THE EFFECT OF CHEMICAL COMPOSITION ON PROCESSING IN A PLASMA ARC CENTRIFUGAL TREATMENT SYSTEM

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ABSTRACT

Recent testing performed at the plasma research center of Retech Systems, LLC processed simulated low-level radioactive wastes (LLW) at a production scale using high-energy plasma as a heat source. Various combinations of metal-oxide feeds were processed in order to determine their effect on plasma torch operation, throughput, plant performance, glass chemistry and density of poured wastes. Testing took place in November of 1999 using a full-scale production Plasma Arc Centrifugal Treatment (PACT) system located at Retech where the melt zone is a rotating cylindrical hearth (centrifuge) and the heating source is a swirl flow, hollow electrode, plasma arc torch. The simulated LLW included concrete cinder block, refractory insulation board, soda-lime glass, and sand. This study has shown that processing these simulated LLW and forming slags of various compositions is difficult if the instantaneous feed composition is very high in silica. The electrical resistance of pure silica is high, especially at low temperatures, increasing plasma torch operating voltage markedly. Because the sand can spread rapidly over the centrifuge bottom, feed rates must be reduced when nearly pure sand is fed to reduce the thickness of the unmelted, unmixed surface centrifuge contents. The difficulties may occur either because a whole drum of sand is fed, or because of segregation of sand while a previously mixed drum is fed through our Archimedes type feeder.

INTRODUCTION

The purpose of this paper is to describe recent processing of simulated low-level radioactive wastes (LLW) at production scale using high-energy plasma as a heat source. The testing took place in November of 1999 using a Plasma Arc Centrifugal Treatment (PACT-8) system located at Retech in which the melt zone is a rotating cylindrical hearth (centrifuge) and the heating source is a swirl flow, hollow electrode, plasma arc torch (Fig.1). The simulated radioactive wastes were concrete cinder block, refractory insulation board, soda-lime glass, and sand. The testing was part of a Retech internal research and development effort to study the influence of glassy slag chemistry on plasma torch operation, throughput, and overall plant performance.

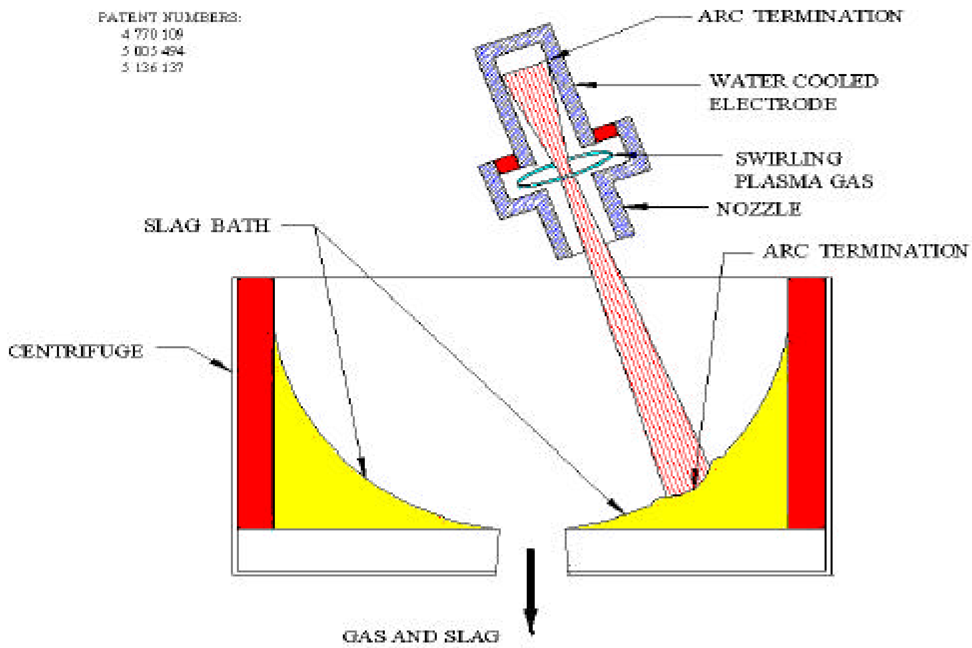

Fig. 1. Plasma arc torch configuration and its relation to the centrifuge and molten bath [1].

