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High-Level Waste Melter Alternate Bubbler Configuration Testing, VSL-04R4800-3, Rev. 0

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Office of River Protection

P.O. Box 450
Richland, Washington 99352

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Final Report

High-Level Waste Melter Alternate Bubbler Configuration Testing

prepared by

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and

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Test Scoping Statement(s): VH-4

Completeness of Testing:

This report describes the results of work and testing specified by the above-listed Test Specification(s), Test Plan(s), and Text Exception(s). The work and any associated testing followed established quality assurance requirements and was conducted as authorized. The descriptions provided in this test report are an accurate account of both the conduct of the work and the data collected. Results required by the Test Plan are reported. Also reported are any unusual or anomalous occurrences that are different from the starting hypotheses. The test results and this report have been reviewed and verified.

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VSL Program Director/Principal Investigator

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Duratek Sub-Contract Manager

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List of Abbreviations

DM	DuraMelter®
DOE	Department Of Energy
HLW	High Level Waste
LAW	Low Active Waste
QAPjP	Quality Assurance Project Plan for Testing Programs Generating Environmental Regulatory Data
QAPP	Quality Assurance Project Plan
RPP-WTP	River Protection Project-Waste Treatment Plant
VSL	Vitreous State Laboratory
WTP	Hanford Tank Waste Treatment and Immobilization Plant

SUMMARY OF TESTING

A) Objectives

Bubbling, which is a key feature of the DuraMelter systems selected for WTP LAW and HLW vitrification, has a profound effect on the achievable melting rates. As a result of WTP flow-sheet projections that show reduced solids content of the feed to the HLW melters and previous testing, it was determined that the existing HLW bubbler configuration would not support the WTP HLW glass production rate requirements. This work was designed to address that shortfall through optimization of the HLW bubbler configuration while minimizing the impact on design. To that end, it is desirable to have a better understanding of the controllable bubbling parameters and their influence on melting rates. The general objectives of the tests described were to characterize the baseline bubbling conditions for which feed processing data are already available from the DM1200; examine minor modifications to the bubbling conditions and/or configurations with the goal of improving bubbler action; and to suggest configurations to be tested in future DM1200 melter campaigns. Specific test objectives are listed below:

Test Objective	Objective Met (Yes/No)	Discussion
With single-nozzle bubblers installed in production run locations observe and record the effects of bubbling for the run tested operating envelope of the bubblers. Describe the test conditions and observations and relate the observations to run melting rates where possible.	Yes	These tests are discussed in Section 3.1.1
Using pairs of single-nozzle bubblers, observe and record the effects of bubbling for conditions representing those for which production data are available. Where possible, relate the observations to melting rates obtained under similar bubbling conditions	Yes	These tests are discussed in Section 3.1.1
Determine the ability of pairs of single-nozzle bubblers supplied by a single air line to provide balanced flow, to clear the bubbler after flooding, and to clear the bubbler after insertion.	Yes	These tests are described in Section 3.1.2 – Tests 1.C and D
If the baseline 0.25" nozzle diameter does not yield successful flooding and insertion behavior, determine whether 0.125" nozzles will satisfy the requirements.	Yes	Since the 0.25" nozzle tests were successful, this optional test was not required.

Test Objective	Objective Met (Yes/No)	Discussion
With double-nozzle 0.125" bubblers installed in the baseline DM1200 locations, observe and record the effects of bubbling for the nominal range of melter bubbler depths and rates. Relate the observations to those of the single bubbler case.	No	Tests were first performed with double-nozzle 0.25" bubblers. Since the 0.25" nozzle tests were successful, this test was not required. The 0.125" orifice tests were deleted by Test Exception 24590-WTP-TEF-RT-04-00021 [8].
Determine the ability of the double-nozzle bubbler to clear after flooding and to clear after insertion under a range of conditions.	Yes	Tests were first performed with double-nozzle 0.25" bubblers. Since the 0.25" nozzle tests were successful, this test was not required.
If the clearing tests are successful, determine whether success can also be obtained with 0.25" nozzles.	Yes	The 0.25" nozzles were able to clear under all tested conditions.
If the balance and clearing tests of the single bubblers supplied from a single airline is not successful, test flow restrictors for each single bubbler to improve the performance.	Yes	The tests indicated that clearing and balanced flow were achieved without any flow restrictors.
Report the results of the tests, relating them to melter production data where possible.	Yes	See the discussion in Section 4.
Construct a physical model of sufficient size to examine bubbler performance as it relates to the WTP HLW melter.	Yes	The description of the model is given in Section 2.2 and the beginning of Section 3.2.
Utilize a model fluid and a bubbler gas that approximates as nearly as is practical the viscosity and density of the molten glass and the buoyancy of the gas.	Yes	See Section 2.2 and the beginning of Section 3.2
Observe and record the effects of bubbler depth, bubbling rate, nozzle size, nozzle orientation, and wall proximity.	Yes	See Section 3.2
Relate the results of the model testing to corresponding tests in the DM1200.	Yes	See Sections 3.2 and 4
From the test results, determine bubbler configurations and conditions to be tested in future DM1200 melter campaigns.	Yes	The recommended bubbler configuration for the DM1200 based on the tests results is two double-nozzle bubblers located in opposite corners of the melter. The nozzle separation should be 8” and the depth 25”. Each bubbler has one nozzle, 11.3” from the center of the feed port. The total air flow rate should be a minimum of 64 l/min or 54 $l/min/m^2$ of melt surface area.

B) Test Exceptions

Test Exception	Description
24590-WTP-TEF-RT-04-00021	Elimination of 0.125” orifice testing in the DM1200.

C) R&T Test Conditions

The tests performed utilizing the DM1200 were done under the following conditions. The melter was in idle condition with no cold cap. The glass temperature was maintained at an approximate average temperature of 1125°C. The temperature ranged from 1095 to 1150°C. The plenum was under moderate negative pressure (-0.1" W.C.) with the off-gas system in the bypass mode. The bubblers employed were previously used L- and J-bubblers or a new double-nozzle J-bubbler. Air was supplied to the bubblers using mass flow controllers, which also indicated the flow rates employed. The flow was measured in standard liters/min. The bubbler back-pressure was measured by indicating transducers located near the bubbler lance connection. The supply piping to the bubblers was identical to that used during normal melter tests with the exception of those tests that supplied two bubblers from a single supply pipe. In that case, a splitter was added to the supply line so that a pair of bubblers could be supplied from one source. For each DM1200 test condition, the melt surface of the DM1200 was examined visually and recorded by video camera for later analysis.

DM1200 bubbler tests were begun on 12-15-2003 using previously-used single-orifice bubblers in configurations and with flow rates duplicating those used in previous melter campaigns. The melt temperature was maintained between approximately 1100°C and 1150°C for the tests; there was no cold cap. Digital video photography was employed to record the melter surface during the bubbling tests at a rate of 30 frames per second. The configurations tested included three bubbling depths, approximately 14", 20", and 26" below the melt surface. Air flow rates in standard liters per minute measured and controlled by mass flow controllers included 16, 32, and 40 l/min per bubbler orifice, representing the rates used in DM1200 melter tests. For specific tests, air flows were tested as high as 90 l/min for a single orifice. These tests were completed on 12-18-03.

On 2-4-04 a single double-orifice bubbler was tested in the DM1200 under conditions similar to those discussed above. To obtain the same per-orifice flow rates as the above tests, the tested flow rates included 32, 64, and 80 l/min.

Beginning on 2-26-04, a variety of bubbler configurations were tested in a physical model system. The physical model tests were performed in an acrylic tank of square cross section. The inside dimensions of the tank were 30" x 30" x 48". Since the nominal nozzle position was 11.5" from the nearest wall in the DM1200, the 30" dimension was considered sufficient for comparison tests. The depth was sufficient to match the depth of the WTP HLW melter. An 18"-high plenum extension was added to allow space for the rising bubbles to splash. The tank was fitted with an acrylic lid. Digital video cameras were used to record the bubbling tests. The model fluid utilized in the tests was a mixture of corn syrup and $ZnBr_2$ which was prepared by NOAH Chemical Co. The specific gravity of the mixture was close to 2 g/cc, compared to a value of about 2.3 g/cc for the molten glass. The viscosity of the mixture was about 85 poise at 20°C (room temperature during the bubbling tests). This compares to the viscosity of the molten glass of about 50 poise at 1150°C. The surface tension of molten glass is about 300 dyne/cm compared to a surface tension for the syrup mixture on the order of 100 dyne/cm. The tank was filled to a depth of about 42". The bubblers were fabricated of clear ½" schedule 40 acrylic pipe with interchangeable orifices. The inside diameter of this pipe is within 1.5% of that of the DM1200 bubbler pipes. For the majority of the tests the bubbler was fitted with the same air ballast as the DM1200 bubblers (vol. = 1.7 l). For additional tests, the ballast was either removed or replaced with a much larger ballast (vol. = 37 l). Available orifices were 1/16", 1/8", ¼" and ½", which could be oriented either horizontally or vertically.

The air was supplied to the bubbler using 3/8" plastic tubing, as in the DM1200. The flow rate was adjusted using a rotameter. In the DM1200, the air is metered and measured at room temperature but it exits the bubbler nozzle at much higher temperature. This causes the actual volume of gas exiting the nozzle to be much higher than that measured. An estimate of the temperature rise and, thus, the volume increase expected was made based on heat transfer calculations. Assuming the glass to be at 1150°C it was estimated that the air would be heated to about 630°C and the volume, based on the ideal gas law, would be increased by a factor of about 2.8. This factor was applied to the standard flow rates to obtain the flows for the model tests. Flow rates of 45, 90, and 113 liters/min were used to correspond to the DM1200 flow rates of 16, 32 and 40 liters/min. Testing was completed on 3-3-04.

D) Results and Performance Against Success Criteria

Bubbler tests were conducted in the DM1200 on single-nozzle bubblers from 12-15-03 until 12-18-03. During that time more than 33 bubbling tests were performed and video records were made. These tests examined the range of bubbler configurations and conditions that have been previously employed for production runs in the DM1200 melter. The range of parameters was expanded to include those that might be reasonably employed in future tests. Flow rates from 16 l/min to 90 l/min per nozzle were examined at bubbler depths from 14 to 16 inches. Examination of the videos allowed qualitative judgments to be made regarding the effectiveness of the bubbling configurations and operating parameters. In general, it was found that higher air flow rates and a greater number of bubbler outlets appeared to show better mixing. Clearing of single bubblers and pairs of bubblers fed from a single air supply was successfully tested after flooding with glass.

Subsequently, a double-nozzle J-bubbler was tested in the DM1200. Ten tests were performed to determine a baseline of performance for this bubbler for comparison to the single-nozzle bubblers. The bubbling characteristics were evaluated based on the subjective observation of the distribution of bright glass over the melt surface. It was assumed that a relatively uniform bright distribution indicated good mixing whereas, by contrast, a surface with dark, obviously dead areas indicated poor mixing. While, on this basis, the results indicated that good mixing was achieved, it was not clear what the distribution of air flow between the two nozzles in the bubbler was; however, the appearance was that the flow was greater in the end nozzle. Flooding and clearing tests were successfully performed on this bubbler.

A model tank of sufficient size (30” X 30” X 48” deep) to simulate the conditions of the full-scale WTP HLW melter was constructed of clear acrylic. Single- and dual-nozzle bubblers were fabricated having interchangeable nozzles including diameters of 1/16", 1/8", ¼" and ½". A model fluid with viscosity and density close to that of molten glass consisting of a mixture of corn syrup and $ZnBr_2$ was used for these tests. More than 85 tests were performed with this model system from 2-26-04 to 3-3-04. The baseline configurations that had been employed in DM1200 melter runs as well as a wide range of depth, flow rate, nozzle diameter, and orientation variations were examined. The result of these tests was the selection of the dual 0.25"-diameter nozzle bubbler for future production run testing in the DM1200 melter.

E) Quality Requirements

This work was conducted under an NQA-1 (1989) and NQA-2a (1990) Part 2.7 based quality assurance program that is in place at the VSL. This program is supplemented by a Quality Assurance Project Plan for RPP-WTP work that is conducted at VSL. Test and procedure requirements by which the testing activities are planned and controlled are also defined in this plan. The program is supported by VSL standard operating procedures that were used for this work.

This work did not generate data to support waste form qualification activities; nor did it generate data to support environmental regulatory data to support permitting activities. Therefore, this work was not subject to DOE/RW-0333P or the WTP QAPjP for environmental and regulatory data.

F) Simulant Use

No waste simulants were used in this work.

G) Issues/Follow-on Work

The present effort was focused on rapid identification and validation of a practical solution to the shortfall in HLW glass production rates, which has been accomplished. However, in the course of this effort, many novel aspects of bubbler operation have been revealed, which suggest that further optimization should be possible. In particular, in addition to the very illuminating physical modeling performed in the present work, it is likely that fluid flow modeling could also be valuable. There have been many recent advances in fluid flow modeling and, in fact, one problem that has seen recent interest is the problem of bubbles rising in a viscous liquid. It is interesting to note that the numerical simulations resulted in similar bubble shapes as those observed in the present work. The observed bubble capture is also described and modeled and follows closely the observations described in this report.

