VITRIFICATION OF MUNICIPAL WASTE COMBUSTOR RESIDUES: PHYSICAL AND CHEMICAL PROPERTIES OF ELECTRIC ARC FURNACE FEED AND PRODUCTS

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Abstract

The U.S. Bureau of Mines (USBM), in cooperation with the American Society of Mechanical Engineers (ASME), conducted over 200 hours of melting tests to vitrify residues from five municipal waste combustion facilities. Combined residues (grate residue and flyash) from three municipal waste combustors, a waste water treatment sludge combustor, and flyash from a refuse-derived-fuel (RDF) boiler, were sequentially melted in a 1-metric-ton (mt) water-cooled-wall electric arc furnace.

Each of the residues underwent magnetic separation, screen size analysis, and bulk chemical analysis prior to melting. The furnace products were examined by optical and electron microscopy and by X-ray diffraction. Bulk chemical analyses were acquired for the metal, fume, and vitrified furnace products. The material balance for the furnace operation indicates that from 69 to 86 pct of the feed reported to the vitrified furnace product, which had leaching potentials well below the EPA limit for each metal, as determined by the EPA TCLP.

The electric arc melting furnace currently is being utilized in a cooperative research project between the USBM and the Idaho National Engineering Laboratory (INEL) for melting tests on simulated low-level radioactive wastes.

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Introduction

Combustion is considered by Federal and State authorities as a practical step for in the disposal of nonrecyclable municipal wastes. A substantial reduction in waste volume (90 pct) is achieved through high-temperature combustion, and conservation of energy resources may be attained by recovering the inherent energy within the wastes as steam or electric power. However, some municipalities do not have sufficient land areas to dispose of even the remaining combustion residues (10 pct). In certain circumstances, there is also a perceived concern in regard to the long-term leaching character of residues placed in landfills for disposal. Current technology addressing this concern consists primarily of utilizing double-lined landfill cells for residue only, and immobilization techniques utilizing portland cement or chemical additives to minimize leaching. However, these immobilization techniques can significantly increase the volumes of wastes that must be landfilled.

It has long been thought that vitrification technologies could be applied to these residues to alleviate environmental concerns. Although other investigative work on vitrification is underway in the U.S., Japan, and elsewhere (*1-4*), there have been few definitive investigations regarding the processing of combined grate residues and air-quality-control (AQC) residues including derived environmental benefits, process costs, technical/operating requirements, and potential beneficial product uses.

The ASME and USBM, and agreed to cooperatively investigate commercial-scale vitrification of combustion residues. The U.S. Department of Energy (DOE) agreed to provide funds for the investigation on a cost-sharing basis, in recognition of the need for the program by affected users and the technical community.

An ASME Vitrification Subcommittee was formed from project participants to plan and conduct the vitrification test program that required (1) design and construction of a sealed 3-phase electric arc melting furnace having water-cooled shell and roof, (2) modification of an existing power supply to accommodate anticipated higher resistivity in the molten residues, and (3) design and construction of feeding and fume control systems. A complete discussion of the program objectives, furnace system, and operations is available from the ASME (*5*). A thorough presentation of the furnace system and specific equipment items is included in the USBM Report of Investigations 9476 (*6*).

An agreement was signed by ASME and USBM in September 1990 to conduct continuous melting tests in the electric arc melting furnace at the USBM Albany, Oregon, Research Center. Furnace design criteria and vitrification test parameters were mutually developed by ASME sponsors and USBM researchers. Participants included industry and Government researchers, furnace manufacturers and operators, academia, solid waste professionals, regulatory agencies, and private engineering consultants. The diversity of participants provided a broad range of experiences, vantage points, and concerns.

This report describes the physical and chemical properties of residues from five municipal waste combustion facilities, and the physical and chemical properties of the furnace products that resulted from processing these residues in the electric arc furnace.

Collection and Transportation of Residues

The residues originated from combustors in the northeastern United States, each representing a different state-of-the-art technology. The residues, collected during the winter of 1991, were selected by plant personnel to be representative of normal plant operation. Releases were obtained from the appropriate State regulatory agency for collecting, transporting, drying, and processing the residues.

Figure 1 traces the flow of each residue from source to final product. Points at which residues were sampled also are indicated. Combined municipal solid waste (MSW) combustor Residues A,

B, and C were extremely heterogeneous and required hand sorting, screening, magnetic separation, and drying prior to melting. These residues were collected and screened to minus 1 in at the plant site, then shipped in polyethylene-lined 1-short ton (st) Supersacks[1] to a drying operation in Elm Grove, Wisconsin. The dried residues were collected and rebagged in the Supersacks for shipment to the USBM test site in Albany, Oregon. Two 5-gal pail samples of residue from each Supersack, with a proportional quantity of the dryer baghouse dust, were collected as the bags were filled and were shipped with the Supersacks.