The objectives of this research study were the following:

1. Determine the effects of varying inorganic metal-oxide feed proportions on:

    - Throughput
    - Plasma torch operation
    - Overall plant performance, for example: heat losses, processing temperatures and pressures, pour slag density.

GENERAL PACT SYSTEM CONFIGURATION

The PACT system contains the following elements (Fig 2.):

- Primary Processing Chamber (PPC): This is composed of the centrifuge, centrifuge chamber and lid. The centrifuge is refractory lined and has an outside diameter of 96 inches (243.8 cm) and an inside diameter of 79 inches (200.7 cm). The plasma torch sits on a refractory lined lid via a two-axis manipulator (Z-axis, up and down, and X-axis, torch motion from the wall of the centrifuge to the pour nozzle). Wastes are processed in the centrifuge and poured into molds, by reducing the centrifuge speed, via a refractory pour nozzle. The lid and centrifuge chamber are double-walled and water-cooled, and seal the furnace so that operating pressure within the chamber can be 20-50 millibars below the ambient pressure. The centrifuge is cooled by a closed water system that directly cools the bottom plate of the centrifuge.
- Plasma Torch: The plasma torch used for this study is a dual mode torch in that both a non-transferred arc (electrode to nozzle arc path) and a transferred arc (electrode to centrifuge arc path) are utilized. The non-transferred arc stabilizes the transferred arc to

maximize throughput and to maintain long arcs without inadvertent current interrupts. The plasma torch is cooled by a closed water system.

- Archimedes Feeders: Waste feeds were loaded into twin Archimedes screw feeders. The rotation of the Archimedes Feeders (AF-1 and AF-2) pushes the wastes toward the PPC. Waste feed falls from the end of the AF into the centrifuge in the PPC.
- Secondary Treatment Chamber (STC): This is a refractory lined chamber that uses a natural gas fired burner to ensure complete combustion of off-gasses coming from the PPC.
- Slag Collection Chamber (SCC-1): This chamber contains the mold transfer system (before and after pouring) and the safety mold.
- Slag Cooling Chamber (SCC-2): After pouring, the mold filled with slag is transferred to the SCC-2 for storage and cooling. The SCC-2 can contain 24 pour molds and is cooled by a re-circulating air system
- Off-gas System: This is composed of a quench system, bag-house, HEPA bank, packed-bed scrubber, off-gas re-heater, induced draft fan, and stack.
- Furnace Water Skid : This is a closed water system that cools the SCC-1 and SCC-2 and all flanges and view ports that are water-cooled. Normally, this skid cools all closed water skid heat exchangers, but for operation in our factory we use our facility open water system.
- Open Water System: The open water circuit cools the PPC lid, STC chamber and all closed water skid heat exchangers.