SECTION 1.0
INTRODUCTION

The River Protection Project - Waste Treatment Plant (RPP-WTP) High-Level Waste (HLW) melter system was originally designed to produce approximately 1.5 metric tons of glass per day per melter. As the project has progressed, that target has been raised to 3 metric tons of glass per day per melter. Further, the water content of the feed presented to the melter has gradually increased making it more difficult to achieve the target melting rates. Bubbling has been recognized as one adjustable operating parameter that, if further optimized, may permit the achievement of the target rate and perhaps provide some operating margin to maintain the desired rates over the expected operating envelope. The main objective of the work discussed in this report is the optimization of the bubbling configuration and operation to achieve the needed processing rates. In view of the advanced stage of design, a constraint on this optimization is that it must be done in such a way that it has minimal impact on the current melter design. The tests and results described herein address bubbler configuration testing under non-feeding conditions. The results of these tests are being used to down-select preferred options for subsequent testing in the DM1200 HLW pilot melter system employing HLW simulants. Those tests are the subjects of separate Test Plans and reports. This report focuses on assessing the characteristics of various alternative bubbler configurations in the idling DM1200 melter and in a physical model system consisting of a room-temperature fluid-filled tank. The tests described in this report are responsive to the Test Specification [1] and test guidance [2] provided by the WTP Project, as detailed in the Test Plan [3].

1.1 Test Objectives

The first test objective was to characterize the baseline bubbling conditions and configurations for which feed processing data were already available from previous tests on the DM1200. The second objective was to determine whether minor modifications to the bubbling conditions and/or configurations could provide more efficient bubbler action. The results of these tests were evaluated to suggest configurations to be used in future DM1200 melter campaigns. The effects that these tests addressed include:

Melter Tests

- Establish Baseline Bubbling Characteristics - Single bubbler/Single nozzle
    - Bubbler depth effects
    - Air flow rate effects
    - Effects of wall proximity

- Examine the two-nozzle option
    - Determine baseline with pairs of single-nozzle bubblers
    - Examine effectiveness of single, double-nozzle bubbler
    - Examine effect of nozzle size
    - Examine effect of nozzle location

Model Tests – Room Temperature Model

- Effects of nozzle size
- Effects of nozzle orientation
- Effects of bubbler depth
- Effects of flow rates
- Effects of nozzle separation
- Effects of wall proximity

The Objectives of these tests were [1-3]:

<u>DM1200 Tests</u>

1. With new or existing single-nozzle bubblers installed in locations representing those for which melter production data are available, observe and record the effects of bubbling for a range of conditions representing the tested operating envelope of the bubblers. Where possible, relate the observations to melting rates obtained under similar bubbling conditions. If correlation is not possible, describe the conditions of the tests, what was observed, and what correlations were investigated.
2. Using pairs of single-nozzle bubblers, observe and record the effects of bubbling for conditions representing those for which production data are available. Where possible, relate the observations to melting rates obtained under similar bubbling conditions.
3. Determine the ability of pairs of single-nozzle bubblers supplied by a single air line to provide balanced flow, to clear the bubbler after flooding, and to clear the bubbler after insertion.
4. If the baseline 0.25” nozzle diameter does not yield successful flooding and insertion behavior, determine whether 0.125” nozzles will satisfy the requirements.
5. With new double-nozzle 0.125” bubblers installed in locations representing the baseline DM1200 locations, observe and record the effects of bubbling for the nominal range of melter bubbler depths and rates. Relate the observations to those of the single bubbler case.
6. Determine the ability of the double-nozzle bubbler to clear after flooding and to clear after insertion under a range of conditions.

7. If the clearing tests are successful, determine whether success can also be obtained with 0.25” nozzles.
8. If the balance and clearing performance of the single bubblers supplied from a single airline is not successful, determine whether adding flow restrictors for each single bubbler can improve the performance.
9. Report the results of the tests, relating them to melter production data where possible.

Physical Model Tests

10. Construct a physical model of sufficient size to examine bubbler performance as it relates to the WTP HLW melter.
11. Utilize a model fluid and a bubbler gas that approximates as nearly as is practical the viscosity and density of the molten glass and the buoyancy of the gas.
12. Observe and record the effects of bubbler depth, bubbling rate, nozzle size, nozzle orientation, and wall proximity.
13. Relate the results of the model testing to corresponding tests in the DM1200.

Draw Conclusions

14. From the test results, determine bubbler configurations and conditions to be tested in future DM1200 melter campaigns.

1.2 Success Criteria

The Success Criteria with respect to the objectives above are [1-3]:

DM1200 Tests

1. With new or existing single-nozzle bubblers installed in locations representing those for which melter production data are available, observe and record the effects of bubbling for a range of conditions representing the tested operating envelope of the bubblers. Where possible, observations are related to melting rates obtained under similar bubbling conditions. If correlations cannot be made, the testing conditions and observations are reported and discussed.
2. Using pairs of single-nozzle bubblers, observe and record the effects of bubbling for conditions representing those for which production data are available. Where possible, relate the observations to melting rates obtained under similar bubbling conditions
3. Determine the ability of pairs of single-nozzle bubblers supplied by a single air line to provide balanced flow, to clear the bubbler after flooding, and to clear the bubbler after insertion.

4. If the baseline 0.25” nozzle diameter does not yield successful flooding and insertion behavior, determine whether 0.125” nozzles will satisfy the requirements.
5. With new double-nozzle 0.125” bubblers installed in locations representing the baseline DM1200 locations, observe and record the effects of bubbling for the nominal range of melter bubbler depths and rates. Relate the observations to those of the single bubbler case.
6. Determine the ability of the double-bubbler to clear after flooding and to clear after insertion under a range of conditions.
7. If the clearing tests are successful, determine whether success can also be obtained with 0.25” nozzles.
8. If the balance and clearing performance of the single bubblers supplied from a single airline is not successful, determine whether adding flow restrictors for each single bubbler can improve the performance.
9. Report the results of the tests, relating them to melter production data where possible.

Physical Model Tests

10. Construct a physical model of sufficient size to examine bubbler performance as it relates to the WTP HLW melter.
11. Utilize a model fluid and bubbler gas that approximates as nearly as is practical the viscosity and density of the molten glass and the buoyancy of the gas.
12. Observe and record the effects of bubbler depth, bubbling rate, nozzle size, nozzle orientation, and wall proximity.
13. Relate the results of the model tests to the DM1200 melter results.

Draw Conclusions

14. From the test results, determine bubbler configurations and conditions to be tested in future DM1200 melter campaigns.

1.3 Test Overview

The Test Plan [3] was responsive to the Test Specification [1] and test guidance [2] provided by the WTP Project. The Test Plan was based closely on the test guidance [2] that was developed by representatives of the HLW melter design group. The test guidance [2] suggested a series of tests to examine the behavior of several potential bubbler design changes. The design changes were intended to explore the possibility of improving bubbler efficiency in the WTP HLW melter by incorporating changes that are intended to assure achievement of the required HLW production rates, provide sound design for reliable operations, and yet have minimal impact on the current design. The tests took advantage of the existing DM1200 melter and the data base of melter production data obtained over a range of bubbling conditions. To expand the tests to include results for a melter depth equal to that of the full-scale WTP HLW melter, a room temperature model was also employed.

1.4 Quality Assurance

This work was conducted under an NQA-1 (1989) and NQA-2a (1990) Part 2.7 based quality assurance program that is in place at the VSL. This program is supplemented by a Quality Assurance Project Plan (QAPP) for RPP-WTP work [4] that is conducted at VSL. Test and procedure requirements by which the testing activities are planned and controlled are also defined in this plan. The program is supported by VSL standard operating procedures that were used for this work [5]. This work was not subject to DOE/RW-0333P. Special requirements of the WTP QAPjP [6] do not apply to this work.

SECTION 2.0
TEST DETAILS/TEST MATRIX

2.1 DM1200 Test Design Details

The test guidance [2] outlined a range of potential bubbler option concepts that might achieve the objectives of improved bubbler efficiency and minimal impact on plant design. In ascending numerical order, the options have modest plant design and construction cost until Option 5, (two independent air supplies to two nozzles for each of the five bubblers). Option 5 would likely have significant cost and schedule impacts. The testing strategy specified in the Test Plan [3] was to determine whether an option other than Option 5 would be likely to achieve the required HLW production rates to support subsequent verification in DM1200 melter runs with HLW simulants.

The tests performed utilizing the DM1200 were done under the following conditions. The melter was in idle condition with no cold cap. The glass temperature was maintained at an approximate average temperature of 1125°C. The temperature ranged from 1095 to 1150°C during the tests. The plenum was under moderate negative pressure (-0.1" W.C.) with the off-gas system in the bypass mode. The bubblers that were employed were previously-used L- and J-bubblers or a new double-nozzle J-bubbler, in configurations specified by the test matrix. Air was supplied to the bubblers using mass flow controllers, which also indicated the flow rates employed. The flow was measured in standard liters/min. The bubbler back pressure was measured by indicating transducers located near the bubbler lance connection. The back pressure was normally slightly larger than the head pressure of the molten glass (about 2.6 to 2.8 psi). The supply piping to the bubblers was identical to that used in previous melter tests performed while feeding, with the exception of those tests that supplied two bubblers from a single supply pipe. In that case, a splitter was added to the supply line, as indicated in Figure 1, so that a pair of bubblers could be supplied from one source.

For each DM1200 test condition, the melt surface of the DM1200 was examined visually and recorded by video camera for later analysis. Figures 2-9 show the camera and representative images of the bubbled DM1200 melt surface. For analysis of the video data, consideration was given to using image analysis software, which it was thought might be useful in evaluating the images of the melter surface to determine bubble frequency, temperature profiles, and bubble area at the surface. While this may be possible, it was determined that the development of reliable procedures to utilize such software would have required a more extensive effort than was planned for these tests. Further, it was found that even simple bubble-counting, performed by attempting to observe and count the bubbles as they broached the melt surface, was highly subjective. This was due to the poor contrast in the hot glass melt and to the inability to distinguish multiple bubbles broaching the surface at nearly the same time. However, the DM1200 tests showed qualitatively the degree of surface activity produced under each bubbling condition. The tests also were able to demonstrate the flow patterns for double-orifice bubblers and, importantly, the clearing of flooded bubblers under a variety of conditions.

Figure 10 shows the DM1200 lid ports that were available for the tests and Figures 11-13 show the test configurations (discussed below) that were utilized in the tests indicated in the test matrices (Tables 1-3). The test matrices indicate tests that were either performed or deemed unnecessary. The data obtained in these tests consisted primarily of the videos and their analysis along with the test conditions, including air flow, bubbler back-pressure, and melt temperature.

2.1.1 Test 1 Design Details

Test 1: Determination of a nozzle diameter for two nozzles that can operate effectively from one air supply (Option 2).

A'. A baseline study using the bubbler configurations and testing conditions described in reference [7]. Briefly, these configurations consist of: 1) the nominal configuration with single bubblers in diagonal corners of the melter with the nozzles about 11.5” from the wall (see Figure 10 a.); 2) the same configuration but with the nozzles about 6” from the wall (see Figure 10 b); 3) double nozzles separated by 8” with one nozzle 11.3” from the feed tube (see Figure 10 c); 4) an asymmetric configuration with one nozzle 11.3” from the feed tube (see Figure 10 c with only the nozzles near port C2 and A2 supplied with air) ; and 5) double nozzles separated by 14” (see Figure 10 d). (Table 1. A').

A. A baseline study of the surface bubbling for the single-nozzle configuration while idling at nominal temperature. After bubbling was initiated for each condition the melt surface was observed and a digital video record was made of the steady-state behavior with the bubbler nozzle located at -14", -20", and -26" with respect to the melt surface and with flow rates covering the normal operational range for the DM1200. The single nozzle was positioned about 11.5" from the nearest melter wall. The nominal flow rate for the DM1200 has been 32 l/min per bubbler for two single bubblers and the range has been from about 16 l/min to a maximum of about 40 l/min for a single bubbler. (Table 1. A).

B. A baseline study of the surface bubbling for **two** pairs of single-nozzle bubblers with **four independent** air supplies and nozzles separated by 8" then 14" while idling at nominal temperature. See Figures 10 c and 10 d for the nozzle locations. Digital video images were recorded for bubbler nozzles at -20" and -26" below the surface with flow rates of 16, 32, and 40 l/min for each nozzle. (Table 1. B).

C. Two bubblers with individual flow indicators were piped with a **single** air supply, as shown in Figure 1. The piping and fittings after the split were identical to insure equal piping and fitting losses. For total flows of 32, 64, and 80 l/min, total flow and individual flows to each bubbler were observed. A digital video record was made of the tests for comparison to the results of Test 1.B. (Table 1. C)

D. The bubblers were allowed to flood up to glass level for more than 60 minutes and air flow was set to initiate flow at 50% of nominal until clearing occurred. The pressure required to clear the nozzles was recorded as well as the approximate time to clear for each nozzle. Digital video recording of the melt surface was made during clearing. A second recording was made after several minutes to examine the steady-state bubbling for the cleared bubblers. (Table 1.D).

