

## ASME/US Bureau of Mines investigative program on vitrification of combustion ash/residue: findings and conclusions<sup>☆</sup>

Herbert I. Hollander<sup>a</sup>, Arthur L. Plumley<sup>b,\*</sup>, Roger S. DeCesare<sup>c</sup>

<sup>a</sup> *Hollander Associates, Wyomissing, PA, USA*

<sup>b</sup> *ABB Combustion Engineering, 1000 Prospect Hill Road, Windsor, CT 06095-0500, USA*

<sup>c</sup> *US Bureau of Mines, Washington, DC, USA*

Received 30 May 1995; accepted 26 July 1995

---

### Abstract

Vitrification of the residues from thermal processes into a dense, glass-like material may provide an opportunity to permanently relieve our concerns regarding aquifer contamination and, if the vitrified products are utilized, conserves those land areas which are suitable for disposal for those discards for which we have not as yet found a practical use.

This discussion briefly describes and illustrates the implementation of the \$1.2 million ASME/BuMines investigative program; the scope and methods followed, equipment systems employed, areas of investigation, findings and conclusions in determining the potential effectiveness of sequentially vitrifying significant quantities of ash/residue from three different types of mass burning municipal solid waste energy recovery facilities, a regional wastewater treatment plant sludge combustor, and air quality control products from a large refuse derived fuel energy recovery facility while utilizing for this purpose a fraction of the electric energy recovered; identifying potential beneficial applications for the resulting products, the environmental implications and projected overall economics.

*Keywords:* Ash; Combustion residue; Flyash; Ash melting; Vitrification; Sludge ash; Frit

---

### 1. Introduction

The perception that residues from thermal processes (albeit free of putrescibles) are comprised primarily of inorganics or mineral matter, which may leach, however slightly, and eventually contaminate aquifers, has increased environmental concerns.

---

\* Corresponding author. Tel.: +1-203-285-4135. Fax: +1-203-285-9512.

<sup>☆</sup> Permission was granted by ASME to employ this condensed summary and only portions of the work which had been covered in their comprehensive report CRTD – Vol. 24, 1994.

Conversion of residues from combustion of wastes into useful products which might be absorbed into our economy would relieve these concerns and perhaps provide new economic development opportunities.

Vitrification of these residues into a dense, amorphous material is one such process which may provide an opportunity to permanently relieve concerns regarding aquifer contamination. If the vitrified products are utilized, this process would conserve those land areas which are suitable for disposal of those discards for which no practical alternate use has been found.

Proof-of-concept melting trials at the Bureau of Mines Rolla, Missouri, Research Center revealed that the vitrified products from the combined combustion residues from the Chicago NW Waste-to-Energy Facility were amorphous, environmentally benign, as much as 3 times denser than the original residue and had the potential for several beneficial uses, in lieu of burial and potential future liability.

## **2. The program**

The American Society of Mechanical Engineers Center for Research and Technology Development and the US Bureau of Mines through cooperative agreements that included over 30 government and industry sponsors, conducted over 200 h of melting tests to vitrify ash/residues from five state-of-the-art municipal waste combustion facilities. Program participants included industry and government researchers, furnace suppliers and operators, academics, solid waste industry professionals, implementing entities, regulatory agencies and private engineering consultants.

The residues [1] for this melting program included dry combined grate and air quality control equipment residues from three mass burning waste-to-energy (WTE) plants, dry combined residue from a multiple hearth wastewater treatment plant (WWTP) sludge combustor, and dry acid gas absorber baghouse residues from a modern WTE plant burning refuse derived fuel.

An electric arc melting furnace [2] having a water-cooled roof and sidewalls, a modified power supply, furnace feeding and fume emission control systems was reconstructed at the Bureau of Mines Albany Research Center (BuMALRC) specifically to feed and continuously melt up to one t/h of combustion residues and permit the vitrified products to be continuously tapped from the furnace all within stringent environmental requirements (Fig. 1). The melting program commenced with short test runs to define operating procedures and culminated in a 100 h operating campaign in which 54 000 lb of combustor residues were melted.

