

**ELECTRIC ARC FURNACE VITRIFICATION:
COOPERATIVE RESEARCH AND DEMONSTRATION TRIALS
CONDUCTED BY THE U.S. BUREAU OF MINES**

Roger S. De Cesare, P.E.¹
Silver Spring, MD

William K. O'Connor¹ and Paul C. Turner¹
Albany Research Center, U.S. Department of Energy

Laurance L. Oden, PhD¹
Albany, OR

¹All authors were formerly employed by the U.S. Bureau of Mines

ABSTRACT

Utilizing years of experience from conducting pyrometallurgical research for the minerals industry, U.S. Bureau of Mines scientists conducted waste vitrification tests in a small, 800-kVA, industrial-scale electric arc furnace facility at its research center in Albany, Oregon [now part of the U.S. Department of Energy, (DOE)] in cooperation with industry and other governmental agencies. The thermal treatment facility is capable of melting a wide range of wastes at feed rates up to 2,000-lb/h (900-kg/h) in full compliance with environmental regulations. Waste materials that have been melted during 16- to 100-h demonstrations include municipal waste combustion residues, simulated mixed TRU-contaminated wastes from DOE sites, and a variety of organic and inorganic wastes containing up to 90-pct combustibles. Summaries of the various melting trials conducted at the facility are presented and current research investigations are described.

INTRODUCTION

For many years pyrometallurgical research was conducted at the U. S. Bureau of Mines (USBM) using many different furnaces and a wide range of feed materials furnished by the ferrous, nonferrous, and nonmetallic mineral industries. This experience provided invaluable insight for conducting research in new environmental technologies. In addition to extensive furnace capabilities, the Bureau had the necessary mineral processing and feed preparation facilities as well as comprehensive analytical laboratories for conducting elemental analyses and mineral characterizations. Over the years, the electric arc furnace (EAF) evolved into a mainstay of the minerals industry; and the Bureau demonstrated, at commercial scale, that EAFs can dependably melt wide varieties of feed materials under vastly different operating conditions.

In October 1995, the Secretary of Interior negotiated with the

House Appropriations Committee to abolish the Bureau of Mines in order to save other Interior programs from funding cuts. The abolishment was completed in January 1996, with Albany Research Center (ALRC) programs being turned over to the DOE. The ultimate fate of the vitrification research program is uncertain as of this writing; this report is a summary of the work as it was conducted by the Bureau.

The Bureau assembled a small, industrial-scale (800-kVA), EAF waste treatment facility at ALRC in response to a need identified by the American Society of Mechanical Engineers (ASME) Research Committee on Industrial and Municipal Wastes; i.e., to develop reliable engineering data for vitrifying residues generated by municipal waste combustion facilities. In 1990, a cooperative agreement was signed by the USBM and the ASME to conduct vitrification demonstrations using EAF technology, and over 30 corporate and Government sponsors agreed to fund these studies. After the major sponsors committed funds, a meeting was held at the ALRC to plan details for conducting a 100-h, continuous residue vitrification demonstration and to determine what modifications would be required to existing EAF equipment at the facility. Participants included industry and government researchers, environmental regulators, U. S. and European furnace manufacturers and operators, solid waste industry professionals, engineering consultants, and academics. These participants represented a broad range of interests and concerns, and contributed greatly to both the EAF facility design and the overall vitrification test plan. Residues from five municipal waste combustion systems were selected to be vitrified during one continuous demonstration; however, limited project funding placed major constraints upon the desire to maximize the experimental design to suit the wishes of all the program sponsors. (Oden and O'Connor, 1994)

EAF technology is highly developed and reliable, well known for open-arc melting operations used by the steel industry. Lesser known, perhaps, but equally as important is the experience of EAF use in the ferroalloy industry, where it is operated in submerged-arc mode using resistance-melting (also referred to as Joule-heating). The Bureau had had considerable experience both with EAF open-arc melting of feed materials for steel and other metallurgical industries as well as with submerged-arc melting of various low-grade ores for the ferroalloy industry. The decision to convert the Bureau's existing one-ton, Lectromelt², batch-operated furnace into a fully instrumented, atmospherically-sealed, and continuously fed unit capable of operating in either open- or submerged-arc modes, resulted in a hybrid EAF capable of melting a variety of materials over a wide range of operating temperatures. Since wastes to be vitrified are not highly conductive (although the wastes frequently contain steel and other conductive materials), submerged-arc melting has advantages for vitrification because the heat is transferred to the melt by both the arc and resistance. Submerged arc operation also discourages entrainment of finely divided feed materials by the furnace offgas. The hybrid EAF proved to be versatile and dependable for long periods of operation without major maintenance, and its sealed atmosphere provides environmental and worker safety. Experienced companies were selected to furnish the three primary subsystems for the EAF facility: Salem Furnace Co. (owner and manufacturer of Lectromelt)--the furnace, Enercon Systems--the air pollution control system (APCS), and T. R. Miles Co.--the continuous feed system. (Hartman, et al, 1993)

In addition to the new 800-kVA hybrid furnace, a smaller EAF was installed at the waste processing facility to conduct preliminary research and feasibility studies prior to committing to extended trials on the industrial-scale furnace. A single phase, 50-lb (23-kg) batch EAF was available at the ALRC and was modified for continuous, 50-kW melting operation at the vitrification facility.

USBM COOPERATORS

American Society of Mechanical Engineers

The ASME sponsored the first continuous industrial-scale EAF vitrification demonstration conducted at the ALRC in the Spring of 1992. The wastes processed were residues from three state-of-the-art municipal waste combustion facilities, sewage sludge combustor residue, and dry scrubber baghouse residue from a refuse-derived-fuel (RDF) combustion facility. Over 54,000-lb (24,500-kg) of these residues were melted during 100-h of continuous operation.

Lockheed/Martin Idaho Technologies--DOE contract managers at the INEL

Following these trials on municipal combustion residues, the Bureau concentrated its efforts on melting demonstrations of the mixed alpha-low-level radioactive wastes stored and buried at the

²Reference to specific trade names or manufacturers does not imply endorsement by USBM, DOE, or ASME.

Idaho National Engineering Laboratory (INEL) Radioactive Waste Management Complex (RWMC). The Bureau's EAF facility was selected for these demonstrations following an INEL review of U.S. vitrification operations. (Eddy et al, 1995) An interagency agreement between the USBM and Department of Energy (DOE) contractors at the INEL was originated in 1993 for Phase 1 demonstration melting tests. These tests were conducted for the Buried Waste Integrated Demonstration (BWID) Arc Melter Vitrification Project. The Phase 1 tests were designed to process feed mixtures prepared to simulate the actual mixed wastes (radioactive and hazardous) after incineration. The basis for these tests was the assumption that buried wastes would be retrieved and incinerated, and that the incinerator ash would be vitrified in the EAF. Therefore, volatile constituents were specified at concentrations such as Cl<2-pct, C and H₂O<5-pct, similar to those in the combustor residues processed during the ASME-sponsored cooperative demonstrations. The INEL feed mixtures were comprised of soil from the RWMC and additives designed to simulate thermally-oxidized radioactive mixed wastes. Cerium oxide was used as the surrogate for the transuranic (TRU) contaminants in the actual wastes, and was added in quantities to provide 0.5-pct CeO₂ in the product slag. Over 47,000-lb (21,400-kg) of five separate feed mixtures were melted during approximately 75-h of semi-continuous operation.

The Phase 2 melting demonstration conducted in cooperation with the INEL were conducted in April of 1995. Feed mixtures were prepared to simulate as-retrieved mixed wastes, without prior incineration; two series of tests were included. The BWID "nominal standard waste stream", an average composition determined for all the buried wastes located at the RWMC, was selected for one series of the Phase 2 melting tests (Table 1-a). It consisted of surrogates for various combustibles, metals, and sludges that in total represent nearly 60-pct by volume of the wastes buried at the site. The nominal waste stream was comprised of mixtures of silicated organics [Regal oil and grease immobilized by absorption in Micro-Cel E (expanded calcium silicate) and Oil-Dri (calcined diatomite; i.e., fossil-derived silica)], nitrates, metals, metal hydroxides, PVC, PE, and wood pellets. This nominal waste mixture was added to a mixture of soil from the RWMC and lime, which was composited to produce a product slag with neutral basicity. Feed mixtures were formulated by decreasing (by 10-pct increments) the ratio of soil and lime mixture to the amounts of nominal waste, from 90-pct soil and lime with 10-pct waste to 40-pct soil and lime with 60-pct waste. The second series of tests for Phase 2 was conducted for the Idaho Waste Processing Facility (IWPF) project at the INEL. Feed mixtures prepared for these tests were designed to simulate mixed wastes that were generated at the DOE's Rocky Flats Plant in Colorado, shipped to, and stored at the INEL (Table 1-b). The wastes were similar in composition (though not identical) to the BWID nominal wastes, but soil and lime were added as necessary to produce an appropriate product slag/glass. The most significant aspect of the IWPF feed mixtures was the extremely high content of volatile organics and chlorides (up to 90-pct combustibles and up to 25-pct Cl). The EAF proved fully capable of processing the highly combustible feeds, although

feedrates had to be reduced due to limitations on secondary combustion of CO and total hydrocarbons (THC) in the close-coupled thermal oxidizer. Over 27,000-lb (12,300-kg) of ten separate feed mixtures were processed during 87-h of continuous operation. (Soelberg, et al, 1995)

Westinghouse Hanford Company--DOE contract managers at the Hanford, WA site

In 1994, Westinghouse Hanford Company (WHC) entered into a memorandum of agreement with the Bureau as part of their Phase 1 testing program on vitrification of low-level radioactive sodium nitrate and nitrite salts, 230,000-m³ of which are stored in alkaline liquid and slurry form at the Hanford site. The Bureau elected to prepare a dry, denitrified furnace feed for the EAF, which constituted a major effort in feed preparation prior to the melting tests. A 24-h melting demonstration was required for the WHC program, which was completed in March, 1995. A total of 30,000-lb (13,600-kg) of dry, denitrified furnace feed was prepared and processed in a series of three melting tests with over 68-h of total melting time.

Southern California Edison

Also in 1994, Southern California Edison Company (SCE) entered into a Cooperative Research and Development Agreement (CRADA) with the USBM to evaluate the feasibility of vitrifying a select group of hazardous wastes specified by SCE. The CRADA with SCE stipulated that the Bureau conduct small-scale EAF tests on bottom ash from a proposed SCE gasifier using refuse-derived-fuel (RDF) and to determine melting temperatures, slag chemistry, and fume characteristics. Following these small-scale tests in the ALRC 50-kW furnace, the CRADA calls for 800-kVA furnace tests on RDF gasifier bottom ash alone and with a surrogate for SCE asbestos wastes.

Enercon Systems, Incorporated

Enercon Systems, Inc. furnished designs for the USBM air pollution control systems, from the initial conversion of the original EAF to the hybrid system that exists today. A CRADA was established between Enercon and the USBM to facilitate transfer of EAF vitrification technology to the waste treatment industry. To accelerate in transferring EAF technology for the treatment of mixed wastes, Enercon is currently seeking an experienced mixed waste contractor as a partner.