E. Since the clearing tests were successful, the insertion tests were unnecessary and were not performed. (Table 1. E).

F. Since the clearing tests were successful with the 0.25” nozzle bubblers, no tests were performed on 0.125” nozzle bubblers.

2.1.2 Test 2 Design Details

Test 2. Single bubbler, dual nozzle verification test of Option 2. In the tests below, balanced flow was judged by visual observation only. An acceptable balance was deemed to be a 60/40 split or better.

A. A double-nozzle J-bubbler was fabricated based on a design sketch supplied by the project (Figure 14). The “as required" length was 84". Because of the success with the 0.25” diameter nozzles in the above tests the initial bubbler was fabricated with 0.25” nozzles rather than with 0.125” nozzles [8]. The bubbler was installed in the melter while maintaining air flow. The nozzle positions are shown in Figure 10 e. The bubbler was operated at 32, 64, and 80 l/min total flow and a digital video record was made for comparison to those of Test 1. (Table 2. A).

B. Since the above tests were successful, flooding tests were performed. The bubbler was allowed to flood up to the glass level with the air shut off for 3 hours. The bubbler was cleared by initiating flow at 50% of nominal. The clearing was digitally recorded, as was the apparent flow distribution between the nozzles. The flooding tests were repeated several times for confirmation. (Table 2.B).

C. Since the flooding tests were successful, the insertion tests were not required.

D. As stated above, the tests were done with the 0.25” nozzles. (Table 2. C).

Since the tests were successful, it was not necessary to perform Test 3 of the Test Plan [3].

2.2 Model Test Design Details

The physical model tests were performed in an acrylic tank of square cross section. The experimental setup is shown in Figures 15 and 16. The inside dimensions of the tank were 30" x 30" x 48". Since the nominal nozzle position was 11.5" from the nearest wall in the DM1200, the 30" dimension was considered sufficient for comparison tests. The depth was sufficient to match the depth of the WTP HLW melter. An 18"-high plenum extension was added to allow space for the rising bubbles to splash. The tank was fitted with an acrylic lid. Digital video cameras were used to record the bubbling tests. The model fluid utilized in the tests was a mixture of corn syrup and $ZnBr_2$ which was prepared by NOAH Chemical Co. based on screening tests performed at VSL. The specific gravity of the mixture was close to 2 g/cc, as compared to a value of about 2.3 g/cc for the molten glass. The viscosity of the mixture was about 85 poise at 20°C (room temperature during the bubbling tests), as compared to the viscosity of the molten glass of about 50 poise at 1150°C. The surface tension of molten glass is about 300 dyne/cm compared to a surface tension for the syrup mixture on the order of 100 dyne/cm. The tank was filled to a depth of about 42". The bubblers were fabricated of clear ½" schedule 40 acrylic pipe with interchangeable orifices. The inside diameter of this pipe is within 1.5% of that of the DM1200 bubbler pipes. For the majority of the tests, the bubbler was fitted with the same air ballast as the DM1200 bubblers (vol. = 1.7 l). For additional tests, the ballast was either removed or replaced with a much larger ballast (vol. = 37 l). Available orifices were 1/16", 1/8", ¼" and ½", which could be oriented either horizontally or vertically.

Air was supplied to the bubbler using 3/8" plastic tubing, as in the DM1200. The flow rate was adjusted using a rotameter. In the DM1200, the air is metered and measured at room temperature but it exits the bubbler nozzle at much higher temperature. This causes the actual volume of gas exiting the nozzle to be much higher than that measured. An estimate of the temperature rise, and thus the volume increase expected, was made based on heat transfer calculations [9]. The assumptions for those calculations were based on nominal melting (feeding) conditions in the DM1200. The plenum temperature was assumed to be 550°C, the bubbler pipe was ¾" schedule 160 with a plenum length of 32" and a glass length of 32". The supplied air flow was assumed to be 32 l/min. Assuming the glass to be at 1150°C, it was estimated that the air would be heated to about 630°C and the volume, based on the ideal gas law, would be increased by a factor of about 2.8. This factor was applied to the standard flow rates to obtain the flows for the model tests with the result that flow rates of 45, 90, and 113 liters/min were used to correspond to the DM1200 flow rates of 16, 32, and 40 liters/min. Adjustments to the correction factor for depth of bubbler insertion were not made.

The model tests indicated a very good linear relationship between flow rate and bubble area. This indicated that it was sufficient to perform the tests in a flow regime similar to that for the melter. At some point, that linear relationship may fail but if the tested flows are close to the actual flows, the linear relationship may be used to determine the actual bubble area for the desired flow. Further, relative effects were of importance for these tests and thus the conclusions reached were not affected by the actual flows employed.

2.2.1 Test 4 Design Details

Test 4. Assessment of Option 1 and Option 2 [3] at Planned Bubbler Depth.

A. Alternative bubbler nozzle diameters and orientations were investigated including 0.125", 0.25", and ½", horizontal and vertical. Video recordings were made of top and side views of the bubbling activity. (Table 4.A).

B. Employing bubblers that were approximately full scale with respect to their fluid contact sections, the effect of bubbler depth was examined as a function of air flow rate. Video recordings were made from the top and side at "steady state" for –14", -26", -42" depths with flow rates of 45, 90 and 113 l/min. (Table 4.B).

C. The tests outlined in 4.B were repeated with a two-nozzle bubbler. In this case, the total flow to the two nozzles was 90 and 165 l/min. Higher flows to the double nozzle were not possible with the available piping. (Table 4.C).

D. Flooding and clearing tests were performed on the two-nozzle bubbler in the same manner as in Test 2.B above. (Table 4.D).

E. Since it has been established that poor results are obtained with the bubbler nozzle close to a melter wall [7], the bubbling behavior as a function of proximity to the wall was examined. Bubbling was observed and recorded on video with the nozzle at a range of distances from the wall from 4" to about 15". (Table 4.E).

F. The results of the model tests were analyzed with respect to the potential impact on mixing and, consequently, melting rates.

SECTION 3.0
TEST RESULTS

3.1 DM1200 Tests

The tests detailed above were performed using the DM1200 melter operated in an idle condition at a glass temperature of about 1125°C. The bubblers employed were existing J- or L-bubblers, or a new double-nozzle bubbler, as appropriate. Videos of the bubbling action were made using a water-cooled video camera designed for installation in a standard melter port. A photograph of the video camera is shown in Figure 2. The camera is capable of viewing the entire melter surface, as is shown in Figures 3-9.

Videos of the melt surface were made for the bubbler conditions indicated in the test matrices. Refer to Section 2.0 and Figure 10 for the location of the bubbler nozzles for specific tests. The heavy lined rectangular border just outside the area of the labeled ports in the figures indicates the area of the melt surface. The port in the middle of the melter is the normal position for the feed nozzle; the camera was located in that port. Comparisons were made to indicate the effectiveness of each set of conditions. The video results were analyzed with respect to melting rates determined using similar bubbler configurations during previous melter campaigns. Test matrix 1A' includes the tests for comparative analysis. For new bubbler configurations, attempts were made to relate the views of the surface to the apparent efficiency of mixing using videos of the baseline cases as a reference. The most promising configuration was selected for melter testing under a separate Test Plan.

Initially, attempts were made to convert the video observations to parameters that could be quantized. The maximum size of the bubble mound, as indicated by the bright nearly circular area formed as the bubble broaches was measured from selected video stills. Some examples of the attempted measurements are shown in Figure 17. It was quickly found that because of poor-contrast, nearly-saturated images, this was extremely difficult to do in a systematic way. In addition, under any bubbler configuration, the emerging bubble size was extremely variable. In general though, it was found that the diameter of the hot erupting glass from the bubble was on the order of 12 to 18". This was important for relating the melter and the model tests. It is possible that image analysis software could be employed to facilitate the analysis. However, it was determined that development of such an analysis capability would have required a more extensive effort than was planned for this work.

A second attempt at quantization of the observations involved estimation of the bubble rate. This was done by counting the bubbles as they emerged from the melt surface. Again, because of poor contrast, this was very difficult and highly subjective. Conscientious repeated attempts to count bubble rates for the same video resulted in a large variability in the results. It was possible to estimate that in general, for the air flow rates measured, the bubbling rates were on the order of 100 bubbles per minute, or more since undercounting was likely. In addition it was found from the model tests performed later that very often bubbles combine near the surface or broach the surface very close in time. Because the glass is opaque it is not possible to tell if a bubble mound is being caused by a single bubble or by two or more bubbles emerging at nearly the same time. The analysis of the melter bubbling tests presented here is thus largely qualitative.

In the flooding and flow distribution tests, flow measurements using flow meters were attempted in the case of pairs of single-nozzle bubblers. It was found that the bubble release caused the flow rate measured near the bubbler to fluctuate widely and a steady-measurement was not possible. Visual observation was thus employed to judge the degree of flow balance between the bubblers. In the case of double-nozzle bubblers, visual observation was also required to judge the flow distribution from each nozzle.

A final series of tests was performed to examine qualitatively the effects of very high flow rates. A single bubbler was observed with flow rates of 40, 60, 80 and 90 l/min and at a depth of 26”. The agitation of the melt surface increased with the flow rate, as one would expect. It was also very apparent that bubbles were coming to the surface very close together in time. In particular, at the highest flow rate the convergence of the bubbles would occasionally result in a narrow jet of glass that would shoot to the melter ceiling. This same effect was later observed in the model tests discussed below. There it could be seen that the jet resulted from a bubble below joining one above just at the surface.

3.1.1 Test A' - Correlations to Production Runs

In this series of tests, bubbler configurations and flow conditions were made identical to those used in a series of production runs. Column 5 of the test matrix (Table 1, Test 1A') indicates the specific melter run referenced in a previous test report [7]. Column 6 of the test matrix indicates the maximum steady-state production rate achieved in the melter run for the given bubbler configuration. Column 7 indicates the corresponding videoed bubbler test number.

Configuration 1 in the test matrix corresponds to the nominal bubbler configuration and flow rate. These conditions have been used in a large fraction of the DM1200 HLW melter runs. The configuration is with single ¼"-nozzle bubblers installed in ports A3 and D1 with the nozzle pointed toward the center of the melter and the nozzle tip about 11.5” from the nearest walls and at a depth of about -20". The test observation was with a pair of bubblers installed; a still from the video is shown in Figure 3. The image is typical of those in the video. The contrast and saturation are not ideal but still reveal the general characteristics of the bubbling action. The bubbling pipes are in the upper left and lower right corners. The pipes visible at the bottom of the image are from the level detector. A small bubble region around the level detector is visible due to its bubbling operation. The pipes at the center and at the left and right edges are thermowells. The thin line at the left of the image is a thermocouple.

Two major circulation cells dividing the rectangular melt pool into two triangles are visible and are due to the J-bubblers. The large nearly circular ring visible in the upper left triangle is the result of the hot glass brought to the surface as a bubble broaches the surface. The diameter of that ring is much larger than that of the rising bubble until the bubble spreads out as it hits the surface. The size and brightness is an indication of the bubbler efficiency. The dark seam between the triangles is where the somewhat-cooled glass submerges as part of the circulation cell.

The above image can be contrasted with that of Figure 4, which shows a similar bubbler configuration except that the J's are oriented parallel to the electrodes. This places the nozzles 6" from the electrode walls. The image was selected to show the largest typical bright area from this bubbler configuration, as was done with Figure 3. It is seen that the bright area is much smaller and the contrast between the brightest area and the seam between the circulation cells appears greater. While the analysis of the images is subjective, it does appear that the mixing is less vigorous in the parallel orientation case and that conclusion is reinforced by viewing the videos themselves rather than selected stills. The poor mixing in the second case is consistent with the significantly lower melting rate achieved, as indicated in the test matrix table for Test 1A' (640 versus 1050 kg/m^2/day).

Configuration 3 in the test matrix corresponds to melter Test 3B of reference [7]. This test employs 4 bubblers with nozzles in the locations indicated in Figure 10 c. The 8" separation of the bubbler nozzle pairs combined with the location of the bubbler lances makes it difficult or impossible to distinguish four circulation cells. This configuration resulted in high glass production rates, as seen in the table for Test 1A' (1300 kg/m^2/day). As can be seen in Figure 5, the bubbling action appears to produce two large bright areas but the circulation also appears to be partially disrupted by the position of the bubbler lances. Particularly in the upper right hand corner, the circulation appears relatively poor. The center seam between the circulation cells appears relatively bright. This area is beneath the feed port and good circulation near the feed entrance may contribute to the good melting rates.

Configuration 4 in the test matrix corresponds to melter Test 3C of reference [7]. This configuration is similar to the nominal Configuration 1 except the bubbler depth is 26" and the nozzle positions are slightly different. The video is not distinguishable from that of Configuration 1; the achieved melting rates are also very similar. Configuration 4 had slightly greater production rates (1100 kg/m^2/day) but the bubbling rate was also slightly higher, with a total air flow of 80 l/min versus 64 l/min for Configuration 1.

