COLD CRUCIBLE INDUCTION MELTER PROTOTYPE AT THE IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY

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ABSTRACT

Engineers at the Idaho National Engineering and Environmental Laboratory (INEEL), in collaboration with Russian scientists from the Electrotechnical Institute and Khlopin Radium Institute in St. Petersburg, have designed, constructed, and operated an alternative technology for converting highly radioactive waste into glass for final disposal. This technology, a cold crucible induction melter (CCIM), has the potential to significantly simplify and reduce the cost of waste stabilization for some of the most challenging radioactive waste streams within the Department of Energy (DOE) complex, as well as throughout the world. The INEEL CCIM technology is essentially a noncontact melter design, with water-cooled walls, that uses a variable frequency power supply to drive an external induction coil to efficiently heat the target waste material. It includes both liquid and solid feed capabilities. Because the CCIM does not use refractory, and can safely operate at temperatures in excess of 2000°C, many of the limitations of conventional ceramic-lined electrode-type joule-heated melters (JHMs) are mitigated. This provides significantly improved adaptability and flexibility for processing radioactive waste, while producing a high quality final waste form. Consequently, CCIMs are expected to provide a service life that is much longer than conventional melters, thus reducing capital, maintenance, and decommissioning costs. The INEEL CCIM prototype is a one-of-a-kind system in North America that is part of a testbed, which includes an integrated offgas control and monitoring system that is fully compliant with the Environmental Protection Agency (EPA) Hazardous Waste Combustor (HWC) Maximum Achievable Control Technology (MACT) Rule requirements. Accordingly, the INEEL CCIM system can be used to process waste simulants for fully characterizing and understanding the capabilities of the CCIM technology to determine if it is a viable alternative for the next-generation vitrification concepts.

INTRODUCTION

The United States and Europe currently use JHM technology to convert highly radioactive waste into glass for final disposal. This technology passes electricity between water- or air-cooled electrodes submerged in a molten pool of glass in a refractory brick-lined chamber. Although fairly reliable, this technology is limited by the susceptibility of the refractory bricks and metal electrodes to corrosion and melting. In addition, the glass chemistry must be carefully controlled or it can exacerbate material problems that lead to electrical short-circuiting and glass leaks, which have caused failures in test melters.

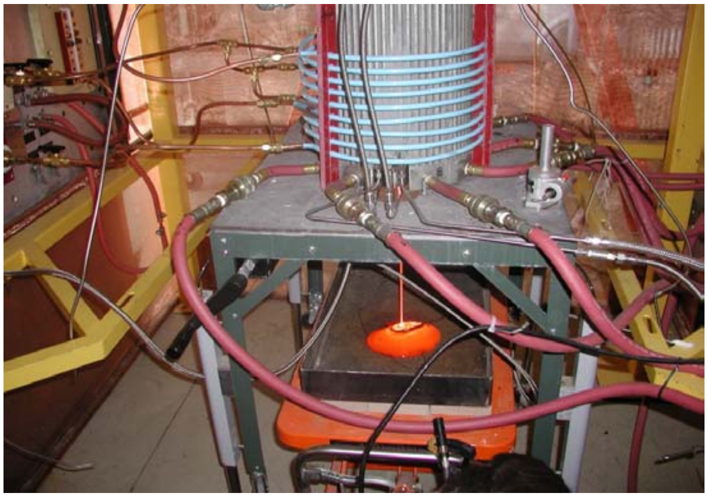
Fig. 1 INEEL CCIM glass pour, September 2003

Recent DOE studies [1,2,3] have identified the need for a more rugged glass melter with a wider operating range. Russian researchers also point out that a new melter concept will be needed to process some of the unique high-activity waste still in storage and unsuitable for processing with the current JHMs at Mayak.[4] In collaboration with Russian colleagues and the University of Montana, a new CCIM-technology test facility was designed and fabricated at the INEEL. The facility has a novel stainless steel segmented crucible with bottom-draining capability, driven by a 60-kW electrical (kWe) variable-frequency power supply, with a fully MACT compliant offgas system, that is capable of processing both liquid and solid feeds. See Fig. 1.

The CCIM inductively heats the melt inside a water-cooled, segmented crucible that is essentially transparent to the magnetic field. This allows the molten material to be maintained at temperatures above 2,000°C, while contained within the solid shell or "skull" of the feed composition. The skull isolates the melt from the crucible, eliminating the need for glass-contact refractory and electrodes, as well as the corrosion and temperature limitations of those materials.

This paper describes the design basis and approach for the major system components including the induction power, mechanical, offgas, cooling, and instrument and control systems. Additionally, it discusses our experiences in start-up and operation of the INEEL CCIM system.

INDUCTION POWER SYSTEM

The induction power system consists of three major components: a radio frequency (RF) generator, a coil transfer relay, and a primary induction coil. The system configuration and each component perform distinct functions and must respond to certain design requirements to ensure overall system performance. Thermodynamic calculations, systems issues, safety concerns, and operational considerations are all factored into system performance requirements. The primary requirements for the CCIM Induction Power System are:

- Nominal maximum output power of 60 kWe, with ability to operate between 10 and 60 kWe.
- Frequency range: 200–400 kHz, 2.0–4 MHz; ± 10%.

Design of the electromagnetic induction power system followed a series of specific intermediate designs and calculations. First, the electrical power of the RF generator was specified based on desired melter throughput and calculated heat loss. These same calculations yielded desired external crucible diameter and desired height of melter volume. Second, a design-basis value of melt resistivity was selected. A survey of various data on borosilicate glasses at nominal operating temperatures of 1,050–1,250°C revealed a range of resistivity values of 2 ohm/cm to 10 ohm/cm. A value of 6 ohm/cm was selected as the design basis for the CCIM prototype.

The next step in the design of the electro-magnetic induction power system was to determine an appropriate operating frequency that provides an optimal melter throughput. It has been determined empirically [5] that for cylindrical melters the diameter should be approximately a factor of 3.8 times the skin depth (represented as δ) at the nominal frequency of operation. The skin depth is calculated:

$$\delta = 5*10^3 (\rho/\mu f)^{1/2} \qquad \text{(Eq. 1)}$$

where
ρ = electrical resistivity in ohm/cm of the melt
μ = magnetic permeability of the melt
f = frequency of the energy being applied in hertz.

Accounting for the 3.8 factor and rearranging, optimal frequency of operation can be determined with:

$$f = 3.6*10^8 (\rho/\mu d^2) \qquad \text{(Eq. 2)}$$

where
d = diameter of the melted volume.

After specification of the power level, physical diameter, coil height, and computation of the optimal operating frequency, it is possible to calculate the number of amp-turns of the primary inductor. The approach used in the CCIM prototype design was outlined by Baker [6] in a classical induction melter paper published in 1957. Briefly, we performed the following procedure:

- Calculate the total magnetic flux using previously determined values for power, diameter,
- resistivity, height, and magnetic permeability of molten glass.
- Calculate the coil voltage for various numbers of coil turns using the total flux value and accounting for skin depth within the coil material.
- While accounting for external reluctance, compute coil current for each turn's configuration.
- Select the number of turns compatible with physical constraints and current capability of the RF source and transfer relay.

These calculations resulted in the selection of a six-turn active coil configuration.