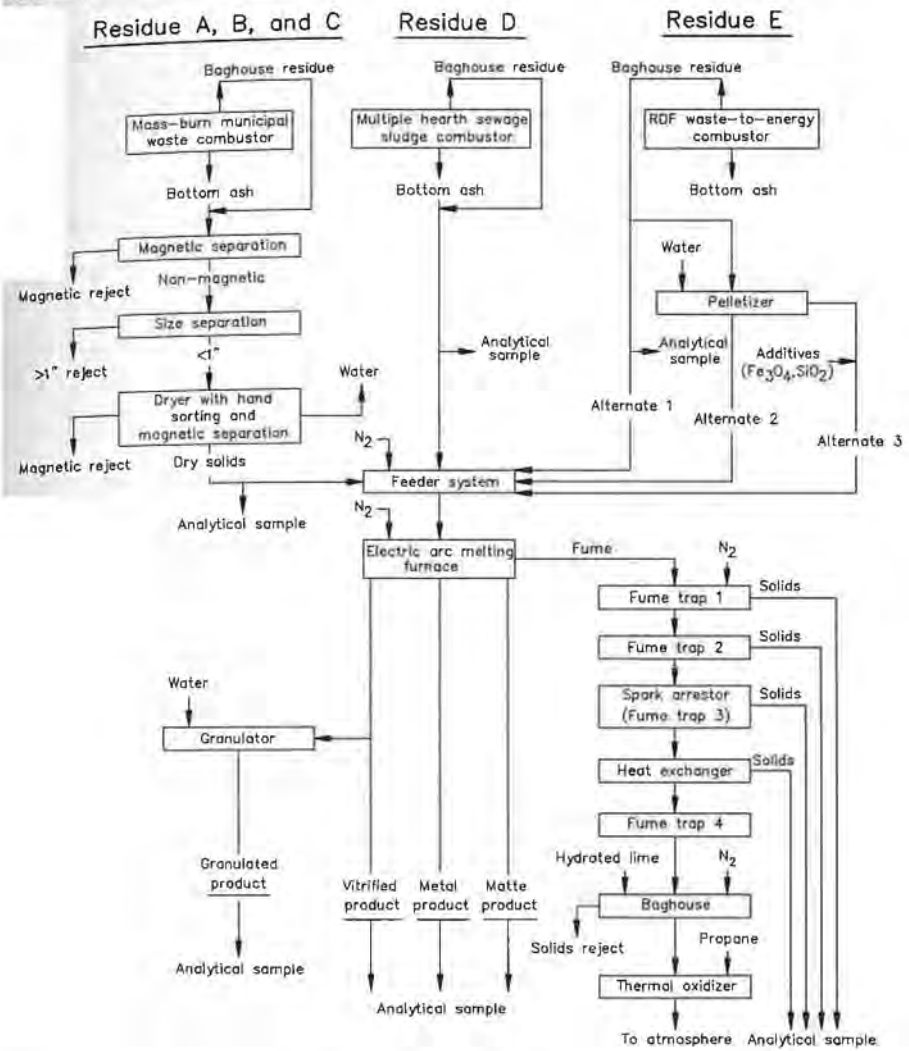

Figure 1 - Project flow diagram.

Sewage sludge combustor Residue D and RDF baghouse Residue E were collected at the plant site, bagged in polyethylene-lined 1-st Supersacks, and shipped directly to the Albany Research Center. Two 5-gal pail samples from each Supersack, collected by plant personnel while the bags were being filled, accompanied the Supersacks.

Analysis and Description of Residues

Sampling Procedures

The chemical analyses and physical determinations underscore the variability of the mass-burn residues. These residues were collected at nearly the same time of the year, so the variability likely derives from the relative mix of residential and industrial sources, specific industrial contributors, and construction debris. The temperature achieved during combustion also can influence the composition of the residues since lower combustion temperatures would be expected to result in higher concentrations of volatile or combustible elements including C, S, and halogens in the grate residue. Higher combustion temperatures would favor increased proportions of metal in the grate residue owing to oxidation of thin metal fragments such as tin-plated steel cans (Fe, Zn), aluminum foil (Al), galvanized steel sheet (Fe, Zn), and coated fasteners (Cd, Zn, Al, Pb). However all volatile metals, compounds, and acid gases that exit the combustor are collected in the fly ash or AQC system and are re-combined with the grate residue.

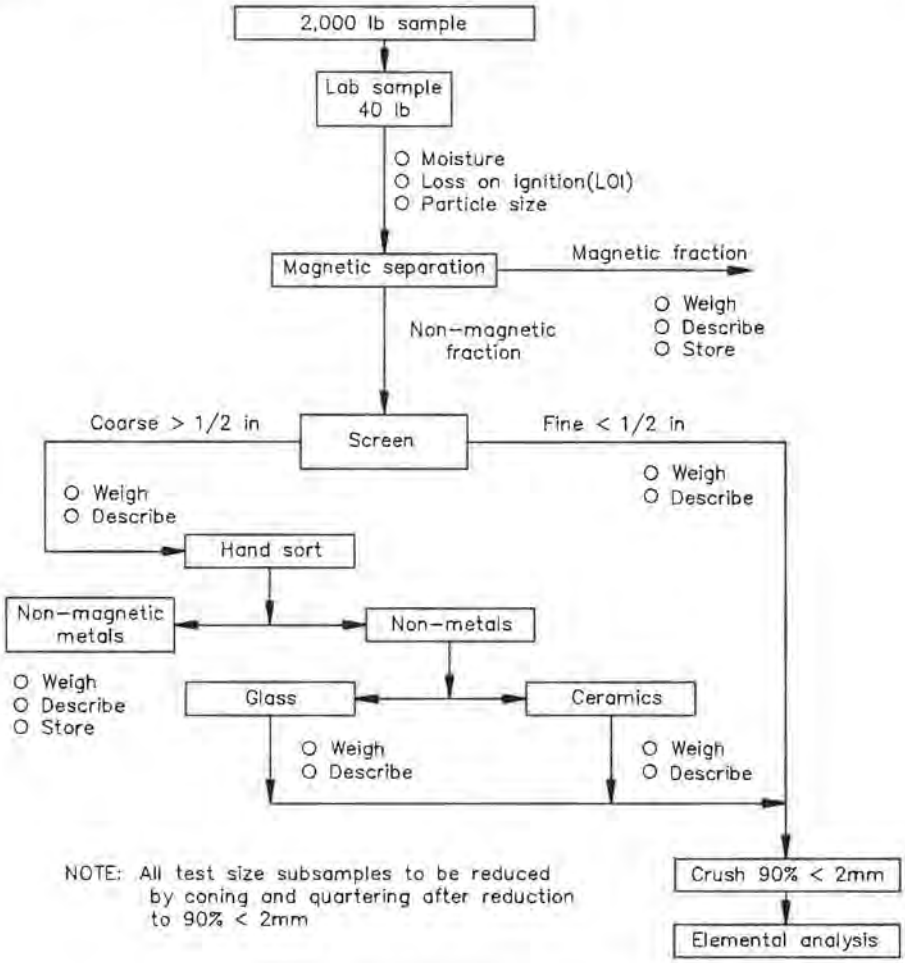

Figure 2 - Residue sampling methodology.

The 5-gal pail samples for each residue were mixed, coned, and quartered to obtain four 40-lb samples representative of each residue. Each of the 40-lb samples was further treated according to the sampling methodology shown in Figure 2 to obtain material for chemical analysis. Thus, four separate analyses were obtained for each residue. The physical properties and chemical composition of the residues are discussed below.

Physical Properties of Residues

Each residue was evaluated with respect to its physical description, bulk density, particle size, magnetic separability, loss on ignition (LOI) at 1,000° C, and moisture content. Table I lists the physical properties of the residues.