Configuration 5 in the test matrix corresponds to melter Test 8B of reference [7]. This test employed 4 bubblers with nozzles in the locations indicated in Figure 10 d. In this case, the nozzle separation for each pair is 14". In Figure 6, the four circulation cells due to the four nozzles are clearly visible. The right half of the image is darker than the left due to gradual fogging of the camera window during the tests. The left hand pair of bubblers is centered below the middle of the image while the right hand pair of bubblers is centered above the middle of the image. This causes the formation of the S shaped boundary between the cells. This configuration was responsible for the highest steady-state melting rate observed in the tests in reference [7] (1400 kg/m^2/day). The lack of contrast in the bright areas indicates that the surface of the melter is fairly uniformly hot, which should contribute to a high melting rate.

3.1.2 Tests 1.A-1. F: Variations of the Baseline Test Conditions for Option 1

Test 1.A was designed to explore both the depth- and flow-rate effects for single orifice bubblers (Option 1). Figures 7A, B, and C show the bubble area from one single-orifice bubbler at three depths, -14, -20, and -26 inches respectively. The flow rate in each case was 16 l/min. The size of the bubble as it broaches the surface appears to be smallest for the -14 inch depth. The apparent size of the bubble emergence is similar for the -20 and -26” depths but larger than that for the -14” depth. At higher bubbling rates, any bubble emergence size difference is much less pronounced, if, in fact, any difference exists. The videos do seem to show more agitation at the surface, however, for the higher flow rates, as one would expect from the higher air flow and presumably greater pumping of glass.

Test 1.B was designed to examine both depth- and flow-rate effects for pairs of single-nozzle bubblers. Two of the tests were already discussed above as parts of Test 1.A'. At higher flow rates, the glass surface became very agitated, as is shown in Figure 8, which shows the case of bubbler pairs with nozzle separations of 8" at a flow rate of 40 l/min per nozzle and at a depth of -20". The glass is even forced across the boundary that normally separates the left and right melter halves and the video displays a great deal of sloshing and splashing of glass from the surface. In the case of bubbler pairs with 14" nozzle separations, the four distinct circulation cells seen in Figure 6 are maintained even at the 40 l/min flow rates. The surface agitation is increased, however.

Test 1.C was designed to examine the flow distribution for two single-nozzle bubblers supplied by a single air supply. For this test, two bubblers were connected to a single air supply, as shown in Figure 1. Flow meters were connected to each bubbler so that the air flow to each could be measured to determine if the distribution was approximately equal. It was found that since the flow meters were close to the bubbler, the release of individual bubbles caused large meter fluctuations and a steady reading was not possible. The equality of air distribution was thus estimated from the videos of the bubbled surface; the flow visually appeared to be equal. In one test in order to illustrate that an unequal distribution could be detected, one bubbler was set to flow at about 24 l/min and the other at about 10 l/min, as estimated from the fluctuating flow indicators. The unequal distribution was easily detected visually.

Test 1.D was designed to test whether two bubblers supplied from one air supply could be cleared if allowed to flood with glass. In the first test, the bubblers were allowed to flood for one hour. Air flow was set by the mass flow controllers to 32 l/min and the glass surface was recorded by video. One bubbler cleared first and the second one cleared within less than a second of the first. The bubbling was very uneven, however, with the second cleared bubbler lagging the first. After about 2 minutes the bubbling was fairly equal and after 5 minutes the bubbling appeared to be fully equalized. This test was repeated several times and flooding was allowed to occur for several hours before clearing was attempted. The bubblers cleared successfully in all cases.

Because the flooding tests were successful with the 0.25"-diameter nozzles, neither the insertion tests nor the tests with 0.125" nozzles were deemed necessary.

3.1.3 Tests 2.A-2.D: Examination of Option 2

Test 2.A was designed to test the baseline conditions for the double-nozzle bubbler (Option 2) with 0.125" nozzles. Since the previous tests indicated no problems in clearing 0.25" nozzles, it was decided to proceed directly with that size rather than the 0.125” size. A double-nozzle J-bubbler was constructed based on the design sketch shown in Figure 14. The bubbler was fabricated from ¾” schedule 160 Inconel 690 pipe. The nozzles were 0.25" in diameter and oriented in the horizontal direction. One nozzle was at the end of the J and the second nozzle was oriented at right angles to the horizontal arm of the J and separated from the first nozzle by about 8". The arm of the J had a block on the bottom to lift it from the melter floor slightly and to support the relatively long horizontal arm of the J (18").

Figure 9 shows the surface of the melter with bubbling from a single two-nozzle bubbler. It is clear from the photo that there are two distinct flow cells. This is somewhat surprising since earlier tests with pairs of single nozzle bubblers with the nozzles separated by 8” showed what appeared to be a single flow cell for each pair. The nozzles were at a depth of 25" and the total flow rate was 32 l/min. The bubbler was oriented to keep the end of the bubbler at least 4" from the bottom electrode. The nozzle positions are shown in Figure 10 e. It appears as if the bubble cell nearest the corner is being forced into the corner by the circulation from the bubbler at the end of the J. The appearance is that the end bubbler is bubbling stronger. The video seems to indicate a similar bubble rate for each, however. At the higher flow rates, the difference is even more pronounced. The circulation of glass appears to almost cover the entire melt surface, which would indicate good total circulation. This should lead to good melting rates.

3.2 Model Tests

Previous tests on the DM1200 melter have indicated that bubbler efficiency is related to bubbler depth [7, 10]. The operating depth of the DM1200 is approximately

27", which is significantly less than the 43.8" depth of the full-scale WTP HLW melter. In order to explore the effects of depths greater than about 26", as well as a variety of other bubbler operating conditions, a physical model was employed. The details of that model are discussed in Section 2.2. This model is full-scale in depth but reduced in cross section with respect to the WTP HLW melter. Since wall effects are known to be important, the minimum dimension in the cross section is 30". A square cross section acrylic tank 30" X 30" X 48" was built for these tests. Due to the hydrostatic load, the tank was reinforced with steel ribs.

An ideal model fluid would have, at a minimum, a viscosity and density close to that of the molten glass. Those values are about 50 poise and 2.3 g/cc, respectively. A solution of $ZnBr_2$ in corn syrup provides a reasonable match to these properties, as discussed in Section 2. The bubbling gas is normally air that is supplied at ambient temperature and near-ambient pressure. The bubbling rates quoted in the melter tests refer to gas flow under standard temperature and pressure conditions, as indicated by a mass flow controller. As the gas flows down through the bubbler pipe, it is heated and expands. Therefore in the room-temperature model tests, adjustments in air flow were made to account for this expansion. Since bubble buoyancy depends primarily on the weight of the displaced liquid (due to the large density difference between a liquid and gas) the buoyancy is approximately the same in the melter and model systems. As noted in Section 2, the surface tension of the molten glass is about three times that of the model fluid. However, at high flow rates the gas is forced out of the nozzle at such a rate and with such force that surface tension should have little effect in bubble formation and release. Furthermore, the length scales involved in the surface disturbances of interest here (several inches) are much greater than the capillary length and are, therefore, gravity rather than surface tension dominated.

Observation and video recording of the bubbler tests were used to examine the results of the different configurations tested, as indicated in the test matrices.

Initial testing in the model system was designed to confirm that the model behavior was consistent with that of the DM1200 and to determine the general functioning of the system. A major advantage of the model system is that because of the relative transparency of the model fluid, it was possible to observe the bubbles as they were formed and progressed towards and broached the fluid surface. The first observations made were of bubbling at very low air flow rates. A sequence of video clips showing the formation and release of a bubble is shown in the top row of Figure 18. The bubble is formed and released over about 0.2 seconds and the bubble shape is approximately spherical. At higher air flow rates, a jet of air exits the nozzle and the bubble is formed at a location beyond the nozzle, as seen in the bottom row of clips in Figure 18. The resultant bubble size is similar to that for the low flow rate and the time of formation is also similar.

Since only the top surface was visible in the DM1200, it was important to examine the appearance of the bubbles as they broached the surface for comparison.

Figure 19 shows a sequence of bubbles as they approach the surface. The arrows show the order of the pictures starting from the upper left. The shapes, shown in the column at the right, display the morphology of the bubbles. The first bubble in the sequence shows an approximately hemispherical upper surface and a flattening bottom surface. The shape becomes mushroom-like and then continues to flatten and become wider. Eventually, as it broaches the surface, it becomes a thin inverted cup with a final diameter about twice that of the initial shape. The final diameter was similar to that observed for the breaking bubbles in the DM1200, as seen in Figure 17. The size of the bubbles was obtained by scaling to the known dimensions of the tank. It should be noted that the large expansion of the bubble diameter occurs very close to the surface.

Another behavior that had not been appreciated before the physical model tests was the fact that the bubbles frequently combined with one another as they rose to the surface. This serves to explain why bubble frequency does not necessarily increase with air flow rate but average bubble size does. Video clips (Figure 20) of Test 44 (0.25" diameter horizontal nozzle, -42" depth, flow rate 45 l/min) show the combination of three bubbles into a single bubble as the surface is approached. The dashed lines track the progress of each bubble from frame to frame. The bubble just below the lowest steel rib of the tank is joined by a second bubble in the frames at 0.33 and 0.43 seconds, a third bubble combines with the resultant bubble at 0.93 seconds. As the following bubble approaches the bubble above, it appears to enter the draft of the leading bubble and it both elongates and accelerates as it is sucked into the leading bubble. Occasionally, a trailing bubble joins the leading bubble at the surface. This results in a jet of fluid (see Figure 21) rising well above the typical convex surface. This is consistent with observations made during the DM1200 tests and occurs more frequently during the higher bubbling rates. Further, the fact that bubbles are observed to frequently reach the surface almost simultaneously provides an explanation for the difficulty encountered in determining the bubbling frequency for the DM1200. Assuming that the bubble counts determined for the DM1200 were low due to undercounting of bubbles reaching the surface in close sequence, it is reasonable to conclude that the true bubble counts for the DM1200 and the model system are similar under similar bubbler operation.

The initial testing with the model system described above confirmed that the general appearance of the bubbling was consistent with what had been observed in the DM1200. That is, the size of the bubble mound as it broached the surface and the frequency of the bubbles were similar in magnitude between the two test systems. The tests proceeded to explore the conditions tested in the DM1200 as well as a range of other conditions detailed in the test matrix. In particular, Option 1 (single ¼"-nozzle bubbler) and Option 2 (double ¼"-nozzle bubbler) were examined. The tests detailed in the test matrix were systematically performed and videos were recorded for side and top views.

It has been speculated that one parameter related to bubbler effectiveness is the size of the bubbles as they rise through the glass. It is reasonable to expect that larger diameter bubbles pump a wider column and, thus, a larger volume of hot glass. Further, to melt the cold cap, heat must be transferred. This is done most effectively by direct contact of the hot glass with the cold cap. Contact also serves to provide fluxing of the un-melted cold cap, which also promotes melting. Larger bubbles broaching the surface push a relatively larger dome of glass into direct contact with the cold cap. Large bubbles also induce long wavelength waves in the melt pool, which also push up into the cold cap. Thus a figure of merit for a bubbler configuration might be the average bubble size.

As discussed above, however, it is not the size of the bubble itself but the associated effects that result in melt rate enhancement. If other constraints on the system frustrate the associated effects, high melting rates may not be achieved. A case in point is that of the bubblers oriented parallel to the electrodes (nozzles 6" from a wall), where.several factors contribute to the lowered melting rates. The first effect is the fact that the size of the circulation cell is reduced because the wall occupies the space on one side of the nozzle, reducing the cell volume almost by half. The second effect is that the glass near a wall is generally colder than that away from the wall. Thus, it is relatively cooler glass that is being pumped to the surface than in the case of a nozzle farther from the wall. The third effect is that the sloshing seen at high bubble rates is likely damped by having the bubbles rise near a fixed wall. Finally, having the bubbles break the surface farther from where the feed strikes the cold cap likely also affects the melting rate. For bubble-assisted melting, it is therefore likely that large bubbles are a necessary but not always a sufficient condition to produce high melting rates.

The average bubble size for each test was estimated by determining the bubble rate, which was determined by counting bubbles as they broke the surface in the recorded videos. Knowing the elapsed time from the video frame rate (30 frames/sec) one is able to obtain the average bubbling rate with reasonable accuracy. It should be noted that the time between bubbles is quite variable (the typical count has a standard deviation of about 4 video frames out of 12 per bubble) but counting for 10 to 15 seconds yields a count of about 30 or more bubbles. This is sufficient to obtain reasonable averages. The bubbles generally assumed an approximately hemispherical shape as they approached the surface. By knowing the volume flow rate of air and the bubble rate, the projected area A of the bubble could be calculated from the formula:

$$A = \frac{\pi \bullet D^2}{4}$$

where D is given by:

$$D = \left(\frac{12}{\pi} \bullet \frac{F}{B} \right)^{1/3}$$

where F is the volume flow rate and B is the bubble rate. This calculation was performed for the videos recorded during the model tests. From the standard deviation in the bubble count rate one can estimate an uncertainty for the projected areas of typically about $\pm$ 3 in^2.

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3.2.1 Test 4.A: Nozzle Configuration Test – Nozzle Diameter/Orientation

The objective of this set of tests was to quickly survey the bubbling effectiveness as a function of nozzle diameter and orientation at the maximum depths available for the DM1200 and WTP HLW melters at the nominal flow rate used in the DM1200. Using the average bubble area as a figure of merit the results of the tests are plotted in Figure 22. It is seen that the horizontal nozzles generally give a larger bubbled area, all other conditions being equal. Likewise the 0.25" diameter and -42" depth generally give a larger bubbled area. The best performance was for the 0.25" horizontal orifice at a depth of -42".

