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National
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of Energy*

EGG-MS-10646
May 1993

Bench-Scale Arc Melter for R&D in Thermal Treatment of Mixed Wastes

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*Work performed under
DOE Contract
No. DE-AC07-76ID01570*

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**Prepared for the
U.S. Department of Energy
Office of Environmental Restoration and Waste Management
Under DOE Idaho Field Office
Contract DE-AC07-76ID01570**

MASTER

ABSTRACT

A small dc arc melter was designed and constructed to run bench-scale investigations on various aspects of development for high-temperature (1,500–1,800°C) processing of simulated transuranic-contaminated waste and soil located at the Radioactive Waste Management Complex (RWMC). Several recent system design and treatment studies have shown that high-temperature melting is the preferred treatment. The small arc melter is needed to establish techniques and procedures (with surrogates) prior to using a similar melter with the transuranic-contaminated wastes in appropriate facilities at the site. This report documents the design and construction, starting and heating procedures, and tests evaluating the melter's ability to process several waste types stored at the RWMC. It is found that a thin graphite strip provides reliable starting with initial high current capability for partially melting the soil/waste mixture. The heating procedure includes (1) the initial high current-low voltage mode, (2) a low current-high voltage mode that commences after some slag has formed and arcing dominates over the receding graphite conduction path, and (3) a predominantly Joule heating mode during which the current can be increased within the limits to maintain relatively quiescent operation. Several experiments involving the melting of simulated wastes are discussed. Energy balance, slag temperature, and electrode wear measurements are presented. Recommendations for further refinements to enhance its processing capabilities are identified. Future studies anticipated with the arc melter include waste form processing development; dissolution, retention, volatilization, and collection for transuranic and low-level radionuclides, as well as high vapor pressure metals; electrode material development to minimize corrosion and erosion; refractory corrosion and/or skull formation effects; crucible or melter geometry; metal oxidation; and desirable melt reduction/oxidation (redox) conditions.

ACKNOWLEDGMENTS

This report was prepared for the Office of Waste Technology Development of EG&G Idaho, Inc., under contract to the U.S. Department of Energy Idaho Field Office. Funding was provided by the Idaho Waste Processing Facility (IWPF).

This is one of a series of reports for technology development under the IWPF funding. Contributions to the report far exceed the list of authors indicated. We appreciate the assistance and efforts of all those who contributed to the development of this technology.

CONTENTS

ABSTRACT	iii
ACKNOWLEDGMENTS	v
ACRONYMS AND NOMENCLATURE	xiii
1. INTRODUCTION	1
1.1 Research and Development Applications	2
1.1.1 Waste Form Processing	3
1.1.2 Dissolution, Retention, Volatilization, and Trapping Studies for Radionuclides and HVPs	3
1.1.3 Electrode Materials	3
1.1.4 Effects of the Arc Power, Jet, and Roots	3
1.1.5 Refractory Corrosion	3
1.1.6 Skull Formation	4
1.1.7 Crucible Geometry	4
1.1.8 Metal Oxidation	4
1.1.9 Melt Oxidation and Reduction State	4
1.1.10 Crystallization/Devitrification of Melt	4
1.2 Input Waste Stream and Final Waste Form Series	4
2. BENCH-SCALE ARC MELTER	7
2.1 System Design and Construction	7
2.1.1 Introduction	7
2.1.2 Experimental Apparatus	7
2.1.3 Analytical Considerations	12
2.2 Data Acquisition Capabilities	19
2.2.1 Introduction	19
2.2.2 Temperature Monitoring System	21
2.2.3 Current and Voltage Measurements	21
2.2.4 Optical Monitoring Capabilities	21
3. OPERATIONAL CHARACTERISTICS	23
3.1 Power Requirements	23
3.2 Carbon Electrode Connections	23

3.3	Heat and Radiation Protection	23
3.4	Crucible Cooling and Protection	25
3.5	Starting Methods	26
3.6	Heating Procedures	26
4.	EXPERIMENTAL RESULTS	31
4.1	Introduction	31
4.2	Description and Purpose of Experiments	31
4.3	Melting Capability	33
4.4	Electrode Wear	34
4.5	Energy Balance	39
4.6	Materials Characterization	56
4.6.1	Introduction	56
4.6.2	Pure Soil (A-100)	56
4.6.3	IEB/A-40	60
4.6.4	Hydrated Metal Oxide, Metal Dissolution and Oxidation, and Cemented Organic Experiments	60
4.7	Cold Trap Analysis	68
4.7.1	Introduction	68
4.7.2	IEB4/A-100 Test	68
4.7.3	Hydrated Metal Oxide Test	68
4.7.4	Silicated Organic Test	68
4.7.5	Metal Dissolution and Oxidation Test	72
4.7.6	Conclusions on Cold Trap Analysis	72
5.	CONCLUSIONS AND RECOMMENDATIONS	74
5.1	Conclusions	74
5.2	Recommendations	74
	REFERENCES	75
	Appendix A—Schematics	A-1

Appendix B—Test Summaries	B-1
Appendix C—Computer Code Listings	C-1

FIGURES

1. Arc melter system	8
2. Left is a front view and right is a side view of the modified plasma reactor chamber showing the ports and electrode drive assembly	9
3. Crucible assembly sitting in the chamber bottom	10
4. Stepping motor controller	11
5. Electrode geometry as viewed through the front port of the reactor chamber	11
6. V-I characteristics of a single TAFA 30-HF power supply	18
7. Data acquisition system for monitoring and storing temperature, flow, and electric power measurements during test runs	20
8. Rear view of the data acquisition system showing the back panel for easy connection to various transducers	20
9. Approximate dimensions of the carbon starting bar or strip	27
10. Current and voltage profile with time for Test 6	27
11. Power profile with time for Test 6	28
12. Current and voltage profile with time for Test 7	28
13. Power profile with time for Test 7	29
14. Convective flow pattern in an 8 kg soil melt	35
15. Soil thermocouple temperature as a function of time for Test 6	35
16. Soil thermocouple temperature as a function of time for Test 7	36
17. Schematic of graphite electrodes	38
18. Plot of uncoated anode erosion rate	41
19. Plot of uncoated cathode erosion rate	41

20. Plot of anode erosion rate for Al_2O_3 coated electrodes	42
21. Plot of cathode erosion rate for Al_2O_3 coated electrodes	42
22. Plot of anode erosion rate for ZrO_2 coatings	43
23. Plot of cathode erosion rate for ZrO_2 coatings	43
24. Current-voltage response of the arc melter for Test 8 on IEB/A-100 soil	45
25. Current-voltage response of the arc melter for Test 9 on IEB4/A-100 soil with ZrO_2 and TiO_2	45
26. Current-voltage response of the arc melter for Test 10a on IEB4/H-series	46
27. Current-voltage response of the arc melter for Test 10b on IEB4/H-series	46
28. Current-voltage response of the arc melter for Test 11 on metal dissolution with ambient argon	47
29. Current-voltage response of the arc melter for Test 12 on metal dissolution with ambient air	47
30. Current-voltage response of the arc melter for Test 13 on metal dissolution with air lance	48
31. Current-voltage response of the arc melter for Test 14 on silicated organics	48
32. Power input and losses to cooling for Test 8 on IEB/A-100 soil	49
33. Power input and losses to cooling for Test 9 on IEB4/A-100 soil with ZrO_2 and TiO_2 ...	49
34. Power input and losses to cooling for Test 10a on IEB4/H-series	50
35. Power input and losses to cooling for Test 10b on IEB4/H-series	50
36. Power input and losses to cooling for Test 11 on metal dissolution with ambient argon	51
37. Power input and losses to cooling for Test 12 on metal dissolution with ambient air	51
38. Power input and losses to cooling for Test 13 on metal dissolution with air lance	52
39. Power input and losses to cooling for Test 14 on silicated organics	52
40. Soil thermocouple temperature as a function of time for Test 8 on IEB/A-100 soil	54

41. Soil thermocouple temperature as a function of time for Test 12 on metal dissolution with ambient air	54
42. Soil thermocouple temperature as a function of time for Test 13 on metal dissolution with air lance	55
43. Soil thermocouple temperature as a function of time for Test 14 on silicated organics ...	55
44. SEM micrograph of the pure soil IEB/A-100 waste form produced in Test 3	57
45. SEM secondary electron image of a metal-like sphere in the graphite (Test 3)	57
46. Metal-like spheres in the glassy region with relatively high carbon diffusion (Test 3)	58
47. Composition of the metal-like spheres in the glassy region with relatively high carbon diffusion (Test 3)	59
48. IEB/A-40 waste form chunks produced in the arc melter (Test 6)	61
49. X-ray diffraction trace for the more crystalline region on the IEB/A-40 waste form produced in the arc melter and its possible mineral phases (Test 6)	62
50. SEM micrographs of the crystalline region of IEB/A-40 produced in Test 6	63
51. SEM micrograph of the IEB4/H-90 waste form produced by the hydrated metal oxide arc melter capability test (Test 10a)	64
52. SEM micrographs of the IEB4/M-90 (Test 12) and IEB4/S-90 (Test 14) waste forms produced by the metal dissolution and oxidation and cemented organic arc melter capability tests	65
53. Speculated zirconia crystallites crystallized from the melt during the metal dissolution and oxidation (argon atmosphere) arc melter capability test (Test 11)	66
54. X-ray diffraction traces of Test 9 cold trap residue. Test 9 melted only pure IEB4/A-100 soil; there were no waste additions	69
55. IEB4/A-100 plus hydrated metal oxides X-ray diffraction traces. These compounds were present in the cold trap residue	70
56. IEB4/A-100 plus hydrated metal oxides X-ray diffraction trace (top), plus the traces of the added metal hydroxides. The added metal hydroxides were not found in the cold trap residue	71
57. X-ray diffraction traces from the silicated organic experiments: cold trap and monocalcium silicate trace	73

TABLES

1. Input waste stream chemical compositions	5
2. Estimated waste form composition from waste streams after incineration and melting	6
3. Mean mass $T(t)$ for 10 kg of IEB/A-100 soil heated at a rate of 10 kW	13
4. Estimation of heat transfer rate between melt at 1,500°C and cooling water surrounding crucible with the slag skull providing the most thermal resistance ($k_{sk} = 1.44 \text{ W/m-K}$)	14
5. Typical convective heat transfer coefficient ranges	14
6. Table of calculated values for heat removal from crucible by cooling water	16
7. Slag properties of IEB/A-100 and A-40 at different temperatures	17
8. Arc melter current and voltage as a function of geometry and temperature	19
9. Description and measurements obtained for arc melter starting and heating preliminary tests	24
10. Descriptions and measurements obtained for simulated-waste arc-melting tests	32
11. Optical pyrometer measurements of the melt from various tests	36
12. Summary of mass balance results for Tests 10-14	37
13. Electrode erosion data (mass in grams)	40
14. Average erosion rates for electrodes during arc melter experiments	44
15. EDS chemistries of metal dissolution and oxidation, (Ar atmosphere) experimental melt. Ar2-1 represents the general glass, Ar2-2 represents the glass located at Spot 2 in Figure 53, and Ar2-3 represents the zirconia particle chemistry located at Spot 3 in Figure 53	67
16. Hydrated metal oxide sludge chemical composition	69
17. Chemical composition of Micro-cel E and Floor DRI	73

ACRONYMS AND NOMENCLATURE

A	area
A_s	cross sectional area (m^2)
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
D	diameter
E	internal energy (J)
h	film heat transfer coefficient (W/m^2-K)
h_{ave}	average h over length of channel
I	electric current (A)
IEB	iron-enriched basalt
IEB4	IEB with ZrO_2 and TiO_2
k	thermal conductivity ($W/m-K$)
L	length
m	mass (kg)
Nu	Nusselt No., $Nu = hD/k$
Pr	Prandtl No.
q	heat flux (W/m^2)
$\dot{Q}$	heat transfer rate (W)
s	height of channel
rf	radio-frequency
R	electrical resistance (Ohms)
Re	Reynolds No.
RTD	resistance thermometer device

RWMC Radioactive Waste Management Complex

SS stainless steel

t time

T temperature

U velocity (m/s)

V voltage (V)

VOC Volts - open circuit

w width of channel

W work rate (W)

x distance

Greek

σ electrical conductivity (Ohm-m)⁻¹

Subscripts

B bulk or mixed condition

c channel

e electrical

h hydraulic

melt melted slag

sk skull

SS stainless steel

w water

Bench-Scale Arc Melter for R&D in Thermal Treatment of Mixed Wastes

1. INTRODUCTION

The objective of this report is to describe the design, construction, and development of procedures for operating a bench-scale arc melter. The arc melter will be used to develop techniques and procedures with simulated waste materials, including radionuclide surrogates, which can be duplicated with transuranic (TRU) and low-level (LL) radionuclides and similar equipment in hot cells at the site. Examples include the dissolution, retention, volatilization, and collection of TRU and LL nuclides and high vapor pressure metals (HVPMs); metal decontamination via surface oxidation; and the waste form phase composition and process development. The arc melter will also be used to test various melter design concepts such as electrode material development to minimize corrosion and erosion, refractory corrosion and/or skull formation effects, and crucible or melter geometry. In addition, the bench-scale melter can provide information on general waste composition processing requirements for nonradioactive, radioactive and hazardous waste streams. Processes of interest include metal melting and oxidation rates, desirable melt oxidation/reduction (redox) conditions, and crystallization/devitrification of the slag. An immediate need is to initiate in-house testing of IEB4, an iron-enriched basalt (IEB) modified with Group IVB oxide additives (ZrO_2 and TiO_2), for ex situ vitrification of the buried and stored TRU-contaminated wastes at the Idaho National Engineering Laboratory (INEL).

A robust thermal treatment process has evolved from preliminary buried waste system design studies (BWSDS)¹ and stored waste system design studies (SWSDS)² for treating TRU-contaminated waste (TRUW) using an iron-enriched basalt medium. Most of the previous research performed on IEB and has shown that for disposal the waste form is long-lived.^{3,4,5} At the end of the IEB research program, it was found that the incorporation of zirconia further adds waste form longevity and lowers leach rates.^{6,7,8} These rates were first identified when Three-Mile Island core debris was being investigated for fuel disposal or recovery.^{9,10,11,12} Present waste form research at the INEL is focused on the improvements attainable with zirconia and titania additives. It is well known that zirconium and titanium oxides are the basic components in SYNROC ceramic waste forms^{13,14,15} and these oxides enhance the IEB4 waste form.^{8,16,17} The thermal treatment process is robust in that the composition of the radionuclides (U, Pu, etc.) has a large tolerance (20–30% as oxides) and in that high-temperature thermal conditions can be obtained to maintain fluidity, even with zirconia and titania additions that may elevate the melting temperature. Ewing and Lutze (Ref. 14) indicate that the higher thermal stability of ceramic waste forms permits higher waste loadings and thus a reduction in the material to be handled and storage in rock units at greater depth or in canister arrays with closer spacings.

The arc melter is a lab/bench prepilot unit (<50 lb capacity) using water-cooled metal crucibles to produce a protective skull. The electrodes must be able to operate above the melt in both oxidizing and reducing atmospheres. In the design and construction of the arc melter, several initial constraints were proposed.

- Construction of the plasma arc melter will only require modification to the existing equipment.
- These modifications will consist of construction of a new electrode mounting and translation device and the addition of a temperature and video monitoring system.
- The use of this arc melter will be limited to nonradioactive isotopes and small amounts of hazardous metals as allowed by the independent safety review committee.
- A water-cooled crucible will be constructed and used for waste analog tests to eliminate potential contamination that could result from use of a ceramic crucible.
- Materials volatilized from the melt are to be collected in a liquid nitrogen cold trap and the scrubbing system.
- The input power to the arc melter will not exceed 240 kW, the maximum available power from the power supplies.

An existing water-cooled plasma reactor chamber was converted into the arc reactor chamber. The motor track for electrode translation, the electrode mount and connectors, thermocouple support, and additional windows were added to the chamber. A water-cooled metal crucible jacket with removable stainless steel (SS) crucible inserts was constructed to perform the melt operation. A heat reflector and ceramic fiber insulation were added to the inside top of the reactor chamber to prevent overheating. An existing off-gas scrubber system can be connected to the arc chamber to remove particles and noxious gases from the off-gas stream. A liquid nitrogen trap was added for cooling and to ensure the harmless integrity of the exhaust gas. A video camera is used to provide instant feedback of the melter in operation. Access was provided for waste additions during operation.

The plasma arc melter is completely instrumented to monitor and store data on (a) temperatures at several locations within the melt, (b) heat losses to cooling water, (c) chemical analysis of off-gas, (d) electrical power input, and (e) arc power. Provisions have been made for periodic sampling and testing of the melt composition during melting of simulated wastes.

1.1 Research and Development Applications

Knowledge accumulated from the research and development phase of the bench-scale arc melter is important. This knowledge will lead to effective cost saving in proper design, construction, and operation of the demonstration unit. The bench-scale prototype melter also provides research and development capabilities to identify extrinsic and intrinsic waste processing parameters that will significantly influence waste form performance characteristics. These processing parameters are an integral part of the functional unit that will provide information to the public that the waste forms are safe and the properties are comparable to their natural analogs.

1.1.1 Waste Form Processing

This arc melter prototype provides the capability for waste form processing. Different waste stream compositions can be tested in the melter to obtain different waste form compositions and associated process characteristics. The performance of these waste forms can then be compared as a function of their chemical compositions and processing characteristics in the melter. This provides the opportunity to define the most desirable procedure to produce a durable waste form.

1.1.2 Dissolution, Retention, Volatilization, and Trapping Studies for Radionuclides and HVPs

This arc melter prototype provides the capabilities for dissolution, retention, volatilization, and trapping studies for the radionuclides (TRUs, activated and fission products) and high vapor pressure metals (HVPs). The melt chemistry, temperature, and interaction of the arc roots and the melt have tremendous influences on the dissolution, retention, and volatilization of the radionuclides and HVPs. It is very desirable to define an operating procedure that allows high dissolution and maximum retention of these elements in the slag. The melter also provides an opportunity for determining the condition under which the HVPs will volatilize from the melt and the means to trap and dispose of these elements.

1.1.3 Electrode Materials

Electrode materials influence directly the melter operations, the melt chemistry, and indirectly the waste form performance characteristics. The abilities of the electrodes to maintain stable arc operations in oxidizing and reducing atmospheres are important. These abilities will define the material lifetime as well as the duration of the arc melter operation due to electrode wear. The electrode materials can influence the melt chemistry significantly during operation, particularly in the case of a dip electrode, which may change the oxidation state of the melt and indirectly influence the waste form performance characteristics. The bench-scale arc melter offers the capability for defining and testing proper electrode materials and electrode wear conditions for optimum waste processing.

1.1.4 Effects of the Arc Power, Jet, and Roots

The arc power directly influences the melt temperature, foaming, and chemistry by excessive vaporization of the volatile components. The electrode wear phenomena are directly due to the actions of the arc roots and jets and are indirectly due to the arc power. The melter offers the opportunity to investigate these interlocking interactions and their relationship to a proper waste processing.

1.1.5 Refractory Corrosion

If a refractory lining is required inside the crucible, the refractory corrosion by the melt at different melt temperatures is important. This is because refractory materials can significantly alter the melt composition and thus the waste form properties. The arc melter has the capability to perform studies to provide the optimum recommendation.

1.1.6 Skull Formation

If a water-cooled metal crucible is used, a skull will form on the crucible wall. The thickness of the skull will determine the rate of heat loss to the cooling water, which in turn affects the melt temperature and the melt circulation to homogenize the melt composition. The melter tests will give an indication of skull thickness and uniformity.

1.1.7 Crucible Geometry

The crucible geometry, dimension, and aspect ratios are important to the thermal equilibration, homogenization, foaming height, and tapping of the melt. The melter design is flexible enough for testing of different crucible geometry.

1.1.8 Metal Oxidation

The Radioactive Waste Management Complex (RWMC) waste streams contain a large quantity of contaminated metals. Dissolution, oxidation, and retention of the metals in the melt is important to melter capability. Arc melter prototype studies will provide the critically needed information for design and operation of the demonstration facility.

1.1.9 Melt Oxidation and Reduction State

The redox state of the melt is critical to the long-term performance of the waste form and can change the waste form composition, thus influencing positively or negatively waste form performance characteristics. The redox state of the melt relates intimately to a number of the above parameters. In situ sampling of the melt periodically will reveal the redox state of the melt during operation. This melter provides easy access for these studies.

1.1.10 Crystallization/Devitrification of Melt

The present design of the prototype allows a short turnover time for waste melting operation. The crucible insert containing the melt can be easily taken out and put in a temperature-controlled environment for crystallization and growth of desirable mineral phases. A new crucible insert can be replaced immediately, and the melting operation can be resumed.

1.2 Input Waste Stream and Final Waste Form Series

The arc melter is to be used to generate waste forms from a variety of input waste streams. The chemical composition of the various waste streams from the Rocky Flats Plant is given in Table 1. IEB is being considered as the stabilizing medium for radioactive and hazardous wastes at the INEL Radioactive Waste Management Complex (RWMC) because the average composition of the waste, after combustion of organics, is that of an iron-enriched basalt. The addition of soil facilitates the processing, improves the stability, and shifts the composition toward a natural basalt. The major focus on IEB considered to date has been the A-series final waste form (FWF), where "A" indicates an "Average" transuranic-contaminated waste (TRUW) composition defined elsewhere³ and given in Table 2. The notation "A-40" means 60 wt% "average" TRUW plus 40 wt% soil. The waste form compositions resulting from the various input

Table 1. Input waste stream chemical compositions.

Content code/ name	Rocky Flats Plant	Original waste chemical composition (wt%)	Primary packaging additions	Designator
1/first stage sludge	741	H ₂ O(60%), SiO ₂ (14%), Al ₂ O ₃ (3%), FeO(0%), Fe ₂ O ₃ (3%), MgO(2%), CaO(2%), Na ₂ O(11%), K ₂ O(2%), other(3%)	Portland cement	(H1)
2/second stage sludge	742	H ₂ O(60%), SiO ₂ (19%), Al ₂ O ₃ (2%), FeO(0%), Fe ₂ O ₃ (2%), MgO(4%), CaO(10%), Na ₂ O(2%), K ₂ O(1%), other(0%)	Portland cement	(H2)
3/organic setups	743	Texaco regal oil(28%), CCl ₄ (19%), Cl ₂ CHCH ₂ Cl(10%), misc. oils (hydraulic, gearbox, freon, etc.) (43%)	Calcium silicates	(S)
4/special setups	744	Alcohols, organic acids and chelating agents (100%) (specific makeup unknown)	Portland cement, magnesia cement	(P)
5/evaporator salts	745	NaNO ₃ (60%), KNO ₃ (30%), misc.(10%)	None	(N)
480/unleached light non-SS source metal	UNK	Fe(62%), other(Cu,Al,Cr,etc.) (26%) SiO ₂ (3%), Al ₂ O ₃ (2%), CaO(2%), other(combustible)(5%)	None	(M)

Table 2. Estimated waste form composition from waste streams after incineration and melting.

