused in part by (a) the method of adding primary combustion air along with the feed material, which could entrain feed dust directly to the plenum gas, (b) increased flow of volatilized gases from the melt that would increase ejection of melt material and draw volatilized, entrained, and ejected melt material into the plenum gas, or (c) operation with much more Cl (resulting in more volatile chloride species of some metals) and much more organics (resulting in more reducing conditions), that can encourage the formation of more volatile metal chlorides and more volatile, reduced metals. If the majority of the APCS solids is from entrained feed dust or ejected material, then using oxygen, oxygen-enriched air, or other methods for introducing oxygen to the furnace that minimize gas flows and particle entrainment may reduce the amounts of APCS solids. Additional work is needed and recommended to clearly determine and model the dominant carryover mechanisms for melter system design and processing optimization.

Results of the XRD analyses (lack of crystalline phases in the baghouse samples) suggest that much of the APCS solids are from volatilization of feed materials. Volatilization of metals may be reduced by (a) reducing the residence time of melt in the furnace, (b) lowering the average melt temperatures, or

(c) lowering the melt temperatures in the region near each electrode, which may be much higher than the average melt temperature. At constant volatilization rates, the amounts of metals volatilization could be significantly reduced by processing feed material through the furnace faster to reduce the melt residence time in the melter. Local melt temperatures can be reduced by reducing the electrical power density in those regions. Power density can be reduced by using larger electrodes or by reducing power levels to the very minimum required. These design parameters should be further investigated.

The benefits of a cold top as a thermal radiation shield for the plenum are clear. The benefits of a cold top for reduction of carryover to the APCS are not yet completely determined. A cold top was present most of the time for the bulk pool for all runs during the Phase 2 demonstration tests. The thickness varied and was difficult to monitor and control with the manual means utilized. No effects of thickness variation were detectable. The presence of a cold top in the high temperature triangular melt region between the 3 electrodes is not clear in all cases. A better means to establish and detect the cold top is needed.

Feed dust entrainment can likely be reduced by (a) using less dusty feed materials, or pelletizing or otherwise packaging dusty feeds, (b) delivering feed directly to the melt and rapidly melting it, and (c) minimizing gas flowrates and turbulence in the plenum. The presence of a cold top of dusty, unmelted feed on the melt may increase feed dust entrainment. The entrained feed dust can potentially contain very nonvolatile small feed particulate materials such as Pu, which are undesirable in the APCS or APCS solids.

The dry-wet offgas system approach, with a baghouse for particulate control followed by wet scrubbing for acid gas control, enables collection of radioactive solids prior to acid gas removal. This enables recycle of the solids for further treatment, and can meet expected future emission limits. Existing offgas components technologies are sufficient but several areas for improvement exist.

Based on the successful results of the demonstration tests, continued support is recommended for arc melter system design, testing, and evaluation in several areas to adapt and optimize system design and process operations for treating mixed waste. Current design and operating practices used for the USBM melter test system are based on those commonly used in the industrial metals smelting industry, without significant remote or automated practices or rigorous contamination control. Several equipment and procedure modifications are required to adapt the existing arc melter system technology, as represented by the USBM system, for production mixed waste treatment. Specific areas of equipment and procedures modifications requiring engineering design adaptation, and appropriate development and demonstration include:

- Automation and remote operation of the system, including routine feeding and tapping operations, in order to reduce the level of personnel involvement and risk.
- Complete system containment and implementation of standard contamination and radiation control practices.
- Feed preparation and mixing subsystems designed to perform adequate and reliable feed preparation, including necessary feed characterization, sizing, segregation, and mixing within complete confinement.
- Increasing and matching the APCS capability and capacity to handle higher gas flow rates as well as low gas flows commensurate with higher feedrates of slagformers to the melt so that the furnace melt residence time and metals volatilization are minimized, taprates are adequate for

trouble-free tapping, and electrical power levels are within design furnace operating ranges for the potentially widely varying range of organic combustible waste feed input materials.

- In furnace feed delivery, cold top control, and oxidant additions methods to control the amounts of volatilization and feed dust entrainment, while providing adequate conditions for pyrolyzing organic matter and oxidizing fixed carbon.
- Configuration, surface temperature, filtering and cleaning methods to prevent undesirable surface deposits and fouling of surfaces and ducting that are not easily cleaned in an alpha environment.
- Removal of APCS solids.

Air pollution control systems and component technologies presently available are adequate for controlling furnace offgas to meet current and expected emission limits. However, opportunities exist for improvement and the final disposition of the solids recovered in the air pollution control system depends on the properties of the solids and secondary waste form requirements. Utilizing the melter system as a thermal separations device, as well as a vitrifier, would benefit from further investigation into process conditions control and optimization. Recommended continued research and development includes (a) process conditions optimization for reducing feed material entrainment and controlling species volatilization from the melter, (b) recycling APCS solids to the melter, (c) demonstrating the performance of potential solidification technologies for APCS solids and scrubber solutions, and (d) developing improved or new technologies that could provide more effective and trouble-free offgas control, including hot filtration and non-fossil-fired offgas oxidation, (e) diagnostics methods for performance of more rigorous and detailed measurements to better evaluate mass balance, partitioning, and partitioning mechanisms, and (f) methods for metals and particulate continuous emissions monitoring for improved processes and emissions control.

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ACRONYMS

ALRC	Albany Research Center (Oregon)
APCS	air pollution control system
BWID	Buried Waste Integrated Demonstration
BWID Nom-90	10% surrogate nominal BWID waste/90% soil
BWID Nom-80	20% surrogate nominal BWID waste/80% soil
BWID Nom-70	30% surrogate nominal BWID waste/70% soil
BWID Nom-60	40% surrogate nominal BWID waste/60% soil
BWID Nom-50	50% surrogate nominal BWID waste/50% soil
BWID Nom-40	60% surrogate nominal BWID waste/40% soil
CEMS	continuous emissions monitoring system
CETRD	Combustion Emission Technical Reference Document
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
EA	Environmental Assessment
EGC	evaporative gas cooler
EPA	U.S. Environmental Protection Agency
FTIR	Fourier-transform infrared (spectroscopy)
FY	Fiscal Year
GC	gas chromatograph
HEPA	high efficiency particulate arrestor
ICAP	ion-coupled argon plasma (spectroscopy)
ID	inside diameter
INEL	Idaho National Engineering Laboratory
IWPF	Idaho Waste Processing Facility

S-0	100% surrogate silicated organic waste
S-40	60% surrogate silicated organic waste/40% soil
C-40	60% surrogate combustible waste/40% soil
C-20	80% surrogate combustible waste/20% soil
kVA	kilovolt-ampere
kW	kilowatt
kWh	kilowatt hour
kWh/lb	kilowatt hours per pound
lb/MWh	pounds per megawatt hour
lb/st	pounds per short ton
lb/ton	pounds per ton
MACT	Maximum Achievable Control Technology
MB	megabyte
MMBtu	million British thermal units
MTI	Microtechnologies Inc.
NC	not calculated
Nom	nominal
OD	outside diameter
PCDD	polychlorinated dibenzodioxins
PCDF	polychlorinated dibenzofurans
PCT-A	Product Consistency Test
PNNL	Pacific Northwest National Laboratory
PVC	polyvinyl chloride
QA	quality assurance
RCRA	Resource Conservation and Recovery Act

rms	root mean square
RWMC	Radioactive Waste Management Complex
SDA	Subsurface Disposal Area
TCLP	Toxicity Characteristic Leaching Procedure
TEQ	toxicity equivalent
THC	total hydrocarbons
TRU	transuranic
TSA	Transuranic Storage Area
USBM	U.S. Bureau of Mines
WC	water column
WHC	Westinghouse Hanford Company
wt%	weight percent
XRD	x-ray diffraction

Graphite Electrode Arc Melter Demonstration

Phase 2 Test Results

1. INTRODUCTION

Significant amounts of wastes and soils at the Idaho National Engineering Laboratory (INEL) and other U.S. Department of Energy (DOE) sites are contaminated with long-lived transuranic (TRU) radionuclides and hazardous organic compounds and metals. The INEL has both buried and retrievably stored wastes at the Subsurface Disposal Area (SDA) and the Transuranic Storage Area (TSA) of the Radioactive Waste Management Complex (RWMC). These wastes consist of various solid, heterogeneous combustibles, structural metals, organic and inorganic sludges, laboratory wastes, and construction debris. A large amount of the interstitial soil associated with the buried wastes is also expected to have some contamination. These wastes will require treatment to meet current and expected DOE and U.S. Environmental Protection Agency (EPA) storage and disposal requirements for mixed transuranic contaminated wastes.

Various treatment technologies are being evaluated and demonstrated for potential application to these types of wastes. The most desirable approach for long-term stabilization of the long-lived TRUs is believed to be melting and dissolution of the TRU elements, as oxides, into a slag at high temperatures. Upon cooling, the slag can solidify into a durable glass or crystalline rock-like matrix. This type of matrix can also immobilize toxic metals in order to eliminate hazardous toxicity characteristics. A recent technical review at the INEL of various melter technologies has resulted in a recommendation that a graphite electrode melter system is most applicable to the types of alpha-contaminated, mixed waste streams stored and buried at the INEL (Eddy et al. 1995). With appropriate design and operation, this type of melting system can suitably treat both the radioactive and the hazardous components of mixed wastes by immobilizing the radionuclides and toxic metals and destroying the hazardous organic compounds. The final waste volume is also substantially reduced, with (a) essentially no added glassformers or other additives, (b) reduction of much of the solid mass via volatilization and oxidation reactions, and (c) densification of the remaining solid material by fusing the feed material and eliminating void space. The resulting primary glass/ceramic product is also far more homogeneous and simpler to characterize and control than the input heterogeneous waste.

1.1 Demonstration Test Program

Several different DOE organizations and the U.S. Bureau of Mines (USBM) have collaborated to perform process demonstration testing of 3-phase AC electric arc furnace melting technology to vitrify materials simulating buried and stored mixed wastes. Tests were conducted at the USBM Albany Research Center (ALRC) in Albany, Oregon, on April 11-14, 1995. Prior to these process demonstration tests, the air pollution control system (APCS) was significantly modified to enable the processing of feed materials containing large amounts of organic and halogenated materials. These modifications included installation of a "dry-wet APCS" with a new thermal oxidizer, a larger baghouse, and a wet scrubber system.

These tests were Phase 2 of the graphite electrode 3-phase AC submerged arc melter demonstration test program. Phase 1 tests, conducted during Fiscal Year (FY) 1993, demonstrated arc melter processing for surrogate incinerator ash for buried mixed wastes that were mixed with soil (Soelberg 1994a). The basis for the Phase 1 tests was the assumption that buried wastes would be retrieved and incinerated, and

that the incinerator ash would be vitrified in an arc melter. The Phase 2 tests were an extension of the Phase 1 tests (Soelberg 1994b). The primary objective of the Phase 2 tests was to demonstrate the capability of the graphite electrode melter system for stably processing heterogeneous solid wastes containing high levels of organics. Successfully demonstrating the melter capability to process widely varying feed materials that contain amounts of organics, chlorides, nitrates, and other volatile materials at levels representative of the INEL will enable the elimination of an up-front incineration step in the conceptual treatment process.

1.2 Objectives

As noted above this test series was the second test series conducted in this demonstration and evaluation project. The purpose of this arc melter test and evaluation project was to evaluate and demonstrate the application of existing industrial AC arc melter processing technology for treating mixed alpha-contaminated wastes and soils. Top level program objectives for all experimental phases included:

- Evaluate and demonstrate application of industrial arc melter processing technology for thermal treatment of mixed alpha-contaminated wastes and soils.
- Obtain performance data for Environmental Restoration and Waste Management treatment systems design and selection.
- Provide data on a large scale for use in developing and verifying analytical tools, models, and scaling relationships for melter system and process design evaluations.
- Identify technology gaps and development needs that require closure for deployment of the technology in a production process environment.
- Define and evaluate potential process, equipment, and operations improvement modifications.

In order to meet these top level program objectives, the objectives of the Phase 2 test program included:

- Determine equipment capability to process as-received, nonincinerated mixed wastes.
- Evaluate the extent of thermal breakdown and partial oxidation (pyrolysis) of solid carbonaceous materials and absorbed liquid hydrocarbons in furnace feeds.
- Determine the effects of and potential for oxidation control in the furnace using air injection through the feed tubes, addition of solid oxidizers in the feed, or injection of oxidizer by lancing.
- Efficiently oxidize furnace offgases in a close-coupled thermal oxidizer.
- Demonstrate continuous slag tapping and as-needed metals tapping capability.
- Determine composition, homogeneity, and properties of the slag, offgas, and metal products.
- Evaluate distribution of a TRU surrogate (Ce), toxic metals, and other elements such as C and Cl among the slag, metal, APCS solids and offgas phases.
- Determine the effects of cold top (unmelted burden of feed material on the melt surface) on furnace process operations.

Funding for this project is summarized in Table 1-1.

Table 1-1. Funding sources for the Phase 2 tests.

Funding source	Portions of the test program that were funded
DOE Office of Waste Management (EM-30) through the Idaho Waste Processing Facility located at the INEL	The majority of the actual demonstration tests including INEL personnel participation, subcontracted offgas analysis, data analysis and reporting; some of the APCS capital cost; and some miscellaneous expendable materials
DOE Office of Technology Development (EM-50) through the Buried Waste Integrated Demonstration (presently called the Landfill Focus Area) at INEL	The majority of the capital cost of the APCS and other system modifications, and a portion of the demonstration tests, data analysis, and reporting
U.S. Bureau of Mines	Design and installation of the APCS and other system modifications, including materials associated with the installation; labor and analysis costs in excess of those funded by DOE for the demonstration tests
Cooperative Research and Development Agreement between Argonne National Laboratory-East and Clean Air Engineering	Testing, data analysis, and reporting costs for the Fourier-transform infrared (FTIR) gas analysis

2. INTEGRATED MELTER TEST SYSTEM

The integrated melter test system includes three primary components: (a) a feed system, (b) a 3-phase AC electric arc melting furnace, and (c) an APCS. The feed system and arc furnace used for the BWID Phase 1 test series had minor modifications prior to the Phase 2 tests; however, significant modifications were made to the APCS to facilitate processing of the combustible-bearing waste mixtures for the Phase 2 test. A process schematic of the system is shown in Figure 2-1. The test system is described briefly in the following sections, and described in more detail in Appendix B.

2.1 Feed System

The feed system can deliver material to the furnace at a maximum rate of about 2,000 lb/hr. The feed system includes the receiving bin, bucket elevator, metering bin with calibrated delivery screws, rotating air lock, splitter screw, and two feed screws. Each feed screw delivers to a pneumatically operated diverter gate that routes material equally through an inverted Y downcomer to two water-cooled feed tubes. Materials to be melted are delivered uniformly to the furnace through four water-cooled feed tubes that extend through ports in the furnace roof to within 18 in. of the surface of the molten slag and are located between the electrodes and sidewall of the furnace.

In order to enable the processing of surrogate waste mixtures containing combustibles, metals, nitrates, hydroxides and solvents, a number of modifications were made prior to the tests. These are summarized as follows:

- The length of the receiving bin was decreased to one-third of its original length to diminish classification and segregation of feed materials by the feed screws.
- The capability of injecting primary combustion air through the feed tubes was added. A blower was installed with a controlling damper and a hot-wire anemometer type flowmeter.
- Heat tapes were placed on the outside of the feed tubes between the metering bin and the furnace to reduce the chance of condensation of moisture on the inside of the feed tubes.

The feed system was originally designed for measuring, controlling, and delivering aggregate and soil-type materials of sizes less than 2.0-in. diameter to the furnace. However, difficulties in this design with high aspect ratio materials have restricted its use to feeding materials of sizes less than 0.5-in. diameter to the furnace. The feed system was sealed from the receiving bin onward to control fugitive dust release. A rotary air lock seal downstream of the metering bin minimized air inleakage through the feed system. Segregation of aggregate, granular, and powder materials is a frequent occurrence in handling equipment because of vibration and stirring of augers. Larger-sized and less dense materials tend to float to the surface while denser and smaller particles tend to sink to the bottom of processing hoppers that contain these kinds of materials. The feed mixtures contained additives of various particle sizes and densities. Efforts made to minimize segregation in the feed hoppers included adding the feed mixtures one barrel at a time and achieving near emptiness in the receiving bin before adding another barrel.

2.1.1 Furnace Description and Design

The furnace is a stationary, refractory-lined, small industrial-scale electric arc melting furnace that is sealed for atmosphere control. The furnace has three moveable 4-in. diameter solid graphite electrodes, automatic power, and electrode vertical positioning control. Power is supplied by a fully instrumented 800 kVA 3-phase supply. The electrodes are positioned at the apexes of an equilateral triangle 11.25 in.

Key

- B - Natural Gas Burner
- T - Temperature probe
- P - Pressure probe
- A - Analysis port
- G - Gas chromatograph port
- F - Flowrate probe (offgas)
- W - Flowrate probe (water)
- R - Rotary air lock valve
- O - Oxygen sensor
- - Indicates refractory lining

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Figure 2-1. Schematic of the APCS from the furnace to the APCS.

- Key**
- B – Natural Gas Burner
 - T – Temperature probe
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 - F – Flowrate probe (offgas)
 - W – Flowrate probe (water)
 - R – Rotary air lock valve
 - O – Oxygen sensor
 - Indicates refractory lining

Figure 2-1. (continued).

from electrode center to center. The electrodes and four water-cooled feed tubes extend through ports in the furnace roof. The feed tubes, furnace roof and sidewalls, and copper slag tapping fixture are water cooled. Slag can be continuously tapped from the furnace; metal is tapped (and the hearth is emptied) through a hole in the bottom center of the hearth. The copper, water-jacketed slag tapping fixture has a 6 in. outside diameter (OD), 1.25 in. inside diameter (ID), and is 7.5-in. long.

2.1.2 Furnace Refractories

The furnace shell bottom is lined with 5 in. (two courses) of chromic oxide-alumina bonded, 90% alumina super duty straight firebricks (Ruby) from Harbison-Walker Refractories. Five courses of ruby-key bricks shape the hearth and form the sidewall up to the steel shelf that is 28 in. above the bottom and approximately 7 in. above the slag taphole. One inch of dry phosphate-bonded silicon carbide (SiC) ramming mix (Norton Company) was placed between the steel bottom and first course of ruby straights to improve heat transfer to the bottom. One inch of the ramming mix is also placed between the ruby keys and the sidewall for heat transfer improvement. The upper sidewall is lined with 4.5-in. GM 70 DE (70% alumina) insulating fire brick from North American Refractories. Fiberfrax batting (Carborundum Company) 1-in. thick is placed between the sidewall and arch brick as added insulation. The hearth is rammed to 6 in. deep at the center with Ruby ramming mix from Harbison-Walker. The roof is lined with 4 in. of Narphos 85P plastic refractory (85% alumina) from North American Refractories. The finished ID of the furnace is about 46 in. at mid-height. The capacity of the hearth is approximately 5 ft³.

2.1.3 Furnace and Transformer Cooling

The base of the furnace is cooled by air flowing at about 1,300 acfm through a plenum formed by six 4-in. high I beams on which the furnace rests. The furnace shell, roof, slag taphole, slag launder, metal taphole collar, power supply transformer, and electrode arms, cables, and clamps are all water cooled. Cooling water is pumped to the furnace from a 1,500 gal cool water sump by a 15 hp centrifugal pump. The furnace shell is cooled by a curtain of water (50 gpm) cascading down the exterior wall from the annular distribution trough near the shell top. All cooling water is collected at the base of the furnace in a trough and is returned by gravity to a 1,500 gal warm water sump through a 6-in. polyvinyl chloride line. Water is pumped from the warm water sump to a Marley Model NC-111 cooling tower with a cross-flow induced draft design. The cooling tower supplies up to 150 gpm of water at 74°F with 142°F maximum return temperature and 70°F wet bulb ambient air temperature.

City water is available for emergency cooling in case of general power failure or pump malfunction. The most critical component is the copper, water-cooled slag taphole (cinder monkey), which is in direct contact with molten slag while the furnace is operating. A flowmeter in the water circuit to the cinder monkey deenergizes and opens the automatic valve in the city water line if power fails or the flowrate from the cooling tower decreases below 20 gpm in that circuit.

Modifications to the cooling water system included (a) thermocouples for continuously monitoring the feed tube cooling water temperatures attached to the outsides of the cooling water piping and (b) a larger water circulation pump for the cooling tower.

2.2 Air Pollution Control System

The APCS used in Phase 1 tests was modified by adding a thermal oxidizer, spray quench section, cyclone, wet scrubber, reheater, and charcoal filter. The improved APCS was designed to completely oxidize the furnace offgases and control particulate, toxic metals and acid gas emissions. The APCS includes:

- A refractory lined vertical shaft gas fired thermal oxidizer, close-coupled to the arc furnace, designed for a maximum temperature of 2,400°F. Two natural gas burners are located in the transition duct between the outlet of the arc furnace and inlet of the thermal oxidizer, and a third burner is located at the inlet of the thermal oxidizer.
- A water spray evaporative gas cooler (EGC) for initial temperature quenching to 500°F, followed by an air-dilution temperature quench section for cooling to 300°F.
- A cyclone for removing coarse particulate upstream of the baghouse.
- A pulse-jet baghouse for particulate removal.
- A wet scrubber for acid gas (primarily HCl and SO₂) removal, with a design gas outlet temperature of around 153°F.
- A cooler and condenser for further offgas cooling and removing condensed water droplets, with a design outlet temperature of 90°F.
- A hot water-heated reheater to raise the offgas above the dewpoint, with a design gas outlet temperature of 100°F. The reheater is necessary to prevent moisture condensation in the downstream equipment and to minimize the steam plume at the stack outlet.
- A bank of four 2,000 acfm-each activated C filters for controlling any residual trace amounts of toxic contaminants.
- Four 2,000 acfm high efficiency particulate arrestor (HEPA) filters, one each attached to the outlet of each carbon filter.

The baghouse was designed for operation with a temperature capability of 375°F and at pressures of -20 in. WC. There are 289 Ryton bags, 16 oz/yd, each 10 ft long. These bags are rated to remove 99.98% of particulate greater than 0.3 μ m. The bags are cleaned with a back pulse-jet of air at 100 psig. This baghouse is rated for a maximum gas flowrate of 10,000 acfm and has an air-to-cloth ratio of 2.94:1. Additional particulate filtration is provided downstream of the baghouse by a HEPA filter unit, also rated to remove 99.98% of particulate greater than 0.3 μ m.

Following a shakedown test, additional modifications to the APCS made before the demonstration tests included:

- Increasing the secondary air flowrate capacity by teeing off of the existing blower for burner 3.
- Adding the capability to preheat the cooling air (for preheating the baghouse) during startup to prevent moisture condensation from hot combustion gases in the baghouse.

3. DESCRIPTION OF SURROGATE WASTE MIXTURES

3.1 Surrogate Waste Mixture Selection

The feed mixtures for these tests were nonradioactive surrogates for mixed and alpha-contaminated wastes at the INEL SDA and TSA. These wastes resulted from many decades of waste disposal and storage. The wastes are from many different DOE facilities, but the greatest portion of these wastes is from the Rocky Flats Plant. The wastes are very heterogeneous, packaged in many different kinds of containers, and represent a wide variety of different waste materials. By volume, the largest single category is combustible-type wastes, at around 26% of the total TSA waste volume, followed by metals (21%), and sludges (11%).

Surrogate waste feed mixtures were prepared to represent three different types of wastes for this Phase 2 demonstration test series: (a) a nominal mixture of buried waste and soil, (b) liquid chlorinated and nonchlorinated organics that were absorbed in silica-based absorbents, and (c) solid combustibles such as paper, rags, and plastic. Soil was added to these mixtures in proportions commensurate to the lesser value of either (a) the expected amounts of contaminated soil or (b) the amount needed to produce an acceptable waste form based on earlier modeling. Some lime (CaO) was added to each mixture of surrogate waste and soil to decrease processing slag viscosity and to increase the molar basicity of the product slag to 1.0. Cerium oxide, a plutonium oxide surrogate, was also added to each mixture to track process partitioning of plutonium and similar TRU radionuclides. The amount added was sufficient to provide approximately 0.5% CeO_2 in the product slags if all Ce partitioned to the slag as expected. Further descriptions of each of the waste streams are given in Table 3-1.

3.2 Surrogate Feed Mixture Compositions

The feed mixtures were prepared by the Albany Research Center from representative waste materials blended with RWMC soil and pebble lime. The material compositions of the surrogate mixtures are shown in Tables 3-2 and 3-3. Not shown in these tables are the soil, lime (CaO), and CeO_2 that were added to these surrogate mixtures. While the actual mixed wastes contained a wide variety of actual substances and materials that were used over several decades, all of the different known or suspected types of materials could not be included in the surrogate mixtures. In order to avoid potential feed handling problems such as room temperature volatilization and loss of volatile hydrocarbons from some known waste feed materials such as carbon tetrachloride, or jamming in the feed system from high aspect ratio or oddly-shaped metal components, these materials were not included. In these cases, surrogate materials that were expected to behave chemically and physically similar to actual waste materials were used to represent some groups of materials in the wastes. Polyethylene was used to represent various kinds of plastics that may have been used over the years and that are presently in the waste. Wood pellets were used in place of the potentially huge variety of wood, paper, and cloth materials. Wood, paper, and cloth (including synthetic and natural blends of cloth) are very similar chemically. Neoprene rubber was used to represent a large variety of rubber materials in the waste. Polyvinyl chloride (PVC) was used in place of highly volatile carbon tetrachloride and trichloroethylene. The ratio of C to Cl in PVC is much higher than in carbon tetrachloride and trichloroethylene. In order to include sufficient total chlorine and yet maintain the proper ratios of Cl and C in the S-series waste feed mixtures, the hydraulic oil (another source of organic carbon known to be in the actual wastes) was eliminated.

The species and elemental compositions of the feed mixtures used (including soil, lime, and CeO_2) are shown in Table 3-4. The species and elemental compositions were calculated from analyses of the individual materials used to prepare the feed mixtures (Appendix A).

Table 3-1. Surrogate and actual waste descriptions.

Surrogate waste type	Description
Nom-xx	The Buried Waste Integrated Demonstration (BWID) nominal composition is a weighted average blend of materials such as metals, solid combustibles, silicated organics, nitrate salts, and metal hydroxide sludges (Bates 1994). The surrogate buried waste feed mixtures were blended with xx% RWMC soil and pebble lime, where xx ranged between 40 and 90% soil. The variation in percentage of soil was based on the desire in the demonstration tests to gradually increase the fraction of nominal waste while monitoring process conditions.
S-0	The S-0 series of wastes describes organic oils and solvents immobilized by mixing with Micro-Cel E (expanded CaSiO_3) and Oil-Dri (calcined diatomite, which is fossil-derived SiO_2). These wastes were generated at the Rocky Flats Plant, and include organic setups (prefix 743, also identified as INEL Content Code 3). While the S-0 wastes are only 5.9 wt% and 3.5 vol% of the total alpha-contaminated wastes at the TSA, these wastes have the highest amounts of volatile organics and chlorides of all the various wastes. S-0, without added soil, was included in the test program because chemical equilibrium modeling conducted for the S-0 composition has indicated that the resultant vitrified slag has a chemical composition expected to produce an acceptable final waste form. No soil or other additives would need to be added to the S-0 wastes for satisfactory vitrification (provided that the assumptions of the model are correct).
S-40	This waste mixture is part of the S-0 series of wastes and is a mixture of 40% RWMC soil and 60% S-0. The S-40 mixture was included in the test program as another feed mixture with lower concentrations of organics and Cl than the S-0 feed mixture.
C-20	The C-0 series represents the Combustibles Category of wastes stored and buried at the TSA. The Combustibles Category includes 12 waste streams, each denoted by a separate content code. By volume, the Combustibles Category is 26% of the total wastes, and is the largest single category of waste. For simplicity, the surrogate C-0 waste mixture was modeled after the composition of Content Code 330, which represents 55 wt% of the total Combustibles Category. By mass, the C-20 waste mixture is 20% RWMC soil and 80% C-0.
C-40	The C-40 feed mixture is 40% RWMC soil and 60% C-0.

Table 3-2. Composition of the nominal feed mixture (w/o added soil, lime, or CeO_2).

Component	Composition in wt%						Total of Each Group in Nom. Comp.
	Hazardous Metals	Solid Combustibles	Silicated Org. (743)	Nitrate Salts (745)	Metal Hydroxide Sludges (741, 742)	Nominal Comp.	
Carbon steel	60.00					22.50	
Stainless steel	30.50					11.44	
Aluminum	5.00					1.88	
Zirconium	2.50					0.94	
Copper	1.50					0.56	
Lead	0.50					0.19	37.50
LD Polyethylene, (-CH ₂ -CH ₂ -)		25.90				6.29	
Wood pellets (paper, wood, cloth)		63.80				15.50	
Neoprene rubber, (-CH ₂ CCl-CHCH ₂ -)n		10.30				2.50	
Diatomite							24.30
Texaco Regal Oil, (CH ₂)n			22.59			3.69	
Wheel bearing grease, (CH ₂)n			2.73			0.44	
PVC, (-C ₂ H ₃ Cl-)n			16.95			9.70	
Microcel E			35.20			5.74	
Diatomite			22.54			3.68	
HD Polyethylene, (-CH ₂ -CH ₂ -)							23.25
NaNO ₃				36.97		2.70	
KNO ₃				18.48		1.35	
NaCl				2.11		0.15	
Na ₂ SO ₄				2.03		0.15	
NaOH				2.03		0.15	
Water				38.37		2.80	
LD Polyethylene, (-CH ₂ -CH ₂ -)							7.29
Al(OH) ₃					15.00	1.15	
Fe(OH) ₃					14.07	1.08	
Ca(OH) ₂					8.60	0.66	
Mg(OH) ₂					10.31	0.79	
KOH					9.64	0.74	
H ₂ O					27.25	2.09	
Portland Cement					15.12	1.16	
LD Polyethylene, (-CH ₂ -CH ₂ -)							7.66
Totals	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 3-3. Compositions of C and S feed mixtures.

Component	Composition in wt%	
	Silicated organics	Combustibles
Carbon steel		1.77
Stainless steel		0.21
Aluminum		1.11
Cadmium		0.04
Copper		0.37
Lead		0.04
LD Polyethylene	3.39	31.73
Wood pellets (wood)		42.57
Neoprene rubber		1.34
Diatomite		1.66
Texaco Regal Oil, (CH ₂)n	16.40	
Wheel bearing grease, (CH ₂)n	1.98	
PVC, (-CH ₃ Cl-)n	42.97	7.89
Microcel E	25.56	
Diatomite	9.70	
HD Polyethylene, (-CH ₂ -CH ₂ -)		
Vermiculite		1.14
Lead oxide (leaded rubber)		1.07
Latex rubber stoppers (leaded rubber)		1.33
Wood pellets (latex rubber)		3.85
Polyethylene (latex rubber)		3.85
Teflon		0.04
Totals	100.00	100.00

Table 3-4. Calculated species compositions for the Phase 2 feed mixtures.

Species	Lime	Normalized RWMC Soil	S-series Nominal Waste	C-series Nominal Waste	Design Composition of Feed Mixtures (%) Renormalized for Added Spikes and Buffer										C-20 Feed	C-40 Feed
					NOM-90 Feed	NOM-80 Feed	NOM-70 Feed	NOM-60 Feed	NOM-50 Feed	NOM-40 Feed	S-40 Feed	S-0 Feed	S-0 Feed	S-40 Feed		
Ce spike					0.52	0.47	0.42	0.37	0.32	0.27	0.35	0.20	0.20	0.35	0.14	0.10
Soil					66.78	61.74	56.09	49.86	43.02	35.60	33.14	0.00	0.00	33.14	18.69	35.51
Lime					25.22	22.25	19.27	16.30	13.32	10.34	16.27	8.32	8.32	16.27	5.87	11.15
Ag2O	2.1e-4	1.1e-4	2.0e-5	7.6e-5	1.3e-4	1.2e-4	1.1e-4	9.5e-5	8.4e-5	7.1e-5	1.1e-4	8.7e-5	8.7e-5	1.1e-4	3.5e-5	6.4e-5
Al			1.79	0	0.13	0.28	0.43	0.60	0.78	0.96	0	0	0	0	0.96	0.68
Al(OH)3			1.15	0	0.09	0.18	0.28	0.38	0.50	0.62	0	0	0	0	0	0
Al2O3	0.16	12.04	0.32	0.82	8.10	7.52	6.86	6.14	5.34	4.48	4.43	0.76	0.76	4.43	2.31	4.33
As	4.0e-4				1.0e-4	8.9e-5	7.7e-5	6.5e-5	5.3e-5	4.1e-5	6.5e-5	3.3e-5	3.3e-5	6.5e-5	2.3e-5	4.5e-5
As2O		6.6e-4	1.5e-4	4.2e-4	4.5e-4	4.3e-4	4.1e-4	3.8e-4	3.5e-4	3.1e-4	4.3e-4	3.8e-4	3.8e-4	4.3e-4	1.7e-4	2.7e-4
BaO		0.12	6.4e-4	2.5e-3	0.08	0.07	0.07	0.06	0.05	0.04	0.04	2.2e-3	2.2e-3	0.04	0.02	0.04
C			19.96	37.62	1.49	3.10	4.83	6.68	8.65	10.73	18.90	34.41	34.41	18.90	38.95	27.54
Ca(OH)2			0.66	0	0.05	0.10	0.16	0.22	0.29	0.35	0	0	0	0	0	0
CaCO3		9.08			6.07	5.61	5.09	4.53	3.91	3.23	3.01	0	0	3.01	1.70	3.23
CaO	91.65	0.24	2.45	7.78	23.46	20.92	18.39	15.88	13.37	10.88	18.90	14.74	14.74	18.90	5.45	10.32
Cd			0	0	0	0	0	0	0	0	0	0	0	0	0.03	0.02
CdO	2.3e-4	2.3e-4	3.5e-5	1.4e-4	2.1e-4	2.0e-4	1.8e-4	1.6e-4	1.4e-4	1.2e-4	1.8e-4	1.5e-4	1.5e-4	1.8e-4	5.9e-5	1.1e-4
CeO2		8.6e-3	5.1e-4	2.1e-3	0.52	0.47	0.42	0.37	0.32	0.27	0.35	0.20	0.20	0.35	0.14	0.10
Cl	4.0e-3	3.2e-3	5.76	21.31	0.43	0.90	1.40	1.93	2.50	3.10	10.71	19.50	19.50	10.71	3.33	2.36
CO2	0.82		0.14	0.58	0.22	0.21	0.19	0.18	0.17	0.16	0.43	0.60	0.60	0.43	0.05	0.09
Cr			2.07	0	0.16	0.32	0.50	0.69	0.90	1.12	0	0	0	0	0.03	0.02
Cr2O3		0.01	3.7e-4	1.5e-3	9.8e-3	9.1e-3	8.3e-3	7.4e-3	6.4e-3	5.4e-3	5.6e-3	1.4e-3	1.4e-3	5.6e-3	2.7e-3	5.2e-3
Cs2O	2.1e-4	1.1e-3	5.1e-5	1.6e-4	7.7e-4	7.1e-4	6.5e-4	5.8e-4	5.1e-4	4.3e-4	4.6e-4	1.6e-4	1.6e-4	4.6e-4	2.2e-4	4.1e-4
Cu			0.56	0	0.04	0.09	0.14	0.19	0.24	0.30	0	0	0	0	0.28	0.20
CuO		8.8e-3	1.5e-4	5.4e-4	5.9e-3	5.4e-3	5.0e-3	4.4e-3	3.8e-3	3.2e-3	3.2e-3	5.0e-4	5.0e-4	3.2e-3	1.7e-3	3.1e-3
F			0	0	0	0	0	0	0	0	0	0	0	0	0.02	0.02
Fe			30.39	0	2.27	4.72	7.36	10.17	13.17	16.35	0	0	0	0	1.77	1.25
Fe(OH)3			1.08	0	0.08	0.17	0.26	0.36	0.47	0.58	0	0	0	0	0	0

Table 3-4. (continued).

Species	Lime	Normalized RWMC Soil	Nominal Waste	S-series Nominal Waste	C-series Nominal Waste	Design Composition of Feed Mixtures (%) Renormalized for Added Spikes and Buffer									
						NOM-90 Feed	NOM-80 Feed	NOM-70 Feed	NOM-60 Feed	NOM-50 Feed	NOM-40 Feed	S-40 Feed	S-0 Feed	C-20 Feed	C-40 Feed
Fe2O3	0.46		0.18	0.53	0.04	0.13	0.13	0.13	0.14	0.14	0.15	0.34	0.52	0.05	0.07
Fe3O4		4.75				3.17	2.93	2.67	2.37	2.05	1.69	1.58	0	0.89	1.69
H			3.14	5.33	8.71	0.23	0.49	0.76	1.05	1.36	1.69	2.68	4.88	6.56	4.64
H2O	5.20	5.13	7.35	3.67	4.73	5.29	5.47	5.66	5.87	6.08	6.32	4.39	3.79	4.83	4.92
Hf			9.4e-4	0	0	7.0e-5	1.5e-4	2.3e-4	3.1e-4	4.1e-4	5.0e-4	0	0	0	0
HgO	1.1e-5	1.1e-5	1.0e-6	3.8e-6	1.8e-7	1.0e-5	9.2e-6	8.4e-6	7.5e-6	6.5e-6	5.5e-6	7.2e-6	4.4e-6	2.8e-6	5.1e-6
K2O	0.06	2.32	0.03	0.10	5.8e-3	1.57	1.45	1.32	1.18	1.02	0.85	0.83	0.09	0.44	0.83
KNO3			1.35	0	0	0.10	0.21	0.33	0.45	0.58	0.73	0	0	0	0
KOH			0.74	0	0	0.06	0.11	0.18	0.25	0.32	0.40	0	0	0	0
Mg			0.05	0	0.23	3.9e-3	8.2e-3	0.01	0.02	0.02	0.03	0	0	0.17	0.12
Mg(OH)2			0.79	0	0	0.06	0.12	0.19	0.26	0.34	0.42	0	0	0	0
MgO	1.24	2.19	0.08	0.23	0.01	1.78	1.64	1.49	1.32	1.14	0.95	1.04	0.31	0.49	0.92
Mn			0.10	0	8.0e-3	7.6e-3	0.02	0.02	0.03	0.04	0.05	0	0	6.0e-3	4.2e-3
Mn2O3						0	0	0	0	0	0	0	0	0	0
MnO2		0.11				0.08	0.07	0.06	0.06	0.05	0.04	0.04	0	0.02	0.04
Mo			0.04	0	0	3.3e-3	6.9e-3	0.01	0.01	0.02	0.02	0	0	0	0
N			0.03	0.04	0.07	2.3e-3	4.9e-3	7.6e-3	0.01	0.01	0.02	0.02	0.04	0.05	0.04
Na2O	0.03	1.59	0.16	0.44	0.06	1.08	1.01	0.94	0.85	0.76	0.65	0.75	0.41	0.35	0.60
Na2SO4			0.15	0	0	0.01	0.02	0.04	0.05	0.06	0.08	0	0	0	0
NaCl			0.15	0	0	0.01	0.02	0.04	0.05	0.07	0.08	0	0	0	0
NaNO3			2.70	0	0	0.20	0.42	0.65	0.90	1.17	1.45	0	0	0	0
NaOH			0.15	0	0	0.01	0.02	0.04	0.05	0.06	0.08	0	0	0	0
Ni			0.99	0	0.02	0.07	0.15	0.24	0.33	0.43	0.53	0	0	0.01	9.7e-3
NiO		6.4e-3	3.6e-4	1.5e-3	1.3e-5	4.3e-3	4.0e-3	3.7e-3	3.3e-3	2.9e-3	2.5e-3	2.9e-3	1.4e-3	1.2e-3	2.3e-3
O			7.64	0.22	22.80	0.57	1.19	1.85	2.56	3.31	4.11	0.11	0.21	17.17	12.14
P			4.6e-3	0	3.6e-4	3.4e-4	7.2e-4	1.1e-3	1.5e-3	2.0e-3	2.5e-3	0	0	2.7e-4	1.9e-4
P2O5	0.03		5.3e-3	0.02	2.3e-3	8.5e-3	8.0e-3	7.5e-3	7.0e-3	6.6e-3	6.2e-3	0.02	0.02	3.6e-3	4.8e-3
Pb	3.0e-4		0.19	0	0.04	0.01	0.03	0.05	0.06	0.08	0.10	4.9e-5	2.5e-5	0.03	0.02
PbO		2.5e-3	4.0e-5	1.3e-4	1.4e-4	1.7e-3	1.5e-3	1.4e-3	1.2e-3	1.1e-3	9.0e-4	8.9e-4	1.2e-4	5.7e-4	9.5e-4

Table 3-4. (continued).

Species	Lime	Normalized RWMC Soil	Nominal Waste	S-series Nominal Waste	C-series Nominal Waste	Design Composition of Feed Mixtures (%)									
						NOM-90	NOM-80	NOM-70	NOM-60	NOM-50	NOM-40	S-40	S-0	C-20	C-40
Pb3O4			0	0	1.07	0	0	0	0	0	0	0	0	0.80	0.57
PO4		0.24				0.16	0.15	0.13	0.12	0.10	0.08	0.08	0	0.04	0.08
S			0.09	0.21	0.09	6.8e-3	0.01	0.02	0.03	0.04	0.05	0.11	0.20	0.06	0.05
Sb						0	0	0	0	0	0	0	0	0	0
SeO	2.4e-4	1.2e-4	2.3e-5	8.5e-5	4.0e-6	1.4e-4	1.3e-4	1.2e-4	1.1e-4	9.4e-5	8.0e-5	1.2e-4	9.8e-5	4.0e-5	7.2e-5
Si			0.10	0	0.25	7.5e-3	0.02	0.02	0.03	0.04	0.05	0	0	0.19	0.13
SiO2	0.34	61.40	6.25	20.99	1.43	41.56	38.95	36.02	32.76	29.17	25.25	30.95	19.23	12.57	22.60
SO3	5.0e-3		0.02	0	0	2.7e-3	4.1e-3	5.5e-3	7.1e-3	8.9e-3	0.01	8.1e-4	4.2e-4	2.9e-4	5.6e-4
SO4		0.05	0.01	0.04	8.9e-4	0.03	0.03	0.03	0.03	0.03	0.02	0.04	0.04	0.01	0.02
TiO2		0.66	0.01	0.04	6.2e-3	0.44	0.41	0.37	0.33	0.29	0.24	0.24	0.04	0.13	0.24
Zn						0	0	0	0	0	0	0	0	0	0
ZnO		0.02	5.1e-4	1.9e-3	0.08	0.01	0.01	9.2e-3	8.2e-3	7.2e-3	6.0e-3	6.3e-3	1.8e-3	0.06	0.05
Zr			0.87	0	0	0.07	0.14	0.21	0.29	0.38	0.47	0	0	0	0
ZrO2		0.02	4.6e-4	1.3e-3	1.7e-4	0.01	0.01	0.01	9.6e-3	8.3e-3	7.0e-3	6.9e-3	1.2e-3	3.7e-3	6.8e-3
Total	100.0	100.0	99.7	100.0	100.0	100.0	100.0	99.9	99.9	99.9	99.8	100.0	100.0	100.0	100.0

The species and elemental compositions of the feed mixtures were not determined by direct analysis of feed mixture samples because of the potential for segregation of the different additives during sampling. Such segregation is common when, as in this case, mixtures of materials of different particle sizes, shapes, and densities are handled. Mixture compositions were calculated from known masses and compositions of materials added to produce these feed mixtures. The chemical composition of the INEL soil and the various individual additives were determined by the USBM using appropriate chemical and instrumental analytical methods. The USBM analyses were augmented with compositions reported in other sources.

The calculated proximate analyses (the measurement of components expected to volatilize or decompose to gases in the melter) for the different feed mixtures are shown in Appendix A. A temperature of 1,000°C was assumed since this temperature is high enough to thermally decompose all of the organic, nitrate, and carbonate materials. The mixture averages on these tables are the mass fractions of each of the feed mixtures that would evolve from the melt as gaseous products (water, volatile organics, chlorides, and products of nitrate, carbonate, and sulfate decomposition).

3.3 Surrogate Waste Mixture Preparation

Extensive feed preparation was required before the melting tests, with the following objectives:

- (a) produce a surrogate mixture that accurately simulates the actual stored and/or buried wastes,
- (b) eliminate furnace charging difficulties by sizing the feed appropriately, and (c) facilitate rapid changes in surrogate mixture and soil ratios immediately before charging the material to the furnace. Industrial materials were selected that either were known to be present in the actual wastes or that duplicated those materials as closely as possible. Once these materials had been chosen, a methodology was conceived to prepare them in a mixture that would not only simulate their physical relationship in the actual wastes, but use their physical characteristics to provide a more suitable feed to the furnace. Rather than feed these constituents separately, certain components were mixed in stages, then combined with the remainder of the feed in a final surrogate waste mixture.

Because the nominal surrogate waste mixture was constant throughout the Buried Waste Integrated Demonstration (BWID) test series, and only the surrogate waste loading in soil would be varied, a master mixture of the surrogate waste components was prepared. Batch weights for each component in the feed mixture were determined, followed by batch mixing. Wheel bearing grease and Texaco Regal oil was over 4 wt% of the nominal mixture, but would be difficult to separately feed to the furnace because of their semisolid or liquid states. Therefore, the appropriate batch weights of grease and oil were thoroughly mixed with some of the dry feed constituents. Prepared in five batches, approximately 740 lb each, this master mixture (Appendix A) contained all the hydroxides, nitrate salts, Portland cement, Regal oil, wheel bearing grease, diatomite, Micro-Cel, and water in the appropriate concentrations for the nominal feed mixture. This master mixture was a relatively dry, free-flowing material ideal for charging to the furnace. Soil, lime, PVC, polyethylene, wood pellets, and the structural metals were added to this mixture in the charge hopper in proper proportion to provide the final feed mixture to the furnace receiving bin. This procedure allowed for flexibility in feed preparation and more efficient use of feed materials by eliminating the need to prepare excess feed of various surrogate waste loadings.

The surrogate feed mixtures for the Idaho Waste Processing Facility (IWPF) test series were prepared in a similar manner. However, the master mixture (Appendix A) contained Regal oil, wheel bearing grease, diatomite, and Micro-Cel only. This material was prepared in two batches, approximately 700 lb each, and resulted in a much dryer mixture than the BWID master mixture.

4. MEASUREMENTS, SAMPLE COLLECTION, AND ANALYSIS

Process data were recorded electronically or manually throughout the melting campaign using a Hydra computer data acquisition system, a Model 3950 True Root Mean Square (RMS) Power and Demand Analyzer ("electric analyzer"), and by using manually recorded logs and data sheets. The process monitoring summary is shown in Table 4-1. All temperatures except the slag temperature were measured using thermocouples. Slag temperature was measured as it was tapped using an optical pyrometer. Air and offgas flowrates were measured using mass flow meters or pitot tubes.

A large number of slag, metal, APCS solids, and offgas samples were collected at various times during the testing for subsequent sample analysis. Additional measurements were conducted at various locations in the APCS.

4.1 Electrical Analyzer and Hydra Data Acquisition System

Process data were recorded electronically or manually throughout the melting campaign using three Fluke Model 2635A Hydra data loggers, a Model 3950 True RMS Power and Demand Analyzer (furnace electrical analyzer), and by manually recorded logs and data sheets. The three Hydras were serviced by a host computer, which displayed process data on monitors located in the control room, at the feed control panel, and in an observation room located above the control room. The electrical analyzer was connected to a lap top computer for data storage.

4.2 Manually Recorded Facility Process Data

Several other parameters were monitored and recorded manually because they were readily instrumented to the data loggers. Most of the automatically logged parameters were also recorded manually for redundancy. This also ensured that the operators were continuously aware of the automatically logged data. The redundant logging proved valuable during the tests, especially when unusual or otherwise notable readings were observed. In this way, process variations and instrument errors were acknowledged and resolved more quickly. The manually recorded logs are summarized below.

Receiving Bin Log—Each batch of feed material was manually weighed using a floor scale before being placed into the receiving bin. The date, time, and weight of all feed materials placed in the receiving bin were recorded in the Receiving Bin Log.

Feeder Log—The feeder operator was responsible for controlling the feedrate to the furnace, which was the controlling factor for all other furnace operations, such as power input, melting rate, cold top height, primary combustion air addition, and APCS operation. The date, time, feedrate, pool depth, cold top height, slag temperature, and other pertinent information were recorded in the Feeder Log. The feedrate was read directly from the feeder control panel, and slag tap temperature was read directly from the infrared pyrometer rather than from the data acquisition system.

Furnace Log—The furnace operator kept a manual log of transformer tap setting, power, voltage, current, cumulative energy, rheostat setting, feedrate, slag tap temperature (from the data acquisition system), and miscellaneous observations on the furnace log. The electrical parameters were read from the furnace control panel rather than the automatic electrical analyzer, for corroboration between this manual log and the data acquisition system. Duplication of some operating parameters on several of the manual logs was intentional, for the same reason.

Table 4-1. Process monitoring summary.

Table 4-1. Process monitoring summary.

Parameter	Units	Recording method		Frequency	Logger ID ^a
		Continuous data logger (automatic)	Manual		
Melter					
Electrode phase to ground voltage	V	X	—	C ^b	Electric
Electrode current	A	X	—	C	Electric
Power factor	—	X	—	C	Electric
Active power	kW	X	—	C	Electric
Conductance factor	I ² /kW	—	X	Once/h	—
Material feedrate	lb/h	X	X	Once/15 min	I2C19
Total material feed	lb/test	—	X	Once/test	Feeder record
Energy efficiency	kWh/lb	X	X	Once/h	Energy cons.
Cold top depth	in.	—	X	C, once/10 min	Feeder log
Slag tap temperature, T ₉	°C	X	—	C	I1C17
Slag taprate	lb/h	—	X	Every slag pot	Glass log
Bath temperature	°C	—	X	Once/test	Furnace log
Slag viscosity (estimate)	—	—	X	30 min or during taps	—
Metal tap temperature	°C	—	X	During taps	Feed log
Furnace static pressure	in. WC	X	X	C	I2C12
Furnace hearth temperature, T ₇	°F	X	—	C	I1C16
Furnace plenum temperature	°F	X	—	C	I1C14
Hearth outer shell temperature, T ₈	°F	X	—	C	I1C15
Electrode consumption	lb/test	—	X	1/test	Electrode log
Primary air flowrate	scfm	X	—	C	I2C16
Primary air temperature	°F	X	—	C	I1C18
Air Pollution Control System					
Crossover gas temperature	°F	X	—	C	I1C1
Thermal oxidizer (TO) inlet T	°F	—	—	—	I1C2
TO outlet temperature	°F	X	X	C	I1C3
Secondary air flowrate	scfm	X	X	C	—
Secondary air temperature	°F	X	—	C	I1C19
TO fuel flowrate	scfm	—	X	30 min	Test log
Evaporative gas cooler (EGC) water flowrate	gpm	X	X	C	I3C1
EGC water temperature	°C	X	—	C	—

Table 4-1. (continued).

Parameter	Units	Recording method			Frequency	Logger ID*
		Continuous data logger (automatic)	Manual			
EGC exit temperature	°F	X	—	C		I1C4
EGC exit pressure	in. WC	X	—	C		I2C2
Cooling air temperature	°F	X	—	C		I1C5
Cooling air pressure	in. WC	X	—	C		I2C3
Cooling air flowrate	scfm	X	—	C		—
Windbox exit temperature	°F	X	—	C		I1C6
Windbox exit pressure	in. WC	X	—	C		I2C4
Baghouse inlet temperature	°F	X	—	C		I1C7
Baghouse inlet pressure	in. WC	X	—	C		I2C5
Baghouse outlet temperature	°F	X	—	C		I1C8
Baghouse outlet pressure	in. WC	X	—	C		I2C6
Baghouse outlet flowrate	scfm	X	—	C		Test log
Scrubber liquor pH	—	—	X	Once/30 min		I2C20
Scrubber outlet gas temperature	°F	X	—	C		I1C9
Scrubber outlet gas pressure	in. WC	X	—	C		I2C7
Condenser water flowrate	gpm	—	X	Once/30 min		Test log
Condenser outlet gas temperature	°F	X	—	C		I1C10
Condenser outlet gas pressure	in. WC	X	—	C		I2C8
Reheater power	kW	—	X	Once/30 min		—
Reheater outlet gas temperature	°F	—	X	30 min		I1C11
After reheat (ID fan inlet pressure)	in. WC	X	—	C		I2C9
HEPA filter inlet gas temperature	°F	X	—	C		I1C12
HEPA filter inlet gas pressure	in. WC	X	—	C		I2C10
HEPA/carbon filter differential pressure P	in. WC	X	—	C		I2C11
Stack gas temperature	°F	X	—	C		I1C13
Stack gas flowrate	scfm	X	—	C		—
TO catch mass	lb/test	—	X	Once/test		APCS record
Cyclone catch mass	lb/test	—	X	Once/test		APCS log
Baghouse hopper catch mass	lb/test	—	X	Once/test		APCS log

Table 4-1. (continued).

Parameter	Units	Recording method		Frequency	Logger ID ^a
		Continuous data logger (automatic)	Manual		
Cooling Water Flowrates and Outlet Temperatures					
Cooling water inlet temperature	°F	X	X	Once/30 min	I1C20
Cooling water flowrate	gpm	X	X	Once/30 min	I2C18
Feed tubes cooling water temperature	°F	X	X	Once/30 min	I3C11
NE feedtube temperature	°F	X	X	Once/30 min	I3C12
SE feedtube temperature	°F	X	X	Once/30 min	I3C13
NW feedtube temperature	°F	X	X	Once/30 min	I3C14
SW feedtube temperature	°F	X	X	Once/30 min	I3C15
Cinder monkey	°C	X	X	Once/30 min	I3C9
Cooling water outlet temperature	°F	X	X	Once/30 min	I2C1

a. Data logger output location

b. C = Continuous, with 2-min automatic printout.

Test Log—The Test Log was used by the sample manager to document the depth to the bottom of the hearth and thermal oxidizer before each test and to record other important process parameters, including readings from the totalizing flowmeters for the evaporative gas cooler (EGC), scrubber water, cooler and condenser water, and natural gas.

Glass and Metal Product Log—The tapping crew recorded the date, tap time (elapsed time), sample time, and weight for each pot filled while tapping from the slag and metal tapholes on the Glass and Metal Product Log.

APCS Solids Log—The Sample Manager kept a record of the date, time, and sample weight for all APCS solids recovered during and/or following each test in the APCS Solids Log.

Scrubber Solution Log—Samples of the scrubber solution were collected at the same sampling intervals as the APCS solids. The Sample Manager recorded the date, time, and volume for each sample in the Scrubber Solution Log.

Electrode Log—This record includes the weight and length of each electrode segment and the date and time placed in service. Individual records were kept for each electrode to identify any asymmetric consumption of the electrodes, which would indicate unbalanced power to the furnace. Electrode consumption for each feed mixture was calculated from the total electrode consumption and the fraction of total power used for each feed mixture.

Melter Inventory Log—The sample manager was also responsible for keeping a working inventory of all furnace feed, products, and input power during the melting tests. These data, plus the calculated feedrate, taprate, cumulative feed, cumulative tap, and energy consumption, were recorded on the Melter Inventory Log. The values recorded were used to determine the overall mass balance of material through the system, and to calculate the melting energy efficiency.

4.3 Sample Collection

The sample collection schedule is shown in Table 4-2. Procedures for the slag and metal sampling were as follows:

- Collect a flat "pancake" sample of slag on a 0.5-in. steel plate each time continuous tapping is initiated, near the mid-fill-point for each cast iron slag mold, and at other appropriate continuous tapping intervals.
- Collect additional "pancake" samples to coincide with each exhaust gas analysis.
- Collect a spoon sample of metal from each tap and pour two 1-in. buttons.
- Archive all slag and metal samples in metal cans. Label each with date, time collected, and sample ID number from the log.