THERMAL WASTE TREATMENT FACILITY

Mineral Processing Capabilities

Modification of waste materials is often a necessary prerequisite to melting. Equipment for crushing, grinding, screening, mixing, pelletizing, drying, and characterizing materials is available at the ALRC. Many wastes can be melted with minimal preparation such as crushing, screening, or pelletizing. Other wastes are simulated (cost effectively) at the EAF facility because of regulatory constraints. Furnace feeds were prepared to simulate soils and concrete contaminated with metals, halogenated hydrocarbons, and radioactive isotopes, in which a cold isotope or

chemically similar surrogate replaced the radioactive isotope. Other industrial wastes containing heavy metals, halogens, metal hydroxide sludges, and/or solutions or slurries containing nitrates, nitrites, sulfates, phosphates, chlorides, carbonates, and other soluble species were pre-processed with industrial minerals and other materials to achieve an acceptable final waste form following vitrification. In some cases, high silica content of the waste (e.g., contaminated soils) produces a highly viscous melt, resulting in a slag that is difficult to tap from the furnace and/or is extremely corrosive to the furnace refractory. High bath temperatures can result in excessive volatilization of metal oxides such as K and Na (slag fluidizers) and Pb and Zn. It is therefore advantageous to make additions of appropriate industrial minerals to the wastes that will result in a slag/glass designed for a sufficiently low melting point to avoid excessive volatilization, fluid enough for continuous tapping, and with significant leach resistance.

Small-Scale, 50-kW EAF

The 50-lb (23-kg), single-phase, 50-kW, EAF installed at the furnace facility is used for scoping studies to determine the required melting and tapping temperatures; slag, fume and offgas chemistries; power consumption; and other appropriate processing parameters of various feed materials prior to conducting extended, large-scale tests. A selection of refractory-lined shells is available for use, some of which are water-jacketed, and power is furnished by two, 2-inch (5-cm) diameter graphite electrodes (with optional 3-inch (7.6-cm) diameter stubs available). The inside dimensions are 13-inch (33-cm) diameter by 13-inch (33-cm) high; and the finished hearth measures 12.5-inch (32-cm) diameter by 3.5-inch (9-cm) deep, providing a capacity of approximately 0.25-cu.ft. (7100-cu.cm). An instrumented fume duct, including thermocouples and velocity probes, connected to a data logger for digitization and transmission to a personal computer serve as the data display and storage system. (O'Connor, et al, TMS 1994) Figure 1 is a schematic of the single-phase EAF system and Figure 2 is a photograph of the 50-kW furnace.

Industrial-Scale, 800-kVA EAF

The 3-phase EAF installed at the ALRC facility has a tapered inside diameter (approximately 42- to 48-inch) (107- to 122-cm) and is 60-inch (1.5-m) high. Features of the furnace include: a) continuous slag tap, b) intermittent metal tap, c) continuous feed system, and d) an APCS capable of reliable operation under a wide variety of changing furnace conditions. The EAF uses refractory-lining with a water-cooled shell and roof (permitting solidified slag to coat inside wall surfaces) that minimizes concern for corrosive slags reacting with furnace refractories while maximizing variations in feed materials that can be melted by the unit. High-alumina Ruby brick is used in the molten slag areas of the furnace, although high-MgO Permanent ramming mix is placed on the exposed surfaces of the hearth and high-alumina Narphos plastic refractory lines the furnace roof. (For the 1995 INEL and WHC tests, the MgO ramming mix was replaced with Ruby mix from Harbison Walker Co. Ruby contains 90-pct coarse alumina aggregate bonded with chromium aluminate.) Water-cooled furnaces are less efficient than dry-wall units, and

to compensate for the resulting heat loss, additional electrical power is required for the three, solid graphite, 4-inch (10-cm) diameter electrodes used to melt materials fed to the unit. (In addition, 6- and 8-inch (15- and 20-cm) diameter solid graphite electrode stubs are available for use during short tests to better define energy-use parameters for this furnace.) Power is provided by an 800-kVA constant voltage transformer with selected outputs ranging from 95- to 350-V. Operation in open-arc, submerged-arc, and intermediate modes is available. Four water-cooled feed tubes installed through the furnace roof spread materials over the molten surface, enabling either hot- or cold-top operation. The finished hearth is 48-inch (1.2-m) in diameter by 9-inch (23-cm) deep, having an approximate 5-cu.ft. (0.14-cu.m) capacity. The EAF is versatile, capable of being operated under either oxidizing or reducing atmospheres, and has a feed system capable of feed rates of 1-tph (900-kg/h) of minus 0.5-inch (1.3-cm) materials having an 80-lb/cu.ft. (1.3-g/cu.cm) bulk density. The EAF is sealed for atmospheric control, and appropriate APCS equipment is available for use as required for various types of wastes being fed to the furnace and suitable for EAF operation under oxidizing or reducing conditions. During extended EAF trials, data is continuously monitored for over 60 process variables, such as feedrate, temperatures, power, and offgas conditions--including samples collected for subsequent analyses. Additional offgas measurements are provided as necessary by EPA-certified contractors. (Hartman, et al, 1993 and Oden, et al-RI 9528, 1995)

Figure 3 is a schematic of the EAF facility used for the ASME cooperative trials on municipal combustion residues. Figure 4 is a photograph of the EAF as it was used in the Spring of 1995 for melting simulated TRU-contaminated wastes.

The furnace facility utilizes screw conveyors for the waste feed system and incorporates a receiving bin, bucket elevator, metering bin, rotary air locks, and four water-cooled feed tubes that extend through the furnace roof to within 18-inch (46-cm) of the surface of the molten pool. The system delivers and spreads materials over the surface of the EAF at rates to 25-cu.ft./h (0.7-cu.m/h) [2,000-lb/h (900-kg/h) for materials with bulk density of 80-lb/cu.ft. (1.3-g/cu.cm)].

Various pieces of APCS equipment are used during specific EAF trials depending upon the nature of the feed materials and whether the furnace is operating in an oxidation or reduction mode. For the ASME-sponsored demonstration on municipal combustion residues, the EAF was operated in a reduction mode and the APCS design was made based on minimum offgas being generated and exhausted, in an effort to keep overall facility costs to a minimum. Approximately 100-cfm (.05 cu.m/s) of offgas was generated in the EAF and passed through a cooler before going to a baghouse filter, an induced draft fan, and a thermal oxidizer. Lime was added at the baghouse to control acid gases.

Two different APCS configurations, jointly designed by USBM and Enercon Systems engineers, were used for the INEL-sponsored Phase 1 and Phase 2 melting demonstrations. In both cases the EAF was operated with an oxidizing atmosphere above

the bath, rather than an inert atmosphere under reducing conditions, as was the case during the ASME-sponsored demonstrations. The first APCS configuration, designed for the INEL Phase 1 tests on simulated thermally oxidized feed mixtures, utilized a wind box to air-quench furnace offgas immediately upon exiting the furnace. [This system was installed to eliminate the plugging of the offgas ducts by molten particulate, a phenomenon encountered during the ASME melting campaign. Air was injected directly into the offgas stream, at a dilution ratio of 5:1, which effectively quenched the molten particulate and eliminated the plugging problem.] Cooled gases, condensed fume, and entrained particulate solids exited the wind box, passed through a cyclonic settling chamber, heat exchanger, baghouse filter, High Efficiency Particulate Air (HEPA) filter, and discharged through a stack to the atmosphere. (Oden, et al-RI 9528, 1995)

The second APCS, a "dry-wet" design, enabled the facility to treat large amounts of organics in the feed materials and provided for oxidation of combustible gases and destruction of chlorinated hydrocarbons in furnace offgases by means of a thermal oxidizer (secondary combustion chamber) close-coupled to the EAF exhaust port, and heated by natural gas burners. Gases from the thermal oxidizer, after cooling by evaporative gas cooling (water spray) and an air-dilution quench, passed through a cyclone separator and baghouse to collect entrained particulate and condensed fume. The dust-free gases then passed in series through a caustic scrubber to remove acid gases, a cooler/condenser that lowered the temperature, induced draft fan, activated carbon and HEPA filters for final polishing, and exited the stack 40-ft (12-m) above the ground. This design completely oxidized furnace offgases and enabled testing of the EAF system for treating non-incinerated wastes containing high levels of organics. (O'Connor et al, 1995) Figure 5 is a schematic of the APCS available for use with the EAF system, Figure 6 is a photograph of the close-coupled thermal oxidizer and melting furnace, and Figure 7 is a photograph of the remainder of the APCS.

Analytical Capabilities

Materials to be fed to either EAF were first fully analyzed and characterized. This helped to determine initial furnace settings and additives required to produce acceptable end product characteristics. Analyses and characterizations were conducted by ALRC analytical laboratory personnel. (Bureau, 1987)

Materials balance and elemental partitioning calculations were carefully made following extended operations of the 800-kVA furnace. Evaluation of elemental partitioning, from feed materials to furnace products, is highly dependent upon the care exercised in characterizing and analyzing elements of concern. Truly representative sampling of very heterogeneous waste materials is usually not possible owing to the prevalence of such items as large metal fragments and components comprised of several different materials. These items cannot be included in samples submitted for chemical analysis; hence, analyses of contained elements may not be completely representative of the bulk wastes.

For some mass balance elements, errors introduced by these sampling problems are very minor; however, for elements contained only in ppm quantities the effects of these sampling errors are incalculable. Therefore, extra analytical methods were employed to make corrections for some analyses that rendered values obtained to be more accurate than uncorrected values.