Table I. Physical properties of residues

Residue	Moisture, pct	LOI, pct	Magnetic fraction, pct	Bulk density
A	1.5	5.7	10.2	1.25 g/cm^3 (78.0 lb/ft^3)
B	1.4	1.4	17.4	1.74 g/cm^3 (109.0 lb/ft^3)
C	0.9	2.5	12.7	1.14 g/cm^3 (71.2 lb/ft^3)
D	0.4	0.7	51.9	0.50 g/cm^3 (31.2 lb/ft^3)
E	1.6	5.2	2.7	0.65 g/cm^3 (40.6 lb/ft^3)

Description. Residues A, B, C, and E were odorless, whereas residue D had a distinctive but not offensive odor. Residues A, B, and E were light gray, residue D was rust-orange, and residue C was dark grey in color. Each of the mass-burn residues (A, B, and C) contained identifiable fragments of glass, ceramic ware, bricks, and other nonmetallic materials as well as nuts and bolts, wire, coins, springs, other pieces of metal, and stainless steel eating utensils. An additional magnetic separation was conducted to determine the magnetic fraction in each residue. Readable pieces of newsprint were observed in residue A. Automobile spark plugs were observed in residues B and C. Residues D and E were homogeneous, fine grained, granular materials.

Moisture Content. The moisture content was determined by drying a 40-lb sample of each residue at 105° C for 12 h. The values determined for the mass-burn residues as-received in Albany, Oregon, were very similar to the values as-shipped from the dryer, confirming the integrity of the polyethylene-lined Supersacks. Moisture levels for residues D and E, as received at the test site, also were well below the 5 pct target level, which was established as the maximum to ensure stable operation in the furnace. Residue E, however, was very hygroscopic. The weight of a pelletized sample increased 7.14 pct when exposed for 2 weeks to ambient indoor air at Albany, Oregon. Thereafter, the sample was a faithful indicator of relative humidity, gaining weight on humid days and losing weight on dry days.

Loss On Ignition. Loss on ignition was determined by heating a 50-g sample in air at 1,000° C for 1 h. The values for LOI have little significance for the heterogeneous mass-burn residues owing to the prevalence of metallic components that oxidized and gained weight upon heating in air. The large LOI, especially for residue E, likely indicates the presence of $CaCO_3$ formed by interaction of $Ca(OH)_2$ or residual CaO with atmospheric CO_2.

Magnetic Separation. Magnetic separability for the 40-lb samples was determined using a dry magnetic separator. The proportion of magnetic material in the mass-burn residues ranged from 10 to 17 pct. The fraction of magnetic material in RDF fly ash residue E was very small. Approximately 50 pct of sewage sludge combustor residue D reported to the magnetic fraction. This is attributed to the use of ferric chloride flocculent or ferrous sulfate for phosphorous removal in the

final water polishing step of sewage treatment. The resultant ferric hydroxide likely was converted in the combustor to magnetite (Fe_3O_4), and the small particles of magnetite carried much of the nonmagnetic residue to the magnetic fraction.

Screen Size Distribution. The screen size distribution of each residue was determined over the range 127 mm (1/2 in) through 0.15 mm (100 mesh). The results are reported in Table II as the weight percent reporting to each of 13 size ranges, and in Table III as the cumulative weight percent finer than each of 13 sizes. The results are repeated in graphical format in Figures 3 and 4, which highlight the dissimilar physical nature of the mass-burn residues. Residue B was considerably coarser than Residue A and C; approximately 50 pct of Residue B was coarser than 1/4 in (6.35 mm), while the same numbers for Residues A and C were 20 pct and 10 pct, respectively. Residue C was significantly finer than either Residue A or B, with over 25 pct of Residue C finer than 0.15 mm (100 mesh).

Table II. Weight Distribution of Sieve-Sized Residues

Size fraction		Weight percent				
Sieve*	Opening, mm	A	B	C	D	E
+1/2 in	+12.5	5.62	20.06	2.10	0.00	0.00
1/2 x 1/4 in	12.5 x 6.35	12.20	31.44	8.45	0.00	0.00
1/4 in x 6	6.35 x 3.35	18.56	15.93	12.21	0.00	0.00
6 x 8	3.35 x 2.38	7.50	4.73	7.75	0.00	0.00
8 x 12	2.38 x 1.68	7.44	4.01	9.01	3.42	0.05
12 x 16	1.68 x 1.18	7.44	3.13	7.26	6.49	0.20
16 x 20	1.18 x 0.83	7.15	2.53	5.41	7.06	0.64
20 x 30	0.83 x 0.59	6.47	2.73	5.45	8.13	1.23
30 x 40	0.59 x 0.42	5.48	2.40	4.45	7.63	2.58
40 x 50	0.42 x 0.30	5.48	2.53	4.97	8.91	4.55
50 x 70	0.30 x 0.21	3.26	1.42	3.08	11.90	4.50
70 x 100	0.21 x 0.15	2.86	1.55	4.38	12.54	11.07
-100	-0.15	10.54	7.54	25.48	33.92	75.18
Total		100.0	100.0	100.0	100.0	100.0
*U.S. sieve series.						

Table III. Cumulative Weight of Sieve-Sized Residues

Sieve*		Cumulative weight percent finer				
Number	Opening, mm	A	B	C	D	E
1/2 in	12.5	94.38	79.94	97.90	100.0	100.0
1/4 in	6.35	82.18	48.50	89.45	100.0	100.0
6	3.35	63.62	32.57	77.24	100.0	100.0
8	2.38	56.12	27.84	69.49	100.0	100.0
12	1.68	48.68	23.83	60.48	95.58	99.95
16	1.18	41.24	20.70	53.22	90.09	99.75
20	0.83	34.09	18.17	47.81	83.03	99.11
30	0.59	27.62	15.44	42.36	74.90	97.88
40	0.42	22.14	13.04	37.91	67.27	95.30
50	0.30	16.66	10.51	32.94	58.36	90.75
70	0.21	13.40	9.09	29.86	46.46	86.25
100	0.15	10.54	7.54	25.48	33.92	75.18
* U.S. sieve series.						