Air pollution control system solid samples were collected and stored every two hours during the 59 hours of melting tests, which was intended to result in quantitative recovery and accountability for the APCS solids. Correlation between the various product logs and the Feeder Log would allow for direct comparisons between contemporaneous products and their common parent feed. This was successful for solids collected from the cyclone, but bridging in the baghouse hopper caused accumulation of the baghouse solids over the duration of the melting tests. Post-test clean-out of the baghouse provided evidence of this bridging, when approximately 800 lb of baghouse solids were removed. This material was collected in seven 55 gal barrels. Pipe samples from each barrel were composited into one representative sample of the mixed product. Although individual analyses of baghouse solids produced from each feed mixture will therefore not be possible, quantitative recovery of the APCS solids was achieved.

Samples of the scrubber solution were collected at the same sampling intervals as the APCS solids. The sample manager recorded the date, time, and volume for each sample in the Scrubber Solution Log.

4.4 Offgas Measurements, Sample Collection, and Analysis

Offgas measurements, sample collection, and analysis were performed to characterize the gaseous and particulate emissions from the melter and APCS performance. Offgas measurements and sample collection were conducted by Entropy Incorporated, Argonne National Laboratory-East, and Clean Air Engineering. Measurements and sampling runs were located at various points in the furnace and APCS. Gaseous measurements included velocity, temperature, and continuous monitoring of gas composition [O₂, CO, CO₂, NO, NO₂, SO₂, total hydrocarbons (THC), and HCl]. These measurements were conducted according to EPA Methods 1, 2, 3A, 6C, 7E, 10, and 25A. Gas temperature measurements in the furnace were conducted using a shielded thermocouple mounted in a suction pyrometer probe to minimize the effects of thermal radiation on the gas temperature measurement. Samples were also

Table 4-2. Chronology of measurements and sample collection.

Furnace product samples												
Date	Feed mixture	Time	Slag tap, start/stop	Slag	Metal	Scrubber	Cyclone	Baghouse	V,T Traverse	MMT/particulate (M5/29)	HCl/Cl ₂ (M26)	Dioxins (M23)
11-Apr	Nom-90	2000				INEL-S1	None	TH-B5				
		2245	Start									
		2300		INEL-SP1								
		2315	SP2									
		2355		INEL-SP2								
		0.00				INEL-S2	None	INEL B-1				
		0050	SP3									
12-Apr	Nom-80	0.00										
		0110		INEL-SP3								
		0200				INEL-S3	INEL C-1	INEL B-2				
		0400				INEL-S4	None	INEL B-3				
		0430	SP4									
		0600				INEL-S5	None	INEL B-4				
		0800				INEL-S6						
		0815					None	INEL B-5				
		0900		INEL-SP4								
12-Apr	Nom-70	0955	SP5									
		1000		INEL-SP5a								
		1040				INEL-S7						
		1045					None	INEL B-6				
12-Apr	Nom-70	1110		INEL-SP5b								
		1143	SP6									
		1200				INEL-S8	None	INEL B-7				
		1215		INEL-SP6a								
		1340		INEL-SP6b		INEL-S9						
		1345					None	INEL B-8				
		1425										
										FO, start, Nom-70-M2-1		

Table 4-2. (continued).

Date	Feed mixture	Time	Slag tap, start/stop	Furnace product samples					V,T Traverse	MMT/particulate (M5/29)	HCl/Cl ₂ (M26)	Dioxins (M23)
				Slag	Metal	Scrubber	Cyclone	Baghouse				
12-Apr	Nom-70	1430		INEL-SP6c					Stop, Nom-70-M2-1			
		1435	Stop									
		1452								FO, start, Nom-70-M5/29-1		
		1455	Start									
		1500		INEL-SP7a								
		1530				INEL-S10	INEL C-2	INEL B-9		Stop, Nom-70-M5/29-1		
		1600		INEL-SP7b								
		1800	Stop									
12-Apr	Nom-60	1810				INEL-S11	None	None				
		1855	Start						FO, start, Nom-60-M2-1			
12-Apr	Nom-60	1900							Stop, Nom-60-M2-1			
		1935		INEL-SP8a								
		2000				INEL-S12	None	None		FO, start, Nom-60-M5/29-1		
		2013							FO, start, Nom-60-M2-2			
		2018							Stop, Nom-60-M2-2			
		2034								Stop, Nom-60-M5/29-1		
		2100				INEL-S13						
		2115					INEL C-3	INEL B-10				
		2120		INEL-SP8b								
		2130	SP9									
		2140		INEL-SP9a								

Table 4-2. (continued).

Date	Feed mixture	Time	Slag tap, start/stop	Furnace product samples					V,T Traverse	MMT/particulate (M5/29)	HCl/Cl ₂ (M26)	Dioxins (M23)
				Slag	Metal	Scrubber	Cyclone	Baghouse				
12-Apr	Nom-60	2340							FO, start, Nom-60-M2-3			
		2344							Stop, Nom-60-M2-3			
		2350								FO, start, Nom-60-M5/29-2		
13-Apr	Nom-60	0020								Stop, Nom-60-M5/29-2		
		0031							FO, start, Nom-60-M2-4			
		0037							Stop, Nom-60-M2-4			
		0050				INEL-S14	INEL C-4-1 INEL C-4-2	INEL B-11				
		0052							FO, start, Nom-60-M2-5			
		0059							Stop, Nom-60-M2-5			
		0103								FO, start, Nom-60-M5/29-3		
		0110		INEL-SP9b								
		0129								Stop, Nom-60-M5/29-3		
		0140	SP10	INEL-SP10a								
		0144							FO, start, Nom-60-M2-6			
		0149							Stop, Nom-60-M2-6			
		0410				INEL-S15	INEL C-5	INEL B-12				
		0530					None	INEL B-13				
13-Apr	Nom-60	0715							IF, start, SP-1			
		0723							Stop, SP-1			

Table 4-2. (continued).

Date	Feed mixture	Time	Slag tap, start/stop	Furnace product samples					V,T Traverse	MMT/particulate (M5/29)	HCl/Cl ₂ (M26)	Dioxins (M23)
				Slag	Metal	Scrubber	Cyclone	Baghouse				
13-Apr	Nom-60	0800				INEL-S16	INEL C-6	INEL B-14				
		0930				INEL-S17						
		0942										
		0950					INEL C-7	None				
		0956							IF, start, SP-2			
									Stop, SP-2			
13-Apr	Nom-50	1005		INEL-SP10b								
		1025		INEL-SP10c								
		1045		INEL-SP10d								
		1102		INEL-SP10e								
		1108							IF, start, SP-3			
		1120	SP11	INEL-SP11a					Stop, SP-3			
		1135				INEL-S18	INEL C-8	None				
		1143		INEL-SP11b								
		1200		INEL-SP11c								
13-Apr	Nom-40	1232		INEL-SP11d								
		1300		INEL-SP11e								
		1330		INEL-SP11f								
		1400		INEL-SP11g		INEL-S19	INEL C-9	None				
13-Apr	S-40	1430		INEL-SP11h								
		1450							FO, start, S40-M2-1			
		1455							Stop, S40-M2-1			
		1530				INEL-S20						
		1600		INEL-MP1b	INEL MP1a							
		1605		INEL-SP11i								
		1610					INEL C-10	None				
		1704		INEL-SP11j								

Table 4-2. (continued).

Date	Feed mixture	Time	Slag tap, start/stop	Furnace product samples					V,T Traverse	MMT/particulate (M5/29)	HCl/Cl ₂ (M26)	Dioxins (M23)
				Slag	Metal	Scrubber	Cyclone	Baghouse				
13-Apr	S-40	1730	Stop				INEL C-11	None				
13-Apr	S-0	1905							BO, start, S0-BO-M2-1			
		1915							Stop, S0-BO-M2-1			BO, start, S0-BO-M23-1
		2000				IWPF-S1	IWPF C-1	None				
		2044										SO, start, S0-S-M23-1
		2200				IWPF-S2	IWPF C-2	None				
		2327										Stop, S0-BO-M23-1
14-Apr		0.00				IWPF-S3	IWPF C-3	None				
14-Apr	S-0	0018							FO, start, S0-FO-M2-1			
		0028							Stop, S0-FO-M2-1			
		0127									BO, start, S0-BO-M26-1	
		0132									FO, start, S0-FO-M26-1	
		0137									Stop, S0-BO-M26-1	
		0142									Stop, S0-FO-M26-1	
		0200	Start	IWPF-SP12a		IWPF-S4	IWPF C-4	None			BO, start, S0-BO-M26-2	
		0210									Stop, S0-BO-M26-2	
		0211									FO, start, S0-FO-M26-2	
		0221									Stop, S0-FO-M26-2	

Table 4-2. (continued).

Date	Feed mixture	Time	Slag tap, start/stop	Furnace product samples					V,T Traverse	MMT/particulate (M5/29)	HCl/Cl ₂ (M26)	Dioxins (M23)
				Slag	Metal	Scrubber	Cyclone	Baghouse				
14-Apr	S-0	0229										Stop, S0-S-M23-1
		0238									BO, start, S0-BO-M26-3	
		0245							IF, start, S0-IF-M2-1			
14-Apr	S-0	0248									Stop, S0-BO-M26-3	
		0300							Stop, S0-IF-M2-1			
		0307							FO, start, S0-FO-M2-2			
		0314							Stop, S0-FO-M2-2			
		0315		IWPF-SP12b								
		0400				IWPF-S5	IWPF C-5	None				
14-Apr	C-20	0441								SO, start, C20-M29-1		
		0520		IWPF-SP12c								
		0610				IWPF-S6	IWPF C-6	None				
		0635								SO, start, C20-M29-1		
14-Apr	C-40	0810				IWPF-S7	IWPF C-7	None				
		0930		IWPF-SP12d		IWPF-S8	IWPF C-8	None				
		1000										
		1030	Stop									
		1200				IWPF-S9	IWPF C-9	None				
		1450				IWPF-S10						

collected for HCl, Cl₂, HF, and F₂ analysis using a modified EPA Method 26 procedure. Total particulate and metals determinations were done using the draft EPA Method 29, modified to include measurement of total particulate in addition to metals. Dioxin tests were conducted using EPA Method 23 at the baghouse outlet and at the stack. Additional details regarding the offgas measurement procedures and constraints are provided in Appendix C.

The continuous monitoring and Fourier Transform Infrared (FTIR) sample locations and times are shown in Table 4-3, and the sample locations and times for the manual measurements (EPA Methods 1, 2, 5/29, 23, and 26) are summarized in Table 4-4. The locations and times for these measurements varied in order to obtain test data at different locations during the tests. Measurements in the furnace and at the furnace outlet were conducted to characterize furnace plenum and furnace outlet conditions. The performance components in the APCS, including the thermal oxidizer, baghouse, acid gas scrubber, charcoal filter, and HEPA filter were evaluated by sampling at the baghouse outlet and at the stack.

Accurate temperature measurements in the furnace plenum and thermal oxidizer inlet and outlet locations required the use of thermal radiation-shielded suction pyrometer measurement devices, also called high velocity temperature measurement devices. The general procedure and typical equipment used for these types of measurements is described in EPRI CS-5552 (Sotter et al. 1988).

Velocity measurements in the high temperature regions were conducted using the same procedures specified for velocity measurements in the cooler regions, per EPA Method 2. The high levels of particulate upstream of the baghouse caused increased plugging, which was monitored and required frequent removal, especially if the particulate was at or above its melting temperature range.

Dioxin measurements were conducted at the baghouse outlet and at the stack to evaluate (a) the potential for forming dioxins upstream from the baghouse during cool-down from the thermal oxidizer, and (b) the ability of the downstream scrubber, charcoal filter, and HEPA filter to control and remove any such dioxins. Dioxin measurements followed EPA Method 23 procedures. Single sampling runs, each four hours long, were conducted at each location. The Method 23 runs were only conducted during the S-0 feed mixture test condition, because that mixture contained the highest concentrations of chlorides and organics and represented a worst-case scenario for the melter and APCS.

Argonne National Laboratory-East and Clean Air Engineering conducted FTIR gaseous analysis at the furnace outlet, baghouse outlet, and stack (Mao and Dermirgian 1995). Species monitored included CO, CO₂, NO_x, and SO₂, and various other polar chlorinated and nonchlorinated hydrocarbons. The draft FTIR sampling and analysis procedure that Argonne and Clean Air Engineering has submitted to the EPA was used for these measurements.

Speciated analysis of some gases was conducted using a Microtechnologies Inc. (MTI) Q300L gas chromatograph (GC), with three capillary columns and electrical conductivity detectors. Early in the test program the GC inlet filter system failed, allowing moisture to infiltrate the instrument, damaging two of the detectors. The GC was unavailable for the remainder of the tests. Data collected prior to the system failure is under evaluation to determine its validity.

Table 4-3. Chronology of gaseous continuous monitoring.

Date		Time	CEMS ^a	FTIR	Comments
10 April	WHC2-B	1725		Start, stack	Started TEAM ^b
11 April	Nom-90	2045			
		0908		Stop	TEAM timeout
		0912		Start, stack	Restarted TEAM
		2344		Stop	TEAM DDE timeout
12 April	Nom-80	0015			
		0030	Start, stack		PG, THC
		0048		Start, stack	TEAM restart
		0252	Stop		
		0254		Stop	Run background, blank test
		0319		Start, furnace	
		0347	Start, stack		PG, THC
		0412	Start, stack		HCl, 8:1 DF
12 April	Nom-70	0420			
		0609	Stop		All
		0815	Start, stack		All
		0915	Stop		
		1130	Start, furnace out		PG, THC
		1352	Stop		
		1413	Start, in-furnace		O ₂ -NO _x , 22:1 DF
		1500	Stop		
		1509	Start, in-furnace		THC only, 22:1 DF
12 April	Nom-60	1530			
		1538	Stop		
		1543	Start, in-furnace		O ₂ , CO ₂ , THC
		1655		Stop	TEAM down
		1702	Stop		
		1709	Start, in-furnace		O ₂ -NO _x , 22:1 DF
		1714	Stop		
		1934	Start, in-furnace		O ₂ -NO _x , 22:1 DF
		2200		Start, stack	

Table 4-3. (continued).

Date		Time	CEMS ^a	FTIR	Comments
12-April	Nom-60	2011	Stop		
		2330	Start, in-furnace		O ₂ -NO _x , 22:1 DF
		2334	Stop		
13 April		0152	Start, in-furnace		O ₂ , CO ₂ , THC, 22:1 DF
		0152		Start furnace	
		0217	Stop		
		0224	Start, in-furnace		O ₂ -NO _x , 22:1 DF
		0224		Start stack	
		0312	Stop		
13 April	Nom-50	0605			
		1010	Start, in-furnace		O ₂ -NO _x , 22:1 DF
13 April	Nom-40	1015			
		1022	Stop		
13 April	S-40	1140			
		1348	Start, in-furnace		O ₂ -NO _x , 22:1 DF
		1438	Stop		
		1504	Start, stack		PG, THC, HCl, 8:1
		1505		Start Bh out	Nondiluted, chilled sample
		1600		Continued Bh out	Used dilution system
		1633	Stop		
		1635		Start stack	
		1650	Start, Bh out		PG, THC, HCl, 8:1
		1729	Stop		
13 April	S-0	1736			
		1836			Switched to Entropy dilution probe for comparison DF = 19 to 20)
		2030	Start, in-furnace		O ₂ -NO _x , 22:1 DF
		2130		Start stack	
		2225		Start furnace	
		2235		Stop	TEAM timeout for DDE

Table 4-3. (continued).

Date		Time	CEMS ^a	FTIR	Comments
13-April	S-0	2242	Stop		
		2246	Start, furnace out		O ₂ , CO ₂ , THC, 22:1 DF
		2255		Start	
		2357	Stop		
14 April		0034		Start furnace	
		0059	Start, stack		PG, THC
		0150		Ambient air	
		0209	Stop		
		0237	Start, Bh out		THC, 22.1 DF
		0237	Start, stack		O ₂ -NO _x
		0250		Start Bh out	
14 April	C-20	0345			
14 April	C-40	0450			
		0522	Stop, Bh out		
		0522	Stop, stack		
		0607	Start, Bh out		PG, THC, 22:1
		0624			PG, THC, 1.1 (NO _x was offscale)
		0737	Stop		
		0742	Start, Bh out		PG, THC, 1.1 (NO _x on 500 ppm fullscale)
14 April	Nom-90	0830			Without metals or C materials
		0953		Stop	Stop test
		1011	Stop		

a. CEMS = continuous emissions monitoring system.

b. TEAM = toxic air emission monitor master program.

Table 4-4. Chronology of manual sampling and measurements.

Procedure: Velocity Traverse (Method 2), Temp. Traverse [Method 2 or suction pyrometer (SP)], MMT/Particulate (Method 5/29), HCl/Cl₂/HF/F₂ (Method 26), Dioxins (Method 23).

Date	Feed material	Location	Procedure	Start time	Stop time	Run number	Comments
12-Apr 95	Nom-70	Furnace Out	V, T Traverse	1425	1430	Nom-70-M2-1	dP=0.10; T=1,462°F
12-Apr 95	Nom-70	Furnace Out	MMT/ Particulate	1452	1530	Nom-70-M5/29-1	
12-Apr 95	Nom-60	Furnace Out	V, T Traverse	1855	1900	Nom-60-M2-1	dP=0.244; T=1,495°F
12-Apr 95	Nom-60	Furnace Out	MMT/ Particulate	2000	2034	Nom-60-M5/29-1	
12-Apr 95	Nom-60	Furnace Out	V, T Traverse	2013	2018	Nom-60-M2-2	dP=0.166; T=1,758°F
12-Apr 95	Nom-60	Furnace Out	V, T Traverse	2340	2344	Nom-60-M2-3	dP=0.0815; T=1,504°F
12-Apr 95	Nom-60	Furnace Out	MMT/ Particulate	2350	0020	Nom-60-M5/29-2	
13-Apr 95	Nom-60	Furnace Out	V, T Traverse	0031	0037	Nom-60-M2-4	dP=0.115; T=1,441°F
13-Apr 95	Nom-60	Furnace Out	V, T Traverse	0052	0059	Nom-60-M2-5	dP=0.0252; T=1,160°F
13-Apr 95	Nom-60	Furnace Out	MMT/ Particulate	0103	0129	Nom-60-M5/29-3	
13-Apr 95	Nom-60	Furnace Out	V, T Traverse	0144	0149	Nom-60-M2-6	dP=0.0312; T=1,185°F
13-Apr 95	Nom-50	In-Furnace		0715	0723	-	T=933°F
13-Apr 95	Nom-50	In-Furnace		0942	0956	-	T=1,682°F
13-Apr 95	Nom-40	In-Furnace		1108	1120	-	T=1,027°F
13-Apr 95	S-40	Furnace Outlet	V, T Traverse	1450	1455	S40-M2-1	dP=0.0552; T=1,791°F
13-Apr 95	S-0	Baghouse Outlet	V, T Traverse	1905	1915	S0-B0-M2-1	dP=0.914; T=156°F
13-Apr 95	S-0	Baghouse Outlet	Dioxin sampling run	1915	2327	S0-B0-M23-1	dP=0.1336; T=165°F
13-Apr 95	S-0	Stack	Dioxin sampling run	2044	0229	S0-S-M23-1	dP=0.4983; T=94°F
14-Apr 95	S-0	Furnace Outlet	V, T Traverse	0018	0028	S0-F0-M2-1	dP=0.0657; T=1,649°F
14-Apr 95	S-0	Baghouse Outlet	HCl/Cl ₂ /HF/F ₂ Sampling run	0127	0137	S0-B0-M26-1	
14-Apr 95	S-0	Furnace Outlet	HCl/Cl ₂ /HF/F ₂ Sampling run	0132	0142	S0-F0-M26-1	
14-Apr 95	S-0	Baghouse Outlet	HCl/Cl ₂ /HF/F ₂ Sampling run	0200	0210	S0-B0-M26-2	
14-Apr 95	S-0	Furnace Outlet	HCl/Cl ₂ /HF/F ₂ Sampling run	0211	0221	S0-F0-M26-2	
14-Apr 95	S-0	Baghouse Outlet	HCl/Cl ₂ /HF/F ₂ Sampling run	0238	0248	S0-B0-M26-3	
14-Apr 95	S-0	In-Furnace	V, T Traverse	0245	0300	S0-IF-M2-1	T=818°F
14-Apr 95	S-0	Furnace Out	V, T Traverse	0307	0314	S0-F0-M2-2	dP=0.0438; T=1,313°F
14-Apr 95	C-20	Stack Outlet	MMT/ Particulate	0441		C20-M29-1	dP=0.2152; T=93°F

4.5 Sample Analyses

Analytical results of the process samples were used to (a) calculate mass balances, (b) calculate distribution and fate of metal and TRU surrogate elements in the feed, (c) determine the hazardous or nonhazardous character of the secondary process streams, and (d) evaluate the physical and chemical properties of the vitrified slag and metal phases.

Process sample analyses were conducted by the ALRC analytical laboratory. Standard EPA-promulgated methods were followed whenever possible. In all cases, the most applicable methods were used to achieve the most accurate results with the lowest possible detection limits. Procedures not covered by standard EPA methodology were based on extensive experience gained from several previous similar melting campaigns, including the BWID Phase 1 test program.

5. TEST OBSERVATIONS AND MELTER SYSTEM PERFORMANCE

The FY 1995 arc melter demonstration test program consisted of a shakedown test for the modified APCS (without melter operation) and continuous melting tests on six BWID and four IWPF feed mixtures. The shakedown test was conducted on March 6, 1995, about four weeks before the melting test series. The melter was not operated during the shakedown test, which was performed to thermally cure the refractory in the refractory-lined ductwork and thermal oxidizer and verify operation of the remainder of the system. The full system demonstration melting tests were conducted April 11 through 14, 1995. The melter was preheated April 10 and 11, immediately preceding the initial test on the Nom-90 mixture. The preheat interval included 10 hours of an unrelated series of melting tests conducted in cooperation with the Westinghouse Hanford Company (WHC), followed by 10 hours to clean out the furnace and APCS using a feed mixture of calcium-aluminum-silicate.

5.1 Air Pollution Control System Shakedown Test

This 12-hour test was conducted March 6, 1995. Primary objectives for the test were to (a) completely cure the refractory in the new thermal oxidizer and refractory-lined ductwork, (b) establish operating parameters for the new APCS, and (c) evaluate control of the primary and secondary combustion air to the furnace and thermal oxidizer, respectively. The melting furnace was not operated during the shakedown test. The refractory in the thermal oxidizer and connecting ductwork had been partially cured to 600°F before installation, but required complete curing to 1,600°F, at a rate of 50°F/h. During this heating interval, the crew was made familiar with the new APCS control panel, and various operational parameters were investigated.

Key parameters identified and resultant significant findings included the following:

- *Exit temperatures from the thermal oxidizer and evaporative gas cooler (EGC)*—At the base of the thermal oxidizer, a 3-MMBtu burner was directed counter current to the exhaust gas flow, and was designed to operate at sufficient fire to provide an exit gas temperature of 1,800–2,250°F. The EGC exit temperature was to be maintained at approximately 500°F to accomplish the dual task of cooling the offgas sufficiently to protect the bag filters in the baghouse, but not so cool as to encourage condensation within the APCS. The balance between the thermal oxidizer output temperature and EGC control level was successfully demonstrated.
- *O₂ concentration at the EGC exit*—The concentration of O₂ at the EGC exit indicated several process conditions, such as the efficiency of the thermal oxidizer in burning the CO from the furnace, the flowrate of secondary combustion air into the thermal oxidizer, and even the richness of the gas and air mixture for the three natural gas burners. Each of these parameters was balanced to maintain roughly 7% O₂ concentration at the EGC exit.
- *Baghouse inlet temperature*—The baghouse inlet temperature was to be maintained between 220 and 300°F, a safe region that would avoid condensation on the bag filters but prevent destruction of the filters by excessive temperature. In operation, the baghouse inlet temperature was typically even lower, ranging between 170–230°F due to additional dilution air used for process control.

- *Static pressure at the acid gas scrubber and cooler-condenser*—The fiberglass acid gas scrubber and cooler-condenser columns were rated for a maximum negative static pressure of 22-in. WC. An excessive negative pressure could cause implosion of the fiberglass columns. An operating negative pressure of ~20-in. WC was determined to be satisfactory.
- *Pressure drop over the fan*—The 50-hp variable speed induced draft fan was designed to run at approximately negative 25-in. WC, so fan speed and system pressure had to be balanced to provide the appropriate pressure drop for the fan to provide the necessary flowrates in the APCS and melter without underpressurizing the scrubber, condenser, or melter. System pressure and fan speed were successfully balanced to maintain the appropriate operating conditions.

As a result of the shakedown test, several modifications were made to the system prior to the Phase 2 demonstration melting tests. The modifications are summarized below:

- Based on calculations of combustible content in the various feed mixtures, primary combustion air flow to the arc furnace at flowrates in excess of 100 scfm would be required. The flowrate from the primary combustion air blower was found to be only 40–50 acfm, so a larger blower was installed.
- Secondary combustion air was initially provided to the thermal oxidizer by splitting the output of the 5-hp cooling air blower. The single blower provided both secondary combustion air and cooling air used downstream of the spray quench section. This design was unsuccessful because of insufficient secondary combustion air flowrate and pressure. The addition of an orifice plate in the cooling air line to provide more backpressure to the cooling air did not improve the situation. To resolve the problem, the secondary combustion air inlet lines were plumbed to the existing blower for the 3-MMBtu burner on the thermal oxidizer. The new configuration required balancing the burner firing rate with the secondary combustion air requirements because air was now provided to both lines by the same blower. This configuration worked well except when feedrates of organics to the melter increased the demand for secondary air beyond its capability.
- Condensation within the baghouse was recognized as a potential problem, primarily from the water of combustion produced by the natural gas burners during system preheat. As a means to preheat the baghouse before firing the burners, an indirect-fired air preheater was installed in the cooling air line, upstream from its connection with the main APCS ductwork. This preheater would be fired for a sufficient time to bring the baghouse inlet temperature to 220°F, at which time the APCS burners would be fired and the cooling air preheater could be shut off. The cooling air line would then revert back to its original design to provide cooling air to the APCS upstream from the baghouse. During the demonstration tests, this operated as desired.
- During initial start-up of the APCS, it is necessary to provide additional air flow to the fan by means of a bypass valve, which is open to the atmosphere and allows ambient air into the APCS. This valve provides sufficient flow to the fan to prevent excessive negative pressure in the APCS at times when there is insufficient gas flowrate from the furnace, thermal oxidizer, and EGC system. The valve was originally located at the cooling air inlet section of the APCS, upstream from the baghouse. Adding ambient-temperature air would be counterproductive to the efforts made to preheat the baghouse. Therefore, the bypass valve was moved to the scrubber exit, downstream from the baghouse, where it performed as desired.

5.2 Demonstration Melting Tests

The furnace preheat interval was started on April 10, when the system was operated for about 10 hours on Westinghouse Hanford Company (WHC) feed material. This preheat feed interval was actually part of a separate series of melting tests being conducted on low-level tank waste in cooperation with WHC, but also served as the initial preheat interval for the Phase 2 INEL tests. Cooling water to the furnace shell was shut off to minimize heat loss from the furnace refractory overnight. The furnace was restarted on April 11 and operated for ~10 hours on a calcium-aluminum-silicate feed mixture to complete the furnace preheat and clean out residual material from the previous melting tests. The INEL surrogate waste mixtures (Nom-90, Nom-80, Nom-70, Nom-60, Nom-50, Nom-40, S-40, S-0, C-20, and C-40) were then melted in succession on April 11-14, 1995.

An overview of the test program is shown in Table 5-1. The continuous demonstration melting tests totaled 56 hours. The total operation time, including startup procedures, preheat, melting operation, and shutdown was approximately 84 hours.

Feed totals for each mixture and overall slag tap totals are included in Table 5-1. Global mass balances over the furnace for the preheat, BWID, IWPF, and cleanout feed intervals were calculated. Separate balances for each individual feed mixture are not possible owing to the (a) continuous operation during feed change-overs, intermittent slag, and metal tapping and (b) incomplete recovery of APCS solids until the end of the test series. The slag weight distribution between the BWID and IWPF feed intervals is based on the actual weight of slag collected during each interval. However, the weight distributions for the metal and APCS solids from each feed interval were calculated from the amounts collected partway through the test program and at the end of the test program.

The metal product weights for each feed interval were calculated based on the metal content in the BWID and IWPF feeds, excluding those metals likely to oxidize to the slag (Al) or volatilize to the offgas (Pb). Thus, the total expected metal product from the BWID and IWPF feed mixtures was 1,424 lb. The difference between the actual metal tapped from the furnace (1,826 lb) and the expected metal product weight (1,424 lb) was attributed to reduction of iron from iron oxide in the feed mill scale or soil.

The APCS solids presented a more difficult rationalization for the final material balance calculations. Because bridging occurred over the rotary airlock valves in the cyclone and baghouse, and the thermal oxidizer base and ductwork could not be sampled until after the test, the majority of the APCS solids were collected after the completion of the test programs. This material represented a mixture of the residues produced during the individual feed intervals, which had to be divided proportionately between the feed mixtures (Table 5-2). Previous melting experience with the preheat and cleanout feed materials provided the estimated particulate percentages for each of those feeds. The remaining particulate was thus assigned to the BWID and IWPF feed intervals, which represented 8.9 wt% of the total BWID and IWPF feed. These percentages were then used to apportion the appropriate weights of the post test particulate by feed mixture, and the totals were included in the final material balance calculations. Trends of furnace power, feedrate, slag tap temperature, stack gas flowrate and selected APCS temperatures are shown for the test program in Appendices D, E, and F.

5.3 Preheat and Cleanout Melts

Two preheat and cleanout melts were conducted prior to the demonstration melting tests. These two melts are described separately in the following sections.

Table 5-1. Global summary of demonstration tests.

Feed type	Test day	Test start/stop times	Operating run duration ^a (h)	Average power ^a (kW)	Total energy (MWh) ^b	Total feed material (lb)	Average feedrate ^a (lb/h)	Average slag tapping rate (lb/h)	Energy Efficiency (kWh/lb)
Preheat 1 ^d	10-Apr	0735-1724	9.82		1,640	2394	244	215	
Preheat 2 ^e	11-Apr	1007-1940	9.55		3,045	4424	463	362	
Preheat interval			19.37		4,685	6818			
Nom-90	11-Apr	2045-0015	3.50	347	1,212	1,495	427	462	0.81
Nom-80	12-Apr	0015-0420	4.08	159	638	1,497	367	383	0.43
Nom-70	12-Apr	0420-1530	11.2	175	1,941	3,998	358	212	0.49
Nom-60	12-Apr	1530-0235	11.1	193	2,122	3,976	359	268	0.54
Soil + lime	13-Apr	0410-0605	1.92	90.4	178	500	260	-	0.35
Nom-50	13-Apr	0605-1015	4.17	194	796	1,486	356	-	0.55
Nom-40	13-Apr	1015-1130	1.25	221	275	977	782	547	0.28
BWID interval			37.2		7,162	13,929			
S-40	13-Apr	1140-1736	5.93	196	1,159	1,594	269	-	0.73
S-0	14-Apr	1736-0345	10.2	147	1,493	1,098	108	-	1.36
C-20	14-Apr	0345-0525	1.67	224	380	300	180	-	1.25
C-40	14-Apr	0525-0615	0.83	123	100	497	599	1,005	0.20
IWPF interval			18.6		3,132	3,489			
Cleanout	14-Apr	0615-1440	8.42		2,012	3,286	390	333	
IWPF + Cleanout			27.0		5,144	6,775			
Totals (for all days)			83.5		16,991	27,522			
Averages (for all days)				186	1,413		369	421	0.64

Table 5-1. (continued).

Feed type	Slag temp. at taphole (°C)		Total slag tapped (wt% of initial feed mass)		Total metal product (wt% of initial feed mass)		Total APCS solids (wt% of initial feed mass)	
	Average	Range	(lb)		(lb)		(lb) ⁱ	
Preheat 1 ^d			2,114	88.3				
Preheat 2 ^e			3,458	78.2				
Preheat interval			5,572	81.7	0	0.00	277	4.06
Nom-90	1,721	1,450-1,880	1,616	108				
Nom-80	1,597	1,400-1,850	1,564	104				
Nom-70	1,524	1,350-1,700	2,368	59.2				
Nom-60	1,495	1,350-1,675	2,970	74.7	1,004	25.3		
Soil + lime	no tap	no tap						
Nom-50	no tap	no tap						
Nom-40	1,472	1,400-1,550	684	70.0				
BWID interval			9,202	66.1	1,403	10.1	1,233	8.85
S-40	no tap	no tap						
S-0	no tap	no tap						
C-20	no tap	no tap						
C-40	1,641	1,400-1,725	834	168				
IWPF interval			834	23.9	11.0	0.32	309	8.86
Cleanout			2,804	85.3	412	12.5	66.0	2.01
IWPF + Cleanout			3,638	53.7	423	6.24	375	5.54
Totals			18,412		1,826		1,885	
Averages	1,575			66.9		6.63		6.85

Table 5-1. (continued).

Feed type	Total amount of vaporized material		Electrode consumption			Waste mixture volume reduction	TCLP Leachability (pass/fail)		Furnace static pressure (in. WC)
	(lb) ^f	(wt% of initial feed mass)	(lb)	(lb/MWh)	(lb/ton feed material)		Slag	Total particulate solids	
Preheat 1 ^d	141	5.88	-	-	-	5.31	-	-	
Preheat 2 ^e	261	5.91	-	-	-	3.09	-	-	
Preheat interval	402	5.90							
Nom-90	212	14.2	-	-	-	1.87	Pass	-	-0.9
Nom-80	258	17.2	-	-	-	2.31	-	-	-0.7
Nom-70	817	20.4	-	-	-	3.90	-	-	-1.4
Nom-60	948	23.8	-	-	-	3.45	Pass	Pass	-0.8
Soil + lime	57.6	11.5	-	-	-	ND ^g	-	-	-1.3
Nom-50	408	27.5	-	-	-	no slag tap	-	-	-1.4
Nom-40	305	31.3	-	-	-	4.36	Pass	-	-1.4
BWID interval	3,005	21.6							
S-40	627	39.3	-	-	-	no slag tap	-	Pass	-1.5
S-0	681	62.0	-	-	-	no slag tap	-	Pass	-1.5
C-20	216	71.9	-	-	-	ND	-	-	-1.3
C-40	270	54.4	-	-	-	ND	Pass	-	-1.4
IWPF interval	1,793	51.4							
Cleanout	173	5.28	-	-	-	2.45		Fail for Cd, Pb ^h	-1.5
IWPF + Cleanout	1,967	29.0							
Totals	5,374		289	18.6	21.0				
Averages		19.5				2.57			-1.3

a. Only for the indicated test times, and includes some occasional short periods when feeding or power was turned off.

b. From facility data acquisition system (DAS) except for the WHC-2 and TH2 feeds which were taken from the manually recorded Furnace Log.

c. From intermittent manual temperature measurements during velocity/flowrate traverses.

d. Westinghouse Company feed mixture B.

e. Calcium-aluminum-silicate feed mixture.

f. Calculated using the composition for the feed materials.

g. ND = no data

Table 5-1. (continued).

Feed type	Average offgas temperatures (°F)				Offgas flowrates (dscfm) ^c			Global mass balance closure
	Furnace plenum ^c	Furnace outlet ^c	Thermal oxidizer outlet ^b	Bh outlet ^b	Furnace outlet	Bh outlet	Stack	
Preheat 1 ^d	-	-	-	-	-	-	-	0.91
Preheat 2 ^e	-	-	-	-	-	-	-	
Preheat interval								
Nom-90	-	1,495	1,736	232	-	1,582	2,372	
Nom-80	-	-	1,919	231	-	1,422	2,069	
Nom-70	-	1,494	1,800	187	182	1,093	1,703	
Nom-60	-	1,424	1,999	190	177	1,221	1,909	
Soil + lime	-	-	1,922	173	-	1,133	1,853	
Nom-50	1,308	-	1,855	204	-	1,334	1,928	
Nom-40	1,027	-	2,070	206	-	1,195	1,870	
BWID interval								1.05
S-40	-	1,791	2,086	187	-	1,139	1,786	
S-0	818	1,481	1,956	174	90.8	945	1,516	
C-20	-	-	2,118	200	-	1,166	1,619	
C-40	-	-	2,017	187	-	1,005	1,700	
IWPF interval								0.84
Cleanout	-	-	-	-	-	915	1,532	
IWPF + Cleanout								0.94
Totals								0.99
Averages	1,051	1,537	1,952	197	150	1,179	1,821	

h. The post test baghouse residue is what failed the TCLP for Cd and Pb and this would have included residue from each of the feed mixtures.

i. The APCS solid mass and fraction of initial feed mass for individual feed intervals was not measured, but was estimated from the measured total APCS solids collected for the entire demonstration test period.

Table 5-2. Distribution of residues (solids) collected from the APCS, by feed mixture.

Feed interval	Feed material total (lb)	APCS solids actually collected (lb)	Portion of the feed material that distributed to the APCS (wt%)	Portion of total APCS solids apportioned to each feed interval (lb)
Preheat 1	2,394	14	6.0 ^a	144
Preheat 2	4,424	103	3.0 ^a	133
BWID	13,929	309	8.9 ^b	1,234
IWPF	3,489	145	8.9 ^b	309
Cleanout	3,286	0	2.0 ^a	66
Total	27,522	1,885	—	1,885

a. Estimated based on prior operating experience.

b. Calculated by difference from the total collected amount.

5.3.1 Preheat and Cleanout Melt 1

The first preheat and cleanout melt began at 0735 on April 10, 1995, and continued until 1720 that same day. Over 2,300 lb of WHC feed material was melted. This material, composed to produce a low-melting-temperature boro-silicate glass, was melted at temperatures ranging from 1,300–1,540°C, with the lower end of the range the desired temperature. The moderate feedrate (approximately 400 lb/h average when the feeder was operating), power input (roughly 200 kW average), and tap temperature were ideal for gradually bringing the furnace refractories, thermal oxidizer, and APCS up to operating temperature. This melt was also conducted to develop operating procedures using the modified transformer configuration (Appendix B, Table B-1, Configuration 2). The modified transformer configuration provided lower power input to the furnace by lowering the secondary voltage supply. This was attempted to permit melting of slags or glasses with lower melting temperatures. Previous experience with low-melting-temperature slags demonstrated that transformer Configuration 1 provided excess power to the furnace, and excessive melt superheating was unavoidable in that configuration. This caused excess volatilization of alkalis and other species from the slag.

The transformer was configured to provide four lower voltage taps, which still permitted flexibility in power input and electrode position, but simply over a lower range. The furnace was started on a triangle of crushed graphite, as successfully practiced in the BWID Phase 1 tests. Approximately 500 lb of feed material was charged into the furnace and leveled under the electrodes. A triangle of crushed graphite was then placed on top of the feed to provide a conductive path between each electrode. Up to 800 lb of residual slag from previous melting tests remained in the furnace before startup. The furnace was started on this pool of frozen slag, which was remelted and tapped from the furnace during the preheat melt. The furnace was operated on Taps C and D (phase-to-phase voltages of 124 and 95 V, respectively) during separate intervals to determine optimum operating conditions that would permit balanced feedrate, melting rate, and corresponding tapping rate.

Semicontinuous tapping was maintained from about 1240–1500 at a power level of ~250 kW, with feedrates up to 570 lb/h. Power was decreased to ~175 kW at 1500, in an attempt to establish steady-state

conditions with an even lower power level. This dictated a slower feedrate (350–400 lb/h), but semicontinuous tapping was again maintained, though the closed-tap intervals were longer because of the slower feedrate. At 1445, furnace pressure increased slightly from the desired negative 0.5-in. WC, even going positive at times, which indicated plugging of the furnace offgas exit duct. Adjustments were made to the APCS to increase the draft from the furnace, but the plugging became more pronounced as the test progressed. Feed was stopped shortly after 1700, while power was maintained until 1720 to remove the cold top. Nine inches of glass (approximately 800 lb) remained in the furnace at the conclusion of the test. Following the melting test, the furnace transformer configuration was changed back to the higher voltage tap settings in preparation for the demonstration melting tests. Burner 1 was removed from the furnace offgas duct to investigate the degree of plugging within the duct. A layer composed primarily of low-melting sodium and boron compounds blocked the duct immediately below the intersection of the furnace exit duct and the crossover-duct. A steel rod was inserted to knock out the obstruction, which fell back into the furnace. Burner 1 was reinstalled, and the remainder of the APCS was left on overnight. The cooling water to the furnace shell was shut off to reduce heat loss from the furnace refractory.

5.3.2 Preheat and Cleanout Melt 2

The second preheat and cleanout melt began at 1007 on April 11, 1995, and continued until 1940 the same day. Over 4,400 lb of a calcium-aluminum-silicate mixture, composed of limestone (CaCO_3), Bayer alumina (Al_2O_3) and silica sand (SiO_2), was melted. This material, with a molar basicity ratio of one, produced a fluid slag at temperatures in excess of 1,700°C at times, and possessed good solvent properties for the residues suspected to remain in the furnace from previous melting tests. This melting interval also prepared the remainder of the system by again bringing the individual components in the APCS up to operating temperature and establishing steady flowrates for the cooling water, compressed air supply, and induced draft fan.

The furnace was started in similar fashion to the first preheat melt conducted the previous day. Residual slag in the furnace was first remelted before initiating continuous feeding. Semicontinuous tapping was established by 1347 and maintained for the duration of the melt. Feedrates up to 1,000 lb/h were successfully demonstrated, with an average power input of 330 kW. Tap setting D (phase-to-phase voltage of 239 V) from transformer Configuration 1 (Table B-1) was used for the entire melting test. Furnace pressure was maintained at -0.5 in. WC throughout the melt, with no indication of offgas plugging. This was not unexpected, because the calcium-aluminum-silicate feed was sized to limit particulate entrainment and contained none of the volatile constituents found in the WHC feed material. Feed was stopped at 1905, the cold top was removed by 1940, and furnace power was temporarily shut off at 2000 in preparation for the start of the demonstration tests. A molten pool of the calcium-aluminum-silicate feed material remained in the furnace to ease the transition to the BWID nominal series feed mixtures.

Because the furnace was operated continuously from the start of the second preheat melt, at 1007 on April 11, until the end of the cleanout melt, at 1440 on April 14, the discussion of the demonstration melting tests reflects this time interval. The first preheat melt, conducted on April 10, yielded operating data and provided experience with the lower transformer tap settings, which proved valuable during the demonstration melting tests. The experience gained in recognizing and correcting the offgas plugging encountered during the first preheat melt prepared the crew for similar conditions during the demonstration melting tests. Furnace and test parameters, such as total feed, input power, and energy consumption were summarized for each feed interval during the demonstration tests. Calculation of the total electrode consumption, in terms of power or feed, includes the power and feed totals from the first preheat melt because the electrodes could not be easily removed and weighed following this melt.

5.4 Buried Waste Integrated Demonstration Melting Test Interval

The BWID demonstration melting test interval commenced at 2045 on April 11, 1995. The furnace was operated continuously for 37 hours on a succession of six surrogate waste and soil compositions. The discussion of the operations during each feed interval follows in chronological order. System parameters, including furnace power input, feedrate, slag tap temperature, and stack gas flowrate are included in Appendix E, Figures E-1-E-5.

5.4.1 BWID Nom-90 Feed Interval

Following the second preheat and cleanout melt, the first batch of the Nom-90 feed mixture was loaded into the receiving bin and conveyed to the meter bin. Segments were added to the north and middle electrodes while power was off. The weighing crew (lift operator and sample manager) composited the final Nom-90 feed mixture, weighing roughly 500 lb/batch, immediately before loading it in the receiving bin. This procedure, followed for the duration of the demonstration tests, was designed to provide flexibility in the preparation of the final surrogate waste mixtures. The duration of the individual feed intervals could not be predicted, and rapid changes in feed composition were anticipated. The final feed preparation system used for the demonstration tests proved extremely successful, though, at times it required extreme diligence on the part of the weighing crew.

Power was restarted at 2015, merely 15 min after the conclusion of the second preheat melt, on April 11, 1995, marking the start of the FY 1995 BWID demonstration melting test series. The furnace was operated on transformer Configuration 1, tap setting D, which provided approximately 330-kW power. Manual electrode control was used for approximately 1 hour and electrode control was switched to automatic at 2115. The Nom-90 feed mixture was started at 2045, and feedrate was gradually increased from 180 lb/h at 2045 to 1,000 lb/h at 2315, while attempting to build a cold top. Primary combustion air was not supplied to the furnace although there is some small amount of "inleakage air" into the furnace from various seal points and along with the feed. This inleakage air is estimated at around 10 acfm at normal system negative pressures of -0.5 in. WC. Semicontinuous tapping was established by 2245, but the melting and tapping rates were so high that the 1,000 lb/h feedrate was not sufficient to sustain a continuous tap. The cold top could not be maintained above 1 to 2 in., although the test plan called for a deeper cold top, up to 8 in. or greater. Furnace operations including power control, tapping, and offgas conditions were excellent, so rather than attempt to increase the feedrate beyond the planned 1,000 lb/h, it was decided to switch over to the Nom-80 mixture somewhat ahead of schedule.

Approximately 1,500 lb of the Nom-90 feed mixture was melted. Samples of the product slag were collected from the two slag pots filled during this feed interval. Sampling of the APCS solids from the cyclone and baghouse, and the scrubber solution from the acid gas scrubber, commenced at 2200, and continued at 2-hour intervals.

5.4.2 BWID Nom-80 Feed Interval

The first batch of the BWID Nom-80 feed mixture was loaded into the receiving bin at 2345, and initially fed to the furnace at 0015 on April 12, with no changes to the furnace operating conditions (330-kW power input). The feedrate was immediately 1,000 lb/h, with the primary combustion air added at the maximum output of the blower, approximately 140 cfm. Semicontinuous tapping was reestablished by 0040, but the cold top still could not be maintained above 1-2-in. deep. This prompted an evaluation of the pretest assumptions concerning power input to the furnace and limitations to the feedrate owing to the maximum offgas flowrates tolerated by the APCS, as discussed below.

The furnace had clearly demonstrated its ability to melt the Nom-90 and Nom-80 feed mixtures at feedrates in excess of 1,000 lb/h. In order to reduce the melting rate and build up a larger cold top, three critical aspects of the feed mixtures were considered as the surrogate waste-to-soil ratio of the feed mixture increased: (a) the volatile content of the feed and corresponding flowrate and CO and THC content of the furnace offgas increased, (b) the thermal oxidizer exit temperature approached its maximum allowable operating temperature of 2,250°F, and (c) the proportion of slagformers in the feed decreased. As the surrogate waste loading in the feed was increased and the proportion of slagformers decreased, the feedrate would have to be increased to maintain the cold top and sustain continuous slag tapping. This was not possible owing to the design limitations of the APCS. The APCS had been designed for offgas flowrates produced from melting the BWID Nom-60 feed mixture at a maximum feedrate of 1,000 lb/h in the arc furnace. Feedrates exceeding this could have resulted in inadequate furnace draft, incomplete oxidation or excessive temperature in the thermal oxidizer, high pressure drop across the baghouse, or other APCS-related operating problems from excessive offgas flowrates. The decision was made to change the furnace transformers back to Configuration 2. This allowed a lower power input to the furnace, lower melt rates, and lower feedrates suited for the higher gas-producing, higher-combustible BWID and IWPF feed mixtures.

The Nom-80 feed mixture was fed to the furnace until 0130 on April 12, at which time feeding ceased, but furnace power continued to melt off the cold top. The cold top was always removed before cutting power to facilitate power restart on the molten pool. Unmelted material on the surface of the melt could interrupt the conductive path between the electrodes. The cold top was eliminated by 0135 and power was shut off at 0142, at which time the shift electrician began changing the transformer configuration, which was completed by 0300.

A thin crust of frozen slag had formed over the surface of the molten pool after nearly 90 min downtime. For this reason, the electrodes had been positioned slightly submerged in the pool, to prevent breakage upon power restart. Attempts to restart the furnace at 0303 using power Configuration 2, tap setting C (124 V, phase-to-phase) were unsuccessful. Power was successfully restarted at 0308 after switching to voltage Tap B (137 V, phase-to-phase), but extremely low power input (100 kW) prompted switching to tap setting A (182 V, phase-to-phase) by 0317. Furnace power was gradually increased to ~180-kW by the end of the Nom-80 feed interval. This was accomplished by increasing the rheostat settings on the furnace control panel, which lowers the electrodes, causing them to carry more current at the constant voltage supply. Feed was restarted at 0320 at an initial feedrate of 400 lb/h, which was increased to 500 lb/h at 0350 and held there for the remainder of the Nom-80 feed interval, which was completed at 0420. Primary combustion air to the furnace was decreased to 45 cfm. All of the planned furnace operating conditions for this feed mixture were achieved when semicontinuous slag tapping was reestablished at 0410.

Two relatively steady-state operating conditions were thus demonstrated for the Nom-80 feed mixture, as follows: (a) 1,000-lb/h feedrate, 330-kW power input, 140-cfm primary combustion air input, and semicontinuous slag tap, and (b) 500-lb/h feedrate, 180-kW power input, 45-cfm primary combustion air input, and semicontinuous slag tap. A total of 1,500 lb of the Nom-80 feed mixture was fed to the furnace during the Nom-80 feed interval.

5.4.3 BWID Nom-70 Feed Interval

The Nom-70 feed interval began at 0420 on April 12. An initial feedrate of 400 lb/h was established, but within 10 min the feed was stopped owing to slight positive pressure excursions (typically well under 1.0 in. WC) in the furnace. The positive pressure excursions were caused by reduced flow out of the furnace due to a plug in the furnace exhaust similar to that encountered toward the end of the first

preheat melt. Furnace power was shut off at 0440 to investigate the plug. Discontinuing the primary air addition (which had been 45 cfm) temporarily eliminated the furnace over-pressure problem, and power was restarted at 0450. However, by 0500 it became clear that a significant plug had developed in the furnace exhaust duct.

Power was again shut off at 0500 to clear the exhaust duct. Burner 1 was removed from the top of the furnace exit duct. The plug was located in the furnace exhaust duct immediately below the intersection of the furnace exhaust and crossover ducts, which form a "cross" about 3 ft from the exit port in the furnace roof. The layer blocking the duct was not a relatively dry crust like that removed after the first preheat melt, but was a sticky, taffy-like combination of molten material and embedded particulate. The duct internal temperature decreased rapidly immediately prior to plug removal because burners 1 and 2 were shut off to permit access inside the duct. This allowed the plug to cool and solidify rather quickly, becoming hard and brittle, after which it was broken free from the duct wall and fell back into the furnace. Burner 1 was reinstalled in the exit duct, and burners 1 and 2 were refired by 0630. This interruption in the furnace operation is indicated on the process parameter plots (Appendix E).

The location and composition of the plug in the exit duct indicated that burner 1 was not functioning by design, requiring some adjustments to the pretest operating procedures. Burner 1 was configured to produce a pencil-flame that penetrated the exit port in the furnace roof. This was intended to keep the refractory-lined section of the exit duct above the melting temperature of the volatile constituents in the feed, which would then either pass through this section of the ductwork in the vapor-phase, or drip back down into the furnace in the molten state. The fact that the plug developed in the duct at least a foot above the exit port in the furnace roof indicated that there was insufficient heat from the burner and the furnace offgas to keep the exit duct walls above the melting temperature of the volatile materials in the feed. It was possible that the burner flame was not reaching the bottom of the duct. The location of the plug immediately below the intersection between the exit duct and the crossover duct suggested that the burner 1 flame was disrupted well before it reached the exit duct. This may be explained by the configuration of burners 1 and 2, where each burner fired directly across the other flame path.

The physical make-up of the plug indicated that firing the burners might actually exaggerate the plugging tendencies. By maintaining the gas temperature in a range that would keep some materials like metal chlorides exiting the furnace in a semimolten state, their tendency to stick to the duct wall and choke off the offgas flow would be increased significantly. The duct wall was cooler because of heat losses through the refractory to the water-cooled section just above the furnace roof. This section was water-cooled because the existing port in the furnace roof limited the duct diameter to 8 in., allowing for only 1 in. of refractory. This resulted in very high heat transfer through the water-cooled section of the duct, and a relatively cool refractory hot face temperature. For these reasons, it was suggested that eliminating burner 1 and perhaps burner 2 would improve operations. This change in operations was considered, but postponed until later in the test series.

The furnace was restarted at 0635 and operated without additional feed until 0800 to restore heat lost from the molten pool during the shutdown interval. An initial feedrate of 400 lb/h was increased to nearly 1,000 lb/h by 0845, with corresponding increases in primary combustion air from 35 to 85 cfm. Semicontinuous slag tapping was established by 0825. Not surprisingly, the high feedrate was faster than the furnace melting rate, and a cold top 9-in. deep was formed. Power was increased temporarily to nearly 300 kW by increasing the rheostat settings, which submerged the electrodes more deeply in the rising molten pool, until the slag tap was reopened and the pool level subsided. Power leveled off at approximately 200 kW until 1000, at which time the feedrate was cut back to 800 lb/h to reduce the cold top. Further reduction of the feedrate to roughly 600 lb/h at 1010, combined with an increase in furnace

power to about 250 kW, effectively reduced the cold top from a maximum of 9-in. at 1010 to 4.5-in. by 1205.

These operator-controlled variations in feedrate and furnace power, were necessary to demonstrate the ability to establish a thick cold top with continuous slag tapping, and the ability to shutdown temporarily for offgas duct cleaning. Although the furnace performed impeccably during this interval, the furnace exit duct again gradually plugged with slag buildup. Positive pressure excursions in the furnace were recognized at 1215, and feed was stopped immediately. Power was maintained until 1237 to remove the cold top, at which time the plug was removed from the furnace offgas exit duct. The procedure used to remove the plug followed that described in the previous section, but improvements in technique and familiarity with the process reduced downtime from 90 to roughly 30 min. The plug resembled that removed at 0500 earlier in the day in composition and location.

Furnace power was restarted at 1305, still operating on transformer Configuration 2, voltage Tap A, at ~250 kW. Feed was started at 1317, at a feedrate of 700 lb/h and primary air addition of 65 cfm. The feedrate was increased to 1,000 lb/h from 1342-1350 to build up the cold top in preparation for the first set of manual offgas sampling measurements, designed to sample offgas at the furnace exit, with a cold top in place above the molten pool. The feedrate was returned to the 700 lb/h mark at 1350 and maintained there for the duration of the Nom-70 feed interval. Continuous tapping was established at 1340 and kept open, at a slag tap temperature of about 1,580°C, for the next 2 hours while the offgas measurements were conducted. This interval, with a feedrate of 700 lb/h, power input of 250 kW, and continuous slag tapping, represents an extremely stable period of operation in the furnace.

Approximately 4,000 lb of the Nom-70 feed mixture were fed to the furnace during the entire Nom-70 feed interval. Samples of the furnace products were collected to correlate with the manual offgas measurements conducted during the stable period of operation from 1330-1530.

5.4.4 BWID Nom-60 Feed Interval

The final batch of the Nom-70 feed mixture had entered the furnace by 1530 on April 12, followed immediately by the first batch of the Nom-60 mixture. No changes were made to the feedrate (700 lb/h) or furnace power (250 kW) during the feed changeover. Primary air was gradually increased from 65 to 85 cfm by 1610, followed shortly thereafter by positive pressure excursions in the furnace. This prompted a quick reduction in the primary air addition to 55 cfm, which brought the furnace back to negative pressure. This condition lasted for 1 hour, during which the furnace power was lowered from 250-200 kW by decreasing the rheostat settings from 100-75%, with a corresponding decrease in the melting rate. The lower power input resulted in a slag melt rate that was unable to keep pace with the feedrate, and the cold top increased to 8 in. Feed was stopped at 1700 to prevent excessive cold top formation. By 1705, positive pressure in the furnace indicated that another plug had developed in the furnace offgas exit duct, and power was shut off for removal of the plug.