## **3. Methods and procedures**

The dried, screened, as-received residues were extensively characterized by BuMALRC to determine physical properties and chemical composition (Table 1 and 2). Of particular interest are the broad range in bulk density; the high

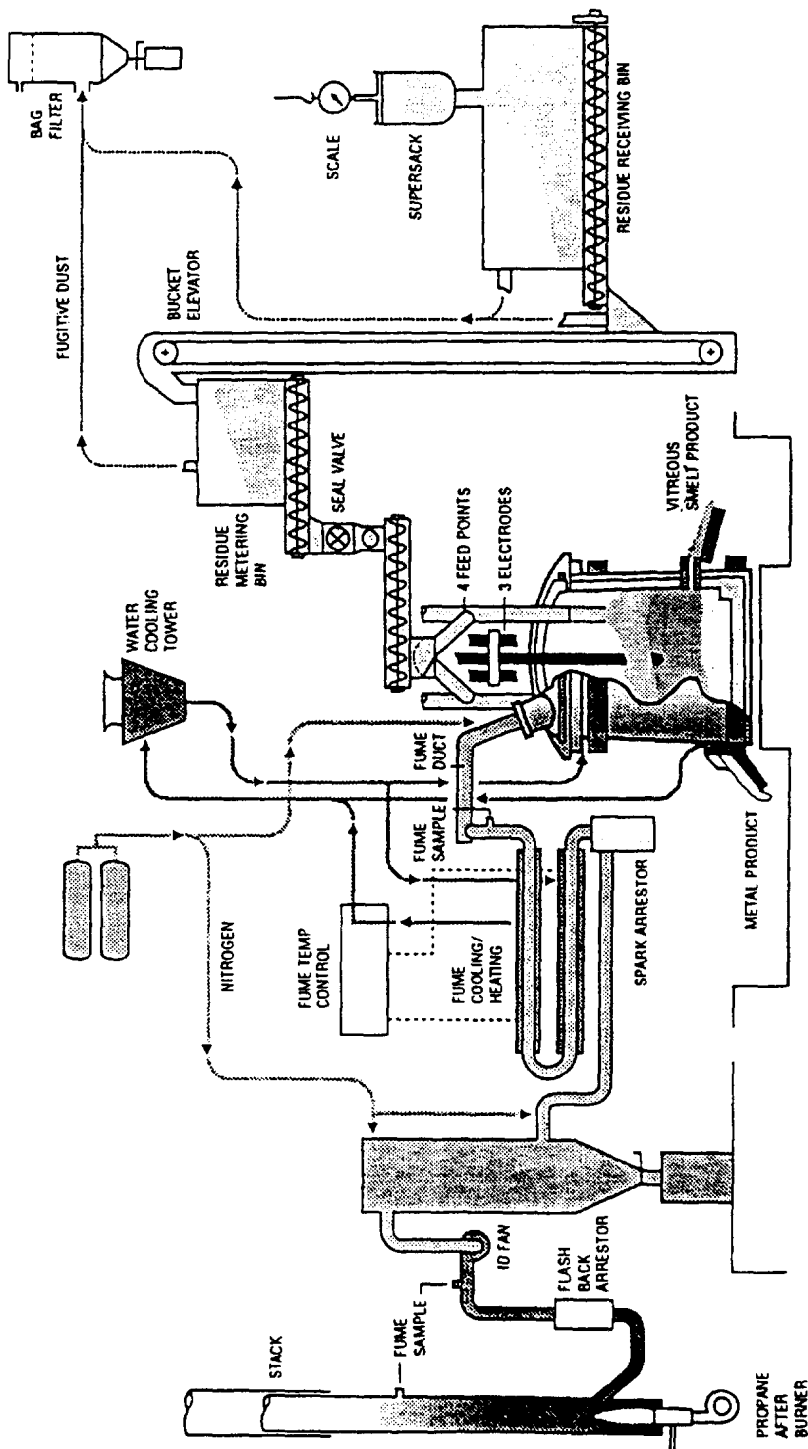


Fig. 1. Process system schematic.