	SiO ₂	Al ₂ O ₃	FeO+ Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	TiO ₂	Misc
A-0	38.0	7.4	34.5	8.3	4.6	4.8	2.4	0.0	0.0
H1-0	25.1	7.0	30.2	12.5	3.0	16.0	2.5	0.0	3.7
H2-0	31.0	4.7	22.7	22.7	6.0	3.2	2.2	0.2	0.3
S-0	33.4	2.9	37.5	25.6	0.0	0.0	0.0	0.0	0.0
P-0	17.4	8.4	24.4	41.8	8.0	0.0	0.0	0.0	0.0
N-0	0.5	0.2	25.3	0.0	0.0	45.0	29.0	0.0	0.0
M-0	2.5	5.1	75.1	1.0	0.0	0.0	0.0	0.0	16.3
SOIL	65.4	13.0	4.5	10.0	2.4	1.7	2.9	0.6	0.0

waste streams shown in Table 1 and the INEL soil being considered are given in Table 2, where A-0, H-0, etc., are the "pure" waste compositions and A-100, H-100, etc., would be pure soil.

It has also been found that the addition of small amounts of TiO₂ and ZrO₂ to the soil (giving IEB4) results in the formulation of crystals in the waste form which incorporate the actinide (transuranic) elements. These crystals are more leach resistant than other glasses and ceramics, including borosilicate glass (BSG) and IEB, and are a component of the composition of the SYNROC ceramic waste forms. The generation of both IEB and IEB4 waste forms are discussed in this report. A shorthand format, IEB4/A-40, has been selected to indicate that the soil is mixed with some TiO₂ and ZrO₂ before combining with 60 wt% of the simulated average TRUW composition. The compositions used are often those assumed after incineration to simulate probable melting conditions, but not always.

2. BENCH-SCALE ARC MELTER

2.1 System Design and Construction

2.1.1 Introduction

A relatively simple design using transferred arcs was desired to examine the various R&D topics.^{16,17,18} A melter using consumable graphite electrodes was selected. The arc melter is designed to provide minimum contact between the graphite electrodes and the melt. Graphite electrodes in contact with the melt can change the oxidation state of the melt causing reduction of some metal oxides—in particular the iron oxide to metallic iron. This change in the oxidation state may have significant negative influence on the durability of the waste form. The reduction of the iron or other transition metal oxides will cause excessive foaming of the melt and make the melt operation difficult to control.

The present design features both the anode and the cathode sustaining the arcs above the melt. A sketch of the arc melter system is shown in Figure 1. This arrangement prevents the electrode from contacting the melt and decreasing the opportunity of melt reduction by the electrodes. The cathodic arc attaches to the melt where the current passes through and provides joule heating of the melt. The anodic arc leaves the surface and reattaches to the anode above the melt. This mode of heating combines both arc and joule heating of the melt and provides a much higher heat transfer and heating rates of the materials than the conventional joule-heated melter. The arc gap above the melt can be constantly adjusted by a step motor to maintain a stable arc operation. Another important feature of the arc melter is a water-cooled crucible-pot assembly, with a removable SS crucible insert. This design is for fast turnaround batch operations, without the need to tap the melt. A small entry port provides thermocouple access to the melt for temperature measurement. Thermocouples are installed to measure the heat loss to the crucible cooling water, the electrode, and the off-gas. Electrode feed openings are insulated and protected by boron nitride. A liquid nitrogen cold trap is used to condense volatile particles from the off-gas. The whole system is completed with a wet scrubber to clean the off-gas.

2.1.2 Experimental Apparatus

2.1.2.1 Melter Chamber. An existing large plasma reactor has been modified to become the melter chamber (see Figure 2). Of the upper chamber's five ports, three are for access, one is for exhaust gas, and one is unused. The top of the chamber has been modified for mounting the electrode feedthrough and translation system. Additional ports have been installed for observation and for thermocouple entry into the melter crucible. A cooling system and heat shield have been installed inside near the top of the upper chamber to prevent overheating during melting. The lower chamber has two ports, one of which is used as the cooling water inlet and the other as an outlet for melter crucible.

2.1.2.2 Water-Cooled Metal Crucible. The schematics for the crucible design are given in Appendix A (Figures A-1 and A-2). Figure 3 shows the crucible assembly sitting in the bottom of the chamber. The crucible is constructed with 0.125 in. thick SS. The water-cooled crucible-pot assembly consists of a right cylindrical outer jacket, or pot, 11 in. in diameter and 16 in. in height

EXPERIMENTAL PLASMA ARC WASTE PROCESSING REACTOR

Figure 1. Arc melter system.

Figure 2. Left is a front view and right is a side view of the modified plasma reactor chamber showing the ports and electrode drive assembly.

Figure 3. Crucible assembly sitting in the chamber bottom.

and removable SS crucible insert with a diameter of 10 in. and heights of either 8 or 14 in. The flexible crucible insert size allows for different batch sizes. The cooling gap between the jacket and the crucible insert is 0.5 in. A ring flange and bolt clamps are used with an O-ring seal to prevent water leakage. A SS disk on legs is inserted into the jacket to reduce the area for cooling water flow and thereby increase the cooling capability along the bottom of the crucible.

2.1.2.3 DC Arc Electrode System. The schematics for the arc electrode system are given in Appendix A (Figures A-3 to A-6). The electrode drive system is illustrated in Figure 1 and pictured in Figure 2. It consists of two brass blocks, internally cooled, each measuring 4 x 3 x 1 in. for electrical connection. Two concentric brass tubes (diameters 1 in. and 0.5 in., respectively) serving as the electrode extension and feedthrough are soldered to the brass blocks. The brass electrode holders are insulated with a 0.25 in. thick boron nitride tube. The boron nitride serves as both electrical and high-temperature insulation. A boron nitride insert further isolates the electrode feedthrough from the arc melter chamber. The entire electrode system is mounted on a worm gear support, and the movement of the electrodes is controlled by a stepping motor (see Figure 4). The brass holders are tapped to receive the electrodes. A 0.5 in. copper threaded rod is used to connect the graphite electrodes to the holder. Two 2 x 0.25 in. disks of boron nitride shield the electrode holder from the intense arc radiation. Two tapered and tapered graphite rods (0.5 x 6 in.) are used as the electrodes. A view of the electrodes through the front port is pictured in Figure 5.

Figure 4. Stepping motor controller.

Figure 5. Electrode geometry as viewed through the front port of the reactor chamber.

2.1.2.4 Cold Trap. Exhaust gas temperatures exiting the melter can reach 350°C and may contain volatilized compounds. A SS liquid nitrogen cold trap is used both to cool the exhaust gas and to condense and trap volatile materials.

2.1.2.5 Off-Gas Treatment System. An existing wet scrubber is in place to use with the are melter system when necessary. The wet scrubber has not been used in the preliminary tests, since noxious gases or hazardous particles are not generated. The scrubber system can be utilized in the future when necessary; for instance, when HVPs like lead, zinc, etc., are present in the melt. The wet scrubber is placed after the cold trap to retain any escaped particles. Scrubber water can be neutralized prior to disposal.

2.1.3 Analytical Considerations

In general, the geometry for the design considerations is as shown in Figure 1 and in Figures A-1 and A-2 using an 8 in. high x 10 in. diameter SS crucible in a 16 in. high x 11 in. diameter jacketing pot. The crucible is filled with soil or simulated waste to a height of approximately 4 in. (approximately 6.5 kg or 14 lbm).

2.1.3.1 Energy Balance Considerations. From simple first law calculations, the energy required to melt A-100 soil to slag can be approximated. Detailed calculations including geometry and more exact property determinations are beyond the scope of this work.

The first law of thermodynamics for a control volume integrated over time can be expressed as

$$\int \dot{Q} dt + \int \dot{W}_e dt = \int \frac{dE}{dt} dt \quad (1)$$

where the changes between input and output flow enthalpy, kinetic energy and potential energy changes are assumed negligible, and $E (=mc_vT)$ is the total internal energy of the soil plus melted slag. Assuming also that the unmelted soil provides a good insulator until the melted slag reaches the walls (as indicated by the slow rise in thermocouple measurements during a run - see Figures 15 and 16), the process can be assumed adiabatic to a first approximation. The resulting First Law equation is

$$\int \dot{W}_e dt = \int mc_v d\bar{T} \quad (2)$$

The average temperature of a 10 kg mass of soil with a c_v of 1,700 J/kg-K initially at 15°C and a constant power input of 100 A at 100 V = 10 kW is given in Table 3 as a function of heating time. The total time to melt into slag is unexpectedly (because of the simplified assumptions) close to the times obtained in the last two tests (Test 6 and 7).

2.1.3.2 Wall Heat Transfer Considerations. The heat transfer rate from the melted slag to the cooling water is estimated. Detailed heat transfer calculations considering geometrical effects and well determined (by measurement) property values are beyond the scope of this work. The heat transfer rate from the melted slag to the cooling water is approximated by assuming a plane wall geometry to determine local effects and reference book property values for similar

Table 3. Mean mass T(t) for 10 kg of IEB/A-100 soil heated at a rate of 10 kW.

Time t (minutes)	Temperature T	
	Seconds	°C
0	0	15
10	600	368
20	1,200	721
30	1,800	1,073
40	2,400	1,426
50	3,000	1,780
60	3,600	2,132

materials. Heat from a 1,500°C slag/skull interface transfers through the skull, the SS crucible wall into the water in steady state. Assuming that the thermal resistance of the SS is negligible and that the water film coefficient will adjust (via boiling if necessary), then the predominant thermal resistance is the skull. Using the linear Fourier heat conduction equation for the heat flux, q

$$q_{sk} = -k_{sk} \frac{dT_{sk}}{dx_{sk}} \quad (3)$$

and recognizing that the heat through each layer is the same in steady state and equal to the total heat transfer,

$$q_{total} = q_{melt} = q_{sk} = q_{SS} = q_w \quad (4)$$

then the heat flux and water heat transfer coefficient can be calculated for different assumed skull thicknesses as shown in Table 4. The properties used are $T_{melt} = 1,500^\circ\text{C}$, $T_{SS} = 150^\circ\text{C}$ (assuming 50°C superheat above the 1-atm boiling temperature on the wall if boiling) $k_{sk} = 2$ to 10 BTU-in/h-ft²-F or 0.288 to 1.440 W/m-K (based on a glassy/granite skull)¹⁹ where the maximum value is used in Table 4 to determine the maximum heat transfer rate. $Q_{w,max}$ in Table 4 is the product of Q_{sk} and the effective area of the melt (taken to be the bottom 4 in. of the crucible). The heat transfer coefficients in Table 4 can be compared with the typical range of values for different types of heat transfer given in Table 5.²⁰

Comparison of the h values for different skull thicknesses in Table 4 with the typical values in Table 5 indicates that boiling heat transfer will probably occur at the crucible-water interface. The velocity of the water flow needs to be sufficient to permit a subcooled nucleate boiling regime in which the vapor bubbles condense rapidly either on the surface or near the generation point. If the velocity is too small, film boiling and burnout (pinholes, etc.) can occur.

Table 4. Estimation of heat transfer rate between melt at 1,500°C and cooling water surrounding crucible with the slag skull providing the most thermal resistance ($k_{sk} = 1.44 \text{ W/m-K}$).

Δr_{sk}		q_{sk} (W/m ²)	h_w		$Q_{w,max}$	
in.	mm		(BTU/hr-ft ² -F)		W/m ² -K	kW
0.125	3.18	3.18	611,320	2,153	12,226	80.5
0.250	6.35	6.35	306,142	1,078	6,123	40.3
0.500	12.70	12.70	153,071	539	3,061	20.2
0.750	19.05	19.05	102,047	359	2,041	13.4
1.000	25.40	25.40	77,760	274	1,555	10.2

Table 5. Typical convective heat transfer coefficient ranges.

Condition	h (BTU/hr-ft ² -F)	h (W/m ² -K)
Air, free convection	1-3	5-15
Air, forced convection	3-50	15-300
Water, forced convection	50-2,000	300-12,000
Water boiling	500-10,000	3,000-55,000
Steam condensing	1,000-20,000	5,500-100,000
Subcooled nucleate boiling	10^4 - 10^7	5×10^4 - 5×10^7

It appears that vertical wall heat transfer rates are marginal because of the modest velocities. Velocities on the crucible bottom are too low because of inverted natural convection for conditions when the soil is all melted. The crucible-pot system was therefore modified using a coil of copper tubing to create two spiral channels from the bottom of the crucible to the top. A disk with a 1-in. center hole was positioned immediately below the crucible bottom, with a decreasing gap at larger radii to lessen the velocity decrease with increasing cross-sectional area. The modified system worked well with a total melt.

2.1.3.3 Cooling Water Flow Considerations. A more complicated, but standard, analysis of the cooling water flow rate to carry away the heat transferred through the crucible was made. The analysis is based on the overall heat transfer relations,

$$\dot{Q} = h_{ave} A_s (T_{wall} - T_B) = \dot{m}_w c_{p,w} (T_{w2} - T_{w1}) \quad (5)$$

where h_{ave} is the average heat transfer coefficient, A_s is the channel cross-sectional area, $T_B = (T_{w1} + T_{w2})$ is the water bulk temperature, and $\dot{m}_w$ is the water mass flow rate. The value for h_{ave} is obtained from the Nusselt Number correlation for laminar or turbulent flow determined by

the Reynolds Number. The hydraulic diameter for a rectangular cross section s by w is used as the characteristic length,

$$D_h = \frac{4 A_s}{\text{wetted perimeter}} = \frac{4 s w}{2s+2w} \quad (6)$$

Above the critical Re of 3,000, the turbulent flow equation of Colburn²¹ neglecting entrance region effects, is used:

$$Nu_D = 0.023 Re_D^{4/5} Pr^{1/3} \quad (7)$$

For laminar flow, the equation of Hausen^{22,23} is used which includes the entrance region effect via the channel length L_c :

$$Nu_{ave} = 3.65 + \frac{0.0668 (D_h/L_c) Re_D Pr}{1 + 0.04 [(D_h/L_c) Re_D Pr]^{2/3}} \quad (8)$$

Table 6 indicates the result of calculations based on a measured maximum water flow rate through the crucible-pot assembly of 8 gpm (0.506 kg/s or $505 \times 10^6 \text{ m}^3/\text{s}$). Different channel sizes are considered. Case 1 is for no additional channels. To remove the heat transferred to the water from the crucible as shown in Table 4 for different skull thicknesses, it appears that channels similar to Case 2 would be required.

2.1.3.4 Voltage-Current-Time Considerations. The initial difficulty in operating and restarting the arc melter was in part due to unresolved starting procedures and in part due to inadequate power supply V-I characteristics with the initial power supplies used. Each arc/Joule heated system operation is different depending on the electrode geometry (gap length L), the material/melt/slag resistance, the arc/Joule voltage-current characteristics, and the power supply characteristics. The following discussion considers these factors for the bench-scale arc melter used here.

The slag properties are obtained from prior IEB research.^{3,5} Electrical conductivities as a function of temperature for soil (A-100) and average waste plus 40% soil (A-40) are given in Table 7 (from Ref. 3).

The voltage and current in the circuit are related by Ohm's Law,

$$V = IR \quad (9)$$

and the resistance is approximated by

$$R = \frac{L}{A\sigma} \quad (10)$$

where A is the cross-sectional area of the slag, L the length between electrodes, and σ the electrical conductivity.

Table 6. Table of calculated values for heat removal from crucible by cooling water.

Case	s (in.)	w (in.)	D _h (in.)	A _s (m ²)	Re _D	U (m/s)	Mode	Nu _{ave} (in.)	L _c (W/m ² -s)	h _{ave} (kW)	Q _{max} (kW)	Q _{min} (kW)
1	10 ₋	0.5	0.984	0.01013	1,505	0.0499	Lam	13	8	425	11	4
2	1.0	0.5	0.667	0.000323	31,916	1.563	Turb	164	—	5,970	148	58
3	0.25	0.5	0.333	0.000081	63,786	6.23	Turb	286	—	20,728	529	202

Notes:

Q_{max} includes the heat transfer to the crucible bottom, Q_{min} does not. For channel flow along the sides of the crucible, Q_{min} is most relevant.

If boiling occurs, h_{ave} will increase significantly in cases 1 and 2.

If use 1/2 by 1/2 in. channels should get approximately 2 x 1/4 = 1/2 the h-value, the velocity, and the heat transfer; therefore, approximately 3,000 W/m²-K, 0.8 m/s and 30 kW, respectively.

Table 7. Slag properties of IEB/A-100 and A-40 at different temperatures.

T (°C)	Electrical conductivity (Ohm-m) ⁻¹	
	A-100	A-40
1,400	0.8	5.0
1,500	1.5	8.0
1,600	3.0	15.0
1,700	6.0	25.0
1,800	12.0	40.0

The V-I characteristics of a single TAFA 30-HF power supply is shown in Figure 6. Each curve represents the V-I characteristic for maximum power (unsaturated reactor) and exceeds the 100% duty cycle ratings. The 100% duty cycle rating is given as 75/150/300 A at 50/100/200 V with open circuit voltages of 100/200/400 V, depending on the buss setup. Attempting to restart the current flow with 80 or with 200 VOC had been unsuccessful; therefore, two power supplies were set up for 400 VOC and used in parallel.

Currents calculated with operating voltage at 200 V and 300 V (assuming 400 VOC) based on different electrode gap lengths, L, different melted slag cross-sectional areas, A, and slag temperatures T for both A-100 and A-40 compositions are given in Table 8. The calculations neglect arc resistance and voltage drop which should be approximately 20 V with small (1-3 mm) arc gaps and are therefore based on the slag resistance only.

Calculations for A-100 slag (melted soil) for the current electrode separation (5 in.) and typical initial cross-sectional areas available ($< 2 \times 2 \text{ in}^2$) indicate that very high temperatures ($> 1,800^\circ\text{C}$) would be required to pass more than 50-75 A at 200-300 V. With A-40 slag (40% soil, 60% average TRU-contaminated waste) the resistance decreases by a factor of 5 to 6, relaxing the constraints imposed by the present power supply.

The reduction of the electrode separation to 3 in. would increase the current capability about a factor of 2, if needed. The smaller gap may significantly lengthen the time to heat the material near the walls. Optimum geometrical considerations still need to be made.

With either composition, the best starting procedure uses a high initial current (200-300 A) through the conducting strip for initial heating of the soil. When the combined graphite/slag resistance increases to cause the voltage to get up to 50-75% of the maximum loaded voltage, start reducing the current to maintain the voltage, heating and continued melting. This procedure was tested and validated on both A-40 IEB and IEB4 compositions, as well on the subsequent melts discussed in this report.

Figure 6. V-I characteristics of a single TAFA 30-HF power supply.

Table 8. Arc melter current and voltage as a function of geometry and temperature.

L (m)	I(A)				200V	300V
	A (m ²)	Slag	T (°C)	R (Ohm)		
<u>5-in. Electrode Gap</u>						
0.125	0.0025	A-100	1,400	62.5	3.2	4.8
(5 in.)	(2 x 2 in.)	1,600	16.7	12	18	
		1,800	4.2	48	72	
0.125	0.0025	A-40	1,400	10.0	20	30
		1,600	3.33	60	90	
		1,800	1.25	160	240	
<u>3-in. Electrode Gap</u>						
0.075	0.0025	A-100	1,400	37.5	5.3	8
(3 in.)	(2 x 2 in.)	1,600	10.0	20	30	
		1,800	2.5	80	120	
0.075	0.0025	A-40	1,400	6.0	33	50
		1,600	2.0	100	150	
		1,800	0.75	267	400	

2.2 Data Acquisition Capabilities

2.2.1 Introduction

The overall purpose of the data acquisition system for these tests is to provide centralized means of simultaneously taking many different readings from thermocouples, voltage sources, etc.; displaying them in real time for monitoring the process; and simultaneously storing them for later analysis. The system was developed around a Fluke model 2285B data logger with an overall capability to handle up to 120 separate data channels (see Figure 7). A back panel was manufactured to easily interface between the data logger and standard connectors for thermocouple and voltage measurements (see Figure 8). The data logger is controlled remotely by an IBM personal computer, with software provided by Fluke. The channels on the data logger are programmed to transmit data through the RS-232 communications port to the computer, where it is displayed and stored.

Figure 7. Data acquisition system for monitoring and storing temperature, flow, and electric power measurements during test runs.

Figure 8. Rear view of the data acquisition system showing the back panel for easy connection to various transducers.

2.2.2 Temperature Monitoring System

The back panel (see Figure 8) has connectors for 5 type-K and 5 type-C thermocouples. In addition, there are 9 channels with connections for 3-wire RTD measurements. The type-K thermocouples (-200 to 1,250°C) are used to monitor various cooling-water temperatures and the type-C (0 to 2,320°C) are used for higher temperature applications such as soil/melt temperature and exhaust temperature. The exhaust and soil temperatures are monitored to assess the progress of the melt. Cooling-water temperatures are monitored both for safety and calorimetry. Starting with Test 5, water flow meters were connected to the various cooling lines. This additional information would be enough to do energy balance calculations; however, the temperature measurements appeared to drift randomly a few degrees while the melter was operating, making any energy balance calculations questionable. For Test 7, the thermocouples were replaced by RTDs in an attempt to improve the measurements. The RTDs appeared to be less susceptible to interference caused by operation of the arc.

Also starting with Test 7, an optical pyrometer was used to make limited measurements of the surface temperature of the melt. The pyrometer is a simple disappearing filament type and could be subject to errors caused by a dust film collecting on the viewing port. This problem was eliminated by improvements to the optical port, making it a simple hinged port that can be easily opened and cleaned while the arc melter is operating.

2.2.3 Current and Voltage Measurements

The back panel is set up with 4 standard BNC connectors for voltage measurements. Because the data logger is limited in measuring only up to 64 VDC and the power supply has a 400 V capability, direct measurements are not possible. For the first 6 tests, voltage and amperage have been read and recorded directly from meters on the power supplies. Test 7 included the first current/voltage measurements by monitoring directly across the current shunt (2,000 A, 50 mV) located in the power console. The voltage measurements directly across the power leads at the arc melter were done by using a 100:1 voltage divider and power surge protector on the input to the data logger that conditions the signal to acceptable levels. The input channel on the data logger is then programmed to automatically compensate for the 100:1 reduction in signal strength and gives a correct voltage reading.

2.2.4 Optical Monitoring Capabilities

Progress of the melt can be seen visually through one of three window ports in the jacket of the arc melter. One port on the top provides the best overall view, and two ports on the side allow additional viewing. During initial tests, the windows tended to fog up with dust and condensed particulate from the melt. To prevent this, the ports have been fitted with outlets for argon gas to flow continuously over the glass. This helped considerably, but in recent low dust tests there seems to be an entrainment of particles by the gas flow that collect on the windows. Future tests will determine the effect of gas flow rate on deposits forming on the windows.

A video system, used for the first time in Test 7, monitors the progress of the melt. This system uses a PULNIX TM-540 (512 x 480 CCD array) to produce video signals that can be recorded with a Sony tape recorder. The CCD array can be coupled to any variety of camera

lenses to get the correct focal length, image magnification, etc. This lens must be fitted with a narrow bandpass filter to reduce the intense light emanating from the arc regions. In this case, a narrow bandpass filter at 632.8 nm was used. Videos have been made of selected portions of all arc melter experiments since Test 7.

3. OPERATIONAL CHARACTERISTICS

Initial tests provided experience and data necessary for improvement of the arc melter toward operational status. Each test provided valuable information for improvement of various parts of the system. Subsequent tests at higher power and greater temperatures revealed more problems, which when solved, resulted in a more reliable and capable system. Overall, the program exhibited normal process development. Table 9 summarizes the description, purpose, location of related figures, energy input, average power, and mass balance for each of the preliminary tests (Tests 1-7). This chapter discusses observations made during the development of the starting and heating procedures.