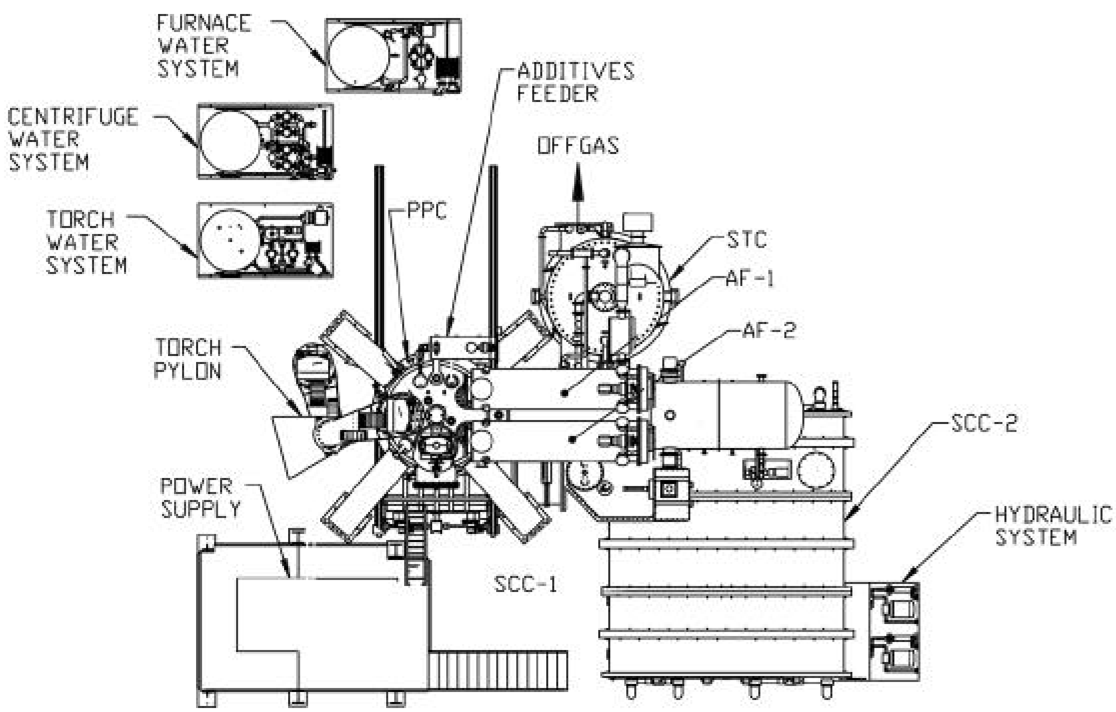

Fig. 2. General diagram of PACT system used for this study

PROCESS RESULTS

To study the effects of waste composition on processing results, six tests were selected from a series of 16 that were conducted studying the effects of a number of variables.

STC and PPC heat-up

The process begins by starting the STC burner on low fire (30% of maximum fire) and allowing the gas temperature in the chamber to reach a steady state (about 180°C). This minimizes thermal shock to the refractory prior to increasing the temperature at a controlled rate. After this brief period (about 20-30 minutes), the burner is set in AUTO mode and ramped up such that the temperature rise in the chamber does not exceed 150°C/hr. When the STC reaches a minimum of 400°C the plasma torch is started. The PPC is heated entirely by the plasma torch. The nitrogen plasma gas flow rate was modulated by varying the supply pressure between 15 and 30 psig (1.03-2.07 bar).

When the STC reaches 700°C the burner is put in MANUAL mode with a fixed fuel and combustion air input. Heat flux from the PPC to the STC, induced by the plasma torch, allows the STC to reach its set point for emission control (air quality permit) of 930°C. This step offers conservation of fuel input from the STC burner since the plasma torch will run for 12-15 hours before the PPC reaches thermal equilibrium. Once the STC reaches 930°C, the burner is placed in AUTO mode with a fixed temperature input value. This allows the burner fuel and air to reduce (throttle back) as the PPC rises to processing temperature. When the total torch power reaches 1200 kW, a full power equilibrium dwell starts (about 1-2 hours). This dwell period allows the centrifuge and lid (both refractory lined in the PPC) to reach a steady state at a PPC temperature of 1450°C. After the PPC reaches steady state, waste feeding and processing begins. Table I shows the results from furnace heat-up.