RESULTS AND DISCUSSION

Mineral Beneficiation

Prior to conducting continuous melting trials on the WHC liquid tank wastes, the liquid wastes were converted to dry, free-flowing, non-hygroscopic materials. The work plan called for the Bureau to analyze the EAF's ability to produce a durable, consistent, homogeneous, borosilicate glass with 25-pct waste loading; to determine partitioning of toxic and radioactive components of the waste to the furnace products; and to evaluate overall EAF system operational and reliability factors. The WHC specified a target final slag composition of 57-pct SiO_2 , 20-pct Na_2O , 10-pct Al_2O_3 , 5-pct B_2O_3 , 5-pct CaO , and 3-pct miscellaneous materials. The Bureau's mineral processing personnel demonstrated two separate methods (designated A and B) for preparing dry, homogeneous furnace feed materials from simulated low-level, high-sodium, liquid tank wastes. Glass-forming oxides and reducing agents were added to decompose nitrates and nitrites in the liquid wastes; this material was pelletized, dried, and heated to induce reaction between reductants and nitrogenous species. Method A additives included alumina, boric acid, bentonite, diatomite, Micro Cel, silica, powdered sugar, and activated carbon. Method B used the same additives used in Method A, except limestone was added and bentonite and Micro Cel were omitted. Thus, about 30,000-lb (13,600-kg) of dry, denitrified, free-flowing, non-hygroscopic, homogeneous furnace feed was prepared, to produce (when melted) an amorphous final waste form containing the specified 25-pct waste loading. (Oden, et al, WHC 1995)

50-kW EAF

Prior to conducting the Phase 1 melting tests in the 800-kVA furnace, over 600-lb (270-kg) of five simulated INEL mixed wastes and soils were processed and melted in the 50-kW furnace during 15 separate tests in 1993. These feed mixtures included the "M-60" (60-pct soil and 40-pct scrap metal), "N-80" (80-pct soil and 20-pct simulated evaporator salts), "N-80-IV" ("N-80" with zirconia and ilmenite to provide necessary Group IV metals; e.g., 5-pct ZrO_2 and 10-pct TiO_2 in the slag), "S-60" (60-pct soil and 40-pct simulated organics immobilized by mixing with Micro-Cell E [CaSiO_3] and Oil-Dry [manufactured from diatomaceous earth]), and "S-60-IV" ("S-60" with zircon and ilmenite to provide 5-pct ZrO_2 and 10-pct TiO_2 in the slag). The ALRC provided the chemical analyses and characterization data on these five mixtures (prepared to be equivalent to buried wastes that had been incinerated) to assist the INEL in their studies on final waste forms. (O'Connor, et al, 1994)

Two series of tests on the SCE bottom ash were conducted in 1994 in the 50-kW furnace. The first was conducted on the

bottom ash only, with no slag modifiers added to the feed. This produced an extremely viscous slag that could not be tapped from the furnace. Basicity ratios were calculated to determine the expected viscosities of subsequent melts. The basicity ratio is the molar ratio of basic oxides (e.g., CaO , MgO , FeO , Na_2O , K_2O) to acidic oxides (e.g., SiO_2 , Al_2O_3 , Fe_2O_3) in the slag. Neutral basicity (ratio of 1.0) is indicative of a slag with reasonably low viscosity (<100-poise) at its melting temperature. A neutral slag is generally not corrosive to the furnace refractory as well. A second series of melting tests was conducted with serpentine, a surrogate for asbestos, included with the bottom ash in the furnace feed. Asbestos is a secondary waste stream that SCE intends to process in the EAF. Anticipated (theoretical) slag compositions were calculated and used to determine basicity ratios for the various feed mixtures (Table 2). The bottom ash and serpentine mixture was melted in the furnace at a bath temperature of 1650°C, but proved too viscous to tap. Following the addition of lime at 20-pct of total feed weight, a furnace bath temperature of 1565°C was reached, and tapping was achieved at a temperature of 1528°C.

Six tests using simulated WHC feed mixtures also were conducted in 1994. Four scoping tests were completed to determine the appropriate final glass composition. Two additional tests were conducted on the Bureau's dry furnace feed prepared from the liquid tank waste simulants. The first of these tests investigated the furnace operations with the dry, denitrified feed, while the second utilized dry, but unreacted feed. Melting conditions were indistinguishable between the two melts, although offgas generation was much higher for the unreacted feed material. In both cases, the desired amorphous glass product was produced at a tap temperature of approximately 1350°C. (Oden, et al, WHC 1995)

800-kVA EAF

Continuous trials lasting 16- to 100-h were thoroughly planned events, carefully designed to meet the objectives of cooperators and sponsors. It is essential to discuss and prioritize research objectives before the start of these testing programs, as well as to decide which test parameters to vary during the trials and which to hold constant. Continuous trial experience has shown that the EAF is both durable and dependable; steady feeding of consistent materials results in very steady furnace operation. However, wastes are notoriously nonhomogeneous; and changing feed compositions can have dramatic effects on all chemical reactions whether or not they take place inside a furnace. Several trials were held at the ALRC facility where waste feed compositions were changed radically; when the changes were anticipated, modifications were made during the operation that compensated for the differences and the trial continued without delays. When changes in feed had not been anticipated, the operating staff had to make quick adjustments based on their expertise; during these occurrences, the versatility of the facility contributed greatly to the successes that were achieved. It is advantageous to have extensive characterization of the feed before the start of the trial to ensure that any fluxes or other necessary additives are on hand to facilitate steady EAF operation.

The ASME-sponsored 100-hour demonstration to vitrify municipal combustion residues was conducted during the Spring of 1992. All residues were melted as received (i.e., previously screened to minus 1-inch (2.5-cm) and dried to 5-pct moisture content) except the baghouse residue, for which iron oxide was added to oxidize contained carbon, and silica was added to improve molten slag fluidity. Residues were melted at up to 1,500-lb/h (680-kg/h). The EAF and APCS operated under a reducing atmosphere, inerted with nitrogen to limit oxygen concentration to below a potentially flammable 5-pct. The 800-kVA EAF proved to be robust and readily accommodated the five different residues. Test results have been published by ASME. (Oden and O'Connor, 1994)

Each of the melted residues formed slag, metal, and matte products, as well as fume solids and baghouse solids. Over 54,000-lb (24,500-kg) of combustor residues were melted during the 100-hour test. The majority of the Pb and Cd contained in MSW residues reported to the fume products and the As and Cu reported to the metal, whereas all four elements in the sewage sludge residue reported to the slag. The Fe and Cr for all residues were split between the metal and slag products; if the metals were present in oxide form in the wastes they reported to the slag products, and if they were present in the reduced metallic form they reported to the metal ingot. Distributions for the TCLP heavy metals among the furnace products for one of the municipal waste combustor residues, which were typical of the distributions for each of the other residues as well, are shown in Figure 8. Vitreous furnace products at 180-lb/cu.ft. (2.9-g/cu.cm) were recovered from 70- to 85-pct of the combined residues fed to the EAF and they easily passed TCLP requirements. These products were examined by light microscopy to identify crystalline phases and various inclusions present—these phases and inclusions did not detrimentally affect the favorable leaching characteristics of the products. (O'Connor, et al, TMS-1994) No further upgrading of metal content in the fume solids for potential recycling was conducted. EAF trial power requirements were a minimum of 20-pct higher than designers expect are possible at this installation; i.e., furnace designers anticipate that for optimal feed rates of 1300-lb/h (590-kg/h) [under steady state operation] approximately 500-kWh/st would be required to vitrify the residues, and power usage at the EAF research facility measured over 600-kWh/st. (0.7-kWh/kg). Economic projections for vitrifying MSW combustion residue at 20-pct moisture, ranged from \$98 up to \$175 per ton, for combustion plants generating from 350-ton down to 60-ton of residues per day. (Oden and O'Connor, 1994)

The INEL Phase 1 cooperative tests were conducted at the ALRC in 1993 on the same five feed mixtures described for the 50-kW EAF melting tests (Table 3). The basalt-derived soils from the RWMC, which made up 60- to 80-pct of the feed mixtures, produced an iron-alumina-silicate when melted. When additional iron derived from the wastes was added to the soils, it produced a final waste form designated as an iron-enriched basalt (IEB). The IEB, as a final waste form, can accommodate both the high waste loadings and the expected range of heterogeneous input waste materials, is leach-resistant, and has high mechanical

and thermal stability. (Eddy, et al., 1992) A baseline test on approximately 6,000-lb (2,700-kg) of RWMC soils, without waste additions, produced an extremely acidic slag (basicity ratio 0.28), which proved to be very viscous at temperatures to 1550°C. The acidic slag also eroded the magnesite hearth in the furnace. Additives, including mill scale (Fe_2O_3), limestone (CaCO_3), and pebble lime (CaO), were used to modify the feed compositions to maintain a fluid slag at approximately 1550°C. (Oden, et al-RI 9529, 1995) The "M-60" feed mixture, which contained approximately 40-pct scrap metal, required a bath temperature of 1558°C to maintain a molten heel of iron within the furnace. The "S-60" and "S-60-IV" feed mixtures (basicity ratios 0.52 and 0.51, respectively) were successfully melted without slag modifiers, although MgO eroded from the hearth refractory and served as a significant fluidizer for these slags. Tapping temperatures ranged from 1450 to 1650°C. The "N-80" and "N-80-IV" feed mixtures (basicity ratios 0.48 and 0.44, respectively) required excessive tapping temperatures, up to 1,850°C, and consequently were modified after 4 hours of operation with additions of mill scale and limestone to increase the basicity ratio to 1.0. These changes increased slag fluidity and lowered tapping temperatures by 5-pct. Over 39,000-lb (17,700-kg) of simulated mixed wastes and 4,200-lb (1,900-kg) of additives were melted at feed rates up to 1,500-lb/h (680-kg/h) during the semi-continuous 80-h test. (Oden, et al, 1993) Distributions for Ce, the TRU surrogate, and the toxic metals among the furnace products for the "M-60" feed mixture are included in Figure 9. The steady state power requirements for a commercial EAF at optimal feed rates are projected to be similar to those determined for municipal residues [i.e., 500- to 600-kWh/st] (0.6-kWh/kg).

The INEL Phase 2 melting demonstrations were conducted in April, 1995. During 87-h of continuous operation, 28,000-lb (12,700-kg) of 14 separate feed mixtures (Table 4) containing up to 90-pct combustibles and up to 25-pct chlorine were successfully melted. Feed rates up to 1,100-lb/h (500-kg/h) were demonstrated, with over 18,000-lb (8,200-kg) of slag produced during two series of melting tests: a) the six BWID nominal feed mixtures were fed during one specific "feed interval", and b) the IWPF feed mixtures were fed during a second specific "feed interval". Optimum operating conditions were achieved with the BWID "Nom-60" feed mixture (60-pct soil and lime mixture, 40-pct waste) at a feedrate of 750-lb/h (340-kg/h), and optimal power requirement is estimated at approximately 700-kWh/st (0.8-kWh/kg). The high combustible content of these feeds limited the feed rate due to high concentrations of CO and THC in the furnace offgas. Secondary combustion of the CO and THC in the close-coupled thermal oxidizer was necessary, and concentrations of these combustible species could not exceed the capacity of the thermal oxidizer. This resulted in less efficient energy usage within the EAF, which demonstrated its ability to melt these materials at feed rates of 1,000-lb/h (450-kg/h) or greater. Processing non-incinerated materials in the EAF is therefore possible, but the APCS must be sized to accept the significant increase in combustible gases exiting the furnace.

Mass distributions for the Ce, the TRU surrogate, and the eight

TCLP elements were calculated over both the BWID and IWPF "feed intervals", and are included in Figures 10 and 11, respectively. Essentially all of the Cd in the various feed materials reported to the APCS equipment for collection. All of the Cr in the IWPF wastes reported to the metal ingot whereas, for the BWID wastes, 95-pct reported to the metal and 5-pct reported to the slag. Between 6- and 10-pct of the Pb in both waste categories reported to the metal, while the remaining vast majority of this element reporting to the APCS. Precise transport analyses of each of the remaining five TCLP elements was hampered in some instances because the elements were present only in quantities close to or below the detection limits of the analytical instruments being used. Two sets of mass distribution calculations were made to determine the range of values possible, with the actual values in all likelihood falling between the two extremes. Thus arsenic, for example, in the BWID wastes reported between 59- and 79-pct to the metal, 15- and 21-pct to the APCS, and between 0- and 26-pct to the slag.