3.1 Power Requirements

While the first test could not be considered successful as far as melting soil, it was very useful in defining the power requirements necessary for this particular melter design. It was suspected the Miller welding power supply would be inadequate to run the arc melter, but its portability and ease of use prompted a trial run with it. The useful operating voltage of 60 V and 80 VOC was not nearly enough to operate the arc melter with the 5-in. spacing between electrodes. The single TAFE power supply with a 100 V operating range did much better, but the voltage was inadequate to restart. Its initial success was probably due to the good conduction path provided by the steel shot embedded in the soil. Once the steel shot melted and sunk to the bottom of the melt, the single power supply could no longer operate. The rest of the tests were done with two TAFE power supplies hooked in parallel and set for an operational voltage of approximately 200 V (400 VOC). This power supply configuration was sufficient to operate the arc melter over the range of operational conditions during a melt. A third power supply is available to provide more current if hooked in parallel with the others, but it is probably not necessary based on the melter tests so far. Another alternative is to connect the two power supplies in series and operate at 400 V and 800 VOC. The cables presently in use are only rated for 600 V, so this arrangement is not possible until new cables are purchased. However, the higher voltage does not appear to be necessary.

3.2 Carbon Electrode Connections

After the first two tests, it became apparent there was a problem on how the carbon electrodes were being attached to the brass, water-cooled holders. The 6 in. long carbon rods were tapered on one end and threaded on the other to be screwed into the holders. Three electrodes broke at exactly the same place at the base of threads on the carbon rod. Before Test 3, a threaded copper insert with a threaded extension was made to attach to the brass holder. The carbon rods were threaded on the inside, then screwed onto the copper insert. For the remaining tests, the carbon electrodes did not break off even though they were used for longer periods and at much higher temperatures.

3.3 Heat and Radiation Protection

Test 3 was the first successful test in that a significant quantity of the soil was melted. The resultant heat and radiation from the melt began to expose weaknesses in the cooling design of

Table 9. Description and measurements obtained for arc melter starting and heating preliminary tests.

Test No.	Date	Experimental description (purpose)	T _{slag} (TC)	V & I char.	Slag matls. char.	Test dur. (min)	Energy			Mass	
							Total (kJ)	Rate (kW)	Initial (kg)	Vitrified (kg)	Vitrified (%)
01	6/5	Soil only, IEB/A-100 No soil preparation (initial starting tests)	—	—	—	30	*	*	[5,4]	0.525	10
02	6/11	Soil only, IEB/A-100 Graphite dumbbell starter (starting tests)	—	—	—	15	6,156	6.8	[6.2]	[0.5]	8
03	6/15	Soil only IEB/A-100 Graphite dumbbell starter (electrode/melter/P.S. mod.)	—	—	Fig.40 to 43	29	61,762	32.2	[6.2]	[2.0]	37
04	6/19	Soil only, IEB/A-100 Graphite starting strip (starting procedure)	—	—	—	18	*	*	6,651	2,440	37
05	6/20	Soil only, IEB/A-100 Graphite starting strip (Heating procedure)	—	—	—	17	23,748	23.4	4,211	0,932	22
06	6/26	Simulated Average Waste IEB/A-40 (Heating procedure/maximum)	Fig.11	Fig.??	Fig.44 to 46	57	63,000	18.4	6,727	5,669	90
07	7/02	Sim. Ave. Waste + TiO ₂ /ZrO ₂ IEB4/A-40 (Heating procedure/steady)	Fig.12	Fig.??	—	64	63,000	16.4	7,375	6,199	84

the melter. The melter was built with no cooling capability on the top, a design flaw from its beginning as a plasma reactor. This flaw was remedied previously by soldering copper cooling coils on the top. For the present use, the cooling coils needed to be removed to make room for the electrodes and ports on top of the melter. During Test 3, the top became very hot (almost glowing red) and necessitated a premature shutdown of the arc melter. Because of the limited space on top of melter, the solution chosen was to put a fiberboard insulator and water-cooled radiation reflector on the inside. The radiation reflector was constructed of 1/16 in. SS plate with copper cooling coils silver soldered to the backside. Holes were cut where necessary to accommodate the electrodes and viewing ports, etc. Subsequent tests have shown this solution to be very effective, with the top of the melter becoming only slightly warm during operation.

3.4 Crucible Cooling and Protection

After Test 3, the effectiveness of the water cooling for the crucible came into question, since a small crater was formed on the inside of the crucible near the top, resulting in a pinhole leak at the bottom of the crater. There was also evidence of melting in several other places around the top part of the crucible. In addition the O-ring in the top on the crucible holder was burned and broken. The drain for the cooling water is about 1 in. below the top of the crucible holder. This results in an air space at the top of the cooling channel and less than adequate cooling. To alleviate this problem, a solid baffle was welded around the outlet to just below the top of the crucible holder. This forces the water up to the top of crucible holder before it can drain out over the baffle. Subsequent runs have resulted in no damage to the O-ring and no visible melting spots around the top part of the crucibles.

The crucible cooling water enters in the crucible container at an angle to induce a swirl around the outside walls. Unfortunately, this results in a stagnant flow of water at the bottom center of the crucible. This was a known problem, but due to time constraints, a fix consisting of channels and baffles to direct water flow to this area was never accomplished prior to Test 5. During Test 5, which was running very smoothly, a hole was melted in the bottom of the crucible causing flooding of the arc melter. The hole was off center about 1 in. and occurred where the slag was closest to the bottom. A factor in melting the hole in the bottom of the crucible was that there was less dirt and therefore melting occurred closer to the bottom. However, a completely successful melt should result in nearly all the material being melted, including the material near the bottom. The center of the crucible on the bottom (water-cooled side) showed extreme discoloration to about 1/2 the radius, indicating that it was at a very high temperature.

In Tests 6 and 7, this cooling problem was solved by using a plate with a 3/4 in. hole in the center to force the water flow to the center of the crucible bottom then outward to the sides. To improve heat transfer from the sides of the crucible, copper coils were placed along the side of the crucible to both direct flow and increase the water velocity. Test 6 ended slightly prematurely when a pinhole leak developed in the side wall of the crucible, above the melt, but below the original fill line. The damage was identical to that in Test 3; but in this case, there were three small round craters in a row with the pinholes in the bottom of each one. Prior to Test 7, the spaces between the coils were filled in with plumber's putty, reducing volume in the cooling cavity and forcing the water to flow faster. This has the effect of increasing heat transfer to the crucible walls and making subnucleate boiling of the cooling water less likely. Protection for the crucibles was increased by lining them with a thin (approx. 1/16 in.) layer of paint-on ceramic on

the inside. In these last two tests, the melt extended to the very bottom of the crucible; and the ceramic liner had been incorporated into the melt. Removal the slag after cooling revealed only a paper thin skull between the slag and the SS of the crucible in some areas, particularly on the bottom.

3.5 Starting Methods

The most reliable starting method obtained is a thin solid graphite strip placed between the electrodes (see Figure 9). The strip provides a good current path and effectively heats up the surrounding soil. Once the soil has melted and becomes a conducting path itself, the graphite strip slowly burns away. Early tests (1-3) experimented with a variety materials and methods that were less than successful at least for this system. The graphfoil worked similarly to the carbon strip except that the ability to heat the soil was not as good and it tended to de-laminate and become ineffective. Carbon powder worked well at the start, but it tended to be blown away in the arc attachment regions. Carbon powder also oxidizes very fast in the middle before good heating of the soil can take place. Metal shavings did not provide a good solid conduction path for starting. Steel shot was better, but there is still the problem of melt contamination with the metal.

Beginning with Test 4 using the thin graphite strips between the electrode contacts, starting procedures were developed that produced consistent results. The current can be quickly raised to about 300 A (at about 50-100 V) with a 5-10 mm arc gap to heat the soil into slag near and under the electrodes. Under these conditions, the TAFA power supplies set at 400 VOC and hooked in parallel seem adequate to start the melts. As the melt progresses, the voltage increases in time as the high conductance graphite burns/sublimes away. If the power supply cannot provide the voltage at the set current (e.g. >200 V at 300 A) the circuit breaks. For this reason, once the graphite strip has been consumed, the current must be reduced (50-150 A) to maintain stable operation.

3.6 Heating Procedures

In the adopted heating procedure initially tried in Test 5 and verified in Tests 6 and 7, the melts are started with a low voltage - high current mode (50-150 V and 150-300 A) and then slowly moved into a high voltage - low current (250-300 V and 50-150 A) operating mode. The voltage-current and power input plots of this behavior are shown in Figure 10 and Figure 11 for Test 6 and in Figure 12 and Figure 13 for Test 7. As the graphite conducting path becomes depleted, current must pass through the melted soil having a higher resistance. This causes the current to decrease and the voltage to rise. Test 6 and each test thereafter shows this behavior.

In Test 6, after stable operation was obtained for 40 minutes, the current was increased to determine the maximum heating limitations of the melter (see Figure 10 and Figure 11). As the current increased, the voltage decreased. At approximately 150 A and 200 V (30 kW), 90% of the soil was melted (Table 9) and the cooling system failed, resulting in a pinhole leak in the side wall resulting in the breaking of the circuit. After Test 6, the melter cooling channels were modified to increase the water velocity. Subsequent tests exceeded 40 kW on occasion, operated

Figure 9. Approximate dimensions of the carbon starting bar or strip.

Figure 10. Current and voltage profile with time for Test 6.

Figure 11. Power profile with time for Test 6.

Figure 12. Current and voltage profile with time for Test 7.

Figure 13 Power profile with time for Test 7.

above 35 kW for extended periods, lasted up to 4 hours (usually limited by electrode life), and occurred under conditions with almost complete melting within the crucible.

Test 7 was operated conservatively (see Figure 12) at a low current (~ 70 A) and higher voltage (200-250 V) with a power level of approximately 17 kW (see Figure 13). The heating process was uneventful. It was terminated when it appeared to be fully melted after 64 minutes. All tests after Test 6 were manually terminated by the operator and were not caused by failure of equipment.

The input energy, average power, and mass balance for the preliminary tests are summarized in Table 9. Tests 6 and 7 represent the culmination of the Phase I development of starting and heating procedures. The energy requirement for melting is 2-3 kW-h/kg, which exceeds the usual large scrap steel melter value of approximately 1 kW-h/kg. The present low efficiency is partially due to scale, but mostly due to the lack of insulating refractory in the SS crucible that results in a high energy loss to the cooling water when the soil becomes melted. The rate of melting is similar to scrap melting, which takes about 1 hour to melt one pot or chamber of material, irrespective of size.

In the earlier tests, after the conducting path was consumed or "lowered" into the melt and if the current was not reduced, a "dust storm" in the arc melter chamber was usually observed for a certain period. The nature of the melting was much different than the adopted mode. The arc length was longer because the arc was attempting to carry the current without significant help from the high-resistance slag. The arc(s) would strike in various locations, including the crucible wall, often forming a violent turbulence in the melt that included the formation of bubbles. The

bubbling, arc jet effects and strong entrainment probably caused the release or flow of the rather fine unmelted soil (dust) in bursts and clouds within the chamber. Lowering the current and the electrode gap to the melt reduces the effect to obtain controllable regimes between a quiescent, a rolling boil, and a firecracker mode, all well below the dust storm turbulence previously obtained. Also, once the melt pool under the electrodes becomes big enough, the current can be increased without promoting the release of soil dust.

As shown in Test 6, heating can be operated in several modes depending on arc gap, current, and stage of melting: (1) a quiescent mode with small arc gap and modest current where most of the surface was dark, yellow circles occurred around the arc attachment immediately below each electrode; (2) strong convective currents resembling a rolling boil mode in which either the slag under the electrodes (early on) or at a location between the electrodes (later), and/or at alternate sides of the crucible in regions where melting had not been obvious before, and finally the whole top of the melt appeared as a slowly or moderately rolling boil; (3) a firecracker mode that appeared to be when the electrodes were just in contact with the surface and at the highest currents allowing continued operation with the V-I characteristics available here. The firecracker mode resembled the random trajectory of bright yellow (as viewed through the protective glass) rockets emitted from the slag at the base of the electrodes and landing elsewhere in the melt or on the walls. At other times, the electrodes were immersed into the slag and operated totally in the Joule-heater type of mode. There was no slag stuck to the electrodes upon emerging from the slag melt and there was little difference in operating conditions (voltage or current).

Foaming does not appear to be a problem with arc melting. Foaming was a major problem when making the IEB/IEB4 materials for the IEB cold tests using induction heating in crucibles and oven heating in crucibles. In the arc melter, the materials were not preprocessed by heating to reduce the amount of gases given off. In Test 7, some obvious foaming caused the arc to occasionally extinguish when foam bubbled up and touched the electrodes. The arc could immediately be restarted by lowering the electrodes to make contact with the melt. It seems that the 400 V open circuit voltage is sufficient (at low current of about 50 A) to restart by contact for this geometry.

4. EXPERIMENTAL RESULTS

4.1 Introduction

This section documents the results of arc melter capability demonstration tests (Tests 8-14) for various simulated waste type compositions stored at the RWMC. The capability tests also evaluated the effects of material addition during arc melter operating conditions. Specific experiments included melting of clean RWMC soil, soil with titania and zirconia additives, soil with simulated cemented organic waste stream, soil with simulated hydrated metal oxide sludges, effects of high aluminum addition on melter operation, and the dissolution and oxidation of high metal waste stream. The dissolution and oxidation of high metal waste stream in the melter were performed under an ambient argon and air atmospheres, and with air lanced into the melt. Electrode corrosion and erosion under different waste stream and melter operating conditions were studied. Mass balance studies for each melt was performed to identify material loss during operation. Energy balance was performed for material addition during arc melter operation to investigate energy sinks in the system. Material characterizations were performed for in situ sampled slags, cold trap materials, and crucible slags. Recommendations for further refinements to enhance the arc melter's capabilities are identified. Table 10 summarizes the test description and the location of figures and tables related to each test.

4.2 Description and Purpose of Experiments

In Phase I, shakedown tests of the arc melter showed that simulated average waste composition of A-0 and RWMC soil could be easily processed into IEB/A-40 and IEB4/A-40 glass-ceramic final waste forms. Steady starting and operating procedures were also established for the arc melter. In Phase II, the scope of work was to perform capability tests for the arc melter under different waste stream scenarios. Capability tests, such as melting of pure soil, soil with 5% percent each of titania (TiO_2) and zirconia (ZrO_2), processing of cemented organic, hydrated metal oxides, and metal dissolution and oxidation (Ar, Air, Air lance environments) with soil were conducted.

These tests were not meant for detailed scientific investigations but to demonstrate melter versatility. Detailed scientific studies of the arc melter process parameters for different waste streams scenarios were not in the scope of this work.

Starting and operating techniques for the arc melter were developed in the first 5 tests. Test 1 used low and high open circuit voltage power supplies to investigate different arc melter starting techniques. Test 2 used two high open circuit power supplies to test a graphite dumbbell as a starting mechanism. Test 3 implemented arc melter enhancements to prevent the melter electrodes from breaking during operation. Tests 4 and 5 established a starting procedure using a 1/4 in. graphite strip and the initial heating current-time procedure required. The heating procedure included, initially a high current and low voltage followed by a low current and high voltage mode.

Tests 6 and 7 were run to test the capability of the arc melter to produce IEB/A-40 and IEB4/A-40 slags for extended times. Test 6 indicated the need for increased cooling at the

Table 10. Descriptions and measurements obtained for simulated-waste arc-melting tests.

Test No.	Date	Experimental description	T_{slag}		V & I char.	Energy balance	Total Mass balance	Elect. corros.	Slag mats char.	Cold trap mats char.
			TC	Optical						
08	8/3	Soil only IEB/A-100	Fig.40	—	Fig.24	Fig.32	—	—	—	—
09	8/6	Soil + TiO_2 + ZrO_2 IEB4/A-100	—	—	Fig.25	Fig.33	—	Fig.18,19 Tab.13,14	—	Fig.54
10a	9/8	Hydrated Metal Oxide	—	Tab.11	Fig.26	Fig.34	Tab.12	Fig.18,19	Fig.51	Fig.55,56
10b	9/9	sludge (H-Series)	—	—	Fig.27	Fig.35	Tab.12	Tab.13,14	—	Tab.16
11	9/11	Metal dissolution, steel with ambient argon (M-Series)	—	Tab.11	Fig.28	Fig.35	Tab.12	Fig.18,19 Tab.13,14	Fig.53 Tab.15	—
12a	9/18	Metal dissolution, steel with	Fig.41	Tab.11	Fig.29	Fig.36	Tab.12	Fig.22,23	Fig.52	—
12b	9/18	ambient air (M-Series)	Fig.41	Tab.11	Fig.29	Fig.36	Tab.12	Tab.13,14	—	—
13	9/23	Metal dissolution steel with air lance (M-Series)	Fig.42	Tab.11	Fig.30	Fig.38	Tab.12	Fig.20,21 Tab.13,14	—	—
14	9/29	Calcium-silicated organic sludge (S-Series)	Fig.14	—	Fig.31	Fig.39	Tab.12	Fig.20,21 Tab.13,14	Fig.52	Fig.57 Tab.17

crucible walls. Additional monitoring equipment was installed for Test 7 to monitor the progress of the melt.

Tests 1-7 provided the experience and data necessary for shakedown of the arc melter for operation of the capability tests. Each test provides valuable information for improving the arc melter. Subsequent tests at higher power and temperatures revealed more problems, which when solved, resulted in an even more reliable and capable system. Additional details for Tests 1-7 are contained in Appendix B.

Tests 8-14 were performed to determine the capability of the arc melter under different process scenarios. Tests 8 and 9 demonstrated the arc melter's capability to melt high-temperature melting RWMC soil, and soil plus 5 wt% each titania (TiO_2) and zirconia (ZrO_2). The soil plus additive test (Test 9) determined that the addition of the 5 wt% each of TiO_2 and ZrO_2 slightly lowered the melting temperature of the soil. The waste form from Test 9 appeared to be a much denser and better glass than the one obtained from Test 8. Test 10 was conducted to demonstrate the arc melter capability for processing the hydrated metal oxide (H-series high Na waste stream) and to evaluate the effects of oxide dehydration on the melting process. The effect of chemical corrosion from the decomposition of the metal hydroxides on the carbon electrodes was also evaluated. Results indicate that the metal hydroxides decomposed upon entering the melt, and the rate of electrode corrosion from the decomposition of the metal hydroxides is much higher than the rate of electrode corrosion in other tests. Tests 11-13 demonstrated metal dissolution and oxidation of a high metal component (Fe) waste stream under ambient argon, ambient air, and bubbling air environments. Metal melted upon entry into the melt and subsequently solidified at the bottom of the crucible. The objectives of Test 14 were to determine the response of the arc melter when cemented organics were added to the melt. Large amounts of carbon were released when the cemented organic was added to the melt. Even though air was injected above the melt during the addition of the cemented organic, increased amounts would be needed to provide a stoichiometric mixture for complete combustion of the organic contained in the simulated sludge. Additional details for these tests are contained in Appendix B.

4.3 Melting Capability

In Phase 1 and 2 testing of the arc melter system, 14 tests have been completed. The testing and development of the arc melter has resulted in system hardware and procedures that can be used for experiments on final waste forms. An adequate power supply configuration along with starting methods and a heating schedule for melting have been developed. In Phase I, problems discovered and eventually solved include secure attachment of carbon electrodes, cooling protection for the top of the melter, and an adequate design for cooling the SS crucible. Phase II demonstrated the capability of the arc melter to process different waste stream scenarios, such as cemented organics, hydrated metal oxide sludges, and metal dissolution and oxidation in argon, air, and bubbling air environments.

Tests 6 and 7 confirmed the ability of the arc melter (and present power supply characteristics) to melt A-40 simulated reference waste in a reasonable period, without extensive pretreatment (e.g., preheating to minimize foaming, remove carbonate related materials, etc.) in a relatively quiescent mode. During these tests, the melts became hot enough to come to a full

rolling boil. This tendency increased the convective heating of the outer parts of the melt and mixing of the materials. The overall effect enhanced the homogeneity of the final waste form. Test 13 (soil was added to the melt in 2 kg increments) showed that 8 kg was the optimum amount for complete melting and mixing of materials in the present crucible. A sample of the convective cells in the melt is shown in Figure 14.

Slag temperatures attained during melting were 1,600-1,800°C in the vicinity of the electrodes and were as high as 1,300°C on the surface of the "unmelted" region near the hot slag. The slag temperature at the electrodes registered a much higher temperature. These temperatures are in excess of 2,000°C. These optical pyrometer measurements were in concurrence with the readings of the thermocouple immersed in the soil, which, after a rise to a plateau of approximately 1,250°C, peaked at approximately 1,770°C as shown in Figure 15 and Figure 16. However, Table 11, shows that inconsistencies exist in the optical pyrometry data from test to test. In the melt, a two-dimensional temperature gradient exists on the surface of the melt. If the temperature is not measured at the same position on the surface of the melt, different surface temperatures are obtained. The optical pyrometer was manually aimed at the surface of the melt during the experiments, introducing the possibility for error in the measurements. Fixturing of the optical pyrometry measurements would reduce temperature differences due to positional error.

A mass balance was determined for Tests 10-14, results of which are summarized in Table 12. In general, the result indicated that approximately 15-16% of the original soil weight was not accounted for. Reasons for these differences are speculated to be from the loss of water of hydration, decomposition calcium carbonates, and volatilization organics into gases. These losses can be up to 11% of the initial soil weight.²⁴ Other losses are thought to be from the entrainment of fine soil particles in the off-gas during melting. These fine particles are not captured in the arc melter cold trap, but pass into the laboratory exhaust system.

4.4 Electrode Wear

Electrode lifetime is an important design consideration in any type of arc furnace. Although the arc melter experiments were not conducted to specifically study the problem of electrode wear, some useful data and information could still be collected while performing the experiments. Since electrode wear may depend somewhat on a particular arc furnace design, obtaining at least some erosion rate data for the arc melter is important.

The electrodes are 1 in. in diameter and 6 in. long and are screwed onto a water-cooled copper attachment. Figure 17 shows a schematic of the graphite electrodes. The graphite is Grade G10, with a density of 1.66 g/cm. The use of carbon electrodes could affect two important aspects of operating the melter for waste remediation. First of all, since the electrodes are of fixed length and erosion will occur at a steady rate, the amount of time the arc melter can operate will depend on the length of the electrodes. Secondly, if carbon from the electrodes is introduced into the melt, it would tend to reduce iron oxides to iron, which is undesirable for creating an IEB waste form. To prevent carbon contamination, the arc melter is normally operated with the

Figure 14. Convective flow pattern in an 8 kg soil melt.

Figure 15. Soil thermocouple temperature as a function of time for Test 6.

Figure 16. Soil thermocouple temperature as a function of time for Test 7.

Table 11. Optical pyrometer measurements of the melt from various tests.

Test number	Temperature (°C)			Comments
	Anode	Cathode	Melt	
10	1,864	1,571	1,433	IEB4/H-80
11	2,738	2,079	1,566	6 kg—IEB4/A-100, during heatup prior to stabilization of melt
12	2,068	1,809	1,618	6 kg—IEB4/A-100
	2,454	1,974	1,405	6 kg—IEB4/A-100
	2,452	2,015	1,553	6 kg—IEB4/M-75
	2,247	2,615	1,669	6 kg—IEB4/M-75
13	2,604	1,699	1,399	6 kg—IEB4/A-100
	2,503	2,184	1,662	8 kg—IEB4/A-100, flow lines
14	—	—	—	No data

Table 12. Summary of mass balance results for Tests 10–14.