Table 1  
Physical properties of residues

| Residue | Moisture (%) <sup>a</sup> | LOI (%) <sup>b</sup> | Magnetic (wt%) | Nonmagnetic (wt%) | Bulk density                                     |
|---------|---------------------------|----------------------|----------------|-------------------|--|
| A       | 1.54                      | 5.66                 | 10.2           | 89.8              | 1.25 g/cm <sup>3</sup> or 78 lb/ft <sup>3</sup>  |
| B       | 1.38                      | 1.44                 | 17.4           | 82.6              | 1.74 g/cm <sup>3</sup> or 109 lb/ft <sup>3</sup> |
| C       | 0.92                      | 2.51                 | 12.7           | 87.3              | 1.14 g/cm <sup>3</sup> or 71 lb/ft <sup>3</sup>  |
| D       | 0.42                      | 0.71                 | 51.9           | 48.1              | 0.50 g/cm <sup>3</sup> or 31 lb/ft <sup>3</sup>  |
| E       | 1.58                      | 5.22                 | 2.7            | 97.3              | 0.65 g/cm <sup>3</sup> or 40 lb/ft <sup>3</sup>  |

<sup>a</sup> 105 °C for 12 h.

<sup>b</sup> 1000 °C for 1 h.

Table 2  
Chemical composition of residues

| Element | Residue concentration, ppm (mg/g) |      |      |      |      |        |
|---------|-----------------------------------|------|------|------|------|--------|
|         | A                                 | B    | C    | D    | E-1  | E-2    |
| Ag      | 16                                | 10   | 28   | 217  | 14   | 8      |
| As      | 34                                | 32   | 40   | 8    | 54   | 31     |
| Ba      | 809                               | 729  | 517  | 1294 | 544  | 31 076 |
| Br      | 28                                | 73   | 86   | 8    | 660  | 376    |
| Cd      | 26                                | 21   | 46   | 24   | 69   | 39     |
| Cr      | 232                               | 324  | 238  | 1371 | 194  | 111    |
| Hg      | 6                                 | 3    | 13   | <1   | 20   | 11     |
| Mo      | <50                               | <50  | <50  | <50  | <50  | <50    |
| Ni      | 259                               | 257  | 219  | 404  | 296  | 169    |
| Pb      | 4094                              | 3801 | 2171 | 211  | 1940 | 1106   |
| Sb      | 142                               | 105  | 192  | 16   | 405  | 231    |
| Se      | 2                                 | <1   | 1    | 8    | 11   | 6      |
| Sn      | 257                               | 210  | 245  | <200 | 200  | 114    |
| Zn      | 4160                              | 3142 | 5900 | 2209 | 5203 | 2966   |

Residues A, B and C are combined residues from modern mass burn WTE plants (bottom ash plus spray-dryer baghouse dust).

Residue D is from a regional WWTP sludge incinerator.

Residue E-1 is combined fly ash and acid gas adsorbed residue from a modern RDF-WTE plant.

Residue E-2 includes mill scale and silica sand additives.

magnetics fraction in the sewage sludge ash/residue which may be attributed to the ferric chloride used for sludge conditioning; and the variation in residual combustible content as determined by loss on ignition (LOI) testing.

#### 4. Findings

A typical material balance across the furnace system is provided for each source of residue in Table 3.

Table 3  
Material balance over electric arc melting furnace

| Product     | Residue A |         | Residue B |         | Residue C |         | Residue D |         | Residue E <sup>a</sup> |         |
|-------------|-----------|---------|-----------|---------|-----------|---------|-----------|---------|------------------------|---------|
|             | Wt. (lb)  | Wt. (%) | Wt. (lb)  | Wt. (%) | Wt. (lb)  | Wt. (%) | Wt. (lb)  | Wt. (%) | Wt. (lb)               | Wt. (%) |
| Vit. prod.  | 20 261    | 78.0    | 6067      | 83.4    | 3717      | 68.7    | 11 478    | 86.4    | 897                    | 86.3    |
| Metal       | 1622      | 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     | 168       | 0.8     | 90                     | 8.7     |
| Baghouse    | 2497      | 9.6     | 479       | 6.6     | 727       | 13.4    | 1388      | 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   | 72 782    | 100.0   | 5408      | 100.0   | 13 288    | 100.0   | 103.9                  | 100.0   |

<sup>a</sup> With additives (mill scale and silica sand).

