WSRC-TR-2002-00196 Rev. 0

DWPF Melter Air-Lift Bubbler:

Development and Testing

For Increasing Glass Melt Rates

and Waste Dissolution

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Official: ______________________________
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Date:______________________________

Westinghouse Savannah River Company
Savannah River Site
Aiken, SC 29808

May , 2002

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DWPF Melter Air-Lift Bubbler: Development and Testing For Increasing Glass Melt Rates and Waste Dissolution

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1.0 Executive Summary

A DOE Tank Focus Area program to assess possible means of increasing Defense Waste Processing Facility Melter melt rate was initiated in FY01. A lumped parameter comparison of DWPF data with earlier pilot scale data indicated that melter capacity for a given feed was limited by overheating of the glass immediately under the reacting feed (cold cap). Bubblers were considered as a means of increasing glass circulation and opening a vent in the cold cap to allow increased electrode power, and thus increased melter total power. Limited locations for a bubbler in the DWPF melter top head, and glass pumping limitations of traditional bubblers led to the development of a novel system utilizing airlift pumping. Airlift pumping has a history of successful use at Pacific Northwest National Laboratory and West Valley Demonstration Project for glass discharge to the waste canisters.

A half-length airlift was used with glycerin to develop a proof-of-principle design, and calibrate a pumping rate method. An Inconel proof-of principle airlift was tested in molten glass, and found to function as an effective pump. A two and one half inch inside diameter unit was found to pump approximately 1.5 tons of molten glass per hour, at a pump head height of eleven inches. Pumping rate was controlled by varying air flow rate to the airlift. Melter feed was not used, so no interaction with the cold cap has been measured. However, Catholic University of America reports satisfactory interactions for traditional bubblers discharging circulating glass below the cold cap (Ref. 1). Prior experience with traditional bubblers in glass, and evaluation of this performance with the lumped parameter heat transfer model indicates that melt rate increases of 10-30% or higher can be expected from a single unit.

Testing to date has not been conducted for life of an airlift device or for its interaction with the melter cold cap. FY02 testing is proceeding to provide design drawings of the glass contact components, evaluate expected unit life and provide initial indications of interactions with the cold cap. A full-scale unit will be installed in the glass hold tank of the DWPF Pour Spout Test Stand at Clemson University, and used for airlift life testing. Although air use rates will be higher than those used in the DWPF glass height bubbler (due to pump work vs. pressure sensing requirements), wear rates in high wear areas are expected to be controlled by using platinum alloy nozzles and cladding. To the extent possible, this unit will also provide information on airlift design details, and foam collapse rate. Design details of glass discharge height, and nozzle design will also be tested on this unit, since they require full scale testing in molten glass. Other design details influencing glass-flow, and the effect of airlift pumping on the circulation of the melter will be tested at full scale in glycerin. The glycerin will allow systematic evaluation of airflow rate, bore diameter, nozzle location, glass discharge height, and glass discharge size. The existing Slurry Fed Melt Rate Furnace (SMRF) will be modified to examine what operating requirements are required to avoid accumulation of the foam at the discharge of the airlift, and to evaluate interactions of bubbles with the feed slurry and cold cap.

Anticipated benefits to DWPF of the airlift bubbler are:

- Enhanced melt rate from direct action of increased overall glass circulation rates improving transfer of electrode power to the bottom of the cold cap. This may be the result of increased overall glass velocity or improved venting of cold cap gases trapped under the cold cap. This effect is estimated at about 10% up to 30% increase per airlift (flange). This is the mode of melt rate improvement of traditional bubblers operated with modest gas flow rates. However in the present case, the efficiency of the pumping action is improved, so that lower gas flows are required, and the gas is not forced to accumulate under the cold cap. (Gas bubbles generated by the melting process still have to vent out of the cold cap.)

- Additional increases to melt rates from enhanced power available to the cold cap and slurry indirectly by heat transfer from the pumped glass to the melter plenum. This effect is projected to provide a melt rate increase of up to 20% per airlift (flange). It increases total power available to the melter by allowing additional electrode power to be applied without overheating of the glass under the cold cap.

- More uniform glass pool temperatures, making it easier to stay within temperature operating limits at the top and bottom of the glass pool.

- Evaluation of the heat transfer across the surface of the glass in DWPF suggests that a barrier layer may be forming. The pumping action of the hot glass from and airlift may push aside or raise the temperature of viscous layers or un-dissolved material floating on top of the glass pool, causing them to dissolve or dissipate.

2.0 Introduction and Summary

The DWPF Melter canister production rate decreased with Macrobatch 2 relative to Macrobatch 1 by approximately 23%. This might be attributed to (1) a higher foam generation in Macrobatch 2 that diminishes heat transfer and (2) higher glass viscosity that reduced melter flow recirculation, or a layer at the top of the glass pool that interferes with transfer of heat or material across the interface. Gas bubbles from chemical reactions are trapped at the lower, high temperature layers of the cold cap resulting in the foam layer. While one approach to increase melt-rate is to use a new frit formulation that reduces the tendency for foam generation, an alternate approach is the use of bubblers. Bubblers that pump glass through the airlift principle can increase the overall melter circulation rate. The higher circulation rate would increase the film heat transfer coefficient to the cold cap (to compensate for the foam thermal resistance) by bringing more hot glass from lower elevations and increasing the velocity gradient under the cold cap. Also by maintaining a high temperature at the uncovered glass surface, radiation to the upper plenum, which is reflected back to the top of the cold cap, provides more heat to dry and calcine the slurry prior to melting. Mechanically aiding the natural flow circulation with bubblers may also help keep the noble metals in suspension, preventing them from settling on the melter floor, which could cause electrical shorting. Thus, the use of bubblers could bring several benefits to melter capacity. During normal melting and idling conditions, the uppermost glass in the glass pool is cooler than the nominal melting temperature. Thus, pumping hot glass to this level (underneath the surface) may help to dissolve any layers that form, and restore any local composition differences resulting from accumulations or local volatilization.

Increased melt rate in DWPF would be achieved by increasing the gross circulation in the melter and by conveying hot glass from the deeper layers of the glass melt to the surface to interact with the cold cap and radiate heat to the upper plenum. Additional benefits could be achieved by increased total melter power, uniformity of the glass pool temperature, and by increased dissolution of material on top of the glass.