The original intention was to proceed to the tests of 4.B using the best configuration from Test 4.A. However, since the total variation was only about 25% and the bubbled area estimates are subject to variability, it was decided to expand the 4.B test matrix to include more nozzle diameter and orientation tests than shown in the original test matrix. The additional matrices are shown in the expanded Table 4 that includes the extra Tests 4.Ba – 4.Be.

3.2.2 Test 4.B: Bubble Observation - Depth and flow rate dependence for the 0.25"-diameter, horizontal nozzle

This test examined the effects of depth and flow rate on the projected bubble area for the case of the 0.25"-diameter horizontal nozzle. The results of these measurements are shown in Figure 23, which includes additional data points not indicated in the test matrix. The lines in the figure correspond to linear fits to each set of data. The bubble area increases with flow rate for each set of depth data. Although the -42" depth clearly has a larger projected area at each flow rate, the scatter at the shallower depths makes conclusions less clear.

3.2.3 Test 4.Ba: Bubble Observation - Depth and flow rate dependence for the 0.25"-diameter, vertical nozzle

This test examined the effects of depth and flow rate on the projected bubble area for the case of the 0.25"-diameter vertical nozzle. The results of these measurements are shown in Figure 24. The lines in the figure correspond to linear fits to each set of data. The bubble area increases with flow rate for each set of depth data. There is also a clear increase in bubble area with bubbler depth.

3.2.4 Test 4.Bb: Bubble Observation - Depth and flow rate dependence for the 0.125"-diameter, horizontal nozzle

This test examined the effects of depth and flow rate on the projected bubble area for the case of the 0.125"-diameter horizontal nozzle. The results of these measurements are shown in Figure 25. The lines in the figure correspond to linear fits to each set of data. The bubble area increases with flow rate for each set of depth data. The spread in bubble area as a function of depth is relatively small and seems to disappear at the high flow rates. The bubble generation with the 0.125" nozzle is qualitatively different from that with the 0.25" nozzle. With the small nozzle the air jets out of the nozzle up to several inches before the large bubbles form. The small nozzle also generates a large number of very small bubbles. In the syrup, these bubbles persist for a very long time – days, weeks, and perhaps longer. They do not combine with other small bubbles when they collide and they do not burst when they reach the surface.

3.2.5 Test 4.Bc: Bubble Observation – Depth and flow rate dependence for the 0.125" diameter, vertical nozzle

This test examined the effects of depth and flow rate on the projected bubble area for the case of the 0.125"-diameter vertical nozzle. These tests caused so many small bubbles to form that visibility was reduced and bubble counting was not possible for most cases. The exiting jet of air from this small nozzle effectively reduces the bubbler depth since the large bubbles form several inches above the nozzle. Consequently, this configuration should be avoided.

3.2.6 Test 4.Bd: Bubble Observation – Flow rate dependence for the 0.5"-diameter, horizontal nozzle at -42" depth

It was decided to add tests with 0.5"-diameter nozzles for two reasons: The first was to see if there was an increase in bubble area as the diameter of the nozzle is increased beyond 0.25". The second was the fact that if erosion caused the nozzle to enlarge in diameter, it would be useful to know how the behavior might change. Thus, this test examined the effects of flow rate on the projected bubble area for the case of the 0.5" diameter horizontal nozzle. The results of these measurements are shown in Figure 26. The line in the figure corresponds to a linear fit to the data. The bubble area increases with flow rate.

3.2.7 Test 4.Be: Bubble Observation - Depth and flow rate dependence for the 0.5"-diameter, vertical nozzle

This test examined the effects of depth and flow rate on the projected bubble area for the case of the 0.5"-diameter vertical nozzle. The results of these measurements are shown in Figure 27. The lines in the figure correspond to linear fits to each set of data.

The bubble area increases with flow rate for each set of depth data. There is also a clear increase in bubble area with bubbler depth. The apparent depth dependence is stronger than was seen with the other nozzles. The projected bubble areas are relatively small compared to the other orientations, except at the -42" depth. Again, it appears that the vertical nozzle orientation is not the preferred option.

3.2.8 Test 4.C: Bubble Observation Using a 0.25"-diameter double-nozzle bubbler

This test examined the effects of depth and flow rate on the projected bubble area for the case of the 0.25"-diameter horizontal double-nozzle bubbler. The nozzle configuration was similar to that used in the DM1200, with the nozzle spacing being about 8". The results of the measurements were similar to the single-nozzle case for the same conditions in terms of bubble size. The dual-nozzle bubbler tests were examined to determine the distribution of bubbles between the first nozzle closest to the supply and the end nozzle. Since the bubble size is very similar for a similar nozzle diameter, the bubble frequency should be a qualitative indication of the distribution of the flow. Data from the tests are summarized in Table 5. These data indicate that the nozzle closest to the supply has a slightly lower flow, about 3% less than the end nozzle for the lower total flow rate of 90 liters per minute but nearly equalizes at the higher flow of 165 liters per minute.

The dual-nozzle bubbler provides the potential for delivering higher total air flow. This leads to a highly agitated tank and one can observe the equivalent of “heavy seas” on the surface. The sequence of video frames shown in Figure 28 indicate that periodically, the bubble from one nozzle is captured by a bubble from the other nozzle. When this occurs, there is a lateral component to the surface flow inducing a large amount of sloshing. If this action also occurs in the melter, it is believed it would provide a larger zone of cold cap contact and higher processing rates. The sequence of video clips shown in Figure 29 shows what might occur due to the cross-over of bubbles shown in the previous figure. The motion relative to the fixed vertical white line indicates the peak of the convex bubbled area first shifts right about 3½" and then left about 8½" before collapsing. The fluid level measured along the left wall oscillates by about an inch. This should induce good contact between the molten glass and the cold cap.

3.2.9 Test 4.Ca: Bubble Observation using a 0.5"-diameter double-nozzle bubbler

As in the previous test the results for the bubble size were similar to those of the single-nozzle case. For the 0.5"-diameter nozzles, (data summarized in Table 5) the inequity in bubble rate is larger than for the 0.25"-diameter nozzles, particularly at the lower flow rate, but is still not dramatically different. Again, with higher flow the differential flow diminishes.

3.2.10 Test 4.D: Flooding/Clearing Tests

Unlike the clearing tests done in the DM1200, the clearing of the bubbler pipe in the model tank could be observed since it was fabricated of clear acrylic. After the pipe was flooded up to the level of the liquid in the tank, the fluid could be forced out by applying a moderately low flow of air. The column of liquid was slowly forced out of the bubbler. The horizontal arm of the bubbler initially only cleared enough to let some air pass. Some liquid remained in the bottom half of the horizontal pipe section. With higher flow this was also largely cleared.

3.2.11 Wall Adherence Tests

Since it was known [7] that having the nozzle close to a wall resulted in low melting rates, it was of interest to determine the behavior of the bubbles in that case. It was thought that the bubbles might adhere to the wall and thus have a restricted flow. It was found that even when putting the nozzle almost in contact with the walls, the bubbles still had a significant layer of fluid between the gas and the wall and maintained a hemispherical shape, i.e., the air did not make direct contact with the wall. It becomes very obvious, however, that with the nozzle close to the wall a significant part of the flow cell is eliminated by the proximity of the wall. The flow cell simply needs space to operate. A pair of tests was compared to see if the bubbled area was affected (since the shape of the bubble did not appear affected by the wall, bubble area was calculated in the same way). One test was done with the nozzle near the center of the tank, i.e., with the nozzle about 15" from the nearest walls. The second test was with the nozzle 4" from the nearest wall. Figure 30 shows the results of those tests. The straight line in the figure is the least square best fit line for all of the measurements for the 0.25"-nozzle at a depth of -42", which had the nozzle from 4 to 15" but most frequently from 6 to 8" from the nearest wall.

To the extent this behavior also occurs in the melter, it is clear that bubble area alone cannot explain the drastic reduction in glass production rates that were observed when the bubblers were positioned close to the melter walls [7]. Clearly, other factors are involved that are at least as important as bubble area and, therefore, caution must be used in inferring the effects of bubble area on melt rate when, in fact, other factors may also be involved. In the case of proximity to a wall, it is clear as stated above that this limits the pumping action of the bubble column because the wall precludes the glass return path on the side toward the wall. Also, if the bubble column is near a wall, it is relatively far from where the feed falls from the feed nozzle. This may also contribute to poor interaction between the bubbles and the feed. Furthermore, being near a wall may inhibit the sloshing that was seen both in the model tank and the DM1200 when the bubble column has more space.

3.2.12 Additional Model Testing

Since the physical model offered a fast and efficient way to evaluate bubbler parameters, it was decided to add some additional tests that appeared useful. The effect of the ballast tank attached to the bubbler pipe was examined. In addition, since the WTP LAW melter uses 1/16"-diameter nozzles, it was decided to examine their behavior.

Tests were performed using a bubbler with a 0.25"-diameter horizontal nozzle at a depth of -42" for three cases. The first case employed the normal spherical ballast tank (volume = 1.7 l) attached at the top of the bubbler. The second case was with the ballast removed. The third case was with a 37-liter ballast tank connected to the bubbler pipe with a short length of ½" i.d. tubing. The results of the tests are shown in Figure 31. The straight line in the graph is the best fit line for all of the 0.25" horizontal nozzle, -42" depth data. To the extent that the projected bubble area is a good figure of merit, it would appear that the use of a ballast tank provides no advantage for the high flow rates explored in these tests. Within the scatter of the data, the results for the three cases are similar. In fact, the large ballast looks slightly worse except at the lowest flow rate. This contrasts with the fact that at very low flow rates, the bubble size is known to be affected by having an air ballast tank. The reason for this difference in behavior is that at low flow rates from the air supply, the pressure in the bubbler pipe near the nozzle can drop below the normal supply pressure if it becomes starved of air. In this case, smaller bubbles will often release from the nozzle. If a ballast tank is present it will help to maintain the supply pressure at the nozzle and the bubbles will grow to a relatively larger size before releasing. At high flow rates, the pressure is easily maintained at the nozzle without a ballast tank and, thus, there is little or no effect from the ballast.

The bubbler was fitted with a horizontal 1/16" inch diameter nozzle and the bubbling was observed. With the air supply piping that was available only low flow rates could be achieved (< 28 l/min). As in the case of the 0.125" nozzle, the air jets from the nozzle, producing an audible popping sound before large bubbles are formed. The 1/16" nozzle produces even more tiny bubbles than the 0.125" nozzle. The use of such small nozzles would appear to offer no advantages.

SECTION 4.0
DISCUSSION AND CONCLUSIONS

Since the major objective of these tests was to determine a preferred configuration for further testing in the DM1200, it is appropriate to evaluate the effects of the various parameters evaluated in the above tests. In particular, bubbler depth, nozzle diameter, nozzle orientation, flow rate, wall proximity, and double- versus single nozzles, were examined. For this evaluation, the projected bubble diameter is selected as an accessible indicator of merit, with larger being better. The rationale behind this selection is that bubble size would appear to contribute to several factors that would affect melting rates, as discussed in Section 3.2. Larger bubbles would give a larger contact area with the cold cap. Larger bubbles should pump more glass, improving mixing and temperature uniformity. Finally larger bubbles induce large amplitude long wavelength sloshing on the melt surface, also promoting contact of the hot glass with the cold cap. It should be noted, however, that certain conditions may inhibit the effectiveness of bubble-related actions and it should be made clear that bubble diameter alone is not sufficient to determine production rate. Some of the effects associated with bubble size may be modified by other conditions. A case in point is that of the nozzles located close to a vertical wall. This likely results in a small effect on bubble diameter but a dramatic lowering of the melting rate. It is speculated that the proximity to a wall decreased circulation, caused the pumping of relatively cooler glass from near the wall, and decreased surface sloshing resulting in the poor melting rate observed.

Based on the bubble size criterion, higher flow rates should be preferred since it is clear from all of the model testing graphs that bubble area increases with flow rate. Larger flow rates should give higher melting rates, and this has been extensively confirmed in melter tests.

With respect to the effect of nozzle orientation, Figure 22 shows that, for comparable conditions, horizontal nozzles gave better performance in every case.

In the case of bubbler depth the evidence is less clear. Although it generally appears that as the bubbler is operated at greater depths the bubble area increases, there is some scatter in the data and at low flow rates the areas are very similar in many configurations. At the higher flow rates, the trend favors a greater depth, as seen in Figure 23 for the 0.25" horizontal nozzle. The trend is clearer for the vertical nozzles, as seen in Figure 24. Another fact involving bubbler depth should be considered, however. It was observed in the model testing that at tank levels below the bubbler nozzle, there was essentially no motion of the fluid. This could be seen very clearly by observing the small persistent bubbles that were present in the model fluid after the first few tests. It was seen that the small bubbles below the nozzle level did not move at all, even with the highest air flow rates. In contrast, even at the far corners away from the nozzle, the liquid circulated at all levels equal to and above the nozzle. It is reasonable to expect that melting rates will be improved by eliminating dead stagnant zones in the melt tank. At a minimum, this is likely to be of importance with respect to control of temperature gradient within the melter, which could lead to cold spots and crystallization. This may also have important implications for the formation and accumulation of the noble metal sludges in the bottom of the melter.