In general, melting of MWC residues, WWTP sludge combustor residue, as well as the RDF baghouse residue produced five principal products [3]:

- vitreous product up to 86%,
- metallic product up to 7%,
- matte product up to 2%,
- fume solids up to 5%,
- baghouse and gas solids.

The combined MWC residues A, B and C and the RDF flue gas cleanup residue E produced dense black glassy vitrified products similar to obsidian or basalt, not unlike some forms of volcanic lava. This observation was confirmed by microscopic and X-ray diffraction. The WWTP sludge combustor residue D melted at a somewhat lower temperature and produced a predominantly crystalline product with a distinct X-ray pattern.

During the melting test of Residue A the fume solids were collected during the first 8 h and recycled gradually into the system residue receiving bin to enhance mixing with the fresh feedstock. The combination residue and recycled fume solids were melted during the following 8 h period. The chemical compositions of the furnace products, including vitrified material, interface surface metal sulfide (matte), metal, and fume exhaust solids, are provided in Table 4 without recycled fume solids, and in Table 5 with recycled fume solids.

As is common in such demonstration programs, for one reason or another frequent unscheduled interruptions were experienced. Consequently, the actual steady-state test runs on each residue were quite short. Establishing and maintaining furnace equilibrium on each residue for more than relatively short periods was very difficult

Table 4  
Composition of furnace feed and products residue A without recycle of fume solids

| Element | Concentration, ppm <sup>a</sup> (mg/kg) |            |       |        |        |
|---------|---|------------|-------|--------|--------|
|         | Feed                                    | Vit. prod. | Metal | Matte  | Fume   |
| Ag      | 16                                      | 2          | 30    | 2580   | 132    |
| As      | 34                                      | 1          | 388   | 18     | 127    |
| Ba      | 809                                     | 1089       | 27    | 333    | 389    |
| Br      | 28                                      | <0.6       | NA    | NA     | 2191   |
| Cd      | 26                                      | 3          | 48    | 16     | 354    |
| Cr      | 232                                     | 703        | 1088  | 6293   | 146    |
| Hg      | 6                                       | 1          | 1.5   | <1     | 6      |
| Mo      | <50                                     | <50        | 384   | <50    | <50    |
| Ni      | 259                                     | 25         | 4454  | 805    | 74     |
| Pb      | 4094                                    | 53         | 156   | 42 100 | 50 414 |
| Sb      | 142                                     | 2          | NA    | 1700   | 782    |
| Se      | 2                                       | <1         | 220   | 69     | 11     |
| Sn      | 257                                     | <200       | NA    | NA     | 3039   |
| Zn      | 4160                                    | 584        | 634   | 5300   | 95 528 |

<sup>a</sup> Weighted mean concentration.

NA: not analyzed.

Table 5  
Composition of furnace feed and products Residue A with recycle of fume solids

| Element | Concentration, ppm <sup>a</sup> (mg/g) |            |       |        |         |
|---------|--|------------|-------|--------|---------|
|         | Feed                                   | Vit. prod. | Metal | Matte  | Fume    |
| Ag      | 18                                     | 2          | 38    | 117    | 14      |
| As      | 1                                      | 421        | 25    | 112    | 54      |
| Ba      | 804                                    | 1125       | 28    | 263    | 280     |
| Br      | 56                                     | <0.6       | NA    | NA     | 2397    |
| Cd      | 30                                     | 2          | 49    | 16     | 539     |
| Cr      | 231                                    | 533        | 1151  | 9842   | 92      |
| Hg      | 6                                      | <1         | <1    | <1     | 8       |
| Mo      | <50                                    | <50        | 293   | <50    | <50     |
| Ni      | 257                                    | 18         | 4051  | 570    | 47      |
| Pb      | 4696                                   | 32         | 452   | 27 100 | 69 301  |
| Sb      | 150                                    | 1          | NA    | 1090   | 800     |
| Se      | 2                                      | <1         | 244   | 37     | 14      |
| Sn      | 293                                    | <200       | NA    | NA     | 2840    |
| Zn      | 5348                                   | 488        | 466   | 5800   | 164 539 |

<sup>a</sup> Weighted mean concentration.

NA: not analyzed.

[4]. Nevertheless the furnace was forgiving, yielding relatively uniform melt products in spite of the erratic conditions encountered.