Table I. PACT furnace heat-up data

Item	Results
STC heat-up time to 700°C, hours	4.2
STC heat-up rate from 180°C start, °C/hr	123.8
STC heat-up time to 930°C, hours	9.25
Full power equilibrium dwell time, hours	2
PPC temperature heat-up time to 1450°C, hours	13
PPC heat-up rate from 400°C start point*, °C/hr	80°C
Total heat-up time (up to first feeding), hours	16.4

*Plasma torch start causes the gas temperature in the PPC to rise to 400°C in 30 minutes

Processing Wastes

Waste feeds were introduced into the furnace in batches of particular compositions. This was done to simulate future processing of slag-forming wastes where drums of materials (drum feeder) or loose feed (screw feeder) may be fed into the furnace. The varying metal-oxide feeds were introduced into the PPC centrifuge and formed a molten slag bath. Once feeding was completed there was a dwell phase prior to pouring. The dwell phase was executed in order to ensure a homogeneous slag product. From the feeding phase we established a feed rate and from feeding plus dwelling and pouring phases we determined the cycle feed rate.

Nitrogen plasma gas, during processing, was pressure modulated between 15 psig (1.03 bar) and 30 psig (2.07 bar); the volume flow rate was 19.5 scfm (34.7 Nm^3/hr) to 25 scfm (44.5 Nm^3/hr). The reason for torch pressure modulation was to move the arc termination inside the electrode, to use more of the electrode surface thereby extending the life of the electrode.

Table II shows torch operational parameters, batch sizes, and PPC condition during the processing of the waste materials. There were three compositions that were scheduled for feeding in duplicate, but operational variations occurred (discussed later) prompting the process team to modify two of the batches to enhance throughput. Therefore, the data presented represents five compositions. The batches were scheduled during the test series (which was run round the clock for several days) to allow the same team to process the second batch of the three planned pairs, possibly with improved rate.

Table II. Torch operational parameters, batch sizes, PPC condition, and throughput during processing of the waste feeds.

Description	**B1**	**B6**	**B9**	**B14**	**B5**	**B10**
Concrete weight, weight %	18.4	16.2	26.7	26.7	12.3	9.9
Insulation board, weight %	0.0	0.0	0.0	0.0	1.4	1.1
Sand weight, #30 mesh, weight %	40.8	35.9	6.7	6.7	86.3	69.2
Soda-lime glass, weight %	40.8	35.9	66.7	66.7	0.0	0.0
Calcium-Oxide (CaO), weight %	0.0	12.0	0.0	0.0	0.0	19.8
Transferred current average, Ampere	1640	1616	1590	1645	841	1480
Transferred voltage, Volts (Average) Non-transferred current, Amperes (Average)	600-900 (750) 420-460 (440)	650-800 (725) 420-460 (440)	625-690 (658) 420-460 (440)	615-680 (640) 420-460 (440)	800-1000 (900) 420-460 (440)	550-750 (650) 420-460 (440)
Non-transferred voltage, Volts (Average)	460-580 (520)	440-580 (510)	400-560 (480)	400-600 (500)	420-640 (530)	480-560 (520)
Total average torch power, kW	1459	1396	1257	1273	990	1191
PPC pressure, in. H_2O (mbar)	-12.5 (-31.1)	-13.5 (-33.6)	-15.5 (-38.6)	-15.5 (-38.6)	-13.5 (-33.6)	-15.5 (-38.6)
PPC temperature, °C	1500-1600	1550-1575	1500-1575	1500-1550	1500-1525	1525-1575
PPC average temperature, °C	1550	1563	1538	1525	1513	1550
Slag temperature, °C Slag average temperature, °C	1600-1675 1650	1600-1700 1650	1625-1725 1650	1600-1650 1625	1600-1700 1650	1600-1700 1650
Feed rate, lbs/hr (kg/hr)	938 (426)	1285 (583)	1323 (600)	1364 (619)	253 (115)	905 (411)
Dwell time, minutes	23	19	27	32	26	20
Cycle feed rate, [total time: feeding, dwelling, pouring], lbs/hr (kg/hr)	630 (286)	864 (392)	738 (335)	692 (314)	226 (103)	567 (257)

From these results the following is noted:

BATCHES B1 AND B6

- The basic feed for these batches was about 1.5 drums of sand and soda-lime glass, and about 1 drum crushed concrete. The drums were opened and the contents dumped into one on the Archimedes screw feeders. The drum size was 200 liters and the waste materials were not compacted. The sand and glass were loaded into the feeder first followed by the concrete. The Archimedes feeder, while rotating the wastes forward (and during feeding), provides partial mixing of the wastes prior to being fed into the furnace.