The WHC liquid wastes that had been converted to non-hygroscopic pellets, were melted in the EAF on three occasions in 1995. Trials were conducted to determine what operational parameters had to be established in the large furnace in order to achieve the same slag product that was produced in the small furnace. The high resistance of slags was evident, as ALRC researchers determined that to achieve the desired 1350°C tapping temperature necessitated operating furnace temperatures higher than 1500°C. (Oden, et al WHC 1995)

Work in Progress

In addition to demonstrating EAF technology for melting wide varieties of waste materials, 800-kVA furnace trials were focussed on establishing generic slag/furnace parameters necessary for optimal melting of wastes while minimizing the release of toxic constituents contained in the wastes to the furnace offgas. Slag parameters such as oxygen potential, flux density, and basicity ratio have been calculated for tests conducted in the 50-kW furnace. Adjustments are then made to the 800-kVA furnace to generate equivalent process parameters and temperature conditions. These adjustments become increasingly complex as efforts are made to match the reduced oxygen potential and increased power density that are more easily achieved in the smaller furnace.

USBM research strived to achieve optimal waste melting by using minimal temperatures (and energy) required to maintain a molten bath with continuous slag tapping. The transfer of heat from the arc to molten pool is dependent on the power density in the electrodes, which is a function of voltage, amperage, and electrode surface area. The results of power density research conducted in the 50-kW EAF were confirmed during demonstration trials conducted in the 800-kVA furnace. The majority of all metal volatilization from the melt occurs due to excessive power density in the zone between the electrodes. Reducing the power density by using larger diameter electrodes, without increasing power input, is one of the keys to reducing metal volatilization. Heat loss from the molten pool creates a

significant temperature gradient between the electrodes and the furnace tap. This was demonstrated when 100-poise temperatures were calculated for several of the slags produced by the EAF. Average tapping temperatures were 250°C higher than the calculated 100-poise temperatures, more closely approximating 25-poise temperatures and indicating that excess heating of the slags had occurred during continuous slag tapping. Auxiliary electrodes were added immediately ahead of the slag tap. The intention was to supply a minor amount of auxiliary heat to the molten pool at the tap, thus eliminating the need to overheat the slag in the zone between the electrodes in order to maintain sufficient heat for tapping.

CONCLUSIONS

USBM scientists investigated the application of EAF technology for vitrifying hazardous and mixed wastes. Using a combination of arc and resistance (Joule) heating within the EAF was determined to be effective for vitrifying wastes. During tests conducted in both the 50-kW and industrial-scale (800-kVA) furnaces, the reliability of EAF technology was confirmed and researchers continue to study furnace parameters necessary for establishing and maintaining optimal operation. Maintaining the melt under a head of unmelted feed material (cold-top operation) has been advantageous for the wastes treated to date. The 800-kVA hybrid furnace proved to be robust, capable of melting wide varieties of feed materials; and Government-industry cooperators continually challenged the system's capabilities by changing waste feed streams frequently during extended continuous furnace trials, making operational adjustments "on the fly", without experiencing serious shutdowns or delays.

Temperatures generated in the zone of an exposed electric arc are known to reach 5000°C. For the submerged arc in the USBM hybrid EAF system, temperatures transmitted to the slags are somewhat less than the exposed arc and studies have looked into minimizing this temperature as much as possible. With highly resistant slags the temperature gradient decreases significantly between the electrode and the furnace walls. Melting that occurs within the region of the electric arc is more likely to result in the liberation of heavy metals from the wastes into fume and offgases, which are filtered by the unmelted wastes in cold-top operation. Filtered gases are exhausted from the furnace to the air pollution control system, for subsequent final treatment of any remaining toxic constituents not captured within the cold top, and released to the atmosphere. Since slags melt and tap readily at less than 1500°C, bath temperatures should be held to minimum requirements to limit metal vaporization. Toxic organic components in wastes are destroyed when held at only 1200-1300°C for 3-5 seconds. In addition, bath temperatures in excess of 1500°C increase the potential for detrimental chemical reactions occurring between the furnace refractories and the molten bath. Thus, depending upon its chemical composition, it is desirable to maintain the molten slag at minimal temperatures that will also tap readily.

Tests conducted in cooperation with the INEL demonstrated the potential for this technology in processing TRU-contaminated mixed wastes containing large quantities of combustibles, chlorides, nitrates, halocarbons, and hydroxides without prior incineration. The cooperative tests with WHC on treating liquid tank wastes were equally successful.

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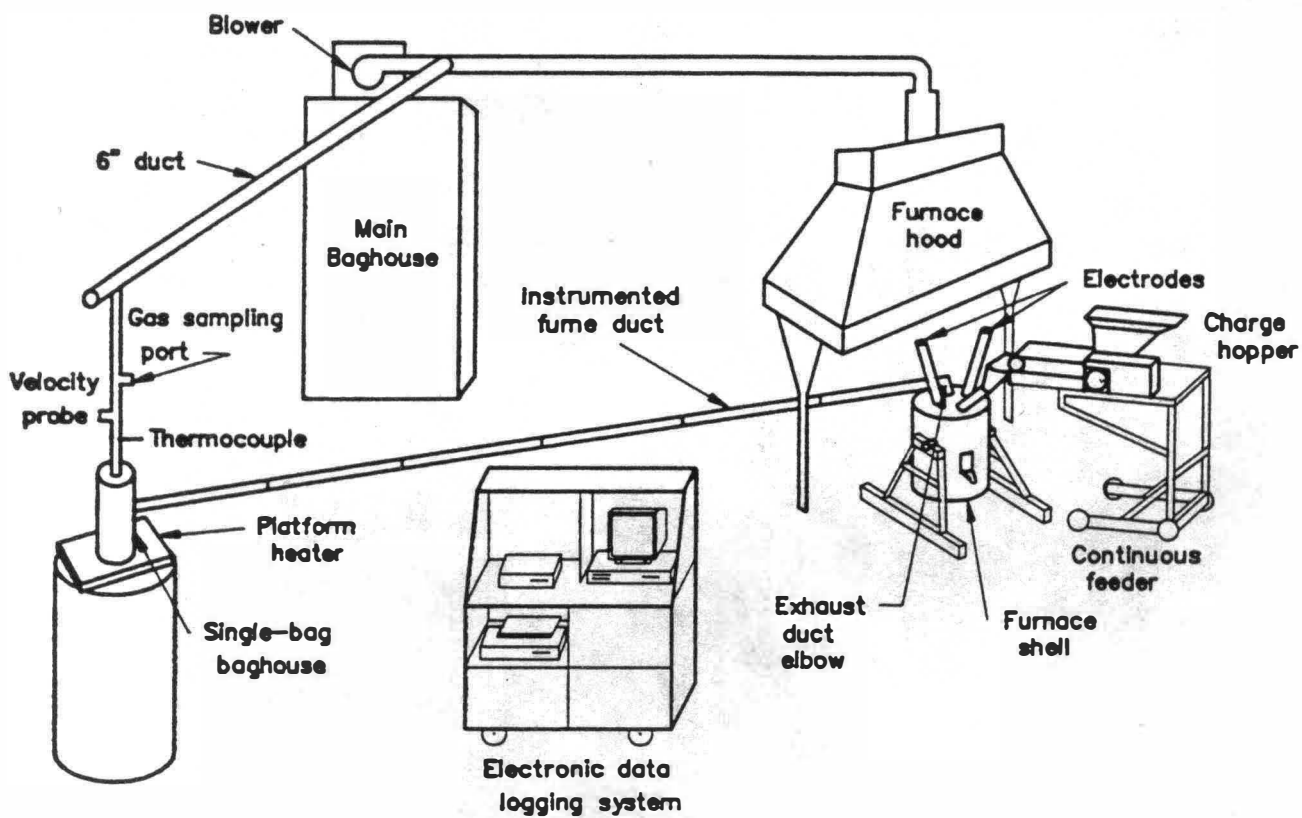