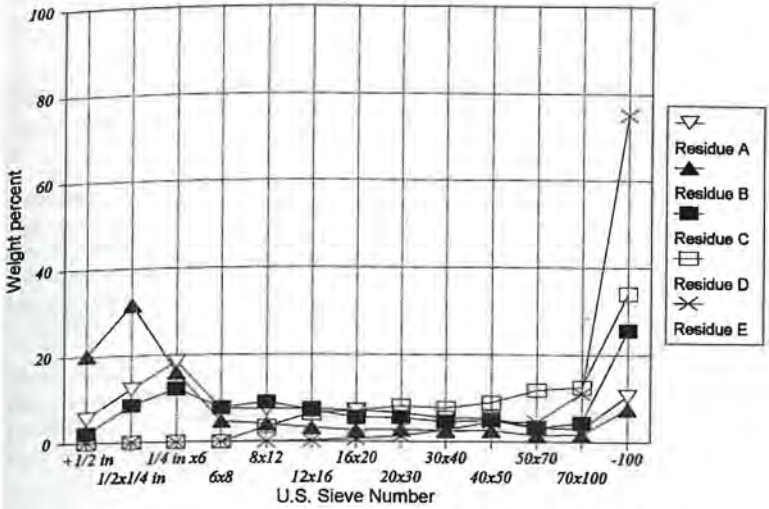

Figure 3 - Weight distribution of sieve-sized residues.

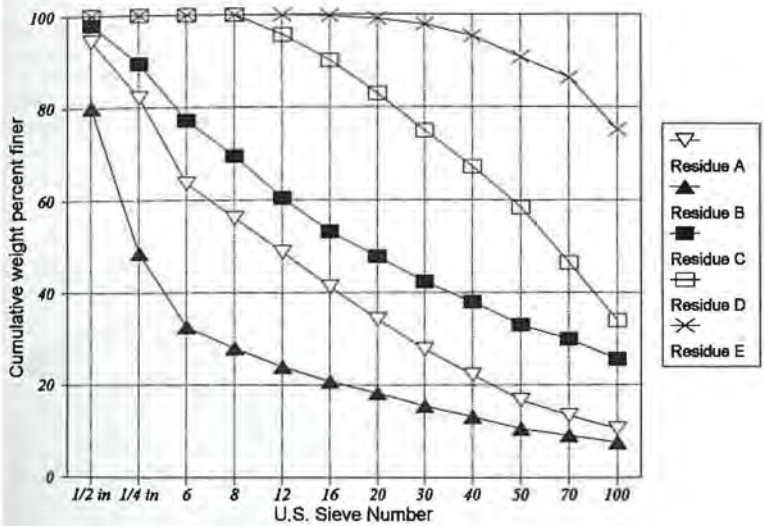

Figure 4 - Cumulative weight of sieve-sized residues.

Large, gravel-like fragments, extremely hard and up to 1 inch in diameter, were abundant in Residue B. Cross sections of these fragments revealed cores of some ceramic material (dinnerware, bricks, etc.) with thick coatings of fine agglomerated material.

Approximately 90 pct of Residue D was finer than 16 mesh (1.18 mm); over 30 pct was finer than 100 mesh (0.15 mm). Approximately 75 pct of Residue E was finer than 100 mesh (0.15 mm).

Chemical Composition of Residues

Samples for chemical analysis were derived from each of the four 40-lb representative samples of each dry residue according to the sampling methodology shown in Figure 2. Thus, each residue was analyzed in quadruplicate to determine the chemical composition. Table IV shows the arithmetic mean of four individual analyses.

Appropriate analytical procedures were used for each of the 38 elements determined. Wet chemical methods were used to determine B, Br (ion chromatography), Cl, Fe, P, and Si. Ba, Be, Bi, Cd, Ce, Co, Cr, Cu, Mn, Mo, Ni, Sn, Sr, Ti, V, Y, and Zn were determined by inductively-coupled plasma (ICP). Atomic absorption-flame emission analysis was used to determine Al, Ca, Hg, K, Li, Mg, Na, and Pb. Ag, As, Se, Sb, and Tl, which were present at very low levels, were determined by graphite furnace analysis. C and S were determined by infra-red analysis.

Truly representative sampling of the very heterogeneous mass-burn combustor residues was not possible owing to the prevalence of large metal fragments, which included tableware, spark plugs, copper and electrical resistance wire, fasteners, coins, springs, and other forms. These materials could not be included in the samples for chemical analysis; therefore, the analyses for the structural metals (Fe, Cu, Cr, Ni, Mn) may not be completely representative of the bulk residue.

The value for Fe in Table IV is more accurate for Residue A than for Residues B and C owing to a correction made by preparing an ingot comprised of a mixture of electrolytic iron and a known proportion of the coarse magnetic metal fraction from Residue A. This ingot was analyzed for Fe, and the concentration of Fe in Residue A was corrected.

A lime scrubber was used to remove acid gases from the AQC system of the RDF combustor. Thus, Residue E had an extremely high Cl content (20.2 pct), primarily as CaCl. Due to this high Cl content, additions of mill scale (as magnetite, Fe_3O_4), and silica (SiO_2), were made to improve the performance of Residue E in the furnace. High Cl was suspected to cause instability in the furnace. The composition of Residue E with and without additives is reported in Table IV.

Evaluation of Products

Description of Products

Five distinctly different materials were produced by melting the mass-burn (MSW) waste-to-energy (WTE) plant and sewage sludge combustor residues. Four of the materials were solids, and the fifth was furnace exhaust gas. The solid materials were identified as vitrified product, metal, matte (metal sulfide), and fume. A physical description of each component was recorded, and the components were sampled for later determination of physical properties and chemical composition.

Figure 5 - Hand sample of vitrified product from Residue A.

Residues A, B, C, and E produced noncrystalline glassy materials, properly termed vitrified products (Fig. 5), whereas the "vitrified" product from Residue D was predominantly crystalline. These materials contained most of the inorganic oxides in the residues, silica being the most abundant. When cooled slowly within large conical cast-iron molds, the