The composition and location of the plug were identical to the previous plugs that had developed during the BWID feed intervals, only this plug was more massive. This required more effort to remove, and consequently, longer downtime. The increased volatile content and the more massive nature of the plug may have been caused by larger amounts of offgas and entrained hot material from the Nom-70 and Nom-60 feed mixtures. Burners 1 and 2 were refired by 1800, and furnace power restarted at 1802.

The furnace operation continued on voltage Tap A (transformer Configuration 2). The rheostats were raised back to 100% for 30 min, resulting in power input of 270 kW. Once stable melting conditions had been reestablished, power input was lowered to the 250-kW level that had proved so successful during

the Nom-70 feed interval (1330–1530). Feed was not started until 1835 to allow for partial removal of the thick cold top that had formed prior to the last power shutdown. The feedrate was maintained at about 640 lb/h for the next several hours, except for a 30-min interval (1905–1935) when it was lowered to 370 lb/h to reduce cold top formation. The slag tap was reopened at 1850, and semicontinuous tapping was maintained until 2200. Primary air addition was 95 cfm during this same interval.

By 1800 hours on April 12, the thermal oxidizer and remainder of the APCS had operated continuously without incident for over 34 hours. Small samples were collected from the baghouse at regular 2-hour intervals, though no material passed the rotary airlock of the cyclone, suggesting that additional material might remain bridged over the rotary airlock in one or both of the devices. However, the scrubber liquor pH steadily declined during the afternoon of April 12. Examination of the caustic pump revealed that the caustic line was blocked with solidified NaOH, which required replacement the following morning. The scrubber liquor pH was ~2.7 until the line could be replaced.

The second set of manual offgas measurements at the furnace outlet were conducted from 1855–2013 during the Nom-60 feed interval. The cold top was maintained between 1–6 in. during the offgas measurements, while power (230 kW) and feedrate (640 lb/h) were kept relatively constant. Tap temperatures during prolonged periods of steady taprate remained remarkably constant at about 1,575°C. This was considered an ideal slag tap temperature because structural metals in the feed required bath temperatures of at least 1,558°C to keep the metal heel molten. Excessively superheating the slag was undesirable because it would cause additional volatilization from the melt.

The furnace was operated without significant changes until 2100, when the feedrate was slowed to 460 lb/h to begin removing the cold top for the third series of manual offgas measurements. These measurements were intended to characterize the furnace offgas when no cold top covered the molten pool, a condition suspected to increase volatilization from the bath. The feedrate was decreased to 370 lb/h at 2133, when the furnace again began to exhibit positive pressure, indicating that another plug had developed in the furnace offgas exit duct. Feed was stopped at 2140, while the power input remained at 230 kW, and the slag taphole remained open. This effectively removed the cold top by 2200, at which time power was shut off and the plug in the offgas duct was removed. Furnace power was restarted 40 min later, at 2240, and the pool was heated until 2305 before restarting the feeder. Power input was still about 230 kW. The feedrate was kept steady at 460 lb/h from 2305 until 0030 on April 13, for the duration of the third series of manual offgas measurements. Primary air addition was 70 cfm, with the cold top kept to a minimum or nonexistent.

Another variation to the furnace operating parameters was added for the fourth series of manual offgas measurements at the furnace outlet. Power input remained at 230 kW, while the feedrate was increased to 750 lb/h to reestablish a cold top over the molten pool. Primary air addition was discontinued for this fourth set of offgas measurements. This would provide three sets of measurements on the Nom-60 mixture with the following operating conditions: (a) constant power input, feedrate, and taprate, with primary air addition and cold top, (b) constant power input, feedrate, and taprate, with primary air addition but no cold top, and (c) constant power input, feedrate, and taprate, with no primary air addition but with a cold top. This series of tests on the Nom-60 mixture was intended to determine the effect of the cold top on volatilization from the bath, and to determine the effectiveness of primary air addition on the pyrolysis of the combustibles in the feed.

By 0200 on April 13, the eighth batch of the Nom-60 feed mixture had been loaded into the receiving bin. By the time this eighth batch was charged to the furnace, approximately 11,000 lb of the BWID nominal feed mixtures would have been melted. Based on the structural metal contents in the various

nominal feed mixtures, this represented about 950 lb of metal that would have accumulated in the furnace hearth as a molten metal heel, assuming total oxidation of Al metal, volatilization of all Pb, negligible loss of Fe, Cr, Cu, and Ni from the metal owing to oxidation, and negligible metal gain from reduction of oxides from the slag. Because the furnace hearth had been rammed with refractory to accommodate 1,000 lb of metal below the water-cooled slag tapping fixture, this was the maximum size of metal heel that should be allowed to accumulate. Thus, it was decided to open the bottom tap of the furnace after the eighth batch of the Nom-60 feed mixture was fed to the furnace.

By 0230 the meter bin was emptied, and the last of the Nom-60 feed mixture was in the furnace. The furnace hearth was sounded (using a metal rod inserted through a port in the furnace wall to measure the depth of the molten bath), showing a depth of 46 in. to the hearth (bottom of the furnace) and 7 in. of liquid. This was believed to be only the depth to the metal heel, which would have been several inches deep as well. The cold top was removed by 0300, but the slag tap had ceased at 0230, suggesting that the majority of the cold top consisted of combustible materials that volatilized or oxidized and did not add significantly to the melt pool. A bath temperature of 1,400°C was recorded at 0310. Although this low temperature measurement is questionable, it indicated that some superheating of the metal might be necessary before tapping the furnace bottom to remelt the metal heel. Power was increased to over 300 kW, while the furnace crew began drilling out the 1.5 in. diameter bottom taphole. The hole was filled with 12 in. of MgO refractory, measured from the hearth bottom. The total hole length was 43 in. After drilling out the MgO plug in the taphole, frozen metal was encountered at the hearth bottom, which required oxygen lancing to initiate tapping. This was accomplished at 0400, when molten metal was tapped from the furnace at a temperature of 1,570°C.

A 500-lb batch of RWMC soil and lime had been loaded in the meter bin before opening the furnace bottom tap. The empty furnace was charged with this feed mixture at 0410, immediately upon termination of the bottom tap. However, power was shut off temporarily at 0405, and the electrodes raised off the bottom, owing to some concern that a self tap (failure of the furnace, hearth, and steel shell, resulting in molten slag spill) could result if the power were applied continuously. This procedure was conservative, because previous experience with this furnace indicated that a self tap would be virtually impossible. Unmelted feed that was charged to the furnace covered the small portion of molten slag that remained in the bottom of the furnace. Once the electrodes were lowered, this unmelted feed acted as an insulator between the electrodes and the molten slag, breaking the conductive path between the electrodes. Attempts to start the furnace in this manner were unsuccessful, so the procedure used to start the furnace at the beginning of the preheat melts was followed.

A triangle of crushed graphite was placed on top of the unmelted feed material, beneath the electrodes. The electrodes were lowered until they contacted the graphite, and power was restarted at 0520. Although this method was successful, the proper method for restarting the furnace after bottom tapping would have required less effort and resulted in shorter downtime. Furnace power should not have been turned off, but maintained continuously as the bottom tap slowed to a stop. Once the bottom tap had ceased, new feed material should have been charged to the furnace while power was still on, and open arc conditions existed in the furnace. A new molten pool could then be established, the electrodes could be gradually raised from the furnace bottom as the pool depth increased, and furnace operations could continue without interruption.

The feeder was started at 0525 at a feedrate of 320 lb/h, which was increased to 770 lb/h at 0530. The remainder of the soil and lime mixture was fed to the furnace by 0550, at which time the feedrate was slowed to 350 lb/h in preparation for feeding the initial batch of the Nom-50 mixture. The furnace bottom tap effectively emptied the furnace, resulting in 1,004 lb of metal and 556 lb of slag. The total metal

weight represents slightly 5% more than the amount of Fe, Cr, Cu, and Ni fed to the furnace. This suggests that there was some minimal metal reduction from the slag for these feed mixtures.

5.4.5 BWID Nom 50-Feed Interval

Successful processing of the BWID Nom-60 feed mixture was considered the primary goal of the BWID demonstration melting test series. Pretest plans included going beyond the surrogate waste loading in the Nom-60 mixture if successful processing of the Nom-60 was demonstrated. This being the case, two additional surrogate waste mixtures with higher waste-to-soil ratios were prepared. The first of these was the BWID Nom-50 feed mixture.

The first batch of the Nom-50 feed mixture was initially fed to the furnace at 0605, at a feedrate of 350 lb/h. The feedrate was increased to 700 lb/h at 0630 and maintained there until 0715. Furnace power was again about 230 kW, and primary air addition rate was 70 cfm. The furnace pressure began to go positive at 0635, and power and feedrate had to be stopped 1 hour later to clear the latest plug in the furnace offgas exit duct. Burner 1 was removed permanently at this time, with a steel plate used to cover the burner port. While this made subsequent cleanouts easier, it did not significantly reduce plugging.

Furnace power was restarted at 0830, at a slightly higher power input level (250 kW). The feedrate was increased gradually from 350 lb/h at 0830 to about 900 lb/h at 0905. The primary air addition rate was still 70 cfm. The molten pool had not reached the slag tap level when the feed was stopped at 0945 from rapid build-up of the cold top, to over 6 in. In-furnace measurements of the plenum temperature were made at 0715 and 0942, yielding temperatures of ~900 and ~1,700°F, respectively. The lower temperature at 0715 was measured when the feedrate was ~700 lb/h and the power level was ~230 kW. The higher temperature at 0956 was measured when the furnace feedrate was zero for around 9 min, following a feedrate of around 950 lb/h. The power level was around 250 kW, even though there was no feeding. While both measurements were made with a relatively thick cold top, it is apparent that there was more heating in the furnace plenum at the time of the second measurement from continued oxidation (releasing heat) from material in the cold top, slightly higher electrode energy input (which may have been less shielded from the plenum as the cold top began to be depleted around the electrodes with the feed off), and no energy consumption from heatup and endothermic volatilization of new feed. No slag was tapped during the Nom-50 feed interval owing to the relatively small amount (~1,000 lb) of slag-forming feed materials fed to the empty furnace following the metals tap. Although no slag was tapped, melting of the Nom-50 feed mixture at feedrates up to 900 lb/h was demonstrated.

5.4.6 BWID Nom-40 Feed Interval

The first batch of Nom-40 feed mixture was fed to the furnace at 1015 on April 13. The feedrate was immediately 850 lb/h and was kept there for the duration of the Nom-40 feed interval. Power input was decreased to about 200 kW by lowering the rheostat settings from 100 to 75%. The primary air addition rate was kept at 70 cfm. The lower power input and high feedrate produced predictable results. The cold top rapidly increased to over 7 in. by 1120. The slag tap was opened for brief periods at 1025, 1045, 1102, and 1120, with slag samples collected from each tap. The last of the Nom-40 feed mixture was fed to the furnace by 1120, at which time the feeder was shut off. This marked the conclusion of the BWID demonstration melting test series.

5.4.7 Summary of the BWID Feed Interval

Continuous slag tapping was not established during the Nom-50 and Nom-40 feed intervals. These materials were fed to an empty or nearly empty furnace, with a hearth capacity of, at most, 1,000 lb of

molten slag below the slag tap level. The five batches of the two feed mixtures contained 475 lb of metal, which accumulated on the bottom of the furnace hearth. Based on the slagformer content in the last Nom-60 and the Nom-50 and Nom-40 feed mixtures, and allowing for up to 300 lb of unmelted Nom-40 feed making up the 8 in. cold top, about 1,200 lb of slag would have been produced from the 2,500 lb of total feed. Intermittent slag tapping was established between 1025 and 1120. These multiple taps accounted for the 100 lb of slag that would have accumulated above the slag tap level. This detailed accounting of the furnace inventory brings to light a significant aspect of the feed mixtures with high volatile content. As the volatiles content of the feed is increased, maintaining a stable molten pool (steady-state conditions defined by balanced feedrate, melting rate, and tapping rate) will become increasingly difficult unless the feedrate is increased in proportion to the increasing feed volatiles content. This phenomenon is discussed further in the following sections, based on experiences during the IWPF baseline melting test series.

Over 14,000 lb of the BWID nominal feed mixtures, with varying surrogate waste and soil ratios, were melted at feedrates up to 1,000 lb/h and power inputs of usually under 230 kW. The average feedrates and power levels in Table 5-1 are much lower than those maximum values obtained during short-duration but stable periods, owing to shut-down periods. Energy efficiencies during these stable periods were much better (as low as 0.25 kWh/lb) than the average values of 0.28–0.81 kWh/lb reported in Table 5-1.

5.5 Idaho Waste Processing Facility Baseline Melting Tests

The IWPF (INEL stored waste) demonstration melting tests commenced at 1140 on April 13, 1995, followed by 19 hours of continuous operation. Four feed compositions were melted with varying success. Each is discussed separately in the following sections. System parameters, including furnace power input, feedrate, slag tap temperature, and stack flowrate, are included in Appendix F, Figures F-1–F-5.

5.5.1 IWPF S-40 Feed Interval

The first batch of the S-40 feed mixture was fed to the furnace at 1140 on April 13. The furnace was not emptied before initiating the S-40 feed interval; thus, a pool of the Nom-40 slag (1,000 lb) and approximately 475 lb of metal remained in the furnace, with a relatively thick cold top, (8 in.). The feedrate was initially 170 lb/h, but was gradually increased to 300 lb/h within 90 min. The furnace continued to be run on Tap A, but the rheostat settings were changed from 90 to 80%, which raised the electrodes and lowered the power slightly to about 225 kW. The rheostats were changed to 65% at 1200, which reduced the power to 182 kW. The primary air addition rate was increased from 30 to 60 cfm with increasing feedrate. However, the S-40 feed material which included MicroCel-E and oil-dry was generally finer particle-sized than the Nom-xx mixtures. This could have resulted in more feed entrainment into the APCS. To reduce the entrainment, the primary air blower was shut off at 1205, when the feedrate was roughly 300 lb/h. This feedrate, without primary air addition, resulted in a thick cold top (9 in.) and relatively high concentrations of volatilized but incompletely oxidized organic gases (CO and THC) in the furnace offgas. The concentration of combustible gases increased not only from the higher feedrate of volatile organic material but from the elimination of primary air that would have partially oxidized some of the combustible gas and diluted the offgas with the nitrogen in the air.

The higher flowrate and concentration of combustible gas from the furnace exceeded the capacity of the secondary air flow, reduced the excess air levels in the thermal oxidizer to zero, and caused the thermal oxidizer exit temperature to exceed the high temperature limit of 2,250°F at 1245. System shutdown was prevented by temporarily increasing the allowable limit temperature to 2,400°F, while the burner 3 fire was decreased. This effectively lowered the thermal oxidizer exit temperature below

2,250°F by 1315, but the thermal oxidizer temperature continued to increase. After 30 min, the temperature approached the higher temperature limit of 2,400°F. The furnace feedrate was reduced to 150 lb/h at 1345, and the primary air addition was resumed, at a flowrate of 70 cfm. These measures again reduced the thermal oxidizer exit temperature below the limit value. At 1435, the feedrate was increased to 300 lb/h to determine whether the primary air addition would prevent excessive temperatures in the thermal oxidizer. The thermal oxidizer exit temperature immediately responded to the increase in feedrate by again rising above 2,250°F. The feedrate was lowered to 225 lb/h at 1445, but the thermal oxidizer exit temperature remained above the original limit value.

The furnace and feeder were shutdown for 25 min at 1520 to remove the latest plug in the furnace exhaust duct, which finally reduced the thermal oxidizer exit temperature below the 2,250°F limit value. The short downtime resulted from the decision to remove burner 1 completely from the system. Access to the duct was achieved by simply removing a steel plate covering the burner 1 port. The location and composition of the plug was virtually identical to the plugs that developed during the BWID feed intervals. The thick cold top (9 in.) was not removed before cutting power because the short downtime was anticipated, and no difficulties were encountered on power restart. Furnace power was reestablished (200 kW) at 1545, at which time the thermal oxidizer exit temperature had decreased to under 2,000°F. At 1600, the feeder was restarted at a feedrate of roughly 160 lb/h, with a primary air flowrate of 70 cfm. This gradually reduced the cold top thickness to 2.5 in., and eliminated the excessive thermal oxidizer exit temperatures for the duration of the S-40 feed interval. Slag tapping was initiated at 1602 and continued throughout the remainder of the feed interval. Tap temperatures ranged from 1,509–1,536°C.

A total of 1,594 lb of the S-40 feed mixture was fed to the furnace. Because the S-40 material was fed to a furnace full of the BWID Nom-40 slag, a material balance for the S-40 feed interval could not be directly determined. Furnace products are totaled for all of the IWPF feed mixtures at the conclusion of this section.

5.5.2 IWPF S-0 Feed Interval

The S-0 feed interval began at 1736 on April 13, 1995, which coincided with another plug in the furnace offgas duct. Power was discontinued while the plug was removed, and restarted at 1800. The feedrate was approximately 200 lb/h, owing to the extremely high combustible content in the S-0 feed (62%). Primary combustion air was shut off at the start of the S-0 feed interval owing to the plug in the offgas duct, but was not restarted once the plug was removed. Several offgas measurement intervals were conducted during the S-0 feed interval, and it was desired to conduct these measurements with no primary combustion air addition to the furnace. The furnace demonstrated its ability to process this high combustible feed that had 62 wt% total combustibles and volatiles. Significantly higher feedrates would result in excessive exit temperatures from the thermal oxidizer, as demonstrated during the S-40 feed interval. The much slower feedrate required a decrease in power, which was accomplished by changing to Tap B at 1835. Rheostat settings were kept at 80%, providing 100-kW power. At 1917, the rheostats were increased to 100%, increasing the power input to roughly 150 kW, where it was maintained for the remainder of the S-0 feed interval.

The cold top, as measured directly below the NE feedtube using a plumb bob technique, was relatively thin during the initial stages of the S-0 feed interval, but the measurement indicated a gradual cold top increase to 7 in. by 2300. Slag had not been tapped since the beginning of the S-0 feed interval, but the low feedrate (200 lb/h) and the high combustible content in the feed (62%), indicated that with the corresponding low content of slagformers in the feed, an excessive buildup of slag material was not possible. The feed was stopped at 2315 to reduce the presumed cold top in preparation for adding electrode segments to the north and middle electrodes. While the power was shut off for electrode

additions, the furnace interior was examined through the inspection door on the furnace roof to evaluate the cold top condition. Bridging of the feed immediately beneath the feedtubes was recognized as a cause for erroneous cold top measurements. The majority of the bath was uncovered (open top) because the feed material had remained under the feedtubes and not been distributed evenly over the bath. A steel rod was used to break up the piles of feed, and the inspection door closed in preparation for power restart. Total downtime was 30 min.

The furnace became unstable at 2400 when the electrodes began to automatically withdraw from the melt, suggesting some arcing above the pool. The furnace was switched from auto control to manual mode at 2410 to force the electrodes down into the pool, and the instability was eliminated. By 0100, the furnace was returned to the automatic mode without further instability for the duration of the S-0 feed interval. Electrical arcing above the molten pool in these S-0 feed runs may have been caused by conduction through high levels of condensed soot in the cold top and/or soot and gaseous ions (such as Cl) in the furnace plenum. While the nominal BWID feed mixtures had C and Cl contents ranging from 2.3–11.2%, and 0.44–3.2%, respectively, the S-0 feed mixture had much higher levels at 35% C and 20% Cl.

Insufficient primary combustion air limited the oxidation of pyrolysis products of the S-0 feed within the furnace, which may have caused a build up of condensed, conductive soot material in the cold top or the furnace plenum (observed on sampling probes in the furnace plenum). The very high level of Cl in the feed may also have contributed high levels of Cl ions in the plenum. Insufficient primary combustion air also resulted in more combustion of the pyrolysis products within the thermal oxidizer, for which there was insufficient secondary combustion air, resulting in low excess oxygen and high temperatures at the thermal oxidizer exit.

At such a low feedrate, the average feedrate of slagformers was only 41 lb/h and the average power level was only 147 kW to prevent superheating of the melt in the regions near the electrodes. These averages are lower than the instantaneous levels of 200 lb/h and 160 kW because of the inclusion of shutdown periods during this feed interval. These feedrates are on the order of one-fifth of the maximum feedrate and power levels. Steady-state conditions of feedrate, power level, melt rate, heat losses, and taprate within the furnace could not be maintained at such low levels. The pool was observed to begin to freeze around the periphery of the refractory hot face, and no longer made contact with the slag tapping fixture, which added to the inability to maintain a continuous or semicontinuous slag tap during the entire S-0 feed interval. Heat loss in the area near the taphole was pronounced because of the water cooling on the tapping fixture. Maintaining a molten pool out to the tapping fixture was critical for enabling tapping to occur.

The slag tap was opened briefly at 0205, but insufficient slag inventory was present to maintain flow and so the tap closed within 2 min. A tap temperature of 1,500°C was recorded. Inspection of the furnace interior verified that the melt pool diameter was decreasing, and was currently 6 in. from the face of the slag tapping fixture.

Coincident with the efforts to establish a slag tap, a temperature probe was inserted into the upper plenum of the furnace at 0240 to compile a temperature profile across the furnace. While the probe was extended between the electrodes to the far wall of the furnace, the furnace became electrically unstable. The electrodes were cycling up and down, in and out of contact with the molten pool. This behavior indicated that the probe was providing a current path between the electrodes. Because the probe was located about 2 ft above the surface of the bath, the control panel (which was in the automatic mode) was correctly changing the electrode position to what the electrical parameters indicated was a much higher level of molten material in the furnace. Of course, this was a false indication of the pool level, and once

the electrodes broke contact with the molten pool, power was lost temporarily. The control panel would then lower the electrodes until contact with the molten pool was reestablished, and a power spike would occur, indicating power had been restored. However, with the temperature probe still present between the electrodes, the cycle would renew, and the furnace power continued to oscillate on and off. Switching the furnace to manual mode would have prevented this cycling until the probe was removed, but to demonstrate that the probe was actually causing the power oscillation phenomenon, it was allowed to continue until the probe was retracted far enough to no longer extend between the electrodes. The power oscillation ceased immediately once the probe was withdrawn, confirming that it had provided a conductive path between the electrodes. This phenomenon had not occurred during previous temperature profile measurements conducted during the BWID demonstration melting tests, suggesting that the extremely high volatile content in the S-0 mixture may have produced an easily ionized atmosphere within the furnace. The air-cooled probe provided a condensation surface on which a 1-2 mm layer of soot condensed. This layer may have been conductive enough to disrupt the proper current flow through the electrodes.

The S-0 feed interval was continued until 0335 to allow for completion of the manual offgas measurements. A total of 1,098 lb of the S-0 mixture was fed to the furnace with essentially no slag tap. A sample of the slag was collected at 0205 during the brief tapping interval but the melt inventory at this time included slag from the Nom-50, Nom-40, S-40, and S-0 feed materials. This slag sample is not representative of only the S-0 feed mixture. Furnace power was maintained at ~160 kW for the final 2 hours of the feed interval.

5.5.3 IWPF C-20 and C-40 Feed Intervals

The first batch of the C-20 mixture began to enter the furnace at 0345 on April 14, 1995. The furnace was switched to Tap C from Tap B, with the rheostats at the 100% setting, providing approximately 150 kW of power. This proved to be insufficient power to heat the melt and establish a slag tap, so the furnace controls were switched back to Tap B at 0430, with the rheostat settings at 80%, (power at ~300 kW). The rheostats were increased to 100% by 0500, with a corresponding increase in power to over 300 kW, in an attempt to initiate a slag tap. This high power level produced a correspondingly high melting rate, so the feedrate was gradually increased from about 200 lb/h to nearly 400 lb/h in an effort to provide more slag-forming material to the molten pool. Primary combustion air addition was increased to 86 scfm to increase oxidation of combustibles in the cold top, which had increased to 7 in. Six inches of cold slag were observed from the slag taphole inward, confirming that the molten pool diameter had not increased toward the taphole since this condition was first observed during the S-0 feed interval. These efforts were not successful at establishing a slag tap, requiring further measures.

The decision was made to increase the soil and lime ratio in the C-series feed mixture, from C-20 (20% soil and lime) to C-40. This would increase the slagformer content in the feed, and perhaps permit slag tapping. Primary combustion air addition was increased to the maximum of 140 cfm coincident with an increase in feedrate from 225-375 lb/h. After 10 hours of operation with essentially no slag tapping, the residual slag in the furnace had become extremely viscous. This was caused in part by volatilization of the Na_2O and K_2O from the melt during the extremely long retention time of this slag in the furnace with little addition of more slagformers. Continued exposure to the high temperatures in the vicinity of the electrodes volatilized some of these two important slag fluidizers from the melt. The combined Na_2O and K_2O levels in the slag decreased from around 2 wt% during the Nom-70 feed interval to well under 0.5 wt% during the S-0 and later intervals. In an attempt to fluidize this residual slag, 98 lb of lime (CaO) was added through the rotary air lock downstream from the meter bin. This led to a successful but short slag tap at 0525. Tap temperatures in excess of 1,700°C were measured, indicating that the tap had penetrated the innermost zone of the molten pool, but the furnace had not remelted the outer zone of slag

in contact with the taphole. An additional 100 lb of lime was added through the rotary air lock, after which the feed was stopped at 0615 when the cold top measurement indicated excessive cold top formation, up to 11 in. This measurement of the cold top was suspect, owing to previous observations of bridging of the feed beneath the feedtubes.

Power was shut off at 0645 to permit observation of the furnace interior through the inspection door and visually determine the depth of cold top. A crust of unmelted charge had formed around the circumference of the pool, particularly beneath the NE and SE feedtubes. The middle electrode is positioned halfway between the NE and SE feedtubes, while the north and south electrodes are positioned much closer to the NW and SW feedtubes. The proximity of the electrodes to the feedtubes has a direct bearing on the assimilation of the cold charge into the bath. Because the feed is proportioned equally to each feedtube, an excess of unmelted charge built-up beneath the NE and SE feedtubes, while the bath remained more open under the NW and SW feedtubes. The crust of unmelted charge was broken up with a steel rod, and an additional 36 lb of lime was added to the center of the molten pool. Power was restarted at 0704, and the slag tap was opened briefly at 0740, but electrical cycling similar to that described during the S-0 feed interval required that the furnace be switched to manual operation. This stabilized the electrode positioning circuits, but the furnace began to pressurize, indicating a plug had developed in the exhaust. Power was shut off at 0810 to remove the plug. The slag tapped before the power shutdown had an extremely strong acetylene odor, and cooled into brittle, thin plates. X-ray diffraction analysis identified larnite, also known as dicalcium silicate (Ca_2SiO_4), as a primary phase within this slag. Larnite would not make a suitable final waste form because of its tendency to crumble over time. However, the larnite formed from the relatively large amounts of CaO added to fluidize the melt, and would not be expected in feed mixtures such as C-20 or C-40 mixtures that have relatively low CaO levels.

At this point, it was concluded that the difficulties encountered trying to reestablish steady-state feeding, melting, and tapping at such low feedrates and power levels made further evaluation of the C-40 feed mixture impractical. The decision was made to forego additional charging of the C-series feed mixtures and feed a material with more slag-forming materials to develop a stable molten pool and flush out the arc melter and APCS.

5.5.4 Summary of the IWPF Feed Interval

Approximately 800 lb of the C-20 and C-40 feed mixtures were charged to the furnace. Added to the totals for the S-0 and S-40 feed mixtures, approximately 3,500 lb of the IWPF feed mixtures were melted. Furnace electrical energy consumption during the IWPF demonstration melting tests increased dramatically, to 1.12 kWh/lb, resulting from the low feedrates for the S-0 and C-series feed mixtures. The high energy consumption could be reduced dramatically by optimizing the APCS for the high gas-producing combustible feed mixtures, which would allow for increased total feedrates, more slag formers entering the furnace, and more continuous operation.

Feedrates, power input, and corresponding energy consumption varied dramatically for each mixture. The S-40 feed mixture was melted successfully at feedrates up to 300 lb/h, power input of about 200 kW, and energy consumption of 0.73 kWh/lb when the capacity of the thermal oxidizer was maximized. By contrast, the maximum feedrate achieved for the S-0 feed mixture was about 200 lb/h, with an accompanying reduction in power input to 100–150 kW, but double the energy consumption at 1.36 kWh/lb. These limitations were dictated by such factors as the high combustible content in the feed, which produced high rates of combustible CO and hydrocarbon gases in the melter furnace exhaust and pushed the thermal oxidizer to its high temperature limit.

In order to provide a sufficient feedrate of slagformers to limit the slag residence time and provide for semicontinuous tapping, the feedrate of the S-0 feed mixture would have to be much greater than it was during the tests. This feedrate would require a larger supply of secondary combustion air for the thermal oxidizer to efficiently oxidize the higher combustible content in the input gas. The final slag product quality must be maintained by sufficient slag former additions, and can be degraded without them as shown by the slag properties resulting from adding large amounts of CaO to the S and C melts.

Feedrates for the C-20 and C-40 feed mixtures reached 375 lb/h, with nominal power input of 150 kW, and a slight reduction in energy consumption at 1.34 kWh/lb.

5.6 Final Cleanout

The Nom-90 feed mixture (modified by excluding structural metals, plastics, and combustibles) was used to feed the furnace during the final cleanout interval, owing to its high soil and lime content and melt fluidity based on its basicity of 0.7. The plug was removed from the furnace exhaust duct, and power was restored at 0820, with the furnace in manual mode using Tap B. The remainder of the C-40 feed mixture was removed from the receiving bin, and the first batch of the modified Nom-90 (Nom-90M) feed mixture was charged to the furnace. The feedrate was initially 440 lb/h, with a 5-in. cold top.

The electrodes were raised in an effort to burn off the residual cold top, which probably contained extremely high concentrations of combustibles. At 0900, 100 lb of mill scale (Fe_3O_4) was added to the meter bin. This addition of a solid oxidant was intended to improve the oxidation of the solid combustibles in the cold top and fluidize the molten pool by the addition of the by-product FeO to the slag. Furnace power was adjusted during this interval as well, with a switch to Tap A at 0825 and a power input of over 300 kW. This power level was excessive, and the furnace was switched back to Tap B at 0900, but only briefly. A final switch back to Tap A, with a reduction in rheostat settings from 100 to 80%, was conducted at 0933. This provided a satisfactory power input of about 200 kW to the furnace, which was maintained for the duration of the test.

By 0915, the furnace electrical operation had become more stabilized, and the feedrate was increased to 660 lb/h. The cold top had increased to over 8 in. by 1030, at which time the slag tap was successfully reopened, and remained open continuously for the duration of the melt. The Nom-90M feed material was about 95% slagformers; therefore, the feedrate of slagformers that enabled semicontinuous tapping was about 627 lb/h. Power was gradually decreased over the next 2 hours, from 220 to 190 kW, by decreasing the rheostat settings from 80 to 50%. During this interval, the feedrate remained constant (660 lb/h), which caused the cold top to increase to 12 in. At 1215, another 100 lb of mill scale was added to the meter bin, followed by a third 100-lb addition of mill scale at 1310. These additions of mill scale had an almost immediate effect on the molten pool by more rapidly oxidizing organic material in the cold top, increasing the melt electrical conductivity, and decreasing the melt viscosity. Power increased from 190 kW at 1220 to over 300 kW by 1310, with no changes in the transformer tap or rheostat settings. A likely explanation is the increase in FeO in the slag owing to partial carbothermic reduction of the Fe_2O_3 in the mill scale to FeO. The FeO not only improved the slag fluidity but increased its conductivity as well.

The cold top was reduced to 7 in. by 1325, while a very fluid slag, at 1,500°C, continued to tap from the furnace. These conditions suggest that the furnace had reached steady-state on the Nom-90M feed mixture. Feed was discontinued at 1350 after over 2,700 lb of the Nom-90M feed mixture and 300 lb of mill scale were fed to the furnace. The cold top was removed by 1407, while the slag tap remained open until the molten pool had drained to the slag tap line. Upon termination of the slag tap, the bottom tap was opened and the furnace contents were emptied. The bottom tap was complete by 1440, marking the end of the final cleanout melt and the demonstration melting test series.

5.7 Maximum Volatiles Input and Minimum Slagformer Input

The current test melter system was designed for furnace feedrates of up to 2,000 lb/h of soil-type feed materials, based on a maximum power input rate of 800 kW and an energy efficiency of 0.40 kWh/lb. The thermal oxidizer was designed for offgas flowrates from melting Nom-60 feed material at a rate of 1,000 lb/h. The average input rates for volatile, slag-forming, and metal components for each of the feed mixtures are shown in Table 5-3. Some of the feed mixtures were also processed stably at significantly higher feedrates for shorter durations of time. The slag tapping rate was somewhat independent of the furnace feedrate, because a minimum taprate was necessary to prevent hardening of the slag in the water-cooled taphole. The taprate depends on the slag viscosity at the melt temperature, the amount of superheat in the melt, and the rate of viscosity increase versus temperature decrease as the slag cools through the taphole. Tapping and thermal oxidizer conditions for the different feed mixtures are summarized in Table 5-4.

The apparent minimum feedrate of slag-forming materials for continuous tapping was over 1,000 lb/h, because continuous tapping was not achieved during this test program. The minimum feedrate of slag-forming materials for satisfactory semicontinuous tapping was around 100 lb/h. The maximum feedrate of volatiles and combustibles for satisfactory thermal oxidizer operation was around 120 lb/h (for volatile, chlorinated organics) to over 250 lb/h (for total solid combustibles). The maximum satisfactory volatiles and combustibles feedrate was much lower for higher chlorine-containing materials (11–20% Cl for the S feeds versus 2.4–3.3% Cl for the C feeds). Chlorine is a known combustion quencher because it reacts with H radicals and ends combustion chain reactions.

Table 5-3. Feedrate of combustible and slag-forming materials to the furnace.

Feed Mixture	Average Feedrate (lb/h)	Feed Composition (wt%)								Feed Heating value (Btu/lb)	Feedrate to the furnace (lb/h)							Heat input to furnace from feed (10 ⁶ Btu/hr)	Total offgas flowrate (scfm)
		Total volatiles and combustibles									Feedrate to the furnace (lb/h)								
		Volatiles	C	Cl	Fixed carbon	combustibles	slag formers ^a	Total metals ^a	Volatiles		C	Cl	Fixed carbon	Total combustibles	slag formers ^a	Metals ^a			
Nom-90	427	13.9	2.28	0.44	0.27	14.2	83.4	2.67	229	59.3	9.74	1.88	1.17	60.5	356	11.4	0.10	17.7	
Nom-80	367	16.6	3.83	0.91	0.57	17.2	77.8	5.55	589	61.0	14.1	3.35	2.09	63.1	285	20.4	0.22	18.9	
Nom-70	358	19.5	5.50	1.42	0.89	20.4	71.7	8.65	976	70.0	19.7	5.08	3.17	73.1	257	31.0	0.35	22.3	
Nom-60	359	22.6	7.27	1.96	1.23	23.8	65.3	12.0	1,390	81.2	26.1	7.04	4.40	85.6	234	42.9	0.50	26.5	
Nom-50	356	25.9	9.16	2.54	1.59	27.5	58.5	15.5	1,830	92.2	32.7	9.05	5.65	97.9	209	55.1	0.65	30.7	
Nom-40	782	29.3	11.2	3.15	1.97	31.3	51.4	19.2	2,297	229	87.3	24.6	15.4	244	401	150	1.80	77.5	
S-40	269	35.4	19.4	10.7	3.87	39.3	60.7	0.00	4,099	95.2	52.1	28.8	10.4	106	163	0.00	1.10	26.5	
S-0	108	55.0	34.6	19.5	7.05	62.0	38.0	0.00	7,550	59.4	37.4	21.1	7.62	67.1	41.1	0.00	0.82	16.6	
S-O, max.	200	55.0	34.6	19.5	7.05	62.0	38.0	0.00	7,550	110	69.2	39.0	14.1	124	76.0	0.00	1.51	30.7	
C-20	180	66.7	39.2	3.33	5.27	71.9	27.7	1.87	8,847	120	70.4	5.98	9.47	129	49.8	3.35	1.59	43.6	
C-40	599	50.7	28.0	2.36	3.73	54.4	45.4	1.32	6,224	303	167	14.1	22.3	326	272	7.90	3.73	108	

a. Assume that all Al, but none of the other metals will oxidize in melter.

Table 5-4. Relationships of feedrate, furnace tapping, and thermal oxidizer performance.

Feed Interval	Feedrate (lb/h)	Slagformer feedrate (lb/h)	Tapping condition	Total volatiles and combustibles feedrate (lb/h)	Thermal oxidizer condition
Preheat 1	Up to 570	—	Semicontinuous	—	Satisfactory
Preheat 2	Up to 1,000	Up to ~950	Semicontinuous	50	Satisfactory
Nom-90	Up to ~1,000	Up to ~834	Semicontinuous	142	Satisfactory
Nom-80	Up to ~1,000	Up to ~778	Semicontinuous	172	Satisfactory
Nom-70	Up to ~1,000	717	Semicontinuous	204	Satisfactory
Nom-60	700	457	Semicontinuous	143	Satisfactory
Nom-50	900	526	No tap due to small amount fed to almost empty furnace	248	Satisfactory
Nom-40	850	437	Intermittent	266	Satisfactory
S-40	300	182	Intermittent	118	Unsatisfactory
S-40	150	91	Intermittent	59	Satisfactory
S-0	200	50	Once	124	Satisfactory
C-20	250	69	None	180	Satisfactory
C-40	250	114	None	136	Satisfactory
Cleanout	660	627	Intermittent	35	Satisfactory

Results:

- Minimum slagformer feedrate for intermittent tapping: ~100 lb/h.
- Minimum slagformer feedrate for continuous tapping: ~1,000 lb/h.
- Maximum volatiles and combustibles feedrate for satisfactory thermal oxidizer operation: ~250 lb/h.
- Maximum volatile organics feedrate for satisfactory thermal oxidizer operation: ~120 lb/h.

6. MASS BALANCE AND DISTRIBUTION AMONG THE FURNACE PRODUCTS

The Phase 1 tests and other arc melting test programs have shown that arc melter vitrification of radioactive and mixed wastes can potentially be used to thermally separate heterogeneous waste mixtures into a few, more homogeneous, easily handled and characterized output streams. A simplified process model of the furnace is shown in Figure 6-1. Mass inputs to the furnace include the feed material, carbon from oxidation of the graphite electrodes, air leakage with the feed material and through seals in the furnace, and primary combustion air. Furnace mass outputs include the tapped glass/ceramic slag product, the tapped melted metal product, and the furnace offgas. The offgas includes the gases evolved from the melt, gaseous oxidation products, air leakage and primary combustion air, entrained feed dust, melt material ejected from the molten pool with gas evolution or turbulence, and volatilized materials that condense upon cooling. In normal operation with continuous feeding and slag tapping for most types of feed materials, a cold top may be formed from unmelted feed material floating on the surface of the molten bath, or melt. The thickness of the cold top may be maintained relatively constant by matching the feedrate and the melting rate. With the three electrodes arranged near the center of the furnace and the four feed tubes arranged outside the perimeter of the electrodes, unmelted feed material (cold top) probably built up under each feed tube.

Using Ce as a surrogate for plutonium and using actual selected toxic metals in the feed materials, the Phase 1 (Baseline) tests have shown that plutonium and much of the toxic metals in preincinerated waste can be permanently stabilized in the glass/ceramic product. The glass/ceramic product can be very durable and nonleaching, suitable for shipping and permanent disposal. Other metals, such as recyclable structural metals, are separated to a metal alloy product that is essentially decontaminated of radionuclides. Hazardous organic contaminants are separated from the wastes and thermally destroyed. Furthermore, arc melting can substantially reduce the waste volume and "homogenize" the product materials, resulting in direct cost savings for subsequent waste characterization, shipping, storage, and disposal.

The objectives of this test program included evaluating the distribution partitioning to the furnace products of (a) TRU elements using Ce as a Pu surrogate, and (b) toxic metals present in surrogate feed mixtures that contained a variety of metals, inorganics, and nonincinerated organic materials. The toxic metals present in the test feed materials at a significant level included Cr, Ni, and Pb, and the structural metals included Fe, Al, and Cu. Natural trace-level oxides of other toxic metals Ag, As, Ba, Cd, and Se were also present at very low (typically ppm-level) concentrations in the feed. The fate of volatile materials and fixed carbon was also to be evaluated. Much of the sample collection, sample analysis, and online measurements were made to evaluate the fate and distribution of feed materials, organics, toxic metals, and the TRU surrogate during the arc melter vitrification process.

6.1 Input and Output Mass Balance Closure for the Furnace

Mass balance closure for the furnace was determined by comparing the output products masses (on both an elemental and global mass basis) to the input mass. These integral mass balances were conducted for the preheat interval, the BWID feed interval, the IWPF feed interval, and the cleanout interval (Table 6-1), rather than for each individual test feed mixture interval. Accurate mass balances could not be made for each separate feed mixture interval for several reasons. First, the residence time of inventory material in the furnace resulted in the blending of a new feed material at the start of its feed interval with existing material in the furnace from the prior feed intervals. This mingled the slag from the preceding and antecedent feed intervals in slag samples collected for analysis. Conducting the mass balances over larger feed intervals reduces the significance of this cross-contamination from one feed interval to the next

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Figure 6-1. Simplified process model of the furnace.

Table 6-1. Total mass balance closure.

Test day	Feed type	Total input feed amount (lbs)	Total energy (MWh) ^a	Electrode consumption (lb) ^b	Total slag tapped ^c		Total metal product		Total APCS solids ^d		Total moisture evolution ^d (lb)	Water of combustion ^f (lb)
					(lb)	(wt % of initial feed mass)	(lb)	(wt % of initial feed mass)	(lb)	(wt % of initial feed mass)		
4/10 to 4/11	Preheat	6,818	4,685	79.7	5,572	81.7	0.00	0.00	277	4.06	30.5	
4/11 to 4/13	BWID	13,929	7,162	122	9,202	66.1	1,403	10.1	1,233	8.85	1,046	1,346
4/13 to 4/14	IWPF	3,489	3,132	53.3	834	23.9	11.0	0.32	309	8.86	146	1,188
4/14	Cleanout	3,286	2,012	34.2	2,804	85.3	412	12.5	66.0	2.01	149	0
4/13 to 4/14	IWPF + Cleanout ^k	6,775	5,144	87.5	3,638	53.7	423	6.24	375	5.54	295	1,188
Total^l		27,522	16,991	289	18,412	66.9	1,826	6.63	1,885	6.85	1,371	2,534

Table 6-1. (continued).

Feed type	CO2 evolution (lb) ^a	SO2 evolution (lb) ^{b,m}	HCl evolution (lb) ^{i,m}	Total gaseous evolution ⁿ		Total corrected output mass (lb)	Mass balance closure ^j
				(lb)	(wt. % of initial feed mass)		
Preheat	372	0.00	0.00	402	5.90	6,251	0.91
BWID	764	0.00	79.6	3,005	21.6	14,843	1.06
IWPF	897	0.98	432	1,793	51.4	2,947	0.83
Cleanout	24.0	0.36	0.10	173	5.28	3,455	1.04
IWPF + Cleanout ^k	921	1.35	432	1,967	29.0	6,403	0.93
Total^l	2,019	0.00	471	5,374	19.5	27,497	0.99

- a. From facility data acquisition system (DAS) except for the WHC-2 and TH2 feeds which were taken from the manually recorded Furnace Log.
- b. Proportioned according to energy usage for each feed interval.
- c. Calculated from slag pots collected.
- d. From combined catches in cyclone, baghouse, thermal oxidizer base, and ductwork.
- e. Calculated from proximate analyses of the feed mixtures for moisture and H₂O loss. The value for the preheat interval includes water of combustion.
- f. Calculated from proximate analyses of the feed mixtures for water created from combustion of volatile organics minus the H which combines with Cl₂ to form HCl.
- g. CO and CO₂ from oxidation of the graphite electrodes is assumed to be negligible, although it is accounted for in the total mass balance for all test days.
- h. Assumes that SO₂ evolves from the feed and that the contribution of reduced sulfur species in feed (S, H₂S, etc.) that oxidize to SO₂ is negligible.
- i. Calculated HCl levels based on Cl mass balance, assuming no production of Cl₂.
- j. Sum of output mass/Sum input mass.
- k. IWPF and Cleanout were combined to account for slag and APCS solids from the IWPF interval that were not tapped or removed until the cleanout interval.
- l. Only the grand total correctly includes all of the APCS solids and slag.
- m. When 0.00 is reported, the calculated value may have actually been slightly negative because of relatively high concentrations in the slag, metal, and/or APCS solids, and were adjusted to 0 for the calculations.
- n. Total gaseous evolution includes total moisture evolution, water of combustion, CO₂, SO₂, and HCl evolution as well as the evolution of any other volatile species which were calculated by difference from the feed material.

one. Also, slag tapping was not possible for some of the IWPF feed mixtures and was limited for other feed mixtures because of the slow feedrates of slag-forming materials during those feed intervals and the partial blockage of the water-cooled slag taphole by solidified melt material. There were only two metal taps, one near the end of the BWID feed interval, and one at the end of the melting campaign. These issues were expected in test planning, and accepted in order to progressively and relatively rapidly demonstrate processing of different furnace feeds.

There was also significant hold-up of APCS solids in the APCS owing to (a) deposition of material in the connecting ductwork and thermal oxidizer, and (b) the inability to completely remove all material collected in the baghouse. The APCS solids were quantitatively recovered from the ductwork and baghouse hopper following the melting campaign. This material represented the integrated collection of APCS solids for most of the melting campaign.

The evolution of gaseous material from the furnace was measured during discrete sampling periods during the test program. The emission rates during these sampling periods were not necessarily representative of the total or average emissions for mass balance calculations. Therefore, the mass emission rates for moisture, water of combustion, and other gaseous emissions from the feed materials were calculated using the feed compositions and feedrates.

Overall, the total mass balance closure was very good. The sum of the output mass (slag, metal, APCS solids, and offgas from the melt) divided by the sum of the input mass (feed material and electrode consumption) averaged 0.99 and ranged from 0.83 to 1.06. This variation from unity for the separate preheat, BWID, IWPF, and cleanout intervals is attributed primarily to the varying carryover of molten material in the melt and unmelted material in the cold top from interval to interval.

Elemental mass balances were calculated using weighted mean feed, slag, metal, offgas, and APCS solids concentrations, and the feed and product flowrates. The weighted mean feed, slag, metal, and offgas solid concentrations are calculated in Appendix G. The weighted mean metal and APCS solids were calculated by apportioning each of these products between the BWID and IWPF feed intervals. Metal that was tapped at the end of the Nom-60 feed interval was apportioned entirely to the BWID feed interval, but metal tapped at the end of the melting campaign contained metal derived from the BWID Nom-50 and Nom-40 feed mixtures, as well as the IWPF feed mixtures. The amount of this metal was apportioned according to the amounts of metals i.e., Fe, Cr, Ni, and Cu in each of the feeds expected to report significantly to the metal product, assuming negligible metal oxidation or reduction that would reduce or increase the amount of metal product. This assumption was justified for the melting interval preceding the first metal tap by comparing the amount of metal product produced with the amounts of these metals fed to the furnace. The 1,004 lb of metal product from the first tap represented only 5% more than the amount of metals (about 950 lb) calculated from the feed inputs. The additional 5% of the tapped metal likely represents some Fe that was reduced from FeO in the high temperature, reducing melt regions near the electrodes.

The final metal tap contained 822 lb. About 418 lb can be ascribed to the BWID Nom-50 and Nom-40 feed mixtures based on negligible Fe oxidation or reduction. About 11 lb of metal resulted from the IWPF feed mixtures, assuming negligible Fe oxidation or reduction. There was about 393 lb additional metal from this metal tap, which resulted from reduction of small amounts of iron oxides naturally present in the soil used in most of these test feeds and from reduction of iron oxide additive (millscale) used in the post-test feed period to completely clean out the furnace. Millscale additive (Fe_3O_4 , magnetite) was used to reduce viscosity of the post-test feed mixture to ensure complete slag draining from the furnace bottom. It also proved to be an effective source of oxygen for complete oxidation of the organics remaining in the residual cold top material from the IWPF interval.

These product concentration and flowrate data provide the basis for the elemental mass balances over the furnace, which are included in Appendix H. Three sets of elemental mass balances were calculated: (a) the mass balance over the entire melting campaign, designated the Global balance, (b) the mass balance over the BWID feed interval, and (c) the mass balance over the IWPF feed interval. Two balances were calculated for each interval: (a) assuming that the concentrations for certain elements that were below detection limits to be zero, and (b) assuming these same concentrations to be at the detection limit. For example, the weighted mean concentration for Ag in the Global product slags was <0.5 mg/kg. The mass balance for Ag was thus calculated two times, assuming the concentration for Ag in the product slags was 0.0 mg/kg and 0.5 mg/kg.

Elemental mass balance closure over the furnace for the Global, BWID, and IWPF feed intervals is illustrated in variance diagrams in Figures 6-2 through 6-4. Complete closure is indicated by the 100 percentile line on the diagrams. The maximum and minimum closure values for elements that had concentration levels below detection limits were based on assuming zero (minimum value) or the detection limit (maximum value). Therefore, the actual closure value falls somewhere between the two values. A single point indicates that the concentration for that particular element was not below detection levels; thus, there was no variation in closure. Generally speaking, closure over the BWID feed interval was superior to either the Global or IWPF feed interval closure. This was because of longer-duration feed intervals, less variation in the feed composition for the BWID feed intervals, and higher levels of slag formers in the feeds relative to volatile components.

The major slag-forming elements (Al, Ca, Fe, Mg, and Si) present in the highest concentrations in the feed mixtures show the best output and input closure results, particularly for the Global and BWID feed intervals. Closure for all the elements varies more for the IWPF feed interval, because (a) there were much smaller amounts of all metals in the S and C feed mixtures than present in the BWID feed mixtures, and (b) difficulty experienced in obtaining a truly representative slag sample. The IWPF feed mixtures were fed to a pool of BWID slag remaining in the furnace, and a relatively small amount of slag was tapped owing to the subsequent low feedrates of slag-forming materials. The slag samples collected during the IWPF feed interval were actually a mixture of slag from the BWID and IWPF feed intervals. The IWPF feed mixtures were significantly different in composition from the BWID feed mixtures, so calculating the elemental mass balances based on a mixed slag sample led to poor closure results.

Mass balance closure for several elements deviated more than $100\% \pm 20\%$ for all of the feed intervals. These elements were Ag, As, Ba, Cd, P, Zn, and Zr. Good mass balance closure is not expected for these elements because they were present only at trace levels in the feed mixtures. Small variations in the feed and product measurements equate to large deviations, as shown, from 100% closure. Measurable amounts of As and Cd found in the APCS solids were significantly higher than the calculated furnace input amounts, suggesting that the actual feed concentrations of these trace metals were somewhat higher than reported in the feed component analyses.

6.2 Elemental Distribution of Feed Materials Among the Furnace Products

Elemental distribution of feed materials between the furnace output products was calculated independently from the feed input rates by dividing the amount of each element measured in each furnace product stream by the amount of each element in the sum of all of the furnace product streams as follows:

Figure 6-2. Global elemental mass balance closure, assuming concentrations below the detection limits to be zero (Global-1) and at the detection limit (Global-2).

Figure 6-3. Elemental mass balance closure for the BWID feed interval, assuming concentrations below the detection limits to be zero (BWID-1) and at the detection limit (BWID-2).

Figure 6-4. Elemental mass balance closure for the IWPf feed interval, assuming concentrations below the detection limits to be zero (IWPf-1) and at the detection limit (IWPf-2).

$$D_{i,j} = c_{i,j}m_j / \sum_j (c_{i,j}m_j) \times 100\%$$

where

- D = Distribution (mass fraction) in %
- i = Element i
- j = Output product (slag, metal, offgas, APCS solids)
- c = Mass concentration
- m = Mass of each output product for each test.

This method uses the measured elemental concentrations of the output products and the output product masses to calculate elemental distribution fractions of the feed materials among the output products. The input masses of each element based on the feedrate and feed mixture concentrations were not used. This approach is more accurate when the output and input mass balance closure for many individual elements deviates significantly from 100%. Such deviation is common for elements that are present at very low or trace levels, as is the case for many of the elements in the feed mixtures.

The weighted mean concentrations of the furnace products used in the elemental distribution calculations are shown for the entire test duration (global products), the BWID feed interval, and the IWPf feed interval in Appendix I. The calculations according to the equation above are shown in Appendix J.

As in the output and input mass balance closure calculations, separate elemental distribution calculations were made for those elements that had concentration measurements below the analytical detection limits.

Elemental distributions between the furnace products for the global, BWID, and IWPF feed intervals are shown graphically in Appendix K and summarized in Table 6-2. The elemental distributions are strongly influenced by the slag product concentrations, because the slag product is much larger than the metal and offgas solid products. These elemental distributions are based only on the solid furnace products (the slag, metal, and APCS solids).

One of the main objectives of the test program was to evaluate the distribution of Ce, the TRU surrogate. As expected, Ce distributed primarily (99.6%) to the slag, and 0.4% to the APCS solids. There was none detected in the metal product, at a detection limit of 1 mg/kg. The decontamination factor (ratio of the concentration of Ce in the slag to the concentration of Ce in the metal) assuming 1 mg/kg (the detection limit) is 5,000. The Ce decontamination factor for the APCS solids compared to the slag is 60. The small amount of Ce that appeared in the APCS solids was probably because of entrainment of some fines from the CeO_2 added to the feed mixtures. This entrainment of CeO_2 dust may be higher than the expected entrainment of Pu from the actual waste because Pu in the actual waste is less likely to be associated with very fine, entrainable particles.

These results show that the metal product from treating alpha-contaminated mixed wastes will have very little if any measurable Pu contamination, assuming that Pu behaves similarly to Ce. The APCS solids will also be relatively decontaminated, with about two orders of magnitude lower Pu contamination than the slag.

The more volatile metals such as Cd, K, Na, Pb, Se, and Zn were concentrated in the APCS solids, primarily in the baghouse catch. Reduction of some of the oxides to metal is believed to occur within the vicinity of the electric arc, followed by volatilization of the metal from the molten slag and subsequent reactions with atmospheric species to also form oxides, hydroxides, chlorides, and sulfates that may heterogeneously or homogeneously condense in the offgas to form a fume. A "fume" is technically defined as solid or liquid particulate matter present in a gaseous flow mixture as a result of vapor condensation. (Fumes can also be referred to as an aerosol.)

The metals Fe, Cr, Cu, and Ni were distributed primarily to the metal product. These metals were fed to the furnace primarily in metallic form as constituents of the structural metals (stainless steel, mild steel, copper shot), and were not oxidized or volatilized within the furnace. There was also some reduction of iron oxides to metallic iron, contributing to the fraction of total Fe that distributed to the melted metal product.

Owing to concentrations below detection levels in the slag and metal products, the elements Ag, As, Hg, and Se exhibit extreme variations on the maximum-minimum plots for the various feed intervals. The true distribution for each of these metals falls somewhere between the two extremes reported for each of these elements. A single point indicates that the concentration for that particular element was not below detection levels; thus, there was no variation in distribution.

The APCS solids include not only material that has volatilized from the melt and then condensed, but also include fine feed dust that has bypassed the melt and been entrained into the plenum gas. This material can contain constituents, volatile or not, that are in the feed as finely divided materials. The relative proportions of entrained and volatilized materials are difficult to estimate for heterogeneous feed mixtures with the very different particle sizes used in this test program because the entrained and volatilized

Table 6-2. Summarized elemental distribution to the furnace products.