Figure 1: Schematic of 50-kW Electric Arc Furnace

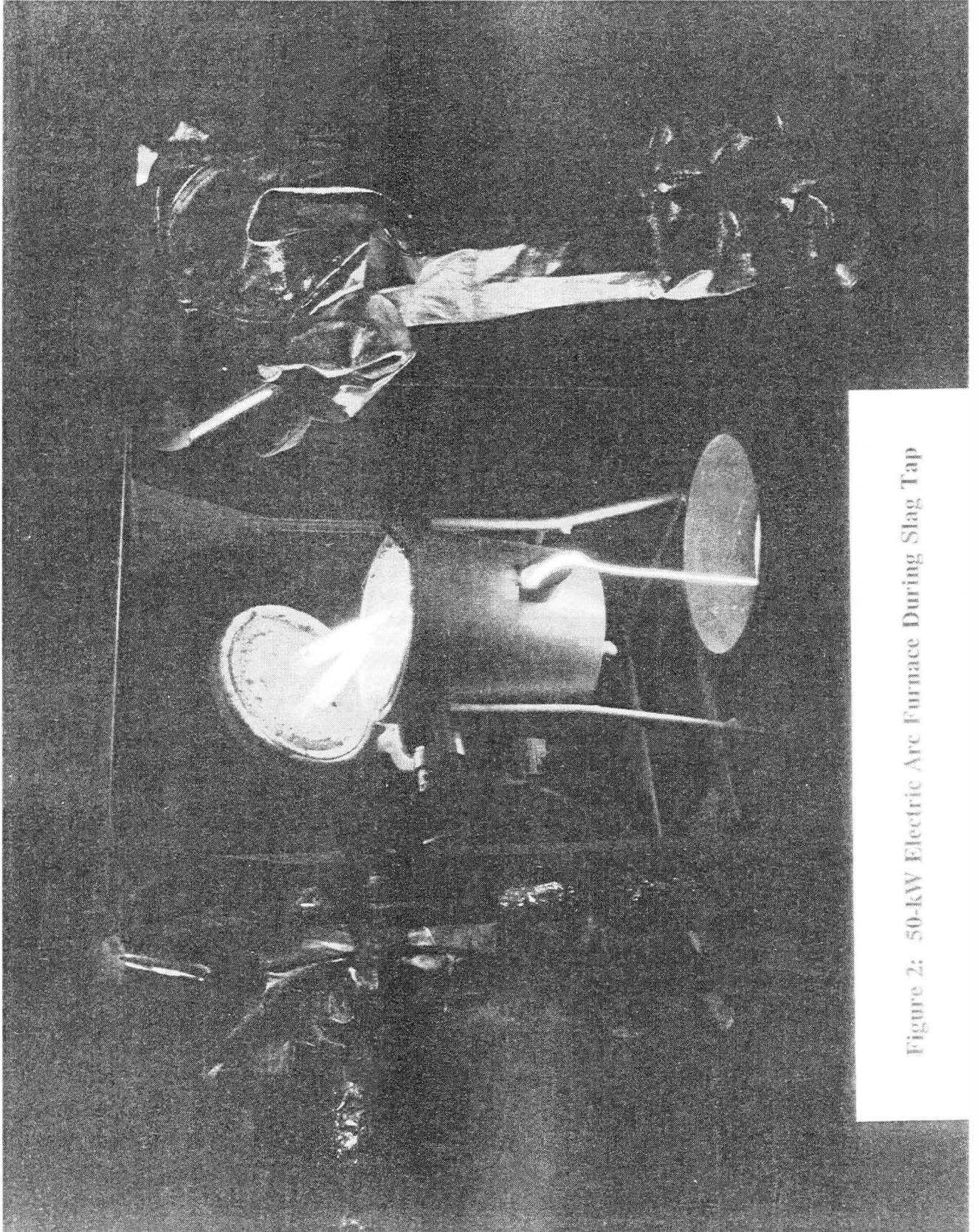
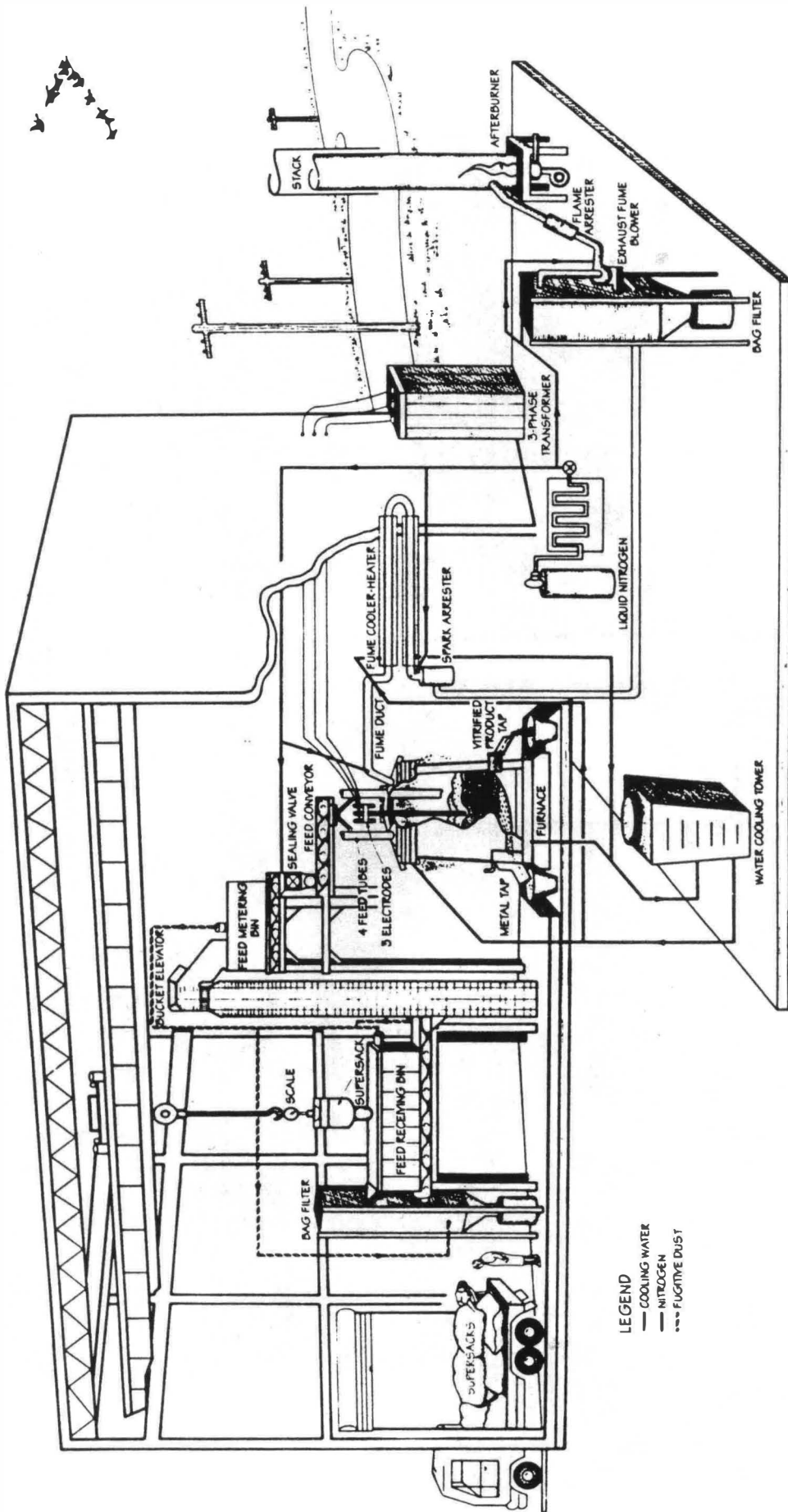


Figure 2: 50-kW Electric Arc Furnace During Slag Tap

SCHEMATIC OF WATER-COOLED ELECTRIC ARC FURNACE SYSTEM



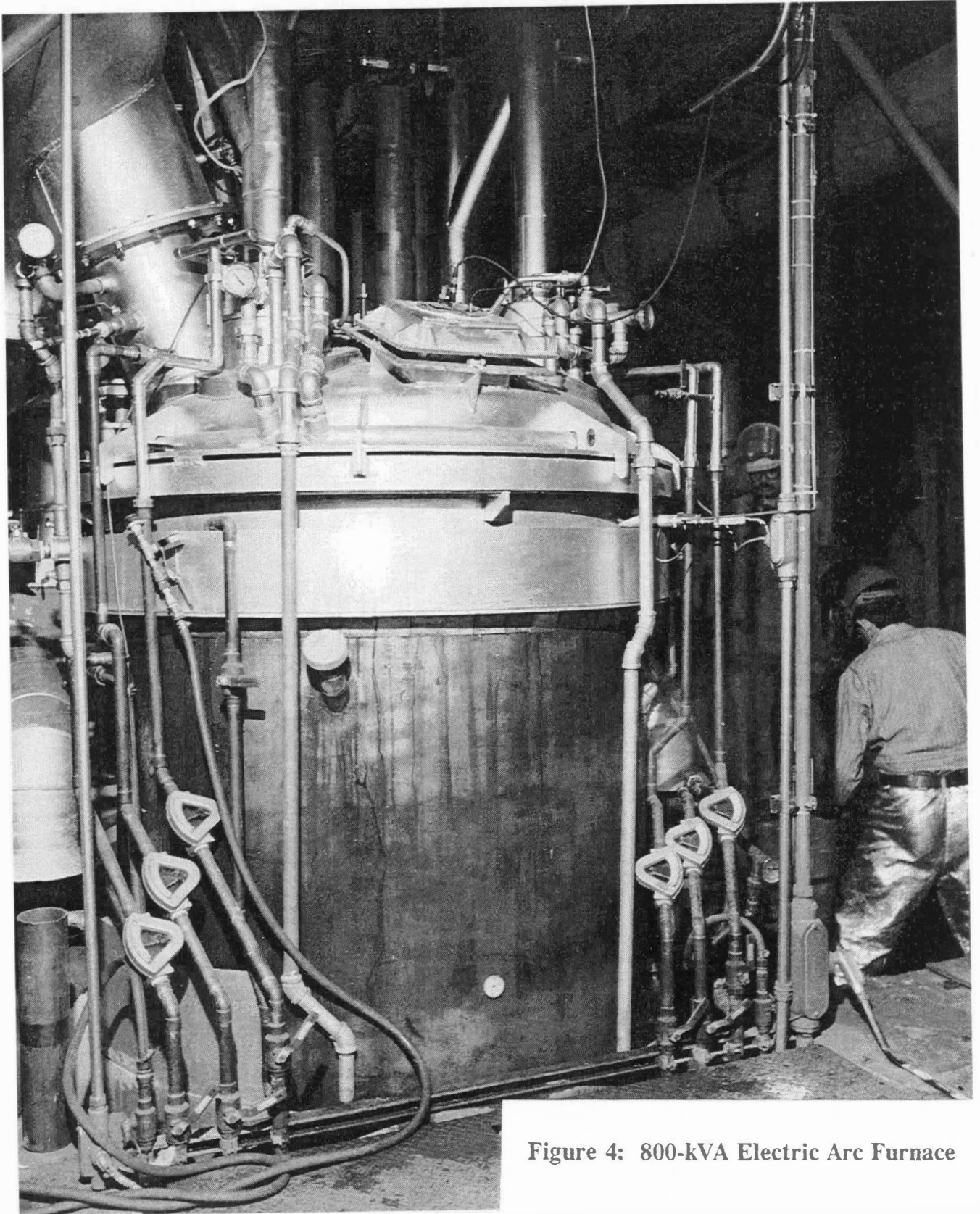
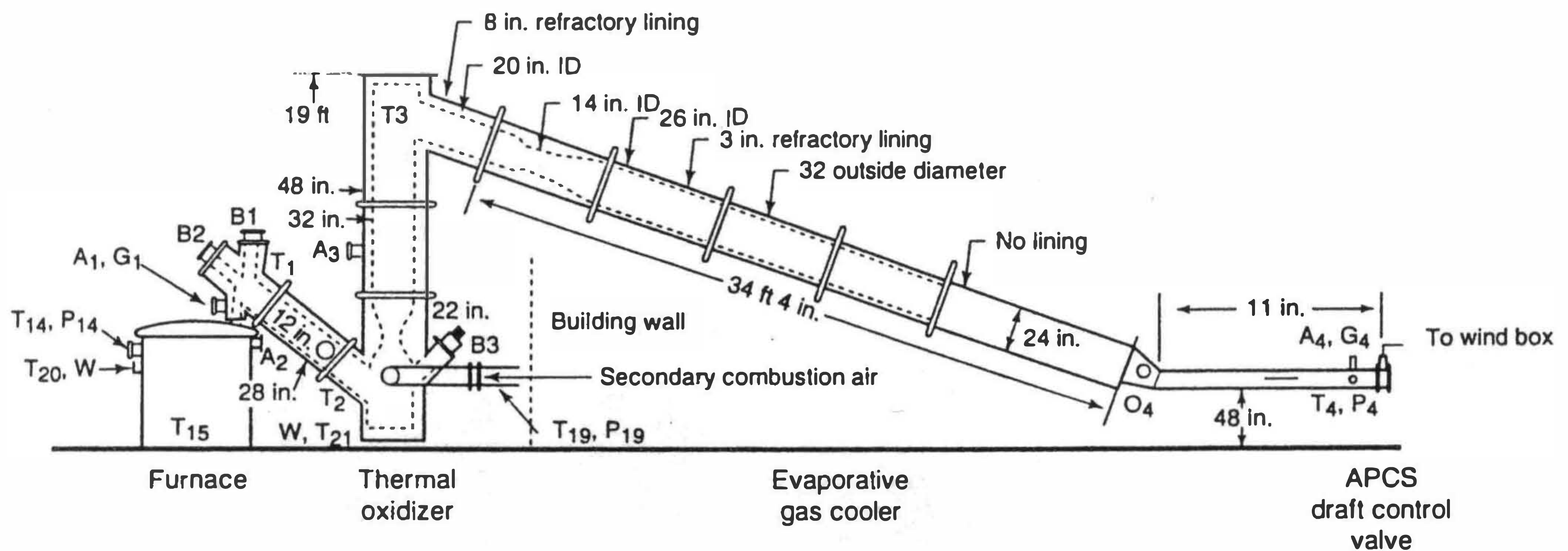