The next step in the process was the physical design of the primary induction coil. The total inductance and leakage inductance of two-coil geometries were measured: a single six-turn coil, and two three-turn coils in parallel. The former operates at higher voltage, and the latter operates at higher total current. Both provide the same number of amp-turns calculated from the coil design procedure outlined in the previous paragraph. Both coils were considered candidates, with final choice dependent upon selection of a commercial RF power generator and its ability to generate and deliver energy at the nominal operating frequency to one or both coils with their respective total inductances.

Finally, an energy-transfer system was designed. Conventional induction melters use a fixed primary inductor and vary the vertical position of the crucible within the induction field to focus the energy deposition depending on operations such as startup, feeding, and glass pouring. This involves using a piston or screw device, which adds complexity to the system, particularly for radioactive application. Instead, the INEEL system employs an innovative coil design that allows energy deposition to be focused at the desired position by activating specific sets of coil turns. The final design for the coil to be used in an actual radioactive environment will be a focus of future research.

Upon completion of coil design, an RF generator was specified. Technical specifications resulting from the above calculations included power level and output current, induction frequency and load inductance, and interface compatibility with the novel coil energy transfer system. A Taylor-Winfield Thermionic C-6000 RF generator was selected. The Thermionic C-6000 electronic induction RF generator consists of three major subsystems, including a high-frequency generator chassis, an enclosed plate transformer unit, and a control workstation. The high-frequency generator chassis contains a twin-tube tuned-grid tuned-plate Class-C triode-type oscillator operating at a nominal output power of 60 kWe. Also contained in the generator chassis are primary and secondary cooling loops. The primary de-ionized water-circulation system provides cooling for the tube anodes, high-voltage oil-filled capacitors, and power inductors. Cabinet air is cooled as necessary via a water-to-air heat exchanger. The secondary system consists of a propylene glycol circulation loop to an external chiller unit. The enclosed plate transformer supplies a nominal 15 kV of 3-phase power to the generator chassis. 480-V input to the plate transformer is switched by a variable duty-cycle phase-controlled firing system in the generator chassis. The 15-kV transformer output, which is rectified with a 3-phase, full-wave bridge in the chassis, is subsequently filtered to provide low-ripple direct current to the triode oscillator. The control workstation is a stand-alone panel, providing front panel monitoring of power, plate and grid current, anode voltage, and interlock status.

During the design process, it was determined that the C-6000 is compatible with two three-turn inductors in parallel, which is one of the two primary inductor candidate configurations identified and characterized earlier. The induction coil is made from 0.95-cm copper tubing, with a nominal internal diameter of 33 cm.

The resulting system provides induction power of up to 60 kWe, at a nominal frequency of approximately 2.6 MHz which is within 5% of the optimal induction frequency. Power is adjustable via the control panel, or the computer interface, continuously over the range of 10–60 kWe. The generator frequency can be reconfigured (i.e. modification of specific inductance and capacitance values) to provide at any frequency over a range of 200–400 kHz or 2–4 MHz. Similarly, the induction coil can be reconfigured to transfer energy over these frequency ranges. Efficiency will vary, however, as throughput rates are optimized only at frequencies related to melt resistivity. The generator is capable of providing power to a wide variety of inductor designs. Note that operation between 400 kHz and 2 MHz is prohibited for commercial operation in the United States. Functionality is included to continuously monitor operating parameters within the power supply system and provide automatic shutdown under preset conditions. In addition, multiple and redundant safety interlocks are provided to protect operators.

MECHANICAL SYSTEM

Key mechanical components of the CCIM system include the crucible, the glass drain system, and the offgas lid. Extensive structural-support components have been designed, fabricated, and procured as necessary for the primary crucible and ancillary systems; however, these components are not discussed in this paper.

The cold crucible provides containment for the material fed into the induction field, while cooling the walls to provide thermal insulation for maintaining structural integrity. The cooling fluid used for this system is de-ionized water. As a result, the cooling system must provide adequate temperature control for the crucible walls while ensuring that the cooling water does not reach its boiling temperature. This must be accomplished while maximizing the energy deposition from the induction coil into the melt chamber formed by the crucible. Several factors impact the energy deposition into the melt, including crucible materials of construction, crucible wall configuration to minimize eddy-current paths, crucible wall configuration to provide an efficient induction-energy path, crucible bottom configuration to minimize eddy-current paths, and relationship of the induction coil geometry to the crucible geometry. The crucible must also accommodate the glass drain system that is necessary. Similarly, the crucible must provide appropriate interface with the offgas lid and associated feed, offgas, and other penetrations.

The basic geometry of the crucible is determined by three main factors: the power level of the high-frequency generator, the relative magnetic permeability of the melt, and the electrical resistivity of the melt. The last two factors—magnetic permeability and resistivity—are particularly critical in optimizing the overall system efficiency, because they drive the coil geometry and operational frequency for a given power level. We selected nominal values for these material properties that are expected to be representative of the waste surrogates to be processed in the CCIM, based on previous research conducted within DOE as well as by the Russian scientists with whom the INEEL collaborates. Specifically, the relative magnetic permeability is assumed to be unity, and the resistivity is assumed to be 6 ohm/cm. Additionally, a 60-kWe high-frequency generator was purchased, thus establishing the values for the three critical parameters. Since the power deposited into the melt is strongly dependent on the ratio of the diameter of the melt volume to skin depth (d/δ), and skin depth is determined by the permeability, resistivity, and frequency of operation, an iterative approach was used to arrive at a nominal optimal diameter of 26.7 cm for the melt chamber. This, in turn, determined the overall crucible height of 40.6

cm, which provides appropriate clearance from the induction coil to minimize eddy-current losses. Industry practice typically uses one coil radius as a rule of thumb for adequate clearance from the top or bottom of the coil.

As previously discussed, the greatest energy flux into the melt occurs within the skin depth, which is measured from the inside diameter of the induction coil. Consequently, the efficiency of the system is maximized when the space between the inside diameter of the coil and between the outside diameter of the melt cylinder is minimized. For this project, the crucible is constructed of 1.27 cm diameter 304 stainless steel cooling tubes with 0.071 cm wall thickness. This size was considered the smallest that could be reasonably machined and welded into a useable assembly based on the designated crucible diameter. One key factor that impacts this choice is the necessity to maintain a fixed separation between the individual cooling tubes for their entire length to reduce the eddy-current losses, thus increasing the energy deposition into the melt volume. Experimental results by U.S. and Russian researchers show that the crucible wall should be constructed using at least 24 sections with nominal separation gaps of 1–2 mm to allow efficient energy deposition. Comparative testing of 4-segment versus 24-segment crucibles showed projected increased melt rates of more than 90% at 60 kWe [7].

Materials of construction are a key consideration when optimizing an induction melter system. The material commonly used in industry for water-cooled induction heating systems is copper. This is due to the low electrical resistivity of copper and to the high thermal conductivity. As a comparison, nominal values for electrical resistivity of copper versus 304 stainless steel at 20°C are 1.7×10^{-6} ohm/cm and 60×10^{-6} ohm/cm, respectively. Similarly, the thermal-conductivity values at 20°C are 340 W/m-K versus 14 W/m-K, respectively. However, for applications involving treatment of radioactive waste streams, the secondary products generated during processing can be highly corrosive, and materials such as stainless steel, Inconel, or Hastelloy are more suitable, regardless of the electrical losses. Although virtually all of the laboratory-scale crucibles being operated by Russian scientists at the Khlopin Radium Institute and at the Electro Technical University are constructed of copper tubing, the units at the Radon Production Association facility, which are used to process actual radioactive waste, use all stainless steel construction.

