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EVALUATION OF A NOVEL TEMPERATURE SENSING PROBE FOR MONITORING AND CONTROLLING GLASS TEMPERATURE IN A JOULE-HEATED GLASS MELTER

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ABSTRACT

A self-verifying temperature sensor that employs advanced contact thermocouple probe technology was tested in a laboratory-scale, joule-heated, refractory-lined glass melter used for radioactive waste vitrification. The novel temperature probe monitors melt temperature at any given level of the melt chamber. The data acquisition system provides the real-time temperature of the molten glass. Test results indicate that the self-verifying sensor is more accurate and reliable than classic platinum rhodium thermocouple and sheath assemblies. The results of this test are reported as well as enhancements being made to the temperature probe. To obtain more reliable temperature measurements of the molten glass for improving production efficiency and ensuring consistent glass properties, optical sensing was reviewed for application in a high temperature environment.

INTRODUCTION

Thermocouples and radiation pyrometers are the most common temperature sensors used by glass industry, but both experience accuracy problems due to sensor drift in long-term operation (e.g., decalibration or changes in emissivity measurements).[1-9] The operator overseeing glass melting must detect and correct these temperature measurement errors. Decalibration occurs because of the extreme temperature and corrosive environment in the glass making process. Classic platinum/rhodium thermocouples are plagued with drift problems, breaks in continuity, and materials degradation. The thermocouple materials experience inter-component interactions and component/environment interactions, including the cumulative effects of trace contaminates diffusing into the thermoelement, over their service in the glass melter. In an attempt to validate melt temperatures, thermocouple readings are sometimes compared against optical pyrometer readings. Pyrometry is dependent on the emissivity of the material being measured as

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well as the viewing angle and temperature. Conventional pyrometers experience gradual fogging of the lens and degradation of the thermopile element as a result of prolonged exposure to heat and fumes. Changes in emissivity readings lead to 10 to 38°C errors in temperature measurement. Thus, conventional temperature monitoring systems require frequent recalibration to determine their current degree of error. However, removing a temperature sensor for recalibration requires personnel time, may be impractical due to deformation of the sheath, and can only be performed at specific times during the production process. When the glass product of interest contains nuclear waste, the issue of personnel safety in accessing a temperature sensor compounds the removal process. As a matter of practice, operators acquire sufficient skill in monitoring the process to attempt to compensate for suspected temperature readout errors by "intuitive" process changes. An accurate and reliable temperature sensor would simplify process qualification, decrease down-time, and improve production efficiency.

The Idaho National Engineering and Environmental Laboratory (INEEL), in collaboration with AccuTru International Corporation (AIC), is developing a self-verifying temperature sensor (SVS) for use in aggressive, high temperature environments such as glass melters. The SVS probe uses a composite of sensing elements calibrated to a traceable National Institute of Standards and Technology standard and is hardened against degradation. The contact probe electronics compares a reading from the primary temperature-sensing element to a calibration matrix to confirm that the primary temperature readout is within the limits-of-error. Temperature data are acquired using twelve unique measurements in the SVS probe, which are processed, using a proprietary algorithm, to output a validated temperature reading. In addition to the temperature output, the probe also provides a confidence measure of the output temperature. Confidence levels indicate acceptable, caution, and unacceptable probe performance based on user input error levels. The SVS provides accurate, verifiable temperature that can be trusted for use in process control and qualification. The probe is designed to replace conventional thermocouples and fits into existing thermowells.

The SVS evaluation has two phases, first in a laboratory scale glass melter and then in a pilot-scale melter. These melters produce zirconium high activity waste (Zr-HAW) glass.* The purpose of these melts, which are conducted for the Department of Energy, Environmental Management, is to demonstrate that the vitrification process yields a consistent HAW glass product that meets or exceeds repository storage criteria. The results of the laboratory-scale evaluation are reported here; the pilot-scale evaluation of the SVS has not yet begun.