Element	Percent Distribution to Furnace Products			
	Slag	Metal	APCS solids	Offgas
Ag	0 ^a	4-24	76-100	—
Al	88-98	0.005-0.03	2-12	—
As	0 ^a	17-80	20-82	—
Ba	37-88	0.1-0.8	15-63	—
C	0.09-0.3	0-5	0-1.4	94-99
Ca	88-95	NC ^b	5-12	—
Cd	0 ^a	NC ^b	100	—
Ce	99.4-99.7	NC ^b	0.3-0.6	—
Cl	0-0.17	0 ^a	2-80	32-98
Cr	0.4-3	94-97	0.3-6	—
Cs	0-29	NC ^b	71-100	—
Cu	0.8-6	71-98	1-23	—
F	2-5	NC ^b	95-98	—
Fe	9-19	63-89	1-18	—
K	0.3-55	NC ^b	45-99.7	—
Mg	23-90	NC ^b	10-77	—
Mn	0.5-28	23-71	9-77	—
Mo	0.5-18	21-84	15-77	—
Na	5-68	NC ^b	32-95	—
Ni	0.3-1.3	94-99.6	0-0.21	—
P	11-17	14-72	15-72	—
Pb	0-0.2	0.6-10	90-99.4	—
Se	0 ^a	0 ^a	100	—
Si	64-90	0.5-3	7-35	—
Ti	46-96	3-10	1-50	—
Zn	1-6	NC ^b	94-99	—
Zr	98-99	0.6-2	0.17-1	—

a. Zero is assumed for measurements below detection limits.

b. Not calculated because these elements were not measured.

materials are mixed together. The XRD results (Section 7.1) suggested that there was significant volatilization based on lack of crystalline SiO_2 (quartz) and carbonate in the baghouse catch.

Elements in the feed mixtures that partition primarily to the offgas are C, H, Cl, N, and S. Distributions for these elements that significantly evolve in the offgas in Appendices J and K are biased because the masses of these elements that evolved in the offgas are not included in the distribution calculations. Assuming a mass balance closure of 100% for the C and Cl, the distribution of these elements can be calculated using the input feedrates and concentrations. The distribution results for C and Cl are shown in Tables 6-3 and 6-4. Around 95% of the C and 64% of the Cl in the feed mixtures partitioned to the offgas. Just under 4% of the C partitioned to the metal product, and no Cl was detected in the metal. Just under 1% of the C partitioned to the APCS solids. Only 0.2% of the C and 0.1% of the Cl partitioned to the slag.

The distribution of Cl between the offgas and the APCS solids depended on the amount of Cl present and other factors such as the amount of Ca, Na, and K in the APCS solids. When the concentration of Cl in the feed during the BWID interval averaged about 1.8%, the total Cl input to the furnace was 252 lb, the Cl distribution to the offgas was only 32%, and Cl distribution to the baghouse was 68%. Chlorine was scrubbed in the offgas and the baghouse through reaction with Ca, Na, and K. The average Ca, Na, K, and Cl levels in the BWID APCS solids were 11.3, 8.3, 4.7, and 14%, respectively. The average molar ratio of the combined Ca, Na, and K to the total Cl was 1.8 to 1. This ratio approaches ratios of 2-5 often used in dry acid gas scrubbing equipment. The molar ratio of combined Ca, Na, and K to the Cl collected in the baghouse was 2.7, indicating that 38% of the Ca, Na, and K was combined with Cl to form CaCl_2 , NaCl , and KCl . There was sufficient Ca, Na, and K to scrub over two-thirds of the Cl in the offgas during the BWID feed interval.

When the feed Cl concentration was much higher (averaging 13.2%) in the IWPF feed mixtures, the Cl input to the furnace was 462 lb. Chlorine distribution to the offgas was much higher at 98%, and the Cl distribution to the APCS solids was only 2%. Levels of Ca, Na, K, and Cl in the baghouse were 14.5, 4.3, 3.3, and 9.6%, respectively. The average molar ratio of the combined Ca, Na, and K to the total Cl was much lower at 0.080 than for the BWID interval. The molar ratio of combined Ca, Na, and K to the Cl collected in the baghouse was 3.7, indicating that 27% of the Ca, Na, and K was combined with Cl to form CaCl_2 , NaCl , and KCl . Not only was there less Ca, Na, and K compared to Cl during the IWPF feed interval, but it was somewhat less efficient for scrubbing Cl. Proportionately less Cl was scrubbed during the IWPF feed interval because of the larger amount of Cl in the offgas compared to the amount of Ca, Na, and K in the baghouse solids.

Table 6-3. Carbon balance for the baseline tests.

Feed type	Feed conc. (%)	Amt. of C in feed (lb)	Electrode consumption (lb) ^a	Conc. of C in slag (ppm)	Amt. of C in slag (lb)	Percent of C partitioned to slag	Conc. of C in APCS solids (ppm)	Amt. of C in APCS solids (lb)	Percent of C partitioned to APCS solids	Conc. of C in metal product (ppm)	Amt. of C in metal product (lb)	Percent of C partitioned to metal	Amt. of C from CO ₂ and CO in furnace offgas (lb) ^b	Percent of C partitioned to offgas
Preheat	5.55	378	79.7	77.4	0.43	0.09	21,800	6.04	1.32		0.00	0.00	451	98.6
BWID	5.94	827	122	280	2.58	0.27	11,024	13.6	1.43	33,400	46.9	4.94	886	93.4
IWPF	25.9	903	53.3	3,445	2.87	0.30	7,414	2.29	0.24		0.00	0.00	951	99.5
Cleanout	0.73	24.0	34.2	0.00	0.00	0.00	8,806	0.58	1.00		0.00	0.00	57.7	99.0
IWPF + Cleanout	13.7	927	87.5	790	2.87	0.28	8,153	3.06	0.30	65,000	27.5	2.71	981	96.7
Total	7.75	2,132	289	319	5.87	0.24	10,949	20.6	0.85	47,625	87.0	3.59	2,308	95.3

a. Electrode consumption for each sampling period was determined by dividing the energy for that time period by the total energy for all the tests and multiplying by the total electrode consumption.

b. The carbon balance was forced to 1 in order to calculate the amount of carbon that went to the offgas.

Table 6-4. Chlorine balance for the baseline tests.

Feed type	Feed Cl conc. (%)	Amt. of Cl in feed (lb)	Conc. of Cl in slag (ppm)	Amt. of Cl in slag (lb)	Percent of Cl partitioned to slag	Conc. of Cl in APCS solids (ppm)	Amt. of Cl in APCS solids (lb)	Percent of Cl partitioned to APCS solids	Amt. of Cl from HCl in furnace offgas (lb)	Percent of Cl partitioned to offgas
Preheat	0.11	7.57	0.00	0.00	0.00	125,000	34.6	NC	NC	NC
BWID	1.81	252	46.0	0.42	0.17	139,427	172	68.2	79.6	31.6
Preheat + BWID	1.25	260	28.7	0.42	0.16	138,189	209	80.4	50.4	19.4
IWPF	13.2	462	220	0.18	0.04	32,401	10.0	2.17	452	97.8
Cleanout	0.00	0.10	0.00	0.00	0.00	152,058	10.0	NC	NC	NC
IWPF + Cleanout	6.82	462	50.4	0.18	0.04	95,888	36.0	7.78	426	92.2
Total	2.62	722	33.0	0.61	0.08	132,914	251	34.7	471	65.2

a. The chlorine balance was forced to 1 in order to calculate the amount of chlorine that went to the offgas.

b. NC = Could not calculate because the estimated Cl in the APCS solids was much larger than the estimated Cl content in the feed.

7. PROPERTIES OF FURNACE PRODUCTS

The properties of the furnace products will significantly influence the viability of electric arc melting for mixed waste treatment. These products will become the final waste forms for currently very heterogeneous mixed wastes. Desirable waste form features that arc melter treatment is expected to achieve include (a) immobilization of long-lived radionuclides, especially TRU elements, and selected Resource Conservation and Recovery Act (RCRA) toxic metals in a durable, long-lived, nonleaching waste form, (b) thermal destruction of all organic material including RCRA hazardous compounds, (c) reduction of the waste volume, and (d) thermal separation and homogenization of the heterogeneous input waste materials to enable easier and less costly packaging, characterization, shipping, and disposal.

Samples of the solid furnace products were collected during the test program for analysis of the product chemical and physical properties. The product sample log is presented in Appendix L.

Slag samples were collected by placing a 12-in.-square by 0.5-in.-thick mild steel plate under the slag launder directly into the slag tap stream. This produced a slag *pancake* weighing about 1 kg and measuring 8 in. in diameter $\times$ 1-in. thick, which cooled quickly. This method ensured that each slag sample would undergo a uniform cooling rate, and any variations in crystallinity would be caused by chemistry alone. The *pancakes* fractured upon cooling, generally within 15 min, and were collected in 1-gal metal cans for archiving. Approximately 250 g of the archive samples were crushed through 0.125 in. mesh, then shatterboxed through 175 μ m screens in preparation for analysis.

Metal buttons were collected during the two metal taps by inserting a cast iron cup into the tap stream, and pouring the metal into ceramic molds on a copper plate. Drillings of the buttons were then sent to the analytical laboratory.

Samples were collected at regular 2-hour intervals from the cyclone and baghouse catches during the demonstration melting tests. However, bridging over the rotary airlock valves caused mixing of the APCS solids during much of the test. An effort was made to analyze all samples collected from distinct feed intervals, recognizing that the bridging problem may have resulted in mixing of residues in all samples. To this end, cyclone samples collected during the Nom-60, S-40, and S-0 feed intervals, as well as baghouse samples collected during the preheat interval, Nom-90, and Nom-60 feed intervals were analyzed. The remainder of the APCS solids were collected after the conclusion of the demonstration tests. These samples included material from the thermal oxidizer base, from within the ductwork itself, and the cyclone and baghouse catches. Representative samples from each location, weighing approximately 250 g, were prepared by standard cone and quartering methods and sent to the analytical laboratory.

7.1 X-ray Diffraction Analysis of Product Slags and APCS Solids

All but one of the product slag samples collected throughout the BWID feed interval were determined to be noncrystalline by x-ray diffraction (XRD) analysis (Table 7-1). Trace amounts of alpha Fe in the SP-4 and SP-6 slag samples indicate some reduction of iron. Only the SP-12a slag sample, collected during the S-0 feed interval, was determined to be primarily crystalline in nature. The phase identified, larnite or dicalcium silicate (Ca_2SiO_4), is a known metastable compound that breaks down to a fine powder over time. The larnite slag was produced after significant lime additions were made to the melt in attempts to fluidize the molten pool. However, the lime was not distributed throughout the bath, but actually fluidized only the central portion. This portion was successfully tapped, but the residual bath remained essentially unchanged. Only after the addition of a solid oxidant and fluidizer (mill scale) was the

Table 7-1. X-ray diffraction analysis of the product slags.

	Primary phase	Secondary phase	Minor phase	Trace phase
Nom-90 SP-2	Noncrystalline	ND	ND	ND
Nom-80 SP-4	Noncrystalline	ND	ND	alpha Fe
Nom-70 SP-6	Noncrystalline	ND	ND	alpha Fe
Nom-60 SP-8a	Noncrystalline	ND	ND	ND
Nom-60 SP-9b	Noncrystalline	ND	ND	ND
Nom-50 SP-10c	Noncrystalline	ND	ND	ND
Nom-50 SP-11a	Noncrystalline	ND	ND	ND
Nom-40 SP-11f	Noncrystalline	ND	ND	Unident cpd(s)
S-40 SP-11j	Noncrystalline	ND	ND	ND
S-0 SP-12a	Ca ₂ SiO ₄ (larnite)	ND	CaCO ₃ (calcite)	Noncrystalline material

Primary Phase: 40 to 100%

Secondary Phase: 20 to 60%

Minor Phase: 5 to 30%

Trace: 1 to 10%

ND: Not detected

remainder of the bath fully melted and mixing of the entire pool accomplished. This is an indication that the SP-12 slag sample does not truly represent the final waste form expected to be produced from melting the S-0 feed mixture.

The XRD results of the APCS solids (Table 7-2) show that the APCS solids had much greater variety in phase compositions than their contemporary slag samples. The thermal oxidizer base, ductwork composite, and post-test baghouse catch samples contained material deposited during all of the feed intervals, including the preheat and cleanout intervals. Therefore, some of these deposits are unrelated to the BWID and IWPF feed materials. The primary phase identified in the sample from the thermal oxidizer base, gehlenite ($\text{Ca}_2\text{AlSiO}_7$), is a product of the calcium-aluminum-silicate material fed during Preheat 2. However, the minor phase pseudowollastonite (CaSiO_3) almost certainly resulted from entrainment of the Micro-Cel E component of the BWID and IWPF feed mixtures. The primary phase identified in the ductwork composite sample, halite (NaCl), is common to all other samples, though in varying concentrations. The NaCl is from volatilization of chlorides and reaction with sodium that was either volatilized or entrained. The minor phase, calcite (CaCO_3), is also present in most of the other samples, and is from entrainment, not volatilization. However, the trace phases, tinalconite ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 5\text{H}_2\text{O}$) and apthitalite [$\text{K}_3\text{Na}(\text{SO}_4)_2$], only occur in samples collected near the beginning of the BWID feed interval (INEL C-4 and INEL B-1). These two phases are products of the WHC Method B feed material, which was used during the Preheat 1 feed interval. Their presence in the later cyclone and baghouse samples confirms that mixing of the APCS solids occurred. The lack of crystalline SiO_2 (quartz) in any of the baghouse samples suggests that much of the APCS solids was from volatilized materials or expelled melt material that subsequently condensed and were captured.

The cyclone catch samples from the Nom-60, S-40, and S-0 feed intervals were also primarily noncrystalline, suggesting significant volatilization rather than entrainment. The secondary and minor phases detected in the Nom-60 samples indicate the residues deposited from the previous feed intervals, as discussed above. However, the S-40 and S-0 samples contained a trace phase unique to the IWPF feed interval, silicon carbide. The presence of silicon carbide in the cyclone catch suggests that some silica was reduced to silicon within the furnace, followed by carburization of the silicon. Reduction of silica to silicon has been demonstrated in the immediate vicinity of the electrodes (O'Connor et al. 1994). The silicon will usually recombine with oxygen in the furnace exhaust to form an amorphous silica powder, but the abundance of organic material in the furnace exhaust apparently allowed the formation of silicon carbide as well. The cyclone sample from the cleanout feed interval contained quartz (SiO_2). Although chemically indistinguishable from the amorphous silica formed by the reduction and oxidation of silica in the furnace feed, the quartz indicates entrained feed, because only the amorphous form would be expected from volatilized silica that has condensed. The fact that the feed during the cleanout interval was the Nom-90M feed mixture, which contained a very high percentage of soil, supports this assertion. The RWMC soil contains approximately 60 wt% SiO_2 , in the form of quartz.

7.2 Viscosity and Density of Product Slags

Viscosities of the product slags were calculated based on their chemical compositions using a silicate glass property software package from Advanced Materials Research, Inc. (Advanced Materials 1995). Properties supported include the full range viscosity and Fulcher Equation coefficients, density, and coefficient of thermal expansion. The property estimation algorithms are based on statistical data augmented by theoretical considerations of silicate glass coordination and structure. The calculated viscosities for several of the BWID slags are plotted in Figure 7-1. The composition of the IWPF slag (SP-12) was out of the applicable range for the major oxides; thus, the viscosity could not be calculated. Note that although the nonmetallic furnace tap product has been referred to thus far as slag, XRD analysis confirms that each slag product could be correctly described as a glass.

Table 7-2. X-ray diffraction analysis of the APCS solids.

	Primary phase	Secondary phase	Minor phase	Trace
Thermal oxidizer base	$\text{Ca}_2\text{AlSiO}_7$ (gehlenite) noncrystalline	ND	CaSiO_3 (pseudowollastonite)	Unident cpd(s) noncrystalline material
Ductwork composite	NaCl (halite) noncrystalline	ND	CaCO_3 (calcite)	$\text{Na}_2\text{B}_4\text{O}_7 \cdot 5\text{H}_2\text{O}$ (tincalconite) $\text{K}_3\text{Na}(\text{SO}_4)_2$ (aphthalite) SiO_2 (quartz) unident cpd(s)
Cyclone Catch				
Nom-60	Noncrystalline	NaCl (halite) KCl (sylvite) CaCO_3 (calcite)	$\text{a}_2\text{B}_4\text{O}_7 \cdot 5\text{H}_2$ (tincalconite)	ND
S-40	Noncrystalline	ND	ND	NaCl (halite) KCl (sylvite) SiC (silicon carbide)
S-0	Noncrystalline	ND	ND	NaCl (halite) KCl (sylvite) SiC (silicon carbide)
Cleanout	SiO_2 (quartz) CaCO_3 (calcite) noncrystalline	ND	KCl (sylvite) NaCl (halite)	Unident cpd(s)
Baghouse catch				
Nom-90	ND	NaCl (halite) $\text{K}_3\text{Na}(\text{SO}_4)_2$ (aphthalite) $\text{a}_2\text{B}_4\text{O}_7 \cdot 5\text{H}_2$ (tincalconite)	CaCO_3 (calcite) KCl (sylvite) unident cpd(s)	Noncrystalline material
Nom-60	ND	NaCl (halite) KCl (sylvite)	ND	CaCO_3 (calcite) unident cpd(s)
Post-test	Noncrystalline	NaCl (halite) KCl (sylvite)	CaCO_3 (calcite)	Unident cpd(s)

Primary Phase: 40 to 100%

Secondary Phase: 20 to 60%

Minor Phase: 5 to 30%

Trace: 1 to 10%

ND: Not detected

Figure 7-1. Calculated viscosities of the BWID product slags.

The term *slag* was used because it does not specifically define the crystallinity of the inorganic, nonmetallic furnace products. Examination of the nominal 800-lb slag monoliths from the BWID Phase 1 demonstration melting tests revealed that the cores of the molds, which underwent a slower cooling rate, were primarily crystalline. In fact, the targeted final waste form for the Phase 1 tests was the iron enriched basalt, which was crystalline by design (Reimann and Kong 1993). Thus, to call these materials glass would have been incorrect. However, similar examination of the nominal 800-lb slag monoliths from the Phase 2 tests revealed that the slag is primarily amorphous throughout, regardless of the radically-varying cooling rate. This is a primary distinction between the final waste forms of the Phase 1 and Phase 2 tests, and is likely caused by (a) the addition of lime to modify the basicity of the slag (and reduce the viscosity), and (b) the elimination of Ti and Zr oxide additives that were included in the Phase 1 tests to enhance the crystalline formation.

The viscosity curves for the BWID product slags are virtually indistinguishable through the SP-8 slag, which was tapped during the Nom-60 feed interval. However, the viscosity curve for SP-11 is much lower than that for the other BWID slag samples. The SP-11 slag sample was collected during the Nom-50 feed interval, which commenced after the first metal tap drained the furnace. A 500-lb mixture of soil and lime was charged to the furnace immediately after the metal tap. This resulted in a high concentration of lime in the slag initially tapped after the first metal tap, and a corresponding decrease in slag viscosity.

The measured slag tap temperatures are compared with their calculated 100 poise temperatures in Table 7-3 and Figure 7-2. The slag and glass melt is considered relatively fluid at 100 poise, so the difference between the tap temperature and the 100-poise temperature may be considered the amount of superheat necessary to achieve a continuous slag tap in this furnace. The amount of superheat ranged from about 100 to 400°C, with a mean of 264°C. The slag taphole in this furnace is positioned between the

Table 7-3. Physical properties of product slags.

Date	Test	Feed	Slag pot number	Sample time	Tap temperature (C)	100 poise temperature (C)	Soft. pt. temperature (C)	Anneal. pt. temperature (C)	Specific Gravity		Coefficient thermal exp. ^a	Devitrification index ^b
									Calculated	Measured		
04/11/95	BWID	Nom-90	SP-1	23:00	1818	1429	1008	899	2.63	ND ^c	8.08	-110
04/11/95	BWID	Nom-90	SP-2	23:55	1698	1361	969	864	2.67	ND	8.10	-116
04/12/95	BWID	Nom-80	SP-3	01:10	1696	1356	979	877	2.67	2.85	8.14	-123
04/12/95	BWID	Nom-80	SP-4	09:00	1580	1371	960	849	2.66	2.83	8.03	-106
04/12/95	BWID	Nom-70	SP-5	11:10	1623	1368	948	833	2.67	2.50	7.99	-100
04/12/95	BWID	Nom-70	SP-6	13:40	1606	1354	947	835	2.68	2.69	8.02	-105
04/12/95	BWID	Nom-70	SP-7	16:00	1529	1331	950	844	2.69	2.75	8.09	-117
04/12/95	BWID	Nom-60	SP-8	19:35	1519	1356	957	847	2.68	2.80	7.92	-108
04/13/95	BWID	Nom-60	SP-9	01:10	1610	1410	954	829	2.66	2.81	7.57	-81
04/13/95	BWID	Nom-50	SP-10	10:25	1612	1395	958	839	2.67	ND	7.63	-90
04/13/95	BWID	Nom-50	SP-11	11:20	1520	1272	997	920	2.72	2.71	8.14	-167
04/14/95	IWPF	S-0	SP-12	02:00	1459	ND	ND	ND	2.97	2.97	ND	ND
04/14/95	Cleanout	Nom-90 mod	SP-13	10:30	1529	1251	982	907	2.72	2.74	8.36	-172
04/14/95	Cleanout	Nom-90 mod	SP-14	12:40	1606	1251	982	907	2.72	2.74	8.36	-172
04/14/95	Cleanout	Nom-90 mod	SP-15	13:45	1509	1251	982	907	2.72	2.74	8.36	-172

a. ppm/°C.

b. Empirical value; positive value indicates stable glass, negative value indicates tendency to devitrify (0 is considered relatively stable).

c. ND = not determined.

Figure 7-2. Measured slag tap temperature compared with calculated 100 poise temperature for the product slags.

apices of the north and middle electrodes, rather than at the apex of one of the electrodes. This increases the distance between the taphole face and the electrode, which requires additional heating of the slag to ensure that the bath has sufficient fluidity at the face of the taphole. The use of the water-cooled tapping fixture also requires additional heat in the slag to maintain sufficient slag fluidity through the tapping fixture. Thus, the estimated 250°C superheat in these slags is not unexpected for this furnace configuration, but this amount of superheat may be avoided in other furnace configurations.

The difference between the softening point and annealing point temperatures (Table 7-3) of the slag and glass is considered its working range. Glasses with shorter working ranges will exhibit a steep rise in viscosity with decreasing bath temperature, which the BWID slags show in Figure 7-1. Because the BWID slags are *short* glasses (mean working range of 121°C), a small decrease in bath temperature could result in a significant increase in viscosity. This phenomenon supports the fact that significant bath superheating was required to maintain continuous slag tapping from the furnace.

Specific gravities of the slag products were calculated based on their chemistries and assumed molecular structure. These values were compared with those determined by direct measurement in Table 7-3. The measured specific gravities are generally higher than the calculated values, though the mean variation is only 3.2%. The measured density values were included in Table 7-4 for comparison with the bulk densities of the feed mixtures. The mean bulk density for the BWID and IWPF feed mixtures was 63.6 lb/ft³, compared with the mean density of 172.6 lb/ft³ for the product slags.

Table 7-4. Bulk densities of the feed mixtures and their corresponding slag densities.

Feed	Bulk density (lb/ft ³)	Slag density (lb/ft ³)
Preheat 1	33.0	154.8
Preheat 2	70.0	169.2
Nom-90	81.8	165.4
Nom-80	73.6	177.3
Nom-70	71.6	165.4
Nom-60	68.0	175.1
Soil + lime	79.5	ND
Nom-50	64.5	166.7
Nom-40	60.8	185.4
S-40	62.7	185.4
S-0	24.7	169.2
C-20	56.0	ND
C-40	55.9	ND
Nom-90M	81.7	171.0
Average	63.6	172.6

The degree of volume reduction achieved from processing both the surrogate feed mixtures and the actual waste can be determined using the initial and final masses and densities from the demonstration test. Volume reduction is achieved by reducing the solid mass through volatilization and oxidation of moisture and organic materials, and by producing slag and metal products from the majority of the remaining solid material that is more dense than the feed materials. Assumptions must be made regarding the final waste form and waste loading for the APCS solids. Volume reduction calculations shown in Table 7-5 for the average surrogate feed mixture were compared to expected volume reductions for actual waste and soil mixtures. The final waste form for the APCS solids is assumed to be Portland cement, with a waste loading of 25 wt%, and no further treatment is assumed for the metal products.

The combined volume reduction factor (initial volume divided by the total final volume including the slag, metal, and immobilized APCS solids) is 2.3 for the surrogate feeds and ranges from 3.2 to 17 for the actual waste mixtures. The estimated volume reduction factor for the actual waste materials is higher than that calculated for the surrogate feed mixtures, because of the lower initial densities of the actual wastes compared to the average density of the surrogate mixtures.

Table 7-5. Solid mass and volume reduction estimates for the average Phase 2 surrogate mixtures and comparable mixed wastes.

Category	Assumed initial mass (lb)	Density (lb/ft ³)	Estimated mass					Estimated volumes of products				Volume reduction factor	Solid mass reduction factor
			Distribution to furnace products					(ft ³)					
			Glass ceramic	Metals	Offgas	solids	Total	Glass ceramic	Metals	Offgas solids			
										Before solidification	After solidification ^a		
Avg. surrogate feed mixture ^b	100	63.6	66.9	6.6	19.6	6.9	100	0.39	0.01	0.11	0.29	2.3	1.2
Actual waste mixtures													
BWID nom-60 ^{c,d,e}	100	68.0	60.0	13.9	24.0	2.0	100	0.35	0.03	0.03	0.08	3.2	1.3
Organic/Ca silicates ^{c,d}	100	48.1	29.1	0.0	68.9	2.0	100	0.17	0.00	0.03	0.08	8.3	3.2
Organic/Ca silicates with 20% soil	100	54.9	41.3	0.0	56.7	2.0	100	0.24	0.00	0.03	0.08	5.7	2.3
Misc. combustible with 20% soil ^c	100	26.5	22.4	3.9	71.7	2.0	100	0.13	0.008	0.03	0.08	17.0	3.5
Misc. combustible with 40% soil ^c	100	40.4	39.3	2.9	55.8	2.0	100	0.23	0.006	0.03	0.08	7.8	2.3

a. Based on a waste loading of 20% and a density of 120 lb/ft³.

b. From measurements made during the Phase 2 tests.

c. Roesner W. S., Soelberg N. R., and Ayers A. L., "Identification of a Treatment Process for the Idaho Waste Processing Facility Project-A Preconceptual Design Study", WM-PD-92-009, Sept. 1992.

d. Gale L. G., Raivo B. D., "Estimated Waste Matrix Compositions of alpha-LL Waste for Treatment Design Bases".

e. Soelberg N. R., Chambers A. C., O'Conner W. K., and Oden L. L., "Arc Melter Vitrification Tests for INEL Alpha-contaminated Wastes", May 1995.

7.3 Chemical Analysis of Product Slag, Metal, and Air Pollution Control System Solids

Chemical analyses of the product slag, metal, and APCS solids are included in Tables 7-6 and 7-7. Oxygen content in the slags and APCS solids was calculated based on the assumed oxide species present in the sample (Al_2O_3 , CaO , SiO_2 , etc.). Relative closure indicates the accuracy of the analyses and assumptions. Mean closure for the BWID and IWPF slag samples was 97.4%, whereas that for the APCS solids was 97.2%. The mean metal closure was 104.4%.

Compositional trends are most readily recognized by plotting the concentrations of the various oxide species versus weight of slag tapped, as in Figures 7-3 and 7-4. The Al_2O_3 , CaO , and TiO_2 concentrations decrease, while CeO_2 , FeO , SiO_2 , and ZrO_2 concentrations increase at the start of the BWID feed interval. This can be attributed to the radically different compositions of the Preheat 2 feed mixture (33.3% Al_2O_3 , 45.8% CaO , 15.7% SiO_2 , and 5% TiO_2) and the BWID feed mixtures. A residual pool of the calcium-aluminum-silicate slag, weighing approximately 800 lb, remained in the furnace at the start of the BWID feed interval. The compositions of the BWID slags were diluted with this slag until the latter was washed out of the furnace, which was accomplished after tapping an additional 2,000 lb of slag.

The levels of major slag-forming oxides Al_2O_3 , CaO , MgO , SiO_2 , and $(\text{K}_2\text{O} + \text{Na}_2\text{O})$ show reasonably consistent compositional trends throughout the remainder of the BWID feed interval, though the Al_2O_3 concentration actually increased slightly, owing to oxidation of metallic Al in the feed. Total Al addition in the BWID and IWPF feed mixtures was 64.7 lb, but the mean Al concentration in the 1,826 lb of total metal products was only 210 mg/kg, or 0.4 lb. The remaining 64.3 lb of Al was oxidized, resulting in the addition of about 122 lb of Al_2O_3 to the slag. Oxygen used in the oxidation of this aluminum was probably obtained from aluminothermic reduction of 257 lb of FeO producing 200 lb of metallic Fe from the slag, based on the following equation:

Feed composition and flowrate calculations show that about 1,174 lb of metallic Fe contained in the BWID and IWPF feed mixtures was fed to the furnace. The mean Fe content in the metal products was 85%, or 1,552 lb. The additional 378 lb of Fe reporting to the metal products resulted from aluminothermic (200 lb) and carbothermic (178 lb) reduction of Fe from the slag. Total carbon required for the carbothermic reduction of FeO was calculated based on the following equation:

The additional 178 lb of Fe reporting to the metal products from carbothermic reduction represented 229 lb of FeO , which required 38 lb of C supplied by either the electrodes, the fixed C in the feed, or some combination of both.

Virtually all of the oxides show a marked change in concentration during the IWPF feed interval. Most prominent are a decrease in SiO_2 concentration, from nearly 50 wt% to less than 30 wt%, and a corresponding increase in CaO content from 30 wt% to nearly 60 wt%. Samples collected during the IWPF feed interval include high concentrations of lime that was charged to the furnace in attempts to fluidize the bath. These do not truly represent the IWPF final waste form, because the majority of the slag produced during the IWPF feed interval remained in the furnace until the cleanout interval. The feedrate

Table 7-6. Compositions of the glass, metal, and APCS products (ppm by weight).

Elements	Glass product from feed mixtures ^a						Metal products			Global weighted average of APCS solids ^d
	Nom-90	Nom-80	Nom-70	Nom-60	Nom-50,	S-0,	MP1b ²	MP2 ^c	Weighted average	
					Nom-40,	C-20,				
					S-40	C-40				
Ag	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	1.00	0.40	1.00
Al	73,800	71,300	62,800	66,800	65,967	52,200	205	215	210	18,746
As	< 5	< 5	< 5	< 5	< 5	< 5	106	94.0	101	24.0
Ba	400	485	643	647	623	93.0	18.0	13.0	16.0	296
C	241	245	350	193	2,047	3,445	33,400	65,000	47,625	10,949
Ca	217,000	216,000	218,000	208,000	260,333	391,000	— ^e	—	—	112,671
Cd	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	71.0
Ce	3,500	2,890	3,840	3,920	4,063	4,535	< 1	< 1	< 1	80.0
Cl	18.0	37.0	86.0	100	211	220	—	—	—	132,914
Cr	540	581	367	207	59.0	2.00	46,700	32,900	40,488	108
Cs	18.0	10.0	6.00	< 3	3.00	< 3	< 3	< 3	< 3	1,194
Cu	50.0	51.0	36.0	34.0	—	16.0	13,300	15,000	14,065	207
F	7.00	7.00	5.00	9.00	5.00	3.00	—	—	—	563
Fe ⁺²	24,000	16,100	7,800	8,000	6,200	3,350	—	—	—	—
Fe ⁺³	2,300	0.00	—	0.00	0.00	0.00	—	—	—	—
Total Fe	26,300	16,100	7,800	8,000	6,200	3,350	860,000	838,000	850,096	8,858
Hg	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.20
K	8,200	8,380	8,360	4,450	1,074	42.0	—	—	—	44,638
Mg	8,810	10,800	12,700	14,400	13,533	1,318	—	—	—	9,684
Mn	407	560	706	517	293	2.00	5,520	4,860	5,223	625
Mo	32.0	5.00	3.00	3.00	3.00	1.00	3,060	1,290	2,263	507
Na	7,870	8,200	8,430	5,190	1,980	852	—	—	—	83,240
Ni	15.0	9.00	9.00	8.00	9.00	2.00	17,300	13,000	15,364	27.0
O ^f	425,192	426,503	423,310	425,650	422,828	372,694	—	—	—	372,347
P	380	76.0	150	39.0	70.0	48.0	4,780	3,630	4,262	911
Pb	7.00	8.00	2.00	< 2	< 2	< 2	509	515	512	4,508
S from SO ₃	190	320	410	420	330	280	—	—	—	—
S from SO ₄	20.0	9.00	10.0	12.0	8.00	3.00	—	—	—	—
Total S	210	329	420	432	338	283	700	600	655	9,435
Se	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	117
Si	216,000	222,000	226,000	230,000	208,333	137,500	40,900	85,500	60,977	152,224
Ti	7,790	5,850	4,000	3,250	2,490	210	2,540	2,080	2,333	695
Zn	21.0	13.0	9.00	20.0	—	4.00	—	—	—	928
Zr	718	1,710	3,640	3,960	5,233	629	113	283	190	21.0
H	—	—	—	—	—	—	—	—	—	5,691
Totals	997,526	992,149	981,672	975,829	995,695	968,449	1,029,151	1,062,981	1,044,381	972,280

a. Compositions for the various feed mixtures were taken from the following slag pots: Nom-90 as SP2; Nom-80 as SP4; Nom-70 as SP6;

Nom-60 as SP9; Nom-50, Nom-40, S-40 as the wt. mean of SP11a, f, j; and S-0, C-20, C-40 as the wt. mean of SP12a, d.

b. MP1 includes metal from feeds Nom-90 to Nom-40 and S-40.

c. MP2 includes metal from feeds S-0, C-20, and C-40.

d. Weighted average of compositions from cyclone, baghouse, thermal oxidizer, and ductwork.

e. Not measured.

f. Calculated based on weights of assumed oxides.

Table 7-7. Weighted mean compositions of the furnace products (ppm by weight).

Elements	Slag				APCS solids ^a	
	Preheat	BWID	IWPF	Cleanout	BWID	IWPF
Ag	0.00	<0.5	<0.5	0.00	1.00	1.00
Al	134,250	69,819	52,200	47,591	19,048	20,194
As	0.00	<5	<5	0.00	22.0	16.0
Ba	33.8	310	93.0	0.00	286	423
C	77.4	280	3,445	0.00	11,024	8,153
Ca	221,605	217,488	391,000	248,000	112,956	144,902
Cd	0.00	<0.1	<0.1	0.00	77.0	54.0
Ce	0.00	3,713	4,535	221	85.0	70.0
Cl	0.00	46.0	220	0.00	139,427	95,888
Cr	130	168	2.00	0.00	113	71.0
Cs	157	3.00	<3	0.00	776	393
Cu	0.00	21.0	16.0	0.00	230	175
F	0.00	4.00	3.00	0.00	501	430
Fe ⁺²	0.00	9,721	3,350	0.00	— ^b	—
Fe ⁺³	3,325	210	0.00	19,594	—	—
Total Fe	3,325	9,931	3,350	19,594	9,393	8,338
Hg	0.00	<0.1	<0.1	0.00	0.2	0.10
K	3,276	6,160	42.0	10,456	46,832	33,413
Mg	2,253	11,688	1,318	9,898	9,678	11,849
Mn	29.6	274	2.00	0.00	674	587
Mo	198	4.00	1.00	0.00	444	168
Na	45,981	7,014	852	5,119	83,311	42,820
Ni	3.41	6.00	2.00	0.00	29.0	24.0
O ^c	409,024	417,637	372,694	406,188	361,319	409,922
P	199	80.0	48.0	0.00	895	679
Pb	0.00	2.00	<2	<2	4,992	3,216
S from SO ₃	0.00	190	280	0.00	—	—
S from SO ₄	0.00	6.00	3.00	0.00	—	—
Total S	0.00	196	283	0.00	8,171	3,192
Se	0.00	<3	<3	0.00	125	89.0
Si	146,457	218,898	137,500	214,979	148,607	202,766
Ti	20,155	2,397	210	0.00	742	584
Zn	0.00	8.00	4.00	0.00	1,043	734
Zr	28.1	1,790	629	0.00	23.0	17.0
H	—	—	—	—	4,837	5,650
Totals	987,181	967,937	968,449	962,046	965,661	994,818

a. Weighted average of compositions from cyclone, baghouse, thermal oxidizer, and ductwork.

b. Not measured.

c. Calculated based on weights of assumed oxides.

Figure 7-3. Concentration trends for the major slag-forming oxides in the product slags.

Figure 7-4. Concentration trends for CeO_2 , Cr_2O_3 , and ZrO_2 (primary Y-axis) and FeO and TiO_2 (secondary Y-axis) in the product slags.

of slagformers in the S-0 and C-series intervals proved insufficient to sustain a satisfactory continuous or semicontinuous tap; thus, the samples collected did not represent the majority of the slag present in the furnace. Initiation of the cleanout feed interval eventually reestablished continuous slag tapping, with dramatic reversals in CaO and SiO₂ concentrations.

Concentration trends for carbon in the product slags are shown in Table 7-8. Carbon concentrations ranged from as low as 0.0193% (193 ppm) to 0.345%, over ten times higher than the minimum values. The low values of 200-300 ppm prevailed during most of the test program. These low carbon levels may be from carbon dispersed as a fine elemental soot-type material in the slag. The higher levels of carbon in the slag occurred during the BWID and IWPF feed intervals when the feed mixtures contained larger amounts of carbon, as shown in Figure 7-5. The higher slag carbon levels may be due to the formation of silicon or calcium carbides in the slag, since there were no visible inclusions of elemental carbon in the slag monolith. The carbon content of the slag is especially sensitive to the amount of fixed carbon in the feed for feed fixed carbon contents ranging from around 0-5%. Carbon in the slag products is not undesirable unless it in any way increases leachability or degradation of the slag monolith over time. The slag leachability tests have shown that all of the slag samples representative of the processed feed mixtures easily passed TCLP and PCT-A tests. Also, none of the representative slag samples had inclusions of carbon, graphite, or other materials that were visible to the unaided eye. Additional analyses such as optical microscopy may provide further data regarding carbon in the slags.

7.4 U.S. Environmental Protection Agency Toxicity Characteristic Leaching Procedure

Four samples of the product slag, two cyclone catch samples, and two baghouse catch samples underwent Toxicity Characteristic Leaching Procedure (TCLP) analysis. The samples selected were intended to cover the range of materials produced throughout the demonstration melting tests. Tables 7-9 and 7-10 include the TCLP limits and results of TCLP analysis for each of these samples. The slag samples were crushed through 0.25-in. mesh, the size requirement for the TCLP tests; however, the APCS solids were by their nature much finer.

Toxicity Characteristic Leaching Procedure results for the slag samples were virtually all below detection limits for each of the metals. Only As in the SP-1, SP-11f, and SP-12d samples, Cr in the SP-12d, and Se in the SP-1 sample, were above detection limits, but even these levels were an order of magnitude below the TCLP limits. Excellent leaching results are of course expected for those metals that were not detected in the slag samples. Where elemental concentrations in the slag samples were above detection limits, the amount of those elements that actually dissolved could be calculated. Barium and Cr levels in the slag samples ranged up to 400 and 540 mg/kg, respectively. There was also measurable Pb (7 ppm) in one sample. Dissolution of these metals was typically under 3% of those metals, although Cr dissolution was 67% in one sample that had only 3 mg/kg Cr.

The cyclone catch samples each passed the TCLP limits, though not to the degree exhibited by the slags. There were larger amounts of several metals for these samples. Barium dissolution was under 1%, Pb dissolution ranged under 33%, Cr dissolution was under 16% and As dissolution was under 57%. Cadmium and Se levels were very low, so even low leachate levels of 0.1-0.5 mg/kg resulted in calculated dissolutions of 100% for these metals.

Table 7-8. Concentration trends for carbon in the product slags.

Feed Mixture	Feed Composition (wt%)		Feedrate to the furnace (lb/h)		Percent (%) C in slag ^a	Primary air rate (cfm)	Slag-former feedrate (lb/h)	Slag density (lb/ft ³)	Average slag residence time (h) ^b
	Total C	Fixed C	Total C	Fixed C					
Nom-90	2.28	0.27	9.74	1.17	0.024	0	356	165	2.32
Nom-80	3.83	0.57	14.1	2.09	0.025	45-140	285	177	3.11
Nom-70	5.50	0.89	19.7	3.17	0.035	0-85	257	165	3.22
Nom-60	7.27	1.23	26.1	4.40	0.019	0-95	234	175	3.73
Nom-50	9.16	1.59	32.7	5.65	0.205	70	209	167	4.00
Nom-40	11.2	1.97	87.3	15.4	0.205	70	401	185	2.31
S-40	19.4	3.87	52.1	10.4	0.205	0-70	163	185	5.68
S-0	34.6	7.05	37.4	7.62	0.345	0	41.1	169	20.6
C-20	39.2	5.27	70.4	9.47	0.345	86	49.8	ND ^c	NC ^d
C-40	28.0	3.73	167	22.3	0.345	140	272	ND	NC

- a. The value of 0.205 for Nom-50, Nom-40, and S-40 feed intervals is from a single slag sample measurement, since only one tapping period was achieved for the melt of material from these feed intervals. The same is true for the value of 0.345 that was measured for S-0, C-20, and C-40.
- b. Slag residence time was calculated from the average slag-former feedrate for each feed mixture, the capacity of the hearth (5 ft³), and the slag density.
- c. ND = Not determined.
- d. NC = Not calculated.

Figure 7-5. Comparison between carbon content of the slag and the feed carbon content.

Table 7-9. TCLP test results for selected slag samples.

Analyte	TCLP Limits (mg/L)	Nom-90 (SP-1)			Nom-60 (SP-8)			S-40 (SP-11f)			S-0 (SP-12d)		
		Element			Element			Element			Element		
		Leachate Conc. (mg/L)	Conc. in slag (mg/kg)	Percent Dissolved ^a	Leachate Conc. (mg/L)	Conc. in slag (mg/kg)	Percent Dissolved	Leachate Conc. (mg/L)	Conc. in slag (mg/kg)	Percent Dissolved	Leachate Conc. (mg/L)	Conc. in slag (mg/kg)	Percent Dissolved
Arsenic	5.0	0.3	< 5	NC ^b	< 0.1	< 5	NC	0.3	< 5	NC	0.04	< 5	NC
Barium	100.0	< 0.2	400	< 1.00	< 0.2	658	< 0.61	< 0.2	631	< 0.63	< 0.2	186	< 2.15
Cadmium	1.0	< 0.1	< 0.1	NC	< 0.1	< 0.1	NC	< 0.1	< 0.1	NC	< 0.1	< 0.1	NC
Chromium	5.0	< 0.1	540	< 0.37	< 0.1	138	< 1.45	< 0.1	58	< 3.45	0.1	3	66.7
Lead	5.0	< 0.1	7	< 28.57	< 0.1	< 2	NC	< 0.1	< 2	NC	< 0.1	< 2	NC
Mercury	0.2	< 0.1	< 0.1	NC	< 0.1	< 0.1	NC	< 0.1	< 0.1	NC	< 0.1	< 0.1	NC
Selenium	0.5	0.1	< 3	NC	< 0.1	< 3	NC	< 0.1	< 3	NC	< 0.1	< 3	NC
Silver	5.0	< 0.1	< 0.5	NC	< 0.1	< 0.5	NC	< 0.1	< 0.5	NC	< 0.1	< 0.5	NC

a. Percent dissolved was based on 1 gram of slag put into 0.02 liters of solvent.

b. NC = Not calculated due to non-detectable levels in the samples.

Table 7-10. TCLP test results for selected APCS residues.

Analyte	TCLP Limits (mg/L)	S-40 (Cyclone)			S-0 (Cyclone)			Nom-60 (Baghouse)			Post-test (Baghouse)		
		Element			Element			Element			Element		
		Leachate Conc. (mg/L)	Conc. in APCS (mg/kg)	Percent Dissolved ^a	Leachate Conc. (mg/L)	Conc. in APCS (mg/kg)	Percent Dissolved	Leachate Conc. (mg/L)	Conc. in APCS (mg/kg)	Percent Dissolved	Leachate Conc. (mg/L)	Conc. in APCS (mg/kg)	Percent Dissolved
Arsenic	5.0	0.1	18	11.1	0.2	7	57.1	< 0.1	14	< 14.29	< 0.1	23	< 8.70
Barium	100.0	< 0.2	816	< 0.49	< 0.2	425	< 0.94	< 0.2	53	< 7.55	2.2	347	12.7
Cadmium	1.0	0.1	2	100	0.1	1	100	0.2	7	57.1	4.9	144	68.1
Chromium	5.0	0.1	43	4.65	0.2	25	16.0	0.2	126	3.17	0.1	49	4.08
Lead	5.0	2.6	674	7.72	1.5	90	33.3	2.5	6440	0.78	61.7	7950	15.5
Mercury	0.2	0.2	< 0.1	NC ^b	< 0.1	< 0.1	NC	< 0.1	0.3	< 100	< 0.1	0.4	< 100
Selenium	0.5	0.5	5	100	0.5	< 3	NC	0.4	< 3	NC	< 0.1	< 3	NC
Silver	5.0	< 0.1	< 0.5	NC	< 0.1	< 0.5	NC	0.1	2	100	0.1	2	100

a. Percent dissolved was based on 1 gram of slag put into 0.02 liters of solvent.

b. NC = Not calculated due to non-detectable levels in the samples.

Only the post test baghouse catch sample, which represented a composite of material reporting to the baghouse during all of the feed intervals, failed the TCLP, for Cd and Pb. The Cd and Pb levels in that sample were 144 mg/kg and 7,950 mg/kg, respectively

7.5 Product Consistency Test (PCT-A) of the Product Slags

Eight samples of the product slag underwent the PCT-A test, an accelerated leach test conducted in (initially) deionized water at 90°C for 7 days. The slag samples were crushed and screened to the specified size range for the test, 100 × 200 mesh (150 × 75 μm). Surface area could thus be estimated for a known weight of the sized material, and release rates determined in g/m²-7 days. Leachate concentrations and normalized mass release rates are provided in Appendix M, and graphical representations of the data for Ca, Ce, K, Na, and Si are included in Appendix N. The normalized mass release rate is calculated by dividing the elemental mass release rate by the weight fraction of that element in the sample. Where leachate concentrations were below detection limits, the normalized mass release rate was calculated assuming the concentration was at the detection limit. Each sample was tested in triplicate, including samples of the Environmental Assessment (EA) glass, provided by the Savannah River Laboratory. Samples of the EA glass were included with each batch of product slags tested. The PCT-A results on the EA glass from both the USBM laboratory and the Corning Engineering Laboratory are included in Tables M-9 through M-11, and represented graphically in Figures N-9 and N-10. Variations between the two laboratory results were minimal, and certainly within acceptable ranges.

Release rates below 0.1 g/m²-7 days indicate a high quality final waste form. The SP4, SP6b, SP8a, and SP10c BWID slags meet this criteria for all elements, while the SP1 and SP11f BWID slags meet the criteria for Ca, Ce, and Si. The SP1 slag fails for Na (0.125 g/m²-7 days), owing to mixing of the Nom-90 feed with melter inventory of slag material from the preheat tests. The sodium concentration is much higher in this slag (1.08 wt%) compared with any of the other BWID slags (0.60 wt% or less). The only other BWID slag to fail the release rate criteria was the SP11f slag, in which the K release rate was 0.129 g/m²-7 days. The K concentration in the SP11f leachate was actually lower (0.20 mg/L) than any of the previous BWID slags (0.40–1.10 mg/L). However, because the K concentration in the SP11f slag (0.08 wt%) was also much lower than the previous BWID slags (0.28–0.69 wt%), the normalized release rate was greater. This illustrates the intent of the normalized release rates, which provide a means to compare glasses with varying compositions.

The two slag samples collected during the IWPF feed interval exhibit significantly different leaching characteristics. The SP11j slag, collected during the S-40 feed interval, meets the 0.1 g/m²-7-day criteria for all the elements. However, the SP12d slag, collected during the C-40 feed interval after lime additions were made to fluidize the bath, meets the criteria for Ce and Si only. Normalized release rates for Ca, K, and Na are 1 to 2.5 orders of magnitude greater than the criteria. Because the SP12d slag is not a truly representative sample of the IWPF product slags, its failure to meet the PCT-A criteria is not unexpected.

The representative product slags generally exhibited excellent leach resistance, particularly for Ce, the TRU surrogate. Selection of the final waste form compositions should be conducted with the final release rate criteria in mind. One suggestion is to substitute MgO for half of the added CaO, which was added to modify the slag basicity. The combination of the two alkaline earths will have the same net result; increasing the slag basicity while lowering its viscosity. However, it has been shown in established glass-making practice that this type of substitution will improve the glass durability.

7.6 Scrubber Solution Concentrations

Scrubber solution samples were collected at 2-hour intervals during the demonstration melting tests. Five of these samples were selected for analysis, the results of which are included in Table 7-11.

Flowrates for the scrubber solution were estimated at 2.5 gpm during the BWID feed interval, but only 1 gpm during the IWPF feed interval, owing to an observed reduction in the overflow from the scrubber.

Estimated amounts of Cl collected in the scrubber support the mass balance calculations in Section 6.2 that suggest relatively high Cl scrubbing efficiency in the baghouse during the BWID feed interval, and very low baghouse scrubbing efficiency during the IWPF feed interval. Using the mean Cl concentration of 18 mg/L in the scrubber solution for the BWID feed interval, only about 1 lb out of 252 lb total Cl was collected in the scrubber, for a scrubbing efficiency of under 1%. This is only an estimate based on approximate scrubber overflow rates and isolated concentrations. The scrubber solution pH ranged around three during a significant portion of the BWID Nom-60 feed interval, when roughly one-third of the 252 lb Cl was fed to the furnace. This low pH may have reduced the HCl scrubbing effectiveness during the Nom-60 feed interval, but higher scrubbing efficiencies than 1% would still be expected. It is apparent that much of the Cl was scrubbed from the gas stream in the baghouse, confirming the calculated value of 68% HCl scrubbing in the baghouse for the BWID feed interval.

The estimated mass of Cl collected by the wet scrubber during the IWPF feed interval was 325 lb, using a much higher average Cl concentration in the scrubber solution of 32,500 mg/L. The total Cl fed to the furnace during the IWPF feed interval was 462 lb. Seventy percent of the furnace input Cl was scrubbed in the wet scrubber, which suggests that there was less Cl scrubbing in the baghouse. This confirms mass balance calculations that show only 2% Cl removal in the baghouse during this IWPF feed interval.

Table 7-11. Scrubber solution concentrations (mg/L).

Analyte	Nom-80 INEL-S2	Nom-60 INEL-S14	S-40 INEL-S20	C-20 OWPF-S5	Cleanout IWPF-S10
Cl	20.0	16.0	24,600.0	40,400.0	1,110.0
F	6.0	4.0	27.0	28.0	17.0
NO ₂	5.0	<0.5	ND ^a	ND	ND
NO ₃	3.0	1.0	ND	9.0	3.0
P	0.6	0.4	1.4	0.4	0.4
PO ₄	<7.0	11.0	17.0	<7.0	<7.0
SO ₄	10.0	42.0	701.0	1,000.0	90.0
pH	8.54	3.68	8.53	8.31	8.58

a. ND = not detected.

7.7 Offgas and Particulate Emissions

Characterization and control of the gaseous and particulate emissions from mixed waste vitrification is very important for protecting the environment and human health. This is especially true for mixed wastes that contain various toxic metals (primarily Pb, Cr, Ni, and some Hg), hazardous organics, and TRU elements. The furnace and APCS must be capable of controlling all harmful emissions to meet local, state, and Federal control requirements. The test facility air pollution control system was modified before the demonstration tests in order to satisfactorily control gaseous and particulate emissions from the surrogate feed mixtures. Modifications included installation of a thermal oxidizer at the furnace gas outlet duct, a baghouse for controlling particulate emissions, a wet scrubber for controlling acid gas emissions, and final charcoal and HEPA filters for controlling trace-level organics and fine particulate.

The offgas monitoring and sample collection for the demonstration tests included measurements to characterize the gaseous and particulate emissions from the melter and APCS performance. Offgas measurements and sample collection were conducted by Entropy Incorporated, Argonne National Laboratory-East, and Clean Air Engineering. Measurements and sampling runs were performed at various points in the furnace and APCS. Gaseous measurements included velocity, temperature, and continuous monitoring of gas composition (O_2 , CO, CO_2 , NO, NO_2 , SO_2 , THC, and HCl). These measurements were conducted according to EPA Methods 1, 2, 3A, 6C, 7E, 10, and 25A. Gas temperature measurements in the furnace were conducted using a shielded thermocouple mounted in a suction pyrometer probe to minimize the effects of thermal radiation on the gas temperature measurement. Samples were also collected for HCl, Cl_2 , HF, and F_2 analysis using a modified EPA Method 26 procedure. Total particulate and metals determinations were conducted using the draft EPA Method 29, modified to include measurement of total particulate in addition to metals. Dioxin tests were conducted using EPA Method 23 at the baghouse outlet and at the stack.

7.7.1 Offgas Concentrations

Average gas concentration measurements are shown in Table 7-12 for continuous emission monitoring system (CEMS) and FTIR sampling periods. The trend charts showing how the concentrations varied during the sampling periods are provided in Appendix O for the CEMS measurements and in Appendix P for the FTIR measurements. The locations and times for these measurements were varied in order to obtain test data at different locations during the tests. Measurements in the furnace and at the furnace outlet were conducted to characterize furnace plenum and furnace outlet conditions. The APCS performance was evaluated by sampling at the baghouse outlet and at the stack. While the best continuous data collection could have been obtained by having multiple sampling systems and analyzers for different locations, this level of emissions measurement effort was beyond the scope of the demonstration tests.

Sample dilution was necessary for CEMS and FTIR monitoring at the furnace and furnace outlet locations, to (a) reduce measured gas concentrations to measurable ranges for the instrumentation (b) protect equipment from the moisture-laden acidic gas streams, and (c) enable some measurements to be made without having to remove water vapor from the gas stream. Dilution was accomplished using a dilution probe and dilution system at different times. The dilution probe diluted the sample at the sampling location, so all of the sample was diluted. The dilution system diluted the sample downstream of the sampling location, thereby allowing the diluted gas to be directed to only those instruments requiring a diluted sample.

The offgas concentrations in the furnace plenum and at the furnace outlet were similar with typically large amounts of CO (6,200–110,000 dry ppm) and total hydrocarbons (8,700–120,000 ppm). According

Table 7-12. Average gas concentration measurements for the CEMS and FTIR sampling periods (as measured, dry).