Soil fraction	Weight fraction of soil (%)				
	Test 10	Test 11 ^a	Test 12	Test 13	Test 14
Fraction of soil vitrified	73.3	54.7	69.1	81.0	73.3
Fraction of soil not vitrified	2.6	3.5	12.6	0	2.6
Fraction of soil condensed or precipitated in cold trap or chamber	8.9	—	1.6	3.6	7.7
Fraction of soil in vapor, fumes, or gases (by difference)	15.2	41.8	16.7	15.4	16.4

a. Test was terminated early because of expected crucible leak.

Material: Graphite, type G10 (see attached)
 Metal Dissolution and Oxide Experiment, Air Environ.

Figure 17. Schematic of graphite electrodes.

electrodes slightly above the melt, with an arc drawn between the electrodes and the melt. Most of the erosion takes place due to direct CO_2 formation from oxygen in the air.

Measurements of carbon electrode erosion began with Test 9 and lasted until Test 14. Starting with Test 12, coatings were plasma sprayed onto the graphite electrodes in an attempt to reduce erosion. The coatings comprised Al_2O_3 or ZrO_2 , with thicknesses of 0.006 and 0.012 in. The coatings proved effective in reducing the rate of erosion. Table 13 shows the measurements and results for all of the operational tests. Included in the table is the amount of current that flowed through the electrodes during each melting test. The Ampere-hours were computed from data taken with the data acquisition system and constitute an average over the length of the experiment.

Figure 18 and Figure 19 show plots of the data in Table 13 for the uncoated anodes and cathodes. A linefit to the data in each case gives the average erosion rate, which is 0.429 g/A·h for the anode and 0.372 g/A·h for the cathode. Figure 20 and Figure 21 show anode and cathode data for the Al_2O_3 coated electrodes and Figure 22 and Figure 23 show similar data but for ZrO_2 coatings. While the coatings generally decrease the amount of erosion, ironically the thicker coatings proved less effective in each case, except for the Al_2O_3 coatings on the anode for which the erosion rate was about the same for thick and thin coats. Table 14 shows the results of the linefits. Overall, the coatings were quite effective in reducing cathode erosion but only somewhat effective for anode erosion. The thin ZrO_2 coating appears most effective; however, with only one data point apiece, specific conclusions such as this should await more investigation.

4.5 Energy Balance

An energy balance analysis is important to determine the overall system efficiency and to account for energy losses during operation of the arc melter. Energy losses for individual system components can be determined that could point out which components may need improvement. Since the analysis requires measurement of water temperatures and flow rates for individual water cooling circuits, the arc melter was fitted with thermocouples and flow meters. In addition, electrical probes were used to measure current and voltage. With the exception of the flow meters, measurements were taken automatically during the course of each experiment with the data logger system. Flow meter readings were taken periodically during the experiments by hand.

Energy balance calculations were accomplished with the aid of several computer programs written in FORTRAN (see Appendix C). Although the data acquisition system automatically saved data in a user defined file, the data file format was not amenable to data processing. The program LOTODAT converts the original data file into a condensed form and writes it to another user defined file. The average water flow rates are specifically written into the LOTODAT program, since these data were not recorded by the data logger. In addition, the program creates a file for input into the arc melter energy balance program, EBALAM, plus a separate plotting file for voltage and current. The program also calculates the total Ampere-hours, the average power and total energy consumed during the experiment. EBALAM can then read the input file created for it and do the energy balance calculations based on the thermocouple readings, cooling water flow rates and current and voltage readings. Because the original data logger files vary somewhat from experiment to experiment, a different version of the FORTRAN programs must

Table 13. Electrode erosion data (mass in grams).

Test number	Experimental description	Initial anode mass	Initial cathode mass	Final anode mass	Final cathode mass	ΔM anode loss	ΔM cathode loss	$I \times t$ (A·h)
08	Soil only IEB/A-100	—	—	—	—	—	—	72.1
09	Soil + TiO ₂ + ZrO ₂ IEB4/A-100	124.0	124.0	67.0	67.0	54.0	54.0	131.5
10a	Hydrated metal oxide sludge	126.3	126.7	67.2	74.9	59.1	51.8	148.6
10b	Hydrated metal oxide sludge	125.4	125.0	48.1	60.3	77.3	64.7	175.9
11	Metal dissolution steel/argon	127.9	127.6	95.6	94.7	32.3	32.9	110.9
12a	Metal dissolution steel/air	125.9	125.9	98.1	119.5	27.8	6.4	84.2
12b	Metal dissolution steel/air	125.9	125.9	42.7	91.5	83.2	34.4	170.9
13	Metal dissolution steel/air lance	125.9	125.9	29.2	22.0	96.7	103.9	311.3
14	Calcium-silicated organic sludge	125.9	125.9	41.8	56.3	84.1	69.6	256.5

Figure 18. Plot of uncoated anode erosion rate.

Figure 19. Plot of uncoated cathode erosion rate.

Figure 20. Plot of anode erosion rate for Al_2O_3 coated electrodes.

Figure 21. Plot of cathode erosion rate for Al_2O_3 coated electrodes.

Figure 22. Plot of anode erosion rate for ZrO_2 coatings.

Figure 23. Plot of cathode erosion rate for ZrO_2 coatings.

Table 14. Average erosion rates for electrodes during arc melter experiments.

Test number	Electrode coating	Anode erosion (g/A·h)	Cathode erosion (g/A·h)
9, 10, 11	Uncoated	0.429	0.372
13	Al ₂ O ₃ , 0.012 in.	0.311	0.334
14	Al ₂ O ₃ , 0.006 in.	0.328	0.271
12b	ZrO ₂ , 0.012 in.	0.487	0.201
12a	ZrO ₂ , 0.006 in.	0.330	0.076

be used with data from each experiment. The data and programs for each experiment are stored together on a floppy disk.

Figures 24–31 show the current-voltage response of the arc melter during each experiment. The arc melter starts in a low-voltage, high current operating mode. As melt pools begin to form under the electrodes and the carbon starting strip is burned away, the arc melter transitions early on into a high voltage mode of operation. The current can be controlled at the power supplies. Early experiments (8 & 9 for example) were done with low currents of about 50 Amperes. Later experiments were done using higher current levels. The graphs show the current and voltage fluctuating during operation, sometimes significantly. This behavior points out the dynamic changes in melter operation as electrodes are shortened by erosion, electrode to melt spacing changes, more of soil/simulated waste becomes melted, additions to the melt are made, etc. The large spike variations seen on some of the graphs (Volts = 433, Amps = 0) occur when the arc is unexpectedly extinguished. In most cases, the arc is easily restarted by lowering the electrodes toward the melt.

Figures 32–39 show the power input and losses to cooling over the duration of the experiment. The bottom dotted line represents the power lost to cooling of the electrode holders. The losses are relatively small and tend to increase only slightly during the experiments. The next dotted line is the sum of electrode and chamber power losses. The distance between the two lines is then lost due the chamber water cooling only. Similarly the distance between the top dotted line and the next lower one will be the power lost to cooling water in the crucible. The solid line is the total power going into the system. The distance between this line and the dotted line below (total water cooling losses) must then be the power being absorbed into melting the soil/simulated waste. The amount of power going into melting the soil varies from approximately 5–10 kW. While increasing the total power into the arc melter tends to raise the amount going into melting the soil, the majority of the extra power is lost to the cooling systems (compare experiments 8 & 9 with 13 & 14). Test 13 is especially interesting, since, except for the first 15 minutes, the total power remains constant once the current is set. The current is increased at 40 minutes and again near the end of the experiment. The cooling water losses, however, show

Figure 24. Current-voltage response of the arc melter for Test 8 on IEB/A-100 soil.

Figure 25. Current-voltage response of the arc melter for Test 9 on IEB4/A-100 soil with ZrO_2 and TiO_2 .

Figure 26. Current-voltage response of the arc melter for Test 10a on IEB4/H-series.

Figure 27. Current-voltage response of the arc melter for Test 10b on IEB4/H-series.

Figure 28. Current-voltage response of the arc melter for Test 11 on metal dissolution with ambient argon.

Figure 29. Current-voltage response of the arc melter for Test 12 on metal dissolution with ambient air.

Figure 30. Current-voltage response of the arc melter for Test 13 on metal dissolution with air lance.

Figure 31. Current-voltage response of the arc melter for Test 14 on silicated organics.

Figure 32. Power input and losses to cooling for Test 8 on IEB/A-100 soil.

Figure 33. Power input and losses to cooling for Test 9 on IEB4/A-100 soil with ZrO_2 and TiO_2 .

Figure 34. Power input and losses to cooling for Test 10a on IEB4/H-series.

Figure 35. Power input and losses to cooling for Test 10b on IEB4/H-series.

Figure 36. Power input and losses to cooling for Test 11 on metal dissolution with ambient argon.

Figure 37. Power input and losses to cooling for Test 12 on metal dissolution with ambient air.

Figure 38. Power input and losses to cooling for Test 13 on metal dissolution with air lance.

Figure 39. Power input and losses to cooling for Test 14 on silicated organics.

significant variations. The obvious dips in the curves are the result of soil additions during the course of the experiment. When soil is added, the melt is cooled and energy is used in melting the extra soil. This has the effect of temporarily reducing cooling water losses and effectively increasing the amount of energy input into the melt.

Figures 40–43 show soil temperature data as recorded by a thermocouple (TC) placed directly into the soil about 1 in. from the crucible wall and equidistant from the electrodes. The type C thermocouples are surrounded by a ceramic sheath for protection, although once the soil becomes melted around the thermocouple, eventually the ceramic will melt along with the thermocouple. As seen from the tests for which data were available, temperature remains quite low until the melt pool actually reaches the TC. The TC then records a rapid rise in temperature to about 1,500-1,600°C, which is followed by failure. The Test 8 temperature profile is similar to Tests 6 and 7 (Figure 15 and Figure 16) where a temperature plateau occurs around 1,300°C before increasing to higher temperatures. The plateau may be due to a change of phase. In the case of the high power Tests 13 and 14, the TCs were completely incorporated into the melt, leaving the wire hanging above the melt. The two TC wires later became fused together, creating another TC that continued to record the temperature just above the melt.

The overall efficiency (power into soil divided by total power) of the arc melter varies considerably for the tests. The average efficiency for Test 8 is about 50% and is the best result. The efficiency of the remaining tests ranges to as little as 20% for Test 14. In general, two parameters seem to affect the efficiency. In Test 8, the efficiency is quite good at the beginning of the test ($\approx 70\%$) and decreases gradually to approximately 35% as the test progresses. This phenomenon is likely due to the insulating effects of the surrounding unmelted soil in the beginning of the test. As the melt pool comes closer to the edge of the steel crucible, more and more heat is lost to the cooling water. This same effect is seen in the other tests, but to a lesser extent. The other obvious parameter controlling arc melter efficiency is the total input power. While increasing the power seems to increase the amount of energy going into melting the soil (see Test 13 results), the overall efficiency goes down.

Recommendations for improving the arc melter efficiency would fall into two categories: physical modifications to the arc melter and arc melter operation. Physical modifications are limited, since they imply reducing cooling water losses by less effective cooling, but yet the cooling is necessary to prevent damage. Energy losses to the electrodes are relatively small but necessary to prevent melting of the metal holders. Attempting improvements here would not be worthwhile. The energy losses to the arc melter chamber are due primarily from radiant heat transfer directly from the melt to the chamber walls and the water cooled heat shield installed in the top of the chamber. Little can be done to prevent these losses. As indicated in Test 8, the addition of refractory insulation would be a key factor in reducing losses to the crucible cooling water during advanced stages. A refractory (ceramic) insert for the SS crucible is planned for the next series of tests. As indicated by the energy balance data, operational methods of increasing efficiency are to operate at low or moderate power levels, if possible. Tests 10 and 13, in which simulated waste or soil were introduced during the test, seem to suggest a highly efficient method of operation. When the materials were dropped into the melt, cooling water losses plummeted; and most of the input power went into melting the additions. Thus, the best method of operation would be to start with a small melt, then add material continuously. Since a continuous feed

Figure 40. Soil thermocouple temperature as a function of time for Test 8 on IEB/A-100 soil.

Figure 41. Soil thermocouple temperature as a function of time for Test 12 on metal dissolution with ambient air.

Figure 42. Soil thermocouple temperature as a function of time for Test 13 on metal dissolution with air lance.

Figure 43. Soil thermocouple temperature as a function of time for Test 14 on silicated organics.

melter system is planned for future waste reduction activities, it would only remain to do testing on the actual system to determine the optimum feed rate for highest efficiency.

4.6 Materials Characterization

4.6.1 Introduction

The arc melter vitrified waste forms were characterized with X-ray diffraction and scanning electron microscopy. The analysis was performed to determine the general composition and features of the waste forms produced from the arc melter initial shakedown and preliminary capability tests.

In Phase I, preliminary microstructure characterization had been performed on the IEB/A-40 and IEB4/A-40 glass-ceramic waste forms. In Phase II, arc melter capability tests had been carried out for processing of pure soil, IEB4/A-100 soil, simulated silicated organics, hydrated metal oxide sludges, and dissolution and oxidation of metals. These waste forms produced are glassy.

4.6.2 Pure Soil (A-100)

The melted slag from some of the initial tests was characterized to learn more about the waste form phase structure under these partially melted conditions. From Test 3, the pure soil (IEB/A-100) waste produced using the dumbbell graphite starter was examined to determine the effect of the graphite in direct contact with the melt. A small sample at the graphite and vitrified mass interface was analyzed by SEM (Figure 44, #0018). Due to fast cooling rates of the melt in the water-cooled crucible, the waste form is highly glassy. A small diffusion zone with high carbon content (upper light gray region) has been detected next to the graphite (lower dark gray region) in the glass. Within the graphite, there is a few metal-like spheres. From EDS analysis, these spheres are found to be high in Fe (Figure 45, Spot 1, #0034) and are formed by carbon reduction of the iron oxide in the soil. Figure 45 also shows regions (Spot 2) close to a particle exhibit high Fe, Si, and low Al in the matrix. This matrix also has a very high carbon content because of the proximity of the graphite dumbbell. In a small glassy region (Figure 46, #0028), where carbon diffusion is relatively high, a relatively large number of similar metal-like spheres were also observed. EDS analysis (Figure 47, top photo, Spot 3, #0037) shows that these spheres also contain high Fe composition and a moderate amount of Si. These spheres are probably alloys of Fe and Si formed by carbon reduction of the melt. Spot 4 (Figure 47, bottom photo, #0039) shows a very high silica phase, with a moderate amount of Na oxide (12.25%). In this pure soil waste form, only glassy phases were observed. The buried dumbbell graphite starter in the soil affects the oxidation (redox) state of the melt and reduces the iron oxide in the soil to Fe. Under the high temperature of the melt, some SiO_2 was also reduced to Si by the carbon. This condition is not favorable for the waste form properties and is one of the reasons that nonimmersible electrodes were selected. When graphite is part of the input waste stream, air or oxygen will have to be added to maintain a desirable redox condition.

Figure 44. SEM micrograph of the pure soil IEB/A-100 waste form produced in Test 3.

Figure 45. SEM secondary electron image of a metal-like sphere in the graphite (Test 3).

Figure 46. Metal-like spheres in the glassy region with relatively high carbon diffusion (Test 3).

Figure 47. Composition of the metal-like spheres in the glassy region with relatively high carbon diffusion (Test 3).

4.6.3 IEB/A-40

Optical microscopy, SEM, and X-ray diffraction analyses were performed on the IEB/A-40 waste form obtained from the arc melter. Figure 48 is the optical appearance of waste form chunks. The waste form consists two distinct layers, a very shiny glass phase, and a shiny rock-like (highly crystalline) phase. The glass phase forms between the thin skull (<2 mm) and the crystalline phase. The thickness (<12 mm) of the glass phase indicates a severe temperature gradient across the material. X-ray diffraction of the more crystalline phase revealed the presence of augite $\{(\text{CaFeMg})\text{SiO}_3\}$ and diopside $\{\text{CaMg}(\text{SiO}_3)_2\}$ pyroxenes, and magnetite spinel (Fe_3O_4) as major phases. These major phases "are known that, from their observed durability, would appear to be either thermodynamically stable in common geochemical environments or slightly unstable but with very low rates of alteration or dissolution."²⁵ Minor pyroxenes such as fassaite $\{\text{Ca}(\text{MgFeAl})(\text{SiAl})_2\text{O}_6\}$, aluminian diopside $\{\text{Ca}(\text{MgAl})(\text{SiAl})_2\text{O}_6\}$, and a minor residue glass are also present. The X-ray diffraction traces for the more crystalline region is shown in Figure 49. SEM analysis of the more crystalline region is shown in Figure 50, #0003 and 0007. The bottom micrograph in Figure 50 shows extensive formation of dendritic pyroxene domains, with bands of magnetite spinels (Fe_3O_4) nucleated inside the pyroxenes. The spinels are higher temperature melting phase than the pyroxenes; and when the melt cools, the spinels will form prior to the pyroxenes and act as nucleation centers for the pyroxenes. EDS analysis of the domains (Spots 1 and 4) supports the X-ray diffraction results of formation of the pyroxenes and spinels (Spots 2 and 3).

4.6.4 Hydrated Metal Oxide, Metal Dissolution and Oxidation, and Cemented Organic Experiments

SEM analysis was performed on waste forms for simulated hydrated metal oxides (H-0), metallic waste (M-0) dissolution and oxidation, and simulated calcium-silicated (S-0) organics. Similar to the pure soil (A-100) melting tests, the high cooling rates resulted in waste forms that are highly glassy and have iron spheres randomly dispersed throughout the melt. As with the pure soil, carbon in the melt affected the redox state of the melt and reduces the iron oxide in the soil to iron. Figure 51 (#0212) and Figure 52 (#0151 and #0058) show SEM photomicrographs of the glass for each of the waste forms tested. In Figure 51, there are two bright phases associated with the H-90 run. From EDS analysis, the round phase is an iron sphere and the bright irregular shaped particles are likely to be zirconia or zircon. Figure 52 shows the IEB4/M-90 and IEB4/S-90 SEM micrographs for metal dissolution and simulated silicated organics, respectively. The large number of Fe spheres observed in the top photo in Figure 52 is a result of steel shot addition to the melt for metal dissolution tests. The steel shot was totally molten and as a result formed round spheres upon cooling. Because of their size and the convective eddies in the melt, these spheres were trapped in the glass rather than accumulating and fusing into a slug at the bottom of the melter as was observed with larger iron nail and bolt segments. Additional detailed analysis of the waste forms was beyond the scope of this work. Only those crystalline phases observed during the general analysis of the glass were briefly investigated.

In the metal dissolution and oxidation experiment, using an argon atmosphere, small crystallites were formed in the melt. The crystallites are shown in Figure 53 (#0141). Table 15 shows the associated EDS compositions of the specimens at Spots 2 and 3. The average chemical compositions of the specimen is designated as Ar2-1 in the table, where "1" indicates the spot.

Figure 48. IEB/A-40 waste form chunks produced in the arc melter (Test 6).

Figure 49. X-ray diffraction trace for the more crystalline region on the IEB/A-40 waste form produced in the arc melter and its possible mineral phases (Test 6).

Figure 50. SEM micrographs of the crystalline region of IEB/A-40 produced in Test 6.

Figure 51. SEM micrograph of the IEB4/H-90 waste form produced by the hydrated metal oxide are melter capability test (Test 10a).

Figure 52. SEM micrographs of the IEB4/M-90 (Test 12) and IEB4/S-90 (Test 14) waste forms produced by the metal dissolution and oxidation and cemented organic are melter capability tests.

Figure 53. Speculated zirconia crystallites crystallized from the melt during the metal dissolution and oxidation (argon atmosphere) are melter capability test (Test 11).

Table 15. EDS chemistries of metal dissolution and oxidation, (Ar atmosphere) experimental melt. Ar2-1 represents the general glass, Ar2-2 represents the glass located at Spot 2 in Figure 53, and Ar2-3 represents the zirconia particle chemistry located at Spot 3 in Figure 53.

Sample location	Oxides (%)									
	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	TiO ₂	MnO	Fe ₃ O ₄	ZrO ₂
Ar2-1	2.29	3.40	12.19	59.07	1.69	7.87	4.50	0.08	3.05	5.86
Ar2-2	1.91	4.12	12.69	59.33	1.53	8.44	4.57	—	3.34	4.06
Ar2-3	2.34	2.66	10.24	46.55	1.40	5.50	4.95	—	1.99	24.37

Due to the size of the particle, EDS analysis, Ar2-3, was inconclusive; however, based on all the oxides listed in Table 15, the crystallites were speculated to be Zirconia (ZrO_2) particles. If these were ZrO_2 particles, the "local solubility" of ZrO_2 might exceed the silicate melt capability. Upon fast cooling, an excess amount of ZrO_2 could then be homogeneously precipitated as fine particles.

4.7 Cold Trap Analysis

4.7.1 Introduction

Cold trap residues collected from several arc melter runs, were identified with X-ray diffraction. The analysis was performed to identify materials that vaporized during the capability test of the arc melter for the processing of IEB4/A-100, silicated organic, hydrated metal oxide sludges, and dissolution and oxidation of metals.

4.7.2 IEB4/A-100 Test

Cold trap residues were collected and analyzed to determine the material that vaporizes during the melting of IEB4/A-100 soil. The composition of IEB4/A-100 was 90 wt% soil with 5 wt% each of zirconia (ZrO_2) and titania (TiO_2). Figure 54 shows the X-ray diffraction traces of the cold trap residue collected. The raw profile was matched against reference standard files for component oxides and against the X-ray profile of unmelted IEB4/A-100 raw soil. The matching Table 15. . . . indicated the cold trap residue was made up of TiO_2 , ZrO_2 , raw soil, and SiO_2 . This analysis establishes a reference baseline for comparison with other runs.

4.7.3 Hydrated Metal Oxide Test

Metal hydroxides were added to an IEB4/A-100 melt to simulate H-90, H-80, H-60 hydrated metal oxide sludge waste compositions. The chemical composition of the sludge is given in Table 16. The sludge composition represents the expected Rocky Flats waste streams, with iron oxide added to simulate the iron content of the waste container.

Cold trap residues were collected throughout the experimental run. These residues were analyzed by X-ray diffraction for escaped metal hydroxides and other metal oxides, which volatilized from the arc melter during operation. Figure 55 is the X-ray diffraction traces of the cold trap residue. When compared to the reference baseline case, it is identical to the IEB4/A-100 cold trap materials, with the exception of hematite (Fe_2O_3) and magnetite (Fe_3O_4). These iron oxides were added to the waste stream to simulate the iron content of the waste container. Figure 56 shows the traces of the starting hydroxides that were not detected in the cold trap residues. This suggested that the simulated hydrated metal oxide sludge wastes were totally destroyed upon entering the melt.

4.7.4 Silicated Organic Test

Cemented organic waste streams were simulated by adding the preblended Micro-cell E, Floor DRI and vegetable oil to an IEB4/A-100 melt to formulate the IEB4/S-90 waste form

Figure 54. X-ray diffraction traces of Test 9 cold trap residue. Test 9 melted only pure IEB4/A-100 soil; there were no waste form additions.

Table 16. Hydrated metal oxide sludge chemical composition.