The proof-of-principle bubbler is basically an airlift device, Figure 1, consisting of an outer tube with upper and lower slots and an inner air-line with sparger. Air bubbles rising from the air sparger at the bottom of the outer tube produce a two-phase mixture inside the larger tube. Due to the lower fluid density inside the pipe housing relative to the fluid outside, flow is induced from the outside through the open bottom end of the tube, up the housing and then out of the upper set of slots. The liquid circulation flow was experimentally determined for this type of bubbler. In contrast, previous bubblers consisted of an air injection tube where air bubbles rose freely in the bulk glass. Liquid circulation has been observed to be localized in small circulation cells along the bubble paths as these rise to the surface (Refs. 2 and 3). Thus much less net flow from lower pool levels to the upper level is achieved in this type of bubbler for the same gas flow rates used.

Development tests were first performed with a half-length airlift in glycerin at various viscosities (achieved by varying the temperature). Promising results showed void fractions as high as 40% were achieved. By measuring the outlet flow with a container equipped with a calibrated orifice, a theoretical model of operation of the bubbler was verified. A calibration curve of the 0.5-inch orifice container was obtained at viscosities that ranged from 6.7 poise to 100 poise. This was accomplished by using chilled glycerin (6.7-17 poise) and a special silicone oil (100 poise). Then a proof-of-principle bubbler, with submergence depth of 25.5-inches was designed, built, and tested in the Stirred Melter at Clemson University on April 19, 2001. A flow capacity curve of glass flow versus air flow was measured using the above calibration curve. A maximum of 2930 lbs/hr glass flow was achieved during the test at 1060^{o} C. This glass flow, transported from lower depths in the DWPF glass pool (1050^{o}C) to the surface, adjacent to the cold cap where the glass surface temperature is estimated at 850^{o}C in a lumped parameter model, represents an available power flow from the electrodes of 110 Kw. This implies that an additional 110 Kw of power could be supplied by the melter electrodes, increasing the total power available for melting. The hot glass energy may melt the cold cap directly, or radiate to the upper plenum, to be reflected to the cold cap. In the event that 20% of this power flow is effectively used to melt glass, this would represent a 20%

increase in the melt rate since about 100 Kw is necessary to evaporate the liquid and melt the glass for a melt rate of 155 lbs/hr.

Higher glass flows than the above experimental values (at Stirred Melter temperature of 1050°C) are expected to be obtained in the DWPF Melter due to reduced frictional losses at actual melter temperatures of 1050°-1170°C, and possibly by optimizing the bubbler design. This flow characteristic will then be used in a CFD (Computational Fluid Dynamics) model of the DWPF glass pool with bubblers to estimate the glass pool flow and melt rate increase against a reference model with no bubblers.

There are a limited number of DWPF melter top head penetrations available for bubbler installation. Consequently, the CFD model will be used to assess the effect of different bubbler locations and numbers (single or multiple) on the glass pool velocity distribution, heat flow to the upper plenum and potential melt rate improvement.

3.0 Theory of the Air-Lift Bubbler

While testing of the bubbler was performed with glass, a theoretical model of the bubbler operation is needed to apply the limited data obtained at Stirred Melter temperatures of 1023- 1060° C to DWPF operating temperature of 1150°C. This model would also support optimization of the bubbler design and parametric studies. Figure 1 shows a schematic of the bubbler. The important parameters are submergence depth, Z_s, lift, Z_l, and void fraction, α. Applying the momentum equation, Eq. 1 is obtained.

$$\rho g Z_s = \rho g(1-\alpha)(Z_s + Z_l) + \frac{(1-\alpha) f \rho V_m^{\,2} (Z_s + Z_l)}{2D} \quad . \qquad [1]$$

For laminar flow, the friction factor is given by

$$f = \frac{64\mu}{\rho D V_m}$$

ρ is the liquid density, g is gravitational acceleration, α is the void fraction, Z_s is the submerged depth, Z_l is the lift or height of the two-phase mixture above the surface of the liquid, D is the inside diameter of the bubbler, and Vm is the mean mixture velocity. If the frictional losses are small, the void fraction is from Eq. 1 simply the ratio,

$$\alpha = \frac{Z_l}{(Z_s + Z_l)} \qquad [2]$$

The bigger the void fraction, the larger is the pressure differential developed between the fluid outside and the two-phase mixture inside the bubbler to overcome frictional losses and drive flow through the bubbler. If the void fraction were known, the average flow velocity, V_m, can be calculated from Eq. 1. A second relation is available from the Drift Flux equation, which has been found (Ref. 4) to characterize bubbly and slug flow, as given in Equation 3.

$$\frac{J_g}{\alpha} = C_o(J_g + J_l) + V_{ts} \qquad [3]$$

where C_o is a distribution parameter (approximately 1.2), J_g is the gas superficial veocity, J_l is the liquid superficial velocity, and V_{ts} is the bubble velocity relative to the average mixture velocity. The sum, $J_g + J_l$, is the mixture velocity, V_m.

For highly viscous fluids, the terminal bubble velocity may be taken as the Stokes flow velocity,

$$V_{ts} = \frac{gd^2\Delta\rho}{18\mu} \qquad [4]$$

where d is the bubble diameter, $\Delta\rho$, is the density difference between liquid and gas, and μ is the liquid viscosity. Thus, theoretically, the void fraction can be related to glass mass flow rate if Equations 3 and 4 apply to glass. The glycerin and glass tests will provide data by which validity of the above model can be tested for a glass bubbler.

4.0 Glycerin Tests

Prior to designing a bubbler for the Stirred Melter, scoping tests with a clear plastic bubbler in glycerin were performed at the Thermal-Fluids Laboratory. Figure 1 shows a schematic of the test setup. A clear 3-inch PVC pipe was used for the housing. This was submerged into a tank of glycerin to a depth of 10.75-inches. Cooling coils in the tank of glycerin provided the capability to vary viscosity. The air sparger consisted of a 0.5-inch diameter copper tube through which three ¼-inch tubes penetrated radially at 120^o to each other. Eight 0.080-inch diameter holes were drilled into the tubes to provide uniform distribution of bubbles over the bubbler cross-section. The sparger was located above the lower slot openings to prevent air from escaping outside the bubbler housing.