The most important function of the crucible is to provide adequate cooling to maintain a slag layer to protect the crucible materials while not allowing the cooling water to be overheated and boil. Analysis of the overall heat balance for the crucible, mating offgas lid, and bottom drain are fairly complex, even for steady-state operations. Simplifications were made for the initial design that provide appropriate conservatism. Beginning with Fourier's Law:

$$Q = -k\nabla T \qquad \text{(Eq. 3)}$$

$$Q = -k(\partial T/\partial x + \partial T/\partial y + \partial T/\partial z) \qquad \text{(Eq. 4)}$$

Combining this with the energy conservation equation (heat diffusion) yields:

$$\partial/\partial x(k\partial T/\partial x) + \partial/\partial y(k\partial T/\partial y) + \partial/\partial z(k\partial T/\partial z) + q' = \rho c_p \partial T/\partial t \qquad \text{(Eq. 5)}$$

For one-dimensional steady-state analysis of a radial system, this partial differential equation can be solved using a a thermal-resistance approach that results in the following governing equation:

$$q = (T_1 - T_{4,\infty})/\{[\ln(r_2/r_1)/2\pi k_{melt}] + [\ln(r_3/r_2)/2\pi k_{slag}] + [\ln(r_4/r_3)/2\pi k_{ss}] + [1/2\pi r_4 L h_{water}]\} \qquad \text{(Eq. 6)}$$

where

$T_{4,\infty}$ = temperature of melt

T_1 = bulk temperature of cooling water

r_1 = distance from crucible center line to center line of skin depth
r_2 = distance from crucible center line to interface between melt and slag layer
r_3 = distance from crucible center line to interface between slag layer and cooling tube wall
r_4 = distance from crucible center line to interface between tube wall and cooling water
k_{melt} = average thermal conductivity of melt
k_{slag} = average thermal conductivity of slag
k_{ss} = average thermal conductivity of stainless steel
h_{water} = convection coefficient of water flowing in cooling tubes.

The crucible designed for INEEL CCIM consists of three primary components: the lower manifold, the cooling tubes, and the upper manifold, all constructed of 304 stainless steel. The lower manifold, which provides the supply and return lines for the cooling water, is a 29.8 cm diameter by 5.08 cm deep hollow disk segmented into eight separate sections. The manifold is segmented because the lowest active coil of the inductor is approximately coincident within the same plane as the upper plate of the lower manifold. This is part of an innovative energy deposition scheme that concentrates the induction energy to appropriate locations during various operational phases. The contact surfaces between the segments are coated with a nonconductive high-temperature ceramic that provides electrical isolation. This approach helps minimize the eddy-current losses in the lower manifold. Each pie-shaped segment consists of two chambers. The lower chamber has greater volume than the upper chamber, which ensures constant, full flow in the upper chamber and cooling tubes. The lower manifold also includes a specially designed bottom drain interface slot that provides for efficient location, ease of maintenance of sacrificial components (the drain tube), peripheral cooling, and ease of replacement of the bottom drain.

The upper manifold is a 2.2 cm deep doughnut-shaped hollow disk with a 41.9 cm outside diameter and a 26.7 cm inside diameter, which provides an interface with the offgas lid. The configuration of the upper manifold is designed to provide an inside volume the same as the cooling tubes to ensure full flow and minimize accumulation of air/steam bubbles in the cooling system. The upper surface of the manifold has six 0.965 cm diameter by 3.81 cm long threaded studs welded on a 39.4 cm diameter bolt circle for mating with the offgas lid. The flow chamber is internally segmented to provide flow control for the cooling water. The upper manifold also contains relief valves to ensure that the crucible could never be over-pressurized due to blockage and steam buildup.

The cooling section consists of sixty-four 1.27 cm diameter by 40.6 cm long tubes attached to the upper and lower manifolds on a 27.3 cm diameter center line, providing a nominal longitudinal tube spacing of 1.5 mm. The isolation gap between the individual cooling tubes is sealed from the outside using a ceramic putty specifically formulated for such applications. The putty is placed on the outside of the cooling tubes because the crucible is operated under a slight vacuum due to the offgas system. Placing the putty on the outside of the tubes eases installation while minimizing flaking into the melt. Figure 7 shows the crucible assembly installed in the prototype.

During operation, the crucible will contain up to 3.75 gal (14.2 L) of melt, while maintaining appropriate temperatures in the crucible walls. Based on calculations, the crucible will be able to effectively function at full generator power (60 kW) and up to 2,000°C. The designed residence time of the water in the crucible will result in a heat flux into the cooling water at this operating level, which will only increase the temperature by about 20°C. At nominal operating levels (20 kW), only a 7°C increase is expected. These calculations are consistent with actual experience in the Russian melters, although the melter configurations are different. The induction coil is separated from the crucible by a 2.54 cm air gap and a voltage resistant clear plastic material.thick fused quartz tube, thus providing only 0.63 in. (1.6 cm) of dead space between the coil and melt volume, using more than 77% of the skin depth energy.

GLASS DRAIN SYSTEM

A key driver for the glass drain system is that it is capable of evacuating the entire crucible. For this reason, a bottom draining configuration was developed. During normal glass draining, the drain tube needs to be heated to between 900°C and 1,000°C. This can be achieved with external heating, but a unique feature of this drain is its location. It is positioned such that the drain tube is centered within the "skin depth", the zone in which 77% of the induction energy is deposited. This provides some incidental induction heating of the drain tube, while locating it at a point where the energy flux is the most consistent and thus, predictable. A separate induction energy source can be used as the heat source for the bottom drain, but this adds complexity to the overall design of the drain. Because this drain is located in the skin depth and is a solid conductive material, the induction field couples with the bottom drain, augmenting the heating for the drain. This brings the average temperature of the drain tube to about 300°C during operation. Additonal heating is needed to reach the desired glass draining temperature range. Significant improvements have been made using advanced ceramics and vapor deposition techniques to manufacture heaters that can achieve and operate at the temperatures required for a molten glass drain system. A novel heating sleeve was designed and manufactured using these advanced technologies for the CCIM project. Resistance heating is accomplished by introducing an electric current into a pyrolitic graphite trace that is vapor deposited onto a boron-nitride ceramic substrate. The heating sleeve is designed to provide 1.5 kW, which, coupled with the induction energy, heats the drain tube to the necessary temperature within the desired timeframe.

The bottom drain assembly is constructed almost entirely of Inconel 693. This is a relatively new alloy that provides comparable corrosion resistance to Inconel 690, the more commonly used material, while offering much better machining capability. This material allowed complexities in the configuration of internal components to be more effectively manufactured. The bottom drain is a 6.35 cm diameter assembly that consists of five main components: outer guide sleeve, cooling spool, drain tube, heating sleeve, and bottom retainer. The assembly is held in place in the crucible by close fit into an interface slot with a retainer lip on the crucible assembly. Contact with the walls of this interface slot provides cooling for the outer guide sleeve, where additional valve-controlled cooling air is provided as needed to achieve desired temperatures. The internal configuration of the drain assembly has been designed to provide maximum heating capacity while minimizing cooldown time. It is capable of achieving temperatures nearing 1,500°C due to the innovative combined heating scheme. For nominal pouring applications of 1,000°C, the drain tube is able to heat up from ambient temperature in less than 2.5 minutes, assuming 50% efficiency. The internal components of the bottom drain include heat-transfer enhancing features that provide reasonably high efficiency (i.e. 86%) for the compactness of the design, at a nominal convection coefficient of 100 W/m^2-K, which is easily achievable using compressed gas flow (forced convection). This allows for rapid cooling of the drain tube such that complete flow shutoff can be achieved within 2 minutes. While an external mechanical sliding closure has been provided, it may prove to be unnecessary.