LABORATORY-SCALE HAW GLASS MELT

The melter test objectives were to collect qualitative processing data on the Zr-HAW glass formulation and to evaluate the SVS temperature probe. The processing data (corrosivity, liquidus temperature, and viscosity) are needed prior to conducting pilot-scale operations using a joule-heated melter. The Zr-HAW glass formulation had been identi-

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* Zr-HAW is the result of dissolving the zirconium calcine and separating the radionuclides, thus reducing the volume of high level waste that requires immobilization in glass.

fied through a series of crucible tests conducted in conventional furnaces; the composition of Zr-HAW glass used in an October 1998 test, Zr-9, is given in Table I.

The laboratory-scale joule melter chamber was fabricated with Monofrax K-3 fire cast refractory and two Inconel 690 electrodes. The power supply for joule heating included a 120 V Variac rheostat with a 0-140 V AC / 22 A output. Current and voltage of the joule power were monitored with two Fluke 87 digital multimeters. A modified (1200°C) Blue M furnace was used for initial heatup. The SVS probe was housed in an Inconel 600 sheath and placed directly in the center of the melt chamber; a Type R thermocouple (TC) was placed in an alumina thermowell at the edge of the melt chamber; a Type K TC was used to monitor the furnace temperature. The refractory melt chamber was filled with the Zr-9 glass constituents in oxide form. Furnace temperature was controlled to maintain a heat-up rate of approximately 50°C per hour to 717°C. During heat-up, glass additives and simulated (nonradioactive) Zr-HAW were added to keep the melt chamber full. Redox was monitored visually throughout the heating cycle and no foaming or phase separation was detected. Joule heating was initiated at 717°C, and thereafter oven resistance heaters were manually adjusted as required. Joule current density was limited to 6 A/in.^{2} (Joule voltage and current readings were recorded at 1 to 5 min intervals.) Melt temperature was increased at approximately 90°C/h to 1150°C. After dwelling for 5 h at 1150°C, joule heating was terminated and the SVS probe and Type R TC were removed. The melt was poured onto a quench plate and collected for analysis.

Temperature data were recorded manually during the workday, and the furnace dwelled at 650°C over night. Figure 1 shows the oven temperature (Type K TC), the melt chamber temperature using conventional technology (Type R TC), and melt cham-

Table I. Zr-9 Frit and 16.2 wt % Zr-9 Glass Compositions

Oxide	Zr-HAW	Zr-9 Frit	Zr-9 Glass
Al_2O_3	2.08	4.97	4.50
B_2O_3	-	11.93	10.00
CaO	0.53	-	0.09
CeO	0.14	-	0.02
Cs_2O	0.26	-	0.04
Fe_2O_3	0.02	-	0.00
Gd_2O_3	0.42	-	0.07
K_2O	2.61	-	0.42
Li_2O_3	-	7.16	6.00
Na_2O	-	17.00	14.25
P_2O_5	1.31	-	0.21
SiO_2	-	58.94	49.39
SrO	0.04	-	0.01
ZrO_2	92.58	-	15.00
Loading			16.20%

ber temperature using the SVS during an October 1998 test. It can be seen that the Type R TC, located at the edge of the melt in an alumina thermowell, closely tracks the *furnace* temperature while the SVS records the true temperature of the melt. During heat-up, when the melt would be expected to be cooler than the resistively-heated furnace, the SVS output the lowest temperature. The temperature sensors show the same temperature trend during dwell at 650°C. Joule heating was initiated at 717°C and an initial "jump" in melt temperature from 717°C to 969°C occurred. During joule heating, when the melt is hotter than the furnace, the SVS recorded the true melt temperature while the Type R TC temperature lagged. The position and size of the thermowell strongly influence the Type R TC readings.