Table IV. Chemical Composition of Residues

Element	Concentration, ppm					
	A	B	C	D	E-1	E-2
Ag	16	10	28	217	14	8
Al	46080	36600	68900	29500	42500	24200
As	34	32	40	8	54	31
B	231	193	257	47	153	87
Ba	809	729	517	1290	544	310
Be	<1	<1	<1	<1	<1	<1
Bi	1500	1170	2050	1410	2050	1170
Br	28	73	86	8	660	376
C	24700	11100	61800	11600	45700	26100
Ca	70600	46700	37600	88800	161000	91800
Cd	26	21	46	24	69	39
Ce	<100	<100	<100	332	<100	<100
Cl	20900	15100	15000	341	202000	115000
Co	28	41	34	21	60	34
Cr	232	324	238	1370	194	111
Cu	4360	6750	8370	3450	407	232
Fe	83300	142000	50100	156000	21400	177000
Hg	6	3	13	<1	20	11
K	8140	7380	10400	14300	10500	5980
Li	16	22	26	17	32	18
Mg	12100	9780	10500	17300	6840	3900
Mn	924	1110	1100	551	589	336
Mo	<50	<50	<50	<50	<50	<50
Na	30300	25700	30900	5240	15200	8690
Ni	259	257	219	404	296	169
P	3820	2770	5290	86400	2520	1440
Pb	4090	3800	2170	211	1940	1110
S	13300	9650	12400	4750	40600	23200
Sb	142	105	192	16	405	231
Se	2	<1	1	8	11	6
Si	200000	216000	198000	108000	104000	149000
Sn	257	210	245	<200	200	114
Sr	631	354	326	834	376	214
Ti	5870	4780	7800	5250	7420	4230
Tl	<5	<5	<5	<5	<5	<5
V	50	56	59	50	56	32
Y	<50	<50	<50	<50	<50	<50
Zn	4160	3140	5900	2210	5200	2970

E-1: Residue E without additives

E-2: Residue E with additives

vitrified products from Residues A, B, C, and E were black, glassy materials visually indistinguishable from natural obsidian. The product from Residue D was a reddish-brown, predominantly crystalline material. When quenched in water, molten products from Residues A, B, C, and D produced coarse granular material.

Metal product, if present within the furnace, formed the bottom layer in the conical cast-iron molds when the metal taphole was opened to drain the furnace. Another solid phase, intermediate in density between the vitrified product and metal, was recognized in each metal tap except for Residue E. That phase was composed of Cu and Fe sulfides and is properly described as a matte.

Deposits in the fume traps and fume duct were collected from the locations shown in Figure 1 each time the duct was cleaned.

Exhaust gases were analyzed by personnel from AMTEST Air Quality, Inc., Preston, Washington. The gas constituents that were measured at one or more locations included particulate matter; chloride as HCl; multiple metals including Hg; SO_2 and CO; base/neutral/acid (BNA) extractable semi-volatile organic compounds; polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzofurans; and volatile organic compounds (VOC). Samples were collected according to EPA sanctioned methodology at one or more of the following locations in the pollution control system: (1) heat exchanger inlet, (2) baghouse inlet, (3) baghouse outlet, and (4) thermal oxidizer stack. The complete AMTEST report is available from the ASME (5).

Table V. Material Balance Over Electric Arc Melting Furnace

Product	Residue A		Residue B		Residue C		Residue D		Residue E-2	
	Wt, lb	Pct	Wt, lb	Pct	Wt, lb	Pct	Wt, lb	Pct	Wt, lb	Pct
Vit. product	20,261	78.0	6,067	83.4	3,717	68.7	11,478	86.4	897	86.3
Metal	1,622	6.2	357	4.9	382	7.1	93	0.7	0.0	0.0
Matte	186	0.7	64	0.9	118	2.2	22	0.2	0.0	0.0
Fume traps	661	2.5	129	1.8	239	4.4	108	0.8	90	8.7
Baghouse	2,497	9.6	479	6.6	727	13.4	1,388	10.4	0.0	0.0
Exhaust gas	751	2.9	182	2.5	225	4.2	199	1.5	52	5.0
Total	25,978	100.0	7,278	100.0	5,408	100.0	13,288	100.0	1,039	100.0

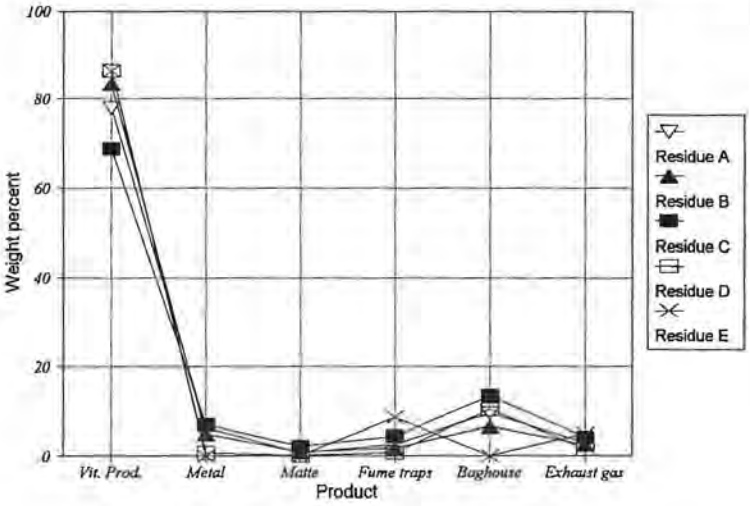

Figure 6. Material balance over electric melting furnace.

Material Balance

Material balances for each of the residues are listed in Table V and presented in graphical format in Figure 6. Percentages are based upon the weight of material melted. Both presentations provide the percent of each residue reporting to vitrified product, metal, and matte, and the total obtained from the fume traps, baghouse, and exhaust gas.

Product Microstructure

The furnace products from each of the residues were examined by light microscopy to identify the phases present and the physical nature of the materials. The vitrified products from Residues A, B, C, and E were essentially amorphous, confirmed by both microscopic examination and X-ray diffraction. However, in some samples of Residues A and C, abundant opaque, spherical inclusions, approximately 10 μm in diameter, were encapsulated within the glass matrix (Fig. 7). The inclusions were identified on a scanning electron microscope (SEM) as Fe oxide with inclusions of Fe and Cu sulfide. The presence of these encapsulated oxide particles did not affect the leaching characteristics of the glass.

Figure 7 - Spherical inclusions within glass matrix of Residue A vitrified product. Left, transmitted light; right, reflected light (scale is 100 μm).

Although the vitrified products from Residues B and E were essentially amorphous, a crystalline phase was detected within the glass matrix by microscopic examination. X-ray diffraction identified the crystalline phase as diopside [$CaMg(SiO_3)_2$]. As with the Fe oxide inclusions in the vitrified products from Residues A and C, the diopside inclusions did not detrimentally affect the leaching characteristics of the glass.

Residue D did not produce a vitrified product, but rather a coarsely crystalline material that was obviously not amorphous, even in hand sample. Microscopic examination revealed that this material consisted of prismatic intergrowths cemented by a fine-grained to amorphous matrix. X-ray diffraction identified the crystalline material as Ca, Mg, and Fe phosphate phases.