Figure 4: 800-kVA Electric Arc Furnace



- 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

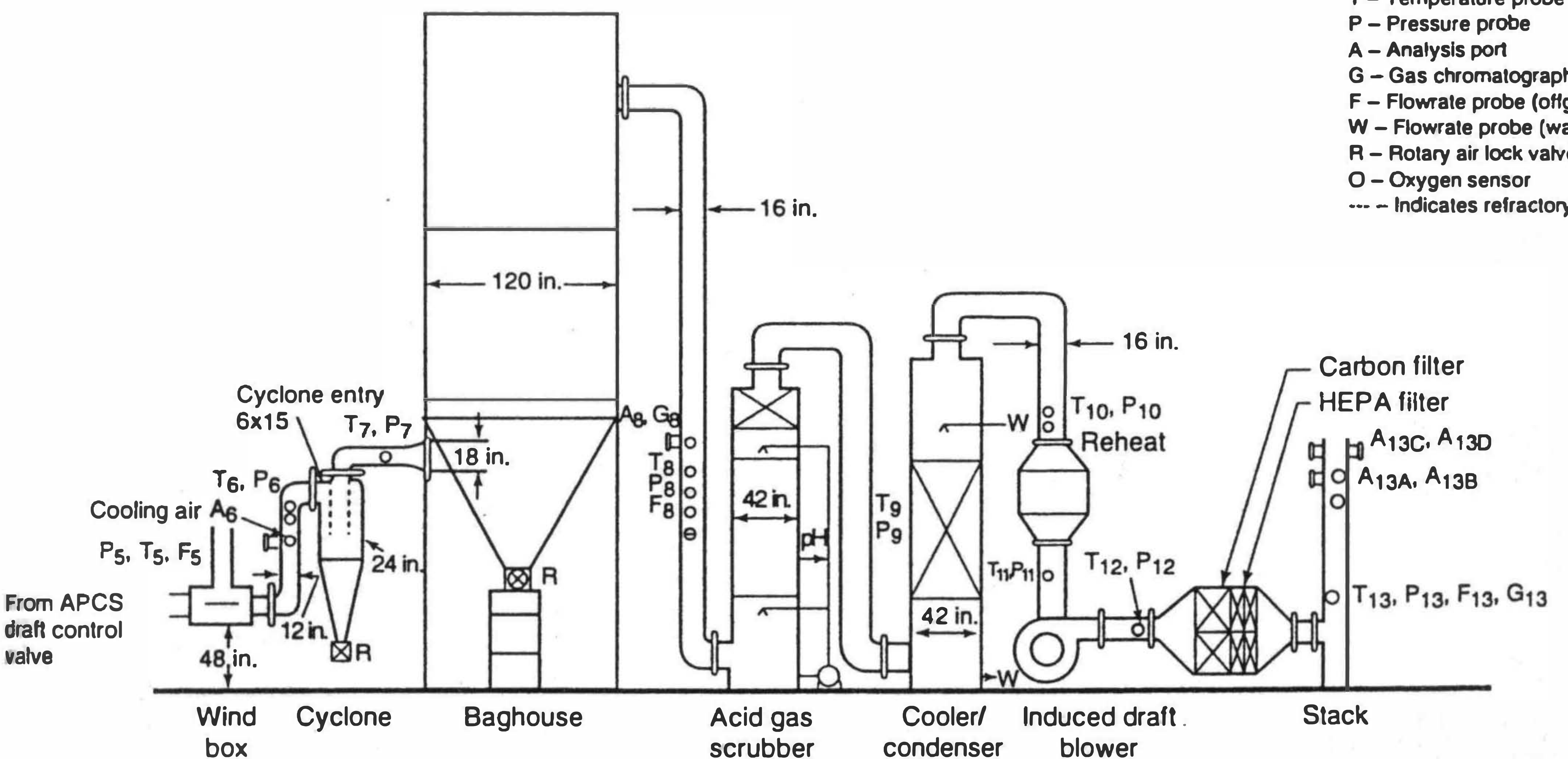


Figure 5: Schematic of APCS Equipment Available for Use on the 800-kVA EAF

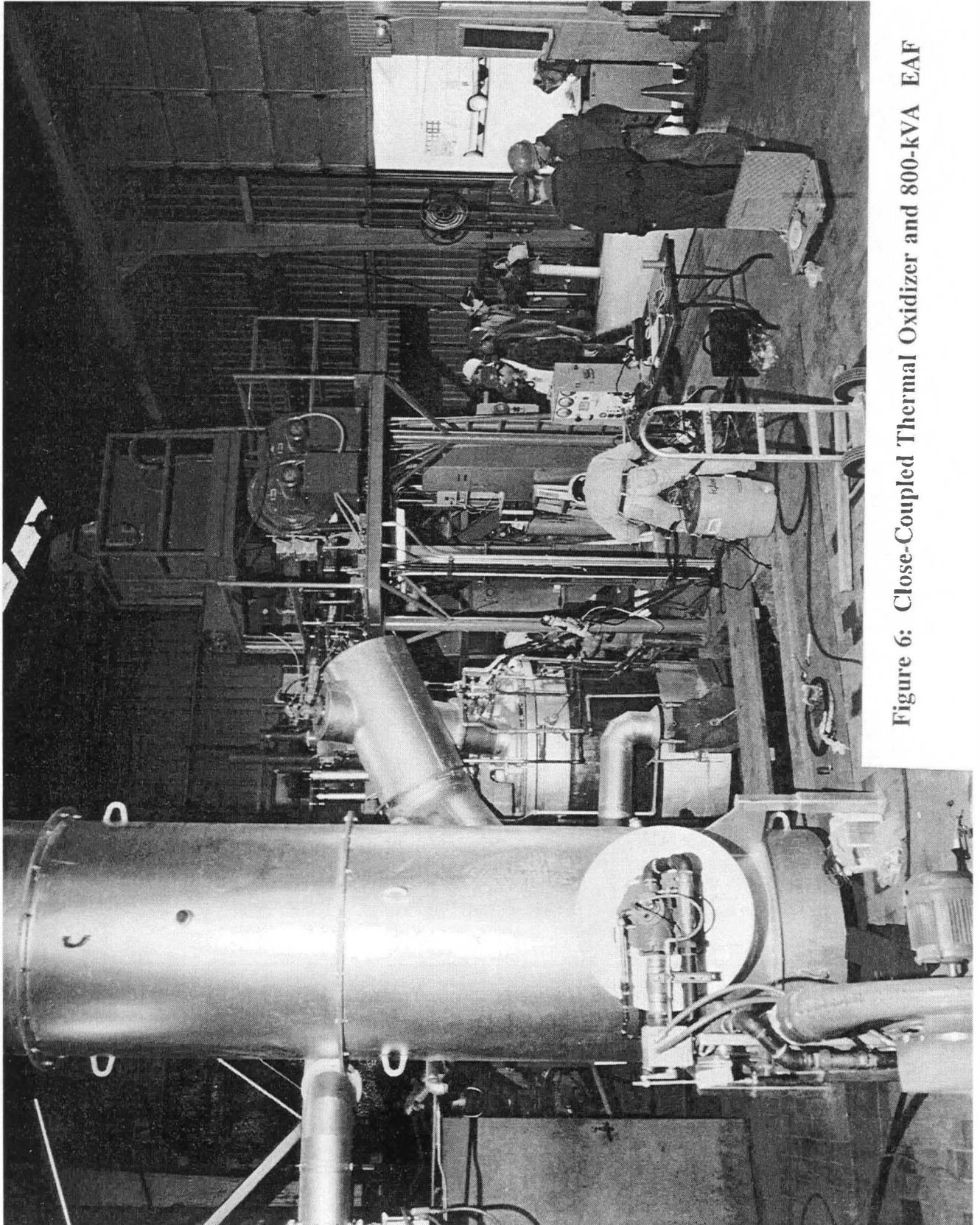


Figure 6: Close-Coupled Thermal Oxidizer and 800-KVA EAF

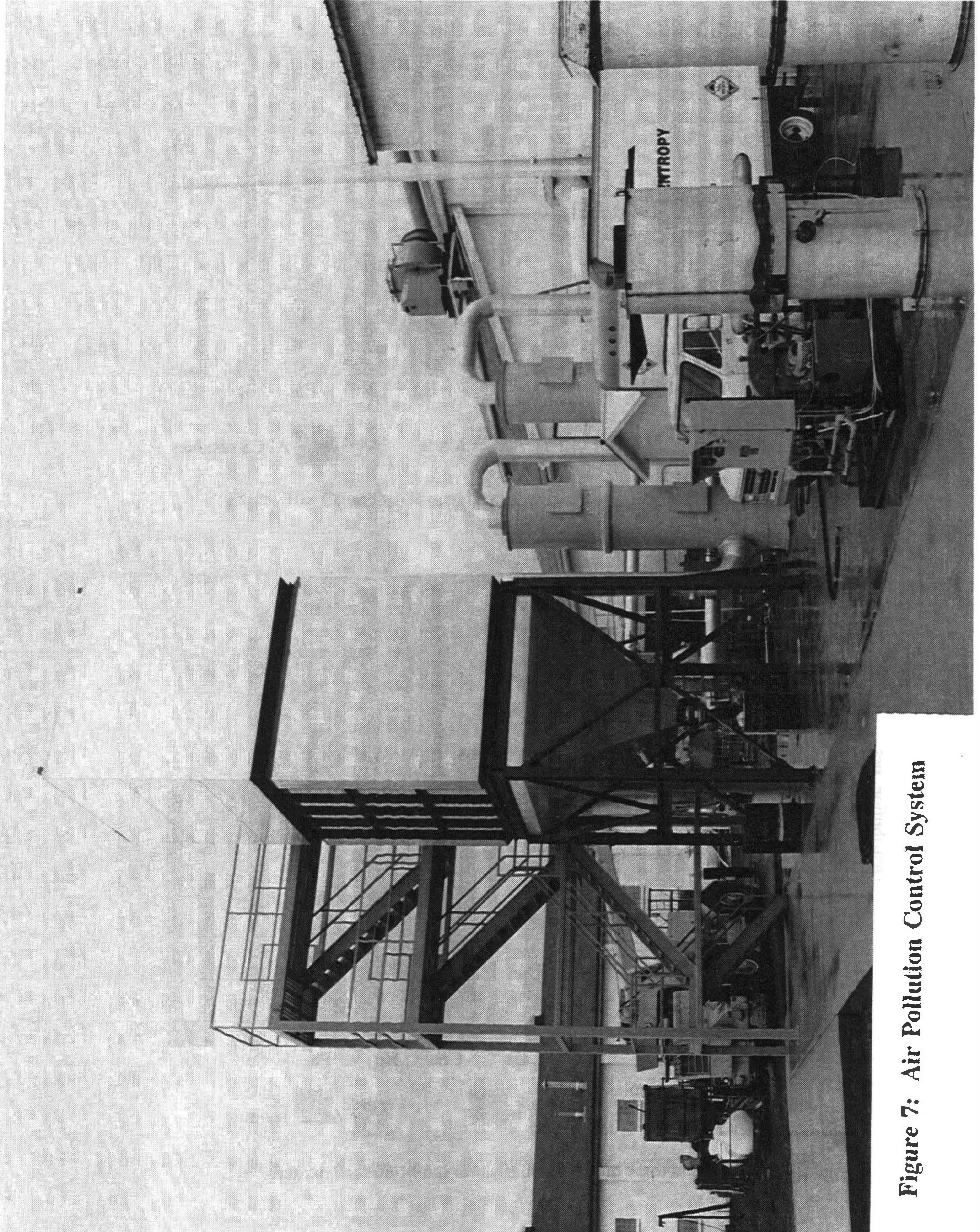


Figure 7: Air Pollution Control System

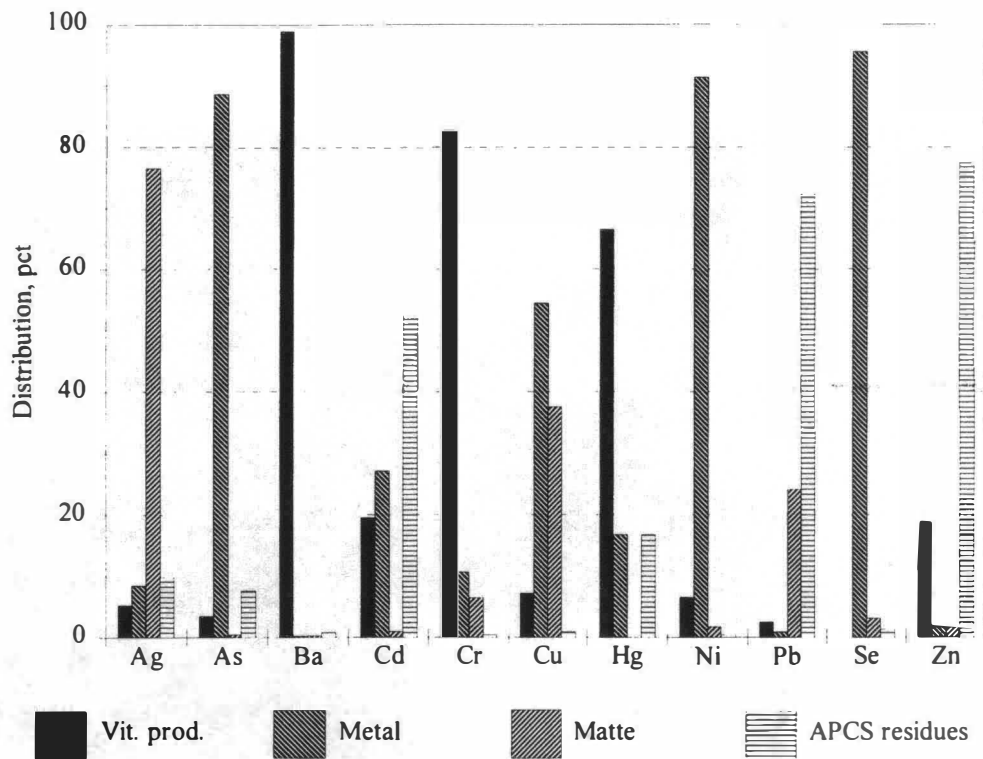


Figure 8.- Toxic metal distribution for Residue A.