Corrosion effects of Zr-HAW on the Inconel 690 electrodes and the K3 refractory were minimal in this test. (Although the Inconel 600 sheath performed well, the sheath material to be used in the pilot-scale melter should be based on the glass formulation selected.) Melter electrodes were removed and quenched. Residual glass was removed manually and by soaking the electrodes in hydrofluoric acid for 15 min. The weight loss of each electrode was less that 1%. The difference in density between the Zr-HAW glass from this melt (2.6754 g/cm^3) and the Zr-HAW crucible glass from formulation development (2.6713 g/cm^3) indicates there was a small addition of chrome, nickel, and zirconium from the refractory or electrodes.

The assumed operating temperature of a melter for vitrifying Zr-HAW is 1150°C with a preferred pouring viscosity in the range of 20 to 100 poise (2-10 pascal-seconds). Viscosity profiles of the laboratory-scale melter glass and the crucible glass as a function of temperature over the range of 950 to 1250°C are nearly the same, thus the pouring viscosity is within the 20 to 100 poise range as shown in Figure 2.

The SVS reliably measured the temperature of the melt. This is essential for producing a waste glass that meets the requirements for repository storage. Because the SVS

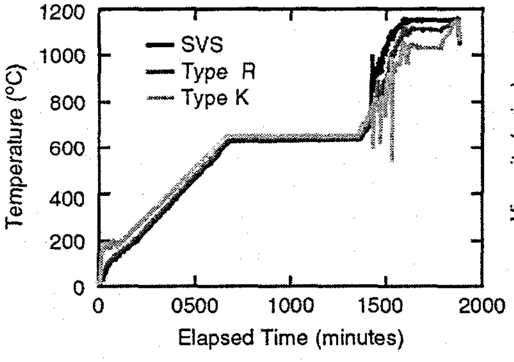

Figure 1. Temperature data acquired during October 1998 melter test. The level portion of the temperature curve is the over night dwell at 650°C.

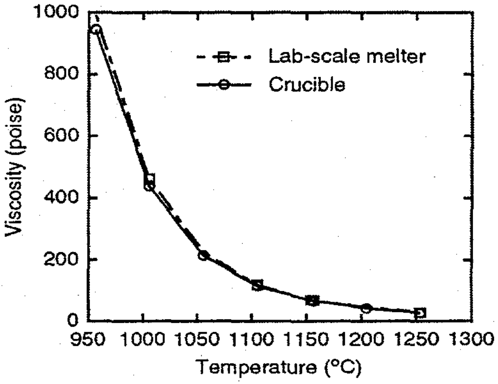

Figure 2. Viscosity of Zr-9 HAW laboratory-scale melter glass and crucible glass as a function of temperature.

temperature is more accurate than that of a TC in a thermowell, using the SVS is expected to yield a better product at a lower operating cost.

WORK IN PROGRESS

Enhancement Of The SVS Sensor

INEEL is developing and demonstrating an optical temperature sensor to be added to the SVS probe. Adding optical sensing eliminates common mode failure of the sensor head and provides an additional measure of temperature, thus increasing the reliability and confidence in the temperature signal. The optical sensing component houses a simulated black body source with a minimum of a 5:1 (length to diameter) ratio cavity for optical temperature determination using the infrared intensity emitted by the cavity surface.[10] (see Figure 3).

The novel approach of housing a black body source in the sensor overcomes the variable emissivity problems experienced when optical readings are obtained directly from molten glass. Temperatures obtained from the optical sensor will be compared to SVS probe temperatures, enhancing the accuracy and reliability of the temperature output. Appropriate materials will be chosen to maintain optical opacity (the cavity needs diffuse reflectivity and low transmission) and mechanical integrity at the desired operating temperature. Acceptable candidate black body cavity materials have been identified and tested for temperatures up to 1250°C. Both alumina and zirconia cavities have been evaluated to 1150°C in a programmable, single-zone tube furnace. Alumina becomes optically transparent in the temperature range evaluated. Depending on furnace design, an alumina cavity can detect heater element radiation when heaters are cycled to maintain the desired furnace temperature. Zirconia is optically opaque in the temperature range of interest and provides a true measure of the internal temperature of the black body cavity. In addition to optical opacity and mechanical properties, chemical reactivity issues raised by placing the black body cavity in the existing probe have been evaluated.