Location	Date	Feed Mixture	Time	Offgas composition from continuous monitoring per EPA procedures								Time	Organic gas speciation from FTIR analysis			
				Feedrate (lb/h)	O2 (%)	CO2 (%)	CO (ppm)	NOx (ppm)	SO2 (ppm)	HCl (ppm)	THC (ppm)		Methane (ppm)	Ethylene (ppm)	Benzene (ppm)	Toluene (ppm)
Stack	4/11/95	Nom-90		766								2020-2356	5.6			
	4/12/95	Nom-80	0031-0043	0	16.9	3.0	2.1	40.4	0.9		6.5					
			0048-0252	402	16.7	2.8	8.1	26.8	1.1		2.5					
			0347-0412	0	16.7	2.8	2.5	29.8	0.4		0.8					
		Nom-80 time weighted average		310	16.7	2.8	6.8	28.3	1.0	0.0	2.5	0016-0418	4.8			
	4/12/95	Nom-70	0420-0609	0	19.6	0.9	10.9	5.6	0.2	3.6	3.3					
			0815-0915	980	17.1	2.7	0.0	30.6	0.2	2.8	12.0					
		Nom-70 time weighted average		348	19	2	7	14	0	3	6	0424-1443 ¹	8.7			
	4/13/95	Nom-60		779								0006-0139 ^a	3.2			
	4/13/95	Nom-50		631								0607-1015 ^a	3.0			
	4/13/95	Nom-40		606								1021-1139 ^a	2.6			
	4/13/95	S-40		419								1145-1500 ^a	2.9			
	4/13/95	S-40	1504-1633	614	18.1	2.3	30.2	21.9	20.3	20.4	0.5					
	4/13/95	S-40		322								1636-1724 ^a	2.9			
	4/13/95	S-0		312								1740-1832	55.0	2.3		
				377								2136-2216 ^a	5.4		1.7	
		S-0 time weighted average		340									33.4	2.3	1.7	
	4/14/95	S-0	0059-0209	515	18.3	2.1	34.2	18.6	0.8		2.1	4.8				
			0237-0344	370	17.1	3.0	10.1	28.2								
		S-0 time weighted average		444	17.7	2.5	22.4	23.3	0.8		2.1					
	4/14/95	C-20	0345-0522 ^a	299	16.4	3.8	270.0	39.6				4.9				
Baghouse Outlet	4/13/95	S-40	1650-1729 ^a	447	18.6	2.0	333	70.5	0.0	63.0	0.0					
	4/14/95	S-0	0127-0137	0						0.00						
			0200-0210	0						0.00						
			0238-0248	0						0.00						
			0237-0344	370							0.5	12.2				
	4/14/95	C-20	0345-0522 ^a	299							10.1					

Table 7-12. (continued).

Location	Date	Feed Mixture	Time	Offgas composition from continuous monitoring per EPA procedures								Time	Organic gas speciation from FTIR analysis			
				Feedrate (lb/h)	O ₂ (%)	CO ₂ (%)	CO (ppm)	NO _x (ppm)	SO ₂ (ppm)	HCl (ppm)	THC (ppm)	H ₂ O (%)	Methane (ppm)	Ethylene (ppm)	Benzene (ppm)	Toluene (ppm)
C-40 time weighted average	4/14/95	C-40	0607-0624	0	17.7	2.7	1.7	26.6	3.1		8.7					
			0625-0737 ^a	92	19.2	1.7	1.0	61.0	1.5		14.0					
				74	18.9	1.9	1.1	54.4	1.8		13.0					
	4/14/95	NOM-90	0830-1011	634	18.7	2.1	123.0	46.0	1.4		21.4					
In-Furnace	4/12/95	Nom-70	1413-1500	727	13.7	12.7	94,460	75				9.1				
			1509-1529	846							8,691	9				
	4/12/95	Nom-60		268									1519-1650 ^a	3,502	1,106	279 180
	4/12/95	Nom-60	1530-1538	601							19,357					
	4/12/95		1543-1702 ^a	110	14.8	10.9					12,645					
	4/12/95		1709-1714	0	17.5	20.5	18,555	16								
			1934-2011	691	14.2	11.9	6,267	407				9				
			2330-2334	623	12.8	11.1	109,498	133				21				
		Nom-60 time weighted average		312	14.7	11.6	16,579	341			13,262					
	4/13/95	Nom-60	0152-0217	0	13.8	5.3					115,818	32	0155-0217	36,266	17,668	4,465
			0224-0312 ^a	127	13.8	7.7	236,840									
		Nom-60 time weighted average		83	13.8	6.9	236,840									
	4/13/95	Nom-50	1010-1015	1,160	16.3	1.4	11,826									
	4/13/95	Nom-40	1015-1022	1,165	16.7	1.0	7,347									
	4/13/95	S-40	1348-1438 ^a	523	14.8	0.5	7,205									
	4/13/95	S-0	2030-2242 ^a	377	16.4	2.5	56,085	43.3								
Furnace	4/13/95	S-0		0									2310-2350	11,117	679	681 391
	4/14/95	S-0		437								2.5	0002-0144		22.1	56.3
Furnace Outlet	4/13/95	S-0	2246-2357	0	15.9	3.3					26,753					
			0132-0140	0						0.00						
			0211-0221	0						0.00						

a. Feeder was shut off for short time periods during these intervals.

to the furnace and furnace outlet FTIR measurements, the total hydrocarbon speciation included up to 36,000 ppm methane, 18,000 ppm ethylene, 700 ppm benzene, and 4,000 ppm toluene. These species are all common products of incomplete combustion (PICs) when combustion conditions are not designed for efficient combustion of organics. While the furnace is designed to effectively vitrify inorganic material and melt metals, it is not designed to efficiently oxidize organics that volatilize from the feed materials. Efficient oxidation of organics in the furnace would require even higher gas temperatures, higher gas velocities, longer residence time, and more complete gas mixing. This would necessitate a larger furnace plenum and would increase the levels of dust entrainment and toxic metals volatilization.

Like typical incineration systems, the best vitrification system for treating wastes that contain significant levels of organic materials should have separate chambers or zones for vitrifying the solid materials and efficiently oxidizing the gaseous materials that evolve from the feed material during heatup, pyrolysis, and melting. This is how the USBM melter facility was designed and operated. The arc furnace provided for effective thermal separations. The offgases contained high levels of PICs that were then efficiently combusted in the gas phase in the thermal oxidizer.

Stack gas concentrations of CO and THC were very low, ranging between 0-30 ppm and 0.5-60 ppm, respectively, during all operating conditions that were within the design operating range of the thermal oxidizer. These stack CO and THC levels are within expected emission limits for these species from this type and size of process. Speciation of THCs in the stack, measured by FTIR, include up to 55 ppm methane, 2 ppm ethylene, and 2 ppm benzene.

When the furnace feedrate of combustible feed materials was sufficiently high to produce combustible gases that exceeded the capacity of the secondary air supply to the thermal oxidizer, the excess O₂ level (set to operate at around 7%) decreased to near zero. This occurred during the S-40 interval several times, when the optimum feedrate was being established that would allow the thermal oxidizer to operate within design conditions. One 25-min period occurred while stack gas CEMS monitoring was being conducted. Stack CO levels during this time reached 1,000 ppm. When the furnace feedrate was reduced from about 160 to 100 lb/h, the CO levels decreased to under 10 ppm.

The test results were somewhat variable for several reasons. Offgas concentrations at different locations were very different, as expected. Offgas environments in the furnace plenum and furnace outlet duct were very harsh for offgas measurements and sample collection. Not only were gas temperatures very high, but there were also relatively large amounts of particulate, moisture, and acid gases. Sample probes and filters used for both gaseous and particulate sampling rapidly plugged, sometimes within minutes after the start of sample collection. Even the continuous gaseous monitoring periods at the furnace and furnace outlet were abbreviated to 10 min or less because of plugging.

Offgas concentrations at each location varied for the different feed mixtures and different operating conditions. The operational variations and short sampling periods sometimes resulted in widely varying gas concentrations for even back-to-back sampling periods for the same feed mixture. There are many furnace operating parameters that will affect the furnace and stack gas emissions. These include the feedrate of primary air, the surrogate waste mixture feedrate and composition, melt and plenum temperatures, and melting rates. The reported instantaneous measurements should be considered correct for each short time period, but some time periods varied significantly from average conditions. Variations within the same operating period were also frequent, and indicate varying rates of feed material heatup and pyrolysis. Varying heatup and pyrolysis rates can occur even when the feedrate is constant when feed material, banked up under the feedtubes, slumps into the melt.

Furnace O₂ levels varied from around 13–17% for most of the sampling periods. This level is somewhat higher than expected, considering the typically high levels of CO and THC. The furnace gas temperatures, however, typically ranged from 800–1,800°F, measured during frequent velocity and temperature traverses. This temperature range is too low to support efficient combustion reactions. Also, much of the O₂ in the furnace from leak air and primary air was poorly mixed with the pyrolysis gases. These low temperature and poor mixing conditions apparently contributed to such high O₂ levels in the offgas.

Furnace NO_x levels varied between 16–340 ppm. The highest NO_x levels occurred during the Nom-60 interval, when steady-state feedrates exceeded 700 lb/h, and the level of sodium and potassium nitrates in the feed mixture was also relatively high at about 1.5%. NO_x levels at the stack were much lower, ranging from 5–40 ppm. This reduction is due in part to 5 to 10-fold dilution of the furnace offgas from added gas volumes in the thermal oxidizer and cooling sections. However, the operating conditions of the furnace and thermal oxidizer prevent significant NO_x formation, compared to such vitrification systems as plasma torch melters that can produce NO_x concentrations of several thousand ppm (Dalton et al. 1994). The low furnace and stack gas NO_x levels measured during the demonstration tests suggest that added equipment to control NO_x is not expected to be necessary to meet NO_x limits in most regions of the United States.

Available HCl measurements at the stack show very low HCl concentrations of under 20 ppm. These measurements were infrequent during the test program, but the 20 ppm HCl measurement was made during the S40 interval, when very high offgas HCl levels were produced. The concentration measurements suggest very efficient HCl control. Stack gas SO₂ levels were also very low, typically under 3 ppm and only once reaching 20 ppm. There was little S in the feed mixtures, so low stack gas SO₂ levels were expected.

7.7.2 Offgas Emission Rates

Offgas emission rates (Table 7-13) were calculated for the CEMS monitoring intervals using the measured concentrations at the stack and baghouse outlet, and estimated from mass balances at the furnace outlet. While melter outlet velocity and flowrate measurements were frequently attempted during the test program, these measurements were quite unreliable owing to (a) the very low velocity heads of typically under 0.1 in. WC, (b) significant variability between measurements, and (c) frequent particulate plugging of the S-type pitots, even though these are designed and used world-wide for velocity measurements in harsh, particulate-laden streams.

Stack gas CO emission rates were typically under 0.1 lb/h, and reached 1.9 lb/h for the C-20 test condition. At 1.9 lb/h and an estimated 5,760 operating hours per year (Feizollahi et al. 1994) for a mixed waste treatment facility, the CO annual emission rate would be 5.5 tons. This is well under the annual CO emission rate of 100 tons considered by the State of Idaho to be significant (IDAPA 16.01.01.87, May 1, 1994). Similar calculations for NO_x, SO_x, and HCl show annual emission rates of 0.9 tons, 1.1 tons, and 0.6 tons. The Idaho limit for significant annual NO_x, SO_x, and HCl emissions is 40 tons for each pollutant.

7.7.3 Acid Gas Measurements

Manual sampling for measuring concentrations of HCl, Cl₂, HF, and F₂ was conducted during the S-0 feed interval. The feed material for this interval had 19.5% Cl. Fluorine was not present in recorded amounts in any of the feed mixtures except for the C-20 and C-40 feeds, but was included in the measurement to assess if there were trace levels of fluorine in the feed materials. These measurements were made at discrete times during the testing to augment the continuous monitoring measurements. As shown in Table 7-14, two tests were conducted at the furnace outlet, upstream of the thermal oxidizer and

Table 7-13. Offgas emissions measured at the baghouse and the stack and calculated at the furnace outlet.

Location	Date	Feed Mixture	CEMS Time	Offgas flowrate (dscfm)	Total offgas species mass emission rates (lb/h)					
					CO	NO _x	SO ₂	HCl	THC	
Stack ^a	4/11/95	Nom-90		2,368						
	4/12/95	Nom-80	0031-0043	2,347	0.0215	0.4430	0.0211		0.0333	
			0048-0252	2,164	0.0764	0.2710	0.0237		0.0118	
			0347-0412	1,676	0.0183	0.2333	0.0067		0.0029	
			Nom-80 time weighted average			2,064	0.0610	0.2726	0.0201	0.0114
	4/12/95	Nom-70	0420-0609	1,809	0.0860	0.0473	0.0036	0.0370	0.0130	
			0815-0915	1,796		0.2568	0.0036	0.0286	0.0471	
	Nom-70 time weighted average			1,684	0.0516	0.1139	0.0034	0.0317	0.0235	
	4/13/95	Nom-60		1,836						
	4/13/95	Nom-50		1,928						
	4/13/95	Nom-40		1,811						
	4/13/95	S-40		1,803						
	4/13/95	S-40	1504-1633	1,831	0.2411	0.1873	0.3708	0.2117	0.0020	
	4/13/95	S-40		1,614						
	4/13/95	S-0		1,419						
				1,667						
			S-0 time weighted average			1,642				
	4/14/95	S-0	0059-0209	1,695	0.2528	0.1473	0.0135		0.0078	
			0237-0344	1,579	0.0695	0.2080				
	S-0 time weighted average									
		4/14/95	C-20	0345-0522	1,616	1.90	0.2990			
	Baghouse Outlet	4/13/95	S-40	1650-1729	866	1.26	0.2852		0.3100	
4/14/95		S-0	0237-0344	1,053					0.0012	
4/14/95		S-0	0127-0137					107.00		
4/14/95		S-0	0200-0210					118.00		

Table 7-13. (continued).

Location	Date	Feed Mixture	CEMS Time	Offgas flowrate (dscfm)	Total offgas species mass emission rates (lb/h)				
					CO	NO _x	SO ₂	HCl	THC
	4/14/95	S-0	0238-0248					477.00	
	4/14/95	C-20	0345-0522	1,170					0.0258
	4/14/95	C-40	0607-0624	902	0.0067	0.1121	0.0279		0.0171
			0625-0737	938	0.0041	0.2673	0.0140		0.0287
C-40 time weighted average									
	4/14/95	NOM-90	0830-1011	885	0.4747	0.1902	0.0124		0.0414
In-Furnace ^b	4/12/95	Nom-70	1413-1500	76.1	31.36	0.0266			
			1509-1529	76.1					1.45
	4/12/95	Nom-60		118					
	4/12/95	Nom-60	1530-1538	118					4.99
	4/12/95		1543-1702	118					3.26
	4/12/95		1709-1714	118	9.55	0.0090			
			1934-2011	118	3.22	0.2244			
			2330-2334	118	56.34	0.0733			
	Nom-60 time weighted average			118	8.53	0.1878			3.42
	4/13/95	Nom-60	0152-0217	118					29.86
			0224-0312	118	121.86				
	Nom-60 time weighted average			118	121.86				
	4/13/95	Nom-50	1010-1015	109	5.61				
	4/13/95	Nom-40	1015-1022	153	4.89				
	4/13/95	S-40	1348-1438	90.4	2.84				
	4/13/95	S-0	2030-2242	31.9	7.81	0.0065			
Furnace Outlet ^b	4/13/95	S-0	2246-2357	31.9					1.87
	4/14/95	S-0	0132-0140					171348.00	
			0211-0221					96280.00	

a. For the stack and baghouse outlet locations, the mass emission rates were calculated using the DAS output flowrate.

b. For all furnace locations, emission rates were calculated using an estimated flowrate.

Table 7-14. Acid gas results from the S-0 feed interval.

Run number	S0-FO-M26-1	S0-FO-M26-2	S0-BO-M26-1	S0-BO-M26-2	S0-BO-M26-3
Feed type	S-0	S-0	S-0	S-0	S-0
Sampling period stop time	0132	0211	0127	0200	0238
Sampling period start time	0140	0221	0137	0210	0248
Location	Furnace outlet	Furnace outlet	Baghouse outlet	Baghouse outlet	Baghouse outlet
Hydrogen chloride concentration (ppmvd)	171,348	96,280	107	118	477
Hydrogen chloride emission rate (lb/h)	83.5	46.5	0.623	0.689	2.77
Chlorine concentration (ppmvd)	1.11	2,795	0.144	0.387	1.57
Chlorine emission rate (lb/h)	0.000500	1.35	0.000838	0.00225	0.00916
Hydrogen fluoride concentration (ppmvd)	10.6	19.2	1.90	0.97	2.27
Hydrogen fluoride emission rate (lb/h)	0.00276	0.00496	0.00594	0.00302	0.00708
Fluorine concentration (ppmvd)	8.27	2.21	2.69	0.289	0.588
Fluorine emission rate (lb/h)	0.00216	0.000571	0.00838	0.000900	0.00183
Primary air flowrate (cfm)	0	0	0	0	0
Offgas temperature (°F)	1,649	1,313	44.0	46.0	50.0
Offgas velocity (ft/s)	15.5	15.5			
Offgas flowrate [Entropy] (dscfm)	88.2	81.4			
Offgas flowrate [DAS] (dscfm)			1,053	1,053	1,053
Feedrate (lb/h)	513	531	508	531	329

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control equipment. Three tests were conducted at the outlet of the baghouse, which was upstream of the wet acid gas scrubber. The furnace outlet HCl concentrations were 171,000 and 96,300 ppm (as measured, dry). The baghouse outlet HCl concentrations were much lower at 107-477 ppm (as measured, dry), owing in part to dilution of the offgas stream, to different furnace feedrates at the different sampling periods, and partial HCl dry scrubbing by the particulate in the baghouse.

7.7.4 Total Particulate Emission Measurements

The total particulate in the offgas includes (a) feed dust entrained in the furnace gas, (b) material volatilized from the hot melt that has or would condense as fume particles or droplets in the cooler offgas sections or the atmosphere, and (c) material ejected from the hot melt as fine droplets from turbulence or melt offgassing, and entrained in the offgas. The volatilized material can condense on the surfaces of entrained feed material or ejected melt material (heterogeneous nucleation) and also form very small fume particles (homogeneous nucleation) that may grow in size with continued condensation or agglomeration. The entrained feed particles, having possibly bypassed higher temperatures in the furnace, can have the same appearance, mineral content, and composition as particles of the same size in the feed mixtures, but may also be enriched with volatilized materials such as toxic metals that have condensed on the entrained particles. The condensed fume particles are also enriched with materials volatilized from the melt. The particles of ejected melt material are similar in composition to the melt, but they may be enriched with condensed material on the surface.

A very limited number of modified Method 29 sampling runs were made at the furnace outlet to characterize furnace emissions during those sample periods, before the downstream particulate filtration and other offgas control steps. A single Method 29 sampling run was also made at the stack during the C-20 feed interval to evaluate air emissions following filtration and scrubbing in the APCS. The Method 29 procedure is designed to capture not only the solid particulate but also any metals in gaseous form at the conditions and location in the APCS. The particulate results from the furnace outlet and stack sampling runs are shown in Table 7-15. The measured furnace outlet total particulate concentrations ranged from 10 to 103 gr/dscf, and the mass emission rates ranged from 13 to 71 lb/hr. The concentration values are similar to levels of uncontrolled particulate emissions from other processes that handle dusty, aggregate-type materials such as fluidized bed combustors, rock crushers, and aggregate processing equipment. Results from the single stack sampling run were orders of magnitude lower, as expected.

There may be some measurement error in the concentration and mass emission values due to (a) not sampling isokinetically, and (b) sampling at a non-ideal sample location, with insufficient upstream and downstream duct diameters, and (c) sampling with less than recommended sample times and sample gas volume. The sample collection was made with the sample rate at around one-half of the isokinetic rate, where the gas velocity at the probe nozzle is equal to the stack gas velocity. This can result in measured concentration and mass emission rate values that are up to around twice as high as the actual values, depending on such factors as particle size range and aerodynamics. Therefore, the actual concentration and mass emission rates are between 50-100% of the measured and reported values.

The measured furnace outlet particulate mass emission rates from the Method 29 tests varied from just under 50% to just over 150% of the furnace outlet particulate mass emission rates calculated for the sampling time periods from the APCS solids collected in the APCS over the feed intervals. This variation is reasonably acceptable, considering the (a) modifications made to the Method 29 sampling procedures, and (b) calculations from the APCS solids collected in the APCS were made from solids collected over a much longer duration and sometimes different conditions than the sample period. Also, while there was variation between the mass emission rates from the individual Method 29 tests and the mass emission rates calculated from the APCS solids collected in the APCS, the average mass emission rates determined using

Table 7-15. Particulate results from the Method 29 sampling tests.

Run number	NOM70 M5/29-1	NOM60 M5/29-1	NOM60 M5/29-2	NOM60 M5/29-3	Average furnace outlet measurements	C20-M29-1
Feed type	Nom-70	Nom-60	Nom-60	Nom-60		C-20 and C-40
Sampling period stop time	1452	2000	2350	0103		0441
Sampling period start time	1530	2034	0020	0129		0635
Location	Furnace outlet	Furnace outlet	Furnace outlet	Furnace outlet		Stack
Total particulate concentration (gr/dscf)	13.5	31.9	10.0	103	39.7	0.0052
Total particulate emission rate (lb/h)	19.1	57.7	13.2	71.1	40.3	0.0626
Total particulate emission rate (% of feedrate)	2.73	9.01	2.88	9.48	6.03	0.0209
APCS catch (lb/h) proportioned by feedrate	44.1	40.2	28.9	47.2	40.1	21.2
Particulate control efficiency in the APCS (%) ^a						99.7
Primary air flowrate (cfm)	65	95	70	0	57.5	86-140
Offgas temperature (°F)	1,462	1,758	1,473	1,173	1,467	93.0
Offgas velocity (ft/s)	31.9	46.8	34.5	17.6	32.7	26.8
Offgas flowrate [Entropy] (dscfm)	165	211	154	80.2	153	1,394
Offgas flowrate (DAS)						1,616
Feedrate (lb/h)	700	640	460	750	638	200-400
Cold top thickness (in.)	4.5	1-6	0-2	1-4.5	0-6	5-11
Melt temperature (°C)	1,580	1,575	1,563	1,560-1,644	1,560-1,644	1,650-1,720
Power level (kW)	243	231	230	225	232	170
Furnace operating conditions:						
Primary air	Y	Y	Y	N		Y
Cold top	Y	Y	N	Y		Y

a. Calculated from the calculated APCS catch (lb/h) and the total particulate emission rate at the stack (lb/h).

the two different methods agreed to within 0.5% of each other. This suggests that (a) modifications in the Method 29 sampling procedures did not significantly impact the accuracy of the averaged measurements, (b) performing replicate Method 29 tests (which were not in the scope of the demonstration tests due to funding limitations) would have increased the accuracy of the measurements for individual feed intervals, and (c) collecting particulate material from the APCS more frequently so that there would be a closer relationship between the Method 29 test periods and the APCS collection periods would have increased the agreement between the APCS and Method 29 measurements.

Three of the furnace outlet particulate sampling runs were conducted during the Nom-60 feed interval at three different operating conditions. For all three runs, the power input and feedrate were relatively constant, but the tests were conducted (a) with and without primary air addition and (b) with and without a cold top of unmelted feed material on the surface of the melt. Expected results would be that increasing the primary air rate would increase feed dust entrainment, and that cold top operation would decrease the evolution of volatilized material from the melt. The results from these three tests runs, however, do not confirm these hypotheses. The lowest particulate emissions (13.2 lb/hr, or 2.8% of the feedrate) occurred when there was essentially no cold top (0-2 inches) and the primary air flowrate was a moderate 70 cfm. The highest particulate emissions (71 lb/hr, or 9.5% of the feedrate) occurred when there was a moderate cold top and no added primary air (except for nominal air leakage, estimated at around 10 cfm). Particulate emissions were almost as high (58 lb/hr, 9.0% of the prevailing feedrate) when there was a cold top and also added primary air.

These findings may occur when the majority of the total particulate in the offgas is actually entrained feed material, rather than volatilized feed materials. Also, there are areas of the furnace such as the high temperature arc zone near the electrodes that may not be covered with cold top even when the rest of the melt is covered. Volatilization from the melt may occur in this very high temperature, reducing (oxygen-lean) area, regardless of the presence of cold top on the rest of the melt.

These results should be considered cautiously since they are a result of single particulate measurements. Additional, more detailed testing and comparisons with other related test programs must be done before conclusions about relationships between furnace plenum gas flowrates, cold top operation, and volatilization can be made.

Methods to reduce the amount of APCS solids, if the APCS solids are primarily entrained feed dust, include using less-dusty feed materials. Soil and other materials that are initially dusty may be pelletized to reduce dust when delivered to the furnace. Delivering feed directly to the melt where it can be melted into the melt, and minimizing gas flowrates and turbulence in the plenum can also reduce feed entrainment. The presence of a cold top of dusty, unmelted feed on the melt may increase feed dust entrainment. The entrained feed dust can potentially contain very nonvolatile materials such as Pu, which are undesirable in the APCS or APCS solids.

Methods of reducing APCS solids if there is significant volatilization from the high temperature arc area near the electrodes include reducing the power density in this area, and quickly circulating the melted material out of the highest temperature areas. The power density can be reduced by reducing power input to the furnace, and by using larger diameter electrodes. Circulation of melt material out of the highest temperature areas can be enhanced by using small amounts of additives to lower the viscosity of the melt. These are subjects of ongoing arc melter research at the USBM melter facility.

7.7.5 Metals Emission Measurements

Metals concentrations and mass emission measurements from the modified Method 29 sampling runs are shown in Tables 7-16 and 7-17. Cesium, as the Pu surrogate, was included in the metals analysis. Like the particulate measurements, there is significant variation between the sampling run results and calculations from the metals analyses of the APCS solids. These metals measurements are subject to the same constraints identified in Section 7.7.4 regarding Method 29 particulate measurements and the APCS solids calculations. Also, many of the metals were not present in detectable levels in the small sample amounts collected in the Method 29 trains. For individual metals, the agreement in measurable mass emission rates from the Method 29 samples and the solids collected in the APCS ranged from 0.18 to 0.11 (not including those metals with "less than" values). The concentration and mass emission measurements from either method for individual metals should be considered as approximate values.

The measured metals concentrations and flowrates for the three sampling runs conducted during the Nom-60 interval were highest when there was a cold top of feed material on the surface of the melt, with or without added primary air. The lowest metals concentrations and emission rates occurred when there was no cold top. This finding is true for all of the metals analyzed, regardless of their relative tendency to volatilize. This finding is consistent with the results for total particulate, but contrary to the hypothesis that a cold top may reduce metals volatilization by (a) reducing plenum gas temperatures and (b) allowing volatilized material to cool and condense in the cold top, and be refluxed back into the melt. This finding is also consistent with the hypothesis that a large fraction of the particulate in the offgas is from entrained feed dust rather than volatilized metals. Also, there are areas of the furnace such as the high temperature arc zone near the electrodes that may not be covered with cold top even when the rest of the melt is covered. Much of the metals volatilization from the melt may occur in this very high temperature, reducing (oxygen-lean) area, regardless of the presence of cold top on the rest of the melt.

Since there was only a limited number of Method 29 measurements conducted, and no replicates, this result should not be considered conclusive. Additional, more detailed testing and comparisons with other related test programs must be done before conclusions about relationships between furnace plenum gas flowrates, cold top operation, and volatilization can be made.

7.7.6 Dioxin Measurements

Dioxin measurements were conducted at the baghouse outlet and at the stack to evaluate (a) the potential for forming dioxins in the post-combustion zone between the thermal oxidizer and the baghouse, and (b) the ability of the downstream scrubber, charcoal filter, and HEPA filter to control and remove any such dioxins. Dioxin measurements followed EPA Method 23 procedures. Single sampling runs, each 4 hours long, were conducted at each location. The dioxin runs were conducted during the S-0 feed mixture test condition, because that mixture contained the highest concentrations of chlorides and organics and represented a worst-case scenario for the melter and APCS.

The dioxin and furan measurements are shown in Tables 7-18 and 7-19. The toxicity equivalent (TEQ) was calculated from the measurements for the combined polychlorinated dibenzodioxins (PCDD) and the polychlorinated dibenzofurans (PCDF). The dioxin/furan measurements at the baghouse outlet, corrected to 7% O₂, were 0.0823 ng/dscm TEQ for total PCDD and 0.5799 ng/dscm TEQ for total PCDF, giving an overall measurement of 0.662 ng/dscm TEQ for total PCDD/PCDF. The emission limit for dioxins according to proposed Maximum Achievable Control Technology (MACT) rules for hazardous waste incineration is 0.2 ng/dscm TEQ at 7% O₂. The baghouse outlet dioxin emissions from this test are about 3.3 times higher than this limit. Corrected measurements at the stack were 0.0652 ng/dscm TEQ for

Table 7-16. Metals concentrations in the offgas (mg/dscm).

Run Number		NOM-70-M5/29-1		NOM-60-M5/29-1		NOM-60-M5/29-2		NOM-60-M5/29-3		Average conc.		C-20-M29
Feed type Location		Nom-70 Furnace out		Nom-60 Furnace out		Nom-60 Furnace out		Nom-60 Furnace out		Nom-60 & 70 Furnace out		C-20 Stack
Arsenic	< ^a	6.02	<	4.88	<	1.11	<	8.82	<	5.21	<	0.240
Aluminum		300		394	<	55.2	<	199	<	237		0.623
Barium	<	6.02	<	8.09		3.68	<	17.5	<	8.82	<	0.240
Calcium		1,269		4,567		2,390		18,188		6,604		4.81
Cerium	<	4.96	<	4.88	<	0.956	<	25.7	<	9.13	<	0.457
Cesium		3.78		15.9		2.26		7.16		7.28		0.0032
Chromium	<	7.79	<	4.88	<	1.60	<	11.9	<	6.53	<	0.240
Copper	<	7.44	<	12.5	<	4.89	<	14.5	<	9.82	<	0.240
Iron		394		315		283		2,451		861		2.28
Lead		228		165		68.0		532		248	<	0.678
Magnesium	<	117		171	<	146	<	1,603	<	509		1.47
Nickel	<	10.1		20.8	<	0.681		30.8	<	15.6	<	0.372
Potassium	<	1,561		2,526	<	358	<	3,996	<	2,110		4.85
Silicon		1,566		15,670		1,844		5,889		6,242		103
Sodium		1,671		3,612		621		5,383		2,822		4.43
Zinc	<	63.1	<	63.1	<	14.0	<	106	<	61.6	<	0.342
Total particulate		30,918		72,982		22,970		236,655		90,881		12.0
Operating conditions:												
Primary air		Y		Y		Y		N				
Cold top		Y		Y		N		Y				

a. < indicates that the measured value is below the detection limit.

Table 7-17. Metals mass emission rates in the offgas (lb/h).

BWID feed interval										IWPF feed interval			
Element	NOM-70 M5/29-1	NOM-60 M5/29-1	NOM-60 M5/29-2	NOM-60 M5/29-3	Average emission rate (lb/h)	Emission rate calculated from APCS solids (lb/h) ^a	Agreement between Method 29 measurements and APCS calculations ^b	Calculated furnace outlet mass emission rate (lb/h) ^c		Calculated metals control efficiency (%) ^d			
								C-20-M29					
Feed type	Nom-70	Nom-60	Nom-60	Nom-60		Nom-60 and 70		C-20					
Location	Furnace out	Furnace out	Furnace out	Furnace out		Furnace out		Stack	Furnace out				
Arsenic	< ^e 0.00372	< 0.00386	< 0.000639	< 0.00265	< 0.00272	0.000734	< 3.70	< 0.00126	0.000262	> 17.3			
Aluminum	0.186	0.312	< 0.0319	< 0.0598	< 0.147	0.632	< 0.233	0.00325	0.336	99.0			
Barium	< 0.00372	< 0.00639	0.00213	< 0.00525	< 0.00437	0.00948	< 0.462	< 0.00126	0.00703	> 84.9			
Calcium	0.784	3.61	1.38	5.46	2.81	3.75	0.750	0.0251	2.41	99.0			
Cerium	< 0.00307	< 0.00386	< 0.000551	< 0.00773	< 0.00380	0.00281	< 1.35	< 0.00239	0.00116	> 32.7			
Cesium	0.00234	0.0126	0.00130	0.00215	0.00459	0.0258	0.178	0.0000166	0.00653	99.7			
Chromium	< 0.00481	< 0.00386	< 0.000921	< 0.00356	< 0.00329	0.00375	< 0.878	< 0.00126	0.00118	> 48.4			
Copper	< 0.00460	< 0.00989	< 0.00282	< 0.00434	< 0.00541	0.00762	< 0.710	< 0.00126	0.00291	> 69.9			
Iron	0.243	0.249	0.163	0.736	0.348	0.312	1.12	0.0119	0.139	92.1			
Lead	0.141	0.130	0.0392	0.160	0.118	0.166	0.710	< 0.00354	0.0535	> 93.8			
Magnesium	< 0.0723	0.135	< 0.0843	< 0.482	< 0.193	0.321	< 0.603	0.00769	0.197	96.2			
Nickel	< 0.00623	0.0164	< 0.000393	0.00926	< 0.00807	0.000971	< 8.31	< 0.00194	0.000406	> 17.3			
Potassium	< 0.965	2.00	< 0.207	< 1.20	< 1.09	1.55	< 0.703	0.0253	0.556	95.6			
Silicon	0.968	12.4	1.06	1.77	4.05	4.93	0.821	0.537	3.37	86.3			
Sodium	1.03	2.85	0.358	1.62	1.47	2.76	0.530	0.0231	0.712	96.9			
Zinc	< 0.0390	< 0.0499	< 0.00806	< 0.0319	< 0.0322	0.0346	< 0.931	< 0.00179	0.0122	> 87.2			
Total particulate	19.1	57.7	13.2	71.1				0.0626					
Operating conditions:													
Primary air	Y	Y	Y	N									
Cold top	Y	Y	N	Y									

a. Calculated from the amount (lb) of the element in the APCS catch divided by the operating duration (h) for the BWID feed interval.

b. Agreement was calculated as the average emission rate divided by the emission rate calculated from the APCS solids.

c. Calculated from the amount (lb) of the element in the APCS catch divided by the operating duration (h) for the IWPF feed interval.

d. Calculated as (calculated furnace outlet mass emission rate) / (calculated furnace outlet mass emission rate + measured stack emission rate).

e. < indicates that the measured value is below the detection limit.

Table 7-18. Dioxin emission measurements for Test Run S0-BO-M23-1 at the baghouse outlet during the S-0 interval.

Parameter	Concentration (ng/dscm)	Emission (lb/h)	Equivalent factor	1989 EPA Toxic Equivalencies	
				Concentration (ng/dscm)	Emission (lb/h)
PCDD					
2,3,7,8-TCDD	3.97E-03	1.81E-11	1.00000	3.97E-03	1.81E-11
Total TCDD	2.80E-01	1.28E-09	0.00000	0.00E+00	0.00E+00
1,2,3,7,8-PeCDD	1.28E-02	5.84E-11	0.50000	6.40E-03	2.92E-11
Total PeCDD	6.30E-01	2.87E-09	0.00000	0.00E+00	0.00E+00
1,2,3,4,7,8-HxCDD	9.57E-03	4.36E-11	0.10000	9.57E-04	4.30E-12
1,2,3,6,7,8-HxCDD	1.47E-02	6.69E-11	0.10000	1.47E-03	6.69E-12
1,2,3,7,8,9-HxCDD	4.90E-03	2.23E-11	0.10000	4.90E-04	2.23E-12
Total HxCDD	1.96E-01	8.93E-10	0.00000	0.00E+00	0.00E+00
1,2,3,4,6,7,8-HpCDD	6.77E-02	3.08E-10	0.01000	6.77E-04	3.08E-12
Total HpCDD	6.77E-02	3.08E-10	0.00000	0.00E+00	0.00E+00
OCDD	1.45E-01	6.59E-10	0.00100	1.45E-04	6.59E-13
Total PCDD	1.43E+00	6.53E-09	—	1.41E-02	6.43E-11
PCDF					
2,3,7,8-TCDF	3.50E-02	1.59E-10	0.10000	3.50E-03	1.59E-11
Total TCDF	3.50E+00	1.59E-08	0.00000	0.00E+00	0.00E+00
1,2,3,7,8-PeCDF	5.83E-02	2.66E-10	0.05000	2.92E-03	1.33E-11
2,3,4,7,8-PeCDF	1.24E-01	5.63E-10	0.50000	6.20E-02	2.82E-10
Total PeCDF	2.08E+00	9.46E-09	0.00000	0.00E+00	0.00E+00
1,2,3,4,7,8-HxCDF	1.00E-01	4.57E-10	0.10000	1.00E-02	4.57E-11
1,2,3,6,7,8-HxCDF	8.87E-02	4.04E-10	0.10000	8.87E-03	4.04E-11
2,3,4,6,7,8-HxCDF	9.10E-02	4.14E-10	0.10000	9.10E-03	4.14E-11
1,2,3,7,8,9-HxCDF	1.05E-02	4.78E-11	0.10000	1.05E-03	4.78E-12
Total HxCDF	1.05E+00	4.78E-09	0.00000	0.00E+00	0.00E+00
1,2,3,4,6,7,8-HpCDF	1.75E-01	7.97E-10	0.01000	1.75E-03	7.97E-12
1,2,3,4,7,8,9-HpCDF	1.49E-02	6.80E-11	0.01000	1.49E-04	6.80E-13
Total HpCDF	2.80E-01	1.28E-09	0.00000	0.00E+00	0.00E+00
OCDF	6.77E-02	3.08E-10	0.00100	6.77E-05	3.08E-13
Total PCDF	7.68E+00	3.49E-08	—	9.94E-02	4.52E-10
Total PCDD/PCDF	9.11E+00	4.14E-08	—	1.14E-01	5.16E-10

Table 7-19. Dioxin emission measurements for Test Run S0-S-M23-1 at the stack during the S-0 interval.

Parameter	Concentration (ng/dscm)	Emission (lb/h)	Equivalent factor	1989 EPA Toxic Equivalencies	
				Concentration (ng/dscm)	Emission (lb/h)
PCDD					
2,3,7,8-TCDD	2.21E-03	1.76E-11	1.00000	2.21E-03	1.76E-11
Total TCDD	9.60E-02	7.61E-10	0.00000	0	0
1,2,3,7,8-PeCDD	8.04E-03	6.41E-11	0.30000	4.02E-03	3.21E-11
Total PeCDD	1.48E-01	1.18E-09	0.00000	0	0
1,2,3,4,7,8-HxCDD	9.80E-03	7.81E-11	0.10000	9.8E-04	7.81E-12
1,2,3,6,7,8-HxCDD	2.01E-02	1.60E-10	0.10000	2.01E-03	1.60E-11
1,2,3,7,8,9-HxCDD	1.61E-02	1.28E-10	0.10000	1.61E-03	1.28E-11
Total HxCDD	2.44E-01	1.94E-09	0.00000	0	0
1,2,3,4,6,7,8-HpCDD	1.46E-01	1.16E-09	0.01000	1.46E-03	1.16E-11
Total HpCDD	2.51E-01	2.00E-09	0.00000	0	0
OCDD	2.76E-01	2.20E-09	0.00100	2.76E-04	2.20E-12
Total PCDD	1.22E+00	9.69E-09	—	1.26E-02	1.00E-10
PCDF					
2,3,7,8-TCDF	7.54E-03	6.01E-11	0.10000	7.54E-04	6.01E-12
Total TCDF	1.76E-01	1.40E-09	0.00000	0.00E+00	0.00E+00
1,2,3,7,8-PeCDF	1.23E-02	9.81E-11	0.05000	6.15E-04	4.91E-12
2,3,4,7,8-PeCDF	1.91E-02	1.52E-10	0.50000	9.55E-03	7.60E-11
Total PeCDF	1.86E-01	1.48E-09	0.00000	0.00E+00	0.00E+00
1,2,3,4,7,8-HxCDF	2.51E-02	2.00E-10	0.10000	2.51E-03	2.00E-11
1,2,3,6,7,8-HxCDF	2.51E-02	2.00E-10	0.10000	2.51E-03	2.00E-11
2,3,4,6,7,8-HxCDF	3.02E-02	2.40E-10	0.10000	3.02E-03	2.40E-11
1,2,3,7,8,9-HxCDF	9.30E-03	7.41E-11	0.10000	9.30E-04	7.41E-12
Total HxCDF	2.21E-01	1.76E-09	0.00000	0.00E+00	0.00E+00
1,2,3,4,6,7,8-HpCDF	1.08E-01	8.61E-10	0.01000	1.08E-03	8.61E-12
1,2,3,4,7,8,9-HpCDF	2.26E-02	1.80E-10	0.01000	2.26E-04	1.80E-12
Total HpCDF	1.96E-01	1.56E-09	0.00000	0.00E+00	0.00E+00
OCDF	8.04E-02	6.41E-10	0.00100	8.04E-05	6.41E-13
Total PCDF	1.12E+00	8.91E-09	—	2.13E-02	1.69E-10
Total PCDD/PCDF	2.34E+00	1.86E+08	—	2.39E-02	2.69E-10

PCDD and 0.110 ng/dscm total TEQ for total PCDF. The total PCDD/PCDF was 0.176 ng/dscm TEQ at the stack outlet, which is about 10% lower than the proposed emission limit.

7.7.7 Offgas Emission Control Efficiencies

Control efficiencies for CO, THC, HCl, total particulate, and dioxins can be calculated by comparing the measured or estimated emission rates upstream and downstream of the control equipment. The CO and THC control efficiencies of 99.999% were determined from measurements at the furnace outlet and at the stack. An HCl control efficiency of 98.9% was determined by estimating the furnace offgas concentration of HCl from mass balances for the furnace, and using the measured stack HCl level of 20 ppm for the S-40 feed mixture.

The total particulate control efficiency for the C-20 feed interval was calculated by comparing the amount of total particulate collected in the APCS to the amount of total particulate in the stack gas measured using the Method 29 sampling train. The particulate control efficiency of 99.7% for the entire APCS, including the baghouse, scrubber, and HEPA filters was estimated from the calculated APCS catch (21.2 lb/hr) and the total particulate emission rate at the stack (0.0626 lb/hr) during the time period of the Method 29 sampling.

The control efficiency for various metals for the C-20 feed interval was calculated in the same way. Several of the metals were not detected in the Method 29 stack measurement, so the control efficiencies for these metals was calculated as a "greater than" value. High measured efficiencies ranging over 86% for most of the metals are indicative of the efficient performance of the APCS.

The dioxin control efficiency across the scrubber, charcoal filter and HEPA filter is 73%. Such a moderate dioxin control efficiency may be a result of relatively low dioxin levels before entering the scrubber.

8. CONCLUSIONS AND RECOMMENDATIONS

The Phase 2 arc melter vitrification tests were the second of two test series for demonstrating graphite arc electrode melter technology for treating alpha-contaminated mixed wastes. The results demonstrate that graphite electrode arc melter technology should be considered a viable and near-term available alternative for treating alpha-contaminated mixed wastes and soils. This type of furnace has many decades of operating experience in the metals and heterogeneous ore smelting industries. Industrial versions of this technology are commercially available from many vendors. Engineering design optimization for radioactive bearing feed materials is necessary, but possible.

The primary objective of the test series was to evaluate and demonstrate arc furnace capability for treating as-received buried and mixed wastes, as opposed to treating ash residuals from a preincinerator step. Feedrates of up to 1,200 lb/h were demonstrated for 10 different heterogeneous feed mixtures. These feed mixtures included compositional extremes of up to 20% metals, 60% volatile and chlorinated organics (20% Cl, 35% C), and 70% combustibles (39% C, 3.4% Cl). Intermediate levels of metals, combustibles, and other waste-type materials were also successfully processed by increasing the proportions of INEL soil. The melter system successfully processed all of the planned feed mixtures and three additional feed mixtures (Nom-50, Nom-40 and C-40). These feed mixtures span a range of metal, combustible, and organic waste materials stored and buried at the INEL TSA and SDA.

The furnace operated satisfactorily within general design and operating constraints for power, feedrates, taprates, and power stability. Slag was tapped semicontinuously. The APCS also operated satisfactorily within design and operating constraints, and efficiently controlled air emissions of particulate, metals, hydrocarbons, dioxins, and acid gases. Operating and design limits were reached for low feedrates, power levels, and taprates.

Stable, relatively steady-state furnace operation was achieved for most test conditions while measurements and samples were collected. The melter system products satisfied treatment objectives for (a) immobilizing transuranics and toxic metals that distributed to the glass/ceramic (slag) product (surpassing leachability requirements), (b) efficiently destroying organic material in the feeds, (c) reducing the volume of the feed materials, and (d) homogenizing the feed materials for easier and less costly characterization, packaging, shipping, and disposal.

The arc melter technology is capable of reliable production operation for this application. Furnace operating parameters were generally within expected values and typical of reliable industrial arc furnace practice norms. Electrode consumption was low, at around 1% of the input feed material (21 lb/ton of feed material), although no efforts were made to minimize electrode consumption by coating the electrodes or optimizing the power levels and feedrates. Electrode consumption at this rate is not a significant operating or cost issue in mixed waste treatment processes, because the graphite electrodes are relatively inexpensive and can be continuously fed to the furnace. Energy efficiency varied during the test program due to significant variations in power levels and feedrates, but energy use as low as 0.20 kWh/lb was observed. The arc melter system processed 28,000 lb of surrogate heterogeneous materials during an 84-h test period essentially without failure (unplanned downtime) except for several short-duration shutdowns for removing deposited material from the furnace outlet duct. This pluggage can be avoided by optimizing the APCS design.

The benefits of a cold top as a thermal radiation shield for the plenum are clear. The benefits of a cold top for reduction of carryover to the APCS are not yet completely determined. A cold top was present most of the time for the bulk pool for all runs during the Phase 2 demonstration tests. The thickness varied and was difficult to monitor and control with the manual means utilized. No effects of

thickness variation were detectable. The presence of a cold top in the higher temperature triangular melt region between the 3 electrodes is not clear in all cases. A better means to establish and detect the cold top is needed.

A few issues with respect to furnace and APCS operations, operating limits, test procedure limits, or to the facility and test program were also identified and are discussed in more detail in the results. These include (a) rapid feed mixture changes that caused mingling of melted material from different feed intervals in the furnace, and infrequent tapping for some feed intervals, which affected sample concentrations and mass balances, (b) difficulty in controlling the feed input rates of slag-forming materials and volatile materials with respect to melt residence times in the furnace, minimum taprates, and maximum offgas rates, (c) ineffectiveness of the primary air in oxidizing feed material, (d) controlling the deposition of condensed and entrained material on the cool duct surface at the furnace outlet, (e) insufficient secondary combustion air for high melter feedrates of organic-containing materials, and (f) inability to continuously remove APCS solids collected in the cyclone and baghouse. While these issues require further engineering design, optimization, and testing for satisfactory resolution in a production system implementation, they are not indicative of melter technology problems, but are simply artifacts of the specific test facility design in which the tests were conducted. Potential engineering solutions for all of these operating issues have been identified.

Additional conclusions and recommendations are summarized in Sections 8.1 to 8.3.

8.1 Arc Melter Test Facility Performance

The melter test facility includes the (a) feed system, (b) melter, (c) APCS, and (d) data management system. Each subsystem was evaluated regarding its performance during the Phase 2 demonstration melting tests.

8.1.1 Feed System Performance

The feed system performed satisfactorily during the demonstration tests. Two recent modifications prevented (a) segregation of feed materials that have varying densities and particle sizes, and (b) moisture condensation and plugging of feed material in the feed tubes. Feed segregation that was observed during previous melting campaigns was prevented by transferring each batch of feed in the receiving bin completely to the meter bin (using the bucket elevator) before charging another batch of feed to the receiving bin. This ensured that all the components from each feed batch were transferred to the meter bin, with no residual material remaining in the receiving bin. This also provided the feed operator with an opportunity to visually inspect the receiving bin between each batch addition. Following this procedure, no segregation of the feed components was observed during the Phase 2 demonstration melting tests. Moisture condensation in the feed tubes that caused some infrequent feed plugging in prior melting campaigns was prevented by heat tapes attached to the feed tubes (above the water-cooled sections), and the two screw feeders connecting the feed tubes and the rotary air lock.

The feed system control logic and data acquisition systems performed within design. Instantaneous feedrate metering was successful, although corrections for the feed bulk density were necessary for each change in feed mixture. These corrections were made after the completion of the demonstration melting tests.

8.1.2 Melter Performance

The arc melter successfully demonstrated its versatility for processing variable feed mixture compositions and feedrates. There was no deterioration of the refractory brick or erosion of the cast hearth refractory, the latter being a significant improvement over the results from the Phase 1 melting tests. The water-cooled components performed within design and showed no signs of degradation.

Slag tap temperatures and the calculated viscosities of the product slags indicate that superheating of the slag was necessary to enable slag tapping. Superheating of the slag up to 250°C above the calculated 100 poise temperature was necessary to achieve sufficient slag fluidity at the taphole. Corrective actions that may reduce the amount of slag superheat (and potentially reduce metals volatilization) include (a) positioning the slag tap nearer to one of the electrodes to permit a hotter portion of the bath to intersect the slag tap face, (b) replacing the water-cooled tapping fixture with uncooled tapping designs, and (c) adding local heating capability for melt in the region of the taphole. Maintaining reasonably high feedrates of slag-forming materials will also improve tapping conditions. Test results show that continuous tapping requires feedrates of slag-forming materials in excess of 1,000 lb/h for the taphole configuration that existed during the tests. Semicontinuous tapping was also acceptable, with slag-forming feedrates of less than 1,000 lb/hr.

Cerium distributed primarily (99.6%) to the slag, and 0.4% to the APCS solids. There was none detected in the metal product. The small amount of Ce that appeared in the APCS solids was probably because of entrainment of some fines from the CeO_2 added to the feed mixtures, or small amounts of ejected melt particles. These results show that the metal product from treating alpha-contaminated mixed wastes will have very little if any measurable Pu contamination, assuming that Pu behaves similarly to Ce. The APCS solids will also be relatively decontaminated, with about two orders of magnitude lower Pu contamination than the slag.

Elements that distributed primarily (over 50%) to the slag product were Al, Ba, Ca, Ce, Si, Mg, Na, and K. Elements that distributed over 50% to the metal product were Fe, As, Cr, Cu, and Ni. Elements that distributed over 50% to the APCS solids included Cd, Pb, Se, Hg, Zn, and Cs.

Because about 90–100% of the Cd, Cs, Se, Pb and Zn in the feed distributed to the APCS solids under the test conditions, the potential for recycling the APCS solids back to the melter is limited but still possible. For example, recycling one-half of the APCS solids to the melter would reduce by one-half the amount of the APCS solids secondary waste stream, but would result in approximately doubling the concentrations of these elements in the APCS solids. With the feed operating conditions that prevailed during these tests, this would increase the Pb and Cs concentrations in the APCS solids to about 1% and 0.2%, respectively. The chloride concentration would also double to around 26%. The acceptability of these levels depends on such factors as the methods used for immobilizing the APCS solids for disposal, the disposal site criteria, and radiation potential from the small amounts of radioactive Cs or other gamma emitters in the actual waste.

There was some carbothermic and aluminothermic reduction of iron oxides in the feed materials. Fixed carbon and possibly some graphite electrode material was oxidized as some of the iron oxides were reduced to produce elemental Fe that added to the metal product.

The levels of APCS solids, at around 6.9% of the feed material fed to the furnace, were much higher than the 2% level observed during the baseline (Phase 1) tests. The increased APCS solids may have been caused in part by (a) the method of adding primary combustion air along with the feed material, which could entrain feed dust directly to the plenum gas, (b) increased flow of volatilized gases from the

melt that would increase ejection of melt material and draw volatilized, entrained, and ejected melt material into the plenum gas, or (c) operation with much more Cl (resulting in more volatile chloride species of some metals) and much more organics (resulting in more reducing conditions), that can encourage the formation of more volatile metal chlorides and more volatile reduced metals. If the majority of the APCS solids is from entrained feed dust or ejected material, then using oxygen, oxygen-enriched air, or other methods for introducing oxygen to the furnace that minimize gas flows and particle entrainment may reduce the amounts of APCS solids.

Results of the XRD analyses (lack of crystalline phases in the baghouse samples) suggest that much of the APCS solids are from volatilization of feed materials. Volatilization of metals may be reduced by (a) reducing the residence time of melt in the furnace, (b) lowering the average melt temperatures, or (c) lowering the melt temperatures in the region near each electrode, which may be much higher than the average melt temperature. The melt residence time is the time required to process feed material through the furnace equivalent to 1 melt volume. The melt residence time, calculated from the melt volume (approximately 5 ft³) and the average feedrates for each feed interval, was as high as 21 hours for the S-40 interval, and as low as 1 hour for the Nom-90 interval. Levels of Na and K in the slag for the S-series and C-series intervals decreased, most likely from volatilization during those feed periods when the volatilization rate was relatively high, and the feedrate and taprates were very low. The residence time for the furnace operating at its capacity of 2,000 lb/h is much lower at about 0.5 hours. The amounts of metals volatilization could be significantly reduced by processing feed material through the furnace faster to reduce the melt residence time, volatilization, and graphite electrode consumption.

Local melt temperatures can be reduced by reducing the electrical power density in those regions. Close control of power levels and feedrates can reduce power levels to the very minimum required. This will reduce local electrode-area temperatures, the amount of superheat in the melt, and improve energy efficiency. Power density can also be reduced by using larger electrodes. Following a review of the melter and electrode design, the USBM has already installed 8-in. diameter electrodes in place of the previous 4-in. diameter electrodes.

In the present melter test facility, the feedrate for high volatility feed materials was limited to 300–800 lb/h (for C-series, S-series, and Nom-40-series feed mixtures) owing to limited capacity of the secondary combustion air. The furnace residence time can be decreased by increasing the capacity of the secondary air flowrate, and reducing the firing rates for the burners that inject the gas-fired thermal oxidizer and ducting to prevent overheating. These actions will enable increased feedrate of high volatilization feed materials that have a higher heat content.

Higher feedrates of high volatility materials are also desirable to improve tapping conditions. Test results show that continuous tapping requires feedrates of slag-forming materials in excess of 1,000 lb/h. For feed materials such as the S-0 and C-20 mixtures, this corresponds to a feedrate of 2,600 and 3,600 lb/h, respectively. Semicontinuous tapping may also be acceptable operation.

The low power limit of the furnace was reached during the S and C feed intervals, when the average feedrate was as low as 108 lb/h (S-0), and the average power level was as low as 123 kW (C-20). The molten pool began to freeze along the refractory walls inside the furnace. At such low power levels, the input power approached the limit necessary to heat, devolatilize, melt the input feed material, and make up for heat losses to the water-cooled furnace shell and the offgas.

8.1.3 APCS Performance

The APCS operated satisfactorily within design and operating constraints, and efficiently controlled air emissions of particulate, metals, hydrocarbons, dioxins, and acid gases. Hydrocarbon destruction efficiency in the gas-fired thermal oxidizer was measured at 99.999%. The CO and THC levels in the stack gas were within expected regulatory limits and within ranges for good combustion practice at all times when the thermal oxidizer was operated within the design envelope. The HCl scrubbing efficiency was calculated at 98.9% for the S-40 feed interval, which had very high levels of feed Cl. Limited dioxin measurements were also made to evaluate the arc melter APCS potential for controlling dioxin emissions. A very low dioxin emission limit of 0.2 ng/dscm toxicity equivalent (TEQ at 7% O₂) for hazardous waste incineration is included in the proposed Maximum Achievable Control Technology (MACT) rule emission limits. Results of single investigatory dioxin sampling train measurements at the baghouse outlet and at the stack show that (a) baghouse outlet dioxin level was 3.3 times higher than the proposed limit, (b) the stack gas level was 10% lower, and (c) the dioxin control efficiency across the wet scrubber, the charcoal absorber, and the HEPA filters was 73%. These measurements were made during the S-0 feed interval when there were very high levels of chlorine (20%) and carbon (35%) in the melter feed. These results suggest that proposed dioxin limits can be met with the melter and APCS design represented by this test facility. Stack gas dioxin levels may be further reduced, if necessary, by such methods as (a) more rapidly quenching the hot offgas to a lower temperature, (b) using more efficient downstream dioxin removal techniques, or (c) reducing the input amounts of Cl in the feed.

Plugging of the furnace exhaust duct with molten and solid aerosols occurred at 2-6 hour intervals, depending on the combustible content and volatile content of the feed mixture. This required temporary shutdowns, generally from 30-60 minutes, to remove the obstruction. The addition of a mechanical scraper in the furnace exhaust duct, similar to the one used during the Phase 1 demonstration tests, could eliminate the plugging at the furnace exit. This addition would be facilitated by removing burner 1, which was demonstrated during the IWPF feed interval. Other potential solutions include (a) redesigning the geometry and cooling of the melter-thermal oxidizer transition to eliminate duct walls, especially at narrow locations, that are significantly cooler than the offgas, and (b) designing added combustion air that sweeps particulate away from the duct walls. Reducing the amount of APCS solids from the high levels observed in the demonstration tests to the more desirable levels of the baseline tests will also help to reduce solids deposition.