The metal and matte products from each of the residues also were examined with light microscopy, SEM, and X-ray diffraction. Their chemical compositions are discussed in the following section. A complete listing of the X-ray diffraction data is available from the ASME (*5*).

Chemical Analysis of Products

Each product recovered from the continuous 100-h melting test and the melting test of Residue E with additives was analyzed extensively. Complete chemical analyses were obtained for the contents of each conical mold, including vitrified product, metal, and matte. In addition, each

granulated product and each fume sample was analyzed. The weighted mean concentrations of furnace feed and products are compared for each residue in Tables VI-XII. A compilation of the entire set of chemical analyses for all furnace products and the distribution data is included in the test report available from the ASME (*5*).

Two tables are provided for Residue A, which underwent roughly 24 hours of continuous operations in the furnace. After the first 12 hours of continuous feeding, the fume solids were collected and subsequently recycled to the furnace over the next 12 hours. The fume solid recycle was conducted to determine the effectiveness of such a recycle scheme on concentrating Pb and Zn in the fume solids. Comparisons between Tables VI and VII indicate that recycling can indeed concentrate these metals in the fume solids.

Beneficial Uses of the Vitrified Products

Samples of the crystalline product from Residue D and the vitrified products from Residues A, B, C, and E-with-additives were tested at the Oregon Department of Transportation Materials Testing Laboratory to determine potential usage as aggregate for road building. The following seven ASTM aggregate tests were conducted:

1. C 29—Unit Weight and Voids in Aggregate,
2. C 88—Soundness of Aggregates by Use of Sodium Sulfate,
3. C 127—Specific Gravity and Absorption of Coarse Aggregate,
4. C 128—Specific Gravity and Absorption of Fine Aggregate,
5. C 131—Resistance to Abrasion of Small Size Coarse Aggregate by use of the Los Angeles Machine
6. C 289—Potential Reactivity of Aggregates (Chemical Method), and
7. D 2419—Sand Equivalent Value of Soils and Fine Aggregate.

The results of the ASTM aggregate tests are listed in Table XIII. The sand equivalent tests demonstrated that the crushed vitrified products from all five residues are very clean and contain only a small proportion of clay-sized fines. Sodium sulfate loss was extremely low for all samples as well. The specific gravity and absorption tests determined that the vitrified products contained few voids, thus absorption was extremely low. Potential reactivity tests, which are a measure of dissolved silica and reduction in alkalinity, demonstrated that all samples would be considered innocuous. Values from the abrasion tests ranged from 35.9 pct for Residue B to 42.2 pct for Residue A, slightly higher than the recommended maximum value of 35 pct for base and shoulder aggregate.

Table XIII. Results of ASTM Aggregate Tests

Vit. Product	Unit wt, lb/ft³	Sodium sulfate loss		Coarse spec. gravity		Fine spec. gravity		Abrasive wear, pct	Potential reactivity		Sand equiv-alent, pct
		Coarse	Fine	Bulk, lb/ft³	Absorp-tion, pct	Bulk, lb/ft³	Absorp-tion, pct		Quantity Sc*	Quantity RC**	
A	89.0	1.5	1.9	168.7	0.30	166.2	0.87	42.2	28	74	92
B	99.0	0.5	1.8	182.5	0.22	180.6	0.60	35.9	22	37	95
C	88.0	0.4	1.1	163.1	0.48	165.0	0.77	38.5	16	65	95
D	102.8	0.3	1.3	190.6	0.27	188.7	0.58	41.9	56	69	93
E-2	90.2	0.8	1.2	174.3	0.26	175.0	0.36	39.6	7	110	95

* Dissolved silica, millimoles/liter.
** Reduction in alkalinity, millimoles/liter.
Coarse aggregate: Plus 4.75 mm (+4 mesh).
Fine aggregate: 4.75 x 0.75 mm (4 x 200 mesh).

Table VI. Residue A Without Recycle of Fume Solids: Composition of Furnace Feed and Products

Element	Concentration, ppm *				
	Feed	Vit. Prod.	Metal	Matte	Fume
Ag	16	2	30	2580	132
Al	46100	71900	121	78	28500
Au	NA	NA	57	13	NA
As	34	1	388	18	127
B	231	145	NA	NA	375
Ba	809	1100	27	333	389
Be	<1	<1	<1	2	<1
Bi	1500	2940	NA	NA	1160
Br	28	<0.6	NA	NA	2190
C	24700	569	1140	690	11400
Ca	70600	119000	NA	NA	91500
Cd	26	3	48	16	354
Ce	<100	<100	NA	NA	<100
Cl	20900	19	NA	NA	181000
Co	28	19	NA	NA	18
Cr	232	706	1090	6290	146
Cu	4360	526	0	311000	2770
Fe	833000	46800	47300	311000	18500
Hg	6	1	1.5	<1	6
K	8140	6460	NA	NA	64200
Li	16	21	NA	NA	29
Mg	12100	22400	NA	NA	7430
Mn	924	1540	<10	6870	475
Mo	<50	<50	384	<50	<50
Na	30300	23700	NA	NA	98600
Ni	259	27	4450	805	74
P	3820	1640	43300	430	18200
Pb	4090	39	156	42100	50400
S	13300	5040	9580	282000	38800
Sb	142	2	NA	1700	782
Se	2	<1	220	69	11
Si	200000	242000	53700	800	33300
Sn	257	<200	NA	NA	3040
Sr	631	595	NA	NA	220
Ti	5870	10400	NA	NA	4770
Tl	<5	<5	179	<5	<5
V	50	55	NA	NA	20
Y	<50	<50	NA	NA	<50
Zn	4160	513	634	5300	95500

* Weighted mean concentration
NA: Not analyzed

Table VII. Residue With Recycle of Fume Solids: Composition of Furnace Feed and Products