When the effects of nozzle diameter are examined, for horizontal nozzles it is found that there are only minor differences in the projected bubble areas. Figure 32 shows a comparison of projected bubble area as a function of nozzle diameter and flow rate at the -42" depth. The data are relatively close for each nozzle size and within the typically data uncertainty of ± 3 in^2, they are indistinguishable. Other considerations have been used to select the 0.25" nozzle as the preferred choice. The 0.125" nozzle generates small bubbles in the liquid which are not desirable. Past experience at VSL has shown that 0.125" nozzles do on occasion clog. One possible reason for clogging of small nozzles is that they may be blocked by internal scale formed in the bubbler pipes. In contrast, we have never experienced a clog with a 0.25" nozzle. The 0.5" nozzle may perform as well as the 0.25" nozzle but there is no reason to prefer it based on the results of the present tests.

Based on DM1200 testing, increasing the number of bubblers (4 versus 2) has generally resulted in higher melting rates, as demonstrated in the tests summarized in reference [7]. Since it is not practical to add additional single-nozzle bubblers to the WTP HLW melters, the concept of the double-nozzle bubbler has been examined. The bubbler tests in the DM1200 discussed above indicated that qualitatively, the glass circulation appeared good with the double-nozzle J-bubbler with nozzles separated by about 8". This matches the maximum practical separation that will be possible in the WTP HLW melters. It was not clear whether the air flow was evenly distributed between the two nozzles in the DM1200 testing. In fact, it appeared that the nozzle at the end of the J was receiving most of the flow although two distinct flow cells were visible. In the model tank testing it was possible to observe the bubbling from each nozzle in detail. It was found (see Sections 3.2.8-10) that the differences in air flow distribution between the two nozzles were minimal. It was also observed that bubbles from one nozzle sometimes were captured by bubbles from the other nozzle. The location of the bubbler in a corner of the DM1200 may encourage this action and result in more bubbles appearing in the circulation cell farthest from the corner. It should be noted that in the tests in the DM1200 with two pairs of single-nozzle bubblers having an 8"” nozzle separation, a single circulation cell was seen for each pair.

The conclusion from the above tests was that a pair of double-nozzle bubblers with 0.25" nozzles separated by 8" and at a depth of 26” be installed in the DM1200 for production rate testing. Because of the lid geometry, the availability of free ports, the necessity of inserting the lower arm of the J into the port and then rotating the J to a vertical position, and the presence of the bottom electrode, the nozzle positioning was fixed. The nozzle positions are as seen in Figure 10 e with the second nozzle pair being mirrored across the center line of the melter and flipped left-to-right. The preliminary results of the melter testing can be summarized as follows. At a total flow rate of 64 l/min the steady-state melting rate was 1050 kg/m^2/day for AZ-101 feed (target glass yield = 400g/l) and a temperature of 1150°C. At a total flow rate of 131 l/min the steady-state power-limited melting rate was 1400 kg/m^2/day. In the low-flow case, the results should be compared with the results of Test 4C of reference [11], where a melt rate of 750 kg/m^2/day was achieved with two single-nozzle bubblers at a depth of -20" and a total flow rate of 65 l/min; or with Test 3C of reference [7] with four single-nozzle bubblers at a depth of -26" and a flow rate of 80 l/min, where a melt rate of 1100 kg/m^2/day was achieved. In this low-flow comparison, the results indicate that the double-nozzle bubbler performs much better than a single-nozzle bubbler and about as well as the corresponding combination of two single-nozzle bubblers. The results have some ambiguity, however, because of the depth difference in one case (-20" compared to -26") and the flow rate difference in the other (64 l/min compared to 80 l/min).

The high-flow-rate case should be compared to the results of Test 3B of reference [7], where the steady-state melting rate was 1300 kg/m^2/day with a total air flow of 135 l/min; or to Test 8B of reference [7], where a melt rate of 1400 kg/m^2/day was achieved with a bubbling rate of 117 l/min, both of which employed two pairs of single-nozzle bubblers separated by 8" and 14", respectively. In this high-flow-rate comparison, the double-nozzle bubblers appear to perform a little better than the pairs of single-nozzle bubblers separated by 8". The pairs of single-nozzle bubblers separated by 14" achieved the same melting rate as the double-nozzle bubblers but with a lower bubbling rate. It may be that the 14" bubbler separation and the somewhat different nozzle locations in this test provided some advantage.

In conclusion, the double-nozzle J-bubbler as described in this report provides comparable performance to that of two single-nozzle bubblers with outlets at the same locations. Importantly, such a bubbler clears easily and provides good flow distribution between the two outlets. Since such a bubbler does not require additional air supplies, the impact on HLW system design is minimal. Consequently, the major objective of increasing HLW throughput by increasing the number of bubbler outlets without impacting design has been accomplished. These conclusions have been confirmed by initial tests with AZ-101 HLW simulants performed on the DM1200 system. Those tests confirmed that, with current HLW simulated feeds, the target melting rate could be met with a comfortable margin using a total bubbler air flow of 64 l/min or 54 l/min/m^2 of melter surface. Further increases in melting rate are possible, as demonstrated in the tests by further increasing the bubbling rates. The limits to that increase have not been tested due to the present power limitations of the DM1200. Further, the relationship between bubbling rates and effects such as feed carryover should be examined to determine the best bubbling rates for melter operations.

The present effort was focused on rapid identification and validation of a practical solution to the shortfall in HLW glass production rates, which has been accomplished. However, in the course of this effort, many novel aspects of bubbler operation have been revealed, which suggest that further optimization should be possible. The results of the physical modeling would be more revealing if the flows generated by the bubbling could be examined in more detail. Examination of the flow patterns and rates might be accessible by observation of the motion of the small bubbles generated in the model tank. This analysis would require a more sophisticated approach than relating bubble size to bubble rates. Other approaches might offer the possibility of even greater understanding. In particular, in addition to the very illuminating physical modeling performed in the present work, it is likely that numerical fluid flow modeling would also be valuable. There have been many recent advances in fluid flow modeling and, in fact, one problem that has seen recent interest is the problem of bubbles rising in a viscous liquid [12, 13]. It is interesting to note that the numerical simulations [12, 13] resulted in similar bubble shapes as those observed in the present work. The observed bubble capture is also described and modeled [12, 13] and follows closely the observations described in this report. Such modeling could be used to examine more fully the details of the bubbler driven flow in the melters.

SECTION 5.0
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Table 1. Test Matrix for Tests 1A-C: Determine Required Nozzle Size – Two Nozzles/One Air Supply.

Test 1.A' Production Run [7] Correlations - Video of Bubbling						
Configuration #	Bubbler depth	Nozzles	Flow Rate l/min	Melter Test # [7]	Glass Prod. Rate $kg/m^2/day$	Bubbler Test #
1	-20”	Single	32	1B	1050	Test 5
2	-20”	Single	32	2C	640	Test 7
3	-26”	Double	32	3B	1300	Test 22
4	-26”	Single	40	3C	1100	Test 10
5	-26”	Double	29	8B	1400	Test 14

Test 1.A Baseline Condition –Video of Bubbling			
Single Bubbler, 0.25” nozzle			
Bubbler Depth	½ Nominal Flow (16 l/min)	Nominal Flow (32 l/min)	Maximum Flow (40 l/min)
-14”	Test 1, 1A, 1B	Test 2, 2A, 2B	Test 3
-20”	Test 4	Test 5	Test 6
-26”	Test 8	Test 9	Test 10

Test 1.B Two Bubbler Baseline – Video of Bubbling						
Two Pairs of Bubblers/ 4 Independent Air Supplies, 0.25” nozzle						
Bubbler Depth	8” Separation			14” Separation		
	16 l/min	32 l/min	40 l/min	16 l/min	32 l/min	40 l/min
-20”	Test 18	Test 19	Test 20	Test 11	Test 12	Test 13
-26”	Test 21	Test 22	Test 23	Test 15	Test 16	Test 17

Test 1.C Air flow Distribution Test – Acceptable = At Least 60/40 split		
Two Bubblers/Single Air Supply, 0.25” nozzle > 14” Separation, -26” Depth		
Total Flow*	32 l/min	64 l/min
-	Test 24	Test 27

Test 1.D Bubbler Flooding Test – Acceptable = 60/40 split of better	
Bubblers as in 1. C 60 minute flooding	
Total Flow*	Test #
32 l/min	28, 29

Test 1.E Bubbler Insertion Test – Acceptable = 60/40 split or better
This test was not required
Test 1.F 0.125” Nozzle Tests
These tests were not required

* Combined flow through both nozzles

Table 2. Test Matrix for Test 2: Examination of Single-Bubbler, Two-Nozzle Case.

Test 2.A Baseline Condition – Video Bubbling			
Single Bubbler, double nozzle, 0.25”			
Bubbler Depth	½ Nominal Flow (32 l/min)	Nominal Flow (64 l/min)	Maximum Flow (80 l/min)
-14”	Test 37	Test 38	Test 39
-20”	Test 34	Test 35	Test 36
-26”	Test 40	Test 41	Test 42
Test 2.B Flooding Tests – Proceed if Test 2.A Results are Acceptable, Otherwise Go To Test 3			
Bubblers as in 2.A 15 minute flooding / up to 30 minute observation			
Total Flow	Test #		
32 l/min	43		
Test 2.C Bubbler Insertion Test – Acceptable = 60/40 split or better			
This test was not required			
Test 2.D			
Performed as 2.A–2.C since testing with 0.125” nozzles was judged to be unnecessary			

Table 3. Test Matrix for Test 3: Examine Flow Restrictors to Balance Flow.

Because of the success of the previous tests it was determined that the tests in Table 3 were not required.

Table 4. Test Matrix for Test 4.

Test 4.A Nozzle Configuration Test – Nozzle Diameter/Orientation				
Single Bubbler - Model Fluid – 90 l/min air flow				
Bubbler Depth	0.125” nozzle		0.25” nozzle	
	Horizontal	Vertical	Horizontal	Vertical
-26”	Test 57	-	Test 48	Test 78
-42”	Test 54	Test 84	Test 45	Test 63

Test 4.B Bubble Observation Using Best Bubbler Configuration From Test 4.A			
Single Bubbler 0.25” horizontal nozzle Reference DM1200 STP flow rates			
Bubbler Depth	16 l/min	32 l/min	40 l/min
	Actual flow rate		
	45 l/min	90 l/min	113 l/min
-14”	Test 50, 117	Test 51, 118	Test 52, 119
-26”	Test 47, 93	Test 48, 94	Test 49, 95
-42”	Test 44, 96	Test 45, 97	Test 46, 98

Test 4.B.a Bubble Observation Using Best Bubbler Configuration From Test 4.A			
Single Bubbler 0.25” vertical nozzle Reference DM1200 STP flow rates			
Bubbler Depth	16 l/min	32 l/min	40 l/min
	Actual flow rate		
	45 l/min	90 l/min	113 l/min
-14”	Test 74	Test 75	Test 76
-26”	Test 77, 90	Test 78, 91	Test 79, 92
-42”	Test 62,86, 87	Test 63, 88	Test 64, 89

Test 4.B.b Bubble Observation Using Best Bubbler Configuration From Test 4.A			
Single Bubbler 0.125” horizontal nozzle Reference DM1200 STP flow rates			
Bubbler Depth	16 l/min	32 l/min	40 l/min
	Actual flow rate		
	45 l/min	90 l/min	113 l/min
-26”	Test 56	Test 57	Test 58
-42”	Test 53	Test 54	Test 55

Test 4.B.c Bubble Observation Using Best Bubbler Configuration From Test 4.A			
Single Bubbler 0.125” vertical nozzle Reference DM1200 STP flow rates*			
Bubbler Depth	16 l/min	32 l/min	40 l/min
	Actual flow rate		
	45 l/min	90 l/min	113 l/min
-14”	Test 80	Test 81	Test 82
-42”	Test 83	Test 84	Test 85

* Combined flow through both nozzles

Table 4. Test Matrix for Test 4 (Continued).