Air flow was measured with a rotameter. The glycerin viscosity was measured with a Ubbelohde viscometer, which agreed with the known viscosity of pure glycerin at room temperature. To measure the liquid flow through the bubbler, an outer container was installed over the upper portion of the bubbler housing to catch the liquid escaping from the upper slots. The liquid then returned to the tank through four ½-inch diameter orifices near the bottom of this container. The height of liquid built up inside this container, together with a calibration of the ½-inch orifices, provided a means of measuring the pumped liquid flow.

A separate 3-inch diameter measuring cup with a ½-inch orifice was calibrated by timing the period for liquid to drop 1-inch, at a given average distance from the top of the orifice. Data for glycerin at 20.8^{o}C, 14^{o}C, and 10.8^{o}C (at viscosities of 6.67, 12.4 and 16.9 poise, respectively) were obtained and plotted as Coefficient of Discharge, Cd, versus Reynolds number (based on orifice diameter) in Figure 2. Tests were also performed with silicone oil having a viscosity of 100 poise and plotted in Figure 2. The premise that the discharge coefficient is a function of Reynolds number is based on the fact that the centerline velocity at the orifice is a quadratic function of total flow. A power law calibration curve, Cd=0.1336Re^0.468 fitted the data points with a small variance. Thus, this method would also apply to glass since the Reynolds number range of the data cover the melter conditions.

Results of the tests with glycerin are summarized in the charts of Figures 3 - 5. Figure 4 gives a plot of the liquid flow vs. air flow in scfm for three glycerin temperatures, 20.6^oC, 13^oC, and 10.5^oC. The measured void fractions, based on Eq.2, are given in Figure 3. Using the Drift-flux theory, bubble velocities relative to the average mixture velocity were obtained for the three glycerin temperatures. These are plotted in Figure 5, showing that the bubble velocity is a function of temperature, i.e., glycerin viscosity. Using Eq. 4, an average bubble diameter of 0.75-inch was obtained at all temperatures.

5.0 Proof of Principle Glass Tests in Stirred Melter

A proof of principle bubbler was designed and fabricated for use in the Stirred Melter at Clemson University. A drawing of the bubbler is shown in Figure 6. All materials were made of Inconel 690. The housing was a 3-inch pipe with four 1-inch wide bottom slots providing a submergence depth of 25.5 inches. A 0.5-inch O.D., air line was used, the end of which is the sparger consisting of three, ¼-inch diameter tubes inserted 120^o apart radially into the tube. Eight 0.090-inch diameter holes were drilled and distributed over the 6 arms of the radial tubes. The four 8-inch long, 1-inch wide upper slots required a lift of 5-inches above the surface of the glass. A 7.5-inch diameter measuring container, 12-inches high covered the upper slots to catch the exiting glass flow. This had four 0.5-inch diameter holes near the bottom end, as in the glycerin test. Along the side of the measuring container, a vertical row of small holes was drilled at 0.5-inch intervals to provide a way of determining the liquid level inside the container by observing the number of jets coming out the side of the container. However, this method did not work out because uniformity of temperatures inside the Stirred Melter resulted in no contrast to discriminate the glass jets. Instead, a stainless steel rod was used as a dip-stick to measure the height of glass inside the container that coated the rod.

The airlift was installed into one of the 8-inch nozzles on top of the Stirred melter. The opposite 8-inch nozzle was used as a view port for the strobe camera. However, mounting difficulties precluded a clear view of the bubbler. Consequently, the dip stick method described above was used to obtain liquid level height data inside the container. The glass tests were performed at two glass temperatures, 1025^oC and 1060^oC. Air flow was measured with a calibrated rotameter and pressure gage.

The data for glass height vs. air flow inside the measuring container are shown in Figure 7. The indicated air flow is the flow at standard atmospheric conditions. Inside the bubbler, the volumetric flow would increase by a factor of 4.7 due to expansion from room temperature to the glass temperature. The height of the glass inside the container quickly exceeded the 5-inch lift above the surface of the glass outside the bubbler. The design objective was for the collapsed liquid inside the container (after escape of all air bubbles) to be below the top surface of the two-phase mixture inside the bubbler so that the measuring container would have no influence on the two-phase flow inside the bubbler. The measured levels inside the container went up to 10-11 inches. This meant that the flow calibration orifice holes were undersized. The strong dependence of the coefficient of discharge of the holes on the liquid viscosity was not realized until after the calibration with 100 poise silicone oil. The viscosity of the glass was determined by taking a sample of the glass and performing a chemical analysis. Then using the PCCS and PNNL models, an approximate glass viscosity of 80 poise at 1150^oC was calculated, which at the testing temperature of 1025-1060^oC corresponds to a value of 120 poise.

The measured pumped glass flow rates at 1060^oC are given in Figure 8. These are based on the theory that the calibration curve, confirmed with the 100 poise oil, also applies to glass. These are conservative estimates of the air-lift pumping capacity because the measuring device probably had a restricting effect on the flow. Since the height of the two-phase mixture inside the bubbler was not measured, the actual void fraction is unknown. It is possible that the maximum void fraction and glass flow was not reached since the curve in Figure 8 did not level out. Also, at higher actual glass temperatures of 1090-1170^oC in the DWPF melter, higher flow rates would be expected for the same glass due to lower laminar friction pressure drop inside the bubbler. It is possible for the void fraction to be calculated based on the equations in the theory section. However, the bubble size in glass is unknown at this time. Further full scale testing in glass would provide the necessary data.

6.0 Conclusions

Development tests of a bubbler based on the air-lift principle were performed in glycerin and glass. This provided the confidence to design a proof-of-principle bubbler for the glass tests in the Stirred Melter. A maximum flow of 2930 lbs/hr was achieved at a temperature of 1060^oC for the 3-inch ID bubbler. The lower viscosity in DWPF should increase this flow due to lower pressure drop in the bubbler for the same inside diameter. However, a prototype bubbler in the DWPF Melter would have thicker walls (smaller ID) for robustness than the proof-of-principle bubbler, and thus higher frictional loss. Higher air flows could probably be used to minimize this flow reduction. The present sparger was designed for optimum bubble size and distribution, but not for extended life. For the actual DWPF bubbler, the sparger design would entail larger orifices and an air-line built into the bubbler wall.