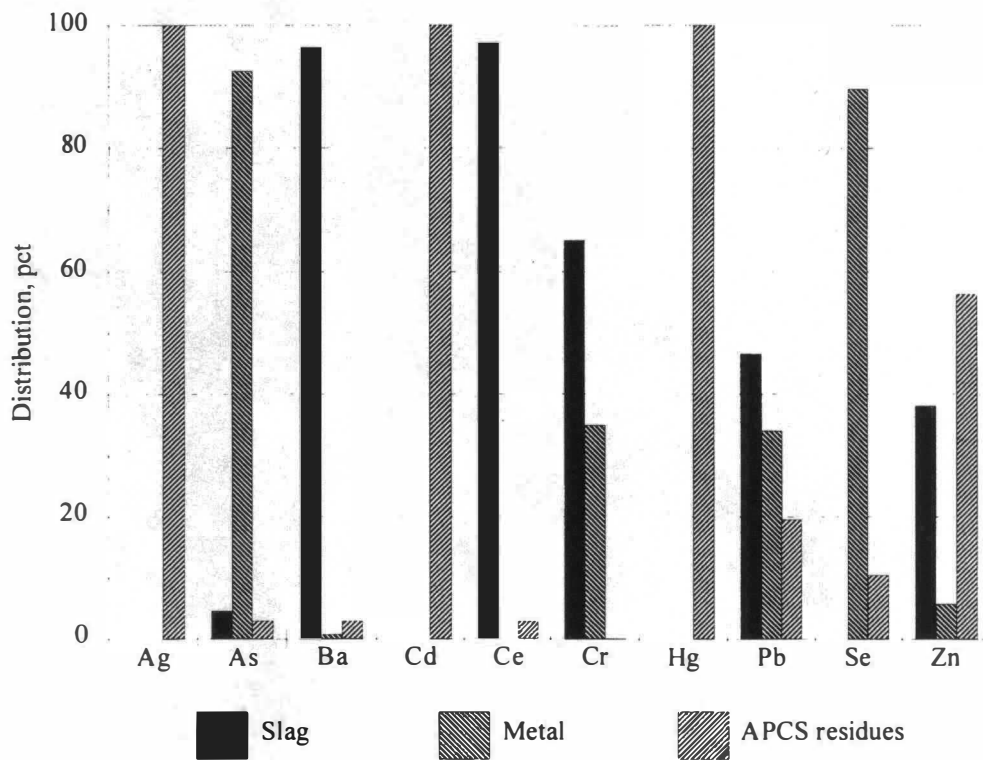


Figure 9.- Cerium and toxic metal distribution for the M-60 feed mixture.

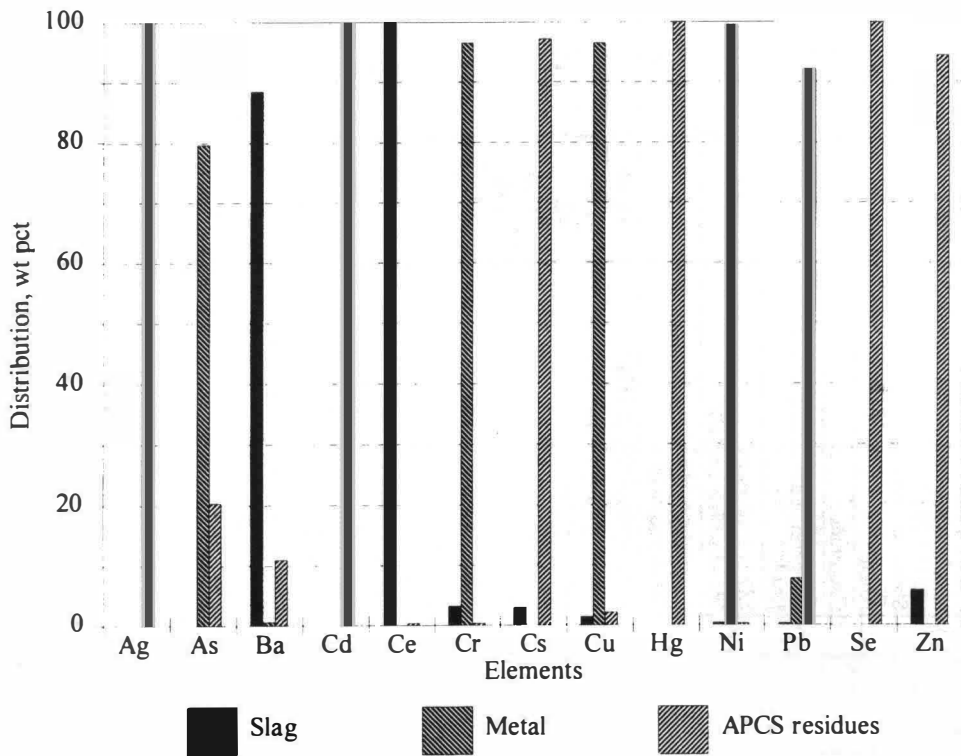


Figure 10.- Ce and toxic metal distribution during BWID feed interval.

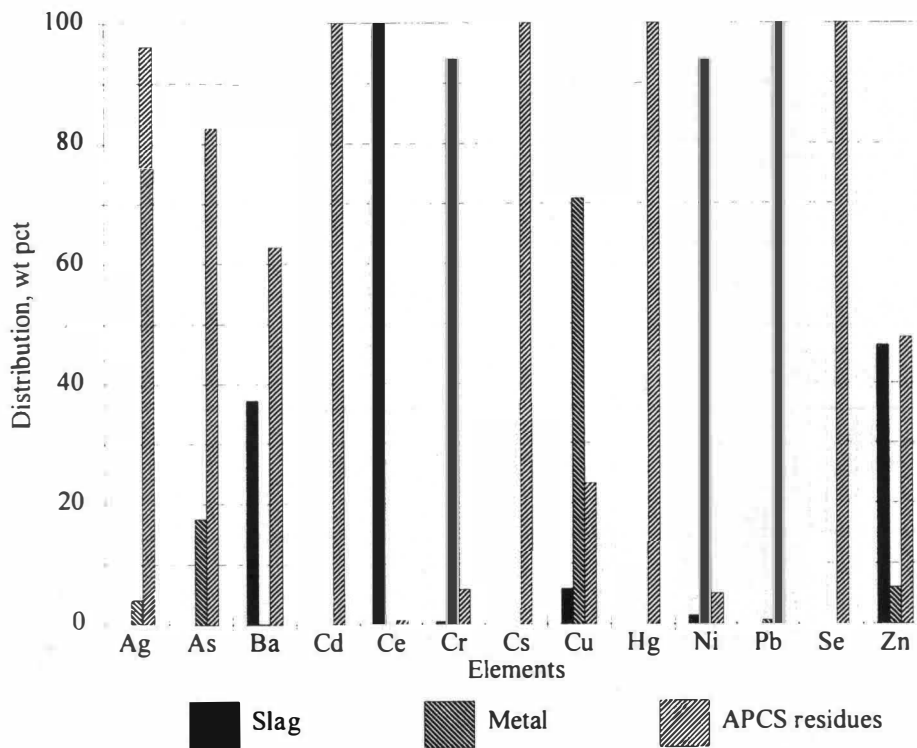


Figure 11.- Ce and toxic metal distribution during IWPF feed interval.

Table 1-a:

Composition for the nominal feed mixture (without added soil, lime, or cerium oxide).