Soil designation	Compound weight (kg)						
	SiO ₂	Al(OH) ₃	Ca(OH) ₂	Mg(OH) ₂	NaOH	Fe ₃ O ₄	Fe ₂ O ₃
H-90	0.090	0.041	0.015	0.019	0.106	0.035	0.063
H-80	0.202	0.092	0.035	0.043	0.238	0.080	0.142
H-60	0.538	0.244	0.092	0.114	0.634	0.212	0.378

Figure 55. IEB4/A-100 plus hydrated metal oxides X-ray diffraction traces. These compounds were present in the cold trap residue.

Figure 56. IEB4/A-100 plus hydrated metal oxides X-ray diffraction trace (top), plus the traces of the added metal hydroxides. The added metal hydroxides were not found in the cold trap residue.

composition. The sludge was composed of 29.1% of Micro-cel E, 4.4% Floor DRI, and 66.5% vegetable oil. The chemical compositions of the Micro-cel E and Floor DRI are given in Table 17.

The X-ray diffraction traces for the cold trap residue and monocalcium silicate are shown in Figure 57. Raw soil, quartz (SiO_2), rutile (TiO_2), baddeleyite (ZrO_2), amorphous carbon, and monocalcium silicate (CaSiO_3) were found in the cold trap residue. When the simulated cemented organic was added to the arc melter, the vegetable oil volatilized and pyrolyzed rapidly above the melt. This process caused incomplete combustion of the oil and a small but sudden increase in melter chamber gas pressure. As a consequence, some carbon residue, Micro-cel E, and Floor DRI were carried into the cold trap.

4.7.5 Metal Dissolution and Oxidation Test

Carbon steel was added to several IEB4/A-100 melts to simulate high metal waste streams. These runs were done to test for dissolution and oxidation of metal in argon and air environments, and air bubbling via a lance in the melt. Cold trap residues were collected and analyzed using X-ray diffraction. The results were similar to those obtained in the analysis of the IEB4/A-100 soil cold trap residue.

This indicates that the elemental iron from the carbon steel did not volatilize from the melt. Experimental observation showed that the steel was partially melted and collected at the bottom of the crucible.

4.7.6 Conclusions on Cold Trap Analysis

Based on X-ray analysis, the cold trap materials for these tests were rather similar. The basic composition is raw soil plus SiO_2 , TiO_2 and ZrO_2 . These materials were collected in the cold trap during initial heating, dehydration, and decomposition of the soil (e.g., carbonates) in the melter. In the dehydration process, particles were entrained in the escaping water vapor and other gases or vapors and carried into the cold trap. Specific additives, such as the iron oxides of the hydrated metal oxide test or CaSiO_3 of the silicated organic test, were also observed in the cold trap for specific tests. These materials could be recirculated into the melter for dissolution in the slag. Incineration prior to melting would reduce the quantity of offgas vapor and gases generated from the soil.

Table 17. Chemical composition of Micro-cel E and Floor DRI.

Element	Micro-cel E weight (%)	Floor DRI weight (%)
SiO ₂	56.0	89.2
Al ₂ O ₃	3.8	4.0
Fe ₂ O ₃	1.0	1.5
CaO	26.0	0.5
MgO	0.7	0.3
Na ₂ O	0.6	0.25
K ₂ O	0.6	0.25
LOI ^a	11.3	—
H ₂ O	—	4.0

a. LOI means material lost on ignition for analysis.

Figure 57. X-ray diffraction traces from the silicated organic experiments: cold trap and monocalcium silicate trace.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A bench-scale arc melter has been designed, constructed, modified, and operated successfully to melt essentially all of the simulated soil/waste mixtures contained therein. The only preparation required with the arc melter is some sizing of the simulated wastes. The melter is not yet equipped with an appropriate oxygen source to conveniently oxidize organics. A simple starting method using a thin graphite strip has been developed to rapidly initiate the melting of the simulated waste. A heating procedure has been devised to melt under relatively quiescent or rolling boil modes. Heating is accomplished via a combination of arc and Joule heating. The whole heating process takes about 1 hour to melt the typical mass of 7 kg or 15 lb. The arc melter provides an easy way to generate vitrified material for detailed cooling and crystallization studies. A data acquisition system monitors and stores process conditions for real-time control and posttest evaluation. A video camera system provides instant video feedback of the waste melting process and video tapes for later review.

5.2 Recommendations

A variety of prepilot plant testing could be done with this low-cost, bench-scale melter including the effects of volatilization, metal melting and oxidation, electrode erosion/corrosion, melter geometry, size effects, skull formation, the reduction/oxidation condition, and the destruction of organic and combustible materials. Specific recommendations for the next stage of work include the following.

The question of the severity of volatilization from an arc melter compared to a Joule heated melter, at lower temperature, has been raised. The quiescent or rolling boil modes of the arc melter appear to be similar to those observed in the JHM, as well as dust emission. Studies identifying the extent of volatilization of TRU surrogates and HVPs should be made as a function of location in the arc melter and operating temperature.

Detailed studies of metal melting and oxidation are required to identify the role of the slag or melt redox state to surface oxidize or decontaminate the metal, the time and methods required for efficient metal melting and/or total oxidation. Melter operation could include separate tapping of slag and molten metal or oxidize all of the metal into the slag. The alkali nitrate sludges might be used to oxidize the metals, reducing the air or oxygen required. Simple tests to identify physical and chemical advantages and disadvantages of options are needed.

The construction of a similar arc melter for use at the INEL TRA facility with radionuclides should be initiated. The melter could include the present crucible assembly plus a special water-cooled lid for observation and electrode immersion, all designed to be located in a glove box. Activities would repeat a limited number of cold experiments in which the disposition of the TRU is significant. Examples include TRU and LL volatilization and metal surface decontamination.

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Appendix A

Schematics

Mechanical Schematics

Figure A-1. Schematic of the crucible assembly showing the crucible insert, the jacket or pot, and the cooling water inlet and outlet.

Figure A-2. Drawing of the crucible insert, jacket pot, and retaining ring with dimensions.

3/18/92

1/2 scale

stainless
steel
crucible

Figure A-3. Location of the electrodes within the crucible.

CARBON ROD ELECTRODE HOLDER (TOP PART)

Figure A-4. Schematic of the carbon rod electrode holder (top).

CARBON ROD ELECTRODE HOLDER

Figure A-5. Schematic of the carbon rod electrode holder (bottom).

TOP OF REACTOR

3/30/92

1/4 SCALE

Figure A-6. Schematic of the top of the reactor for insertion of the electrodes.

Electrical Schematics

Figure A-7. Plasma treatment disconnect relay circuit.

Title		PLASMA TREATMENT DISCONNECT RELAY CIRCUIT
Size	Document Number	REV
A	PTDR.C.SCH	1
Date:	October 2, 1981	Sheet 1 of 1

NOTE: ZENER DIODES ARE GENERAL INSTRUMENT
TRANSIENT VOLTAGE SUPPRESSORS

Figure A-8. Transient voltage input protection circuit.

Title		TRANSIENT VOLTAGE INPUT PROTECTION CIRCUIT
Size	Document Number	REV
A	TVIP.SCH, JOB# 091	1
Date:	June 30, 1992	Sheet 1 of 1

Figure A-9. Stepper drive circuit.

Title		STEPPER DRIVE CIRCUIT	
Size	Document Number	REV	1
A	PTSTEP.SCH		
Date:	September 25, 1991	Sheet	1 of 1

Figure A-10. Stepper interface cable.

Title	STEPPER INTERFACE CABLE
Size	Document Number
A	PLASSTP2.SCH, JOB #094
Date:	May 12, 1992
Sheet	1 of 1
REV	1

25 PIN MALE D

Figure A-11. Limit switch connection diagram.

Title	LIMIT SWITCH CONNECTION DIAGRAM		
Size	Document Number	PLASSTP3.SCH, JOB #094	REV 1
A		May 12, 1992	Sheet 1 of 1

Figure A-12. Parallel test circuit for manual control of stepper motor.

Title	PARALLEL TEST CIRCUIT		
Size	Document Number	PLASSTP1.SCH, JOB #094	REV
A			1
Date:	May 12, 1992	Sheet	1 of 1

Figure A-13. Plasma waste treatment DAS block diagram.

CHANNELS	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
ISOTHERMAL	C	C	C	C	C	K	K	K	K	K										
	0	1	2	3	4	0	1	2	3	4										

CHANNELS	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
ISOTHERMAL	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
	0	0	1	1	2	2	3	3	4	4	5	5	6	6	7	7	8	8	9	9

CHANNELS	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
VOLTAGE	E	E	E	E							T	T	T	T	T					
	0	1	2	4							1	2	3	4	5					

CHANNELS	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
EXCITATION	X	X			X	X			X	X			X	X			X			
	0	1			2	3			4	5			6	7			8			

Figure A-14. Data acquisition channel connection.

Title			
DATA ACQUISITION CHANNEL CONNECTION			
Size	Document Number	REV	
A	PLASDAS.SCH, JOB #091	1	
Date:	May 8, 1992	Sheet	1 of 1

Figure A-15. Plasma treatment thermocouples.

Title		PLASMA TREATMENT THERMOCOUPLES	
Size		Document Number	
A		PTTC.SCH	
Date:		October 2, 1991	
		Sheet 1 of 1	
		REV 1	

Appendix B

Test Summaries

Appendix B

Test Summaries

The investigations into starting procedures, "soil" heating procedures, and the injection and melting of various simulated waste streams are discussed below in some detail. This is included to remind us of the envelope in which arc melting processes must occur and so that researchers can appreciate some of the nuances of arc melting, its differences from Joule heater melting, and some of the characteristics of melting different materials under different operating conditions. Additions and modifications were made to the instrumentation and equipment throughout Tests 1-7 as a part of developing the melting facility. These changes are also documented below.

Test 1: Initial Starting Trials

The first test was run on 6/5/92 to study starting methods. It used a portable Miller welding power supply having an overall capability of supplying 14 kW of power. The power supply has an open circuit voltage of 80 V and can operate at up to 300 A maximum depending on the operating voltage. The stainless steel (SS) crucible was filled with 3.5 in. of "clean" Radioactive Waste Management Complex (RWMC) soil (approximate A-100 composition). Large lumps in the soil were broken apart, but many small ones remained. A graphfoil strip approximately 1 x 6 in. was placed on top of the soil to start the melting process. With the carbon electrodes lowered onto the graphfoil, the power supply was turned on and the current was increased to 50 A until the graphfoil started to glow red. After heating for approximately 5 minutes, the electrodes were raised, which drew an arc on one electrode. Two minutes later, the electrode broke off at the base of the threaded part, ending the test.

In the next run with a graphfoil conducting strip, the current was raised to approximately 150 A. Argon (instead of ambient air) was put into the chamber to stabilize arcing effects. The graphfoil evaporated near the hotter electrode, but arced across the space. Then the graphfoil laminations peeled upward and the arc/current went out. Whenever the circuit was broken, it was usually not possible to restart without opening the chamber port and reforming a conducting path with graphfoil.

Instead of the graphfoil with its de-lamination problem, a new technique was tried in the form of a hand-packed cylinder of aluminum shavings. However, the overall conductive area of the shavings was apparently too small and the metal melted or arced/sparked temporarily across small gaps. The current capability was only 25-50 A and melting of the shavings soon broke the circuit. Very little joule heating was evident.

Next some graphite was ground from an old electrode and poured between and under the electrodes in a depression formed in the soil. The amount of graphite was probably half what might be needed, and the shape of the depression resulted in a flatter conducting path than desired. The current path was started at approximately 50 A, but soon obtained an open circuit (presumably because the graphite powders were blown away by the strong arc jet) and would not restart. It appeared that the graphite electrode to graphite powder was not a good conductor and/or a higher breakdown voltage (>80 V) was needed.

Additional graphite was added to the conducting path, plus some cut up aluminum from the shavings, plus a square of graphfoil under each electrode, plus a 1 x 4 in. piece of graphfoil was laid on top of the path between the electrodes. Higher currents 100-150 A were obtained, but again the conducting path was broken and was not able to be restarted. Arcing under one electrode with conduction only under the other electrode was observed.

Steel shot in a 3/4 in. semicircular stainless boat was next used for the conducting path. The current was started about 50 A and was raised to 150-200 A. The left electrode was the hottest in that arcing occurred between the electrode and melted shot, which melted the end of the boat; whereas, the right electrode operated in conduction mode and the soil/melt was dull red. As the iron melted and the electrodes lowered to maintain operation, the right electrode teeter-tottered the boat near the left electrode up to break the circuit. A large amount of arcing from the left electrode (anode) was observed normal to the attachment point, which often rose to the side of the electrode and circled the electrode in irregular fashion.

The circuit appeared to be broken when the arc length or circuit path was increased. The Miller P.S. appeared to be operating near or at the top of its operating voltage at the current used. Power supply characteristics decrease voltage with increase in current; whereas, arc characteristics increase voltage with current above approximately 100 A. Attempted increases in current would increase arc voltage needed, but decrease voltage available. In addition, the open circuit voltage available was apparently insufficient to enable restarting a higher resistance path. As a result, a power supply with more favorable voltage-current characteristics was used for further tests.

Power for the arc melter was switched to a single TAFA power supply with 200 VOC and capable of operating at 100 V and 400 A. The power supply was operated manually and not through the power console. Steel shot under the electrodes with the remains of the 3/4 in. semicircular boat used between electrodes was the conducting path. A piece of graphfoil was placed on top of the steel shot between the electrodes. The current was started about 50 A and was slowly raised to 350-400 A over 1/2 h. At the low currents, 50-200 A, the graphfoil became red (about 800°C), but the shot under it did not melt. At 250-300 A (about 30 VDC), the color turned yellow, and the shot near the left electrode (anode) melted and an arc appeared as the melted metal sank into the soil. The right electrode remained in the conduction mode, and the soil/melt under the graphfoil became dull red. As the current was increased to 350-400 A (at <50 VDC), the iron melted and sank "uniformly" into the soil (as was found after excavation). About this time, a dramatic storm occurred in the melter, with clouds of whitish-grey "smoke" swirling around making it difficult to see the melt surface. Later, the smoke subsided and the melt surface had become quiescent with a larger reddish glow near the left electrode and a smaller one near the right electrode, both under the surface of the melt. The surface of the melt had cooled and appeared dark, like the surface of a lava flow. Variations in current did not appear to have much influence on the appearance. Attempts to increase the current further resulted in spurious voltage fluctuations from the operating 50 VDC up to 150-200 VDC, during which the circuit was broken. Restarting by lowering the electrodes did not occur, even with 200 VDC open circuit. The electrodes were raised to find a significant amount of material attached to and stretching below and between the electrodes. There was also one or two layers of material attached to the bottom of this material. It was left to cool over the weekend.

With the higher voltage capability provided by the TAFE power supply, the arc melter ran for about 30 minutes, when the arc suddenly extinguished. Attempts at restarting were unsuccessful. The resulting melt comprised 0.525 kg of slag and 0.320 kg of carbon steel in the form of a solid mass at the bottom of the melt. This metal came from the shot and shavings used in starting the melt.

Excavation showed that the steel shot had melted and sunken fairly evenly to a depth of about 5-8 cm (2-3 in.). The left electrode (anode) arced all the way down to the melted metal through a hole surrounded by melted soil. At the right electrode, similar arcing was not apparent, with a solid connection (electrical?) to the melted metal and also a sloping down of the melted (glassy) soil toward the metal under the left electrode. The soil surrounding the melted shot was partially vitrified. It may be that continuing steadily at 300-350 A (<50 VDC) would have resulted in additional melting of the soil; however, much of the current was being carried in the metal melt with a low Joule heating effect. (The melt thickness around the metal was only about 1-2 mm.)

Test 2: Graphite Dumbbell Starter

Voltage-current characteristics for the test run on 6/11/92 were improved by connecting two of the TAFE power supplies in parallel giving 400 VOC and 200 V at 600 A (120 kW total). The power supplies were connected to the remote control console. This is the normal method of operation and also provides for rf starting capability, if needed. The taps on each power supply were changed to provide an VOC of 400 V and an operational power of 60 kW at 200 V and 300 A (120 kW total).

A new crucible was used with 4 in. of soil (approximately 6.5 kg) with the lumps crushed and screened so that the lumps are no larger than 1 mm in diameter. To aid in starting, two carbon cylinders 3 in. high by 1.5 in. in diameter were connected by a 1/2 in. diameter rod near the cylinder bottoms. This carbon piece, similar to a dumbbell in appearance, was inserted into the soil with the cylinders located just below the electrodes.

The test lasted 15 minutes and ended when the right electrode broke off. Most of the soil heating occurred under the right electrode after an arc was initiated by raising the electrodes. The left electrode remained in contact with the carbon cylinder. Figure B-1 shows the extent of soil melting around the carbon starting block. The maximum soil temperature as measured by a ceramic coated thermocouple located about 1 in. from the outside of the crucible and centered on the electrodes was almost 40°C. The left electrode also broke off at a slight touch when attempting to remove it from its holder.

Test 3: Electrode and Melter Modifications

Test 3 was run on 6/15/92. The power supply configuration remained the same as for Test 2, with two TAFE units in series giving 400 VOC with 200 V and 600 A operating conditions. To prevent the electrodes from breaking, the attachment was reworked so that the metal holder screws into the carbon rods rather than the rods screwing into the holder. The soil and crucible from Test 2 was reused. Approximately 2.3 kg of the soil was melted, resulting a greenish, very light slag. The density was low because of the many bubbles entrained in the slag.

Figure B-1. Soil has been removed to reveal partial melting around "dumbbell" carbon starter during Test 2. Note the placement of the thermocouple 1 in. from the crucible wall and the tip about halfway down into the soil.

The test lasted 30 minutes and was halted when the top of the arc melter jacket became extremely hot. During the melt, the carbon starting cylinders rotated sideways and floated to the top of the melt. The temperature measured by the thermocouple rose gradually during the experiment to almost 100°C, then rose dramatically to 913°C just before shutdown. Figure B-2 shows a cutaway view of the melt with the carbon cylinders inside. Immediately after the melter was shut down, a small water leak was discovered inside the melter. After tearing the system down, a pinhole inside a crater on the side of the crucible was discovered. The crater may have been the result of an arc strike.

Test 4: Graphite Starting Strip

For Test 4 on 6/19/92, the power supply setup was the same with two TAFA units in parallel and 400 VOC. A cooling plate and insulation were added on the inside top of the chamber as protection against overheating. Thermocouples were placed on all water cooling inlets and outlets. The power supply cooling water was hooked into the arc melter jacket and cooling plate. Water flow meters were on all inlet cooling lines. A new crucible was filled with 6.651 kg of soil (about 4.5 in. deep) with a thermocouple placed as in previous experiments and approximately 2 in. deep. A small carbon starting strip with dimensions as in Figure 9 was used to start the melt.

This test was stopped temporarily after 10 minutes when an accidental movement of the electrodes drove them into the melt. The melt was removed from the electrodes and the test was resumed for an additional 8 minutes resulting in a total melt of 2.440 kg. The soil temperature

Front A

Front B

Figure B-2. Cutaway view of Melt 3 showing the numerous bubbles that formed in the melt. The carbon starter, also shown, had turned sideways and floated to the top of the melt (Test 3).

measured by the thermocouple reached a maximum of 622°C eight minutes after shutting down the arc melter. The arc melter was turned off when large puffs of smoke and steam began to escape from holes and windows in the jacket. Examination afterward showed that dust on the walls and in the window ports was wet, but there were no pools of water. The origin of the water still remains unknown.

Test 5: Heating Procedure Trial

Test 5, on 6/20/92, had the purpose of (1) double checking the new starting procedure with the 1/4 in. thick graphite strip, (2) checking the initial heating current-time procedure, and (3) determining if additional cooling methods were necessary when most of the soil melted to slag.

The remaining dirt from Test 4 (2.5 in. deep and 4.211 kg) was used. Another carbon strip as in Test 4 was used for starting. The starting procedure worked well, with the only exception that the right electrode was predominantly in the conduction mode instead of arcing.

The configuration of the arc melter remained the same as in Test 4. The thermocouple was placed about 1/2 in. from the crucible wall. The run lasted for 18 minutes and resulted in a melt of 0.932 kg. The resulting slag was green in color as in Test 3, and it had less entrained bubbles with a resulting higher density.

The heating procedure consisting of a high initial current and low voltage followed by a decreasing current as the voltage rises worked well. The melt became red over a large area of the surface. Contrary to previous runs, the dust storm did not occur and vision inside the chamber was not obscured until the arc went out.

The arc melter shut down by itself at the same time large puffs of smoke and steam blew out of the melter. The crucible and melter jacket were filled with water. Subsequent investigation showed that a 6-mm hole had been burned in the bottom of the crucible allowing cooling water to flood the melt.

Test 6: IEB/A-40 Simulated Average Waste Trial

Test 6, on 6/26/92, switched from a pure soil to simulated average waste plus 40% soil, the IEB/A-40 mixture. This mixture was used to determine the effect of a mixture with a more favorable slag electrical conductivity and viscosity, as well as to test the simulated waste mixture.

The power supply configuration remained unchanged. Modifications prior to this test included the installation of a disk under the crucible. The disk has a 1.0 in. diameter hole in the center to direct water flow to the center of the bottom of the crucible to increase heat transfer limits when the slag reaches the bottom of the crucible. Copper coils placed along the side of the crucible will direct water flow with increased velocity and improve heat transfer from the sides of the crucible. The soil for this test was modified by adding iron oxides, etc., to conform to an A-40 mixture. The crucible contained 6.727 kg of material with a depth of 4.5 in.

The test went smoothly and lasted about one hour and resulted in a slag mass of 5.669 kg with a volume reduction of about 1/2. The slag broke into small pieces, less than 1 in. in diameter, when it was removed from the crucible. The slag in general was dense with no bubbles. Its color was black, with a shiny glassy appearance.

The starting technique with the 1/8 in. graphite strip worked perfectly. After the starting sequence and the melt were well established in Test 6, the current was subsequently increased from about 50 A to as high as 175 A near the end of the test. The voltage also increased from a conservative 150 V during initial heating, to a relatively steady 250 V during the last half of the test. As the current increased later in the test, the rate of melting increased and caused some of the A-40 left on the sides of the crucible to fall into the melt. Figures 10 and 11 show the current, voltage, and resulting power input data recorded manually during the course of the test. Figure 15 shows the temperature profile recorded by the ceramic coated thermocouple embedded in the soil. The Type-C thermocouple was placed 1 in. from the crucible wall, equidistant from the electrodes.

Figures B-3 and B-4 show the vitrified waste immediately after removing the crucible from the chamber. Figure B-5 shows the crucible contents after loosening (breaking) the solidified slag into chunks to remove it. Essentially all of the A-40 mixture was melted and turned into slag.

During Test 6, heating could be operated in several modes depending on arc gap, current, and stage of melting: (1) a quiescent mode with small arc gap and modest current where most of the surface was dark and yellow circles occurred around the arc attachment immediately below

Figure B-3. Crucible with slag after Test 6. Bubbles formed on top of the slag when water from pinhole leaks on the side of the crucible sprayed onto the melt.

Figure B-4. Closeup view of Test 6 shows where the soil has fallen away from the side of the crucible and into the melt. This was the result of increased power input near the end of the test.