The number and locations of airlift that can be introduced into the DWPF melter are limited based on the location of the existing top head penetrations. Therefore, the CFD model of the DWPF melt pool will be used to assess the effect of potential bubbler locations, with initial work focussing on the center thermowell position.

An energy transfer of 110 Kw from the lower levels of the DWPF Melter glass pool to the glass surface was calculated using the measured glass flow of 2930 lbs/hr, a temperature difference of 200^oC (1050^oC-850^oC) to the cold cap/glass surface interface. This power may melt the cold cap directly, or increase the uncovered glass surface so that a larger amount of heat is radiated from the glass surface to the cold cap surface, via the upper plenum. A 20% conversion rate would increase the melt rate by 20%, since the total energy currently being used to evaporate the slurry water and melt glass is comparable at 100 Kw.

7.0 Path Forward

The airlift is being developed in FY02 with Tank Focus Area support, and assistance from DWPF. The main FY02 objective is to provide an engineered drawing of the glass contact materials, and define the utilities and methods required to operate and monitor it. Within funding and time limitations, the FY02 program also includes design evaluations to maximize melt rate improvement, to maximize bubbler life, and to reduce the consequences of potential process upsets. Small scale slurry feed testing will provide an indication of foam stability and the airlift's effects on offgas flow stability.

Prior to installation in DWPF, it is recommended that airflow requirements be defined, performance curves be developed, a control scheme be developed, and airlift life and failure modes estimated. FY02 Full scale airlift testing with glass and glycerin is expected to provide the most essential parts of this information.

The following tasks are presently being pursued to develop the airlift for use in the DWPF Melter:

1. Physical engineering will be conducted with a full size airlift mockup and glycerin at a viscosity of 60 poise. Critical engineering dimensions and features will be finalized based on these tests, such as air flow rate, depth of insertion, and height of the bottom ends of the outlet slots above or below the glycerin surface. Flow characteristics at the outlet slots of the bubbler, the foam propagation at the surface of the glycerin, and flow circulation patterns in the tank will be used to assess proper orientation of the glass discharge and determine the region of influence of the airlift.

2. An airlift prototype will be fabricated and tested in the Full Scale DWPF Pour Spout Test Stand for failure mode and erosion testing for up to 2 months. Figure 9 gives the current design details of this prototype and Figure 10 shows its installation in the DWPF Pour Spout Test Stand at Clemson University. This is primarily a life test to determine wear rates and to minimize the adverse consequences of possible equipment failure in the DWPF. This testing will also provide full-scale verification of airlift pumping performance in glass.

3. Slurry Melt Rate Furnace (SRMF) tests will be performed with a miniature airlift to obtain an early indication of melt rate increase and to investigate actual physical mechanisms that would occur with operation of a bubbler in a melter environment. Gas flow stability, and foam stability will be particular considerations, since they require control for program success. To the extent possible, data will be obtained on power use and temperatures in the glass, cold cap, and plenum, as well as melt rate and bubbler flow. This will be

useful in determining melt rate performance, and will also aid the modeling described below.

The following tasks could aid optimization of a bubbler in DWPF, but are not required for initial installation.

1. 2-dimensional FIDAP Computational Fluid Dynamics analysis of the DWPF Melter will incorporate a cold cap, one feed tube, and one airlift. The objective is to evaluate the potential melt rate improvement for an imposed airlift flow in this geometry, and develop a realistic representation of the cold cap. Modeling of the joule heating and flow circulation would include the effects of temperature dependent properties of thermal conductivity, viscosity, specific heat and electrical conductivity. The simulated cold cap would include the effects of foam porosity, heat of reaction, and radiant heat to and from the upper plenum as boundary conditions. The interaction of the airlift flow with the cold cap and the extent of cold cap melting and radiation to the upper plenum will thus be investigated.

2. For a more realistic prediction of the potential melt rate improvement, a 3-dimensional FIDAP Computational Fluid Dynamics analysis of a DWPF Melter model that incorporates one airlift located at the center thermowell position will be conducted. Using the same methodology as in the 2D analysis, the potential melt rate improvement based on increased flow recirculation inside the glass pool and heat transfer to the upper plenum and thence to the cold cap will be obtained.

Project Performance Risk

FY02 research is focussed on delivery of the minimum essential information required for trials in the DWPF. Melt rate increases will be maximized, and process performance risks will be identified and minimized within the limitations of time and funding. Optimum performance would require detailed testing of the interaction of the hot glass, foam and the cold cap, aqueous feed, and plenum temperatures at a larger scale than is currently available: The characteristic lateral distance of the cold cap feed pile is about 24-36 inches, and very small airlifts can not realistically duplicate the two phase flow in full size airlifts.

Possible performance issues are inability to remove the airlift, separation of airlift parts causing electrical short circuiting, accumulation of foam in the plenum, increases in gas surging, and increased wear of melter materials near the airlift. Materials settled on the bottom of the melter may also become suspended, and start circulating, which might be either an advantage or disadvantage. Ability to remove the airlift has high certainty because the airlift is based on the existing DWPF center thermowell design, and both the center thermowell and the glass height measuring bubbler have recently been successfully removed. Potential separation of the parts is being reduced by the use of ½ inch thick Inconel for fabrication, and by life testing to estimate wear rates and failure modes. Additionally, the recent bubbler removal after 6 years service did not show any tendency for parts to wear in such a way that they would fall off. Accumulation of additional foam in the melter could interfere with melter operation and further reduce heat transfer between the lid heaters and the cold cap, further reducing melt rate. The foam detector would warn of such an event, and turning off the gas flow to the airlift would allow the melter to recover. Thermocouples in the proposed airlift, and SMRF testing of slurry feeding with an airlift will address the foaming issues. Off-gas surging is a source of surging of glass flow in the pour spout, and indicates a possible overfeeding condition. Use of an airlift should increase the actual capacity of the melter, resulting in less surging. However, the potential interactions of hot glass pumped to the surface, and the aqueous feed are not known. Thus, SMRF tests will investigate the surging changes. The airlift is a strong pumping device, and dependent on it elevation from the bottom of the melter, it will suspend deposited particles, such as spinel and noble metals. This could be an advantage, since it would reduce the tendency for materials to accumulate and reduce melter effectiveness. On the other hand, large amounts of suspended material might cause adverse effects on pour spout performance by altering or partially blocking the flow of glass through the spout.