OFFGAS LID

The offgas lid is designed to operate at a nominal plenum temperature of 600°C to minimize acid reflux on the crucible and in the offgas system. During operation a slight vacuum (i.e. 1-2 kPa) is maintained while providing positive control of air in-leakage to approximately 5 scfm. The offgas lid is a chambered "top-hat" design, with angled upper corners and a mating flange forming the "brim" of the top hat. The complete outer shell, including the bottom flange, is constructed of 304 stainless steel, while the inner shields, inner flange, and penetration tubes are of Hastelloy. The angled surface is designed such that three 5.08 cm view ports can be used to see the entire melt surface and crucible walls above the melt line. The complete lid assembly, including all flanged port connections, weighs less than 37.3 kg, is easily installed and removed, while providing the primary interface between the crucible and many other ancillary components.

The offgas lid interfaces with the offgas system via a 14.0 cm duct. It also includes a 5.08 cm dry feed port, 2.54 cm wet feed port, and four 2.54-cm thermowell ports for thermocouple applications. All interface ports are flanged as appropriate to interface with mating systems. The offgas lid assembly has a 26.7 cm inside diameter and is 15.2 cm high on the inside. The bottom flange is an 45.7 cm diameter ring, with mating holes for the crucible upper manifold bolts located on a 39.4 cm diameter bolt circle. It also contains eight cooling air supply and return ports located around the perimeter just above the bottom flange. A graphol gasket is applied between the interface surfaces to help seal and control air in-leakage.

One of the primary benefits of a cold crucible system is the absence of refractory in the melter. Unfortunately, most offgas lids for melters contain a layer of refractory to provide insulation as well as corrosion protection for the material. This limits the application of the CCIM system and defeats the purpose of some of the research of this project. Therefore, an innovative design was developed for the offgas lid that eliminates all refractory while protecting the materials and maintaining outer temperatures at 50°C or less. A series of heat shields are used to form chambers within the offgas lid, some of which are air-cooled. The design was developed by modeling the lid for radiant heat transfer using a wide-band exponential model for a CO_2-H_2O-Soot offgas composition at 600°C. A method that approximates the inside of such a chamber using a speckled furnace gray model was employed [8]. The top of the offgas lid was angled to minimize hot spots that generally occur at corners in heated ducts. The exact angle was selected such that full view of the melt surface could be achieved. All penetrations into the inner heat shield are seal-welded to ensure that the offgas cannot enter the cooled chambers and precipitate. Additionally, an extensive literature search was performed to locate experimental values for emissivity of various materials at various temperatures and in various conditions. The analysis showed that the design goals could be met with this approach if a convection coefficient of 195 W/m^2-K could be achieved in one chamber, which is quite possible using compressed gas forced convection. Operational temperatures above the nominal 1,200°C will require additional air in-leakage and increased cooling air flow, which are designed to be valve-controllable for the specific need. The heated cooling air is vented to the offgas system to the reheater section prior to entry into the system's high-efficiency particulate air (HEPA) filters, providing better overall energy efficiency.

Since no refractory is used, the inner materials must be protected from the corrosive environment generated when processing certain types of waste. To that end, a high-temperature advanced ceramic material was identified that is specifically formulated to match the thermal expansion of Hastelloy, and is easily applied to the surfaces. This coating was also accounted for in the thermal-analysis model, since it impacts the emissivity of the material.

FEED SYSTEM

The feed systems for the CCIM were designed to handle solids, liquids, and slurries. Separate systems convey dry or wet materials to the melter plenum. The feed lines drop straight into the melter, precluding holdup, and the feed lines may each be isolated. The solid feed system has been designed to handle glass frit, glass- forming chemicals, and granular or powdered sugar (used as a chemical-reducing agent). The stainless steel liquid feed system will handle most corrosive nitric acid-based solutions. A mixer located in the feed tank will maintain any slurries used as a feed as in suspension.

The solid feed system consists of a K-tron Twin Screw Volumetric Feeder (Model K2 MV-T35). A variety of feeder screws can accommodate various bulk materials. The various screws can provide feed rates of solids from 1.25–2,500 L/hr (1.7–3,400 kg/hr). All parts in contact with the material being fed are stainless steel. An oversized feed hopper (60 L) will ensure that the nominal solids feed rate of 3–10 kg/hr can be maintained for several hours without recharging the feeder.

The liquid feed system has the capacity to feed a solution or slurry through stainless steel lines to the CCIM at a rate up to 20 L/hr using a Masterflex L/S pump. The feed tank has a capacity of 200 L. An impeller in the tank provides mixing to maintain the feed as a homogenous liquid or suspended slurry. The solution is pumped through a line and recirculated back to the feed tank, providing a constant feed supply to the feed pump while helping to maintain a well-mixed feed. The feed pump for the liquid system is capable of pumping up to 204 L/hr. Feeds are deposited in the center of the melt, in line with a view port and monitoring camera, which allows studies on maximizing melter throughput and visual observation of surface cover and turbulence.

OFFGAS SYSTEM

The CCIM offgas treatment system is designed to provide the necessary control of offgas emissions from the CCIM as well as a test bed for evaluating offgas system unit operations. The offgas system is a smaller-scale working model of a full offgas system that would be required in a full-scale waste treatment facility to meet HWC MACT standards. The primary design drivers included:

- Control a slight vacuum in the CCIM plenum space during operation.
- Enable testing and demonstration of the complete treatment system model, including evaluations of offgas composition, flow rate, and conditions, and of key offgas system unit operations, including NO_x reduction, organics oxidation, acid gas scrubbing, particulate filtration, and mercury control.
- Control specific air pollutants in the CCIM offgas to levels expected to meet applicable regulations, assuming that the HWC MACT standards would apply to a CCIM system designed to treat INEEL sodium bearing waste (SBW).
- Ensure worker and facility protection during testing from various hazards in the feed or offgas, including high temperatures, particulate matter, Cd, Hg, NO_x, and CO.

Various options for high-performance offgas systems for mixed waste treatment are grouped into four general approaches [9]:

- Dry systems (partial cooling, dry particulate filtration, and dry acid gas scrubbing)
- Dry-wet systems (partial cooling, dry particulate filtration, and wet acid gas scrubbing)
- Wet-dry systems (total quench and wet scrubbing for both particulate matter and acid gases, followed by dry final particulate filtration)
- Entirely wet systems (total quench and wet scrubbing for both particulate matter and acid gases).
- Dry offgas systems avoid any liquid secondary waste streams, which is a requirement at some facilities. Acid gas scrubbing is accomplished by dry adsorption of acid gases onto hydrated lime sorbent injected upstream of the baghouse and collected in the baghouse. But entirely dry offgas systems require operator control and maintenance of dry sorbent feed systems. This is not possible in mixed waste systems, where workers may be exposed to radioactivity.