Figure B-5. Removal of the slag caused it to break into glassy shards. The melting extended to the bottom corners of the crucible.

each electrode; (2) a rolling boil mode in which either the slag under the electrodes (early on) or at a location between the electrodes (later), and/or at alternate sides of the crucible in regions where melting had not been obvious before, and finally the whole top of the melt appeared as a slowly or moderately rolling boil; (3) a firecracker mode that appeared to be when the electrodes were just in contact with the surface and at the highest currents which allowed continued operation with the V-I characteristics available here. The firecracker mode resembled the random trajectory of bright yellow (as viewed through the protective glass) rockets emitted from the slag at the base of the electrodes and landing elsewhere in the melt or on the walls. At other times, the electrodes were immersed in the slag and operated totally in the Joule-heater type of mode. There was no slag stuck to the electrodes upon emerging from the slag melt and was little difference in operating conditions (voltage or current).

Both starting technique and heating procedure worked almost perfectly. More than half of the time was spent in an operating mode characterized by direct short arcing to the pool surface with Joule heating via current flow through the liquid slag. During the heating procedure, when the current limits of the melter were being tested the circuit would open, but could be immediately restarted by lowering the electrodes to make contact with the melted slag. No dust storms, significant vaporization, or foaming was observed throughout the test.

The end of the test occurred while testing the current limits and attempting to melt the rest of the A-40 skull. A pin hole leak developed in the side wall of the crucible, above the melt, but below the original fill line. It is unlikely that the spot is arc-initiated, since it occurred well after transition to a predominantly Joule-heater operating mode. While the cause is not definitely

known, it may be simply due to the shift from nucleate to film boiling on water side of the crucible. This reinforces the need to implement a better design for cooling the crucible side walls. The bottom of the crucible indicated only slight discoloring, so its cooling modification may be adequate.

Test 7: IEB4/A-40 Simulated Average Waste Trial

Test 7, on 7/2/92, was performed to compare the effect of the addition of ZrO_2 and TiO_2 to the IEB/A-40 in Test 6, as well as to try a conservative run without straining the system.

The most important change prior to this test was modification to the copper coils surrounding the crucible. Spaces between the coils were filled with plumbers putty. This reduction in volume forces the water to flow faster and to increase heat transfer to the crucible walls. The data logger was set up to automatically monitor voltage and current. In addition, an optical pyrometer and a video camera system were set up to monitor the progress of the melt.

The soil used for this test was the remaining A-40 (6.638 kg) plus 5 wt% additions each of titanium oxide (TiO_2) and zirconium oxide (ZrO_2). This created a total mass of 7.375 kg, which filled the crucible to 4.75 in. when compacted. The test went smoothly and lasted slightly more than 1 hour resulting in 6.199 kg of dark glassy slag (IEB4). The material was very dense and hard, even more so than the material in Test 6. Although the slag broke into pieces as in the previous test, the pieces were much larger, at least 2 in. in diameter for the larger pieces. The surface appearance was not quite as glassy, but slightly duller, indicating some possible crystallization during cooling.

For Test 7, the starting technique and heating procedure again worked almost perfectly, with exceptions discussed below. Figures 12 and 13 show the current, voltage, and resulting power input data during the course of the test. The data was recorded using the PC and data logger system. This data recorded every 30 seconds shows the operating transition that occurs early on in the melt, that is from a low voltage - high current mode to the steady state high voltage - low current operating mode.

The melt exhibited some foaming not observed in the previous IEB melt. During foaming, the arc would occasionally extinguish, but could immediately be restarted by lowering the electrodes to make contact. This occurred at an early stage in the heating but after depletion of the starting stick. Even without a significant slag channel area, the 400 V open circuit voltage is sufficient (at low current of about 50 A) to restart by contact for this geometry. The electrodes remained free and clean of solidified slag even though dipped into the slag or after foaming. The foaming was small corresponding to 1 to 2 in. in height and fairly uniform across the melt. The atmosphere within the chamber remained clear, with relatively little dust attaching to surfaces compared to initial runs.

Optical pyrometer readings indicated the slag under the electrodes was 1,600-1,800°C, while the nearby "darker" material, a crust on the slag, was about 1,300°C. Figure 16 shows the soil temperature profile 1 in. from the crucible wall as recorded by the thermocouple. After the temperature of the thermocouple in the slag exceeded 1,500°C and the time of operation reached 1 hour, the system was shut down by simply raising the electrodes.

In this test, the system was not put under stress by raising the current near the end in order to try and melt the soil clinging to the sides of the crucible. Figure B-6 shows the crucible and slag after being removed from the melter. Note the unmelted soil around the edges. An indication of the constituency is given in Figure B-7, in which agglomerated IEB4/A-40 mixture was melted early in the process around the thermocouple insulation and ceramic shield and remained in place throughout the test. Increasing the heating period and/or power level may have melted this agglomerated slag/soil. An insertable and removable thermocouple is planned for future work. The soil contained within the slag however, melted thoroughly under these low-power conditions. After shutdown, the melt appeared a uniform red by naked eye over the whole pot surface. When removed from the crucible, the chunks were similar to those from Test 6, but appeared to be more brittle and had many sharp edges and small slivers typical of vitrification, but without crystallization. After being washed, the samples lost the reddish color and appeared dark brown. The cooling rate, measured with the optical pyrometer, was relatively rapid due to the water cooling of the crucible.

Tests 8 & 9: IEB/A-100 & IEB4/A-100 RWMC Soil Trials

Test 8, on 8/3/92, and Test 9, on 8/6/92, were performed for the purpose of demonstrating the arc melter capability to melt the high melting temperature RWMC soil, and soil plus 5 wt% each of TiO_2 and ZrO_2 , respectively. The soil plus additive test is to also see if the addition of 5 wt% TiO_2 and ZrO_2 will lower or raise the melting temperature of the soil.

In Test 8, the operation started with 10 kg of pure soil. The arc melter was started following the standard procedure. Figures 24 and 32 show the current, voltage, and resulting power input data during the course of the test. In the early phase of melting, a localized molten pool formed beneath the electrodes. The cathode pool was larger in size than the anode pool and the anode arc root motion was more intense. The consuming graphite strip provided a current path between the two pools. The end of the graphite strip close to the anode was consumed much faster than the other end. The arc became unstable and required higher voltage from the power supply to sustain the current when the anode arc gap became too large. Finally, the circuit opened when the graphite strip burned too short. A second graphite strip was used to restart the arc, and finally a molten conducting path between the electrodes was achieved. It is important that the molten pools of soil beneath the electrodes coalesce to establish a conducting path for a self-sustaining arc prior to consuming the graphite strip to a critical length. In the progress of soil melting, a gentle dust storm was observed before the soil was completely melted. This dust storm was caused by out gassing (dehydration and carbonate decomposition) of the soil when it reached a certain temperature. After melting for about 1 hour, the soil appeared all molten and the arc was cut off. Figure 40 shows the soil temperature profile 1 in. from the crucible wall as recorded by the thermocouple. When examining the pure soil waste form, it was found that only 2/3 of the soil, about 7 kg had been melted. All the soil could have been melted if the process was kept longer.

In Test 9, soil plus 5 wt% each of TiO_2 and ZrO_2 , the same general observations were made. Figures 25 and 33 show the current, voltage, and resulting power input data during the course of the test. With approximately the same heating time and power requirement, the soil plus additives were completely melted. It appeared that additives behaved as fluxes to lower the melting temperature of the soil. The desired explicit comparison of temperatures was not possible

Figure B-6. Crucible with slag after Test 7. In this test, the power levels were maintained low throughout the test; and the soil around the edges did not melt away from the sides of the crucible.

Figure B-7. A crust of agglomerated soil formed around the thermocouple early on and remained throughout the test.

because valid optical measurements were not obtained for Test 8 (out of calibrated range) and valid thermocouple measurements were not obtained in Test 9 (thermocouple malfunctioned early). Comparable voltage-current characteristics were essentially identical, suggesting that the $\text{ZrO}_2/\text{TiO}_2$ addition had no significant effect. Comparing the two waste forms, the soil plus TiO_2 and ZrO_2 gave a much denser and better glass than the pure soil.

The conclusions and recommendations from this test are the following.

1. There is no particular problem melting pure soil or soil plus ZrO_2 and TiO_2 .
2. There is no particular difference in the melting characteristics of IEB with or without ZrO_2 and TiO_2 (IEB/A-100 or IEB4/A-100).
3. Both Tests 8 and 9 processes completely melted the IEB/IEB4 at essentially constant voltage and current throughout the process.

Test 10: IEB4/H-Series Hydrated Metal Oxide Trial

Test 10 to melt simulated Rocky Flats 741 sludge was performed in two parts, the first on 9/8/92 (Test 10a) and the second on 9/9/92 (Test 10b). The purpose of this experiment is to demonstrate the arc melter capability for processing the hydrated metal oxides (H series high Na waste stream) and to evaluate the effects of oxide dehydration on the melting process. The changes in the slag composition with increasing waste additions are investigated. Aluminum was also added to the melt at the end of the H-series runs to determine the Al limits (as Al_2O_3) in the slag that will freeze the melt and to identify changes in the slag composition with increasing amounts of aluminum oxide.

The composition of simulated hydrated metal oxides used was that for simulated sludge compositions given by Landman^a and did not include the container or contents other than the simulated sludge. The compositions are given in the table below. The high Na sludge (analogous

Composition of simulated hydrated metal oxide sludge from Landman.^a

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
High Na	36.3	14.0	6.6	4.8	5.3	28.4	4.6
High Ca	46.9	4.3	5.9	22.8	10.7	5.7	3.7

a. W. H. Landman, Jr., "Sludge Compositions," TWTF/Reedy Creek Engineering Design File No. 19, TWTF-68, November 13, 1981.

to H1-Series) was used in Test 10. The H1 series compositions include both container and other contents as obtained by Grandy^b

The operation started with the melting of 3 kg IEB4/H-100 base soil (90% soil plus 5% each of TiO_2 and ZrO_2) in the arc melter crucible under ambient air. Figures 26, 27, 34, and 35 show the current, voltage, and resulting power input data for Tests 10a and 10b during the course of the test. Metal hydroxides (to simulate the hydrated metal oxide sludge) were later added to the melt to decrease the base soil composition by 10%. The resulting slag composition is designated H-90. After the melt reestablished equilibrium, a slag sample was taken for analysis. More simulated waste was added to the melt to further decrease the IEB4/100 base soil composition, successively, by 10% to produce H-80, H-70, and H-60 slags. Slag samples were taken, after each addition of the simulated waste, for analysis. With each addition of the high Na simulated waste the melt became more fluid. This property was expected for high alkali flux additions to a silicate melt. During the H-70 run, the arc circuit opened and it could not be reestablished by touch starting. Unfortunately, the melt cooled down too fast to allow for sampling, and H-70 was declared a "no-test."

On 9/9/92, the remaining simulated hydrated oxide was added to the solidified slag to help restart the arc melter, in addition to the graphite strip. After the H-60 composition had been reached and a specimen was taken, aluminum metal was then added to the melt. The effect of Al (as Al_2O_3) on the slag chemistry should be to stiffen or freeze up the melt. During addition, the aluminum floated on top of the melt then eventually melted. Diffusion of molten Al into the melt and ignition of metal vapor were evident. Finally the electrode burned too short and the test had to be terminated. Only 2 wt% of Al (100 gm, 1/10 of originally planned) was able to be added. In this experiment, chemical corrosion was much more severe on the graphite electrodes than in ambient air. This was due to accelerated attack on the carbon electrodes by $\text{H}_2\text{O}(\text{g})$, OH , H , and O from the decomposing metal hydroxides in the melt. The anode corrosion rate was noticeably much higher than the cathode. Both electrodes achieved a tapered shape.

The following general conclusions and recommendations evolved from this test.

1. The metal oxide mix provided a good starting medium (with graphite starting strip).
2. The aluminum did not melt fast enough nor oxidize fast enough to affect the melt/slag in this application.
3. The amount of water vapor or hydroxides should be minimized in a melter with graphite electrodes to minimize wear rate.

Test 11: IEB4/M-Series Soil and Metal with Argon Atmosphere Trial

Test 11 was performed on 9/11/92. The melt was initiated on IEB4/M-100 with an argon flow rate of 25 scfh for 13 minutes; whereupon, a lot of dust was formed and the arc went out.

b. J. D. Grandy, T. L. Eddy, and G. L. Anderson, *TSA Waste Stream and Final Waste Form Composition*, EGG-MS-10617, January 1993.

Figures 28 and 36 show the current, voltage, and resulting power input data during the course of the test. After restarting, melting continued for 47 minutes before adding iron nails. After five minutes, 0.805 kg of iron had been added and an apparent eruption, from steam or carbonate release, occurred. The experiment was terminated because it was thought that the chamber had developed a leak. See other metal test descriptions.

Test 12: IEB4/M-Series Soil and Metal with Air Atmosphere Trial

Experiment 12, to melt soil and metal in an air atmosphere, was performed on 9/18/92. Figures 29 and 37 show the current, voltage, and resulting power input data during the course of the test. The first attempt to run the experiment failed because the soil did not melt sufficiently between the two electrodes, and when the current was disrupted (after 6 minutes of operation) it could not be restarted. This apparently occurred because the 1 x 6 x 3/16 in. graphite strip did not reach sufficient temperature (yellow-hot) to heat the soil beneath it. Even though the current was raised to 250 A, the strip did not get red hot. It appears that the strip was too thick and did not offer enough resistance to heat up (I^2R) sufficiently.

The slag generated was removed and the experiment was restarted with a new charge of soil. The thicker starter strips (about 3/16 in.) were cut back into a dumbbell shape to give similar cross-sectional area as successful starts. The starting procedure was reinitiated at 4:15 p.m. Initial currents were 200-250 A and reduced as the voltage rose with time. The strip still did not get yellow hot other than at each end near the arc attachment. As the ends sublimed/burned away (no flame was evident) the strip decreased in length, the arc length to the strip ends increased, and the voltage rose. The current was decreased to maintain the arc, but near the end the rate of decrease increased drastically with time and the current ceased even at the lowest setting. The latter change occurred over a few seconds. The arc would not start, again because the soil had not sufficiently melted.

A thin graphite strip (1 x 6 x 1/32 in.) was placed over the other imbedded strip. When the electrodes made contact, the strip fractured on each end. Some of the steel shot was placed on each end of the graphite strips under the electrodes, and after a false start and some more steel shot, the arc was restarted. Very erratic starting and heating ensued, characterized by voltage and current fluctuations, spurious arcing, and power supply cracking sounds. Operation was even unstable at low currents of 9 A and voltages of 200-300 V. At 6:00 pm we decided to check if the arc V-I characteristics were now increasing by steadily increasing the current rheostat by 10 unit intervals and monitor V and I. As the rheostat setting increased, the current increased (from a low of 9 A) and the voltage also slowly increased (from a low of 300 V). During this time, the additional power heated up the slag/soil sufficiently to operate in a stable mode and the test was off and running. The soil was apparently heated throughout in about 1 hour (7:15 p.m.) as indicated by a 30°C crucible leaving temperature and observation of the sides of the melt. Prior to that time, some of the unmelted top material had slagged and hardened. It was partially pushed into the melted material. Figure 41 shows the soil temperature as obtained from the thermocouple measurements. After reaching a peak value, the thermocouple malfunctioned.

Next (7:20 p.m.), a slag sample was dipped and the first five metal decontamination samples were taken. Starting at 7:33 p.m., metal rod pieces were dropped into the melt between the electrodes over a period of 15 minutes. The rods would plop into the melt and melt or sink, and

subsequently fell on top of each other and slowly melt and/or sink. The rest of the shot charge was then added in a couple of minutes. Two kg of steel and iron were added to the 6 kg of melted soil. During this and the above soil melting, the current was often operated near 200 A; whereas, in previous melts the current was held below 100 A. At one time, the partially melted slag-metal at the side was partially pushed into the melt to encourage melting. The completion of the metal melting was suggested by observations of the melt, time, and repeated high and stable crucible leaving water temperatures. The second five metal decon samples were taken (8:33 p.m.). The decon samples had considerable slag surrounding them so it was decided to use them as the slag samples also. The cathode electrode was operated slightly submerged to keep the anode arc gap smaller and to prevent arcing to the SS chamber near the anode. The current was extinguished about 8:43 p.m., because the electrodes were getting quite short; otherwise, the experiment could apparently have continued indefinitely.

Conclusions and recommendations made as a result of this test were:

1. The starting/heating procedure is inconsistent. It appears that we need to return to the previously determined starting procedures with the approx. 1/16 thick graphite rod, high (200 A) initial starting currents to melt the soil between the electrodes. (Subsequent tests started with a 3/32 in. graphite strip and higher currents and have not had problems starting.)
2. A short starting and heating cycle is needed to be able to run the main tests for a reasonable duration without having to replace the electrodes. In the actual pilot/treatment facility, starting would probably be done with a more easily started material, e.g., an A-40 mixture. This is not advantageous when we are also making basic IEB and IEB4 for use in waste form materials characterization tests. Nevertheless, we may wish to determine and specify a different starting series-soil mix if this continues to be a nuisance. (All subsequent starts were performed with soil or soil plus ZrO_2/TiO_2 mixture without significant problems.)
3. The power supply noise may be caused by the arc motion. It was not heard or a problem when more than one power supply was connected in parallel. Even though the process operates at well below the 100% duty cycle curve, we may want to use two units in parallel to see if the noise continues. (Subsequent tests used two power supplies and did not experience the stated noise or instabilities.)
4. With strong soil concentrations and V/I fluctuations, we are riding and apparently fluctuating across the envelope on the V-I characteristics for one power supply unit. The second power supply may need to be hooked in series to give a steeper V-I characteristic and more stable operation. (Subsequent use of two power supplies in parallel did not indicate that additional voltage would be necessary.)
5. The melt is not melting as uniformly as it should, especially in the regions farthest from the electrodes. This appears to be caused by the lack of an optimum thickness of melt. The melt is so thin compared to its diameter or length that the convective eddies developed in the electrode region are not reaching or are out of sync with the unmelted regions. The pattern also appears to be a function of the operating current. It is recommended that different size soil melts be run successively, varying the current at each condition, to check the optimum melt thickness for improved convection in the present geometry. Recommended soil mass/slag heights to be

examined are (1) 6 kg/1.5 in., (2) 8 kg/2.0 in., (3) 10 kg/2.5 in., (4) 12 kg/3.0 in., (5) 14 kg/3.5 in., and (6) 16 kg/4.0 in. (Eight kg gave nice horizontal streamlines following a hyperbolic streamlines. Larger mass streamlines were not as well defined, but may have had a more vertical orientation.)

6. The electrodes burned more equally (possibly because the cathode was kept under the surface near the end), were less pointed (flatter ends) with the zirconia coating, and were operated for at least twice as long as in the other experiments. The alumina coatings should also be tested and the best of the two coatings be used in future melts.

Test 13: IEB4/M-Series Soil and Metal with Air Lance Trial

Objectives. This experiment, performed on 9/23/92, is the first attempt to melt soil and metal with an air lance in the arc melter. The topics to be investigated were:

1. Melt depth studies: Observation of the melt flow patterns after each of 2-kg additions of soil to the initial 6 kg.
2. Voltage drop measurements: immersing both, one and neither electrodes to estimate the effect of electrode fall (voltage drop) heating compared to Joule heating.
3. Oxidation by air lance of metal added to the slag: to compare oxidation rates and processes with similar runs with ambient air and argon.

Starting Procedure. Recent starting procedures have not been smooth or timely. This experiment attempted to return to the standard starting strip and current-time procedure developed in Phase I of this project. The standard graphite dumbbell starting strip has been about 3/32 in. (though on the original plans 0.065 in., a little over 1/16 in., is given). The first strip used (0.059 in., a little under 1/16 in.) became yellow hot at 200 A/100V, but burned up rapidly. The arc became unstable, went out, and was unable to be touch started. The remainder of the strip was removed and a 0.090 in. (almost 3/32 in.) strip of 1 in. width (not dumbbell shaped) was used. After starting, the strip did not glow at 200 A, and as the arc voltage increased to over 250 V and the current was decreased to less than 50 V, the arc went out, and was unable to be touch started. Some steel shot was poured around and between each electrode contact region, the arc started, but was erratic and went out. Finally two 0.060 in. graphite dumbbell strips were placed, one on top of the other, over the other materials. After starting, both ends of the graphite strip burned away, and longer horizontal arcs occurred. The long arcs are important in radiant heating of the slag, as well as the hot graphite strip. At the same time, the soil/slag under each electrode melted with the current oscillating between melt conduction and arc to graphite. As time went on, the graphite was shifted toward and under the right electrode (anode) in a similar way to that in Phase I Experiments 6 and 7. The current is alternating between the melt and the arc-graphite mode. As the strip burned away, the slag between the electrodes became yellow and the melt was on its way.

Two TAFA power supplies were connected in parallel for 400 VOC (open circuit), and a 200V/300A 100% duty cycle. Figures 30 and 38 show the current, voltage, and resulting power input data during the course of the test. During starting, there was none of the "cracking" heard in Experiment 12 when only one unit was used. At 200 V and 150 A, one would not expect to

exceed the power supply envelope, but the signals were transient and the meters did not indicate the current fluctuations observed from the multimeter connected to the current shunt. It appears that the current variation, in switching from conduction to arcing modes, varies much more than the voltage. At later, stabler periods, the voltage could extend to 350 V and maintain the arc. Figure 42 shows the soil temperature as obtained from the thermocouple measurements. After reaching a peak value, the thermocouple malfunctioned.

In summary, it appears what is needed is to return to a dumbbell graphite strip, 0.094 in. (3/32 in.) thick, 6 in. long, 1 in. square ends, and 1/2 in. wide between the ends. The initial starting current needs to be high (about 200 A) to get the electrode regions melted, but should continue to be decreased as the strip decreases in length to reduce fluctuations. Keeping the electrodes near the melt also helps because of partial current flow through the slag and arcing through any vapor. Additional hardware to reduce fluctuations would be a choke or doubling the power supply voltage. The starting phase should take 5 to 10 minutes. A small amount of more conducting soil (e.g., A-40) could be placed in a shallow region between the electrodes to improve starting (but may alter the desired composition).

Once the starting procedure takes hold, the current can be raised in the rolling boil mode (with the electrodes just touching or just above the melt surface) up to the point where the boil shifts into a more violent mode. If the arc goes out, it has always been immediately restarted by touching the melt. See table of time, video index, power settings, and comments.

Heating Procedure. After the 4th restart, stable operation occurred in about 6 minutes. The following heating period was marked by a much larger current (e.g., 170 A versus 50 A) compared to many of the previous runs. This was accompanied by a larger voltage (e.g., 180 V versus 100 V). The 6 kg of soil became mostly melted after an additional 25 minutes. Two kg of soil were added in scoops through a 1.5" tube at 60° to horizontal. The soil landed between and in front of the electrodes, rapidly melt into the slag, and was essentially all melted when the addition stopped after 18 minutes. The voltage and current were relatively steady, averaging about 140 A and 190 V over the period. On one occasion the soil put out the arc, which was immediately restarted by touching the slag with the electrodes.

With the additional melt depth due to 8 kg instead of 6 kg of soil (estimated at 2.4 in. versus 1.8 in.), hyperbolic-like flow streamlines developed in each quadrant with the flow toward the origin and through the melt attachment under each electrode. Video frames of the flows for 8 kg of soil are shown in Figure 14. The flow streamlines are nonexistent for 6 kg, strongest at 8 kg, and weaker at 10 kg. The second addition of 2 kg of soil took only 7 minutes with the soil again being melted essentially when the addition stopped. For the second addition of soil, the current was raised and remained relatively steady at approximately 170 A and 210 V.