FY02 test are intended to investigate these potential effects to determine if design changes, operating controls, or further tests will be necessary.

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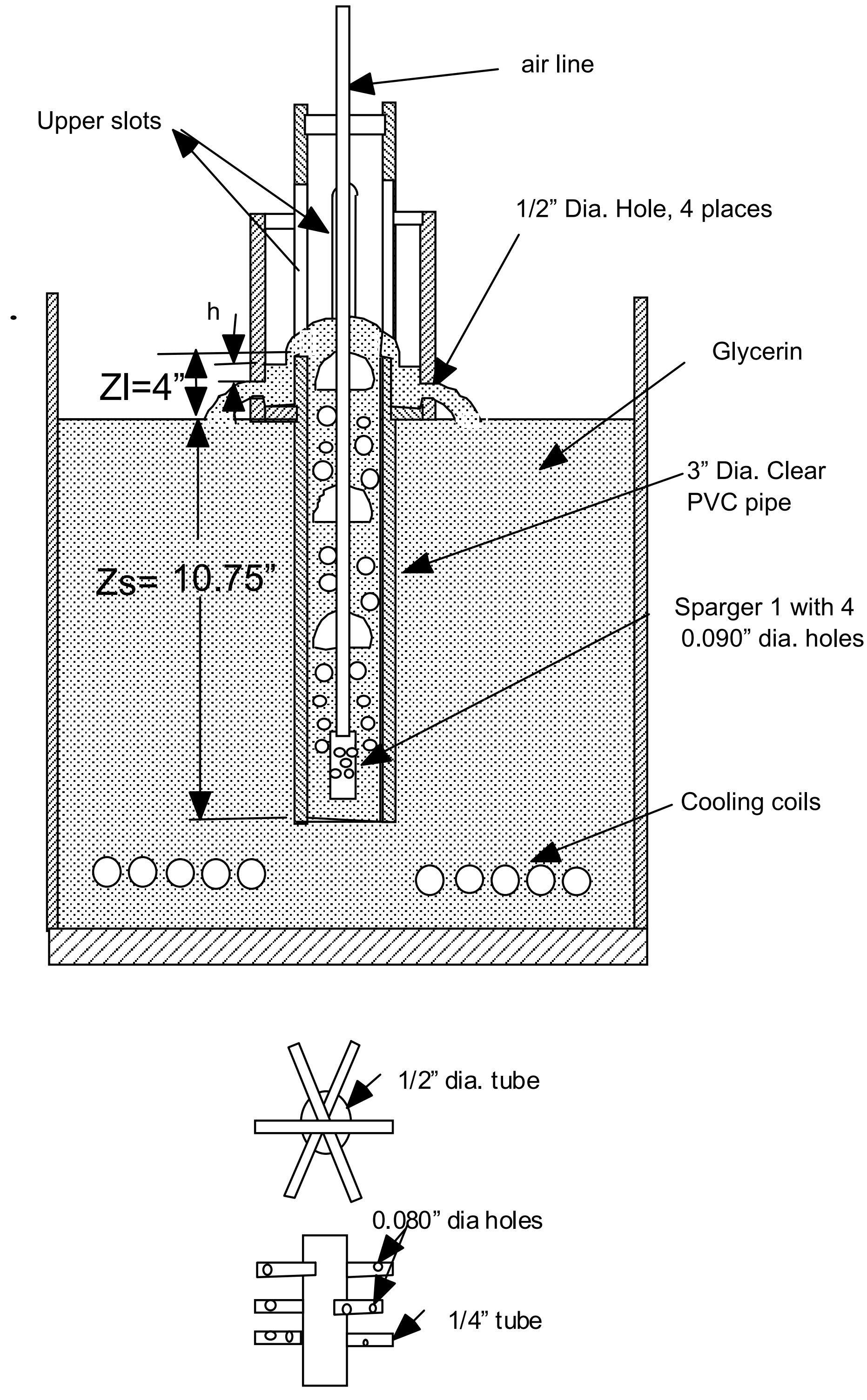
Figure 1 Airlift Bubbler in a Tank of Glyerin



Sparger with 8 -0.080" dia holes

(Actual sparger used)