Each of the four general types of offgas systems has several distinct advantages and disadvantages because of the differences in how each type addresses particulate matter and acid gas control. After considering these advantages and disadvantages, a wet-dry system model was selected for the CCIM test system.

Wet-dry systems have been used more widely in mixed waste treatment systems than any other approach. The offgas in a wet-dry system is rapidly cooled, and all contaminants, including particulate matter, radionuclides, toxic metals, and acid gases, are wet scrubbed. These produce a single secondary aqueous mixed waste with some suspended and dissolved matter. After wet scrubbing, the offgas is reheated (to prevent moisture condensation in downstream control equipment) and dry-filtered to remove trace-level particulate matter and other contaminants.

Entirely wet systems are commonly used in many thermal processes including hazardous waste incineration and some mixed waste incineration systems such as the Toxic Substances Control Act Incinerator. Wet systems do not include postscrubbing reheating and HEPA filtration, a standard for most radioactive and mixed waste handling and treatment processes. Wet-dry systems provide very high and redundant removal efficiencies for pollutants subject to the HWC MACT standards. The CCIM offgas system has the following performance capabilities:

- Reduces NO_2 levels in the offgas to less than 100 ppmv; reduces NO levels to less than 1,000 ppmv.
- Meets all the HWC MACT standards.
- Operates stably within temperature, excess oxygen, and offgas composition requirements, with a 50% increase in the offgas flow rate and with a turndown in the outlet offgas to 10% of the design offgas flow rate.
- Rapidly cools, within less than 1 second, the hot thermal-oxidizer offgas to the offgas dew point. The rapid cooling minimizes catalytic dioxin/furan formation by limiting the residence of the offgas in the catalytic dioxin-forming temperature range of 200–400°C.
- Achieves 99.95% removal of Hg from the offgas, when the input total Hg concentration is about 40,000 μg/wscm, regardless of whether the Hg is present in the gas as elemental Hg or $HgCl_2$.
- Uses engineered or administrative controls to avoid fires in the carbon bed.

The primary components of the CCIM offgas system are shown in Figure XX with one key difference - the cyclone, ME (mist eliminator), and HEME (high-efficiency mist eliminator) have now been replaced with a high-efficiency Wet Electrostatic Precipitator (WESP), which is described below, as are the other system components.

Heated Duct to the Thermal-Reaction Chamber

The heated Inconel duct enables the flow of offgas from the melter to the thermal- reaction chamber. Often, in traditional JHMs, this duct includes a "film cooler" designed to blend air or steam with the melter offgas to minimize deposition of particulate matter in the melter offgas on the interior walls of this duct, eventually plugging the duct. For the CCIM test system, this duct is heated to at least 800°C using a high-temperature electric-resistance heating element to heat the duct wall. This will cause any particulate depositions to melt enough to flow out of the end of the tube and back into the melter. This also avoids dilution of the melter offgas typically by a factor of 5–10 times, thereby minimizing the downstream offgas flow rate and sizes of downstream offgas equipment.

Thermal-Reaction Chamber

The thermal reaction chamber performs nonselective, noncatalytic, thermal NO_x reduction similar to more traditional fossil-fuel-fired staged combustion, except that energy required to heat and maintain the gas at NO_x reduction reaction temperatures (around 1,000°C) is provided by electric heating. The heated duct at the inlet of the thermal-reaction chamber preheats the melter offgas to about 830°C. The offgas is further heated in the first stage of the thermal-reaction chamber by an electric tube heater to a maximum of about 1,150°C. The tube heater has a maximum temperature rating of 1,200°C. The tube heater and the reaction chamber are sized and configured to provide adequate heat transfer surface area, mixing, and residence time to heat and maintain the gas at design temperature for at least 2 seconds of residence time. Methane is added to react with oxygen and NO_x in the inlet gas. NO_x reduction reaction products include N_2, CO, CO_2, and H_2O. The stoichiometry is maintained oxygen-deficient to favor NO_x-reduction reactions. Because of the reducing stoichiometry, this section is called the reducing section.

The second stage of the thermal-reaction chamber includes evaporative cooling of a water spray into the offgas to cool the NO_x-reduced offgas to about 840°C. The cooled-gas exit temperature is the highest allowed temperature at this point in the offgas system that ensures the resulting gas temperature downstream of the oxidizer section is acceptable.

In the oxidizer section, air is added to provide oxygen for complete oxidation of CO and other products of incomplete combustion that were formed or remain in the reducing-section offgas. The oxidizer section is designed consistent with typical efficient thermal-oxidizer designs, with a residence time of at least 2 seconds at a gas temperature of at least 1,000°C. To avoid excessive thermal NO_x formation, the water spray in stage two keeps temperatures under 1,000°C.

Offgas Quench Section

Following thermal oxidation, the offgas is cooled (quenched) by water-spray evaporation to the adiabatic dew point of the offgas with the added evaporated water. This section is constructed of Hastelloy steel to tolerate the initially high offgas temperature and to provide good resistance to corrosion at both high and low temperatures.

Wet Scrubber System

Immediately following the temperature quench stage, the offgas will pass through a wet scrubber designed to remove acid gases and some of the residual particulate matter. The scrubber system includes the high performance scrubber itself, the scrub tank that collects and holds scrub solution, a WESP, and the scrub solution recirculation system. The recirculation system includes a pump, valves, and piping to recirculate scrub solution to the spray quench nozzles in the offgas quench section, to the scrubber, and to WESP washing nozzles.

The scrubber system is a high-performance scrubber, using added energy input in the form of atomizing air and pressurized scrub solution to (a) aerosolize and mix the scrub solution with the offgas for efficient acid gas and particulate scrubbing, and (b) provide some suction on the offgas as it flows through the scrubber. This is different from most traditional venturi scrubbers, which use energy from sometimes high-pressure drop of the offgas itself to aerosolize and mix the scrub solution with the offgas. Avoiding high offgas pressure drops in the offgas system is desired to minimize high vacuums that cause:

- Higher ambient air in-leakage.
- Higher adiabatic water dew-point temperatures and higher water content in the offgas.
- Higher volatility of mercury and other more volatile species.
- Higher induced draft fan requirements.

The WESP, a key component of the wet scrubber system, uses a specially designed high-voltage grid plate to provide extremely high-performance particulate matter removal, almost eliminating the need for HEPA filtration. The unit includes a self-cleaning technology, which allows much closer grid placement and much higher voltages for improved removal of particulate matter.

Offgas Reheater

After the WESP, the offgas is reheated and slightly diluted by blending with preheated air to raise the offgas mixture temperature above its dew point. This reheat design is unique compared with other designs that simply use electric- or steam-heated elements to directly heat the offgas. In this design, the offgas is indirectly heated by first preheating ambient air to about 500°C and then mixing the preheated air with the offgas. This design is better for mixed waste systems because the heating elements are not exposed to the offgas and because the offgas temperature need not be raised as high as otherwise—for the moisture content of the offgas is lowered slightly by dilution from the air. The amount of dilution is small, typically well under 10%.

Offgas HEPA Filter

The HEPA filter removes particulate matter from the offgas downstream of the reheater. The amount of particulate matter remaining in the offgas at this point is low, because most of the matter is removed in the quench and scrubber sections. A new prototype HEPA filter designed for easier replacement in a mixed waste system will be evaluated in this test system.