Post-test inspection of the refractory-lined crossover duct connecting the furnace exhaust duct to the thermal oxidizer revealed a gradual buildup of entrained and condensed particulate and organic matter within the ductwork. The geometry of the crossover duct is dictated by the constraints of the current melter lid and furnace building. The buildup of material in this section of the duct is primarily attributed to its geometry. Changing the geometry of the ducting and the location of the thermal oxidizer with respect to the melter in the design of the final treatment facility would significantly decrease this tendency.

Bridging of particulate over the rotary air locks in the cyclone and baghouse caused mixing of particulate during the demonstration tests and prevented a more rigorous evaluation of APCS performance and materials partitioning for the different feed intervals. Bridging can be reduced by operating the rotary valves continuously, which was not done during the preheat intervals. Once the bridging occurred, it could not be removed until the end of the test series. Other corrective activities that have been implemented subsequent to the Phase 2 tests include heated, insulated sheet metal enclosures added to the air locks to reduce condensation. A manually-actuated mechanical scraper was also added to the baghouse hopper, designed to physically break up bridging. The heated enclosure and mechanical scraper has proven extremely effective at eliminating the bridging phenomenon in the baghouse hopper during subsequent melting tests.

8.2 Mass Balance Closure

Mass balance closure, or the comparison of the furnace input and output flowrates, to the input flowrates, was very good, with some limitations. The feed mixtures were generally fed to the furnace in rapid succession without emptying the furnace except at the end of the Nom-60 feed interval and after the cleanout. Materials of each feed interval thereby mingled with the preceding and anteceding feed intervals in the melt, making sample analyses and mass balances less specific to individual feed intervals. This effect was reduced by performing mass balances over larger time periods (the preheat, BWID, IWPF, and cleanout intervals) rather than for each feed mixture.

Mass balance closure was very good for the total input feed and output products, at an average of 0.99 (ratio of output mass divided by the input mass) for the entire melting campaign. Elemental mass closure balances for major feed and slag constituents (Al, Ca, Fe, Mg, and Si) was also reasonably good. Closure for the IWPF interval was not as good because of the limited number of slag samples. The IWPF mixtures were fed to the existing molten pool of BWID feed materials at relatively low flowrates and for shorter periods of time. Insufficient slag was tapped during the IWPF feed interval to be representative of only the IWPF feed mixtures.

Mass balance closure for many of the trace-level and low-concentration elements deviated from 100%. The combination of feed variations from the expected feed analyses, low concentrations (sometimes below detection limits), split distributions between different furnace products, and lack of representative samples from some of the feed intervals resulted in varying mass balance closures.

8.3 Recommendations for Future Work

Based on the successful results of the demonstration tests, continued support is recommended for arc melter system design, testing, and evaluation in several areas to adapt and optimize system design and process operations for treating mixed waste. Current design and operating practices used for the USBM melter test system are based on those commonly used in the industrial metals smelting industry, without significant remote or automated practices or rigorous contamination control. Several equipment and procedure modifications are required to adapt the existing arc melter system technology, as represented by the USBM system, for production mixed waste treatment. Specific areas of equipment and procedures modifications requiring engineering design adaptation, and appropriate development and demonstration include:

- Automation and remote operation of the system, including routine feeding and tapping operations, in order to reduce the level of personnel involvement and risk.
- Complete system containment and implementation of standard contamination and radiation control practices.
- Feed preparation and mixing subsystems designed to perform adequate and reliable feed preparation, including necessary feed characterization, sizing, segregation, and mixing within complete confinement.
- Increasing and matching the APCS capability and capacity to handle higher gas flow rates as well as low gas flows commensurate with higher feedrates of slagformers to the melt so that the furnace melt residence time and metals volatilization are minimized, taprates are adequate

for trouble-free tapping, and electrical power levels are within design furnace operating ranges for the potentially widely varying range of organic combustible waste feed input materials.

- In furnace feed delivery, cold top control, and oxidant additions methods to control the amounts of volatilization and feed dust entrainment, while providing adequate conditions for pyrolyzing organic matter and oxidizing fixed carbon.
- Configuration, surface temperature, filtering and cleaning methods to prevent undesirable surface deposits and fouling of surfaces and ducting that are not easily cleaned in an alpha environment.
- Removal of APCS solids.

Air pollution control systems presently available are adequate for controlling furnace offgas to meet current and expected emission limits. However, the final disposition of the solids recovered in the air pollution control system depends on the properties of the solids and secondary waste form requirements. Recommended research and development includes (a) reducing feed material entrainment and volatilization from the melter, (b) recycling APCS solids to the melter, (c) demonstrating the performance of potential solidification technologies for APCS solids and scrubber solutions, and (d) developing improved or new technologies that could provide more effective and trouble-free offgas control, including hot filtration and non-fossil-fired offgas oxidation, and (e) performance of more rigorous and detailed measurements to better evaluate mass balance, partitioning, and partitioning mechanisms.

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Appendix A

Chemical Species Compositions of the Surrogate Wastes and Individual Feed Components

Table A-1. Estimated compositions of the additives used to prepare the surrogate waste mixtures.

Additive	Comp.	Additive	Comp.	Additive	Comp.	Additive	Comp.
Lime (a)		Diatomite (a)		Portland Cement (b)		Soil (a)	
CaO	91.6	Ag ₂ O	0.00	SiO ₂	20.8	Ag ₂ O	0.00
SiO ₂	0.34	Al ₂ O ₃	4.29	Al ₂ O ₃	6.56	Al ₂ O ₃	12.04
CO ₂	0.82	As ₂ O	0.00	Fe ₂ O ₃	2.76	As ₂ O	0.00
Fe ₂ O ₃	0.46	BaO	0.01	SO ₃	1.63	BaO	0.12
Al ₂ O ₃	0.16	CaO	0.59	CaO	59.8	CaCO ₃	9.08
MgO	1.24	CdO	0.00	MgO	2.41	CaO	0.24
SO ₃	0.00	CeO ₂	0.00	CO ₂	1.03	CdO	0.00
Cs ₂ O	0.00	Cl	0.02	Water	5.00	CeO ₂	0.01
HgO	0.00	CO ₂	0.00	Wood pellets (wood, paper, cloth) (f)		Cr ₂ O ₃	0.01
K ₂ O	0.06	Cr ₂ O ₃	0.00	C	34.5	Cs ₂ O	0.00
SeO	0.00	Cs ₂ O	0.00	H	6.54	CuO	0.01
Ag ₂ O	0.00	CuO	0.00	O	48.9	Fe ₃ O ₄	4.75
CdO	0.00	Fe ₂ O ₃	2.09	N	0.09	HgO	0.00
Na ₂ O	0.03	HgO	0.00	Water	10.0	K ₂ O	2.32
P ₂ O ₅	0.03	K ₂ O	0.35	Microcel E (a)		MgO	2.19
Cl	0.00	MgO	0.28	Ag ₂ O	0.00	MnO ₂	0.11
Pb	0.00	Na ₂ O	3.73	Al ₂ O ₃	1.57	Na ₂ O	1.59
As	0.00	NiO	0.00	As ₂ O	0.00	NiO	0.01
Water	5.20	P ₂ O ₅	0.04	BaO	0.01	PO ₄	0.24
Carbon steel		PbO	0.00	CaO	30.2	PbO	0.00
Fe (a)	99.2	SeO	0.00	CdO	0.00	SO ₄	0.05
C (a)	0.08	SiO ₂	86.21	CeO ₂	0.01	SeO	0.00
P (a)	0.02	SO ₄	0.05	Cl	0.00	SiO ₂	61.40
S (a)	0.01	TiO ₂	0.22	CO ₂	2.28	TiO ₂	0.66
Mn (b)	0.45	ZnO	0.00	Cr ₂ O ₃	0.01	ZnO	0.02
Si (b)	0.25	ZrO ₂	0.01	Cs ₂ O	0.00	ZrO ₂	0.02
Stainless steel (a)		Water	2.09	CuO	0.00	Cl	0.00
Fe	70.5	Latex rubber stoppers (b)		Fe ₂ O ₃	1.27	Water	5.13
Cr	18.1	C	76.2	HgO	0.00	Polyethylene (a)	
Ni	8.68	H	10.3	K ₂ O	0.25	C	85.6
C	0.10	O	2.32	MgO	0.78	H	14.1
Zirconium (c)		N	0.65	Na ₂ O	0.31	O	0.20
Zr	93.0	S	1.18	NiO	0.01	N	0.03
Mo	4.70	Al ₂ O ₃	0.09	P ₂ O ₅	0.07	S	0.05
Si	1.50	CaO	1.93	PbO	0.00	Al ₂ O ₃	0.00
Fe	0.40	Fe ₂ O ₃	0.09	SeO	0.00	CaO	0.00
Cr	0.30	PbO	0.01	SiO ₂	49.4	MgO	0
Hf	0.10	MgO	0.58	SO ₄	0.15	Al(OH) ₃ (d)	100
Cu	0.09	P ₂ O ₅	0.12	TiO ₂	0.09	Fe(OH) ₃ (d)	100
Mn	0.09	SiO ₂	0.39	ZnO	0.01	Ca(OH) ₂ (d)	100
Copper (d)		Na ₂ O	0.12	ZrO ₂	0.00	Mg(OH) ₂ (d)	100
Lead (b)		TiO ₂	0.20	Water	13.6	NaOH (d)	100
Pb	99.9	ZnO	5.80	Teflon (b)		NaNO ₃ (d)	100
Cu	0.10	KOH (d)	100	C	24.0	Na ₂ SO ₄ (d)	100
Cadmium (d)		KNO ₃ (d)	100	F	76.0	NaCl (d)	100

Table A-1. (continued).

Additive	Comp.
Aluminum	
Al (a)	95.6
Mg (b,e)	2.80
Si (b,e)	1.60
Lead oxide (g)	
Pb ₃ O ₄	98
Mn	0.00005
Acid insol. matter	0.03
H ₂ O insol. matter	0.05

Additive	Comp.
Neoprene rubber (a)	
C	54.70
H	5.65
Cl	37.87
N	0.26
S	1.52
PVC (a)	
C	44.4
H	5.57
Cl	49.6
N	0.05
S	0.39

Additive	Comp.
Wheel bearing grease (a)	
C	82.5
H	12.2
S	1.36
O	3.77
N	0.14
Vermiculite (b)	
Al	19.0
Fe	39.2
Mg	17.1
Si	19.7
H ₂ O	5.00

Additive	Comp.
Texaco Regal Oil (a)	
C	85.4
H	13.5
S	0.10
O	0.87
N	0.10

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- a. Analysis provided by USBM.
- b. Analysis from EDF "Estimated Waste Matrix Compositions of alpha-LL Waste for Treatment Design Bases", by L.G. Gale and B.D. Raivo.
- c. Analysis provided by vendor.
- d. Assumed 100% pending additional analysis.
- e. Numbers were renormalized to obtain 100% for the additive composition.
- f. Analysis from Combustion Handbook.
- g. Analysis provided by USBM although assumed 100% Pb₃O₄ for calculation purposes.
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Table A-2. Calculated proximate analysis of NOM-90 feed mixture.

Component	NOM-90	Composition (wt %).															Total
		Moisture Loss	Volatile Organics Loss	H ₂ O	Nitrate Decomposition Loss				Carbonate Decomposition Loss		Sulfate Decomposition Loss		Chloride Evolution Loss		Fixed Carbon	Solid Inerts	
					N ₂	O ₂	NO	NO ₂	CO	CO ₂	SO ₂	O ₂	HCl	Cl ₂			
Ce spike	0.52															100	100
Soil	66.8	9.86								5.58	0.03	0.01		0.01		84.5	100
Lime	25.2									0.80	0.15	0.08				99.0	100
Mill scale																100	100
Carbon steel	1.68														0.20	99.8	100
Stainless steel	0.86															100	100
Aluminum	0.14															100	100
Zirconium	0.07															100	100
Copper	0.04															100	100
Lead	0.01															100	100
Polyethylene	0.47		100														100
Wood pellets (paper)	0.00	7.66	79.9												12.1		99.7
Wood pellets (wood)	1.16	7.66	79.9												12.1		99.7
Neoprene rubber	0.19		100														100
Oil Dri sorbent	0.00	4.00														96.0	100
Wood pellets (cloth)	0.00	7.66	79.9												12.1		99.7
Texaco Regal Oil	0.28		100														100
Hydraulic oil	0.00		100														100
Wheel bearing grease	0.03		90.0												10.0		100
PVC	0.73		24.5										47.7	10.3	17.5		100
Microcel E	0.43	10.0														90.0	100
Oil Dri	0.27	4.00														96.0	100
NaNO3	0.20				11.0	39.5	9.41	3.61								36.5	100
KNO3	0.10				9.24	33.3	7.92	3.04								46.7	100
NaCl	0.01												62.4			37.6	100
Na2SO4	0.01										45.1	11.3				43.6	100
NaOH	0.01			22.5												77.5	100
H2O	0.37	100															100
Al(OH)3	0.09			34.6												65.4	100
Fe(OH)3	0.08			25.3												74.7	100
Ca(OH)2	0.05			24.3												75.7	100
Mg(OH)2	0.06			30.9												69.1	100
KOH	0.06			16.1												83.9	100
Portland Cement	0.09	1.49									1.95	0.97				95.6	100
Mixture Averages	100	7.09	2.07	0.09	0.03	0.11	0.03	0.01	0.00	3.93	0.06	0.03	0.35	0.08	0.27	85.8	100

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Table A-3. Calculated proximate analysis of NOM-80 feed mixture.

Component	Composition (wt %)																
	NOM-80	Moisture Loss	Volatile Organics Loss	H2O	Nitrate Decomposition Loss				Carbonate Decomposition Loss		Sulfate Decomposition Loss		Chloride Evolution Loss		Fixed Carbon	Solid Inerts	Total
					N2	O2	NO	NO2	CO	CO2	SO2	O2	HCl	Cl2			
Ce spike	0.47															100	100
Soil	61.7	9.86								5.58	0.03	0.01		0.01		84.5	100
Lime	22.3									0.80	0.15	0.08				99.0	100
Carbon steel	3.50														0.20	99.8	100
Stainless steel	1.78															100	100
Aluminum	0.29															100	100
Zirconium	0.15															100	100
Copper	0.09															100	100
Lead	0.03															100	100
Polyethylene	0.98		100														100
Wood pellets (paper)	0.00	7.66	79.9												12.1		99.7
Wood pellets (wood)	2.41	7.66	79.9												12.1		99.7
Rubber	0.39		100														100
Oil Dri sorbent	0.00	4.00														96.0	100
Wood pellets (cloth)	0.00	7.66	79.9												12.1		99.7
Texaco Regal Oil	0.57		100														100
Hydraulic oil	0.00		100														100
Wheel bearing grease	0.07		90.0												10.0		100
PVC	1.51		24.5										47.7	10.3	17.5		100
Microcel E	0.89	10.0														90.0	100
Oil Dri	0.57	4.00														96.0	100
NaNO3	0.42				11.0	39.5	9.41	3.61								36.5	100
KNO3	0.21				9.24	33.3	7.92	3.04								46.7	100
NaCl	0.02												62.4			37.6	100
Na2SO4	0.02										45.1	11.3				43.6	100
NaOH	0.02			22.5												77.5	100
H2O	0.76	100															100
Al(OH)3	0.18			34.6												65.4	100
Fe(OH)3	0.17			25.3												74.7	100
Ca(OH)2	0.10			24.3												75.7	100
Mg(OH)2	0.12			30.9												69.1	100
KOH	0.11			16.1												83.9	100
Portland Cement	0.18	1.49									1.95	0.97				95.6	100
Mixture Averages	100	7.15	4.30	0.19	0.07	0.24	0.06	0.02	0.00	3.62	0.06	0.03	0.73	0.16	0.57	82.8	100

Table A-4. Calculated proximate analysis of NOM-70 feed mixture.

Component	Composition (wt %)																
	NOM-70	Moisture Loss	Volatile Organics Loss	H2O	Nitrate Decomposition Loss				Carbonate Decomposition Loss		Sulfate Decomposition Loss		Chloride Evolution Loss		Fixed Carbon	Solid Inerts	Total
					N2	O2	NO	NO2	CO	CO2	SO2	O2	HCl	Cl2			
Ce spike	0.42															100	100
Soil	56.1	9.86								5.58	0.03	0.01		0.01		84.5	100
Lime	19.3									0.80	0.15	0.08				99.0	100
Mill scale																100	100
Carbon steel	5.45														0.20	99.8	100
Stainless steel	2.77															100	100
Aluminum	0.45															100	100
Zirconium	0.23															100	100
Copper	0.14															100	100
Lead	0.05															100	100
Polyethylene	1.52		100														100
Wood pellets (paper)	0.00	7.66	79.9												12.1		99.7
Wood pellets (wood)	3.75	7.66	79.9												12.1		99.7
Rubber	0.61		100														100
Oil Dri sorbent	0.00	4.00														96.0	100
Wood pellets (cloth)	0.00	7.66	79.9												12.1		99.7
Texaco Regal Oil	0.89		100														100
Hydraulic oil	0.00		100														100
Wheel bearing grease	0.11		90.0												10.0		100
PVC	2.35		24.5										47.7	10.3	17.5		100
Microcel E	1.39	10.0														90.0	100
Oil Dri	0.89	4.00														96.0	100
NaNO3	0.65				11.0	39.5	9.41	3.61								36.5	100
KNO3	0.33				9.24	33.3	7.92	3.04								46.7	100
NaCl	0.04												62.4			37.6	100
Na2SO4	0.04										45.1	11.3				43.6	100
NaOH	0.04			22.5												77.5	100
H2O	1.18	100															100
Al(OH)3	0.28			34.6												65.4	100
Fe(OH)3	0.26			25.3												74.7	100
Ca(OH)2	0.16			24.3												75.7	100
Mg(OH)2	0.19			30.9												69.1	100
KOH	0.18			16.1												83.9	100
Portland Cement	0.28	1.49									1.95	0.97				95.6	100
Mixture Averages	100	7.18	6.69	0.30	0.10	0.37	0.09	0.03	0.00	3.28	0.07	0.03	1.14	0.25	0.89	79.6	100

Table A-5. Calculated proximate analysis of NOM-60 feed mixture.

Component	Composition (wt %)																
	NOM-60	Moisture Loss	Volatile Organics Loss	H2O	Nitrate Decomposition Loss				Carbonate Decomposition Loss		Sulfate Decomposition Loss		Chloride Evolution Loss		Fixed Carbon	Solid Inerts	Total
					N2	O2	NO	NO2	CO	CO2	SO2	O2	HCl	Cl2			
Ce spike	0.37															100	100
Soil	49.9	9.86								5.58	0.03	0.01		0.01		84.5	100
Lime	16.3									0.80	0.15	0.08				99.0	100
Mill scale																100	100
Carbon steel	7.53														0.20	99.8	100
Stainless steel	3.83															100	100
Aluminum	0.63															100	100
Zirconium	0.31															100	100
Copper	0.19															100	100
Lead	0.06															100	100
Polyethylene	2.11		100														100
Wood pellets (paper)	0.00	7.66	79.9												12.1		99.7
Wood pellets (wood)	5.19	7.66	79.9												12.1		99.7
Rubber	0.84		100														100
Oil Dri sorbent	0.00	4.00														96.0	100
Wood pellets (cloth)	0.00	7.66	79.9												12.1		99.7
Texaco Regal Oil	1.23		100														100
Hydraulic oil	0.00		100														100
Wheel bearing grease	0.15		90.0												10.0		100
PVC	3.25		24.5										47.7	10.3	17.5		100
Microcel E	1.92	10.0														90.0	100
Oil Dri	1.23	4.00														96.0	100
NaNO3	0.90				11.0	39.5	9.41	3.61								36.5	100
KNO3	0.45				9.24	33.3	7.92	3.04								46.7	100
NaCl	0.05												62.4			37.6	100
Na2SO4	0.05										45.1	11.3				43.6	100
NaOH	0.05			22.5												77.5	100
H2O	1.64	100															100
Al(OH)3	0.38			34.6												65.4	100
Fe(OH)3	0.36			25.3												74.7	100
Ca(OH)2	0.22			24.3												75.7	100
Mg(OH)2	0.26			30.9												69.1	100
KOH	0.25			16.1												83.9	100
Portland Cement	0.39	1.49									1.95	0.97				95.6	100
Mixture Averages	100	7.20	9.26	0.41	0.14	0.51	0.12	0.05	0.00	2.91	0.07	0.03	1.58	0.34	1.23	76.2	100

Table A-6. Calculated proximate analysis of NOM-50 feed mixture.

Component	Composition (wt %)																
	NOM-50	Moisture Loss	Volatile Organics Loss	H2O	Nitrate Decomposition Loss				Carbonate Decomposition Loss		Sulfate Decomposition Loss		Chloride Evolution Loss		Fixed Carbon	Solid Inerts	Total
					N2	O2	NO	NO2	CO	CO2	SO2	O2	HCl	Cl2			
Ce spike	0.32															100	100
Soil	43.0	9.86								5.58	0.03	0.01		0.01		84.5	100
Lime	13.3									0.80	0.15	0.08				99.0	100
Mill scale																100	100
Carbon steel	9.75														0.20	99.8	100
Stainless steel	4.96															100	100
Aluminum	0.81															100	100
Zirconium	0.41															100	100
Copper	0.24															100	100
Lead	0.08															100	100
Polyethylene	2.73		100														100
Wood pellets (paper)	0.00	7.66	79.9												12.1		99.7
Wood pellets (wood)	6.72	7.66	79.9												12.1		99.7
Rubber	1.08		100														100
Oil Dri sorbent	0.00	4.00														96.0	100
Wood pellets (cloth)	0.00	7.66	79.9												12.1		99.7
Texaco Regal Oil	1.60		100														100
Hydraulic oil	0.00		100														100
Wheel bearing grease	0.19		90.0												10.0		100
PVC	4.20		24.5										47.7	10.3	17.5		100
Microcel E	2.49	10.0														90.0	100
Oil Dri	1.59	4.00														96.0	100
NaNO3	1.17				11.0	39.5	9.41	3.61								36.5	100
KNO3	0.58				9.24	33.3	7.92	3.04								46.7	100
NaCl	0.07												62.4			37.6	100
Na2SO4	0.06										45.1	11.3				43.6	100
NaOH	0.06			22.5												77.5	100
H2O	2.12	100															100
Al(OH)3	0.50			34.6												65.4	100
Fe(OH)3	0.47			25.3												74.7	100
Ca(OH)2	0.29			24.3												75.7	100
Mg(OH)2	0.34			30.9												69.1	100
KOH	0.32			16.1												83.9	100
Portland Cement	0.50	1.49									1.95	0.97				95.6	100
Mixture Averages	100	7.19	12.0	0.53	0.18	0.66	0.16	0.06	0.00	2.51	0.07	0.03	2.05	0.44	1.59	72.5	100

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Table A-7. Calculated proximate analysis of NOM-40 feed mixture.

Component	Composition (wt %)																
	NOM-40	Moisture Loss	Volatile Organics Loss	H2O	Nitrate Decomposition Loss				Carbonate Decomposition Loss		Sulfate Decomposition Loss		Chloride Evolution Loss		Fixed Carbon	Solid Inerts	Total
					N2	O2	NO	NO2	CO	CO2	SO2	O2	HCl	Cl2			
Ce spike	0.27															100	100
Soil	35.6	9.86								5.58	0.03	0.01		0.01		84.5	100
Lime	10.3									0.80	0.15	0.08				99.0	100
Mill scale																100	100
Carbon steel	12.1														0.20	99.8	100
Stainless steel	6.15															100	100
Aluminum	1.01															100	100
Zirconium	0.50															100	100
Copper	0.30															100	100
Lead	0.10															100	100
Polyethylene	3.39		100														100
Wood pellets (paper)	0.00	7.66	79.9												12.1		99.7
Wood pellets (wood)	8.34	7.66	79.9												12.1		99.7
Rubber	1.35		100														100
Oil Dri sorbent	0.00	4.00														96.0	100
Wood pellets (cloth)	0.00	7.66	79.9												12.1		99.7
Texaco Regal Oil	1.98		100														100
Hydraulic oil	0.00		100														100
Wheel bearing grease	0.24		90.0												10.0		100
PVC	5.22		24.5										47.7	10.3	17.5		100
Microcel E	3.09	10.0														90.0	100
Oil Dri	1.98	4.00														96.0	100
NaNO3	1.45				11.0	39.5	9.41	3.61								36.5	100
KNO3	0.73				9.24	33.3	7.92	3.04								46.7	100
NaCl	0.08												62.4			37.6	100
Na2SO4	0.08										45.1	11.3				43.6	100
NaOH	0.08			22.5												77.5	100
H2O	2.63	100															100
Al(OH)3	0.62			34.6												65.4	100
Fe(OH)3	0.58			25.3												74.7	100
Ca(OH)2	0.35			24.3												75.7	100
Mg(OH)2	0.42			30.9												69.1	100
KOH	0.40			16.1												83.9	100
Portland Cement	0.62	1.49									1.95	0.97				95.6	100
Mixture Averages	100	7.17	14.9	0.66	0.23	0.81	0.19	0.07	0.00	2.07	0.07	0.03	2.54	0.54	1.97	68.7	100

Table A-8. Calculated proximate analysis of S-40 feed mixture.

Component	S-40	Composition (wt %)															Fixed Carbon	Solid Inerts	Total
		Moisture Loss	Volatile Organics Loss	H2O	Nitrate				Carbonate		Sulfate		Chloride						
					Decomposition Loss				Decomposition Loss		Decomposition Los		Evolution Loss						
					N2	O2	NO	NO2	CO	CO2	SO2	O2	HCl	Cl2					
Ce spike	0.35															100	100		
Soil	33.1	9.86								5.58	0.03	0.01		0.01		84.5	100		
Lime	16.3									0.80	0.15	0.08				99.0	100		
Mill scale																100	100		
Carbon steel	0.00														0.20	99.8	100		
Stainless steel	0.00															100	100		
Aluminum	0.00															100	100		
Cadmium	0.00															100	100		
Copper	0.00															100	100		
Lead	0.00															100	100		
LD Polyethylene, (-CH2-CH2-)	1.70		100														100		
Wood pellets (paper & cardboard)		7.66	79.9													12.1	99.7		
Wood pellets (wood), (C6H10O5)n	0.00	7.66	79.9													12.1	99.7		
Neoprene rubber, (-CH2CCl-CHCH2-)n	0.00		100														100		
Oil Dri sorbent	0.00	4.00														96.0	100		
Wood pellets (latex rubber)	0.00	7.66	79.9													12.1	99.7		
Texaco Regal Oil, (CH2)n	8.24		100														100		
Hydraulic oil, (CH2)n			100														100		
Wheel bearing grease, (CH2)n	0.99		90.0												10.0		100		
PVC, (-CH3Cl-)	21.6		24.5										47.7	10.3	17.5		100		
Microcel E	12.8	10.0														90.0	100		
Oil Dri	4.87	4.00														96.0	100		
Polyethylene (latex rubber)	0.00				11.0	39.5	9.41	3.61								36.5	100		
Vermiculite	0.00	5.00														95.0	100		
Lead oxide	0.00		37.6		0.28						1.02	0.50				60.6	100		
Teflon	0.00	24.0											62.5	13.5			100		
Latex rubber stoppers	0.00		86.5		0.65						2.36	1.14				9.34	100		
Magnesium																100	100		
Nickel																100	100		
Antimony																100	100		
Zinc																100	100		
Mixture Averages	100	4.75	16.1	0.00	0.00	0.00	0.00	0.00	0.00	1.98	0.03	0.02	10.3	2.23	3.87	60.7	100		

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Table A-9. Calculated proximate analysis of S-0 feed mixture.

Component	S-0	Composition (wt %)														Fixed Carbon	Solid Inerts	Total
		Moisture Loss	Volatile Organics Loss	H2O	Nitrate Decomposition Loss				Carbonate Decomposition Loss		Sulfate Decomposition Loss		Chloride Evolution Loss					
					N2	O2	NO	NO2	CO	CO2	SO2	O2	HCl	Cl2				
Ce spike	0.20															100	100	
Soil	0.00	9.86								5.58	0.03	0.01		0.01		84.5	100	
Lime	8.32									0.80	0.15	0.08				99.0	100	
Mill scale																100	100	
Carbon steel	0.00														0.20	99.8	100	
Stainless steel	0.00															100	100	
Aluminum	0.00															100	100	
Cadmium	0.00															100	100	
Copper	0.00															100	100	
Lead	0.00															100	100	
LD Polyethylene, (-CH2-CH2-)	3.10		100														100	
Wood pellets (paper & cardboard)		7.66	79.9												12.1		99.7	
Wood pellets (wood), (C6H10O5)n	0.00	7.66	79.9												12.1		99.7	
Neoprene rubber, (-CH2CCl-CHCH2-)n	0.00		100														100	
Oil Dri sorbent	0.00	4.00														96.0	100	
Wood pellets (latex rubber)	0.00	7.66	79.9												12.1		99.7	
Texaco Regal Oil, (CH2)n	15.0		100														100	
Hydraulic oil, (CH2)n			100														100	
Wheel bearing grease, (CH2)n	1.81		90.0												10.0		100	
PVC, (-CH3Cl-)	39.3		24.5										47.7	10.3	17.5		100	
Microcel E	23.4	10.0														90.0	100	
Oil Dri	8.87	4.00														96.0	100	
Polyethylene (latex rubber)	0.00				11.0	39.5	9.41	3.61								36.5	100	
Vermiculite	0.00	5.00														95.0	100	
Lead oxide	0.00		37.6		0.28						1.02	0.50				60.6	100	
Teflon	0.00	24.0											62.5	13.5			100	
Latex rubber stoppers	0.00		86.5		0.65						2.36	1.14				9.34	100	
Magnesium																100	100	
Nickel																100	100	
Antimony																100	100	
Zinc																100	100	
Mixture Averages	100	2.69	29.4	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.01	0.01	18.8	4.05	7.05	38.0	100	

Table A-10. Calculated proximate analysis of C-20 feed mixture.

Component	C-20	Composition (wt %)																
		Moisture Loss	Volatile Organics Loss	H2O	Nitrate				Carbonate		Sulfate		Chloride		Fixed Carbon	Solid Inerts	Total	
					Decomposition Loss				Decomposition Loss		Decomposition Loss		Evolution Loss					
					N2	O2	NO	NO2	CO	CO2	SO2	O2	HCl	Cl2				
Ce spike	0.14															100	100	
Soil	18.7	9.86								5.58	0.03	0.01		0.01		84.5	100	
Lime	5.87									0.80	0.15	0.08				99.0	100	
Mill scale																100	100	
Carbon steel	1.33															0.20	99.8	100
Stainless steel	0.16																100	100
Aluminum	0.84																100	100
Cadmium	0.03																100	100
Copper	0.28																100	100
Lead	0.03																100	100
LD Polyethylene, (-CH2-CH2-)	23.9		100															100
Wood pellets (paper & cardboard)		7.66	79.9													12.1		99.7
Wood pellets (wood), (C6H10O5)n	32.1	7.66	79.9													12.1		99.7
Neoprene rubber, (-CH2CCl-CHCH2-)n	1.01		100															100
Oil Dri sorbent	1.25	4.00															96.0	100
Wood pellets (latex rubber)	2.90	7.66	79.9													12.1		99.7
Texaco Regal Oil, (CH2)n	0.00		100															100
Hydraulic oil, (CH2)n			100															100
Wheel bearing grease, (CH2)n	0.00		90.0													10.0		100
PVC, (-CH3Cl-)	5.94		24.5											47.7	10.3	17.5		100
Microcel E	0.00	10.0															90.0	100
Oil Dri	0.00	4.00															96.0	100
Polyethylene (latex rubber)	2.90				11.0	39.5	9.41	3.61									36.5	100
Vermiculite	0.86	5.00															95.0	100
Lead oxide	0.80		37.6		0.28							1.02	0.50				60.6	100
Teflon	0.03	24.0												62.5	13.5			100
Latex rubber stoppers	1.00		86.5		0.65							2.36	1.14				9.34	100
Magnesium																	100	100
Nickel																	100	100
Antimony																	100	100
Zinc																	100	100
Mixture Averages	100	4.62	55.5	0.00	0.33	1.14	0.27	0.10	0.00	1.09	0.05	0.02	2.86	0.62	5.27	28.1	99.9	

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Table A-11. Calculated proximate analysis of C-40 feed mixture.

Component	C-40	Composition (wt %)															Solid Inerts	Total	
		Moisture Loss	Volatile Organics Loss	H2O	Nitrate Decomposition Loss			Carbonate Decomposition Loss			Sulfate Decomposition Loss		Chloride Evolution Loss		Fixed Carbon				
					N2	O2	NO	NO2	CO	CO2	SO2	O2	HCl	Cl2					
Ce spike	0.10																	100	100
Soil	35.5	9.86										5.58	0.03	0.01			0.01	84.5	100
Lime	11.2											0.80	0.15	0.08				99.0	100
Mill scale																		100	100
Carbon steel	0.94																		
Stainless steel	0.11															0.20		99.8	100
Aluminum	0.59																	100	100
Cadmium	0.02																	100	100
Copper	0.20																	100	100
Lead	0.02																	100	100
LD Polyethylene, (-CH2-CH2-)	16.9		100																100
Wood pellets (paper & cardboard)		7.66	79.9																99.7
Wood pellets (wood), (C6H10O5)n	22.7	7.66	79.9													12.1			99.7
Neoprene rubber, (-CH2CCl-CHCH2-)n	0.71		100																100
Oil Dri sorbent	0.88	4.00																96.0	100
Wood pellets (latex rubber)	2.05	7.66	79.9													12.1			99.7
Texaco Regal Oil, (CH2)n	0.00		100																100
Hydraulic oil, (CH2)n			100																100
Wheel bearing grease, (CH2)n	0.00		90.0													10.0			100
PVC, (-CH3Cl-)	4.20		24.5												47.7	10.3	17.5		100
Microcel E	0.00	10.0																	100
Oil Dri	0.00	4.00																90.0	100
Polyethylene (latex rubber)	2.05			11.0	39.5	9.41		3.61										96.0	100
Vermiculite	0.61	5.00																36.5	100
Lead oxide	0.57		37.6		0.28								1.02	0.50				95.0	100
Teflon	0.02	24.0																60.6	100
Latex rubber stoppers	0.71		86.5		0.65								2.36	1.14			13.5		100
Magnesium																		9.34	100
Nickel																		100	100
Antimony																		100	100
Zinc																		100	100
Mixture Averages	100	5.47	39.2	0.00	0.23	0.81	0.19	0.07	0.00	2.07	0.05	0.02	2.02	0.44	3.73		45.6		100

Table A-12. Batch composition of the BWID master mixture by component.

Component	wt lb	wt %
Al(OH) ₃	148.93	4.03
Ca(OH) ₂	85.47	2.31
Diatomite	476.90	12.90
Fe(OH) ₃	139.87	3.78
KNO ₃	174.83	4.73
KOH	95.83	2.59
Mg(OH) ₂	102.31	2.77
Micro-Cel	744.79	20.15
Na ₂ SO ₄	19.23	0.52
NaCl	19.81	0.54
NaNO ₃	349.67	9.46
NaOH	19.23	0.52
Portland cement	150.23	4.06
Texaco regal oil	477.88	12.93
Water	633.67	17.14
Wheel bearing grease	57.69	1.56
Total	3,696.34	100.00

Table A-13. Batch composition of the IWPF master mixture by component.

Component	wt lb	wt %
Diatomite	252.67	18.08
Micro-Cel	665.79	47.65
Texaco regal oil	427.19	30.57
Wheel bearing grease	51.58	3.69
Total	1,397.23	100.00

Appendix B

Albany Research Center Integrated Melter Test Facility

Appendix B

Albany Research Center Integrated Melter Test Facility

B-1. FEED SYSTEM

Feed mixtures were combined in a 1,000-lb-capacity charge hopper, then transferred by overhead crane to the receiving bin. The receiving bin was modified to one third of its original 60 ft³ volume to limit segregation of the feed by the twin tapered, counter-rotating, 12-in. diameter screws in the base of the bin. A divider was inserted to shorten the bin to roughly one third its original length. Feed was discharged from the receiving bin to a bucket elevator, and lifted 17 ft to a 10 ft³ residue metering bin. The height of material in the metering bin was controlled by a sonic level indicator with high and low set points.

Two calibrated counter-rotating 6-in.-diameter screws discharged feed material from the metering bin through a rotary air lock to a 6-in.-diameter splitter screw, which delivered feed material to two 6-in.-diameter delivery screws. Each delivery screw discharged into the furnace through a pneumatically activated diverter gate that divided and routed the feed to two separate 6 in. diameter transfer tubes. Feed was thereby uniformly admitted into the furnace through four ports in the roof. Primary combustion air was provided to the furnace by a one-half hp blower. Flowrate was controlled by a manually operated electronic butterfly valve and monitored by hot-wire anemometer. The combustion air entered the feed system in two ports in the splitter screw, immediately after the rotary air lock. Thus, combustion air traveled through each delivery screw and entered the furnace, with the feed, through the four feed tubes connected to ports in the furnace roof. Heat tapes were attached to the outer surface of the four feed tubes. Temperature of the tapes was maintained at or near 105°C to limit condensation within the feed tubes.

Feed materials and primary combustion air entered the furnace through the four transfer tubes (2 for each delivery screw), which were slip-fit into four water-cooled tubes that extended through the roof to within 18-in. of the molten pool. These double-walled carbon steel tubes are 48-in. long with an 8.625-in. outside diameter (OD) and 5.5-in. inside diameter (ID). The annular water jacket in each tube is divided length wise by spacers to form 6 water passages. Cooling water for each passage is supplied by nominal 1/4-in. copper tubes that extend down the length of the passage to within 0.5 in. of the bottom of the passage.

The height of unmelted charge (cold top) in the furnace was determined manually by lowering a weight suspended on a 1/16 in.-diameter stranded stainless steel cable in the manner of a plumb bob through one of the feed tubes. The feed system, rated to deliver up to 2,000 lb/h of minus 0.5 in. screened and dried material with a bulk density of approximately 80 lb/ft³, could be operated manually or controlled automatically by a programmable controller. The feed system is described in detail in the operations manual (Miles 1991).

Fugitive dust generated during dumping of the charge hopper and operation of the feed system was vented to a baghouse through a system of ducts connected to the receiving bin, bucket elevator,

and residue metering bin. The baghouse was emptied at the end of the test series, and the weight of fugitive dust was subtracted from the weight of material placed in the receiving bin.

B-2. ELECTRIC ARC MELTER AND POWER SUPPLY

B-2.1 Furnace Description and Design

The furnace has a refractory-lined steel shell with water-cooled sidewalls, partially water-cooled roof, and air-cooled bottom. The capacity of the hearth is about 5 ft³. The carbon steel shell is 65-in. high and tapers from 60 in. ID at the bottom to 56 in. ID at the top. Three carbon steel straps (2-in. wide × 0.060-in. thick) were welded to the inside bottom of the shell in a triangular array before placing the refractory lining in the shell. These straps were worked between the bricks and through the refractory ramming mix during construction of the hearth to provide an electrical circuit to ground between each pair of electrodes. The furnace shell was then securely grounded to the outside. A concrete pedestal supports the furnace between two rectangular pits, each 3-ft 6-in. deep × 5-ft 10-in. wide × 7-ft long.

The conceptual design and engineering drawings for the modified furnace, including refractory selection and placement, cooling-water needs, voltage and power requirements, water-cooled tapping fixture, and general furnace operating procedures, were provided by Lectromelt Corporation (Davis 1995).

The domed carbon steel roof contains a tubular water passage near the outer edge to protect the roof-to-shell seal, which consists of two annular channels in the shell and two knife edges in the roof. The inner channel contains fine sand, and the outer channel contains a silicone elastomer. Water jackets cover about 70% of the exterior surface of the roof encompassing the electrode, charge, and exhaust gas ports.

The three central ports in the roof accommodate 4-in. diameter graphite electrodes. The water-cooled feed tubes, each 8.625 in. OD, extend through the four charging ports in the roof. Exhaust gases exit the furnace through the 8-in. diameter circular exhaust port in the roof. The 6-in. square inspection port in the roof was fitted with a door that opens to provide access to the furnace interior. A remote-controlled color video camera was mounted on a pin-hole port fabricated in the inspection door. This camera provided real-time viewing of the furnace interior during operation.

B-2.2 Furnace Refractories

The bottom of the furnace shell was lined with 5-in. (2 courses) of straight Ruby (chromic oxide-phosphate bonded 90% alumina super-duty) firebrick. Five courses of Ruby key bricks shape the hearth and form the sidewall up to the steel shelf 28 in. above the bottom, which is approximately 7 in. above the slag taphole. One inch of dry phosphate-bonded silicon carbide (SiC) ramming mix was placed between the steel bottom and the first course of Ruby straights to improve heat transfer to the bottom. This ramming mix was also placed in a 1 in. layer between the Ruby keys and the sidewall for the same reason. The upper sidewall was lined with 4.5-in. GM 70 DE (70% alumina) insulating arch fire brick. One inch of Fiberfrax (mullite batting) was placed between the sidewall and the arch brick for additional insulation. At mid-height, the finished ID of the furnace is about

46 in. The hearth was rammed to a depth of 6 in. at the center with Ruby ramming mix. This represented a change in refractory from the BWID Phase 1 test series, in which Permanente 165 AF ramming mix (98% MgO) was used to ram the hearth. The basic MgO refractory was completely eroded by the acidic slags produced from melting the BWID mixtures, which contained significant proportions of the RWMC soil (60 to 100% soil). The volume of the hearth, when finished to 48 in. diameter $\times$ 9-in. deep at the center, is approximately 5 ft³.

A series of melting tests using the BWID Phase 1 S-60 series mixture was conducted in the Albany Research Center 50-kW electric arc melter to determine the most appropriate refractory for the hearth of the pilot-scale furnace. Permanente 165 (MgO), Alfrax (Al₂O₃), Ruby (90% Al₂O₃ - 10% Cr₂O₃), and Union Carbide Cold-Carbon ram mix (C) were investigated. Although the carbon ram mix held up well, it was eliminated from consideration owing to concerns regarding the exposure of the entire bath to additional carbon. The Ruby ram mix was found to be far superior to the other refractories in durability and erosion resistance when exposed to the molten S-60 slags, therefore it was selected for installation in the pilot-scale furnace.

The roof was lined with 4 in. of NARPHOS 85P plastic refractory (85% alumina). This material was selected for ease of placement considering the complexity of the roof, and for the ability to withstand the potentially corrosive condensable fumes within the furnace and the high temperatures anticipated during open arc operation. The roof refractory was extended into the inspection port to provide a 6-in.-square opening. The underside of the inspection door was fitted with Fiberfrax styrofoam refractory, with a 1-in.-diameter viewing hole cut through the center. The roof refractory fit closely to the outside of each feed tube, and the annular space between each feed tube and roof port was packed with Fiberfrax to minimize gas leakage.

Two-part ceramic seals prepared from Cast-O-Last G Ad-Tech were fitted into the annular space between electrode and roof port to minimize gas leakage around the electrodes. A completed electrode seal consists of a ceramic fiber gasket between a shelf on the bottom seal and the top of the roof port, and ceramic fiber packing within the annular space between the bottom and top parts of the seal. The upper part of the seal was clamped to the roof to compress the ceramic packing around the electrode.

Tapping metal and draining the furnace was done through a 1.5-in.-diameter hole in the bottom center of the hearth that was built into the furnace lining during construction. The water-cooled slag tapping fixture was grouted in the furnace sidewall with the Ruby ramming mix. This tapping fixture is a welded, double-walled, copper structure 6-in. diameter $\times$ 10-in. long with a 1-in. diameter central hole designed to permit continuous tapping of slag at rates of up to 2,000 lb/h.

B-2.3 Furnace and Transformer Cooling

The base of the furnace is cooled by about 1,300 cfm of air flowing through a plenum formed by six 4-in.-high I-beams upon which the furnace rests. The furnace shell, roof, slag tapping fixture, launder, metal taphole collar, feed tubes, and emissions control duct are water-cooled and constitute one of two cooling-water circuits servicing the furnace. The second circuit consists of cooling-water for the transformer and electrode arms, cables, and clamps. Cooling-water from these two circuits is pumped to the furnace and ancillary equipment from a 1,500-gal cool water sump by a 1.5 hp centrifugal pump. The furnace shell is cooled by a curtain of water (50 gpm) that cascades down the

outer shell wall from the annular distribution trough near the top of the shell. All cooling water from circuit 1 is collected at the base of the furnace in a trough and is returned by gravity to a 1,500-gal warm water sump through a 6-in. PVC pipe. Cooling water from circuit 2 is routed directly into the 6-in. PVC pipe downstream from a flowmeter and thermocouple inserted into the exit stream from the furnace. This arrangement of the two cooling-water circuits permits flowrate and delta T measurements of the furnace cooling-water, for energy balance calculations. Water is pumped from the warm water sump to a cooling tower of cross flow, induced draft design (Marley Cooling Tower Company 1991). The cooling tower supplies water at a rate of 150 gpm and a temperature of 70°F (when the return water is 142°F and the ambient wet bulb temperature is 70°F).

Municipal water is available for emergency cooling in case of general power failure or malfunction of the circulating pumps. The most critical water-cooled components are the slag tapping fixture, which is in direct contact with the molten pool in the furnace, and the feed tubes. All other water-cooled components are less susceptible to damage during a short-term stoppage of water if furnace power is also stopped. A flowmeter in the water circuit to the tapping fixture de-energizes and opens the automatic valve in the city water line if power fails or if the flowrate from the cooling tower decreases below 20 gpm in the circuit to the slag tapping fixture. Municipal water is then delivered to the entire cooling water circuit.

B-2.4 Power Supply and Furnace Operation

The furnace is powered by a 3-phase 800-kV·A transformer and three 250-kV·A single-phase transformers, which can be configured to provide separate voltage characteristics to the furnace. This flexibility is necessary because the facility has been used to melt slags with significant variations in resistivity. The first electrical configuration consists of the 3-phase and three single-phase transformers connected such that the primary circuit of each 250-kV·A transformer is in parallel with one of the primary phases of the 3-phase transformer, and the secondary circuit of each 250-kV·A transformer is in series with the corresponding secondary phase of the 3-phase transformer. The second electrical configuration bypasses the three 250-kV·A single-phase transformers, connecting the secondaries from the 3-phase 800-kV·A transformer directly to the furnace. Table B-1 lists the secondary open-circuit voltage measured at the furnace for both transformer configurations and their corresponding transformer tap settings.

Table B-1. Power supply characteristics.

Tap	Configuration 1		Configuration 2	
	Phase-to-phase voltage	Phase-to-ground voltage	Phase-to-phase voltage	Phase-to-ground voltage
A	352	192	182	105
B	304	168	137	79
C	256	145	124	72
D	239	134	95	55

Voltage regulation of 3 to 5% of the mean from open circuit to full load is provided by the power supply with 2,080 A maximum output current measured at the furnace. Power can be increased for a given transformer tap position by increasing the electrode positioning rheostats. A rheostat for each phase, working through the electrode positioning circuit for that phase, adjusts the electrode position to decrease the arc length, or even submerge the electrode in the melt, thereby providing increased current. Power to the furnace is a function of the voltage (transformer tap), current (electrode position as determined by rheostat setting), and the resistivity of the slag. A rheostat controls each electrode independently, thereby providing a means to balance the power.

B-3. AIR POLLUTION CONTROL SYSTEM

The air pollution control system is shown in the system schematic (Figure B-1). The system was designed to meet the demands of current research efforts to vitrify materials containing significant proportions of water, combustibles, chlorides, sulfates, nitrates, and nitrites. The primary components were (a) refractory-lined ductwork serviced by two 800,000-Btu natural gas burners, (b) refractory-lined thermal oxidizer serviced by one 3-MMBtu natural gas burner, (c) evaporative gas cooler (EGC), (d) cooling air windbox, (e) cyclone, (f) pulse-jet baghouse, (g) acid gas scrubber, (h) cooler and condenser, (i) heat exchanger, (j) induced draft blower, and (k) activated carbon and HEPA filter banks. Temperature, pressure, gas flow, and sampling locations are indicated in Figure B-1.

B-3.1 Refractory-Lined Ductwork and Thermal Oxidizer

Reducing conditions within the furnace and refractory-lined ductwork leading to the thermal oxidizer were maintained to destroy NO_x before the thermal oxidizer and minimize the tendency for accretions to form within the ducts. The viscosity of glasses and slags, and hence the propensity for accretion formation, increases with the state of oxidation of the transition elements. Trivalent iron tends to participate in and extend the silicate network, whereas divalent iron tends to terminate the network.

Temperature within the ductwork was maintained above the melting temperature of anticipated condensates and particulates by the combined input from two 800,000-Btu natural gas burners. All ducts slope to the thermal oxidizer, which is fitted with a removable refractory-lined catch basin, so that all molten materials can be collected at a single source. The thermal oxidizer, which is heated by a 3-MMBtu natural gas burner, was operated in the oxidizing mode by injecting air below the venturi. The thermal oxidizer was designed to oxidize CO and all residual hydrocarbons and destroy all remaining carbon-chlorine bonds. Design temperatures were 1,600°F within the plenum of the furnace, achieved by limiting combustion air to the volume needed to oxidize carbon in the feed to CO, and 2,250°F in the refractory-lined ductwork and the thermal oxidizer.

B-3.2 Evaporative Gas Cooler, APCS Valve, Windbox, and Bypass Valve

Close-coupled to the thermal oxidizer is a cooler designed to decrease the temperature of the offgas from 2,250 to 500°F by means of evaporative cooling. This is an automated unit that cools the exhaust gases to 500°F at the output by air atomization of water. The APCS valve following the

Key

- B - Natural Gas Burner
- T - Temperature probe
- P - Pressure probe
- A - Analysis port
- G - Gas chromatograph port
- F - Flowrate probe (offgas)
- W - Flowrate probe (water)
- R - Rotary air lock valve
- O - Oxygen sensor
- Indicates refractory lining

Figure B-1. Simplified process model of the furnace.

RED1002

cooler regulates gas flow to provide negative 0.5-in. WC column in the furnace. Air is collected in hoods over the glass and metal tapholes by a 5-hp cooling air blower. Flowrate is regulated by the cooling air valve. Cooling air is then injected into the windbox downstream from the APCS valve to decrease the temperature to 300°F, which is the appropriate entry temperature for the baghouse.

During start-up of the APCS, a bypass valve was opened to the atmosphere to provide sufficient air flow to the induced draft blower. Failure to provide this air flow would cause excessive static pressure in the scrubber and cooler and condenser columns. Once the three natural gas burners in the refractory-lined duct and thermal oxidizer were fired, system pressure and flowrate were adjusted while the bypass valve was closed, isolating the system. The bypass valve was originally located immediately upstream from the windbox, in the cooling air line. However, for reasons discussed below, the bypass valve was moved to the scrubber exit, downstream from the baghouse.

The original APCS operating procedure called for firing the natural gas burners to bring the EGC exit temperature to 500°F and the baghouse inlet temperature to 300°F, at which time the EGC would be activated and cooling air would be injected to maintain these two temperatures. However, results from the shakedown test indicated that water of combustion from the natural gas burners would cause condensation in the baghouse before it could be heated to the desired operating temperature. This required preheating the baghouse with indirectly heated air. To accomplish this, the cooling air line was modified after the shakedown test to include an indirect natural gas fired preheater used to preheat the baghouse before firing the natural gas burners. The preheater was located in the cooling air line between the cooling air valve and windbox. Since the bypass valve was open to the atmosphere during this preheat interval, its location upstream from the baghouse permitted the addition of air at ambient conditions, usually with a high moisture content during the winter months in Oregon, which was counter-productive to the preheating effort. Therefore, the bypass valve was moved to the scrubber exit, downstream from the baghouse. The revised start-up procedure for the APCS required preheating the baghouse to at least 220°F before firing the natural gas burners. Once this was accomplished, the cooling air line reverted to its original design. The remainder of the APCS operating procedure was unchanged.

B-3.3 Cyclone and Baghouse

The cyclone between the windbox and baghouse was designed with two primary functions: (1) to provide additional residence time to allow incandescent particles to cool, and (2) to remove large particles from the offgas stream. The baghouse contains 289 4.5-in.-diameter × 10-ft-long, 16-oz/yd Ryton bags, rated to remove 99.98% of particulate greater than 0.3 microns. Flowrates to 10,000 acfm at pressures of negative 20-in. WC provide an air-to-cloth ratio of 2.94:1. The bags are shaken with a back pulse of 100 psig air at 3-s intervals. The baghouse allows for changing of the bags from the clean air side of the tube sheet as a safety measure and to expedite changing of the bags. The cyclone and baghouse catches were fitted with rotary air locks, which operated continuously except during sampling intervals.

B-3.4 Scrubber and Cooler and Condenser

Acidic species were removed from the exhaust gases in the caustic scrubber following the baghouse. The baghouse was located upstream of the scrubber to allow collection of particulate and

condensed fume solids without contamination by scrubbed (acid gases). Gases exited the scrubber saturated with water vapor at 150°F. The cooler and condenser decreased the temperature to 90°F by circulating water from the cooling tower. Both the scrubber and cooler and condenser columns were fabricated from fiberglass, rated to negative 22-in. WC. Static pressure in the columns was maintained at approximately negative 20-in. WC during the melting tests.

B-3.5 Gas Reheater, Induced Draft Blower, and Filters

Slight reheat of the offgas to 100°F prior to the blower was necessary to prevent condensation in the blower and in the activated carbon and HEPA filters, because the condensed gas was saturated with water vapor at 90°F. Reheating prior to the blower also minimized the visible steam plume from the stack. A copper tube heat exchanger was fabricated for this reheat section. A 36-kW SuperTrol temperature control unit provided 120 gpm of water at 180–250°F to the heat exchanger.

Offgas exiting the heat exchanger was ducted immediately into a 50-hp variable-speed induced draft fan, which discharged the offgas into a bank of four 2,000-acfm activated carbon filters. Four 2,000-acfm HEPA filters were close-coupled to the carbon filters, which were all contained in a sealed, weather-tight stainless steel enclosure. Clean gases were finally discharged through a 30-ft stack into the atmosphere. Fan speed, system pressure, and flowrate were balanced to provide negative 0.5-in. WC in the furnace, not more than negative 20-in. WC in the scrubber and cooler condenser columns, and 25-in. WC pressure drop over the fan. Flowrate at the stack ranged from 3,000 to 4,000 acfm during the melting tests.

B-4. FACILITY STAFFING AND SAFETY

B-4.1 Staffing

The operating personnel were assigned to perform specific duties during the test series. The 24-hour operation required two 12-hour shifts, each with identical personnel assignments. Two persons composed the furnace tapping crew, and one person each was assigned to operate the feed system, furnace controls, APCS controls, gas chromatograph (GC), overhead crane, and fork lift. Each shift also included a sample manager, who was responsible for collecting, recording, and storing all process samples collected during the test series. A supervisor and an electrician were on duty at all times. Duties of the various operators are listed in Table B-2.

B-4.2 Safety

All personnel attending the furnace were required to wear protective clothing, respirators, gloves, boots, safety glasses, and hard hats. Face shields and reflective heat-resistant clothing were required of the tapping crew. Additional common sense measures were practiced, including maintaining a safe distance when not actually conducting a task.

Table B-2. Operating personnel assignments.