Figure 2 Calibration Curve for 0.5-inch Orifice in Viscous Flow

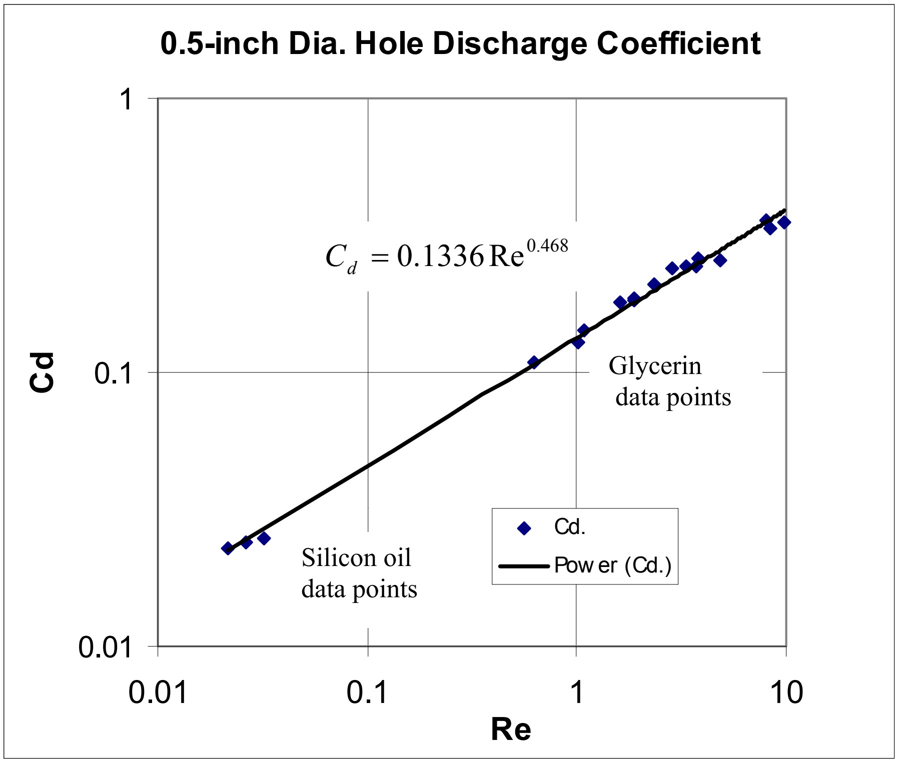


Figure 3 Measured Void Fraction Inside Airlift with Flowing Glycerin

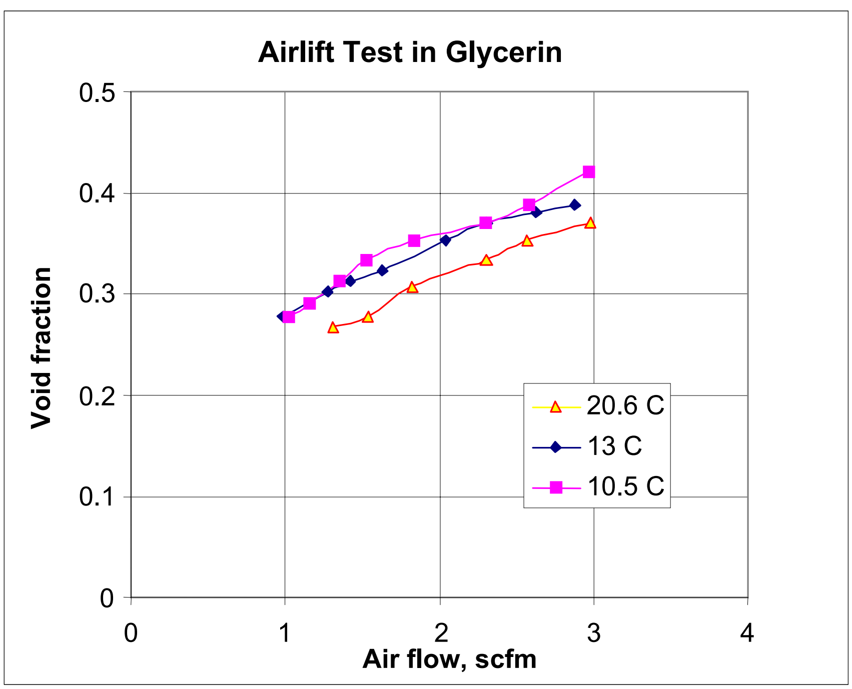


Figure 4 Measured Glycerin Flow as a Function of Injected Air Flow

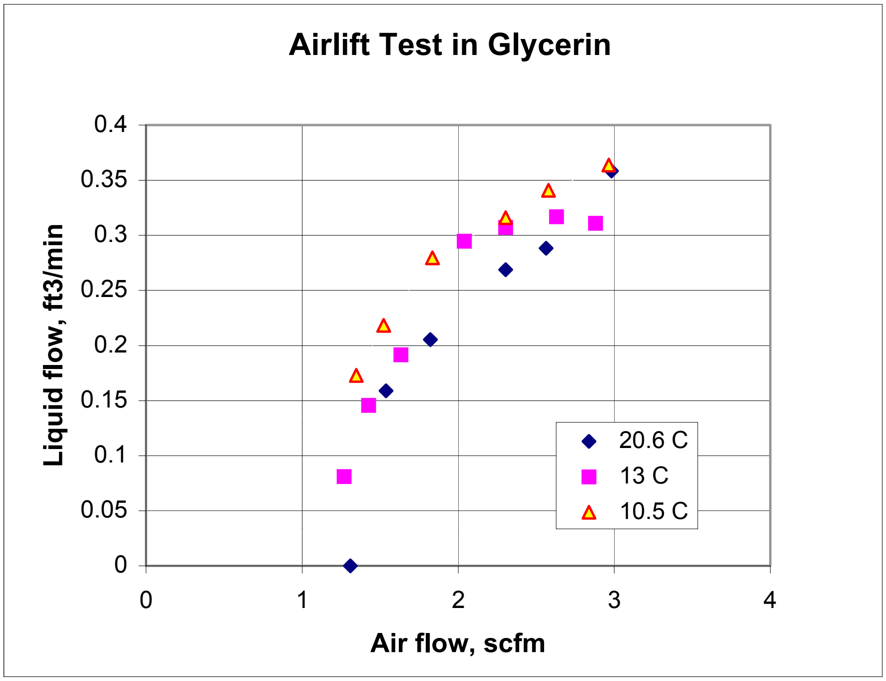