Metal Addition. After the second soil addition, 1 kg of iron concrete bolts cut into 2" lengths were added over a period of 8 minutes. As in Exp. 12, they seemed to melt and/or sink immediately. Later, one bolt with a head was found unmelted and merged into the solidified iron mass at the bottom of the melter, as well as some of the large nails added later. As soon as the iron bolt rods were added, bubbles appeared in the slag between the electrodes.

Air Lance. Approximately, 1 hour and 37 minutes after the 4th start, the air lance was lowered into the melt. A 3/32" hole normal to the 1/2" mullite tube and 3/8" from the bottom passed 61.6 scfh. The bottom of the lance tube was filled with 1/4" of Sauerisen cement above which was a 1/4" boron nitride plug. The lance was inserted near the side wall between the electrodes. The air jet was directed back between the electrodes under the melt and stirred up a whitish frothy slag as it was immersed. The flow was reduced to 49.3 scfh air to reduce the extent of agitation. In a short period of time (about a minute), the bottom of the lance appeared to melt or break off (evenly) from thermal stresses. Later the open ended lance was reinserted. The flow and reaction splashed whitish slag onto the melter walls, electrodes, and the lance. The bottom of the lance again was broken off or melted almost as rapidly as it was fed into the melter. After reaching the top of the SS tube to which the lance was attached, it was removed. Upon removal, a 4-5" length was observed to fall off the lance into the melt. The end of the lance as removed showed no signs of melting, but then was above the piece broken off.

A cup sample was dipped out of the slag followed by the addition of 1 kg of 10p nails. The nails are about 5" long and often "stuck" in the melt, to slowly tip and fall into the melt, receive arcs from an electrode, or melt into the slag. The iron appeared to have been melted into the slag after about 5 minutes. Most of the nails and rods were found to have been melted, but several were sticking out of the solidified iron on the bottom of the melter.

A second alumina lance was being prepared for oxidation studies when the arc went out. The anode copper adapter and a little of bronze supporting tube had melted, dropping the remaining graphite anode and boron nitride radiation ring into the melt. The graphite anode floated to the cathode region and resembled a slowly burning cork in a red hot bath. The boron nitride ring dropped straight down, became partially covered with slag, but remained essentially intact for reuse. No evidence of the copper was to be seen. We now know that the critical length of anode to maintain the arc at >200 A is approximately 2". The total operating time was 2 hours.

After the cooling and breaking up of the slag, it was found that essentially all of the soil had been melted except a very thin layer next to the Sauerisen cement-lined crucible on which the Sauerisen cement was still intact. The metal was in the shape of an irregular monolith on the bottom of the melter and in an "elliptical" shape covering the areas under and between the electrodes. The solidified metal indicated that the first 210 kg of steel shot probably sank and solidified first. The bolt rods solidified at the bottom on top of and around the 210 kg mass. The melted nails merged into the top of the bolt rods in the middle, but gave a porcupine effect at the edges of the metal monolith. The copper was found sporadically resolidified around the anode end of the solidified iron at the bottom of the melter.

Voltage Drop Measurements. An experiment on the measurement of the anode and cathode fall values at the electrodes and at the arc-melt interfaces was made to quantify the heating effect of the arc-melt interface fall regions. The fall region is a thin, high voltage drop region where free electrons are accelerated into the current path, or recombination and subsequent ionization occurs to maintain quasineutrality and the ion current. The relatively large " $V \times I$ " energy in the region is dissipated as heat. The information obtained can provide information on the electric energy disposition for modeling and design as well as optimization. The procedure involves alternately immersing both, one, and neither electrode in the melt to

measure the differences in overall voltage (at constant current) and by difference the respective fall voltage drops. The heat dissipation is obtained from $V \times I$.

Between the additions of soil, a brief study of electrode voltage fall values was made. The values read on the current and voltage multimeters oscillated several units during the measurements. The results are therefore qualitative at best. The current was approximately 140 A. No attempt was made to do a parameter study with current because of the relatively large fluctuations. With both electrodes in the melt with negligible fall region the voltage was 195 volts. Raising the anode just out of the melt, the change in voltage was 35 V; therefore, the estimated sum of the anode plus melt falls (double fall) is 35 V. Raising the cathode also just out of the melt, increased the voltage an additional 10 V. Neglecting the arc length voltage drop, the average double fall is $(35 + 45/2)/2 = 29$ V. If the operating mode is with both electrodes just out of the melt, and if the fall at the melt is directly heating the melt, then two of the four falls or one double fall results in heating the melt. The fall and Joule heating contributions for this condition are estimated at:

$$\text{Fall heating: } 29 \text{ V} \times 140 \text{ A} = 4.06 \text{ kW}$$

$$\text{Joule heating: } (240-29) \text{ V} \times 140 \text{ A} = 29.54 \text{ kW}$$

This shows that when the electrodes are kept close to the melt, most of the heating is by the Joule heating mode. The short electrode-melt gap also provides the most quiescent operating condition (which also depends on the current level). The fraction of fall heating will vary depending on melt depth, current, and molten metal in the bottom of the melter.

Conclusions and Recommendations from Test 13 are the following.

1. The starting procedure is still unstable and needs to be refined as recommended above.
2. The heating period has been reduced by increasing the rate to 24-30 kW.
3. The optimum melt depth for the soil in this melter appears to be that corresponding to 7 to 9 kg of soil load. The soil is melted essentially as soon as it is added (within several minutes). Excellent flow streamlines in the slag are shown on the video tape that could be used to check models.
4. Metal added appears to melt and then solidify on the bottom. If desired, additional thicknesses of Sauerisen cement, Ruby refractory, or equivalent should be added to the bottom and sides of the melter to reduce heat loss, to keep more of the metal molten inside the melter for tapping or reactions, and to make the melter more energy efficient. The metal must remain molten if tapping is to be used in continuous treatment systems.
5. By the time the lance experiments were started, the electrodes were so far along in their life cycle that air lance experimentation time was limited. Longer electrodes could be used or shorter more focussed experiments could be run. The lance may have broken from thermal stresses or shocks. The necessity of using a lance in lieu of slag and convective oxidation requires a much more sophisticated experiment than can be done within the scope of work on this project.

and would require other modifications in the melter (e.g., the additional refractory discussed above) to be successful.

6. The power supply noise experienced in Exp. 12, was not found with the two power supplies connected in parallel. The noise was probably caused by current and voltage fluctuations exceeding the operating envelope of one power supply. These fluctuations are not as obvious on the panel meters as observed on the digital meters.

7. The melter is capable of operating in the steady state with all of the soil molten. The addition of refractory will put even less strain on the cooling system. The main limitation to long runs is the electrode erosion/corrosion. In practice, consumable electrodes would be continuously fed into the melter. There are therefore no obvious maintenance problems to this type of melter. The auxiliaries will have maintenance and repair schedules identical to those practiced in similar industrial applications.

Table of Test 13 Time, Video Index, Current, Voltage and Comments.

<u>Time</u>	<u>Video</u>	<u>SetPoint</u>	<u>Amperes</u>	<u>Volts</u>	<u>Comments</u>
2:51					1st start (1/2 x 0.059 in.)
2:53					arc out
3:38	133		240		2nd start (1 x 0.090 in.)
3:45	218				arc out
4:20	218	30	240	120	3rd start (+ two 1/2 x 0.059 in.)
		40	280	150	
		50	310	180	
		50	210	250	
4:27	309	40	100-180	300	
4:28	314				arc out
5:09	314				4th and final start (added 210 g steel shot)
4:48					mass spec. #1 taken (same as before start)
	331	20	200	120	
	365	20	170	180	
5:15					arc out, touch restart
5:16	404				
5:18		30	205	180	
5:21					arc out, touch restart
5:27	547				stable operation, video tape off
5:29	547	20	170	160	unique arc jet
	556	20	200	100	video in.

5:40	556				start adding 2 kg soil (to 8 kg)T-soil = 1,640°C, arc out, touch restart
5:45		20	130	200	
5:47		20	150	180	
5:52		20	130	200	
5:53		30	170	210	
5:55	699				video off
5:58					stopped adding soil
6:00	699				video on, bubbles at side and convection
6:05	710	30	158	220	video of melt streamlines
	715				video in. for complete melt
	720				video off
6:07					optical Pyrometric reading #1 (anode, cathode, middle)
6:12		30	195	164	electrode fall measurements: both electrodes in melt
		30	140	230	cathode in melt
		30	140	240	both electrodes out (large fluctuations)
6:18					started second 2-kg addition of soil (to 10 kg)
6:25					stopped adding soil (almost all melted when stop)
6:32	720				video on (flow patterns not as good as with 8 kg)
6:34			180	200	optical pyrometer readings #2
6:38	728				adding 2 kg of metal: (bolts, nails, 2.21 total kg)
6:46	789				adding air via lance (61.6 scfh)
6:50	821				bottom of lance melted or broken, withdrawn
6:52	845				lowered broken lance into melt, splashing
6:53					arc out, touch restart
6:55		30	175	200	dip slag sample #1
6:59	875				add 2 kg more metal (4.21 total kg)
7:04	894	40	250	170	raised current, stopped video
7:06					mass spec. reading #2 (no change)
7:08					lost arc: anode copper fitting melted, rolling in slag near cathode essentially intact, boron nitride ring dropped straight down, copper/fitting not to be seen.
7:10	94				shut down, anode graphite floating near cathode
	104				dip slag sample #2

Test 14: IEB4/S-Series Calcium Silicated Organics Trial

Objective. Test 14 was performed on 9/29/92, with the following objectives.

1. To gain experience in melting calcium silicated organics to (a) determine the response when injected into the melter, (b) determine melting rates and how melting compares to added soil, (c) determine possible sizing constraints, and (d) compare V-I characteristics and temperature-viscosity effects.
2. To generate vitrified samples of the S-series as a base for future FWF experiments.
3. To continue testing the starting procedure, soil heating procedure, and equipment operation under different melting conditions.

Starting Procedure Stage. It took four restarts (as with Experiment 12) to get through the starting bottleneck of heating the soil between the electrodes sufficiently to get melt conduction. It appears that a better conducting medium than INEL soil or the higher voltages is required to ensure starts in the shortest time in this melter. Large melt pools were formed under the electrodes very early in the starting stage. The heat is being transferred to the area between the electrodes apparently by radiation from the arc to the end of the retreating graphite strip.

Heating Procedure Stage. The heating procedure, after starting, was run at near the highest currents manageable. Figures 31 and 39 show the current, voltage, and resulting power input data during the course of the test. The arc went out on several occasions because of oscillations beyond the V-I envelope available or occasionally during injection of simulated waste when the electrodes were above the melt. In each case, the current was easily restarted by touching the melt with the electrodes.

This experiment resulted in more fumes during the soil heating (not related to the ingestion of CSO) than in other experiments, with the exception of some of the initial experiments in which the power levels were also kept high. Another source of the fumes is when the electrodes are under the melt surface at high current. It was difficult to establish that this was the cause at this writing. Detailed examination of the videotapes may shed light on the origin of the fumes. At the end of the soil heating stage, the melt was level all around and looked totally melted with the exception of small amounts of fused soil on opposite sides of the crucible walls and farthest away from the electrodes.

Calcium Silicated Organics Stage. The calcium silicated organics (CSO) were prepared in accordance with simulated waste used for testing the method of sizing by cryofracturing with liquid nitrogen.¹ The CSO mixture was prepared in 1.297 kg batches with 0.378 kg of MICRO-CEL E (powdered calcium silicate), 0.057 kg of an oil adsorbent, and 946 ml (0.862 kg) of household vegetable oil (to simulate the organic wastes). The amount of oil was insufficient to give a solidified product. The consistency of the CSO mixture resembled an oil-agglomerated material that is no longer powdery containing lumps of oil-impregnated Oil-dry. The CSO mixture is to be combined with soil in an S-series final waste form, indicated by S-X, where X indicates the initial wt% of soil and 1-X the initial wt% of CSO in the series. Individual

containers with CSO mixture weights for mixing with the melted soil to give S-100, S-90, S-80, S-70, S-60, S-50, and S-40 were prepared for the experiment.

After the soil was almost if not completely melted, the CSO were added to the melt by shoveling 0.667 kg (about 2 l), approximately a tablespoon at a time, down the feed funnel and tube. Air is blown through a 1/4 in. tube down into the crucible melter at a rate of 61.6 scfh. The response of the system on each injection was consistent. Immediately, a burst of flame flashes back up the tube and out the funnel. On the video, the CSO are seen to drop onto the melt, with smoke or fumes quickly released. Sometimes the smoke occludes the whole chamber; other times there is little emission. The melt is briefly and thinly covered with a cold cap of CSO. There were also mild smells reminiscent of cooking oil in a hot pan.

The melter operation was quite steady all during the 40 minutes of feeding the CSO. Changes in current from 100 to 160 A as initiated by the operator were relatively stable (in both current and voltage) at each current range. The material not in the fumes or smoke melted into the slag at a slower rate than the soil added (also at a faster rate) in Experiment 13, but appeared to be almost completely melted when the run was terminated. Figure 43 shows the soil temperature as obtained from the thermocouple measurements. After reaching a peak value, the thermocouple malfunctioned.

An excessive amount of carbon soot was released during the CSO feeding. The melter chamber and cold trap were covered with soot. When the exhaust duct was raised from the cold trap exit, streamlines of soot could be seen flowing from one to the other. The environment in the present melter was not designed for combustion (time, temperature, and turbulence), and this test emphasized that point. The RETECH plasma centrifugal reactor (PCR) at the INEL CDIF at Butte, Montana, has demonstrated excellent combustion of wood chips and diesel oil in that plasma reactor system. It may be prudent to examine "pot melter" combustion in the arc melters at the USBM-Albany or the MIT-EPI installations, if that is one of their proposed functions. The System Design Studies^{2,3} and Thermal Processing Technologies study⁴ recommended the melter be located after an incinerator. For future input waste stream limits and waste form development, it is not necessary to include the combustibles with the noncombustibles and metals in the bench-scale arc melter generation of waste form materials. This test confirmed our suspicions.

Table of Test 14 Time, Video Index, Current, Voltage and Comments.

<u>Time</u>	<u>Video</u>	<u>Setpoint</u>	<u>Amperes</u>	<u>Volts</u>	<u>Comments</u>
8:50	112	20	200	42	Start 1: 3/32 graphite dumbbell strip, strip is bright - not original dark
		10			reduced current
8:53		20	180	150	strip stuck to cathode, increased current to melt off
8:55	180		160		
	184				arc out, strip melted away too fast, anode coating flaked off more than cathode

9:19	184				Start 2: 3/32 in. graphite dumbbell strip
9:20		20	205	110	bright strip as before
9:21		30	215	150	
9:22		40	250	180	
9:23		30	200	190	
		227			arc out, could not touch restart
9:48	227	20	220	90	Start 3: 4 in. x 1 in. x 1/8 in. graphite on top of dumbbell, granulated slag put between electrodes (much slag formed in previous runs)
	268	30	195	180	steady operation
9:51	302				video off
9:52					decreased electrode gap
9:55					arc out, no touch restart
10:11	303	0	115	100	Start 4: 4 x 1 x 1/8 strip shifted toward cathode, half dumbbell put under anode, 3/32 dumbbell put on top of both.
10:14		10	110	180	
10:15		5	60	230	
10:19	339	7.5	120	120	video off
10:20		7.5	120	125	
10:22		7.5	90	180	
10:24		5	130	100	decreased arc gap
10:25		5	115	120	
10:25		10	121	150	raised current
10:26	340	10	75	250	video on, arc running through melt, minimum arcing
10:27		10	140	130	
10:27		20	173	120	
10:28	378	20	50	220	
10:29	403				conduction mode, dust storm, foaming? (cathode too deep?), arc out, touch restart.
10:32		10	28	300	
10:33	450	20	55	310	stopped video tape
10:34		30			
10:36					arc out, touch restart
10:39		10	70	250	
10:39		20	85	280	soil T = 602°C
		20	110	230	smoke storm/dust storm

10:44	450	20	110	230	need to lower electrodes to keep from arcing and high voltage excursions
		10	87	210	smoking out cracks, cold trap probably plugged
	471				no flow from exhaust pipe
10:50		10	100	190	
10:53		20	120	220	system cloudy
		20	102	250	
10:58	472	30	123	260	cloudy but clearing, weak light at electrode-melt interface, is changing to more arc and bubbling at cathode
	485	30	148	240	clearing up, cold trap found plugged, frozen liquids in bottom
11:03		30	135	240	soil TC over temperature, arc out, smoking stopped, touch restart
11:15	486	30	115	260	air in (61.6 scfh), no change in video picture
	526				air off
***					move cathode down until hear hissing, then back off slightly
	539	30	120	260	videotape off
11:20					looks all melted (thru glass thru window)
11:26					optical pyrometer readings (anode, cathode)
					cleaned out cold trap, cut 2 in. off end inside
11:33		30	95	270	
11:35					start adding Ca Silicated Org. (CSO), (0.667 kg CSO for S-90), flame burst out feed tube, arc out, touch restart
11:38		30	150	240	air on (61.6 scfh)
11:42	614	15	99	235	continue 1st addition of CSO, procedure repeats for all additions: throw tablespoon of CSO down funnel into tube, flame flashes back up tube from funnel, smoke/fumes are seen when CSO hits melt, smoke/fumes emit from cracks and feed tube, video view is occluded by smoke fumes, and/or melt is briefly and thinly cold capped, mild smells of hot vegetable oil in pan.
	640				tried air off to minimize blow out, but no change, arc out, touch restart

11:50	700	15	105	220	air on (24.6 scfh)
11:54	731				many little boiling bubbles(?), under dark top, dropped electrodes to melt
11:57		15	125	185	trying to put CSO in faster,
11:59					Mass Spec 2 (first was before start and before feeding CSO)
					Note: Dark videos are smoke/fume conditions
12:02		15	118	220	air increased to 61.6 scfh, much carbon soot on cold trap outlet
12:05	842				more liquid nitrogen added to cool trap exhaust
12:07		20	110	220	raise power - not melting on side
12:10					Mass Spec 3 sounds/smells like frying something (quietly)
12:11		30	160	215	raise power
12:18		20	105	225	reduce power to save anode, cannot see it under the boron nitride ring anymore
12:23		20	150	230	Mass Spec 4, cup slag samples (3 taken)
	878	20	90	260	last video after slag samples, almost all melted, except top front away from electrodes
12:24					terminated test.

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Appendix C
Computer Code Listings

Data Logger Formating Code

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C *****
C Convert Data-Logger files to regular data
C by Jon Grandy
C 9/14/92
C
C To be used with AMRUN01x.DAT
C *****
C PROGRAM LOGTODAT
C *****
C
COMMON/DATA0/ NODP
COMMON/DATA1/ VOLTS(90),AMPS(90),TCI(90),TCO(90),HZC(90)
COMMON/DATA1/ TJI(90),TJO(90),HZJ(90),TEO(90),TEI(90),HZE(90)
COMMON/PERR1/ PEA(90),PEV(90),PET1C(90),PET2C(90),PEHZC(90)
COMMON/PERR1/ PET1J(90),PET2J(90),PEHZJ(90)
COMMON/PERR1/ PET1E(90),PET2E(90),PEHZE(90)
C
C DIMENSION      TEX(90),TSL(90)
C
C CHARACTER*21  D,DT
C CHARACTER*24  INFILE,OUTFILE,EINFILE,VIFILE
C
C -----
C I=1
C NODP=1
C MAX=90
C MTIME=0
C
C -----
C Clear screen and get input/output data file information from
C operator
C
C CALL SYSTEM ("CLS")
C
WRITE (*,*) '                                PROGRAM: LTD01.FOR      '
WRITE (*,*) '                                THIS PROGRAM READS A DATALOGGER FILE      '
WRITE (*,*) '                                AND CREATES A NEW "DATA ONLY" FILE      '
WRITE (*,*) 'PLUS AN INPUT FILE FOR THE ENERGY BALANCE PROGRAM      '
WRITE (*,*) '
WRITE (*,*) '                                NAME OF INPUT FILE - '
READ (*,*) INFILE
WRITE (*,*) '
WRITE (*,*) '                                NAME OF OUTPUT FILE - '
READ (*,*) OUTFILE
WRITE (*,*) '
WRITE (*,*) '                                NAME OF ENERGY BALANCE INPUT FILE - '
READ (*,*) EINFILE
WRITE (*,*) '
WRITE (*,*) '                                NAME OF VOLTAGE/CURRENT PLOT FILE - '
READ (*,*) VIFILE
WRITE (*,*) '
WRITE (*,*) '                                ENTER NUMBER OF MINUTES BETWEEN DATA ENTRIES - '
READ (*,*) MT
WRITE (*,*)

```

```

C -----
C Open the file and get the data.
C
OPEN (UNIT=2,FILE=INFILE,STATUS='OLD')
OPEN (UNIT=3,FILE=OUTFILE,STATUS='UNKNOWN')
OPEN (UNIT=5,FILE=VIFILE,STATUS='UNKNOWN')
C
005 FORMAT (A21,A21)
010 FORMAT (A,F9.1)

READ (2,005,ERR=110) D,DT          !Date and time
C   PRINT *, DT
READ (2,*,ERR=110)

C
READ (2,010,ERR=110) D,VOLTS(I)    !Volts
C   PRINT *,D,VOLTS(I)
READ (2,010,ERR=110) D,AMPS(I)     !Amps
C   PRINT *,D,AMPS(I)
READ (2,*,ERR=110)
READ (2,*,ERR=110)
READ (2,*,ERR=110)
READ (2,010,ERR=110) D,TSL(I)      !Soil temperature
C   PRINT *,D,TSL(I)
READ (2,010,ERR=110) D,TEX(I)      !Exhaust temperature
C   PRINT *,D,TEX(I)
READ (2,010,ERR=110) D,TCI(I)      !Crucible H2O temperature in
C   PRINT *,D,TCI(I)
READ (2,010,ERR=110) D,TCO(I)      !Crucible H2O temperature out
C   PRINT *,D,TCO(I)
READ (2,010,ERR=110) D,TJI(I)      !Jacket H2O temperature in
C   PRINT *,D,TJI(I)
READ (2,010,ERR=110) D,TJO(I)      !Jacket H2O temperature out
C   PRINT *,D,TJO(I)
READ (2,010,ERR=110) D,TEO(I)      !Electrode H2O temperature out
C   PRINT *,D,TEO(I)
READ (2,*)
C   PAUSE
C
DO 100 I=2,MAX,2
J=I
READ (2,*,ERR=110)
READ (2,*,ERR=110)
READ (2,010,ERR=110) D,VOLTS(J)    !Volts
C   PRINT *,D,VOLTS(J)
READ (2,010,ERR=110) D,AMPS(J)     !Amps
C   PRINT *,AMPS(J)
READ (2,*,ERR=110)

C
J=I+1
READ (2,*,ERR=110)
READ (2,*,ERR=110)
READ (2,010,ERR=110) D,VOLTS(J)    !Volts
C   PRINT *,D,VOLTS(J)
READ (2,010,ERR=110) D,AMPS(J)     !Amps
C   PRINT *,D,AMPS(J)
READ (2,*,ERR=110)
READ (2,*,ERR=110)
READ (2,*,ERR=110)

```