Test 4.B.d Bubble Observation Using Best Bubbler Configuration From Test 4.A			
Single Bubbler 0.5” horizontal nozzle Reference DM1200 STP flow rates			
Bubbler Depth	16 l/min	32 l/min	40 l/min
	Actual flow rate		
	45 l/min	90 l/min	113 l/min
-42”	Test 59	Test 60	Test 61
Test 4.B.e Bubble Observation Using Best Bubbler Configuration From Test 4.A			
Single Bubbler 0.5” vertical nozzle Reference DM1200 STP flow rates			
Bubbler Depth	16 l/min	32 l/min	40 l/min
	Actual flow rate		
	45 l/min	90 l/min	113 l/min
-14”	Test 70	Test 71	Test 72
-26”	Test 68	Test 69	Test 70
-42”	Test 65	Test 66	Test 67
Test 4.C Bubble Observation Using Double-Nozzle Bubbler			
Double Bubbler - Model Fluid- 0.25” horizontal nozzle Reference DM1200 STP flow rates*			
Bubbler Depth	32 l/min	60 l/min	
	Actual flow rate		
	90 l/min	165 l/min	
-14”	Test 107, 109	Test 108, 110	
-26”	Test 101, 103	Test 102, 104	
-43”	Test 99, 105	Test 100, 106	
Test 4.C.a Bubble Observation Using Double-Nozzle Bubbler			
Double Bubbler - Model Fluid - 0.5” horizontal nozzle Reference DM1200 STP flow rates*			
Bubbler Depth	32 l/min	60 l/min	
	Actual flow rate		
	90 l/min	165 l/min	
-43”	Test 113, 115	Test 114, 116	
Test 4.D Flooding/Clearing Tests - Conduct flooding and clearing tests under a range of flow rates from a few liters/min to maximum rates			
Test 4.E Wall Adherence Test			
Single Bubbler – Model Fluid – 42” depth, 0.25” horizontal nozzle			
Wall Separation	Actual flow rate		
	45 l/min	90 l/min	113 l/min
4”	Test 120	Test 121	Test 122
15”	Test 96	Test 97	Test 98

* Combined flow through both nozzles

Table 5. Dual Nozzle Bubbler Bubble Distribution.

	Total bubbler flow, lpm	End nozzle bubbles / minute	First nozzle bubbles / minute	% difference between first and end nozzle
H: 0.25”dia-2	90	158	153	-3%
H: 0.25”dia-2	165	166	164	-1%
H: 0.5”dia-2	90	135	155	13%
H: 0.5”dia-2	165	137	148	7%

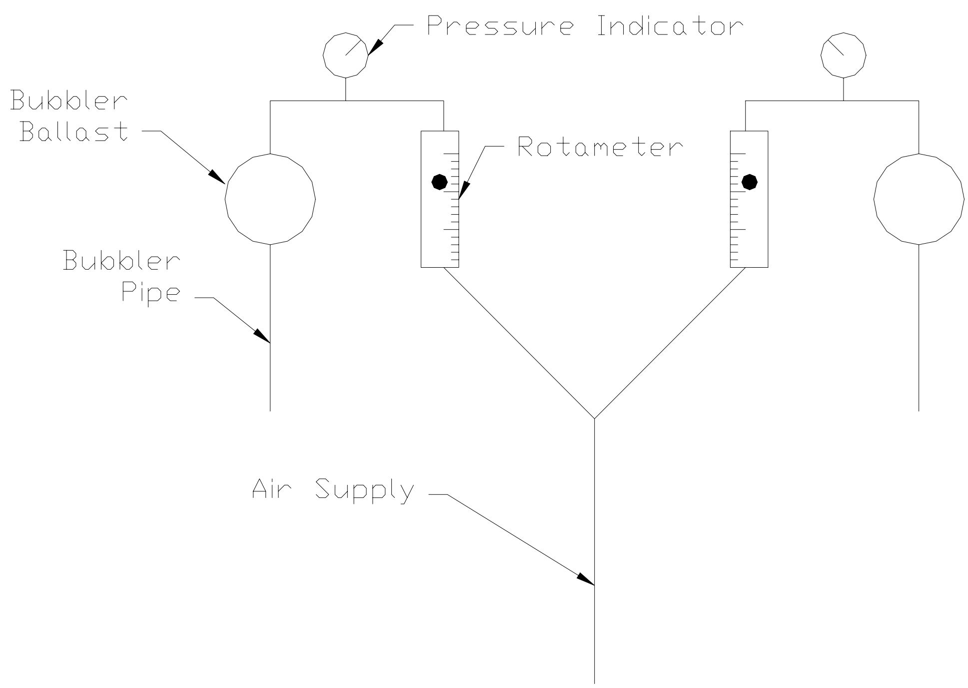


Figure 1. Dual bubbler single air supply schematic. The components and line lengths are equal in both legs.

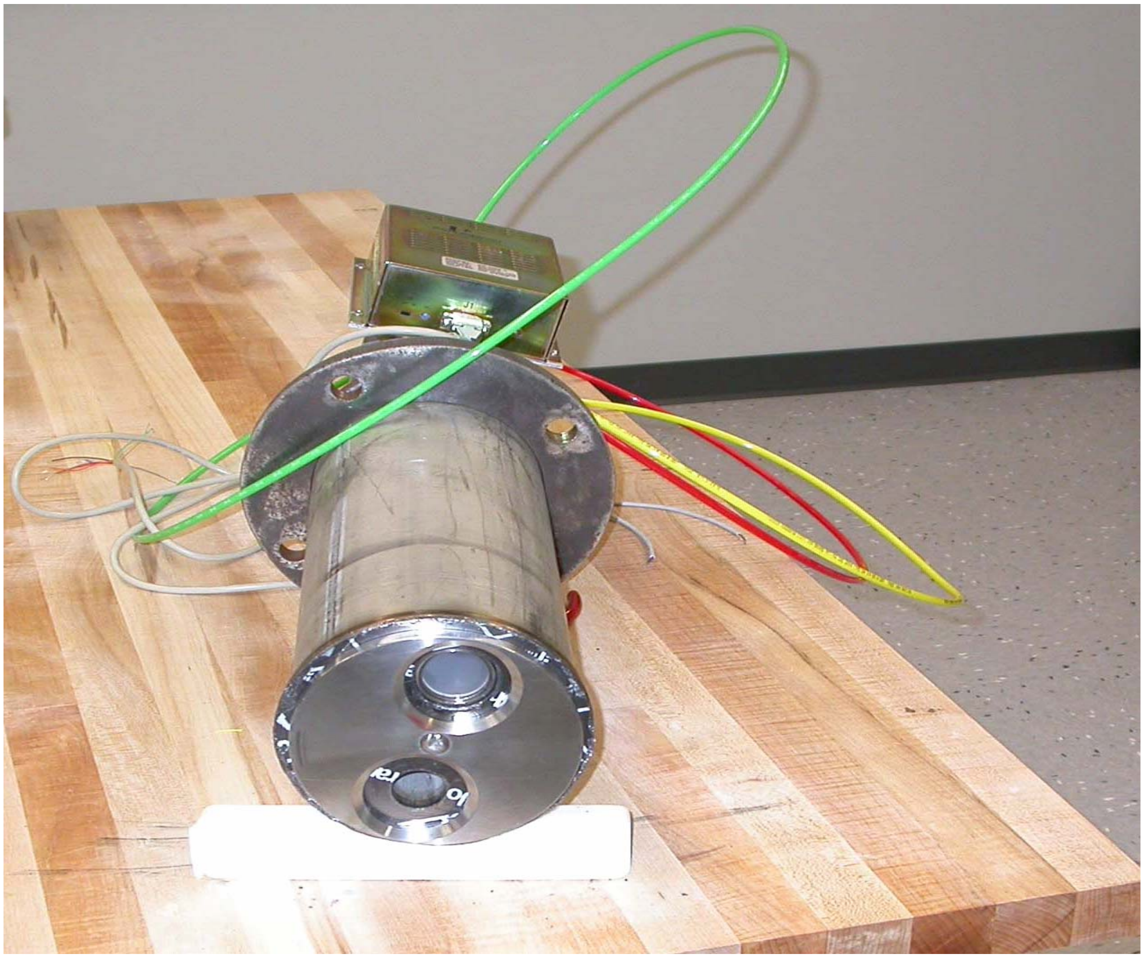


Figure 2. Water-cooled video camera for installation in a DM1200 melter port.

Figure 3. Still image from video of bubbling for the nominal bubbler configuration with J bubblers in ports A3 and D1 pointed toward the melt center and the nozzles 11.5" from the nearest wall. Configuration 1 from Test 1.A'.

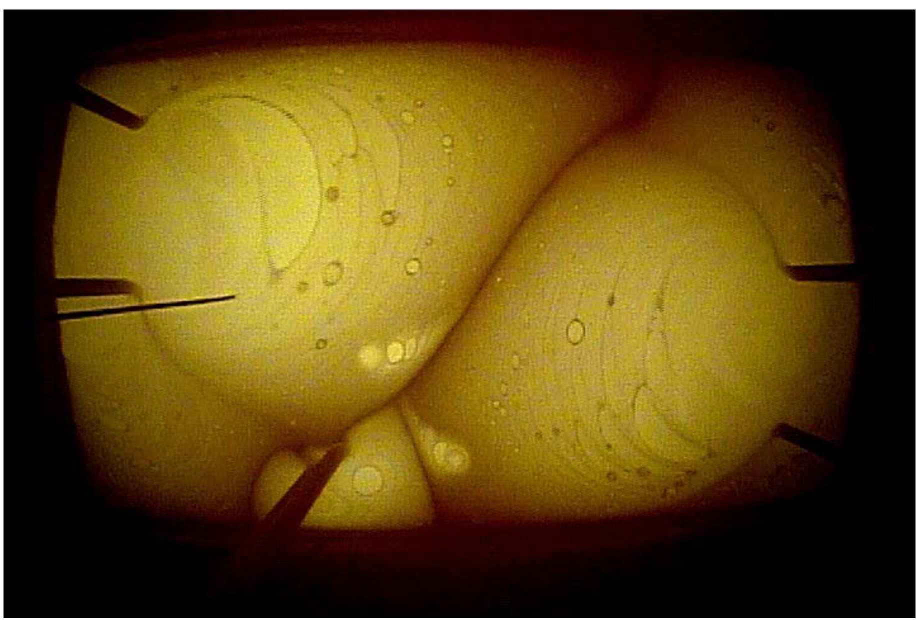


Figure 4. Still image from video of bubbling for two J bubblers in ports A3 and D1 with J's parallel to the electrodes and the nozzles 6" from the nearest wall.

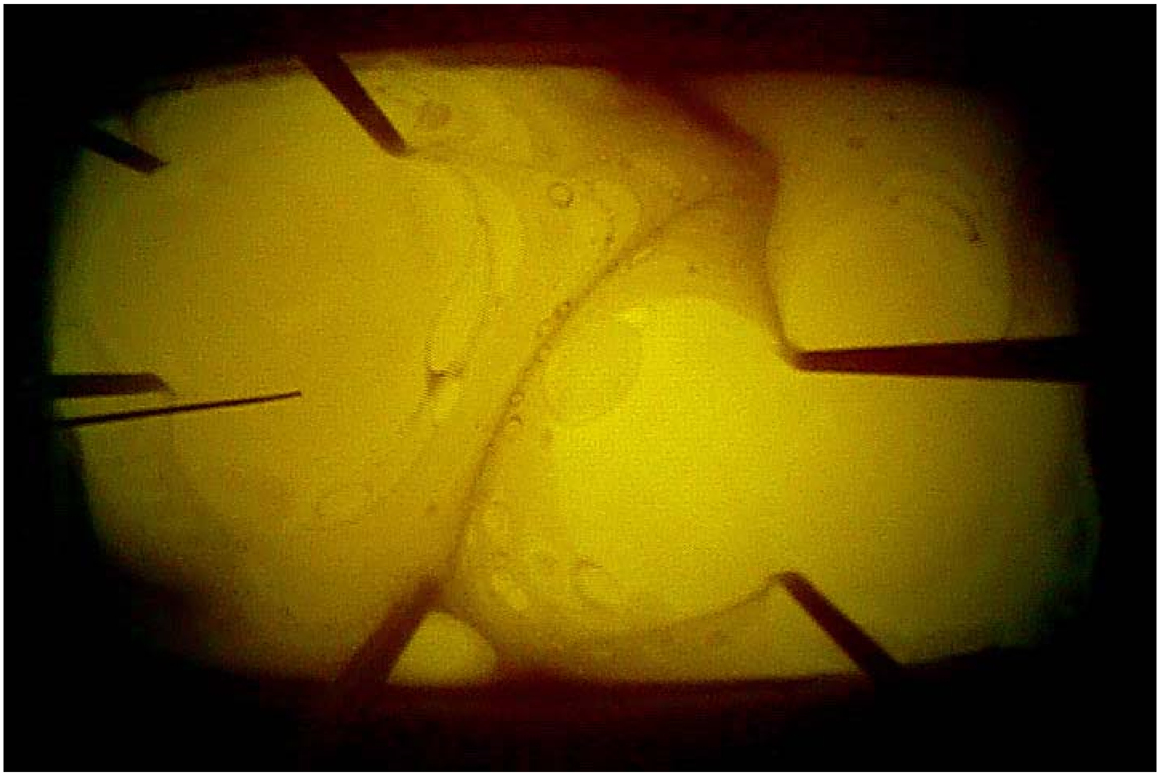


Figure 5. Still image from video of bubbling for 4 single nozzle bubblers in the 8" separation configuration. The four circulation cells are not easily distinguished.