Figure 5 Calculated Bubble Drift Velocity in Glycerin Airlift

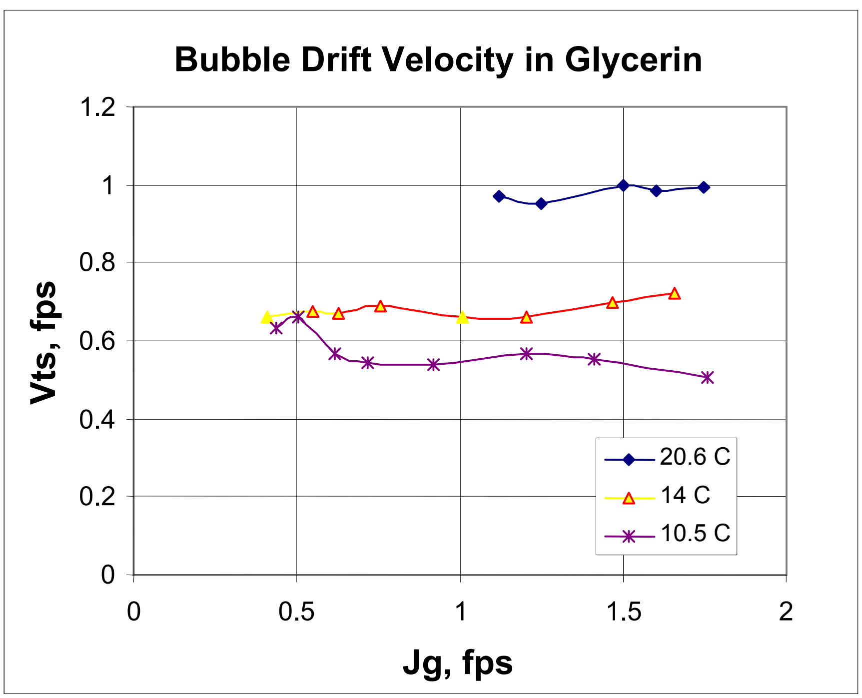


Figure 6 Proof of Priniciple Airlift for Clemson/Stir Melter Tests

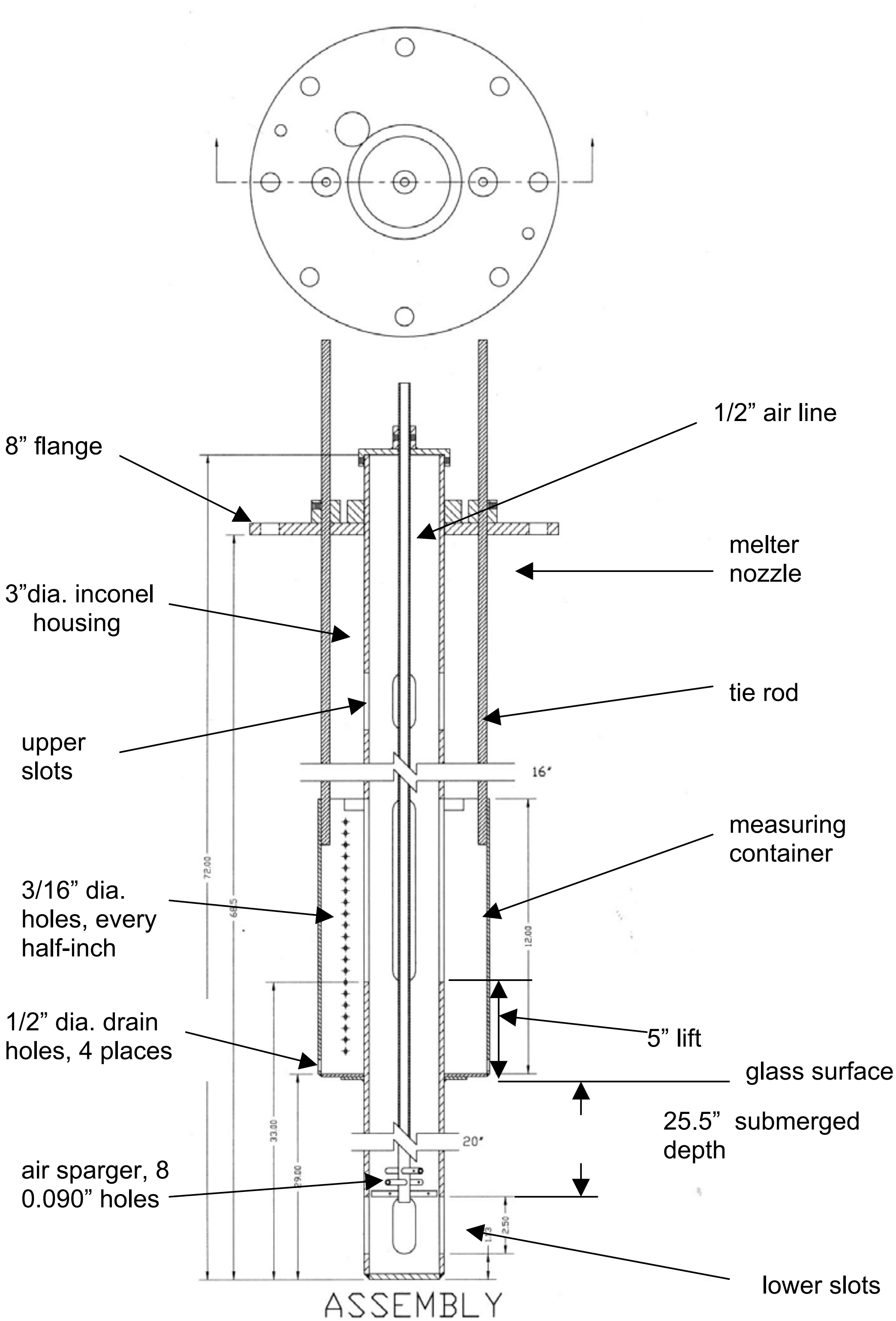


Figure 7 Glass Height inside Measuring Container During Proof- of-Principle Airflift Glass Tests