Assignment	Responsibilities
Weigher	Weighs and delivers materials to receiving bin. Keeps the Receiving Bin Log.
Feeder Operator	Operates the feeder and primary combustion air system and keeps the Feeder Log.
Furnace Operator	Operates the furnace and keeps the Furnace Log
APCS Operator	Operates the APCS.
Sample Manager	Collects or supervises the collection of all process samples and keeps the Electrode Log, APCS Solids Log, Glass and Metal Product Log, Test Log, and Melter Inventory Log; also doubles as the assistant Weigher.
Gas Chromatograph Operator	Operates the GC.
Lift Operator	Operates fork and barrel lifts to transfer feed materials to the receiving bin and glass and metal products to the storage area; doubles as the Weigher.
Crane and Tapping Crew	Operates the overhead crane and taps the furnace to remove glass and metal; keeps the Glass and Metal Product Log.

B-4.3 Air Quality Control

Escape of fumes into the furnace building was significantly decreased by withdrawing dilution air for the offgas quench system through hoods over the tapholes. The hood over the metal taphole was closed while tapping slag to maximize fume collection over the slag taphole. Similarly, the hood over the slag taphole was closed while tapping the metal side.

Air quality within the building was monitored by stationary, continuous ambient air samplers installed at the base of the metering bin platform. A reference sampler was installed in the control room. The monitors analyzed for Cl_2 , O_2 , and NO_2 , with immediate alarms if the threshold limit values for any species was exceeded. No alarms were sounded during the test series. The monitors recorded the gas analyses at 1-min intervals, with the files downloaded to a host computer at the start of each 12-hour shift. These files are stored in Quatro Pro 5.0 spreadsheets on one 3.5-in. 1.44-MB computer diskette.

Two 25-hp induced draft blowers were added to the building exhaust system for further assurance of air quality control within the melter building. These blowers were designed to exchange the building's air supply every 2 min, and were ducted to the atmosphere on the building's roof.

B-5. REFERENCES

Davis, H. F. Jr., (Consulting Metallurgical Engineer, 327 Sandalwood Court, Carnegie, PA 15106-1544), private communication, 1995, (available upon request from W. K. O'Connor, Bureau of Mines, 1450 Queen Ave., SW, Albany, OR 97321-2198).

Marley Cooling Tower Co., 1991, Marley Manual, series NC and NC Modular Steel Double-Flow Cooling towers, publication OM-NC1-A.

Miles, T. R., "Feed System Operations Manual 1991-92," (available upon request from W. K. O'Connor, Bureau of Mines, 1450 Queen Ave., SW, Albany, OR 97321-2198).

Appendix C

**Data Collection,
Sample Collection and Analysis**

Appendix C

Data Collection, Sample Collection and Analysis

C-1. OFFGAS MONITORING AND SAMPLING PROCEDURES

The offgas monitoring and sample collection for the demonstration tests included measurements to characterize the gaseous and particulate emissions from the furnace and APCS performance. Offgas measurements and sample collection were conducted by Entropy Incorporated, Argonne National Laboratory-East, and Clean Air Engineering. Measurements and sampling runs were conducted at various points in the furnace and APCS. Gaseous measurements included velocity, temperature, and continuous monitoring of gas composition [O_2 , CO, CO_2 , NO, NO_2 , SO_2 , total hydrocarbon (THC), and HCl]. These measurements were conducted according to EPA Methods 1, 2, 3A, 6C, 7E, 10, and 25A [49 Code of Federal Regulations (CFR) 60, 1990, Appendix A]. Gas temperature measurements in the furnace were conducted using a shielded thermocouple mounted in a suction pyrometer probe to minimize the effects of thermal radiation on the gas temperature measurement. Samples were also collected for HCl, Cl_2 , HF, and F_2 analysis using a modified EPA Method 26 procedure. Total particulate and metals determinations were done using the draft EPA Method 29, modified to include measurement of total particulate in addition to metals. Dioxin tests were conducted using EPA Method 23 at the baghouse outlet and at the stack.

The locations and times for the continuous monitoring and Fourier Transform Infrared (FTIR) measurements varied in order to obtain test data at different locations during the tests. Measurements in the furnace and at the furnace outlet were conducted to characterize furnace plenum and furnace outlet conditions. The performance of components in the APCS, including the thermal oxidizer, baghouse, acid gas scrubber, charcoal filter, and HEPA filter were evaluated by sampling at the baghouse outlet and at the stack.

Many different sample ports and locations were available for conducting the offgas measurements. Sample ports upstream of the ID fan were designed to minimize air leakage owing to the design negative pressure of 0.5-in WC in the furnace up to about 20-in. WC at the ID fan inlet. Minimizing air leakage reduced the amount of pressure and flowrate excursions in the furnace and APCS, improved worker safety, and minimized the potential for sampling leaked ambient air rather than process gas.

C-1.1 Subcontracted Measurements and Sampling

C-1.1.1 Continuous Monitoring Procedures

The continuous gaseous emissions monitoring was conducted according to EPA continuous monitoring methods using a continuous emissions monitoring system (CEMS) by Entropy Incorporated. Some modifications to the procedures were necessary in some cases to obtain the best quality data within the constraints of the sample locations and conditions. Variations included (a) use of less stringent $\pm 2\%$ calibration gases (for two of the calibration gases) rather than EPA protocol

gases specified in the methods, (b) sample periods of variable length or averages so that sample collection could coincide with melter system operating periods, and (c) use of calibration gases for measurements when the measured values were very low on the instrument range or on different instrument ranges. Other deviations are included in the following discussion.

Sample gas was continuously extracted using a sample probe and sampling and conditioning system. Following filtration and cooling to condense moisture and protect instrumentation, the sample was analyzed continuously for O₂, carbon monoxide, carbon dioxide, nitrogen oxides (occasionally including separate NO and NO₂), and sulfur dioxide. Total hydrocarbons were analyzed without cooling below about 250°F, to minimize condensation of hydrocarbons at lower temperatures. Gaseous hydrochloric acid was continuously monitored using an air dilution probe that cooled the sample by air dilution to prevent moisture and HCl condensation. Owing to difficulties related to using the air dilution probe at sample locations with high gas temperatures and high particulate loadings, continuous HCl measurements were performed only downstream of the baghouse.

Continuous sample extraction at the in-furnace and furnace outlet locations was accomplished using 0.75-in. heavy-wall quartz glass sample probes and 0.625-in. diameter Teflon™ sample lines to a heated filter. The extracted sample was diluted with ambient air downstream of the filter to maintain a fast CEMS response time, but allow a sampling rate of offgas to minimize particulate buildup on the heated filter. In this way, continuous sampling intervals of longer than a few minutes were possible at the high temperature, high particulate loading locations. Surgical tubing was used for the connection between the quartz probe and the Teflon™ sample line.

Continuous sample extraction downstream from the baghouse was conducted using a standard stainless steel sample probe and sampling system. The sample gas was filtered and cooled to remove moisture before introduction to the gas analyzers. Flow to each instrument was controlled using a sample gas manifold with individual control valves and flowmeters for each instrument. All fittings and sample lines were constructed of stainless steel, Teflon™, or other materials inert to the offgas. Leak checks, bias, residence time, interference, and sampling procedures were conducted according to the EPA reference procedures.

C-1.1.2 Metals and Particulate Sampling Procedures

Gaseous and particulate metals emissions were determined using the EPA multiple metals train (Draft EPA Method 29, October 29, 1990), modified to include measurement of total particulate in addition to metals. This procedure is modelled after the EPA Method 5 procedure (49 CFR 60, 1990, Appendix A) for determining total particulate emissions from stationary sources. Sampling and measurements were conducted by Entropy Incorporated.

The procedures for sampling at the furnace outlet location were modified somewhat owing to the physical constraints of the sample location and sample port. With only one port in the nominal 1-in.-diameter duct, sampling was conducted across only one diameter of the duct. The procedures in EPA Method 1A were followed for particulate sample traversing in small ducts. Six traverse points were used. The sample time was also typically abbreviated to 30 min or less owing to rapid buildup of particulate in the sample lines and on the filter. Because of the small port diameter and high gas temperatures, a straight, unsheathed, quartz glass sample probe was used, without a sharp-edged goose-necked nozzle. The front end of the probe was beveled at 45 degrees to make it more readily

accessible to particulate in the sample gas. Sample collection was not isokinetic, but generally constant at a very low flowrate to increase the sampling time. For simplicity, no more than one filter change was conducted per test run. To minimize air leakage around the probe during insertion and operation, a sealing gland with a fully ported ball valve was used. The tip of the probe was inserted in the sealing gland before opening the ball valve to ensure a seal at all times.

The Method 5/29 sampling at the stack complied with the procedures specified in Methods 5 and 29, modified to (a) exclude the impingers that contain absorbing solution (acidified potassium permanganate) for capturing mercury, (b) elimination of mercury analysis by cold vapor atomic absorption spectrometry, and (c) inclusion of gravimetric analysis of the train front half for solid particulate determination. Using the modified Method 5/29 procedure, an offgas sample was collected isokinetically from the offgas stream to obtain the most representative gaseous and entrained particulate sample. Using a heated, glass-lined sample probe with a sharp-edged glass nozzle, the duct was traversed during sample collection to minimize the effects of velocity and concentration stratification. The sample was passed through a filter heated to $250 \pm 25^{\circ}\text{F}$, which was used to capture particulate or aerosol material at that temperature. The filtered sample was then passed through a series of glass impingers that contain absorbing solution for capturing metals and other materials. The last impinger contained silica gel for complete drying of the gas sample. The impingers were placed in an ice bath to rapidly cool the gas sample, with the temperature of gas exiting the last impinger (silica gel) maintained at 68°F or less. The volume and sample rate of filtered, dried sample gas was controlled and monitored with a calibrated dry gas meter, sharp-edged orifice, and sample pump.

The stack Method 5/29 run was conducted during the C-20 feed mixture test condition, because that mixture had the highest concentrations of toxic metals and some chlorides. The sample time for this run was abbreviated to 125 min rather than the scheduled 4 h, with a single traverse, owing to operating time limitations for the C-20 feed mixture. A simultaneous furnace outlet Method 5/29 run would have been desirable for directly determining the APCS control efficiency for metals and particulate, but this was not possible with the available personnel and time constraints.

Following sample collection, the sample was quantitatively recovered from the inside of the nozzle and sample probe, filter housing, connecting glassware, and impingers. The front half of the sample train (from the probe nozzle to the filter) will undergo gravimetric analysis to determine the solid particulate levels in the offgas. The front and back halves (downstream of the filter, including the impinger catch) will be analyzed for the target metals and surrogate radionuclides by ion-coupled argon plasma spectroscopy or by graphite furnace atomic absorption spectroscopy.

Chemical reagents of the minimum purity and specifications identified in the Draft EPA Method 29 procedures were used for all sampling and analysis activities. All materials that contacted the sample were glass or other nonmetallic, noncontaminating material. All connections were leak free, ground glass fittings, or other noncontaminating materials, except for the probe-umbilical connection for the furnace outlet sampling, which was surgical tubing. All glassware and sample containers were carefully cleansed using the specified metals-free reagents and dried in a dust-free environment after cleaning.

C-1.1.3 High-Temperature Measurements

Accurate temperature measurements in the furnace plenum and thermal oxidizer inlet and outlet locations required the use of thermal radiation-shielded suction pyrometer measurement devices, also called high-velocity temperature measurement devices. The general procedure and typical equipment used for these types of measurements is described in Electric Power Research Institute (EPRI) CS-5552 (Sotter et al. 1988). The thermocouple tip was shielded from thermal radiation by a metal or ceramic sheath. The gas was drawn through the probe at a sufficiently high velocity that the convection heat transfer to the thermocouple was far greater than radiative heat transfer from the sheath or open end of the sheath, and also far greater than conductive heat transfer from the thermocouple to the water-cooled probe. The potential errors from radiative and conductive heat transfer were minimized relative to the convective heat transfer from the gas, enabling the thermocouple to more accurately sense the actual gas temperature.

Velocity measurements in the high-temperature regions were conducted using the same procedures specified for velocity measurements in the cooler regions, per EPA Method 2. The high levels of particulate upstream of the baghouse caused increased plugging, which was monitored and required frequent removal, especially if the particulate was at or above its melting temperature range.

C-1.1.4 Dioxin Measurements

Dioxin measurements were conducted at the baghouse outlet and at the stack to evaluate (a) the potential for forming dioxins upstream from the baghouse during cooldown from the thermal oxidizer, and (b) the ability of the downstream scrubber, charcoal filter, and HEPA filter to control and remove any such dioxins. Dioxin measurements followed EPA Method 23 procedures. Single sampling runs, each 4 hours long, were conducted at each location.

The Method 23 runs were conducted during the S-O feed mixture test condition, because that mixture contained the highest concentrations of chlorides and organics and represented a worst-case scenario for the furnace and APCS system.

C-1.2 Fourier Transform Infrared Analysis

Argonne National Laboratory and Clean Air Engineering conducted FTIR gaseous analysis at the furnace outlet, baghouse outlet, and stack. Species monitored included CO, CO₂, NO_x, SO₂, and various other polar chlorinated and nonchlorinated hydrocarbons. The draft FTIR sampling and analysis procedure that Argonne and Clean Air Engineering has submitted to the EPA was used for these measurements.

The furnace outlet FTIR run was conducted by diverting a portion of the sample from the Entropy CEMS probe, filter, and dilution system. A tee was inserted just downstream from the heated filter, so the FTIR used its own heated sample line. The FTIR sample was further diluted to ensure that the concentrations of some species did not exceed the concentration limitations of the instrument. Sample dilution was also required at the baghouse but not at the stack.

C-1.3 Gas Chromatograph Analysis

Speciated analysis of some gases was conducted using a Microtechnologies Inc. (MTI) Q300L GC, with three capillary columns and electrical conductivity detectors. Manufacturer information for the GC is listed in Table C-1.

Hydrogen can only be detected when Ar is the carrier gas, because H₂ and He have similar retention times on the molecular sieve column. Likewise, CO can only be detected using He carrier gas owing to similar retention times for CO and Ar. Quantitative measurements for Cl₂, HCl, NO, NO₂, and SO₂ cannot be obtained because these species are too reactive, except for very high concentrations of NO and SO₂. It was possible to detect aldehydes on the OV-1 column. High concentrations of acidic gases, especially HCl but also NO₂ and SO₂, can rapidly damage components of the GC; therefore, these species were scrubbed from the sample gas for all sample locations except those downstream from the acid gas scrubber. The sample gas from locations upstream from the baghouse was filtered and cooled below ambient temperature to prevent particulate or water droplets from entering the GC injector. A redundant Genie filter was included in the GC inlet for added protection.

The GC inlet filter system failed during the preheat tests, allowing moisture to infiltrate the instrument, damaging two of the detectors. Condensed moisture in the sample lines was not purged routinely, which led to an excessive build up of moisture that eventually defeated the inlet filter system. The GC was unavailable for the remainder of the tests.

C-1.4 Analytical Methods

Analytical results for the process samples will be used to (a) calculate mass balances, (b) calculate distribution and fate of metal and transuranic (TRU) surrogate elements in the feed, (c) determine the hazardous or nonhazardous character of the secondary process streams, and (d) evaluate the physical and chemical properties of the vitrified slag and metal phases.

Table C-1. Manufacturer specifications for the MTI gas chromatograph.

Column	Carrier gas	Detectable species
Molecular sieve 10-m long	He or Ar	He, H ₂ (with Ar carrier), CO, N ₂ , O ₂ (with He carrier), C ₁
Pora Plot Q, 4-m long	He or Ar	CO ₂ , C ₂ -C ₄
OV-1, 4-m long	He or Ar	CCl ₄ , trichlorethylene, several other halogenated hydrocarbons, and volatile organic compounds

Sample analyses will be conducted by the Albany Research Center analytical laboratory. Standard EPA-promulgated methods will be followed whenever possible. In all cases, the most applicable methods will be used to achieve the most accurate results with the lowest possible detection limits. Procedures not covered by standard EPA methodology will be based on extensive experience gained from several previous similar melting campaigns, including the BWID Phase 1 test program. Quality assurance (QA) activities specified by these methods typically include spikes, duplicates, and splits. However, analysis standards are not readily available for some elements; QA activities will be conducted only when standards are available.

C-2. REFERENCE

Sotter, J. G. et al., 1988, *Guidelines for Fireside Testing in Coal-Fired Power Plants*, EPRI CS-5522, Project 1891-3 Final Report, March.

Appendix D

**Operating Parameters
During Preheat Intervals**

Figure D-1. Input power to the furnace during the first preheat melt.

Figure D-2. Feedrate during the first preheat melt.

Figure D-3. Power input to the furnace during the second preheat melt.

Figure D-4. Feedrate during the second preheat melt.

Appendix E

**Operating Parameters
During the BWID Feed Interval**

Figure E-1. Power input to the furnace during the BWID feed interval.

Figure E-2. Feedrate during the BWID feed interval.

Figure E-3. Slag tap temperature during the BWID feed interval.

Figure E-4. Stack flowrate during the BWID feed interval.

Figure E-5. Temperatures from various points in the APCS during the BWID feed interval.

Appendix F

Operating Parameters During the IWPF and Cleanout Feed Intervals

Figure F-1. Input power to the furnace during the IWPF feed interval.

Figure F-2. Feedrate during the IWPF feed interval.

Figure F-3. Slag tap temperature during the IWPF and cleanout feed intervals.

Figure F-4. Stack flowrate during the IWPF and cleanout feed intervals.

Figure F-5. Temperatures from various points in the APCS.

Appendix G

Elemental Compositions of the Furnace Feeds and Products, by Feed Interval

Table G-1. Elemental composition of the preheat feed mixtures and furnace products.

Feed			
Element	Preheat interval		Total feed wt. mean
	Method B	TH + silica	
wt, lb	2,394	4,424	6,818
wt, pct	35.1	64.9	100
Ag	NA	NA	0.00
Al	47,500	126,090	98,495
As	NA	NA	0.00
Ba	30.0	NA	10.5
C	27,100	70,809	55,461
Ca	32,000	233,462	162,723
Cd	NA	NA	0.00
Ce	NA	NA	0.00
Cl	3,160	NA	1,110
Cr	30.0	NA	10.5
Cs	1,200	NA	421
Cu	NA	NA	0.00
F	2,580	NA	906
Fe	5,600	129	2,050
H	11,600	1,234	4,874
Hg	NA	NA	0.00
K	11,800	220	4,286
Mg	1,300	1,790	1,618
Mn	10.0	NA	3.51
Mo	900	NA	316
Na	136,300	446	48,148
Ni	NA	NA	0.00
O ^s	490,100	470,633	477,468
P	800	NA	281
Pb	NA	NA	0.00
S	800	NA	281
Se	NA	NA	0.00
Si	229,700	52,302	114,592
Ti	500	22,272	14,627
Zn	NA	NA	0.00
Zr	30.0	NA	10.5
Total	1,003,040	979,387	987,692

Element	Slag		Total slag wt. mean
	Method B	TH + silica	
	Preheat 1	Preheat 2	
wt, lb	2,114	3,458	5,572
wt, pct	37.9	62.1	100
Ag	NA	NA	0.00
Al	66,702	175,544	134,250
As	NA	NA	0.00
Ba	89.0	NA	33.8
C	204	NA	77.4
Ca	52,429	325,029	221,605
Cd	NA	NA	0.00
Ce	NA	NA	0.00
Cl	NA	NA	0.00
Cr	342	NA	130
Cs	413	NA	157
Cu	NA	NA	0.00
F	NA	NA	0.00
Fe+2	NA	NA	0.00
Fe+3	8,467	181	3,325
Hg	NA	NA	0.00
K	8,133	306	3,276
Mg	1,860	2,493	2,253
Mn	78.0	NA	29.6
Mo	523	NA	198
Na	120,178	622	45,981
Ni	9.00	NA	3.41
O ^s	436,869	392,002	409,024
P	524	NA	199
Pb	NA	NA	0.00
S+3	NA	NA	0.00
S+4	NA	NA	0.00
Se	NA	NA	0.00
Si	266,916	72,816	146,457
Ti	2,400	31,009	20,155
Zn	NA	NA	0.00
Zr	74.0	NA	28.1
Total	966,210	1,000,002	987,181

Element	APCS residues	
	Baghouse	
	Preheat Int.	
wt, lb	116	
wt, pct	100	
Ag	1.00	
Al	1,940	
As	76.0	
Ba	< 1	
C	21,800	
Ca	6,330	
Cd	5.00	
Ce	< 1	
Cl	125,000	
Cr	162	
Cs	8,780	
Cu		
F	1,970	
Fe	952	
H	9,111	
Hg	< 0.1	
K	38,400	
Mg	341	
Mn	34.0	
Mo	2,490	
Na	228,000	
Ni	1.00	
O ^s	342,759	
P	1,920	
Pb	190	
S	47,700	
Se	7.00	
Si	39,000	
Ti	28.0	
Zn		
Zr	1.00	
Total	876,998	

Table G-2. Elemental composition of the BWID feed mixtures (mg/kg).

Element	BWID feed interval							Total feed wt. mean
	Nom-90	Nom-80	Nom-70	Nom-60	Soil+lime	Nom-50	Nom-40	
wt. lb	1495	1497	3998	3976	500	1486	977	13929
wt. pct	10.7	10.7	28.7	28.5	3.6	10.7	7.0	100.0
Ag	1.2	1.1	0.99	0.89	1.28	0.78	0.66	1
Al	44500	43200	41600	39800	46490	37800	35500	40912
As	5.1	4.8	4.5	4.1	4.5	3.7	3.3	4
Ba	700	600	600	500	753	400	400	552
C	22300	37400	53500	70700	8520	89000	108400	59354
Ca	192300	172600	152800	133000	206995	113000	92900	147014
Cd	1.9	1.7	1.6	1.4	2	1.3	1.1	2
Ce	4200	3800	3400	3000	56	2600	2200	3125
Cl	5000	10300	16000	22100	34	28600	35500	18087
Cr	1600	3300	5100	7000	73	9000	11200	5737
Cs	7.2	6.7	6.1	5.5	7.8	4.8	4	6
Cu	500	900	1400	1900	51	2500	3100	1581
F	NA	NA	NA	NA	NA	NA	NA	NC
Fe	47000	70300	95200	121700	25967	149900	179700	104192
H	8200	10900	13800	17000	5721	20300	23800	14906
Hf	0.7	1.5	2.3	3.1	NA	4.1	5	3
Hg	0.093	0.085	0.078	0.069	0.09	0.06	0.051	0.1
K	13800	13700	13500	13200	14133	13000	12600	13374
Mg	11000	10400	9800	9100	11576	8300	7500	9536
Mn	600	600	600	700	632	700	800	654
Mo	33	69	100	100	NA	200	200	104
N	500	1000	1600	2300	NA	2900	3600	1839
Na	8700	9000	9200	9400	8632	9600	9800	9246
Ni	800	1600	2400	3300	36	4300	5400	2727
O	438300	421600	403300	383300	458174	361600	338300	396276
P	600	500	500	400	597	400	300	461
Pb	200	300	500	600	17	800	1000	525
S	200	200	300	300	129	300	400	279
Sb	NA	NA	NA	NA	NA	NA	NA	NC
Se	1.2	1.1	0.99	0.89	0.61	0.78	0.66	1
Si	194300	182200	168600	153500	208438	136800	118600	163040
Ti	2600	2400	2200	2000	2855	1700	1400	2121
Zn	87	81	74	66	94	58	48	71
Zr	700	1400	2200	3000	102	3800	4700	2452
Totals	998737	998367	998291	997982	1000091	997574	997363	998182

NA: not analyzed

NC: not calculated

Table G-3. Elemental composition of the BWID product slags (mg/kg).

Elements	BWID feed interval														BWID slag wt. mean
	SP1	SP2	SP3	SP4	SP5	SP6	SP7	SP8	SP9	SP10a	SP10c	SP11a	SP11f	SP11j	
wt, lb	776	840	764	800	812	836	720	822	754	1194	200	228	228	228	9202
wt, pct	8.43	9.13	8.30	8.69	8.82	9.08	7.82	8.93	8.19	12.98	2.17	2.48	2.48	2.48	100.00
Ag	NA	<0.5	NA	<0.5	NA	<0.5	NA	<0.5	<0.5	NA	<0.5	<0.5	<0.5	<0.5	<0.5
Al	101000	73800	74700	71300	63500	62800	59700	65400	66800	65900	65100	70300	65300	62300	69819
As	NA	<5	NA	<5	NA	<5	NA	<5	<5	NA	<5	<5	<5	<5	<5
Ba	NA	400	NA	485	NA	643	NA	658	647	NA	700	732	631	506	310
C	NA	241	NA	245	NA	350	NA	314	193	NA	400	1450	3550	1140	280
Ca	210000	217000	215000	216000	209000	218000	222000	225000	208000	204000	219000	213000	274000	294000	217488
Cd	NA	<0.1	NA	<0.1	NA	<0.1	NA	<0.1	<0.1	NA	<0.1	<0.1	<0.1	<0.1	<0.1
Ce	1080	3500	2930	2890	4320	3840	4800	4310	3920	4850	2960	3450	4060	4680	3713
Cl	NA	18	NA	37	NA	86	NA	83	100	NA	90	43	240	350	46
Cr	NA	540	NA	581	NA	367	NA	138	207	NA	72	99	58	21	168
Cs	NA	18	NA	10	NA	6	NA	<3	<3	NA	<3	<3	<3	<3	3
Cu	NA	50	NA	51	NA	36	NA	34	34	NA	32	32	28	28	21
F	NA	7	NA	7	NA	5	NA	7	9	NA	8	8	6	2	4
Fe+2	11600	24000	17700	16100	7100	7800	4700	4000	8000	3300	3600	5400	5400	7800	9721
Fe+3	NA	2300	NA	0	NA	0	NA	0	0	NA	0	0	0	0	210
Hg	NA	<0.1	NA	<0.1	NA	<0.1	NA	<0.1	<0.1	NA	<0.1	<0.1	<0.1	<0.1	<0.1
K	4550	8200	7210	8380	8530	8360	7130	6010	4450	4430	3400	1700	776	745	6160
Mg	4780	8810	8990	10800	12000	12700	13000	13900	14400	14100	14200	14700	13700	12200	11688
Mn	NA	407	NA	560	NA	706	NA	554	517	NA	464	480	265	134	274
Mo	NA	32	NA	5	NA	3	NA	3	3	NA	2	3	3	4	4
Na	10800	7870	7250	8200	8420	8430	8140	6710	5190	5160	3810	2900	1470	1570	7014
Ni	NA	15	NA	9	NA	9	NA	9	8	0	26	10	8	10	6
O	418281	425192	402117	426503	407861	423310	408190	426865	425650	409823	417934	417072	429735	421723	417637
P	NA	380	NA	76	NA	150	NA	170	39	NA	74	82	92	35	80
Pb	NA	7	NA	8	NA	2	NA	<2	<2	NA	2	<2	<2	<2	2
S+3	NA	190	NA	320	NA	410	NA	450	420	NA	380	380	290	320	190
S+4	NA	20	NA	9	NA	10	NA	9	12	NA	16	8	6	9	6
Se	NA	<3	NA	<3	NA	<3	NA	<3	<3	NA	<3	<3	<3	<3	<3
Si	204000	216000	205000	222000	221000	226000	220000	226000	230000	224000	222000	216000	207000	202000	218898
Ti	NA	7790	NA	5850	NA	4000	NA	3400	3250	NA	2690	3050	2270	2150	2397
Zn	NA	21	NA	13	NA	9	NA	6	20	NA	14	53	17	16	8
Zr	NA	718	NA	1710	NA	3640	NA	4550	3960	NA	5760	7100	5450	3150	1790
Totals	966091	997526	940896	992150	941731	981672	947660	988580	975828	935563	962734	958053	1014357	1014895	967937

NA: not analyzed

Table G-4. Elemental composition of the BWID APCS residues (mg/kg).

Elements	Cyclone Nom-60	Baghouse Nom-90	Baghouse Nom-60	Thermal Ox. Post test	Ductwork Post test	Cyclone Post test	Baghouse Post test	APCS Residues wt. mean
wt. lb	93	126	90	200	108	13	602	1234
wt. pct	7.6	10.2	7.3	16.2	8.8	1.1	48.8	100.0
Ag	1	1	2	<0.5	<3	1	2	1
Al	11750	2840	1360	79700	8810	38000	7460	19048
As	27	33	14	26	1	13	23	22
Ba	448	16	53	379	117	484	347	286
C	13225	31800	2420	685	18200	32700	9290	11024
Ca	162000	57500	52300	214000	82400	192000	96200	112956
Cd	3	6	7	0.7	36	162	144	77
Ce	22	2	5	84	5	7	140	85
Cl	62050	21300	255000	160	91500	40600	216000	139427
Cr	88	164	126	298	84	54	49	113
Cs	1718	81	1750	23	34	81	1030	776
Cu	121	174	426	93	129	107	295	230
F	545	1410	590	58	1400	1190	260	501
Fe	9575	2290	5780	11800	12100	18800	9900	9393
H	4228	5977	3633	NA	1117	17700	6867	4837
Hf	NA	NA	NA	NA	NA	NA	NA	NC
Hg	<0.1	<0.1	0.30	<0.1	<0.1	<0.1	0.40	0.2
K	38550	42200	17100	14800	32400	38400	67000	46832
Mg	9430	1010	2950	13900	4860	14400	11900	9678
Mn	724	79	1040	395	307	496	898	674
Mo	639	1460	268	73	1470	10	175	444
N	NA	NA	NA	NA	NA	NA	NA	NC
Na	80250	206000	113000	27700	150000	16700	61600	83311
Ni	15	12	11	106	10	23	16	29
O	376000	362570	315403	400348	298000	545000	360000	361319
P	645	1860	740	940	1460	780	640	895
Pb	932	715	6440	430	4170	5730	7950	4992
S	7600	26300	13150	670	24100	1060	3500	8171
Sb	NA	NA	NA	NA	NA	NA	NA	NC
Se	3	4	<3	<3	1420	<3	<3	125
Si	151650	70000	130000	185000	83000	153000	167000	148607
Ti	454	114	49	3830	274	174	92	742
Zn	533	1240	1310	414	851	363	1300	1043
Zr	6	1	1	81	5	9	17	23
Totals	933229	837159	924928	955993	818260	1118044	1030095	965661

NA: not analyzed

NC: not calculated

Table G-5. Elemental composition of the IWPF feed mixtures (mg/kg).

Element	IWPF feed interval				Total feed wt. mean
	S-40	S-0	C-20	C-40	
wt. lb	1594	1098	300	497	3489
wt. pct	45.7	31.5	8.6	14.2	100.0
Ag	1	0.81	0.33	0.6	1
Al	23400	4000	21900	29700	18063
As	4.5	3.8	1.7	2.8	4
Ba	400	20	200	400	263
C	181200	323000	396400	282900	258816
Ca	147300	105600	48700	88800	117366
Cd	1.6	1.3	300	200	55
Ce	2900	1700	1200	800	2077
Cl	122500	223000	33700	23800	132433
Cr	38	9.7	300	200	75
Cs	4.4	1.5	2.1	3.9	3
Cu	25	4	2800	2000	538
F	NA	NA	200	200	46
Fe	13800	3600	24600	25300	13157
H	28700	47600	68700	50300	41164
Hf	NA	NA	NA	NA	NA
Hg	0.067	0.041	0.026	0.048	0.05
K	690	800	3700	6900	1868
Mg	6300	1900	4900	6900	4880
Mn	200	0	200	300	151
Mo	NA	NA	NA	NA	NC
N	500	900	1000	700	697
Na	5600	3000	2600	4500	4367
Ni	23	11	100	100	37
O	311700	191900	312000	356600	280420
P	300	95	200	300	227
Pb	8.7	1.3	9800	6900	1830
S	500	700	1000	700	634
Sb	NA	NA	NA	NA	NC
Se	1	0.81	0.33	0.6	1
Si	144700	89900	60800	107100	114884
Ti	1400	200	800	1500	985
Zn	51	14	3600	2500	693
Zr	51	9.1	27	50	36
Totals	992299	997972	999731	999658	995772

NA: not analyzed

NC: not calculated

Table G-6. Elemental composition of the IWPF product slags (mg/kg).

Elements	IWPF feed interval		IWPF slag wt. mean
	SP12a	SP12d	
wt, lb	417	417	834
wt, pct	50.00	50.00	100.00
Ag	<0.5	NA	<0.5
Al	60800	43600	52200
As	<5	NA	<5
Ba	186	NA	93
C	6890	NA	3445
Ca	372000	410000	391000
Cd	<0.1	NA	<0.1
Ce	5400	3670	4535
Cl	440	NA	220
Cr	3	NA	2
Cs	<3	NA	<3
Cu	33	NA	16
F	6	NA	3
Fe+2	5300	1400	3350
Fe+3	0	NA	0
Hg	<0.1	NA	<0.1
K	34	50	42
Mg	1505	1130	1318
Mn	3	NA	2
Mo	3	NA	1
Na	1540	165	852
Ni	5	NA	2
O	398112	347275	372694
P	96	NA	48
Pb	<2	NA	<2
S+3	560	NA	280
S+4	7	NA	3
Se	<3	NA	<3
Si	150000	125000	137500
Ti	420	NA	210
Zn	8	NA	4
Zr	1258	NA	629
Totals	1004608	932289	968449

NA: not analyzed

Table G-7. Elemental composition of the IWPF APCS residues (mg/kg).

Elements	Cyclone S-40	Cyclone S-0	Thermal Ox. Post test	Ductwork Post test	Cyclone Post test	Baghouse Post test	APCS Residues wt. mean
wt, lb	39	106	36	19	2	107	309
wt, pct	12.5	34.4	11.5	6.2	0.8	34.6	100.0
Ag	<0.5	<0.5	<0.5	<3	1	2	1
Al	10700	18200	79700	8810	38000	7460	20194
As	18	7	26	1	13	23	16
Ba	816	425	379	117	484	347	423
C	2450	9220	685	18200	32700	9290	8153
Ca	142000	182000	214000	82400	192000	96200	144902
Cd	2	1	0.7	36	162	144	54
Ce	20	26	84	5	7	140	70
Cl	44500	28000	160	91500	40600	216000	95888
Cr	43	25	298	84	54	49	71
Cs	115	49	23	34	81	1030	393
Cu	107	117	93	129	107	295	175
F	850	380	58	1400	1190	260	430
Fe	10400	3950	11800	12100	18800	9900	8338
H	4400	7322	NA	1117	17700	6867	5650
Hf	NA	NA	NA	NA	NA	NA	NC
Hg	<0.1	<0.1	<0.1	<0.1	<0.1	0.40	0.1
K	33200	6060	14800	32400	38400	67000	33413
Mg	13000	11900	13900	4860	14400	11900	11849
Mn	1180	175	395	307	496	898	587
Mo	27	11	73	1470	10	175	168
N	NA	NA	NA	NA	NA	NA	NC
Na	35500	12900	27700	150000	16700	61600	42820
Ni	14	12	106	10	23	16	24
O	422955	475717	400348	298000	545000	360000	409922
P	1140	320	940	1460	780	640	679
Pb	674	90	430	4170	5730	7950	3216
S	1100	756	670	24100	1060.0	3500	3192
Sb	NA	NA	NA	NA	NA	NA	NC
Se	5	<3	<3	1420	<3	<3	89
Si	245000	252000	185000	83000	153000	167000	202766
Ti	472	99	3830	274	174	92	584
Zn	363	396	414	851	363	1300	734
Zr	3	3	81	5	9	17	17
Totals	971054	1010161	955993	818260	1118044	1030095	994816

NA: not analyzed

NC: not calculated

Table G-8. Elemental composition of the cleanout feed mixture and furnace products.

Feed		Slag					APCS residues					
Element	Clean. int. Nom-90M	Element	Cleanout feed interval			Total slag wt. mean	Element	Thermal Ox. Post test	Ductwork Post test	Cyclone Post test	Baghouse Post test	APCS res. wt. mean
wt, lb	3,286	wt, lb	SP13	SP14	SP15		wt, lb					
wt, pct	100	wt, pct					wt, pct					
Ag	1.00	Ag	NA	NA	NA	0.00	Ag	0.50	3.00	1.00	2.00	1.78
Al	39,135	Al	47,591	47,591	47,591	47,591	Al	79,700	8,810	38,000	7,460	23,728
As	4.00	As	NA	NA	NA	0.00	As	26.0	1.00	13.0	23.0	20.9
Ba	633	Ba	NA	NA	NA	0.00	Ba	379	117	484	347	329
C	7,314	C	NA	NA	NA	0.00	C	685	18,200	32,700	9,290	8,806
Ca	218,571	Ca	248,000	248,000	248,000	248,000	Ca	214,000	82,400	192,000	96,200	121,518
Cd	2.00	Cd	NA	NA	NA	0.00	Cd	0.70	36.0	162	144	101
Ce	47.0	Ce	221	221	221	221	Ce	84.0	5.00	7.00	140	110
Cl	31.0	Cl	NA	NA	NA	0.00	Cl	160	91,500	40,600	216,000	152,058
Cr	140	Cr	NA	NA	NA	0.00	Cr	298	84.0	54.0	49.0	107
Cs	7.00	Cs	NA	NA	NA	0.00	Cs	23.0	34.0	81.0	1,030	681
Cu	280	Cu	NA	NA	NA	0.00	Cu	93.0	129	107	295	229
F	NA	F	NA	NA	NA	0.00	F	58.0	1,400	1,190	260	363
Fe	87,568	Fe+2	NA	NA	NA	0.00	Fe	11,800	12,100	18,800	9,900	10,699
H	5,202	Fe+3	19,594	19,594	19,594	19,594	H	NA	6,688	17,700	6,867	5,513
Hg	0.10	Hg	NA	NA	NA	0.00	Hg	0.10	0.10	0.10	0.40	0.30
K	11,910	K	10,456	10,456	10,456	10,456	K	14,800	32,400	38,400	67,000	51,209
Mg	10,238	Mg	9,898	9,898	9,898	9,898	Mg	13,900	4,860	14,400	11,900	11,545
Mn	1,025	Mn	NA	NA	NA	0.00	Mn	395	307	496	898	714
Mo	NA	Mo	NA	NA	NA	0.00	Mo	73.0	1,470	10.0	175	302
Na	7,272	Na	5,119	5,119	5,119	5,119	Na	27,700	150,000	16,700	61,600	63,958
Ni	168	Ni	NA	NA	NA	0.00	Ni	106	10.0	23.0	16.0	34.9
O ^s	432,083	O ^s	406,188	406,188	406,188	406,188	O ^s	400,348	343,020	544,957	360,409	369,702
P	524	P	NA	NA	NA	0.00	P	940	1,460	780	640	803
Pb	15.0	Pb	< 2	< 2	< 2	0.00	Pb	430	4,170	5,730	7,950	5,844
S	111	S+3	NA	NA	NA	0.00	S	670	24,100	1,060	3,500	5,265
Se	1.00	S+4	NA	NA	NA	0.00	Se	3.00	1,420	3.00	3.00	169
Si	175,650	Se	NA	NA	NA	0.00	Si	185,000	83,000	153,000	167,000	160,857
Ti	2,399	Si	214,979	214,979	214,979	214,979	Ti	3,830	274	174	92.0	925
Zn	79.0	Ti	NA	NA	NA	0.00	Zn	414	851	363	1,300	1,042
Zr	85.0	Zn	NA	NA	NA	0.00	Zr	81.0	5.00	9.00	17.0	29.4
Total	1,000,495	Zr	NA	NA	NA	0.00	Total	955,997	868,854	1,118,004	1,030,507	996,666
		Total	962,046	962,046	962,046	962,046						

Appendix H

**Elemental Mass Balance
Over the Furnace**

Table H-1. Global elemental mass balance, assuming concentrations below detection limits to be zero (wt mean concentrations in mg/kg).

	Feed		Slag			Metal			APCS residues			Total products
wt, lb	27520		18412			1826			1885			22123
wt, pct	100.0		83.2			8.3			8.5			100.0
Element	wt. mean	wt., lb	wt. mean	wt., lb	dist., pct	wt. mean	wt., lb	dist., pct	wt. mean	wt., lb	dist., pct	Closure, pct
Ag	1	0.02	<0.5	0.00	0.00	0.4	0.001	3.27	1	0.002	10.70	14.0
Al	52069	1433	85135	1567	109.39	210	0.4	0.03	18746	35	2.47	111.9
As	3	0.09	<5	0.00	0.00	101	0.18	212.90	24	0.05	52.96	265.9
Ba	391	11	170	3	29.02	16	0.03	0.27	296	0.6	5.18	34.5
C	77468	2132	319	6	0.28	47625	87	4.08	10949	21	0.97	5.3
Ca	155686	4284	231240	4258	99.37	NC	NC	NC	112671	212	4.96	104.3
Cd	8	0.22	<0.1	0.00	0.00	<0.1	0.00	0.00	71	0.1	60.96	61.0
Ce	1851	51	2095	39	75.71	<1	0.00	0.00	80	0.2	0.30	76.0
Cl	26223	722	33	0.61	0.08	NC	NC	NC	132914	251	34.72	34.8
Cr	2932	81	124	2.28	2.82	40488	74	91.61	108	0.2	0.25	94.7
Cs	109	3	49	0.90	30.18	<3	0.00	0.00	1194	2	75.31	105.5
Cu	902	25	11	0.2	0.83	14065	26	103.50	207	0.4	1.57	105.9
F	230	6	2	0.04	0.57	NC	NC	NC	563	1	16.75	17.3
Fe	65361	1799	9105	168	9.32	850096	1552	86.30	8858	17	0.93	96.5
H	14591	402	NC	NC	NC	NC	NC	NC	5691	11	2.67	2.7
Hf	1	0.04	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Hg	0.1	0.001	<0.1	0.00	0.00	<0.1	0.00	0.00	0.2	0.0004	24.83	24.8
K	9489	261	5664	104	39.93	NC	NC	NC	44638	84	32.22	72.2
Mg	7068	195	8090	149	76.58	NC	NC	NC	9684	18	9.39	86.0
Mn	474	13	146	3	20.59	5223	10	73.18	625	1.2	9.04	102.8
Mo	131	4	62	1	31.89	2263	4	114.88	507	1	26.57	173.3
N	1019	28	NC	NC	NC	NC	NC	NC	NC	NC	NC	0.0
Na	18030	496	18239	336	67.68	NC	NC	NC	83240	157	31.62	99.3
Ni	1405	39	4	0.07	0.19	15364	28	72.55	27	0.05	0.13	72.9
O	405976	11172	411251	7572	67.77	NC	NC	NC	372347	702	6.28	74.1
P	394	11	102	2	17.37	4262	8	71.73	911	2	15.83	104.9
Pb	499	14	1	0.01	0.10	512	1	6.80	4508	8	61.84	68.7
S	305	8	111	2.04	24.34	655	1	14.27	9435	18	212.13	250.7
Se	1	0.02	<3	0.00	0.00	<3	0.00	0.00	117	0.22	1237.77	1237.8
Si	146437	4030	192691	3547.83	88.04	60977	111	2.76	152224	287	7.12	97.9
Ti	5109	141	7307	134.53	95.69	2333	4	3.03	695	1.3	0.93	99.6
Zn	133	4	4	0.08	2.20	NC	NC	NC	928	2	47.69	49.9
Zr	1258	35	932	17.15	49.53	190	0.3	1.00	21	0.040	0.12	50.6
Totals	995554	27398	972887	17913		1044380	1907		972280	1833		

Table H-2. Global elemental mass balance, assuming concentrations below detection limits to be at the detection limit (wt mean concentrations in mg/kg).

	Feed		Slag			Metal			APCS residues			Total products
wt, lb	27520		18412			1826			1885			22123
wt, pct	100.0		83.2			8.3			8.5			100.0
Element	wt. mean	wt., lb	wt. mean	wt., lb	dist., pct	wt. mean	wt., lb	dist., pct	wt. mean	wt., lb	dist., pct	Closure, pct
Ag	1	0.02	0.5	0.01	45.74	0.4	0.001	3.27	1	0.002	10.70	59.7
Al	52069	1433	85135	1567	109.39	210	0.4	0.03	18746	35	2.47	111.9
As	3	0.09	5	0.09	106.70	101	0.18	212.90	24	0.05	52.96	372.6
Ba	391	11	170	3	29.02	16	0.03	0.27	296	0.6	5.18	34.5
C	77468	2132	319	6	0.28	47625	87	4.08	10949	21	0.97	5.3
Ca	155686	4284	231240	4258	99.37	NC	NC	NC	112671	212	4.96	104.3
Cd	8	0.22	0.1	0.002	0.83	0.1	0.0002	0.08	71	0.1	60.96	61.9
Ce	1851	51	2095	39	75.71	1	0.002	0.004	80	0.2	0.30	76.0
Cl	26223	722	33	0.61	0.08	NC	NC	NC	132914	251	34.72	34.8
Cr	2932	81	124	2.28	2.82	40488	74	91.61	108	0.2	0.25	94.7
Cs	109	3	49	0.90	30.18	3	0.01	0.18	1194	2	75.31	105.7
Cu	902	25	11	0.2	0.83	14065	26	103.50	207	0.4	1.57	105.9
F	230	6	2	0.04	0.57	NC	NC	NC	563	1	16.75	17.3
Fe	65361	1799	9105	168	9.32	850096	1552	86.30	8858	17	0.93	96.5
H	14591	402	NC	NC	NC	NC	NC	NC	5691	11	2.67	2.7
Hf	1	0.04	NC	NC	NC	NC	NC	NC	NC	NC	NC	0.0
Hg	0.1	0.001	0.1	0.002	123.70	0.1	0.0002	12.27	0.2	0.0004	24.83	160.8
K	9489	261	5664	104	39.93	NC	NC	NC	44638	84	32.22	72.2
Mg	7068	195	8090	149	76.58	NC	NC	NC	9684	18	9.39	86.0
Mn	474	13	146	3	20.59	5223	10	73.18	625	1.2	9.04	102.8
Mo	131	4	62	1	31.89	2263	4	114.88	507	1	26.57	173.3
N	1019	28	NC	NC	NC	NC	NC	NC	NC	NC	NC	0.0
Na	18030	496	18239	336	67.68	NC	NC	NC	83240	157	31.62	99.3
Ni	1405	39	4	0.07	0.19	15364	28	72.55	27	0.05	0.13	72.9
O	405976	11172	411251	7572	67.77	NC	NC	NC	372347	702	6.28	74.1
P	394	11	102	2	17.37	4262	8	71.73	911	2	15.83	104.9
Pb	499	14	1	0.01	0.10	512	1	6.80	4508	8	61.84	68.7
S	305	8	111	2	24.34	655	1	14.27	9435	18	212.13	250.7
Se	1	0.02	3	0.06	310.13	3	0.01	30.76	117	0.22	1237.77	1578.7
Si	146437	4030	192691	3548	88.04	60977	111	2.76	152224	287	7.12	97.9
Ti	5109	141	7307	135	95.69	2333	4	3.03	695	1.3	0.93	99.6
Zn	133	4	4	0.1	2.20	NC	NC	NC	928	2	47.69	49.9
Zr	1258	35	932	17	49.53	190	0.3	1.00	21	0.040	0.12	50.6
Totals	995554	27398	972895	17913		1044387	1907		972280	1833		

Table H-3. Elemental mass balance during the BWID feed interval, assuming concentrations below detection limits to be zero (wt mean concentrations in mg/kg).

Element	Feed			Slag			Metal			APCS residues		
	wt, lb	wt, mean	wt., lb	wt. mean	wt., lb	dist., pct	wt. mean	wt., lb	dist., pct	wt. mean	wt., lb	dist., pct
Ag	1	1	0.01	<0.5	0.00	0.00	<0.5	0.00	0.00	1	0.002	11.38
Al	40912	570	570	69819	642	112.74	205	0.3	0.05	19048	23	4.12
As	4	0.1	0.1	<5	0.0	0.00	106	0.1	249.32	22	0.03	45.39
Ba	552	8	8	310	3	37.13	18	0.03	0.33	286	0.4	4.58
C	59354	827	827	280	3	0.31	33400	47	5.71	11024	14	1.64
Ca	147014	2048	2048	217488	2001	97.73	NC	NC	NC	112956	139	6.80
Cd	2	0.02	0.02	<0.1	0.00	0.00	<0.1	0.00	0.00	77	0.1	442.47
Ce	3125	44	44	3713	34	78.48	<1	0	0.00	85	0.1	0.24
Cl	18087	252	252	46	0.4	0.17	NC	NC	NC	139427	172	68.24
Cr	5737	80	80	168	2	1.94	46700	66	82.58	113	0.1	0.17
Cs	6	0.1	0.1	3	0.0	34.61	<3	0.0	0.00	776	1.0	1167.50
Cu	1581	22	22	21	0.2	0.87	13300	19	85.36	230	0.3	1.29
F	NC	NC	NC	4	0.03	NC	NC	NC	NC	501	1	NC
Fe	104192	1451	1451	9931	91	6.30	860000	1215	83.73	9393	12	0.80
H	14906	208	208	NC	NC	NC	NC	NC	NC	4837	6	2.87
Hf	3	0.04	0.04	NC	NC	NC	NC	NC	NC	NC	NC	NC
Hg	0.1	0.001	0.001	<0.1	0	0.00	<0.1	0	0.00	0.2	0.0003	25.83
K	13374	186	186	6160	57	30.43	NC	NC	NC	46832	58	31.00
Mg	9536	133	133	11688	108	80.97	NC	NC	NC	9678	12	8.98
Mn	654	9	9	274	3	27.63	5520	8	85.57	674	0.8	9.11
Mo	104	1	1	4	0.04	2.85	3060	4	299.72	444	0.5	37.91
N	1839	26	26	NC	NC	NC	NC	NC	NC	NC	NC	NC
Na	9246	129	129	7014	65	50.11	NC	NC	NC	83311	103	79.76
Ni	2727	38	38	6	0.1	0.14	17300	24	64.34	29	0.04	0.10
O	396276	5520	5520	417637	3843	69.62	NC	NC	NC	361319	446	8.07
P	461	6	6	80	1	11.48	4780	7	105.19	895	1	17.18
Pb	525	7	7	2	0.01	0.20	509	1	9.84	4992	6	84.23
S	279	4	4	196	2	46.35	700	1	25.42	8171	10	258.88
Se	1	0.01	0.01	<3	0.00	0.00	<3	0.00	0.00	125	0.15	1183.58
Si	163040	2271	2271	218898	2014	88.70	40900	58	2.54	148607	183	8.07
Ti	2121	30	30	2397	22	74.64	2540	4	12.15	742	0.9	3.10
Zn	71	1	1	8	0.1	7.84	NC	NC	NC	1043	1	129.97
Zr	2452	34	34	1790	16	48.23	113	0.2	0.47	23	0.028	0.08
Totals	998182	13904	13904	967937	8907		1029151	1454		965661	1191	

NC: not calculated

Table H-4. Elemental mass balance assuming concentrations below detection limits to be at the detection limit (wt mean concentrations in mg/kg).

	Feed		Slag			Metal			APCS residues			Total products
wt, lb	13929		9202			1413			1233			11848
wt, pct	100.0		77.7			11.9			10.4			100.0
Element	wt. mean	wt., lb	wt. mean	wt., lb	dist., pct	wt. mean	wt., lb	dist., pct	wt. mean	wt., lb	dist., pct	Closure, pct
Ag	1	0.01	0.5	0.005	34.38	0.5	0.001	5.28	1	0.002	11.38	51.0
Al	40912	570	69819	642	112.74	205	0.3	0.05	19048	23	4.12	116.9
As	4	0.1	5	0.0	76.59	106	0.1	249.32	22	0.03	45.39	371.3
Ba	552	8	310	3	37.13	18	0.03	0.33	286	0.4	4.58	42.0
C	59354	827	280	3	0.31	33400	47	5.71	11024	14	1.64	7.7
Ca	147014	2048	217488	2001	97.73	NC	NC	NC	112956	139	6.80	104.5
Cd	2	0.02	0.1	0.001	4.31	0.1	0.0001	0.66	77	0.1	442.47	447.4
Ce	3125	44	3713	34	78.48	1	0.001	0.003	85	0.1	0.24	78.7
Cl	18087	252	46	0.4	0.17	NC	NC	NC	139427	172	68.24	68.4
Cr	5737	80	168	2	1.94	46700	66	82.58	113	0.1	0.17	84.7
Cs	6	0.1	3	0.0	34.61	3	0.004	5.17	776	1.0	1167.50	1207.3
Cu	1581	22	21	0.2	0.87	13300	19	85.36	230	0.3	1.29	87.5
F	NC	NC	4	0.03	NC	NC	NC	NC	501	1	NC	NC
Fe	104192	1451	9931	91	6.30	860000	1215	83.73	9393	12	0.80	90.8
H	14906	208	NC	NC	NC	NC	NC	NC	4837	6	2.87	2.9
Hf	3	0.04	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Hg	0.1	0.001	0.1	0.001	88.78	0.1	0.0001	13.63	0.2	0.0003	25.83	128.2
K	13374	186	6160	57	30.43	NC	NC	NC	46832	58	31.00	61.4
Mg	9536	133	11688	108	80.97	NC	NC	NC	9678	12	8.98	90.0
Mn	654	9	274	3	27.63	5520	8	85.57	674	0.8	9.11	122.3
Mo	104	1	4	0.04	2.85	3060	4	299.72	444	0.5	37.91	340.5
N	1839	26	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Na	9246	129	7014	65	50.11	NC	NC	NC	83311	103	79.76	129.9
Ni	2727	38	6	0.1	0.14	17300	24	64.34	29	0.04	0.10	64.6
O	396276	5520	417637	3843	69.62	NC	NC	NC	361319	446	8.07	77.7
P	461	6	80	1	11.48	4780	7	105.19	895	1	17.18	133.8
Pb	525	7	2	0.01	0.20	509	1	9.84	4992	6	84.23	94.3
S	279	4	196	2	46.35	700	1	25.42	8171	10	258.88	330.6
Se	1	0.01	3	0.03	211.60	3	0.004	32.49	125	0.15	1183.58	1427.7
Si	163040	2271	218898	2014	88.70	40900	58	2.54	148607	183	8.07	99.3
Ti	2121	30	2397	22	74.64	2540	4	12.15	742	0.9	3.10	89.9
Zn	71	1	8	0.1	7.84	NC	NC	NC	1043	1	129.97	137.8
Zr	2452	34	1790	16	48.23	113	0.2	0.47	23	0.028	0.08	48.8
Totals	998182	13904	967945	8907		1029159	1454		965661	1191		

NC: not calculated

Table H-5. Elemental mass balance during the IWPF feed interval, assuming concentrations below detection limits to be zero (wt mean concentrations in mg/kg).