Activated Carbon Bed for Mercury Capture

The granular activated carbon bed is a packed bed of 1.5–3 mm sulfur-impregnated activated carbon particles. Sulfur-impregnated activated carbon has been determined in several studies at the INEEL and elsewhere [10, 11, 12] to be the best technology for capturing mercury, regardless of speciation, in mixed waste offgas. Several remaining issues relating to mercury capture with sulfur-impregnated carbon that can be evaluated in this test system include (a) potential capture efficiencies and loading based on bed design and operating parameters; (b) capture of other potential trace-level pollutants including volatile and semivolatile organic compounds, dioxins, and halogen compounds; and (c) leachability and stabilization characteristics of spent carbon.

Induced Draft Fan

The induced draft fan provides the motive force to draw the offgas from the CCIM offgas plenum through the offgas system. Since offgas flow rates may vary widely under different test conditions, the induced draft fan is equipped with a variable-speed controller, flow-/pressure-control dampers, and upstream, damper-controlled addition of ambient air to augment and control the total gas flow rate and vacuum. The offgas is then exhausted through a dedicated stack.

Figure 2 and Fig. 3 show the various offgas components and how the offgas system interfaces with the melter.

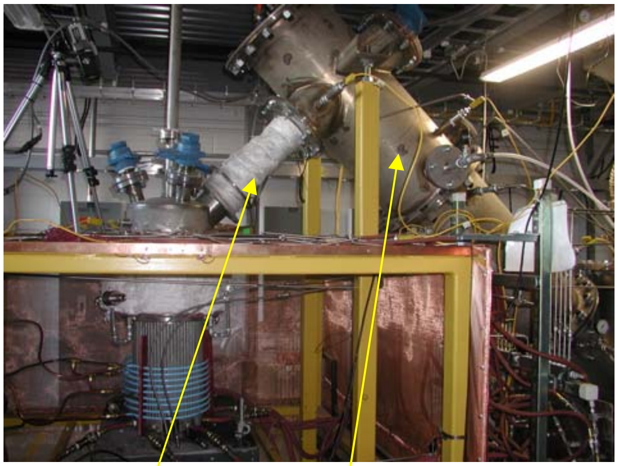

Fig. 2 Heated duct and thermal reaction chamber

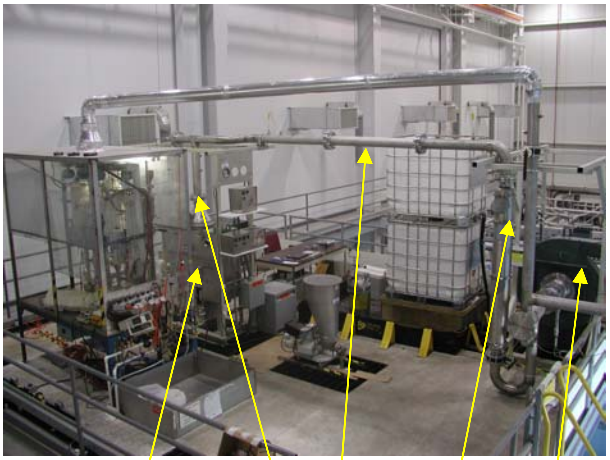

Fig. 3 WESP, Reheater, HEPA, Carbon Bed, ID Fan

COOLING SYSTEM

The cooling system for the INEEL CCIM prototype consists of three primary subsystems: generator cooling, crucible cooling, and emergency cooling. For normal operations, the generator and crucible cooling systems are closed-loop designs to conserve water. The emergency cooling system gravity feeds to the facility sump drain, and is used only in the event of failure of the crucible cooling system to safeguard operating personnel and prevent significant equipment damage.

The RF generator has factory-set coolant requirements to remove the waste heat generated. It requires coolant temperatures below 26.7°C for the system to be operable and is designed to shut down at higher temperatures. The cold crucible does not have the low coolant temperature requirements of the RF generator, which would be unnecessarily conservative.. A higher operating temperature for the crucible allows advantageous cost-effective options in the cooling system design. This is the reason that two separate cooling systems are used in the INEEL CCIM.

The heat generated by the RF generator is primarily due to inefficiencies of the generator itself. For example, to provide 60 kWe to the melt, the RF generator requires a 120 kWe feed because approximately 50% of the input power is dissipated as heat. The C-6000 RF generator includes primary and secondary cooling loops. The primary loop circulates distilled water through the generator to a liquid-liquid heat exchanger. This loop is internal to the facility and requires no freeze protection. The secondary loop circulates a water and propylene glycol coolant from the liquid-liquid heat exchanger toan 88 kW chiller, which is located outside of the test facility. The coolant was selected for freeze protection of the secondary loop. The chiller is necessary to maintain the primary coolant loop below the 26.7^{o}C shutoff temperature of the generator. All coolant is recirculated, generating no secondary waste.

Heat is removed from the crucible to maintain the crucible in a safe condition when containing a glass melt. The crucible must be cooled to maintain the desired operational properties of a cold crucible. The crucible cooling system also includes a primary and secondary loop. The primary loop circulates de-ionized water through the crucible to a liquid-liquid heat exchanger. The primary loop is completely internal to the facility and does not require freeze protection. The secondary loop circulates water and propylene glycol coolant from the liquid-liquid heat exchanger to an outdoor air-cooled radiator. The coolant was selected for freeze protection of the secondary loop. All coolant is recirculated, generating no secondary waste. An air-cooled radiator was selected because of the relatively high operating temperature of the primary loop. This higher temperature allows for the needed temperature difference to cool with a radiator in forced ambient air. The cooling water in the crucible can absorb close to 50 kWe at maximum power, which will increase the water temperature by approximately 20°C, based on the designed flow rate and residence time. The heat exchanger is sized to manage this heat load. Temperatures greater than 100°C may be considered, but the ramification to pressure vessel design and code stamp becomes significant to a research prototype that may be significantly altered or changed out in short time.

The materials of construction for the crucible and the thermal mass of the melt it contains necessitate an emergency cooling system. If a power or cooling system fails, the emergency cooling system removes sufficient residual heat of the melt to lower the bulk temperature to acceptable levels. Emergency cooling water is provided by the facility demineralized water supply via a single manual valve operation to minimize impacts to the system in a power failure. Emergency cooling is accomplished using normally open solenoid valves powered closed in the primary cooling loop to permit recirculation of the cooling water. When triggered, these valves open to permit the pressurized building water supply to cool the crucible. In the unlikely event that both power and facility water systems fail, a 1.89 m^3 cooling reservoir is available to gravity-flow water to the crucible. The reservoir has been sized to lower the bulk temperature of the glass in the crucible to 200°C. The flow rate has been calculated to minimize water volume requirements. The system is designed such that as the gravity-flow system empties and as the head pressure decreases so that equilibrium is reached, drain valves on the supply and return manifolds open, evacuating the crucible and thus minimizing the potential for boiling residual water in the system. In the event that steam is generated, the crucible has been designed with pressure relief valves to safely reduce pressure, precluding overpressure-induced crucible damage.