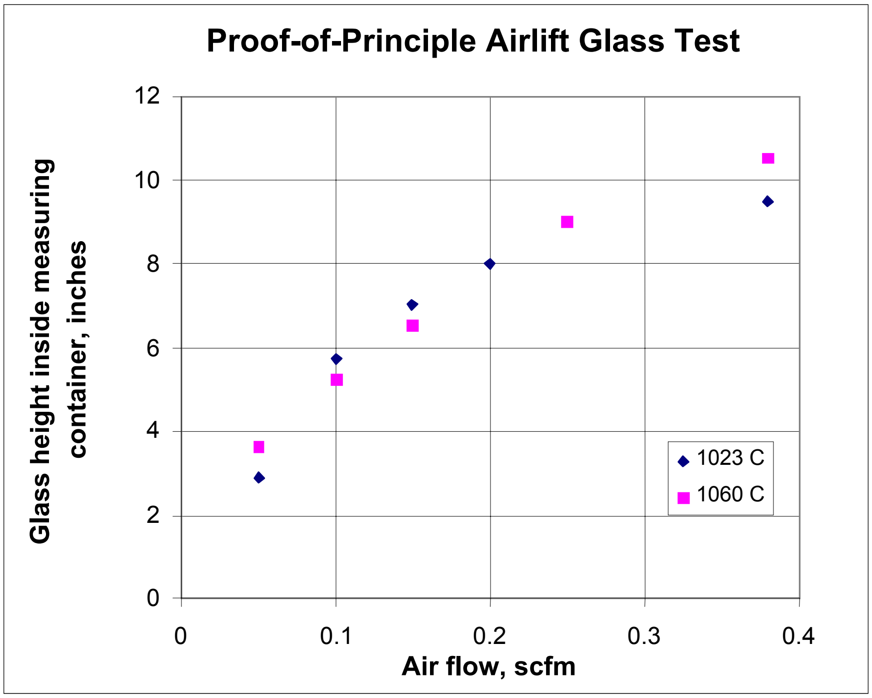


Figure 8 Measured Glass Flow Rate in Proof of Principle Airlift

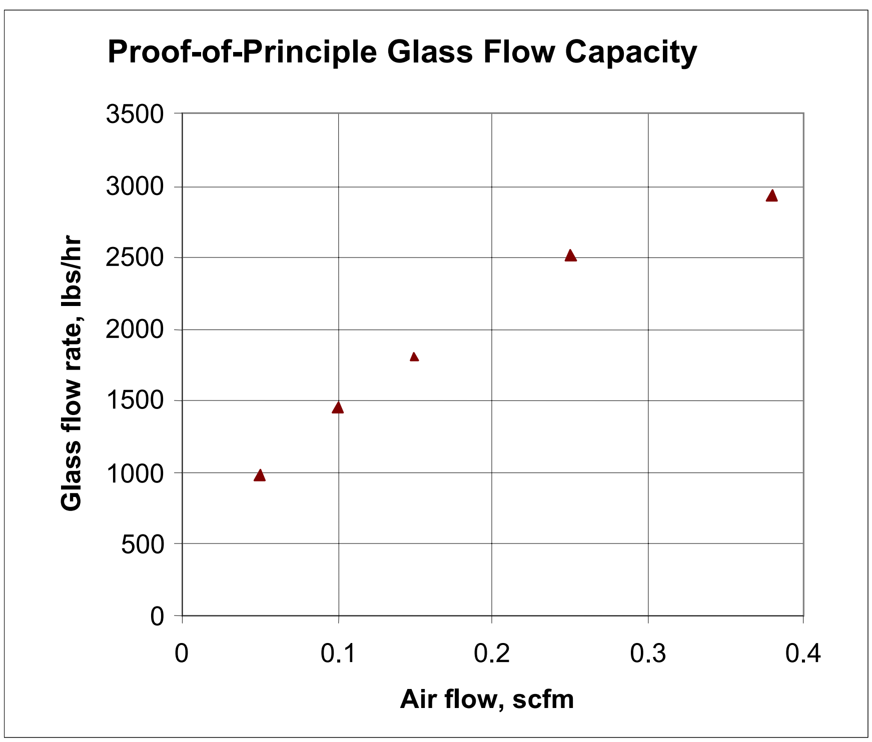


Figure 9 DWPF Airlift Bubbler Design Details

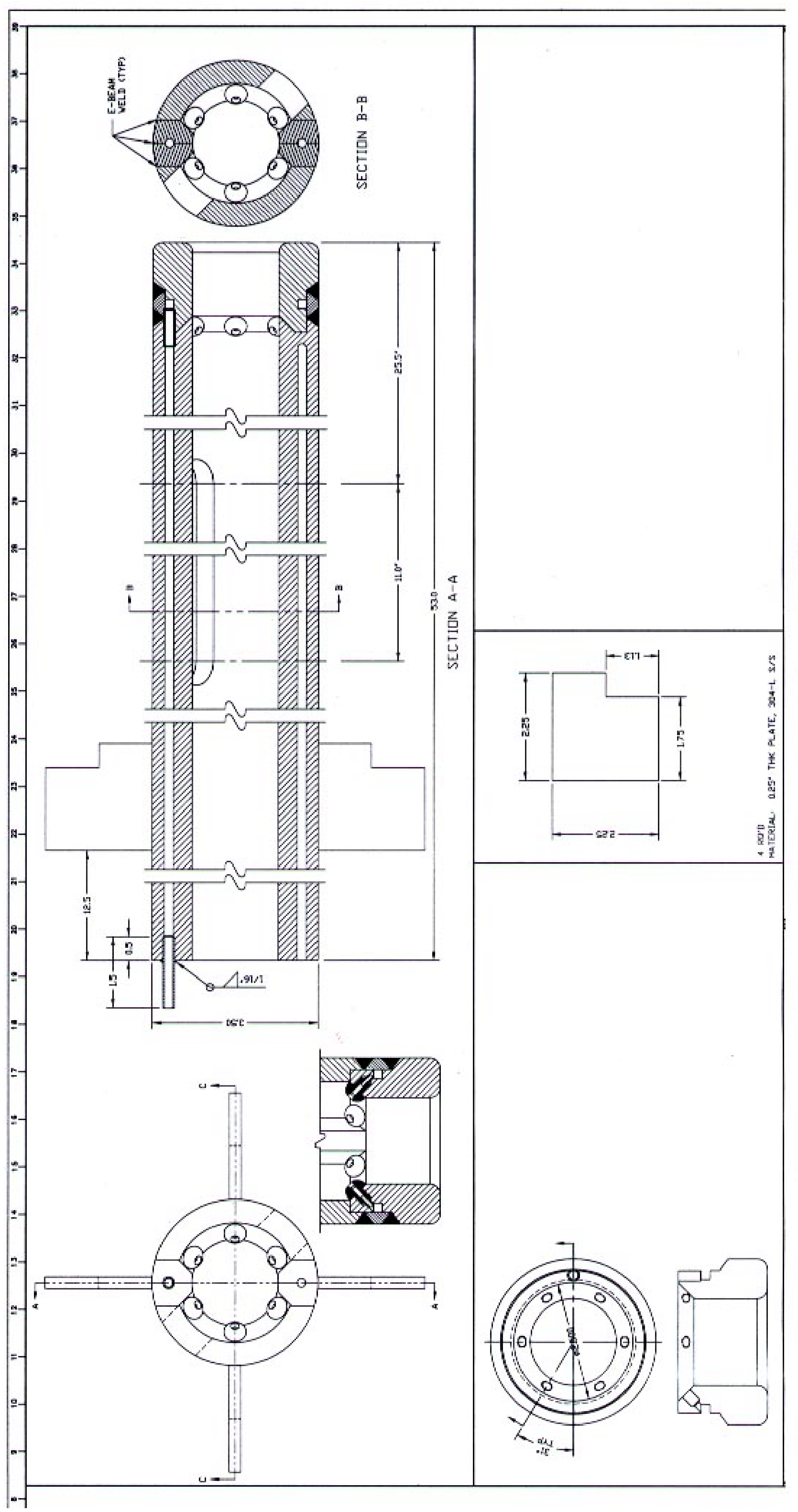


Figure 10 DWPF Airlift Bubbler Mockup in the DWPF Pour Spout Test Stand