The electric power required to melt the residues was influenced significantly by mechanical/operational factors. Periods of furnace down time, slowing feeding rates yet keeping the furnace at temperature, and thermochemical reactions within the furnace increased the power consumption [4]. During periods of uninterrupted (though not necessarily steady-state) operations, the operating power ranged from 616 to 1040 kWh/t. (This variation is believed to result largely from intermittent furnace operation encountered and the non-equilibrium thermal conditions experienced prior to the measurement.) The designer of the furnace installed at the Bureau's test facility estimates that at a residue feed rate of 1300 lb/h an optimally designed furnace system of this size and type could reduce power consumption to as low as 500 kWh/t under normal continuous operation for most types of combustion residues. This rate of power usage would range from 1/3 to 1/5 of that which can be produced from the energy recovered from burning the amount of municipal waste corresponding to the amount of residue being vitrified.

To assess environmental implications, the products from the electric furnace were tested in accordance with EPA's TCLP and a summary is provided in Table 6. The leaching potentials of the vitrified products and metals were below the EPA limit for each of the eight regulated metals.

A summary of parametric fume solids data for each residue is provided in Table 7. TCLP specified extracts of the small quantity of fume solids in most cases exceeded the TCLP limit for lead (Pb) and cadmium (Cd). Although the weight percents of fume solids were quite small, if the metals therein were to be further concentrated, these solids may then have potential as a source of raw material for recovery of

Table 6  
Residue and vitrified product leaching analyses – TCLP (ppm)

| Parameter | Residue A<br>vitrified | Sludge residue D |           | Flyash residue E |           | U.S. EPA<br>criteria |
|-----------|------------------------|------------------|-----------|------------------|-----------|----------------------|
|           |                        | As recvd.        | Vitrified | As recvd.        | Vitrified |                      |
| Arsenic   | 0.09                   | <0.09            | <0.09     | <0.09            | <0.09     | 5.0                  |
| Barium    | 0.4                    | 0.08             | 0.08      | 1.6              | 0.3       | 100                  |
| Cadmium   | 0.007                  | <0.007           | 0.001     | 0.06             | 0.007     | 1.0                  |
| Chromium  | <0.02                  | 0.02             | 0.02      | 0.06             | 0.1       | 5.0                  |
| Lead      | 0.3                    | 0.3              | 0.04      | 8.2              | 0.1       | 5.0                  |
| Mercury   | 0.0005                 | <0.003           | 0.0003    | 0.008            | 0.008     | 0.20                 |
| Selenium  | <0.07                  | <0.07            | 0.07      | <0.07            | 0.07      | 1.0                  |
| Silver    | <0.01                  | 0.01             | 0.01      | 0.07             | 0.01      | 5.0                  |

Residue A: Modern mass burn WTE plant.

Residue D: Regional WWTP sewage sludge incinerator.

Residue E: Modern RDF WTE plant: flyash + AQC deposits.

Pb, Cd, and possibly zinc (Zn) and tin (Sn) or, otherwise, disposed of them in accordance with applicable regulations.

Under the circumstances encountered, no attempt was made to identify and employ additives which might enhance absorption of these metal oxides into the furnace products. This activity should be included in future vitrification investigative programs.

Thermal oxidizer-stack emissions were controlled to meet current regulatory requirements and were monitored for acid gases, metals, and dioxins. Mercury emissions were measured at the residue dryer baghouse outlet, dried residue furnace feed, at the furnace fume baghouse outlet, and in all resulting furnace products (Table 8). The environmental significance of the measured values is ultimately determined by the local regulatory agency. The Oregon DOT Laboratories subjected the vitrified products to the appropriate ASTM tests for aggregate in Portland cement or asphaltic concretes which indicated they may be suitable even for the wearing course for roadways (Table 9).

Other apparent uses include aggregates for flowable construction fill, road ice control, walkway or garden tiles, roofing granules, grit for air blast cleaning, and high temperature mineral wool insulation and possibly other uses. As with natural aggregates uncovered storage should be acceptable since there should be little concern regarding rainwater run-off contamination (Table 10).

Although only a small weight percent of the total ... the 'matte' fraction may have some value to metal refiners and smelters by virtue of its copper and precious metal content.