- Toward the end of mixed waste feeding, sand that had separated from the bulk feed began falling into the furnace in very high concentrations. The sand feed caused the transferred voltage to increase as indicated in Table I. To a plasma torch operator the first signal for torch problems due to feeding is an increase in transferred arc torch voltage. The dual mode torch is less sensitive to changes in feed composition when compared to a single mode transferred arc torch, but the sand feed still had a significant effect on dual mode transferred voltage. The sand formed a fused layer on the surface of the slag bed that caused a change in torch performance. Plasma torch operators lowered the transferred current and decreased the feeder speed. This was necessary to ensure that we did not reach 1000 V (open circuit voltage), which would cause arc-out. This reduced the thickness of the high silica top layer and allowed feeding to continue without interruption.

- For batch B6 it was decided to add CaO to the concrete feed to try to increase throughput and effectively reduce the transferred voltage if feed segregation occurred. Sand separation did occur but CaO chunks were present in the sand feed. The feeding and cycle times for B6 were both about 37% higher than B1. The primary reason for this was that the CaO addition helped to prevent the sand from fusing together by forming $CaO\text{-}SiO_2$ [2]. The results were reduction in transferred voltage, higher transferred arc current, and ability to feed at higher rates.

BATCHES B9 AND B14

- The basic feed for these batches was about 1.5 drums of soda-lime glass, and 1.5 drums crushed concrete and sand. The drums were opened and the contents dumped into one on the Archimedes screw feeders. The drum size was 200 liters and the waste materials were not compacted. The sand and concrete were loaded into the feeder first followed by the glass.

- The overall performance of the plasma torch, feeding, and throughput for both cases was about the same. There were no visible signs of feed segregation probably due to the significant reduction in sand load.

Fig. 3. Example of pour mold containing glassy slag: Batch B9

BATCHES B5 AND B10

- The basic feed for these batches was about 1.25 drums of sand and, and about 1 drum crushed concrete and insulation board. The sand drums were opened and the contents dumped into one on the Archimedes screw feeders. The drum size was 200 liters and the waste materials were not compacted. The sand was loaded into the feeder first followed by the concrete and insulation board.

- Feeding Batch 5 was problematic for the same reasons as described for Batch B1, only more pronounced. Feeding a batch consisting mostly of sand caused the torch to experience high transferred arc voltage. In this case the operator reduced the transferred current, lowered the vertical height of the torch, and decreased the feeder speed to compensate for the high voltage. The end result was low throughput.

- For batch B10 it was decided to add CaO to the feed to try to increase throughput and effectively reduce the transferred voltage when nearly all sand was fed. The feeding and cycle times significantly improved above the B5 values as indicated in Table II.

In general, it does appear that with these types of glass forming compositions, that having a CaO/SiO_2 ratio of about 0.30 in the slag (Table IV) seems to provide good torch performance and processing throughput. These data also show that with a CaO/SiO_2 ratio of less than 0.16 torch performance may suffer. Immediate action by the operator to prevent arc-out lowers throughput. Prior to feeding these types of wastes in the future, it would be better to calculate slag chemistry in order to predict likely processing performance.

Table III shows the data for heat losses during processing. The heat is picked up by the cooling water of the double jacketed and water-cooled chambers (PPC, GSC, etc.).

Table III. Heat loss results from significant circuits during processing

Description	B1	B6	B9	B14	B5	B10
Heat loss to torch electrode average, kW	220	215	190	218	150	195
Heat loss to torch nozzle average, kW	221	220	230	245	175	215
Heat loss to centrifuge average, kW	80	90	90	88	85	88
Heat loss to centrifuge chamber average, kW	49	48	45	45	43	48
Heat loss to PPC lid average, kW	215	228	230	220	210	215
Heat loss to power supply average, kW	17	16	17	14	9	16
Heat loss to gas separation chamber average, kW	66	60	60	53	43	53
Total heat loss (affecting PPC), kW	868	877	862	883	715	830
Heat loss affecting PPC, as % of torch power	60	63	74	69	72	70

From these results the following is noted:

- Heat loss information provides the operators with some of the knowledge of when to start feeding and to execute pouring. The heat loss data shows that the batches were carried out at comparable losses as a fraction of input power, ranging from 60% to 74%.