	Feed		Slag			Metal			APCS residues			
wt, lb	3489		834			11			309			1154
wt, pct	100.0		72.3			1.0			26.8			100.0
Element	wt. mean	wt., lb	wt. mean	wt., lb	dist., pct	wt. mean	wt., lb	dist., pct	wt. mean	wt., lb	dist., pct	Closure, pct
Ag	1	0.003	<0.5	0.00	0.00	1	0.00001	0.31	1	0.0002	7.49	7.8
Al	18063	63	52200	44	69.08	215	0.002	0.00	20194	6	9.90	79.0
As	4	0.01	<5	0.0	0.00	94	0.001	7.81	16	0.005	36.78	44.6
Ba	263	1	93	0.1	8.43	13	0.0001	0.02	423	0.13	14.23	22.7
C	258816	903	3445	3	0.32	65000	1	0.08	8153	3	0.28	0.7
Ca	117366	409	391000	326	79.63	NC	NC	NC	144902	45	10.93	90.6
Cd	55	0.19	<0.1	0.00	0.00	<0.1	0.00	0.00	54	0.02	8.61	8.6
Ce	2077	7	4535	4	52.19	<1	0	0.00	70	0.02	0.30	52.5
Cl	132433	462	220	0.2	0.04	NC	NC	NC	95888	30	6.41	6.5
Cr	75	0.3	2	0.001	0.55	32900	0.4	138.86	71	0.02	8.40	147.8
Cs	3	0.01	<3	0.0	0.00	<3	0.0	0.00	393	0.1	1080.52	1080.5
Cu	538	2	16	0.01	0.73	15000	0.2	8.78	175	0.1	2.88	12.4
F	46	0.2	3	0.003	1.57	NC	NC	NC	430	0.1	83.35	84.9
Fe	13157	46	3350	3	6.09	838000	9	20.08	8338	3	5.61	31.8
H	41164	144	NC	NC	NC	NC	NC	NC	5650	2	1.22	1.2
Hf	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Hg	0.05	0.0002	<0.1	0	0.00	<0.1	0	0.00	0.1	0.00004	23.28	23.3
K	1868	7	42	0.03	0.54	NC	NC	NC	33413	10	158.41	158.9
Mg	4880	17	1318	1	6.45	NC	NC	NC	11849	4	21.50	28.0
Mn	151	1	2	0.001	0.24	4860	0.05	10.13	587	0.18	34.34	44.7
Mo	NC	NC	1	0.001	0.00	1290	0.01	NC	168	0.1	NC	NC
N	697	2	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Na	4367	15	852	1	4.67	NC	NC	NC	42820	13	86.84	91.5
Ni	37	0.1	2	0.002	1.53	13000	0.1	111.34	24	0.01	5.87	118.7
O	280420	978	372694	311	31.77	NC	NC	NC	409922	127	12.95	44.7
P	227	1	48	0.04	5.06	3630	0.04	5.04	679	0.2	26.51	36.6
Pb	1830	6	<2	0.00	0.00	515	0.01	0.09	3216	1	15.56	15.7
S	634	2	283	0.2	10.68	600	0.01	0.30	3192	1	44.55	55.5
Sb	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Se	1	0.003	<3	0.00	0.00	<3	0.00	0.00	89	0.03	953.91	953.9
Si	114884	401	137500	115	28.61	85500	1	0.23	202766	63	15.63	44.5
Ti	985	3	210	0.2	5.10	2080	0.02	0.67	584	0.2	5.25	11.0
Zn	693	2	4	0.003	0.14	NC	NC	NC	734	0.2	9.38	9.5
Zr	36	0.1	629	1	422.11	283	0.003	2.51	17	0.005	4.22	428.8
Totals	995772	3474	968448	808		1062981	12		994816	307		

NC: not calculated

Table H-6. Elemental mass balance during the IWPF feed interval, assuming concentrations below detection limits to be at the detection limit (wt mean concentrations in mg/kg).

	Feed		Slag			Metal			APCS residues			
wt, lb	3489		834			11			309			1154
wt, pct	100.0		72.3			1.0			26.8			100.0
Element	wt. mean	wt., lb	wt. mean	wt., lb	dist., pct	wt. mean	wt., lb	dist., pct	wt. mean	wt., lb	dist., pct	Closure, pct
Ag	1	0.003	1	0.0004	14.48	1	0.00001	0.31	1	0.0002	7.49	22.3
Al	18063	63	52200	44	69.08	215	0.002	0.004	20194	6	9.90	79.0
As	4	0.01	5	0.004	31.48	94	0.001	7.81	16	0.005	36.78	76.1
Ba	263	1	93	0.1	8.43	13	0.0001	0.02	423	0.13	14.23	22.7
C	258816	903	3445	3	0.32	65000	1	0.08	8153	3	0.28	0.7
Ca	117366	409	391000	326	79.63	NC	NC	NC	144902	45	10.93	90.6
Cd	55	0.19	0.1	0.0001	0.04	0.1	0.000001	0.001	54	0.02	8.61	8.7
Ce	2077	7	4535	4	52.19	1	0.00001	0.0002	70	0.02	0.30	52.5
Cl	132433	462	220	0.2	0.04	NC	NC	NC	95888	30	6.41	6.5
Cr	75	0.3	2	0.001	0.55	32900	0.4	138.86	71	0.02	8.40	147.8
Cs	3	0.01	3	0.003	22.28	3	0.00003	0.29	393	0.1	1080.52	1103.1
Cu	538	2	16	0.01	0.73	15000	0.2	8.78	175	0.1	2.88	12.4
F	46	0.2	3	0.003	1.57	NC	NC	NC	430	0.1	83.35	84.9
Fe	13157	46	3350	3	6.09	838000	9	20.08	8338	3	5.61	31.8
H	41164	144	NC	NC	NC	NC	NC	NC	5650	2	1.22	1.2
Hf	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Hg	0.05	0.0002	0.1	0.0001	45.46	0.1	0.000001	0.60	0.1	0.00004	23.28	69.3
K	1868	7	42	0.03	0.54	NC	NC	NC	33413	10	158.41	158.9
Mg	4880	17	1318	1	6.45	NC	NC	NC	11849	4	21.50	28.0
Mn	151	1	2	0.001	0.24	4860	0.05	10.13	587	0.18	34.34	44.7
Mo	NC	NC	1	0.001	NC	1290	0.01	NC	168	0.1	NC	NC
N	697	2	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Na	4367	15	852	1	4.67	NC	NC	NC	42820	13	86.84	91.5
Ni	37	0.1	2	0.002	1.53	13000	0.1	111.34	24	0.01	5.87	118.7
O	280420	978	372694	311	31.77	NC	NC	NC	409922	127	12.95	44.7
P	227	1	48	0.04	5.06	3630	0.04	5.04	679	0.2	26.51	36.6
Pb	1830	6	2	0.002	0.03	515	0.01	0.09	3216	1	15.56	15.7
S	634	2	283	0.2	10.68	600	0.01	0.30	3192	1	44.55	55.5
Sb	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Se	1	0.003	3	0.003	86.86	3	0.00003	1.15	89	0.03	953.91	1041.9
Si	114884	401	137500	115	28.61	85500	1	0.23	202766	63	15.63	44.5
Ti	985	3	210	0.2	5.10	2080	0.02	0.67	584	0.2	5.25	11.0
Zn	693	2	4	0.003	0.14	NC	NC	NC	734	0.2	9.38	9.5
Zr	36	0.1	629	1	422.11	283	0.003	2.51	17	0.005	4.22	428.8
Totals	995772	3474	968462	808		1062988	12		994816	307		

NC: not calculated

Appendix I

Weighted Mean Elemental Composition of the Furnace Products

Table I-1. Weighted mean elemental composition of the global furnace products, assuming concentrations below detection limits to be zero (mg/kg).

	Slag	Metal	APCS residues	Total
wt, lb	18412	1826	1885	22123
wt, pct	83.2	8.3	8.5	100.0
Element	wt. mean	wt. mean	wt. mean	wt. mean
Ag	<0.5	0.4	1	0.1
Al	85135	210	18746	72468
As	<5	101	24	10
Ba	170	16	296	168
C	319	47625	10949	5130
Ca	231240	NC	112671	202051
Cd	<0.1	<0.1	71	6
Ce	2095	<1	80	1750
Cl	33	NC	132914	11352
Cr	124	40488	108	3454
Cs	49	<3	1194	142
Cu	11	14065	207	1188
F	2	NC	563	50
Fe	9105	850096	8858	78498
H	NC	NC	5691	485
Hf	NC	NC	NC	NC
Hg	<0.1	<0.1	0.2	0.02
K	5664	NC	44638	8517
Mg	8090	NC	9684	7558
Mn	146	5223	625	606
Mo	62	2263	507	282
N	NC	NC	NC	NC
Na	18239	NC	83240	22272
Ni	4	15364	27	1274
O	411251	NC	372347	373992
P	102	4262	911	515
Pb	1	512	4508	427
S	111	655	9435	950
Se	<3	<3	117	10
Si	192691	60977	152224	178372
Ti	7307	2333	695	6333
Zn	4	NC	928	83
Zr	932	190	21	793
Totals	972887	1044380	972280	978736

NC: not calculated

Table I-2. Weighted mean elemental composition of the global furnace products, assuming concentrations below detection limits to be at the detection limit (mg/kg).

	Slag	Metal	APCS residues	Total
wt, lb	18412	1826	1885	22123
wt, pct	83.2	8.3	8.5	100.0
Element	wt. mean	wt. mean	wt. mean	wt. mean
Ag	0.5	0.4	1	0.5
Al	85135	210	18746	72468
As	5	101	24	15
Ba	170	16	296	168
C	319	47625	10949	5130
Ca	231240	NC	112671	202051
Cd	0.1	0.1	71	6
Ce	2095	1.0	80	1750
Cl	33	NC	132914	11352
Cr	124	40488	108	3454
Cs	49	3	1194	143
Cu	11	14065	207	1188
F	2	NC	563	50
Fe	9105	850096	8858	78498
H	NC	NC	5691	485
Hf	NC	NC	NC	NC
Hg	0.1	0.1	0.2	0.11
K	5664	NC	44638	8517
Mg	8090	NC	9684	7558
Mn	146	5223	625	606
Mo	62	2263	507	282
N	NC	NC	NC	NC
Na	18239	NC	83240	22272
Ni	4	15364	27	1274
O	411251	NC	372347	373992
P	102	4262	911	515
Pb	1	512	4508	427
S	111	655	9435	950
Se	3	3	117	13
Si	192691	60977	152224	178372
Ti	7307	2333	695	6333
Zn	4	NC	928	83
Zr	932	190	21	793
Totals	972895	1044387	972280	978744

NC: not calculated

Table I-3. Weighted mean elemental composition of the BWID furnace products, assuming concentrations below detection limits to be zero (mg/kg).

	Slag	Metal	APCS residues	Total
wt, lb	9202	1004	1233	11439
wt, pct	80.4	8.8	10.8	100.0
Element	wt. mean	wt. mean	wt. mean	wt. mean
Ag	<0.5	<0.5	1	0.1
Al	69819	205	19048	58237
As	<5	106	22	12
Ba	310	18	286	282
C	280	33400	11024	4345
Ca	217488	NC	112956	187131
Cd	<0.1	<0.1	77	8
Ce	3713	<1	85	2996
Cl	46	NC	139427	15066
Cr	168	46700	113	4247
Cs	3	<3	776	86
Cu	21	13300	230	1209
F	4	NC	501	57
Fe	9931	860000	9393	84484
H	NC	NC	4837	521
Hf	NC	NC	NC	NC
Hg	<0.1	<0.1	0.2	0.02
K	6160	NC	46832	10003
Mg	11688	NC	9678	10446
Mn	274	5520	674	777
Mo	4	3060	444	320
N	NC	NC	NC	NC
Na	7014	NC	83311	14622
Ni	6	17300	29	1526
O	417637	NC	361319	374911
P	80	4780	895	580
Pb	2	509	4992	584
S	196	700	8171	1100
Se	<3	<3	125	13
Si	218898	40900	148607	195699
Ti	2397	2540	742	2231
Zn	8	NC	1043	119
Zr	1790	113	23	1452
Totals	967937	1029151	965661	973064

NC: not calculated

Table I-4. Weighted mean elemental composition of the BWID furnace products, assuming concentrations below detection limits to be at the detection limit (mg/kg).

	Slag	Metal	APCS residues	Total
wt, lb	9202	1004	1233	11439
wt, pct	80.4	8.8	10.8	100.0
Element	wt. mean	wt. mean	wt. mean	wt. mean
Ag	0.5	0.5	1	0.6
Al	69819	205	19048	58237
As	5	106	22	16
Ba	310	18	286	282
C	280	33400	11024	4345
Ca	217488	NC	112956	187131
Cd	0.1	0.1	77	8
Ce	3713	1	85	2996
Cl	46	NC	139427	15066
Cr	168	46700	113	4247
Cs	3	3	776	86
Cu	21	13300	230	1209
F	4	NC	501	57
Fe	9931	860000	9393	84484
H	NC	NC	4837	521
Hf	NC	NC	NC	NC
Hg	0.1	0.1	0.2	0.11
K	6160	NC	46832	10003
Mg	11688	NC	9678	10446
Mn	274	5520	674	777
Mo	4	3060	444	320
N	NC	NC	NC	NC
Na	7014	NC	83311	14622
Ni	6	17300	29	1526
O	417637	NC	361319	374911
P	80	4780	895	580
Pb	2	509	4992	584
S	196	700	8171	1100
Se	3	3	125	16
Si	218898	40900	148607	195699
Ti	2397	2540	742	2231
Zn	8	NC	1043	119
Zr	1790	113	23	1452
Totals	967945	1029159	965661	973072

NC: not calculated

Table I-5. Weighted mean elemental composition of the IWPF furnace products, assuming concentrations below detection limits to be zero (mg/kg).

	Slag	Metal	APCS residues	Total
wt, lb	834	11	309	1154
wt, pct	72.3	1.0	26.8	100.0
Element	wt. mean	wt. mean	wt. mean	wt. mean
Ag	<0.5	1	1	0.2
Al	52200	215	20194	43134
As	<5	94	16	5
Ba	93	13	423	180
C	3445	65000	8153	5292
Ca	391000	NC	144902	321377
Cd	<0.1	<0.1	54	14
Ce	4535	<1	70	3296
Cl	220	NC	95888	25834
Cr	2	32900	71	334
Cs	<3	<3	393	105
Cu	16	15000	175	202
F	3	NC	430	117
Fe	3350	838000	8338	12642
H	NC	NC	5650	1513
Hf	NC	NC	NC	NC
Hg	<0.1	<0.1	0.1	0.04
K	42	NC	33413	8977
Mg	1318	NC	11849	4125
Mn	2	4860	587	205
Mo	1	1290	168	58
N	NC	NC	NC	NC
Na	852	NC	42820	12082
Ni	2	13000	24	132
O	372694	NC	409922	379109
P	48	3630	679	251
Pb	<2	515	3216	866
S	283	600	3192	1065
Sb	NC	NC	NC	NC
Se	<3	<3	89	24
Si	137500	85500	202766	154480
Ti	210	2080	584	328
Zn	4	NC	734	200
Zr	629	283	17	462
Totals	968448	1062981	994816	976410

NC: not calculated

Table I-6. Weighted mean elemental composition of the IWPF furnace products, assuming concentrations below detection limits to be at the detection limit (mg/kg).

	Slag	Metal	APCS residues	Total
wt, lb	834	11	309	1154
wt, pct	72.3	1.0	26.8	100.0
Element	wt. mean	wt. mean	wt. mean	wt. mean
Ag	1	1	1	0.6
Al	52200	215	20194	43134
As	5	94	16	9
Ba	93	13	423	180
C	3445	65000	8153	5292
Ca	391000	NC	144902	321377
Cd	0.1	0.1	54	15
Ce	4535	1	70	3296
Cl	220	NC	95888	25834
Cr	2	32900	71	334
Cs	3	3	393	107
Cu	16	15000	175	202
F	3	NC	430	117
Fe	3350	838000	8338	12642
H	NC	NC	5650	1513
Hf	NC	NC	NC	NC
Hg	0.1	0.1	0.1	0.11
K	42	NC	33413	8977
Mg	1318	NC	11849	4125
Mn	2	4860	587	205
Mo	1	1290	168	58
N	NC	NC	NC	NC
Na	852	NC	42820	12082
Ni	2	13000	24	132
O	372694	NC	409922	379109
P	48	3630	679	251
Pb	2	515	3216	867
S	283	600	3192	1065
Sb	NC	NC	NC	NC
Se	3	3	89	26
Si	137500	85500	202766	154480
Ti	210	2080	584	328
Zn	4	NC	734	200
Zr	629	283	17	462
Totals	968462	1062988	994816	976420

NC: not calculated

Appendix J

**Distribution of Elements
Among the Furnace Products**

Table J-1. Global distribution of elements among the furnace products, assuming concentrations below detection limits to be zero.

	Slag		Metal		APCS residues		Total	
wt, lb		18412		1826		1885		22123
wt, pct		83.2		8.3		8.5		100.0
Element	wt., lb	part., pct	wt., lb	part., pct	wt., lb	part., pct	wt., lb	Closure, pct
Ag	0.000	0.0	0.001	23.4	0.002	76.6	0.003	100.0
Al	1567	97.8	0.4	0.02	35	2.2	1603	100.0
As	0.00	0.0	0.2	80.1	0.05	19.9	0.2	100.0
Ba	3	84.2	0.03	0.8	0.6	15.0	4	100.0
C	6	5.2	87	76.6	21	18.2	113	100.0
Ca	4258	95.2	NC	NC	212	4.8	4470	100.0
Cd	0.00	0.0	0.00	0.0	0.1	100.0	0.1	100.0
Ce	39	99.6	NC	NC	0.2	0.4	39	100.0
Cl	0.6	0.2	NC	NC	251	99.8	251	100.0
Cr	2	3.0	74	96.8	0.2	0.3	76	100.0
Cs	1	28.6	NC	NC	2	71.4	3	100.0
Cu	0.2	0.8	26	97.7	0.4	1.5	26	100.0
F	0.04	3.3	NC	NC	1	96.7	1	100.0
Fe	168	9.7	1552	89.4	17	1.0	1737	100.0
H	NC	NC	NC	NC	11	100.0	11	100.0
Hf	NC	NC	NC	NC	NC	NC	NC	NC
Hg	0.00	0.0	0.00	0.0	0.0004	100.0	0.0004	100.0
K	104	55.3	NC	NC	84	44.7	188	100.0
Mg	149	89.1	NC	NC	18	10.9	167	100.0
Mn	3	20.0	10	71.2	1.2	8.8	13	100.0
Mo	1	18.4	4	66.3	1.0	15.3	6	100.0
N	NC	NC	NC	NC	NC	NC	NC	NC
Na	336	68.2	NC	NC	157	31.8	493	100.0
Ni	0.1	0.3	28	99.6	0.05	0.18	28	100.0
O	7572	91.5	NC	NC	702	8.5	8274	100.0
P	2	16.6	8	68.4	2	15.1	11	100.0
Pb	0.01	0.2	0.9	9.9	8	90.0	9	100.0
S	2	9.7	1	5.7	18	84.6	21	100.0
Se	0.000	0.0	0.00	0.0	0.2	100.0	0.2	100.0
Si	3548	89.9	111	2.8	287	7.3	3946	100.0
Ti	135	96.0	4	3.0	1.3	0.93	140	100.0
Zn	0.1	4.4	NC	NC	2	95.6	2	100.0
Zr	17	97.8	0.3	2.0	0.040	0.23	18	100.0
Totals	17913		1907		1833		21653	

NC: not calculated

Table J-2. Global distribution of elements among the furnace products, assuming concentrations below detection limits to be at the detection limit.

	Slag		Metal		APCS residues		Total	
wt, lb		18412		1826		1885		22123
wt, pct		83.2		8.3		8.5		100.0
Element	wt., lb	part., pct	wt., lb	part., pct	wt., lb	part., pct	wt., lb	Closure, pct
Ag	0.009	76.6	0.001	5.5	0.002	17.9	0.012	100.0
Al	1567	97.8	0.4	0.02	35	2.2	1603	100.0
As	0.09	28.6	0.2	57.1	0.05	14.2	0.3	100.0
Ba	3	84.2	0.03	0.8	0.6	15.0	4	100.0
C	6	5.2	87	76.6	21	18.2	113	100.0
Ca	4258	95.2	NC	NC	212	4.8	4470	100.0
Cd	0.002	1.3	0.0002	0.1	0.1	98.5	0.1	100.0
Ce	39	99.6	NC	NC	0.2	0.4	39	100.0
Cl	0.6	0.2	NC	NC	251	99.8	251	100.0
Cr	2	3.0	74	96.8	0.2	0.3	76	100.0
Cs	1	28.6	0.01	0.2	2	71.3	3	100.0
Cu	0.2	0.8	26	97.7	0.4	1.5	26	100.0
F	0.04	3.3	NC	NC	1	96.7	1	100.0
Fe	168	9.7	1552	89.4	17	1.0	1737	100.0
H	NC	NC	NC	NC	11	100.0	11	100.0
Hf	NC	NC	NC	NC	NC	NC	NC	NC
Hg	0.002	76.9	0.0002	7.6	0.0004	15.4	0.0024	100.0
K	104	55.3	NC	NC	84	44.7	188	100.0
Mg	149	89.1	NC	NC	18	10.9	167	100.0
Mn	3	20.0	10	71.2	1.2	8.8	13	100.0
Mo	1	18.4	4	66.3	1.0	15.3	6	100.0
N	NC	NC	NC	NC	NC	NC	NC	NC
Na	336	68.2	NC	NC	157	31.8	493	100.0
Ni	0.1	0.3	28	99.6	0.05	0.18	28	100.0
O	7572	91.5	NC	NC	702	8.5	8274	100.0
P	2	16.6	8	68.4	2	15.1	11	100.0
Pb	0.01	0.2	0.9	9.9	8	90.0	9	100.0
S	2	9.7	1	5.7	18	84.6	21	100.0
Se	0.055	19.6	0.01	1.9	0.2	78.4	0.3	100.0
Si	3548	89.9	111	2.8	287	7.3	3946	100.0
Ti	135	96.0	4	3.0	1.3	0.93	140	100.0
Zn	0.1	4.4	NC	NC	2	95.6	2	100.0
Zr	17	97.8	0.3	2.0	0.040	0.23	18	100.0
Totals	17913		1907		1833		21653	

NC: not calculated

Table J-3. Distribution of elements among the furnace products during the BWID feed interval, assuming concentrations below detection limits to be zero.

	Slag		Metal		APCS residues		Total	
wt, lb		9202		1004		1233		11439
wt, pct		80.4		8.8		10.8		100
Element	wt., lb	dist., pct	wt., lb	dist., pct	wt., lb	dist., pct	wt., lb	Closure, pct
Ag	NC	NC	NC	NC	0.002	100.0	0.002	100.0
Al	642	96.4	0.2	0.03	23	3.5	666	100.0
As	NC	NC	0.1	79.6	0.03	20.4	0.1	100.0
Ba	3	88.5	0.02	0.6	0.4	10.9	3	100.0
C	3	5.2	34	67.5	14	27.3	50	100.0
Ca	2001	93.5	NC	NC	139	6.5	2141	100.0
Cd	NC	NC	NC	NC	0.1	100.0	0.1	100.0
Ce	34	99.7	NC	NC	0.1	0.3	34	100.0
Cl	0.4	0.2	NC	NC	172	99.8	172	100.0
Cr	2	3.2	47	96.5	0.1	0.3	49	100.0
Cs	0.03	2.9	NC	NC	1	97.1	1	100.0
Cu	0.2	1.4	13	96.6	0.3	2.0	14	100.0
F	0.03	5.1	NC	NC	0.6	94.9	0.7	100.0
Fe	91	9.5	863	89.3	12	1.2	966	100.0
H	NC	NC	NC	NC	6	100.0	6	100.0
Hf	NC	NC	NC	NC	NC	NC	NC	NC
Hg	NC	NC	NC	NC	0.0003	100.0	0.0003	100.0
K	57	49.5	NC	NC	58	50.5	114	100.0
Mg	108	90.0	NC	NC	12	10.0	119	100.0
Mn	3	28.3	6	62.3	0.8	9.3	9	100.0
Mo	0.04	1.1	3	83.9	0.5	14.9	4	100.0
N	NC	NC	NC	NC	NC	NC	NC	NC
Na	65	38.6	NC	NC	103	61.4	167	100.0
Ni	0.1	0.3	17	99.5	0.04	0.21	17	100.0
O	3843	89.6	NC	NC	446	10.4	4289	100.0
P	0.7	11.1	5	72.3	1	16.6	7	100.0
Pb	0.01	0.2	0.5	7.6	6	92.1	7	100.0
S	2	14.3	0.7	5.6	10	80.1	13	100.0
Se	NC	NC	NC	NC	0.2	100.0	0.2	100.0
Si	2014	90.0	41	1.8	183	8.2	2239	100.0
Ti	22	86.4	3	10.0	0.9	3.6	26	100.0
Zn	0.1	5.7	NC	NC	1	94.3	1	100.0
Zr	16	99.1	0.1	0.7	0.028	0.17	17	100.0
Totals	8907		1033		1191		11131	

NC: not calculated

Table J-4. Distribution of elements among the furnace products during the BWID feed interval, assuming concentrations below detection limits to be at the detection limit.

	Slag		Metal		APCS residues		Total	
wt. lb		9202		1004		1233		11439
wt. pct		80.4		8.8		10.8		100
Element	wt. lb	dist. pct	wt. lb	dist. pct	wt. lb	dist. pct	wt. lb	Closure. pct
Ag	0.005	69.4	0.001	7.58	0.002	23.0	0.007	100.0
Al	642	96.4	0.2	0.03	23	3.5	666	100.0
As	0.05	25.6	0.1	59.2	0.03	15.2	0.2	100.0
Ba	3	88.5	0.02	0.6	0.4	10.9	3	100.0
C	3	5.2	34	67.5	14	27.3	50	100.0
Ca	2001	93.5	NC	NC	139	6.5	2141	100.0
Cd	0.001	1.0	0.0001	0.11	0.1	98.9	0.1	100.0
Ce	34	99.7	0.001	0.003	0.1	0.3	34	100.0
Cl	0.4	0.2	NC	NC	172	99.8	172	100.0
Cr	2	3.2	47	96.5	0.1	0.3	49	100.0
Cs	0.03	2.9	0.003	0.30	1	96.8	1	100.0
Cu	0.2	1.4	13	96.6	0.3	2.0	14	100.0
F	0.03	5.1	NC	NC	0.6	94.9	0.7	100.0
Fe	91	9.5	863	89.3	12	1.2	966	100.0
H	NC	NC	NC	NC	6	100.0	6	100.0
Hf	NC	NC	NC	NC	NC	NC	NC	NC
Hg	0.001	71.4	0.0001	7.79	0.0003	20.8	0.0013	100.0
K	57	49.5	NC	NC	58	50.5	114	100.0
Mg	108	90.0	NC	NC	12	10.0	119	100.0
Mn	3	28.3	6	62.3	0.8	9.3	9	100.0
Mo	0.04	1.1	3	83.9	0.5	14.9	4	100.0
N	NC	NC	NC	NC	NC	NC	NC	NC
Na	65	38.6	NC	NC	103	61.4	167	100.0
Ni	0.1	0.3	17	99.5	0.04	0.21	17	100.0
O	3843	89.6	NC	NC	446	10.4	4289	100.0
P	0.7	11.1	5	72.3	1	16.6	7	100.0
Pb	0.01	0.2	0.5	7.6	6	92.1	7	100.0
S	2	14.3	0.7	5.6	10	80.1	13	100.0
Se	0.03	14.9	0.003	1.6	0.2	83.5	0.2	100.0
Si	2014	90.0	41	1.8	183	8.2	2239	100.0
Ti	22	86.4	3	10.0	0.9	3.6	26	100.0
Zn	0.1	5.7	NC	NC	1	94.3	1	100.0
Zr	16	99.1	0.1	0.7	0.028	0.17	17	100.0
Totals	8907		1033		1191		11131	

NC: not calculated

Table J-5. Distribution of elements among the furnace products during the IWPF feed interval, assuming concentrations below detection limits to be zero.

	Slag		Metal		APCS residues		Total	
wt. lb		834		11		309		1154
wt. pct		72.3		1.0		26.8		100.0
Element	wt., lb	part., pct	wt., lb	part., pct	wt., lb	part., pct	wt., lb	Closure, pct
Ag	NC	NC	0.00001	3.9	0.0002	96.1	0.000	100.0
Al	44	87.5	0.002	0.005	6	12.5	50	100.0
As	NC	NC	0.001	17.5	0.00	82.5	0.01	100.0
Ba	0.1	37.2	0.0001	0.1	0.13	62.8	0.2	100.0
C	2.9	47.0	1	11.7	3	41.2	6	100.0
Ca	326	87.9	NC	NC	45	12.1	371	100.0
Cd	NC	NC	NC	NC	0.02	100.0	0.02	100.0
Ce	4	99.4	NC	NC	0.02	0.6	4	100.0
Cl	0.2	0.6	NC	NC	30	99.4	30	100.0
Cr	0.001	0.4	0.4	93.9	0.02	5.7	0	100.0
Cs	<3	0.0	NC	NC	0.1	100.0	0.1	100.0
Cu	0.01	5.9	0.2	70.9	0.1	23.3	0	100.0
F	0.003	1.8	NC	NC	0.1	98.2	0.1	100.0
Fe	3	19.2	9	63.2	3	17.7	15	100.0
H	NC	NC	NC	NC	2	100.0	2	100.0
Hf	NC	NC	NC	NC	NC	NC	NC	NC
Hg	NC	NC	NC	NC	0.00004	100.0	0.0000	100.0
K	0.03	0.3	NC	NC	10	99.7	10	100.0
Mg	1	23.1	NC	NC	4	76.9	5	100.0
Mn	0.001	0.5	0.05	22.6	0.18	76.8	0	100.0
Mo	0.001	1.6	0.01	21.2	0.1	77.2	0.1	100.0
N	NC	NC	NC	NC	NC	NC	NC	NC
Na	1	5.1	NC	NC	13	94.9	14	100.0
Ni	0.002	1.3	0.1	93.8	0.008	4.95	0	100.0
O	311	71.0	NC	NC	127	29.0	437	100.0
P	0.04	13.8	0.04	13.8	0.2	72.4	0	100.0
Pb	NC	NC	0.01	0.6	1	99.4	1	100.0
S	0.2	19.2	0.01	0.5	1	80.2	1	100.0
Sb	NC	NC	NC	NC	NC	NC	NC	NC
Se	NC	NC	NC	NC	0.03	100.0	0.0	100.0
Si	115	64.3	1	0.5	63	35.1	178	100.0
Ti	0.2	46.3	0.02	6.0	0.18	47.7	0	100.0
Zn	0.003	1.5	NC	NC	0.2	98.5	0.2	100.0
Zr	1	98.4	0.003	0.6	0.0052	0.99	1	100.0
Totals	808		12		307		1127	

NC: not calculated

Table J-6. Distribution of elements among the furnace products during the IWPF feed interval, assuming concentrations below detection limits to be at the detection limit.

	Slag		Metal		APCS residues		Total	
wt. lb		834		11		309		1154
wt. pct		72.3		1.0		26.8		100.0
Element	wt., lb	part., pct	wt., lb	part., pct	wt., lb	part., pct	wt., lb	losure, pc
Ag	0.0004	65.0	0.00001	1.4	0.0002	33.6	0.001	100.0
Al	44	87.5	0.002	0.005	6	12.5	50	100.0
As	0.004	41.4	0.001	10.3	0.00	48.4	0.01	100.0
Ba	0.1	37.2	0.0001	0.1	0.13	62.8	0.2	100.0
C	2.9	47.0	1	11.7	3	41.2	6	100.0
Ca	326	87.9	NC	NC	45	12.1	371	100.0
Cd	0.0001	0.5	0.000001	0.01	0.02	99.5	0.02	100.0
Ce	4	99.4	0.00001	0.0003	0.02	0.6	4	100.0
Cl	0.2	0.6	NC	NC	30	99.4	30	100.0
Cr	0.001	0.4	0.4	93.9	0.02	5.7	0	100.0
Cs	0.003	2.0	0.00003	0.03	0.1	98.0	0.1	100.0
Cu	0.01	5.9	0.2	70.9	0.1	23.3	0	100.0
F	0.003	1.8	NC	NC	0.1	98.2	0.1	100.0
Fe	3	19.2	9	63.2	3	17.7	15	100.0
H	NC	NC	NC	NC	2	100.0	2	100.0
Hf	NC	NC	NC	NC	NC	NC	NC	NC
Hg	0.0001	65.6	0.000001	0.9	0.00004	33.6	0.0001	100.0
K	0.03	0.3	NC	NC	10	99.7	10	100.0
Mg	1	23.1	NC	NC	4	76.9	5	100.0
Mn	0.001	0.5	0.05	22.6	0.18	76.8	0	100.0
Mo	0.001	1.6	0.01	21.2	0.1	77.2	0.1	100.0
N	NC	NC	NC	NC	NC	NC	NC	NC
Na	1	5.1	NC	NC	13	94.9	14	100.0
Ni	0.002	1.3	0.1	93.8	0.008	4.95	0	100.0
O	311	71.0	NC	NC	127	29.0	437	100.0
P	0.04	13.8	0.04	13.8	0.2	72.4	0	100.0
Pb	0.002	0.2	0.01	0.6	1	99.3	1	100.0
S	0.2	19.2	0.01	0.5	1	80.2	1	100.0
Sb	NC	NC	NC	NC	NC	NC	NC	NC
Se	0.003	8.3	0.00003	0.1	0.03	91.6	0.0	100.0
Si	115	64.3	1	0.5	63	35.1	178	100.0
Ti	0.2	46.3	0.02	6.0	0.18	47.7	0	100.0
Zn	0.003	1.5	NC	NC	0.2	98.5	0.2	100.0
Zr	1	98.4	0.003	0.6	0.0052	0.99	1	100.0
Totals	808		12		307		1127	

NC: not calculated

Appendix K

Elemental Distribution Plots

Figure K-1. Global distribution for Ce and the toxic metals among the furnace products, assuming concentrations below detection limits to be zero.

Figure K-2. Global distribution for Ce and the toxic metals among the furnace products, assuming concentrations below detection limits to be at the detection limit.

Figure K-3. Global distribution for Ce and the toxic metals in the slag products, assuming concentrations below detection limits to be zero (Global-1) and at the detection limit (Global-2).

Figure K-4. Global distribution for Ce and the toxic metals in the metal products, assuming concentrations below detection limits to be zero (Global-1) and at the detection limit (Global-2).

Figure K-5. Global distribution for Ce and the toxic metals in the APCS residues, assuming concentrations below detection limits to be zero (Global-1) and at the detection limit (Global-2).

Figure K-6. Distribution for Ce and the toxic metals during BWID feed interval, assuming concentrations below detection limits to be zero.

Figure K-7. Distribution of Ce and the toxic metals during BWID feed interval, assuming concentrations below detection limits to be at the detection limit.

Figure K-8. BWID distribution for Ce and the toxic metals in the slag products, assuming concentrations below detection limits to be zero (BWID-1) and at the detection limit (BWID-2).

Figure K-9. BWID distribution for Ce and the toxic metals in the metal products, assuming concentrations below detection limits to be zero (BWID-1) and at the detection limit (BWID-2).

Figure K-10. BWID distribution for Ce and the toxic metals in the APCS residues, assuming concentrations below detection limits to be zero (BWID-1) and at the detection limit (BWID-2).

Figure K-11. Distribution of Ce and the toxic metals during IWPF feed interval, assuming concentrations below detection limits to be zero.

Figure K-12. Distribution of Ce and the toxic metals during IWPF feed interval, assuming concentrations below detection limits to be at the detection limit.

Figure K-13. IWPF distribution for Ce and the toxic metals in the slag products, assuming concentrations below detection limits to be zero (IWPF-1) and at the detection limit (IWPF-2).

Figure K-14. IWPF distribution for Ce and the toxic metals in the metal products, assuming concentrations below detection limits to be zero (IWPF-1) and at the detection limit (IWPF-2).

Figure K-15. IWPF distribution for Ce and the toxic metals in the APCS residues, assuming concentrations below detection limits to be zero (IWPF-1) and at the detection limit (IWPF-2).

Appendix L

Complete Furnace Product Sample Log

Table L-1. Slag and metal product sample record.

Date	Test	Feed	Slag Pot Number	Sample No.	Sample Time	Slag wt, lb	Metal wt, lb	Full Elemental'	Partial Elemental''	TCLP	PCT-A	XRD
04/10/95	Preheat 1	Method B	WHC2-SP1	WHC2-SP1	14:20	804	---					
04/10/95	Preheat 1	Method B	WHC2-SP2	WHC2-SP2a	15:35	744	---					
04/10/95	Preheat 1	Method B	WHC2-SP2	WHC2-SP2b	15:55	---	---					
04/10/95	Preheat 1	Method B	WHC2-SP3	WHC2-SP3	16:30	566	---					
04/11/95	Preheat 2	TH + silica	TH2-SP1	---		764	---					
04/11/95	Preheat 2	TH + silica	TH2-SP2	---		818	---					
04/11/95	Preheat 2	TH + silica	TH2-SP3	---		800	---					
04/11/95	Preheat 2	TH + silica	TH2-SP4	---		808	---					
04/11/95	Preheat 2	TH + silica	TH2-SP5	---		268	---					
04/11/95	BWID	Nom 90	INEL-SP1	INEL-SP1	23:00	776	---		Yes	Yes	Yes	
04/11/95	BWID	Nom 90	INEL-SP2	INEL-SP2	23:55	840	---	Yes				Yes
04/12/95	BWID	Nom 80	INEL-SP3	INEL-SP3	01:10	764	---		Yes			
04/12/95	BWID	Nom 80	INEL-SP4	INEL-SP4	09:00	800	---	Yes			Yes	Yes
04/12/95	BWID	Nom 70	INEL-SP5	INEL-SP5a	10:00	812	---					
04/12/95	BWID	Nom 70	INEL-SP5	INEL-SP5b	11:10	---	---		Yes			
04/12/95	BWID	Nom 70	INEL-SP6	INEL-SP6a	12:15	836	---					
04/12/95	BWID	Nom 70	INEL-SP6	INEL-SP6b	13:40	---	---	Yes			Yes	Yes
04/12/95	BWID	Nom 70	INEL-SP6	INEL-SP6c	14:35	---	---					
04/12/95	BWID	Nom 70	INEL-SP7	INEL-SP7a	15:00	720	---					
04/12/95	BWID	Nom 70	INEL-SP7	INEL-SP7b	16:00	---	---		Yes			
04/12/95	BWID	Nom 60	INEL-SP8	INEL-SP8a	19:35	822	---	Yes		Yes	Yes	Yes
04/12/95	BWID	Nom 60	INEL-SP8	INEL-SP8b	21:20	---	---					
04/12/95	BWID	Nom 60	INEL-SP9	INEL-SP9a	21:40	754	---					
04/13/95	BWID	Nom 60	INEL-SP9	INEL-SP9b	01:10	---	---	Yes				Yes
04/13/95	BWID	Nom 60	INEL-SP10	INEL-SP10a	01:40	838	---		Yes			
04/13/95	BWID	Nom 60	INEL-MP1	INEL-MT1'''	04:00	460	1004	Yes				
04/13/95	BWID	Nom 60	INEL-MP1	---	04:00	---	---					
04/13/95	BWID	Nom 60	INEL-MP2	---	---	96	---					
04/13/95	BWID	Nom 50	INEL-SP10	INEL-SP10b	10:05	---	---					
04/13/95	BWID	Nom 50	INEL-SP10	INEL-SP10c	10:25	---	---	Yes			Yes	Yes
04/13/95	BWID	Nom 50	INEL-SP10	INEL-SP10d	10:45	---	---					
04/13/95	BWID	Nom 50	INEL-SP10	INEL-SP10e	11:02	---	---					
04/13/95	BWID	Nom 50	INEL-SP11	INEL-SP11a	11:20	684	---	Yes				Yes
04/13/95	BWID	Nom 50	INEL-SP11	INEL-SP11b	11:43	---	---					
04/13/95	BWID	Nom 50	INEL-SP11	INEL-SP11c	12:00	---	---					
04/13/95	BWID	Nom 40	INEL-SP11	INEL-SP11d	12:32	---	---					
04/13/95	BWID	Nom 40	INEL-SP11	INEL-SP11e	13:00	---	---					
04/13/95	BWID	Nom 40	INEL-SP11	INEL-SP11f	13:30	---	---	Yes		Yes	Yes	Yes
04/13/95	BWID	Nom 40	INEL-SP11	INEL-SP11g	14:00	---	---					
04/13/95	IWPF	S 40	INEL-SP11	INEL-SP11h	14:30	---	---					
04/13/95	IWPF	S 40	INEL-SP11	INEL-SP11i	16:05	---	---					

Table L-1. (continued).

Date	Test	Feed	Slag Pot Number	Sample No.	Sample Time	Slag wt, lb	Metal wt, lb	Full Elemental ¹	Partial Elemental ²	TCLP	PCT-A	XRD
04/13/95	IWPF	S 40	INEL-SP11	INEL-SP11j	17:04	---	---	Yes			Yes	Yes
04/14/95	IWPF	S 0	IWPF-SP12	IWPF-SP12a	02:00	834	---	Yes				Yes
04/14/95	IWPF	S 0	IWPF-SP12	IWPF-SP12b	03:15	---	---					
04/14/95	IWPF	C 20	IWPF-SP12	IWPF-SP12c	05:20	---	---					
04/14/95	IWPF	C 40	IWPF-SP12	IWPF-SP12d	09:30	---	---		Yes	Yes	Yes	
04/14/95	Cleanout	Nom 90 mod	IWPF-SP13	---	---	762	---					
04/14/95	Cleanout	Nom 90 mod	IWPF-SP14	---	---	922	---					
04/14/95	Cleanout	Nom 90 mod	IWPF-SP15	---	---	418	---					
04/14/95	Cleanout	Nom 90 mod	IWPF-MP3 ³	INEL-MT2 ³	---	506	822	Yes				
04/14/95	Cleanout	Nom 90 mod	IWPF-MP4	---	---	196	---					
Totals						18412	1826					

¹ full elemental - Ag, Al, As, Ba, C, Ca, Cd, Ce, Cl, Cr, Cs, F, Fe, Hg, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Se, Si, SO₄, Ti, Zr

² partial elemental - Al, Ca, Ce, Fe, K, Mg, Na, Si

³ metal sample - Ag, Al, As, Ba, C, Ce, Cd, Cr, Cs, Cu, Fe, Hg, Mo, Mn, Ni, P, Pb, S, Se, Si, Ti, Zr

Table L-2. APCS product sample record.

Date	Test	Feed	Sample Location	Sample No.	Sample Time	Full Elemental'	Partial Elemental''	TCLP	XRD
04/18/95	Both	Composite	T. O. base (comp.)	INEL-T1	Post-test	Yes			Yes
04/18/95	Both	Composite	T.O. top layer	INEL-T1a	Post-test		Yes		
04/18/95	Both	Composite	T.O. fibrous layer	INEL-T1b	Post-test		Yes		
04/18/95	Both	Composite	T.O. middle layer	INEL-T1c	Post-test		Yes		
04/18/95	Both	Composite	T.O. bottom layer	INEL-T1d	Post-test		Yes		
04/13/95	BWID	Nom 60	Cyclone catch	INEL-C4	00:50	Yes			Yes
04/13/95	BWID	S 40	Cyclone catch	INEL-C10	16:10	Yes		Yes	Yes
04/12/95	BWID	Nom 90	Baghouse catch	INEL-B1	00:00	Yes			Yes
04/13/95	BWID	Nom 60	Baghouse catch	INEL-B11	00:50	Yes		Yes	Yes
04/14/95	IWPF	C 20	Cyclone catch	IWPF-C5	04:00	Yes		Yes	Yes
04/14/95	IWPF	Nom 90 mod	Cyclone catch	IWPF-C9	12:00	Yes			Yes
04/18/95	IWPF	Composite	Baghouse catch	IWPF-B1	Post-test	Yes		Yes	Yes
04/18/95	Both	Composite	Ductwork (comp.)	INEL-D1	Post-test	Yes		Yes	Yes

' full elemental - Ag, Al, As, Ba, C, Ca, Cd, Ce, Cl, Cr, Cs, F, Fe, Hg, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Se, Si, SO₄, Ti, Zr

" partial elemental - Al, Ca, Ce, Fe, K, Mg, Na, Si

Table L-3. Scrubber solution sample record.

Date	Test	Feed	Sample Location	Sample No.	Sample Time	Full Elemental'	Partial Elemental	TCLP	XRD
04/12/95	BWID	Nom 90	Scrubber solution	INEL-S2	00:00	Yes			
04/13/95	BWID	Nom 60	Scrubber solution	INEL-S14	00:50	Yes			
04/13/95	IWPF	S 40	Scrubber solution	INEL-S20	15:30	Yes			
04/14/95	IWPF	C 20	Scrubber solution	IWPF-S5	04:00	Yes			
04/14/95	IWPF	Nom 90 mod	Scrubber solution	IWPF-S10	14:50	Yes			

' full elemental - Cl, F, NO₃, NO₂, PO₄, SO₄, pH

Appendix M

Product Consistency Test (PCT-A) Results

Table M-1. Product consistency test (PCT-A) of INEL-SP1 slag.

Chemical	Element	Oxide wt. %	Elemental Weight %	Averaged Elemental Leachate Concentration' (mg/L)	Normalized Mass Release Rate" (g/m ² -7 day)
CaO	Ca	29.383	21.0002	16.77	0.040
CeO2	Ce	0.133	0.1080	< 0.01"	< 0.005
K2O	K	0.548	0.4550	0.73	0.081
Na2O	Na	1.456	1.0800	2.70	0.125
SiO2	Si	43.642	20.4001	14.27	0.035

' Average obtained by summing multiple tests and dividing by the number of tests.

" Normalized mass release rates determined by dividing the elemental mass release rates by the weight fraction of that particular element in the glass.

" Release rates calculated assuming concentrations are at the detection limit values.

Initial pH = 6.67 (ASTM-I water)

Final pH = 10.28 (Final leachate)

Table M-2. Product consistency test (PCT-A) of INEL-SP4 slag.

Chemical	Element	Oxide wt. %	Elemental Weight %	Averaged Elemental Leachate Concentration' (mg/L)	Normalized Mass Release Rate" (g/m ² -7 day)
CaO	Ca	21.600	15.4375	22.77	0.074
CeO2	Ce	0.289	0.2353	0.01	0.002
K2O	K	0.838	0.6957	1.10	0.079
Na2O	Na	0.820	0.6083	1.03	0.085
SiO2	Si	22.200	10.3772	16.01	0.077

Initial pH = 6.27

Final pH = 10.27

Table M-3. Product consistency test (PCT-A) of INEL-SP6b slag.

Chemical	Element	Oxide wt. %	Elemental Weight %	Averaged Elemental Leachate Concentration' (mg/L)	Normalized Mass Release Rate" (g/m ² -7 day)
CaO	Ca	21.800	15.5805	23.70	0.076
CeO2	Ce	0.384	0.3126	< 0.01	0.002
K2O	K	0.836	0.6940	1.00	0.072
Na2O	Na	0.843	0.6254	1.00	0.080
SiO2	Si	22.600	10.5641	18.01	0.085

Initial pH = 6.27

Final pH = 10.32

Table M-4. Product consistency test (PCT-A) of INEL-SP8a slag.

Chemical	Element	Oxide wt. %	Elemental Weight %	Averaged Elemental Leachate Concentration' (mg/L)	Normalized Mass Release Rate" (g/m ² -7 day)
CaO	Ca	31.482	22.5002	25.63	0.057
CeO2	Ce	0.529	0.4310	< 0.01	< 0.001
K2O	K	0.724	0.6010	0.90	0.075
Na2O	Na	0.904	0.6710	0.80	0.060
SiO2	Si	48.349	22.6001	20.93	0.046

Initial pH = 6.67

Final pH = 10.38

Table M-5. Product consistency test (PCT-A) of INEL-SP10c slag.

Chemical	Element	Oxide wt. %	Elemental Weight %	Averaged Elemental Leachate Concentration' (mg/L)	Normalized Mass Release Rate" (g/m ² -7 day)
CaO	Ca	21.900	15.6519	24.87	0.079
CeO ₂	Ce	0.296	0.2410	< 0.01	0.002
K ₂ O	K	0.340	0.2823	0.40	0.071
Na ₂ O	Na	0.381	0.2826	0.50	0.088
SiO ₂	Si	22.200	10.3772	17.51	0.084

Initial pH = 6.27

Final pH = 10.39

Table M-6. Product consistency test (PCT-A) of INEL-SP11f slag.

Chemical	Element	Oxide wt. %	Elemental Weight %	Averaged Elemental Leachate Concentration' (mg/L)	Normalized Mass Release Rate" (g/m ² -7 day)
CaO	Ca	38.338	27.4002	33.03	0.060
CeO ₂	Ce	0.499	0.4060	< 0.01	< 0.001
K ₂ O	K	0.093	0.0776	0.20	0.129
Na ₂ O	Na	0.198	0.1470	0.20	0.068
SiO ₂	Si	44.284	20.7001	18.23	0.044

Initial pH = 6.67

Final pH = 10.54

Table M-7. Product consistency test (PCT-A) of INEL-SP11j slag.

Chemical	Element	Oxide wt. %	Elemental Weight %	Averaged Elemental Leachate Concentration' (mg/L)	Normalized Mass Release Rate" (g/m ² -7 day)
CaO	Ca	41.136	29.4002	36.90	0.063
CeO ₂	Ce	0.575	0.4680	< 0.01	< 0.001
K ₂ O	K	0.090	0.0745	0.10	0.067
Na ₂ O	Na	0.212	0.1570	0.10	0.032
SiO ₂	Si	43.214	20.2001	19.90	0.049

Initial pH = 6.67

Final pH = 10.62

Table M-8. Product consistency test (PCT-A) of INEL-SP12d slag.

Chemical	Element	Oxide wt. %	Elemental Weight %	Averaged Elemental Leachate Concentration' (mg/L)	Normalized Mass Release Rate" (g/m ² -7 day)
CaO	Ca	41.000	29.3027	901.00	1.537
CeO ₂	Ce	0.367	0.2988	< 0.01	0.002
K ₂ O	K	0.005	0.0042	1.27	15.258
Na ₂ O	Na	0.017	0.0122	6.20	25.326
SiO ₂	Si	12.500	5.8430	2.04	0.017

Initial pH = 6.27

Final pH = 11.96

Table M-9. USBM (PCT-A) analysis of Environmental Assessment glass (batch 1).

Chemical	Element	Oxide wt. %	Elemental Weight %	Averaged Elemental Leachate Concentration' (mg/L)	Normalized Mass Release Rate" (g/m ² -7 day)
CaO	Ca	1.120	0.8005	0.20	0.012
B ₂ O ₃	B	11.280	3.5032	642.93	9.176
K ₂ O	K	0.040	0.0332	2.40	3.614
Na ₂ O	Na	16.810	12.4705	1599.90	6.415
SiO ₂	Si	48.730	22.7784	617.33	1.355

Initial pH = 6.67

Final pH = 12.00

Table M-10. Product consistency test (PCT-A) of Environmental Assessment reference material (batch 2).

Chemical	Element	Oxide wt. %	Elemental Weight %	Averaged Elemental Leachate Concentration' (mg/L)	Normalized Mass Release Rate" (g/m ² -7 day)
CaO	Ca	1.120	0.8005	0.10	0.006
B ₂ O ₃	B	11.280	3.5032	514.19	7.339
K ₂ O	K	0.040	0.0332	1.90	2.861
Na ₂ O	Na	16.810	12.4705	1269.90	5.092
SiO ₂	Si	48.730	22.7784	503.67	1.106

Initial pH = 6.27

Final pH = 11.99

Table M-11. Corning Engineering Laboratory PCT-A analysis of Environmental Assessment glass.

Chemical	Element	Oxide wt. %	Elemental Weight %	Averaged Elemental Leachate Concentration' (mg/L)	Normalized Mass Release Rate" (g/m ² -7 day)
B ₂ O ₃	B	11.280	3.5032	587.00	8.378
Na ₂ O	Na	16.810	12.4705	1662.00	6.664
SiO ₂	Si	48.730	22.7784	893.00	1.960

Final pH = 11.95

Appendix N

Product Consistency Test (PCT-A) Plots

Figure N-1. Product consistency test (PCT-A) of SP-1 slag.

Figure N-2. Product consistency test (PCT-A) of SP-4 slag.

Figure N-3. Product consistency test (PCT-A) of SP-6b slag.

Figure N-4. Product consistency test (PCT-A) of SP-8a slag.

Figure N-5. Product consistency test (PCT-A) of SP-10c slag.

Figure N-6. Product consistency test (PCT-A) of SP-11f slag.

Figure N-7. Product consistency test (PCT-A) of SP-11j slag.

Figure N-8. Product consistency test (PCT-A) of SP-12d slag.

Figure N-9. Product consistency test (PCT-A) of the Environmental Assessment reference material. Comparison between the USBM batch 1 and the manufacturer's (Corning Engineering Laboratory) analytical results.

Figure N-10. Product consistency test (PCT-A) of the Environmental Assessment reference material. Comparison between the USBM batch 2 and the manufacturer's (Corning Engineering Laboratory) analytical results.

Appendix O

Offgas Composition Trend Charts from U.S. Environmental Protection Agency Continuous Emission Monitoring Measurements

Figure O-1. CEMS stack offgas composition for Nom-80 feed mixture (0031-0252).

--- O2
— CO2

---x--- NOx
---Δ--- SO2
---△--- HCl
---○--- CO
---○--- C1

Figure O-2. CEMS stack offgas composition for Nom-80 feed mixture (0347-0412).

Figure O-3. CEMS stack offgas composition for Nom-70 (0420-0505).

Figure O-4. CEMS stack offgas composition for Nom-70 (0815-0915).

Figure O-5. CEMS in-furnace offgas composition for Nom-70 (1413-1500).

Figure O-6. CEMS in-furnace offgas composition for Nom-70 (1509-1538).

Figure O-7. CEMS in-furnace offgas composition for Nom-60 (1543-1702).

Figure O-8. CEMS in-furnace offgas composition for Nom-60 (1709-1714).

Figure O-9. CEMS in-furnace offgas composition for Nom-60 (1934-2011).

Figure O-10. CEMS in-furnace offgas composition for Nom-60 (2330-2334).

O-12

Figure O-11. CEMS in-furnace offgas composition for Nom-60 (0152-0217).

Figure O-12. CEMS in-furnace offgas composition for Nom-60 (0224-0312).

Figure O-13. CEMS in-furnace offgas compositions for Nom-50 and Nom-40 (1010-1022).

Figure O-14. CEMS in-furnace offgas composition for S-40 (1348-1438).

Figure O-15. CEMS stack offgas composition for S-40 (1504-1633).

Figure O-16. CEMS baghouse outlet offgas composition for S-40 (1650-1729).

Figure O-17. CEMS in-furnace offgas composition for S-0 (2030-2242).

61-0

Figure O-18. CEMS furnace outlet offgas composition for S-0 (2246-2357).

Figure O-19. CEMS stack offgas composition for S-0 (0059-0209).

Figure O-20. CEMS baghouse outlet offgas composition for S-0, C-20, and C-40 (0237-0522).

Figure O-21. CEMS baghouse outlet offgas composition for C-40 (0607-0737).

Figure O-22. CEMS baghouse outlet offgas composition cleanout interval (0830–1011).

Appendix P

Offgas Composition Trend Charts from Fourier Transform Infrared Measurements

Figure P-1. Stack offgas composition (FTIR-CEM) for melt Nom-90.

Figure P-2. Stack offgas composition (FTIR-CEM) for melt Nom-80.

Figure P-3. Stack offgas composition (FTIR-CEM) for melt Nom-70.

Figure P-4. Furnace outlet offgas composition (FTIR-CEM) for Nom-60 (1519-1650).

Figure P-5. Stack offgas composition (FTIR-CEM) for Nom-60.

Figure P-6. Furnace outlet offgas composition (FTIR-CEM) for Nom-60 (0155-0217).

Figure P-7. Stack offgas composition (FTIR-CEM) for Nom-50.

Figure P-8. Stack offgas composition (FTIR-CEM) for Nom-40.

Figure P-9. Stack offgas composition (FTIR-CEM) for S-60 (1145-1500).

Figure P-10. Baghouse outlet offgas composition (FTIR-CEM, sample chilled without dilution) for S-40 (1506-1542).

Figure P-11. Baghouse outlet offgas composition (FTIR-CEM, sample diluted) for S-40 (1600-1630).

Figure P-12. Stack offgas composition (FTIR-CEM) for S-40 (1636-1724).

Figure P-13. Stack offgas composition (FTIR-CEM) for S-0 (1740-1832).

Figure P-14. Stack offgas composition (FTIR-CEM) for S-0 (2136-2216).

Figure P-15. Furnace outlet offgas composition (FTIR-CEM) for S-0 (2310-2350).

Figure P-16. Furnace outlet offgas composition (FTIR-CEM) for S-0 (0002-0144).

Figure P-17. Baghouse outlet offgas composition (FTIR-CEM) for C-20.

Figure P-18. Baghouse outlet offgas composition (FTIR-CEM) for C-40 (0528-0610).