Component	Composition in Weight %						Total of Each Group in Nom. Comp.
	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, (-C112-C112-)		25.90				6.29	
Wood pellets (paper, wood, cloth)		63.80				15.50	
Neoprene rubber, (-C112CCI-C112-)n		10.30				2.50	
Oil Dri sorbent							24.30
Texaco Regal Oil, (C112)n			22.59			3.69	
Wheel bearing grease, (C112)n			2.73			0.44	
PVC, (-C113Cl-)			16.95			9.70	
Microcel E			35.20			5.74	
Oil Dri			22.54			3.68	
LD Polyethylene, (-C112-C112-)							23.25
NaN03				36.97		2.70	
KNO3				18.48		1.35	
NaCl				2.11		0.15	
Na2SO4				2.03		0.15	
NaOH				2.03		0.15	
Water				38.37		2.80	
LD Polyethylene, (-C112-C112-)							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	
H2O					27.25	2.09	
Portland Cement					15.12	1.16	
LD Polyethylene, (-C112-C112-)							7.66
Totals	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 1-b:

Compositions of the C and S feed mixtures.

Component	Comp. in Weight %	
	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
Oil Dri sorbent		1.66
Texaco Regal Oil, (C112)n	16.40	
Wheel bearing grease, (C112)n	1.98	
PVC, (-C113Cl-)	42.97	7.89
Microcel E	25.56	
Oil Dri	9.70	
LD Polyethylene, (-C112-C112-)		
Vermiculite		1.14
Leaded rubber		2.40
Teflon		0.04
Latex (surgens gloves)		7.69
Magnesium		
Nickel		
Antimony		
Zinc		
Totals	100.00	100.00

Table 2: Chemical Compositions of SCE Feeds and Theoretical Slags

Component	Conc., mg/kg						
	Serpentine	SCE Bottom Ash	Theoretical Slag	Bottom Ash with 10 pct Serpentine	Theoretical Slag	Ash/Serp/ 20 pct Lime	Theoretical Slag
Ag2O	---	6	6	5	6	4	4
Al2O3	17400	86500	93431	79590	86594	62290	66695
As2O3	---	9	10	8	9	6	7
BaO	---	64	69	58	63	45	48
CaO	15000	49000	52926	45600	49613	235800	252476
CdO	---	230	248	207	225	161	172
CeO2	---	40	43	36	39	28	30
Cl	---	2040	0	1836	0	1428	0
CO2	---	8543	0	7689	0	5980	0
CrO2	---	548	592	493	537	384	411
Cs2O	---	10	11	9	10	7	7
CuO	---	5413	5847	4872	5300	3789	4057
Fe3O4	61000	41000	44285	43000	46784	34800	37261
H2O	142000	0	0	14200	0	14200	0
HgO	---	<0.1	0	<0.1	0	<0.1	0
K2O	---	15910	17185	14319	15579	11137	11925
MgO	388300	23800	25707	60250	65552	55490	59414
Na2O	100	23500	25383	21160	23022	16460	17624
NiO	---	108	117	97	106	76	81
P2O5	---	1910	2063	1719	1870	1337	1432
PbO	---	1211	1308	1090	1186	848	908
SO3	---	917	0	825	0	642	0
SeO2	---	9	10	8	9	6	7
SiO2	377000	671000	724767	641600	698064	507400	543284
TiO2	---	3900	4213	3510	3819	2730	2923
ZnO	---	1558	1683	1402	1526	1091	1168
ZrO2	---	89	96	80	87	62	67
Al	---	30	---	27	---	21	---
Cr	---	400	---	360	---	280	---
Cu	---	7800	---	7020	---	5460	---
Fe	---	40000	---	36000	---	28000	---
Ni	---	100	---	90	---	70	---
Zn	---	2100	---	1890	---	1470	---
Total	1000800	989000	1000000	989051	1000000	991502	1000000

Slag Basicity

Bottom Ash Only	Bottom Ash/ Serpentine	Ash/Serp/ 20 pct Lime
0.21	0.26	0.63

Sample Calculation (Ash/Serp)

Basic Oxides 206240

Acid Oxides 784658

Basicity 0.26

Table 3. Calculated Chemical Composition of the INEL 1993 Feed Mixtures.

Component	Concentration, ppm							
	S60	S60-IV	N80	N80-Mod	N80-IV	N80-IV-Mod	M60	M60-Mod
Ag2O	5	4	7	4	6	4	6	4
Al2O3	75718	68047	82132	51940	71594	50580	75416	45920
As2O3	7	6	10	6	9	6	8	6
BaO	432	432	432	288	432	288	504	216
CaO	87436	83726	56074	165543	49286	180936	58968	265787
CdO	0.3	0.3	0.4	0.3	0.4	0.3	0.4	0.2
CeO2	3961	3957	3971	2646	3966	2645	4620	1988
Cl	12093	12690	85	53	81	57	25	50
CO2	26555	23359	99890	166447	95754	68137	29657	61009
CrO2	581	528	418	446	311	418	204	369
Cs2O	4048	4301	<50	<50	<50	<50	<50	<50
CuO	32	28	42	459	37	504	35	442
F	552	552	552	368	552	415	644	351
Fe3O4	161050	161386	92328	187915	88271	204963	26991	179898
H2O	70577	63178	75043	47470	66866	51640	63731	41713
HgO	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
K2O	14085	12390	60758	38534	58628	40960	15370	35797
MgO	25173	23992	17993	12446	15523	11472	14479	10770
Na2O	18275	6722	71891	45077	70786	49649	8115	43853
NiO	23	20	30	268	27	294	26	258
P2O5	1293	1413	1637	1078	1433	1079	1363	994
PbO	14	12	19	12	16	12	16	12
SO3	29208	29513	756	476	545	613	221	711
SeO2	0.6	0.5	0.7	0.5	0.7	0.5	0.6	0.4
SiO2	441135	406393	430499	272585	379236	266639	378234	241195
TiO2	20574	49926	11317	7135	65103	45405	2762	39665
ThO2	22	22	25	16	30	20	26	17
UO2	2	1	2	1	11	8	2	7
ZnO	78	69	103	65	90	63	87	57
ZrO2	76	25826	100	63	33448	23889	85	21024
Al	---	---	---	---	---	---	18400	---
Cr	---	---	---	---	---	---	17100	---
Cu	---	---	---	---	---	---	7400	---
Fe	---	---	---	---	---	---	249500	---
Ni	---	---	---	---	---	---	9600	---
Pb	---	---	---	---	---	---	7400	---
Zn	---	---	---	---	---	---	14700	---
Total	993006	978496	1006114	1001342	1002041	1000698	1005693	992110

Table 4 - Calculated Elemental Composition of the INEL 1995 Feed Mixtures (mg/kg)

Element	Preheat interval		BWID feed interval										IWPF feed interval				Clean. interval Nom-90M	Total feed wt. mean
	Method B	TH+silica	Nom-90	Nom-80	Nom-70	Nom-60	Soil+lime	Nom-50	Nom-40	S-40	S-0	C-20	C-40	Nom-90M	Total feed wt. mean			
wt. lb	2394	4424	1495	1497	3998	3976	500	1486	977	1594	1098	300	497	3284	27520			
wt. pct	8.7	16.1	5.4	5.4	14.5	14.4	1.8	5.4	3.6	5.8	4.0	1.1	1.8	11.9	100.0			
Ag	NA	NA	1.2	1.1	0.99	0.89	1.28	0.78	0.66	1	0.81	0.33	0.6	1	1			
Al	47500	126090	44500	43200	41600	39800	46490	37800	35500	23400	4000	21900	29700	39135	52069			
As	NA	NA	5.1	4.8	4.5	4.1	4.5	3.7	3.3	4.5	3.8	1.7	2.8	4	3			
Ba	30	NA	700	600	600	500	753	400	400	400	20	200	400	633	391			
C	27100	70809	22300	37400	53500	70700	8520	89000	108400	181200	323000	396400	282900	7314	77468			
Ca	32000	233462	192300	172600	152800	133000	206995	113000	92900	147300	105600	48700	88800	218571	155686			
Cd	NA	NA	1.9	1.7	1.6	1.4	2	1.3	1.1	1.6	1.3	300	200	2	8			
Ce	NA	NA	4200	3800	3400	3000	56	2600	2200	2900	1700	1200	800	47	1851			
Cl	3160	NA	5000	10300	16000	22100	34	28600	35500	122500	223000	33700	23800	31	26223			
Cr	30	NA	1600	3300	5100	7000	73	9000	11200	38	9.7	300	200	140	2932			
Cs	1200	NA	7.2	6.7	6.1	5.5	7.8	4.8	4	4.4	1.5	2.1	3.9	7	109			
Cu	NA	NA	500	900	1400	1900	51	2500	3100	25	4	2800	2000	280	902			
F	2580	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	200	200	NA	230			
Fe	5600	129	47000	70300	95200	121700	25967	149900	179700	13800	3600	24600	25300	87568	65361			
H	11600	1234	8200	10900	13800	17000	5721	20300	23800	28700	47600	68700	50300	5202	14591			
Hf	NA	NA	0.7	1.5	2.3	3.1	NA	4.1	5	NA	NA	NA	NA	NA	1			
Hg	NA	NA	0.093	0.085	0.078	0.069	0.09	0.06	0.051	0.067	0.041	0.026	0.048	0.1	0.1			
K	11800	220	13800	13700	13500	13200	14133	13000	12600	690	800	3700	6900	11910	9489			
Mg	1300	1790	11000	10400	9800	9100	11576	8300	7500	6300	1900	4900	6900	10238	7068			
Mn	10	NA	600	600	600	700	632	700	800	200	0	200	300	1025	474			
Mo	900	NA	33	69	100	100	NA	200	200	NA	NA	NA	NA	NA	131			
N	NA	NA	500	1000	1600	2300	NA	2900	3600	500	900	1000	700	NA	1019			
Na	136300	446	8700	9000	9200	9400	8632	9600	9800	5600	3000	2600	4500	7272	18030			
Ni	NA	NA	800	1600	2400	3300	36	4300	5400	23	11	100	100	168	1405			
O	490100	470633	438300	421600	403300	383300	458174	361600	338300	311700	191900	312000	356600	432083	405976			
P	800	NA	600	500	500	400	597	400	300	300	95	200	300	524	394			
Pb	NA	NA	200	300	500	600	17	800	1000	8.7	1.3	9800	6900	15	499			
S	800	NA	200	200	300	300	129	300	400	500	700	1000	700	111	305			
Se	NA	NA	1.2	1.1	0.99	0.89	0.61	0.78	0.66	1	0.81	0.33	0.6	1	1			
Si	229700	52302	194300	182200	168600	153500	208438	136800	118600	144700	89900	60800	107100	175650	146437			
Ti	500	22272	2600	2400	2200	2000	2855	1700	1400	1400	200	800	1500	2399	5109			
Zn	NA	NA	87	81	74	66	94	58	48	51	14	3600	2500	79	133			
Zr	30	NA	700	1400	2200	3000	102	3800	4700	51	9.1	27	50	85	1258			
Totals	1003040	979387	998737	998367	998291	997982	1000091	997574	997363	992299	997972	999731	999658	1000494	995553			