Accumulated ingots of the ferrous fraction may be considered as a scrap resource by foundries or minimills or municipally specified for use in non-stress applications such as fence posts, tree grates, bench or table supports, counter weights, stanchions, etc.

The cost projections in the BuMines estimate summarized in Table 11 are based upon wet residues having 20% moisture, and on installation of adjacent stand-alone



Table 7  
Fume solids leaching analyses – TCLP (ppm)

| Constituent | EPA limit <sup>a</sup> | Residue A <sup>c</sup> |                   | Residue B          |                   | Residue C          |                   | Residue D          |                   | Residue E <sup>d</sup> |                   |
|-------------|------------------------|------------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|------------------------|-------------------|
|             |                        | Conc. <sup>b</sup>     | TCLP <sup>a</sup> | Conc. <sup>b</sup> | TCLP <sup>a</sup> | Conc. <sup>b</sup> | TCLP <sup>a</sup> | Conc. <sup>b</sup> | TCLP <sup>a</sup> | Conc. <sup>b</sup>     | TCLP <sup>a</sup> |
| Arsenic     | 5.0                    | 117                    | <0.1              | 166                | <0.1              | 106                | 0.4               | 68                 | 0.6               | 174                    | 0.3               |
| Barium      | 100.0                  | 314                    | <0.1              | 271                | 1.1               | 273                | 0.08              | 1088               | <0.1              | 289                    | 0.2               |
| Cadmium     | 1.0                    | 482                    | 16                | 451                | 8                 | 195                | 0.9               | 207                | 1.4               | 636                    | 4.2               |
| Chromium    | 5.0                    | 109                    | <0.01             | 155                | <0.1              | 193                | <0.1              | 1047               | 0.3               | 229                    | <0.1              |
| Lead        | 0.2                    | 63 483                 | 200.00            | 73 923             | 75.00             | 14 138             | 13.00             | 3616               | 8.60              | 58 058                 | 28.00             |
| Mercury     | 1.0                    | 7                      | 0.001             | 13                 | 0.001             | 2                  | <0.001            | 4                  | <0.001            | 18                     | 0.002             |
| Selenium    | 1.0                    | 13                     | <0.1              | 13                 | <0.1              | 7                  | <0.1              | 136                | 0.1               | 30                     | 0.1               |
| Silver      | 5.0                    | 122                    | <0.1              | 69                 | <0.1              | 122                | <0.1              | 225                | <0.1              | 203                    | <0.1              |

<sup>a</sup>Concentration (ppm).

<sup>b</sup>Weighted mean concentration (ppm).

<sup>c</sup>Residue A with fume solids recycle.

<sup>d</sup>Residue E without additives.

Table 8  
Summary of parametric emission data on furnace fume

| Constituent                           | Mass emission rate (lb/h) |                 |             |                                  |                           |                 |
|---------------------------------------|---------------------------|-----------------|-------------|----------------------------------|---------------------------|-----------------|
|                                       | Baghouse                  | Inlet           | Baghouse    | Outlet prior to thermal oxidizer |                           |                 |
|                                       | HCl<br>(mean)             | SO <sub>2</sub> | Particulate | HCl<br>(mean)                    | SO <sub>2</sub><br>(mean) | CO <sup>a</sup> |
| Residue D                             | 0.037                     | NA              | 0.001       | 0.002                            | 0.17–>1.89                | 7.3–14.7        |
| Residue A                             | 0.002                     | NA              | 0.003       | 0.007                            | 0.27–>0.67                | <4.7–20.7       |
| Residue A with<br>fume solids recycle | 0.008                     | NA              | 0.001       | 0.003                            | >0.36–>0.82               | <1.4–<25.1      |
| Residue B                             | 0.683                     | 0.52            | 0.001       | 0.0004                           | >0.56–>1.2                | <7.4–9.7        |
| Residue C                             | 0.045                     | NA              | 0.001       | 0.002                            | 0.07–0.24                 | >37–37.2        |
| Residue E with<br>additives           | 2.21                      | NA              | 0.007       | 1.64                             | 0.21                      | 17.0            |

NA: not analyzed.