```

      READ (2,010,ERR=110) D,TSL(J)      !Soil temperature
C      PRINT *,D,TSL(J)
      READ (2,010,ERR=110) D,TEX(J)      !Exhaust temperature
C      PRINT *,D,TEX(J)
      READ (2,010,ERR=110) D,TCI(J)      !Crucible H2O temperature in
C      PRINT *,D,TCI(J)
      READ (2,010,ERR=110) D,TCO(J)      !Crucible H2O temperature out
C      PRINT *,D,TCO(J)
      READ (2,010,ERR=110) D,TJI(J)      !Jacket H2O temperature in
C      PRINT *,D,TJI(J)
      READ (2,010,ERR=110) D,TJO(J)      !Jacket H2O temperature out
C      PRINT *,D,TJO(J)
      READ (2,010,ERR=110) D,TEO(J)      !Electrode H2O temperature out
C      PRINT *,D,TEO(J)
      READ (2,*)
C
      NODP=NODP+2
100 CONTINUE
110 CONTINUE
C      PRINT *, ' NODP =',NODP
C
C      -----
C      Write XY-data to the new file.
C
020 FORMAT (1X,I5,2(F7.1,1X),5(F6.1,1X),2(F7.1,1X))
C
      WRITE (3,*) '" ORIGINAL FILE NAME - ',INFILE,'"
      WRITE (3,*) '" CURRENT FILE NAME - ',OUTFILE,'"
      WRITE (3,*) '" EXP DATE AND TIME - ',DT,'"
      WRITE (3,*)
      WRITE (3,*) '" # OF DATA POINTS - "',NODP
      WRITE (3,*)
C
C
      WRITE (3,*) '"
&LEC      SOIL      EX"
      WRITE (3,*) '"TIME      VOLTS      AMPS      IN      OUT      IN      OUT
&OUT      TEMP      TEMP"
      WRITE (3,*)
C
      DO 200 I=1,NODP
      MTIME=MTIME+MT
      WRITE (3,020) MTIME, VOLTS(I),AMPS(I),TCI(I),TCO(I),TJI(I),TJO(I),
&      TEO(I),TSL(I),TEX(I)
200 CONTINUE
C

```



```

C -----
C Write voltage-current data file
C
C 030 FORMAT (1X,I5,1X,3(F7.1,1X))
C
C WRITE (5,*) '" ORIGINAL FILE NAME - ',INFILE,'"
C WRITE (5,*) '" CURRENT FILE NAME - ',VIFILE,'"
C WRITE (5,*) '" EXP DATE AND TIME - ',DT,'"
C WRITE (5,*)
C WRITE (5,*) '" # OF DATA POINTS - ',NODP
C WRITE (5,*)
C
C WRITE (5,*) '" TIME VOLTS AMPS K-WATTS"'
C WRITE (5,*)
C
C TAMP=0.0
C TPWR=0.0
C MTIME=0
C DO 500 I=1,NODP
C MTIME=MTIME+MT
C VOLTS(I)=-1.0*VOLTS(I) !Voltage to positive quantity
C PWR=VOLTS(I)*AMPS(I)/1000 !Power kiloWatts
C TPWR=TPWR+PWR
C TAMP=TAMP+AMPS(I) !Cumulative amps
C WRITE (5,030) MTIME, VOLTS(I),AMPS(I),PWR
C 500 CONTINUE
C
C CALL SYSTEM ("CLS")
C WRITE (*,*)
C WRITE (*,*)
C WRITE (*,*)
C AMPHRS=TAMP*MT/60 !Amp-hours
C WRITE (*,*) ' TOTAL AMP-HRS - '
C &,AMPHRS
C WRITE (*,*)
C AVPWR=TPWR/REAL(MTIME) !Average power during run
C WRITE (*,*) ' AVERAGE POWER (kW) - '
C &,AVPWR
C WRITE (*,*)
C TENG=TPWR*60*REAL(MT) !Total energy consumed
C WRITE (*,*) ' TOTAL ENERGY (kJ) - '
C &,TENG
C WRITE (*,*)
C
C -----
C
C CLOSE (2)
C CLOSE (3)
C CLOSE (5)
C
C CALL EBALDAT (INFILE,EINFILE,DT)
C
C WRITE (*,*) ' PROGRAM END '
C END
C

```

```

C -----
C SUBROUTINE EBALDAT (INFILE,EINFILE,DT)
C -----
COMMON/DATA0/ NODP
COMMON/DATA1/ VOLTS(90),AMPS(90),TCI(90),TCO(90),HZC(90)
COMMON/DATA1/ TJI(90),TJO(90),HZJ(90),TEO(90),TEI(90),HZE(90)
COMMON/PERR1/ PEA(90),PEV(90),PET1C(90),PET2C(90),PEHZC(90)
COMMON/PERR1/ PET1J(90),PET2J(90),PEHZJ(90)
COMMON/PERR1/ PET1E(90),PET2E(90),PEHZE(90)

C
C CHARACTER*24 INFILE,EINFILE
C CHARACTER*21 DT

C
010 FORMAT (1X,11F7.1)

C
OPEN (UNIT=9,FILE=EINFILE,STATUS='UNKNOWN')

C
C
WRITE (9,*) '" ORIGINAL FILE NAME - ',INFILE,'" '
WRITE (9,*) '" CURRENT FILE NAME - ',EINFILE,'" '
WRITE (9,*) '" EXP DATE AND TIME - ',DT,'" '
WRITE (9,*)
WRITE (9,*) '" # OF DATA POINTS - "',NODP/2+1
WRITE (9,*)

C
WRITE (9,*) ' VOLTS AMPS T1C T2C FREQ-C T1J T2J FR
&EQ-J T1E T2E FREQ-E'
WRITE (9,*)
DO 100 I=1,NODP,2

C
TEI(I)=TCI(I)
HZC(I)=1301.7 !Average during experiment
HZJ(I)=1114.8 !Average during experiment
HZE(I)=221.1 !Average during experiment
VOLTS(I)=(VOLTS(I)+VOLTS(I+1))/2 !Average two readings
AMPS(I)=(AMPS(I)+AMPS(I+1))/2 !Average two readings

C
WRITE (9,010) VOLTS(I),AMPS(I),TCI(I),TCO(I),HZC(I),TJI(I),
& TJO(I),HZJ(I),TEI(I),TEO(I),HZE(I)
C WRITE (*,010) VOLTS(I),AMPS(I),TCI(I),TCO(I),HZC(I),TJI(I),
C & TJO(I),HZJ(I),TEI(I),TEO(I),HZE(I)
100 CONTINUE

C
C WRITE (*,*)
C WRITE (*,*) ' PEA PEV PET1C PET2C PEHZC PET1J PET2J P
C &EHZJ PET1J PET2J PEHZJ'
C WRITE (*,*)
C
C
WRITE (9,*)
WRITE (9,*) ' PEA PEV PET1C PET2C PEHZC PET1J PET2J P
&EHZJ PET1J PET2J PEHZJ'
WRITE (9,*)
DO 200 I=1,NODP,2
PEV(I)=2.0 !Assign probable errors
PEA(I)=2.0
PET1C(I)=0.1
PET2C(I)=0.1
PEHZC(I)=82.4
PET1J(I)=0.1

```

```

      PET2J(I)=0.1
      PEHZJ(I)=5.5
      PET1E(I)=0.1
      PET2E(I)=0.1
      PEHZE(I)=9.9
C
      WRITE (9,010) PEV(I),PEA(I),PET1C(I),PET2C(I),PEHZC(I),PET1J(I),
&      PET2J(I),PEHZJ(I),PET1E(I),PET2E(I),PEHZE(I)
C      WRITE (*,010) PEA(I),PEV(I),PET1C(I),PET2C(I),PEHZC(I),
C      &      PET1J(I),PET2J(I),PEHZJ(I),PET1E(I),PET2E(I),PEHZE(I)
      200 CONTINUE
C
      CLOSE (9)
Cc
      RETURN
      END
C

```

Energy Balance Code

```

C -----*
C PROGRAM      EBALAM1
C -----*
C J. D. Grandy  10/23/91  INEL/EG&G Idaho, Inc. - IRC, M.S.-2210
C
C EHBAL: JDG 10/23/91 Complete Modification of EBALx programs
C EBAL_AM: JDG 6/29/91 Do calculations for Arc Melter.
C EBAL_AM7: JDG 9/25/92 Do calculations for AMRUN07 data.
C EBAL_AM1: JDG 9/30/92 Do calculations for AMRUN01 data.
C
C -----
C This program calculates net power and power losses to the arc
C melter and its cooling systems.
C -----
C COMMON/DATA0/  NODP
C COMMON/DATA1/  VOLT(90),AMP(90),T1C(90),T2C(90),HZC(90)
C COMMON/DATA1/  T1J(90),T2J(90),HZJ(90),T1E(90),T2E(90),HZE(90)
C COMMON/PERR1/  PEA(90),PEV(90),PET1C(90),PET2C(90),PEHZC(90)
C COMMON/PERR1/  PET1J(90),PET2J(90),PEHZJ(90)
C COMMON/PERR1/  PET1E(90),PET2E(90),PEHZE(90)
C
C COMMON/DATA2/  PWRIN(90),PWRNT(90),EFFIC(90)
C COMMON/DATA2/  PWRWC(90),PWRWJ(90),PWRWE(90)
C COMMON/DATA2/  FLOWC(90),FLOWJ(90),FLOWE(90)
C COMMON/PERR2/  PEPIN(90),PEPNT(90),PEEFF(90)
C COMMON/PERR2/  PEPWC(90),PEPWJ(90),PEPWE(90)
C COMMON/PERR2/  PEFC(90),PEFJ(90),PEFE(90)
C
C CHARACTER*25  INFILE,OUTFILE,GRAFILE
C CHARACTER*42  EXPR(3)
C
C -----INPUT VARIABLES
C
C NODP    -   Number of data points (up to 10)
C
C AMPS    -   Torch operating amperage (V)
C VOLTS   -   Torch operating voltage (A)
C
C T1C     -   Temperature (C) of input cooling water to crucible
C T2C     -   Temperature (C) of output cooling water to crucible
C HZC     -   Frequency (Hz) of crucible water flowmeter
C T1J     -   Temp. (C) of input cooling water to arc melter jacket
C T2J     -   Temp. (C) of output cooling water to arc melter jacket
C HZJ     -   Frequency (Hz) of arc melter jacket water flowmeter
C T1E     -   Temp. (C) of input cooling water to electrodes
C T2E     -   Temp. (C) of output cooling water to electrodes
C HZE     -   Frequency (Hz) of electrode water flowmeter
C
C PEx     -   Probable error of "x"
C

```

```

C -----OUTPUT VARIABLES
C
C FLOWC - Water flow to crucible [lps]
C FLOWJ - Water flow to arc melter jacket [lps]
C FLOWE - Water flow to electrodes [lps]
C
C PWRIN - Total power in [kW]
C PWRWC - Power lost in crucible [kW]
C PWRWJ - Power lost in jacket [kW]
C PWRNT - Power in minus power lost [kW]
C EFFIC - Efficiency [%]
C
C -----
C CALL SYSTEM ("CLS") !Clear screen first
C
C WRITE (*,*)
C WRITE (*,*) ' PROGRAM: EBAL_AM1.FOR'
C WRITE (*,*) ' ENERGY BALANCE FOR ARCMELTER DATA'
C WRITE (*,*)
C WRITE (*,*)
C WRITE (*,*) ' NAME OF INPUT FILE - '
C READ (*,*) INFILE
C WRITE (*,*)
C WRITE (*,*) ' NAME OF OUTPUT FILE - '
C READ (*,*) OUTFILE
C WRITE (*,*)
C WRITE (*,*) ' NAME OF GRAPHER PLOTTING FILE - '
C READ (*,*) GRAFILE
C
C CALL DATAIN (INFILE,EXPR)
C
C -----
C DO 200 I=1,NODP
C
C DO 100 J=1,NODP !Convert to Kelvin to prevent
C T1C(I)=T1C(I)+273.16 ! divide by zero when T=0.0 °C
C T2C(I)=T2C(I)+273.16
C T1J(I)=T1J(I)+273.16
C T2J(I)=T2J(I)+273.16
C T1E(I)=T1E(I)+273.16
C T2E(I)=T2E(I)+273.16
100 CONTINUE
C
C PWRIN(I)=ABS((AMP(I)*VOLT(I))/1000) !Input power & probable error
C IF (PWRIN(I).EQ.0) THEN
C PEPIN(I)=0
C GOTO 109
C ENDIF
C PEPIN(I)=SQRT(PEV(I)**2/VOLT(I)**2+PEA(I)**2/AMP(I)**2)*PWRIN(I)
109 CONTINUE
C
C METNUM=2 !Crucible water flow
C HERTZ=HZC(I)
C PEHZ=PEHZC(I)
C CALL H2OFLOW (METNUM,HERTZ,PEHZ,FLOW,PEFL) !Water flow & error
C FLOWC(I)=FLOW
C PEFC(I)=PEFL
C

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```

METNUM=1                                !Jacket water flow
HERTZ=HZJ(I)
PEHZ=PEHZJ(I)
CALL H2OFLOW (METNUM,HERTZ,PEHZ,FLOW,PEFL) !Water flow & error
FLOWJ(I)=FLOW
PEFJ(I)=PEFL
C
METNUM=3                                !Electrode water flow
HERTZ=HZE(I)
PEHZ=PEHZE(I)
CALL H2OFLOW (METNUM,HERTZ,PEHZ,FLOW,PEFL) !Water flow & error
FLOWE(I)=FLOW
PEFE(I)=PEFL
C
DELTC=T2C(I)-T1C(I)                    !Temp. changes & errors
IF(DELTC.EQ.0) DELTC=0.001
PEDTC=SQRT(PET2C(I)**2+PET1C(I)**2)
DELTJ=T2J(I)-T1J(I)
IF(DELTJ.EQ.0) DELTJ=0.001
PEDTJ=SQRT(PET2J(I)**2+PET1J(I)**2)
DELTE=T2E(I)-T1E(I)
IF(DELTE.EQ.0) DELTE=0.001
PEDTE=SQRT(PET2E(I)**2+PET1E(I)**2)
C
PWRWC(I)=FLOWC(I)*4.186*DELTC          !Power losses & errors
PEPWC(I)=SQRT(PEFC(I)**2/FLOWC(I)**2+PEDTC**2/DELTC**2)*PWRWC(I)
PWRWJ(I)=FLOWJ(I) * 4.186 * DELTJ
PEPWJ(I)=SQRT(PEFJ(I)**2/FLOWJ(I)**2+PEDTJ**2/DELTJ**2)*PWRWJ(I)
PWRWE(I)=FLOWE(I) * 4.186 * DELTE
PEPWE(I)=SQRT(PEFE(I)**2/FLOWE(I)**2+PEDTE**2/DELTE**2)*PWRWE(I)
PWRNT(I)=PWRIN(I)-PWRWC(I)-PWRWJ(I)-PWRWE(I)
PEPNT(I)=SQRT(PEPIN(I)**2+PEPWC(I)**2+PEPWJ(I)**2+PEPWE(I)**2)
C
EFFIC(I)=((PWRIN(I)-PWRNT(I))/PWRIN(I))*100
PEEFF(I)=SQRT(PEPNT(I)**2/PWRNT(I)**2+PEPIN(I)**2/PWRIN(I)**2)
&      *EFFIC(I)
C
CALL PYROTEMP (IRANGE,MAMPS,PEMA,TEMP,PET)
TPD(I)=TEMP
PETD(I)=PET
C
200 CONTINUE
C
CALL DATAOUT (OUTFILE,GRAFILE,EXPR)
C
WRITE (*,*)
WRITE (*,*) '                                PROGRAM END '
C
STOP
END
C

```

```

C -----
SUBROUTINE DATAIN (INFILE,EXPR)
C -----
COMMON/DATA0/ NODP
COMMON/DATA1/ VOLT(90),AMP(90),T1C(90),T2C(90),HZC(90)
COMMON/DATA1/ T1J(90),T2J(90),HZJ(90),T1E(90),T2E(90),HZE(90)
COMMON/PERR1/ PEA(90),PEV(90),PET1C(90),PET2C(90),PEHZC(90)
COMMON/PERR1/ PET1J(90),PET2J(90),PEHZJ(90)
COMMON/PERR1/ PET1E(90),PET2E(90),PEHZE(90)
CHARACTER*25 INFILE
CHARACTER*24 DUM
CHARACTER*42 EXPR(3)

C
OPEN (UNIT=10,FILE=INFILE,STATUS='OLD')

C
READ (10,*) EXPR(1)
READ (10,*) EXPR(2)
READ (10,*) EXPR(3)
READ (10,*)
READ (10,*) DUM,NODP ! NODP = Number of data pts.
READ (10,*)
READ (10,*)
READ (10,*)

C
DO 100 I=1,NODP
  READ (10,*) VOLT(I),AMP(I),T1C(I),T2C(I),HZC(I),T1J(I),
    & T2J(I),HZJ(I),T1E(I),T2E(I),HZE(I)
  C   WRITE (*,'(1X,11F7.1)') VOLT(I),AMP(I),T1C(I),T2C(I),
  C   & HZC(I),T1J(I),T2J(I),HZJ(I),T1E(I),T2E(I),HZE(I)
100 CONTINUE
  C   WRITE (*,*)
  C
  READ (10,*)
  READ (10,*)
  DO 200 I=1,NODP
    READ (10,*) PEA(I),PEV(I),PET1C(I),PET2C(I),PEHZC(I),PET1J(I),
      & PET2J(I),PEHZJ(I),PET1E(I),PET2E(I),PEHZE(I)
    C   WRITE (*,'(1X,11F7.1)') PEA(I),PEV(I),PET1C(I),PET2C(I),PEHZC(I),
    C   & PET1J(I),PET2J(I),PEHZJ(I),PET1E(I),PET2E(I),PEHZE(I)
200 CONTINUE
  C
  RETURN
  END
C

```



```

C -----
C SUBROUTINE DATAOUT (OUTFILE, GRAFILE, EXPR)
C -----
COMMON/DATA0/ NODP
COMMON/DATA2/ PWRIN(90), PWRNT(90), EFFIC(90)
COMMON/DATA2/ PWRWC(90), PWRWJ(90), PWRWE(90)
COMMON/DATA2/ FLOWC(90), FLOWJ(90), FLOWE(90)
COMMON/PERR2/ PEPIN(90), PEPNT(90), PEEFF(90)
COMMON/PERR2/ PEPWC(90), PEPWJ(90), PEPWE(90)
COMMON/PERR2/ PEFC(90), PEFJ(90), PEFE(90)

C CHARACTER*25 OUTFILE, GRAFILE
C CHARACTER*42 EXPR(3)

C 13 FORMAT(1X, F8.4, ' ±', F7.4, 4X, F8.4, ' ±', F7.4, 4X, F8.4, ' ±', F7.4)
C 15 FORMAT(1X, A8, 6(F7.2, ' ±', F5.2))
C 20 FORMAT(1X, 6(F9.2))
C 25 FORMAT(1X, I5.0, 5(1X, F9.2))

C OPEN (UNIT=11, FILE=OUTFILE, STATUS='UNKNOWN')

C ----- WRITE TO DISK -----
C
C WRITE (11,*)
C WRITE (11,*) ' COOLING WATER FLOW RATES (liters/second)'
C WRITE (11,*)
C WRITE (11,*) ' EXP - # CRUCIBLE JACKET
C & ELECTRODES'
C
C DO 220 I=1, NODP
C WRITE (11,13) FLOWC(I), PEFC(I), FLOWJ(I), PEFJ(I),
C & FLOWE(I), PEFE(I)
C 220 CONTINUE
C
C WRITE (11,*) '','', EXPR(1), ''
C WRITE (11,*) ' " CURRENT FILE NAME - ', OUTFILE, ' "'
C WRITE (11,*) '','', EXPR(3), ''
C WRITE (11,*)
C WRITE (11,*) '"INPUT POWER AND COOLING WATER LOSSES (kilo-Watts)"'
C WRITE (11,*)
C WRITE (11,*) '"INPUT PWR CRUCIBLE JACKET ELECTRODES BALANCE"'

C DO 300 I=1, NODP
C WRITE (11,20) PWRIN(I), PWRWC(I), PWRWJ(I), PWRWE(I), PWRNT(I)
C WRITE (11,15) PWRIN(I), PEPIN(I), PWRWC(I), PEPWC(I), PWRWJ(I)
C & PEPWJ(I), PWRWE(I), PEPWE(I), PWRNT(I), PEPNT(I)
C 300 CONTINUE
C
C CLOSE (11)
C

```

```

C ----- WRITE TO GRAPHER FILE -----
C
C OPEN (UNIT=12,FILE=GRAFILE,STATUS='UNKNOWN')
C
C WRITE (12,*) ' ',EXPR(1),' '
C WRITE (12,*) ' ' CURRENT FILE NAME - ',GRAFILE,' '
C WRITE (12,*) ' ',EXPR(3),' '
C WRITE (12,*)
C MT=0
C DO 400 I=1,NODP
C MT=MT+2 !Two minute intervals
C E1=PWRWE(I)
C E2=PWRWE(I)+PWRWJ(I)
C E3=PWRWE(I)+PWRWJ(I)+PWRWC(I)
C E4=PWRIN(I)
C E5=PWRNT(I)
C WRITE (12,25) MT,E1,E2,E3,E4,E5
400 CONTINUE
C
C CLOSE (12)
C
C RETURN
C END
C

```

```

C -----
C SUBROUTINE H2OFLOW (METNUM,HERTZ,PEHZ,FLOW,PEFL)
C -----
C This subroutine calculates the water flow and probable errors
C from frequency readings taken with one of a number of flowmeters.
C -----
C METNUM      - An integer identifying a particular meter.
C HERTZ       - Frequency reading (Hz)
C PEHZ        - Probable error in measurement (Hz)
C FLOW        - Calculated flow (lps)
C PEFL        - Probable error in flow (lps)
C
C E0,E1       - Coefficients of curvefit to calibration data
C PECE        - Probable error (lps) due to linefit
C -----
C
C For WF1 data:
C Flow Technology S/N 120287 Prop. ID No. L-11228
C Calibration 6/3/88 (E0 = -0.18405E-02, E1 = 0.64396E-03)
C Calibration ?/?/91 (E0 = -1.18559E-02, E1 = 1.00739E-02) gpm
C IF (METNUM.EQ.1) THEN
C   PECE=0.0005031
C   E0 = -0.18405E-02      ! in lps
C   E1 = 0.64396E-03      ! in lps/Hz
C   GOTO 109
C ENDIF
C
C For WF2 data:
C Flow Technology S/N 8605584 EG&G S/N 701084
C Calibration 6/7/88
C IF (METNUM.EQ.2) THEN
C   PECE=0.0003491
C   E0 = -.76973486D-03    ! in lps
C   E1 = .16123227D-03     ! in lps/Hz
C   GOTO 109
C ENDIF
C
C For WF3 data:
C Flow Technology S/N 806067 EG&G S/N ?
C Calibration 8/11/92
C (GRAPHER ... E0 = -5.931E-04 lps, E1 = 2.92598E-04 lps/hz)
C IF (METNUM.EQ.3) THEN
C   PECE=0.0003491
C   E0 = -.5931D-03        ! in lps
C   E1 = .292598D-03       ! in lps/Hz
C   GOTO 109
C ENDIF
C
C WRITE (*,*) ' ERROR: FLOWMETER NUMBER NOT SPECIFIED CORRECTLY'
C STOP
C
C 109 FLOW = E0 + E1*HERTZ
C     FLOWE = E0 + E1*(HERTZ+PEHZ)
C     PEFL=(FLOWE-FLOW) + PECE
C

```

RETURN
END

C

END

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