Element	Concentration, ppm *				
	Feed	Vit. Prod.	Metal	Matte	Fume
Ag	18	3	38	1370	117
Al	45800	66500	97	100	17200
Au	NA	NA	47	10	NA
As	35	1	421	25	112
B	233	106	NA	NA	283
Ba	804	1020	28	263	280
Be	<1	<1	1	5	<1
Bi	1490	2980	NA	NA	681
Br	56	<0.6	NA	NA	2400
C	24500	358	1140	840	4950
Ca	70800	105000	NA	NA	55900
Cd	30	2	49	16	539
Ce	<100	<100	NA	NA	<100
Cl	22900	18	NA	NA	161000
Co	28	19	NA	NA	8
Cr	231	549	1150	9840	92
Cu	4340	453	40600	292000	2690
Fe	82500	42200	833000	318000	16900
Hg	6	<1	<1	<1	8
K	8870	6530	NA	NA	64600
Li	16	22	NA	NA	36
Mg	12100	17900	NA	NA	4450
Mn	918	1480	65	7680	464
Mo	<50	<50	293	<50	<50
Na	31200	25500	NA	NA	100000
Ni	257	18	4050	570	47
P	4010	1560	42100	310	16900
Pb	4700	35	452	27100	69300
S	13600	5380	10900	293000	62100
Sb	150	1	NA	1090	800
Se	2	<1	244	37	14
Si	198000	247000	49200	900	32300
Sn	293	<200	NA	NA	2840
Sr	626	628	NA	NA	114
Ti	5850	10300	NA	NA	2680
Tl	<5	<5	200	<5	<5
V	50	52	NA	NA	<20
Y	<50	<50	NA	NA	<50
Zn	5350	503	466	5800	165000

* Weighted mean concentration
NA: Not analyzed

Table VIII. Residue B: Composition of Furnace Feed and Products

Element	Concentration, ppm *				
	Feed	Vit. Prod.	Metal	Matte	Fume
Ag	10	2	130	1630	69
Al	36600	70100	111	239	20500
Au	NA	NA	69	26	NA
As	32	3	355	73	166
B	193	69	NA	NA	603
Ba	729	1070	21	13	271
Be	<1	<1	<1	<1	<1
Bi	1170	2560	NA	NA	658
Br	73	<0.6	NA	NA	2420
C	11100	540	1140	420	2810
Ca	46700	97600	NA	NA	53200
Cd	21	9	47	19	451
Ce	<100	<100	NA	NA	<100
Cl	15100	74	NA	NA	172000
Co	41	31	NA	NA	10
Cr	324	1770	420	332	155
Cu	6750	1480	80600	312000	7330
Fe	142000	123000	811000	382000	27200
Hg	3	<1	<1	<1	13
K	7380	5860	NA	NA	61700
Li	22	23	NA	NA	43
Mg	9780	15200	NA	NA	3990
Mn	1110	2240	23	1040	476
Mo	<50	<50	408	<50	<50
Na	25700	21500	NA	NA	94200
Ni	257	77	5120	2160	92
P	2770	2010	29900	1100	18200
Pb	3800	271	1490	24700	73900
S	9650	2560	37000	253000	50800
Sb	105	11	NA	1360	862
Se	<1	<1	210	48	13
Si	216000	224000	9400	900	47800
Sn	210	<200	NA	NA	3260
Sr	354	568	NA	NA	98
Ti	4780	9410	NA	NA	2270
Tl	<5	<5	172	<5	<5
V	56	85	NA	NA	<20
Y	<50	<50	NA	NA	<50
Zn	3140	1960	730	3300	147000

* Weighted mean concentration
NA: Not analyzed

Table IX. Residue C: Composition of Furnace Feed and Products

Element	Concentration, ppm *				
	Feed	Vit. Prod.	Metal	Matte	Fume
Ag	28	2	45	3290	122
Al	68900	97100	98	146	27100
Au	NA	NA	59	11	NA
As	40	<1	232	28	106
B	257	124	NA	NA	821
Ba	517	807	<20	270	273
Be	<1	<1	3	4	<1
Bi	2050	3400	NA	NA	1340
Br	86	<0.6	NA	NA	856
C	61800	437	980	510	12300
Ca	37600	107000	NA	NA	45500
Cd	46	1	24	8	195
Ce	<100	<100	NA	NA	<100
Cl	15000	9	NA	NA	71300
Co	34	23	NA	NA	19
Cr	238	1160	3130	15800	193
Cu	8370	401	79400	485000	6200
Fe	50100	32600	745000	153000	14500
Hg	13	<1	<1	<1	2
K	10400	7150	NA	NA	44200
Li	26	29	NA	NA	37
Mg	10500	18500	NA	NA	5270
Mn	1100	1410	75	16100	1190
Mo	<50	<50	375	<50	<50
Na	30900	31300	NA	NA	92400
Ni	219	18	3320	285	60
P	5290	3440	58600	440	14100
Pb	2170	15	93	16100	14100
S	12400	4860	2610	270000	52900
Sb	192	3	NA	1350	748
Se	1	<1	<100	55	7
Si	198000	227000	71700	1200	135000
Sn	245	<200	NA	NA	1640
Sr	326	557	NA	NA	109
Ti	7800	12500	NA	NA	5920
Tl	<5	<5	<100	<5	<5
V	59	44	NA	NA	<20
Y	<50	<50	NA	NA	<50
Zn	5900	136	420	7900	69000

* Weighted mean concentration
NA: Not analyzed

Table X. Residue D: Composition of Furnace Feed and Products

Element	Concentration, ppm *				
	Feed	Vit. Prod.	Metal	Matte	Fume
Ag	217	211	946	25000	225
Al	29500	36300	98	503	16300
Au	NA	NA	1727	448	NA
As	8	5	379	12	68
B	47	64	NA	NA	132
Ba	1290	1150	26	19	1090
Be	<1	<1	<1	<1	<1
Bi	1410	1470	NA	NA	949
Br	8	<0.6	NA	NA	65
C	11600	293	1760	510	2070
Ca	88800	106000	NA	NA	73100
Cd	24	12	50	56	207
Ce	332	<100	NA	NA	<100
Cl	341	24	NA	NA	6600
Co	21	21	NA	NA	15
Cr	1370	1380	377	121	1050
Cu	3450	2280	46400	261000	4470
Fe	156000	166000	835000	380000	114000
Hg	<1	<1	1.4	<1	4
K	14300	11400	NA	NA	61300
Li	17	16	NA	NA	31
Mg	17300	34600	NA	NA	12700
Mn	551	585	<10	201	338
Mo	<50	<50	723	<50	<50
Na	5240	7290	NA	NA	31900
Ni	404	313	10900	3800	324
P	86400	92900	45800	1200	163000
Pb	211	278	443	13200	3620
S	4750	301	30100	283000	8100
Sb	16	10	NA	730	82
Se	8	1	236	840	136
Si	108000	114000	4600	1000	48000
Sn	<200	<200	NA	NA	877
Sr	834	625	NA	NA	550
Ti	5250	5170	NA	NA	4130
Tl	<5	<5	173	<5	<5
V	50	41	NA	NA	<20
Y	<50	<50	NA	NA	<50
Zn	2210	1620	540	2000	10900