The radiation from the black body cavity is collected using a 62.5 μm collimator coupled to a 62.5 μm multimode 1x2 optical fiber coupler with a 50/50 beam split. The

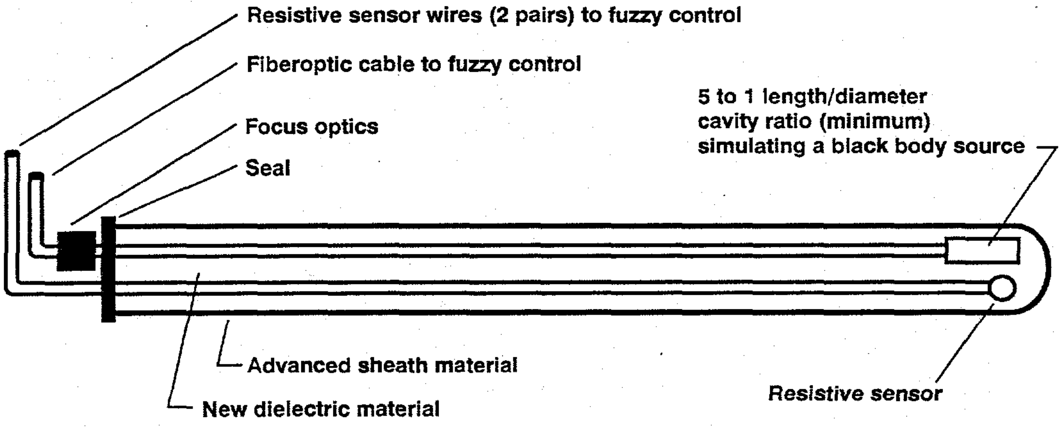

Figure 3. Enhanced temperature sensing probe.

fiber and collimator are located at the exterior end of the probe, away from the molten glass region. Communication industry 62.5 μm components provide acceptable light collection and transmission to the detection electronics. Although only a fraction of the radiated light can be collected into the fiber, sufficient light is collected to achieve repeatable detection with the beam splitter. The light is presented to both a silicon and a germanium detector, providing temperature information at two optical wavelengths. In addition to temperature information, the two-color approach being used provides a means to calculate a confidence factor that the temperature detected is accurate.

Enhancement Of Data Acquisition Method

Manual recording of the melt furnace runs is not an optimum data acquisition method for accurately monitoring the melt process. The SVS probe system includes a computer that acquires the SVS probe temperature, but all critical process parameters must be monitored. A PC-based portable diagnostic system (PDS) is being fabricated at the INEEL that will initially acquire data from multiple temperature sensors, as well as current and voltage data, during joule heating. The INEEL PDS technology has been successfully implemented in Department of Energy, Department of Defense, and U.S. industry welding processes to monitor voltage, current, and wirefeed speed. The PDS integrates a variety of transducers, signal conditioning circuitry, data acquisition hardware, computer hardware, and computer software to provide data acquisition functionality. The data acquisition, signal conditioning, and isolation components are assembled into a sub-chassis that provides a compact, electrically shielded enclosure for the PDS. The sub-chassis is enclosed in a rugged suitcase with integral wheels and a telescoping handle. The ruggedness of the PDS makes it suitable for exposure on an industrial production floor and its portability facilitates transporting from one location to another. The PDS software is written in LabVIEW© programming language, which provides a user-friendly, graphical interface that requires minimal training for operation. LabVIEW's data acquisition capabilities provide the PDS with high level data acquisition functionality. The PDS can be used to monitor the melt process and provide the operator the means to identify and proactively mitigate problems before the process moves out of the desired parameter space. In addition to data acquisition functionality, control strategy based on fuzzy logic can be added to the PDS.