<sup>a</sup> After thermal oxidizer, CO ~ 0.2 ppm during steady-state operating period.

electric furnace equipment systems, each having independent air quality controls. Assuming an electric power cost of 5 cents/kWh, depending on system capacity, the calculated owning and operating costs range from \$98/residue ton for a plant processing 350 tpd of MWC residue to \$175/residue ton for a plant processing 60 tpd of residue.

These costs when expressed as additional tipping fees for MSW delivered to the WTE plant could range from \$10/t MSW to \$45/t MSW. No allowance is included for landfill cost avoidance or possible substitution value/revenue received for products having beneficial use. The extent of front-end and back-end recycling as well as other methods for calculating cost of capital may also alter these cost projections.

## 5. Conclusions

For commercial implementation for a specific residue it would be prudent to conduct a continuous 24 h/d melting test program for 3–5 d to ascertain specific furnace performance and thereby obtain sufficient definitive reproducible information for establishing the parametric data basis for design, operation, regulatory requirements and realistic cost projections.

The ASME/BuMines Investigative Program on Vitrification of Combustion Ash/Residue, conducted in response to public concern regarding potential leachability and the desire to maximize recycling/reuse, demonstrated that vitrification by electric arc furnace melting is technically and operationally feasible for significantly decreasing the volume and leachability of municipal waste combustor residues and can provide new materials which have potential beneficial use in lieu of burial.

The peer reviewed comprehensive report [5] of this ASME/Bureau of Mines program was issued in the Summer of 1994.

Table 9  
ASTM aggregate testing data

| Residue | Unit weight<br>(lb/ft <sup>3</sup> ) | Sodium sulfate<br>loss (%) |        | Coarse spec. gravity          |                   | Fine spec. gravity            |                   | Abrasive<br>wear (%) | Potential reactivity     |                          | Sand<br>equivalent<br>(%) |
|---------|--------------------------------------|----------------------------|--------|-------------------------------|-------------------|-------------------------------|-------------------|----------------------|--------------------------|--------------------------|---------------------------|
|         |                                      | Coarse                     | Fine   | Bulk<br>(lb/ft <sup>3</sup> ) | Absorption<br>(%) | Bulk<br>(lb/ft <sup>3</sup> ) | Absorption<br>(%) |                      | Quantity Sc <sup>a</sup> | Quantity Rc <sup>b</sup> |                           |
| A       | 5.0                                  | 117                        | <0.1   | 166                           | <0.1              | 106                           | 0.4               | 68                   | 0.6                      | 174                      | 0.3                       |
| B       | 100.0                                | 314                        | <0.1   | 271                           | 1.1               | 273                           | 0.08              | 1088                 | <0.1                     | 289                      | 0.2                       |
| C       | 1.0                                  | 482                        | 16     | 451                           | 8                 | 195                           | 0.9               | 207                  | 1.4                      | 636                      | 4.2                       |
| D       | 5.0                                  | 109                        | <0.01  | 155                           | <0.1              | 193                           | <0.1              | 1047                 | 0.3                      | 229                      | <0.1                      |
| E       | 0.2                                  | 63 483                     | 200.00 | 73 923                        | 75.00             | 14 138                        | 13.00             | 3616                 | 8.60                     | 58 058                   | 28.00                     |

<sup>a</sup> Dissolved silica, millimol/l.

<sup>b</sup> Reduction in alkalinity, millimol/l. Coarse aggregate: plus 0.87 inch (+4 mesh). Fine aggregate: 0.187 × 0.029 inch (4 × 200 mesh).

Prepared: Oregon Department of Transportation Laboratories.

Additional notes: (1) Quantity of material crushed and tested: 20 kg sample per residue source. (2) Specific molds from which samples were taken: Residue A – Mold AV-9; Residue B – Mold BV-4; Residue C – Mold CV-5; Residue D – Mold DV-7; Residue E – Mold EV-1. (3) Equipment used to crush the samples: 7 inch jaw crusher. Two passes.