INSTRUMENTATION AND CONTROL

The CCIM prototype system is primarily controlled using a computer-based manual control console. Feed, crucible, induction power, offgas, and cooling systems are all controlled in this manner. The CCIM control and instrument display system provides for:

- Remote-manual operation of all controls necessary for normal nonemergency operation
- Simultaneous near real-time display of all instrument values and control states
- Real-time video display of crucible side wall and upper melt surface.
- Capability to accommodate future addition of automated control, interlocks, and programmed alarm and emergency response functions.

The CCIM instrumentation system includes a variety of instruments. Parameters measured include temperature, voltage, fluid flow, and several specialized instruments. All requirements include signal conditioning and any software algorithms. Cooling system temperature measurements must be accurate within 1°C at nominal operating temperature. Offgas and melt measurements need to be within 2% of nominal values. Flow measurements must be within 5% of nominal values. Because of uncertainties associated with measurement application, there is only an accuracy requirement of 1% receiving and displaying of the output of the optical pyrometer, and an accuracy specified for the instrument itself. The instrumentation system also provides operator-controlled archiving capability for any of the measured parameters at a specified time interval.

The prototype CCIM control and instrument system consists of multiple components or subsystems: control computer, LabVIEW software, P&ID displays, Instrument Interface, plant instruments, Control Interface, plant controls, and video monitoring system. The control and instrumentation system includes four 17-in. color monitors and one 21-in. color monitor for engineering development and P&ID display. A high-level summary P&ID with limited control and instrument icons is presented on the 21-in. monitor, with detailed engineering values and other system P&IDs presented on the remaining four monitors. Figure 4 shows the primary P&ID display.

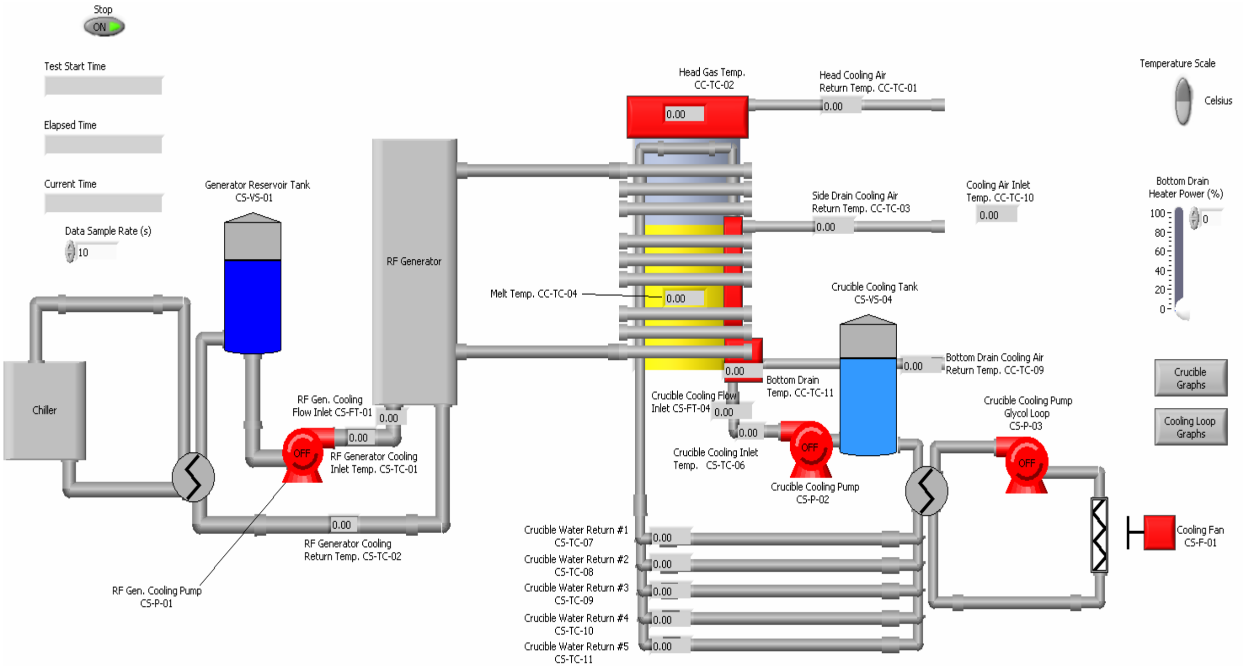

Fig. 4 Primary INEEL CCIM P&ID display

A total of 37 plant instruments are monitored and capable of being displayed on thevarious P&ID screens. The current design contains 22 Type-K thermocouples and two turbine flow meters monitored by the computer. The RF generator monitor panel provides instrumentation-performing monitoring and display of generator anode voltage, anode current, grid current, and state of interlocks. Instruments are provided to measure coolant flow, accumulator tank level, secondary coolant temperature, anode over-current, and anode over-voltage. Manually read instruments in the CCIM prototype include four crucible segment coolant flows, one side drain valve coolant flow, an RF generator secondary coolant system temperature and pressure, and a crucible heat pressure. Additional computer interfaced and manual measurements will be added as experimental work proceeds.

Solid-state relays are used to directly operate specific system equipment, or, in cases where the current surge may be above 40 A, they oiperate power contactors capable of handling a higher current surge. The power for 27 devices is controlled by the screen inputs, including seven pumps, four fans, and 10 valves for the cooling, feed, and offgas systems. Power is also controlled in this fashion for three motors in the feed system and three heaters in the offgas system.

As noted earlier, there is a requirement to remotely observe both the crucible side wall and the top of the melt. The video monitoring system performs these functions. It consists of three remotely powered television cameras and a video processing and display console. A Sony micro-camera monitors the crucible side wall. It is a 1.6 cm diameter concentric in-line unit that attaches to the structure inside the crucible barrier. A second tripod-mounted camera has remote focus and zoom, and is installed to monitor through an access window so that the top of the melt can be observed. A third general purpose tripod-mounted camera is supplied with remote focus and pan-tilt-zoom features. It can be used for a wide variety of test applications such as views of the liquid and dry feed tanks. The video console contains a 13-in. color monitor, a time and date display generator, a quad splitter that allows one or all three cameras to be displayed, and an industrial-grade video recorder

ACCOMPLISHMENTS AND RESULTS

During FY 2003, the entire CCIM prototype installation was completed, including the offgas system. Several melter runs were completed, ranging from barely initiating a melt to completely draining the crucible. In every case, new data were collected, points were learned, and problems were solved. The following narrative describes some of the test results.

During initial shakedown testing several issues were identified and resolved. For example, we experienced arcing between the inductor and the crucible during an early run. The RF generator manufacturer, Taylor Winfield, recommended spacing the internal diameter of the primary induction coil at least 1.27 cm away from a conductive load or crucible. The original design incorporated this suggestion and spaced the coil at this minimum distance to optimize efficiency. Note that efficiency is a function of many things, one of which is maximizing the ratio of subtended areas of the load to the coil diameter. Making these areas as close to equal as possible will deliver highest efficiency, everything else being the same. However, because of the size of the coil and crucible combination, it was difficult to maintain even spacing. In particular, the coil can be easily warped into a slightly ovoid shape when connecting the leads to the generator. Various types of insulation including rubber mat, fiberglass, and electrical insulating mat were placed between the coil and the crucible, but this proved unsatisfactory. During the test run, an electrical arc was observed and it burned a hole in one cooling stay of the stainless steel crucible before the RF generator over-current protection system removed this potential from the coil. In another case, clear high-voltage insulating mat was touching the coil and crucible, and displacement current burned a hole through three layers of the mat. As a result, spacing between the coil and the crucible was increased to 2.54 cm, and the primary inductor was powder-coated with a nonconductive material. Performance following this modification has been satisfactory, and this is the current configuration of the primary inductor.