Table IV shows data for the poured materials.

Table IV. Significant pouring results: density, and major metal-oxides formation

Description	B1	B6	B9	B14	B5	B10
Specific gravity of the combined feed, calculated from the mixing rule and measured specific gravities of each of he components (which matched literature values) [3], g/cm^3	2.443	2.471	2.380	2.380	2.251	2.332
specific gravity, g/cm^3	2.580	2.641	2.490	2.448	2.261	2.362
Na_2O in slag, weight %	5.3	4.7	8.7	8.5	ND*	ND
MgO in slag, weight %	1.2	1.1	1.9	1.6	0.3	0.2
Al_2O_3 in slag, weight %	1.84	1.6	2.8	2.9	1.9	1.5
SiO_2 in slag, weight %	76.7	67.5	64.3	64.2	90.9	72.9
CaO in slag, weight %	12.5	22.9	18.9	19.1	5.3	24.1
Fe_3O_4 in slag, weight %	1.62	1.43	2.4	2.4	1.1	0.9
CaO/SiO_2 ratio	0.16	0.34	0.29	0.30	0.06	0.33

* ND means Not Detectable as determined by X-Ray Fluorescence (XRF) analysis using a rhodium x-ray tube; characteristic x-rays were collected by a lithium drifted silicon detector.

From the data in Table IV the following is noted:

- All the poured slag densities were higher than the calculated composite feed density, and B5 density was the lowest. Fused silica has a density of about 2.01 g/cm^3 [4]. As metal-oxides of higher density are mixed with it the density increases. Thus the high SiO_2 content in the slag of batch B5 explains its low density.

- From the primary oxides analysis we can also see that the dominant ceramic alloying constituents were CaO and SiO_2. Worth noting is that batches B9 and B14 had the lowest SiO_2 concentration, near equal CaO/SiO_2 ratios, and the highest throughput. One should not discount the presence of Na_2O as helping to improve slag conductivity thereby aiding in throughput.

CONCLUSION

This study has shown that processing inorganic, non-metallic simulated radioactive wastes and forming glassy slags of various compositions can be done effectively, although there were some difficulties when nearly pure silica was fed. Varying instantaneous waste feed compositions can decrease throughput and cause plasma torch operating difficulties. The Archimedes feeder can provide adequate mixing of many feed wastes but sand particles can potentially separate to the trailing edge. To counter feeder segregation, feeding could be done using a second feeder and metering the feed into the centrifuge better. Another issue is that the materials were dumped from 200-liter drums right into the rear of the feeder. This may be the primary cause of the segregation of the sand that caused the increase in transferred voltage seen in several batches. The problem is that sand, of high surface area, distributes over the surface of the centrifuge bottom, fuses, and causes torch transferred voltage to increase until the sand is melted and mixed with the other oxides in the slag. It is preferred that an all silica feed be alloyed with CaO or Na_2O to prevent extremely high operating voltages. The ratio of CaO/SiO_2 for these types of wastes should be about 0.30, and at least greater than 0.16. Another important issue is to mix the ceramic ingredients chosen as well as possible. Feeds containing up to 65% silica that are chemically associated with CaO and Na_2O in the form of glass have no adverse effect on plasma torch performance and throughput. Heat losses in the PPC varied little with composition, ranging from 60-74% of the input power. The densities (specific gravities) of the slag from all the pour batches were higher than calculated feed densities. Batch B5 had the lowest density due to having the highest silica content and lowest metal-oxide alloying constituents.

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