Fuzzy Logic Control Strategy

The expert knowledge of a human operator, captured in a rule-based control strategy called a fuzzy observer, arbitrates the two temperature measurements from the enhanced sensor and their confidence values. The fuzzy observer uses linguistic rules to emulate the rule-of-thumb thought process used by humans to "control" process parameters. For example, one rule set would state the trust an operator places in a new temperature sensor versus the trust the operator places in a temperature sensor that has been used for several months. The full integration of the temperature sensor data can be achieved through the use of a fuzzy logic observer. The integrated data will be used by a fuzzy logic based control system to attain the process goals. Currently, process temperatures are typically controlled manually by a skilled operator through the use of proportional-integral (PI), proportional-differential (PD), or proportional-integral-differential (PID) set point controllers. While such conventional controllers are used to control the furnace, forehearth, and delivery channel, closed loop control of the glass production process is not fully implemented by these control approaches. The importance of human experience and knowledge within a closed loop control system for the glass industry is due to the lack of a comprehensive first principle model for a general glass melting and forming operation. Human experience and knowledge is still key to control of glass production.

Many artificial intelligent control methods[11-14] are being studied; the two leading methods are neural networks and fuzzy logic. Neural network intelligent controllers are, for the most part, empirically based and require large amounts of actual process data to develop an acceptable controller response. Such data must include both the desired operating regions as well as the undesired operating regions. Of course, obtaining an adequate set of "undesired" operating data from an efficient production operation is not appropriate. Moreover, the neural network's dependence on actual process data implies that the actual furnace configuration is tightly coupled to the controller's performance. Therefore, neural network controllers are more appropriate for optimization of inner loop set point controllers on a plant by plant basis than for industry-wide application.

Fuzzy logic methods, however, allow development of controllers based on a qualitative understanding of a physical process. And because this type of controller is tied to an understanding of the physical operation of a process instead of the equipment configuration, it is more robust when the plant configuration changes. A fuzzy logic system's performance depends greatly on the logic or expert knowledge built into its design; this can be a drawback as well as a strength. As glass chemistries are evaluated in both the laboratory- and pilot-scale furnaces for various surrogate waste feedstocks, a knowledge base will be established. The fuzzy logic method of control uses a solution strategy much like the one the glass furnace operator employs when making process change decisions. Among the advantages of a fuzzy logic controller are that it interpolates the gaps in the experience and knowledge base to cover unexpected results and that it can make control decisions using smaller steps than an operator may have used. For these reasons, fuzzy logic was chosen as the control strategy for the temperature observer.

CONCLUSION

The INEEL is conducting laboratory- and pilot-scale experiments to vitrify simulated waste that represents HAW from radioactive waste currently stored at the INEEL. Vitrification reduces the waste volume and creates a stable waste form that is suitable for transport and long-term storage. Data collected from laboratory-scale melter runs will be used to design pilot-scale melter runs. Test results from the laboratory-scale joule heated melter indicate that the primary process parameters—corrosivity, liquidus temperature, and viscosity—are acceptable. It is recommended, however, that additional testing in a pilot-scale melter be conducted to verify crucible and laboratory-scale melter test results. Accurate monitoring of the molten glass temperature is necessary to ensure a homogeneous, consistent waste form that can be characterized to determine its long-term storage properties. However, accurate temperature measurement has been problematic for the aggressive chemistry of HAW borosilicate glass. INEEL and AIC are collaborating in an effort to improve the reliability of temperature sensing and control in production of glass waste forms. The SVS monitored temperature from 18 to 1150°C. The SVS performed well, providing a true glass temperature with excellent sheath corrosion resistance. A portable diagnostic system is being fabricated to provide computer-controlled monitoring of temperature, as well as current and voltage, during joule heating. The PDS will provide a cost-effective tool to monitor furnace melter runs and allow for duplication of parameters when comparing various glass formulations. The PDS can be enhanced to incorporate linguistic rules for a fuzzy observer control strategy, increasing the reliability of temperature measurements provided to the master controller.

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