The two major U.S. manufacturers of high-frequency RF generators for induction heating are Lepel and Taylor Winfield. Our RF generator is a Taylor Winfield C-6000. RF generators of moderate power (above 50 kW) are typically triode oscillators, and the C-6000 is no exception. It consists of two large water-cooled triodes wired in a tuned-grid tuned-plate configuration. The resonant frequency is determined by the tank circuit, consisting of two vacuum capacitors and the primary inductor. Also affecting frequency directly is the inductance of the buss work, power transfer relay, and feed lines. Our nominal design basis frequency is 2.6 MHz. Currently, however, the system is operating at a somewhat lower frequency of 1.9 MHz, probably due to increased inductance of these components. There also appears to be stray capacitance lowering the frequency. The parallel capacitors that nominally form half of the tank circuit consisted of two 750-pF vacuum capacitors mounted in a water-cooled retainer assembly. We initially began at a somewhat lower frequency of oscillation than our design basis. So we back-calculated the total system inductance, assuming the parallel capacitors were the only contributors to capacitance in the resonant circuit, and we determined that changing one of the capacitors to a 500-pF unit would raise our frequency to 2.6 MHz. We tried this and the frequency went up less than predicted, confirming our suspicion that stray capacitance affects resonant frequency. We plan to deal with this empirically in the future and to reduce the vacuum capacitor values until we reach our design basis frequency.

Following long runs at high power, we have had some problems with the generator disconnect breaker tripping off. This is associated with a very warm operating atmosphere in the unit, with case temperature warm to the touch. This occurs despite the secondary coolant system being run through a chiller. Consequently, we plan to install an exhaust fan on the top of the unit and air inlets at the bottom of the unit to limit the internal case temperature to that of ambient air. Cooling these high-voltage units is tricky, however. We use chilled water to cool the vacuum tube anodes, feed lines, capacitor retainers, and the primary inductor itself. The manufacturer and our Russian colleagues warned us to keep the water temperature well above the dew point to avoid condensation, which could cause arcing and trip the system offline.

During the later shakedown testingt, we experienced a major corona discharge witbin the energy transfer relay cabinet. The relay itself is mounted on a platform supported by four aluminum standoffs and constructed of a sheet of high-voltage fiberglass insulating stock called Glastic. Along the side and below the platform is a copper tube, which is an extension of the high-voltage RF feed to the upper inductor. The copper tubing connects to Goodyear Wingfoot flexible tubing just below the platform, and the connection is secured by a metal hose clamp. The screw protrusion of the hose clamp was rotated such that it was approximately 1.27 cm below the platform. Following one test, we observed both a corona discharge pattern over about one-third of the platform bottom and an area excavated by the discharge dissipation. This area was more than 2.54 cm in diameter and extended into the platform approximately 1.27 cm. The short-term fix was to turn the platform over, rotate the hose clamp 180 degrees, bend the high-voltage RF line to be 2.54 cm from the platform, and wash the entire assembly with undenatured ethyl alcohol. After making this modification, we encountered no further problems with the platform.

Other interesting phenomena experienced during melter runs were associated with coupling of the RF field within the CCIM enclosure. The inductor coil sections are fed by a series of three independent lines from the generator output and share a return line. This configuration apparently causes uneven heating, as was observed during early testing. In fact, higher heating of up to 40ºC of the segments contiguous to the inductor feed lines was noted, as was the support table surface in the same region. This led to speculation that the bending of each feed and return line creates a magnetic field unaligned with the axis of the crucible, thus subtending a greater cross-sectional area and inducing stronger eddy currents. We are currently investigating this possibility and considering ways to reduce or eliminate this effect by rerouting the feed lines where they attach to the primary inductor.

Supports for the induction coil were constructed of black ABS plastic predrilled to fit the outer diameter of the tubing. During early testing, we observed excessive heating of these ABS plastic spacers, as well as the black plastic end caps and black anodized aluminum bodies on the pressure relief valves. This All of the valve bodies were replaced with stainless steel, and the inductors supports were assembled using a Glastic sheet. To date, these modifications have eliminated all of the overheating issues.

The offgas lid was successfully demonstrated to be able to maintain 50ºC while the head space is at significantly higher temperatures. During one test, the head space temperature reached 350ºC, while the outside surface was 48ºC. Calibrated valves were not installed during this run, so the amount of air flow is not precisely known, making an overall heat-balance calculation difficult. This will be accomplished in future testing.

While a glass drain was accomplished, it was only possible using manual means. The primary heat source for the bottom drain, which is the ceramic heating sleeve, was inoperable due to inadvertent use of an inappropriate power supply. However, the drain tube achieved temperatures above 350ºC at the very bottom, outside of the crucible, with no other external heat source. This is encouraging and tracks well with the anticipated nominal temperature at steady state based on design calculations.

FUTURE RESEARCH AND DEVELOPMENT

Researchers at the INEEL are collaborating with U.S. and Russian colleagues to develop modeling capabilities to bridge the many gaps between theory and operation of CCIMs. Electrical and heat transfer models have been developed and, to some extent, validated by the testing completed to date. We hope to be able to continue refinement and validation of the INEEL modeling results with practical testing and to refine the designs based on results of this testing. The initial CCIM modeling efforts have extended the basic relationships for energy deposition versus applied frequency and melt resistivity using heat transfer theory and available thermodynamic data for glasses. Goals are to establish a basis for efficient design (melting a homogenous glass at maximum throughput) and establishing a basis for control algorithms. Power consumption is a significant concern, particularly for industrial applications. But this concern is still secondary to concerns about glass quality and production rate. A modeling capability that would allow visualization of the temperature profile and potentially the mixing characteristics in the melt for a variety of crucible/coil configurations would enable a virtual design process to narrow the range of hardware to be fabricated for actual testing. This would accelerate the development process and thus reduce overall costs. Potential benefits are significant when one considers DOE's investment in melter development over the last 25 years. Models developed to date could be used to predict the performance of melter prototypes and be evaluated against actual performance data.

Plans for research and development in CCIM technology center on three objectives:

1. Verify theoretical modeling to improve INEEL understanding of CCIM design and controlling phenomena
2. Establish a design basis through characterizing the technology's capabilities, validating prototype design calculations, and identifying key operating parameters and interactions
3. Improve current designs with innovations in crucible/coil materials, the bottom drain system configuration and interaction, and RF generator operational parameter control.

A major impediment to implementation of the CCIM technology to DOE and other radioactive waste processing applications has been the relatively limited understanding and lack of specific performance data. Establishing a firm nonproprietary design basis available for evaluation by potential customers is key to overcoming this issue. We would like to continue testing and evaluation such that the INEEL

CCIM test bed is available for inspection and external review. In addition, a more general evaluation of overall performance is needed, including:

- Startup and shutdown characteristics
- Stability during varied process conditions such as feeding, pouring, and idling
- Response to slurry feeding
- Corrosion and reflux of acids above the melt
- Bottom draining initiation, control, and termination
- Undesirable species buildup.

The ultimate goal of this research and development is to improve state-of-the-art waste stabilization technology.

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