Table 10  
Potential market value – Vitrification products (\$/t)

|  |      |
|--|------|
| Crushed aggregate                                  | 12   |
| Fritted for air blast grit                         | 45   |
| Cast block or tile                                 | 150  |
| Spun into high temperature mineral wool insulation |      |
| Loose form/bulk blowing                            | 200  |
| Blanket form                                       | 1000 |
| Vacuum formed products                             | 1500 |
| Board – medium density                             | 2000 |
| Vitrification metal product as scrap               | 75   |

Table 11  
Generic economic estimates

|   |             |             |             |
|---|-------------|-------------|-------------|
| Plant capacity – dry residue (tpd)                            | 300         | 150         | 50          |
| (Residue at 20% H <sub>2</sub> O) (tpd)                       | ~ 350       | ~ 175       | ~ 60        |
| Total capital costs (\$)                                      | 31 513 000  | 17 335 900  | 10 930 200  |
| <i>Operating costs (\$/dried st)</i>                          |             |             |             |
| Raw materials   | 7.22        | 7.22        | 7.26        |
| <i>Utilities</i>  |             |             |             |
| Electricity (\$0.051/kWh)                                     | 42.32       | 42.80       | 44.59       |
| Water and gas   | 10.24       | 9.82        | 10.53       |
| Direct labor  | 7.11        | 11.50       | 26.39       |
| <i>Plant maintenance</i>                                      |             |             |             |
| Labor   | 6.89        | 8.12        | 16.21       |
| Materials   | 5.74        | 6.77        | 13.51       |
| Depreciation (20 yr life)                                     | 15.36       | 16.91       | 32.18       |
| Other costs (see Appendix D, Table 2 [5])                     | 20.97       | 26.61       | 55.10       |
| Operating cost/dry t  | \$115.85    | \$129.75    | \$205.77    |
| Cost/t residue at 20% H <sub>2</sub> O                        | 98.47       | 110.29      | 174.90      |
| Cost/t MSW at combustion plant<br>10–25% residue              | 10.00–25.00 | 11.00–28.00 | 18.00–45.00 |
| <i>Basis</i>  |             |             |             |
| Total plant power consumption 840 kWh/t residue (5% moisture) |             |             |             |
| Independent air quality control system                        |             |             |             |
| Residue <2 in with magnetics removed                          |             |             |             |
| No credit for beneficial use/value of vitrified products      |             |             |             |
| No credit for landfill cost and liability avoidance           |             |             |             |
| No costs allotted for process residuals management            |             |             |             |

Inquiries should be addressed to: Howard E. Clark, Ph.D., Director, Center for Research and Technology Development, American Society of Mechanical Engineers, 1828 L Street N.W., Suite 906, Washington, DC 20036 (Tel.: (202) 785-3756. Fax: (202) 785-8120).

## **References**

- [1] A.L. Plumley, R.S. DeCesare and H. Hollander, ASME/Bureau of Mines vitrification of residue from municipal waste combustion, A Progress Report, Presented at the Int. Power Generation Conf., Atlanta, GA, 18–22 October 1992.
- [2] A.D. Hartman, L.L. Oden and J.C. White, Facility for melting residues from combustion: Design criteria and description of equipment, US Department of Interior, Bureau of Mines RI-9476, 1993.
- [3] H. Hollander, A.L. Plumley and R.S. DeCesare, ASME/Bureau of Mines investigative program on vitrification of combustion ash/residue, Presented at the 3rd Int. Conf. and Seminar on Municipal Waste Combustion, Williamsburg, VA, March 1993.
- [4] H. Hollander, A.L. Plumley and R.S. DeCesare, ASME/Bureau of Mines investigative program on vitrification of combustion ash/residue: Status Report, Presented at the 9th Int. Conf. on Solid Waste Management, University of Pennsylvania, Philadelphia, PA, November 1993.
- [5] L.L. Oden and W.K. O'Connor, ASME/US Bureau of Mines investigative program report on vitrification of residues (ash) from municipal waste combustion systems, Final ASME Report CRTD, Vol. 24, 1994.

## **Disclaimer**

The American Society of Mechanical Engineers, the U.S. Bureau of Mines, NYSERDA, USDOE, EPRI and the other program sponsors recognize that there are many other methods and systems which may accomplish the same objectives as the system employed in this program. Therefore ASME/BuMines and the Sponsors make no specific representations, endorsements, expressed or implied, advocate or recommend a particular method or system for this purpose.