* Weighted mean concentration
NA: Not analyzed

Table XI. Residue E-1 Without Additives: Composition of Furnace Feed and Products

Element	Concentration, ppm *			
	Feed	Vit. Prod.	Metal	Fume
Ag	14	6	88	203
Al	42500	94700	108	8020
Au	NA	NA	82	NA
As	54	3	342	174
B	153	244	NA	192
Ba	544	811	26	289
Be	<1	<1	1	<1
Bi	2050	3970	NA	286
Br	660	8.5	NA	2910
C	45700	690	1140	5340
Ca	161000	158000	NA	28300
Cd	69	<1	50	636
Ce	<100	165	NA	<100
Cl	202000	810	NA	210000
Co	60	19	NA	0
Cr	194	1330	1890	229
Cu	407	567	64500	5000
Fe	21400	34200	828000	24300
Hg	20	<1	1.8	18
K	10500	1600	NA	76800
Li	32	10	NA	69
Mg	6840	34200	NA	3190
Mn	589	1070	120	1000
Mo	<50	<50	489	<50
Na	15200	4400	NA	106000
Ni	296	26	5680	59
P	2520	2500	37100	29700
Pb	1940	280	326	58100
S	40600	11100	20400	39600
Sb	405	4	NA	991
Se	11	2	257	30
Si	104000	193000	29400	63500
Sn	200	<200	NA	3950
Sr	376	500	NA	84
Ti	7420	16100	NA	1260
Tl	<5	<5	215	<5
V	56	44	NA	<20
Y	<50	<50	NA	<50
Zn	5200	595	679	113000

* Weighted mean concentration
NA: Not analyzed

Table XII. Residue E-2 With Additives: Composition of Furnace Feed and Products

Element	Concentration, ppm *		
	Feed	Vit. Prod.	Fume
Ag	8	4	140
Al	24220	46100	11600
Au	NA	NA	NA
As	31	4	121
B	87	160	358
Ba	310	580	84
Be	<1	<1	<1
Bi	1170	1960	444
Br	376	7.6	4000
C	26100	140	3040
Ca	91800	110000	45800
Cd	39	9	607
Ce	<100	<100	<100
Cl	115000	9700	225000
Co	34	36	18
Cr	111	1180	306
Cu	232	759	6940
Fe	177000	168000	59900
Hg	11	2.6	25
K	5980	650	66900
Li	18	11	64
Mg	3900	44400	4400
Mn	336	1910	1270
Mo	<50	<50	<50
Na	8690	3200	96900
Ni	169	139	318
P	1440	3300	18500
Pb	1110	140	11600
S	23200	1160	37900
Sb	231	42	607
Se	6	<1	34
Si	149000	191000	55700
Sn	114	<200	3210
Sr	214	223	130
Ti	4230	8820	1990
Tl	<5	<5	<5
V	32	72	21
Y	<50	<50	<50
Zn	2970	774	77700

* Weighted mean concentration
NA: Not analyzed

The results of the ASTM tests indicate the potential for use as the wearing course in roads, particularly for asphaltic concrete. Other appropriate uses are grit for air blast cleaning, aggregate for walkway or garden tiles, granules for roofing, mineral wool insulation, construction fill or flowable backfill around buried pipe, and other uses requiring an inert material. There should be no concern with run-off water when the vitrified product is stored uncovered outdoors.

EPA Toxicity Characteristics Leaching Procedure (TCLP)

Samples of the furnace products from melting tests of the five residues were evaluated by the EPA TCLP in strict compliance with established protocol. The results of the TCLP tests for As, Ba, Cd, Cr, Pb, Hg, Se, and Ag, the actual concentration of each metal in the products, and the EPA limit are available from the ASME (*5*).

The vitrified products, granulated products, metal, and matte from Residues A, B, C, D, and E were found to have a leaching potential well below the EPA limit for each TCLP element. Fume solids for Residues A, B, D, and E exceeded the EPA limits for Pb and Cd, while the fume solids from Residue C exceeded the limit for Pb. It should be noted that the fume solids have the potential, with managed recycle through the furnace, to be a source of recoverable Pb and Cd, as well as Zn and Sn.

The chemical analyses were used with the material balance to calculate the distribution of the eight TCLP elements and six other important elements (Cl, Cu, Fe, P, S, and Zn) over the furnace products. This information is also available from the ASME (*5*).

Conclusions

The experimental program to melt municipal refuse combustor residues successfully demonstrated the applicability of existing electric arc furnace melting technology to vitrify a variety of combustor residues.

- Three combined grate and fly ash residues from MSW combustors, combined residue from a sewage sludge combustor, and fly ash from a WTE plant burning RDF with lime slurry injection for AQC were extensively characterized to provide the most comprehensive physical description and chemical composition available for these materials.

- Melting of the MSW combustor residues produced five distinct products. Between 69 and 86 pct of the combined residues and fly ash, when melted with additives to improve operation, was recovered in vitrified products with density about 180 lb/ft^3. Metallic materials in the furnace feed were recovered in a metal ingot accounting for up to 6.2 pct of the feed material. All residues except fly ash produced a metal sulfide phase (matte) that accounted for up to 2.2 pct of the feed material. The remainder of the residues was recovered as condensed solids (fume) in the air quality control system or was vented to the atmosphere as clean exhaust gas.

- All furnace products were tested by the EPA TCLP in compliance with established protocol. The leaching potentials of the vitrified products, metals, and mattes were well below the EPA limit for each listed metal. The fume solids exceeded the limit for Pb and/or Cd. The fume solids have the potential to be a source of recoverable Pb and Cd, as well as Zn and Sn.

- The vitrified products satisfied ASTM requirements for aggregate in portland cement or asphaltic concretes. Other potential uses include grit for air blast cleaning, aggregate for walkway or garden tiles, roofing granules, mineral wool insulation, and construction fill.

The metal ingot may be acceptable for recycle to steel mills or iron foundries, and the matte is likely recyclable to primary Cu smelters by virtue of its high Cu and minor precious metal content.

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PROCESS MINERALOGY XII:

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