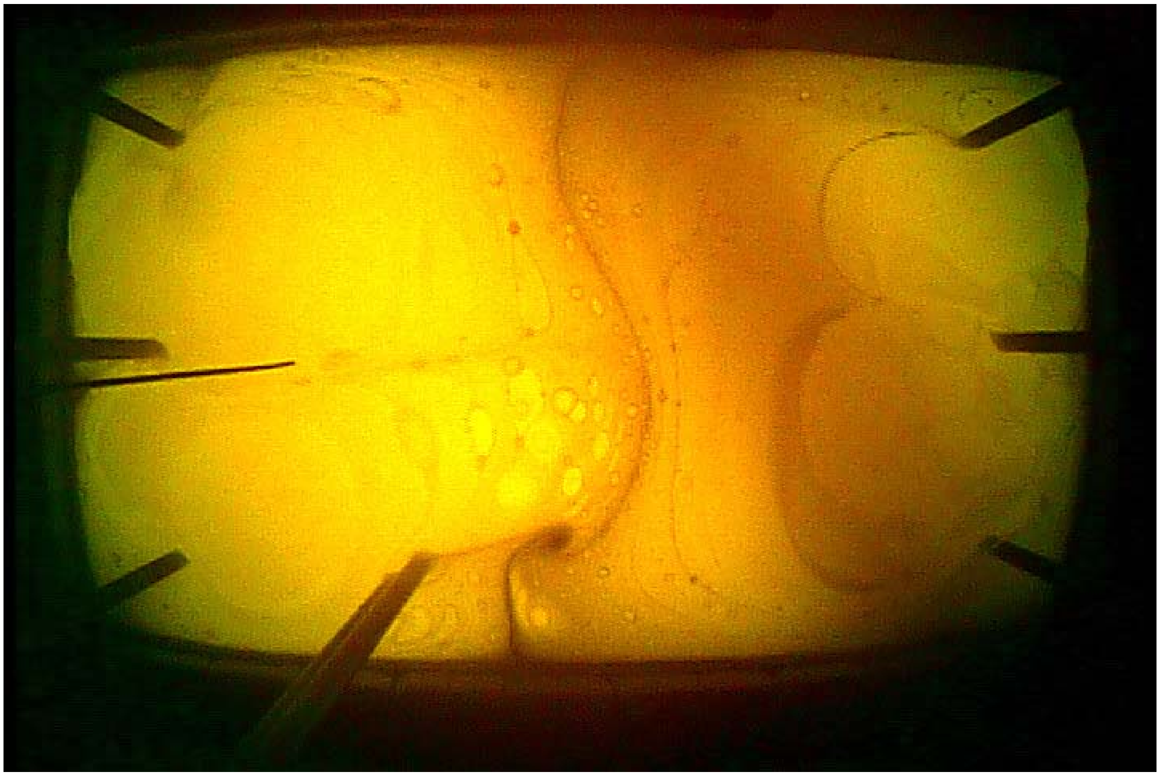
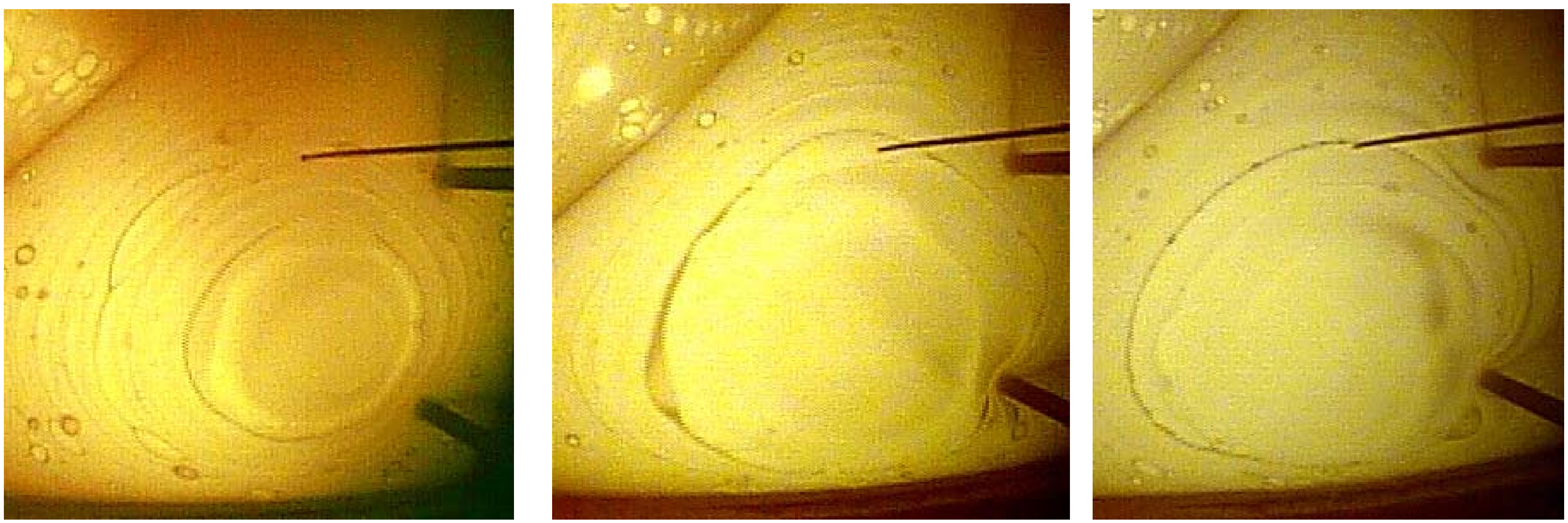


Figure 6. Still image from video of bubbling of 4 single lance bubblers in the 14" separation configuration of configuration 5 of the test matrix 1.A'. Four distinct circulation cells are visible.

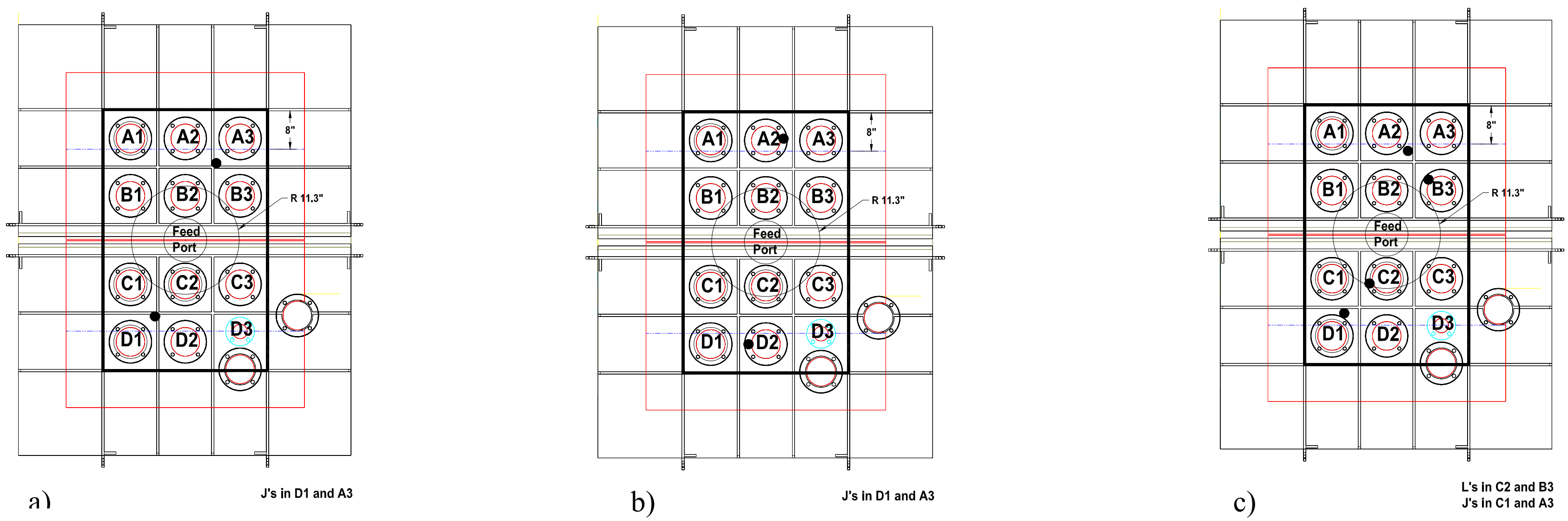


A B C

Figure 7. Images from videos of the bubbled area from one of two J bubblers installed in the configuration of Test 1.A. From left to right the bubblers are at depths of 14, 20, and 26" respectively.

Figure 8. Still image of the 8” separation configuration at a high flow rate of 40 l/min for each nozzle at a depth of 20”.

Figure 9. Still image of the bubbling for a double nozzle bubbler. The bubbler depth was 25" and the total flow was 32 l/min for the two nozzles.



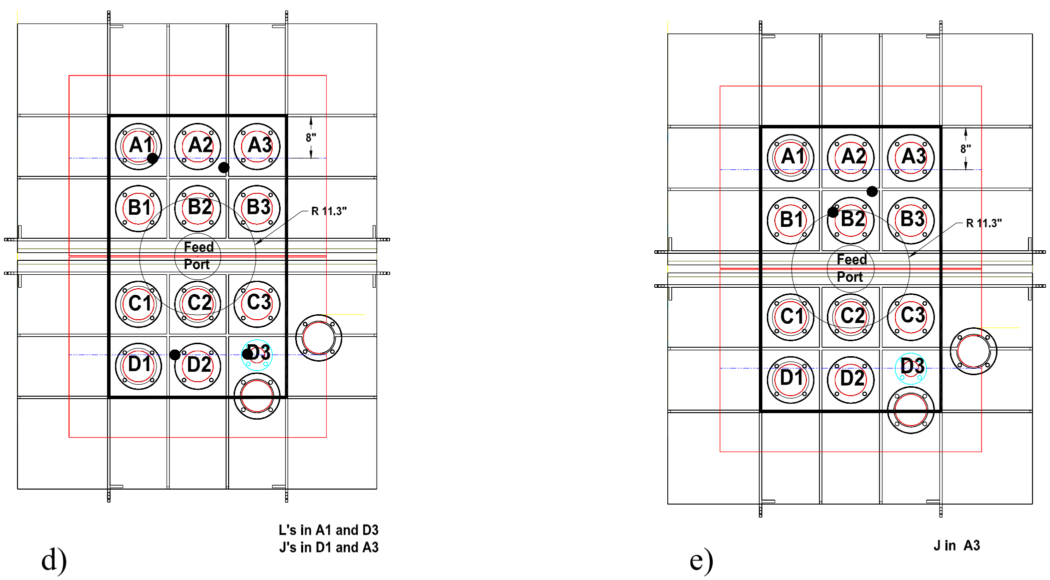
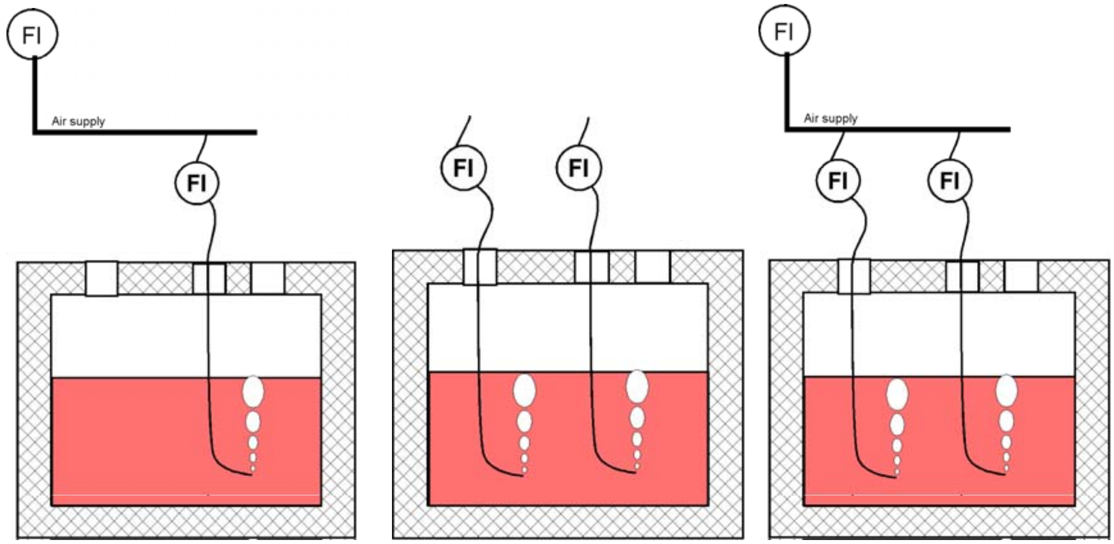
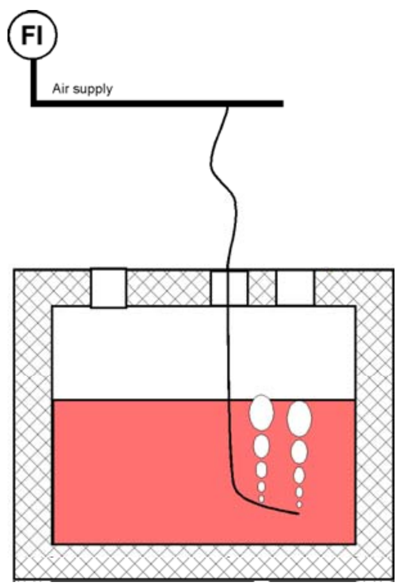


Figure 10. Nozzle locations with respect to the melter lid for the a) nominal 2J, b) parallel 2 J, c) 4 bubbler 8" separation, d) 4 bubbler 14" separation and e) dual nozzle configuration. Dark rectangle marks the melt pool boundaries. The dark spots mark the nozzle positions.

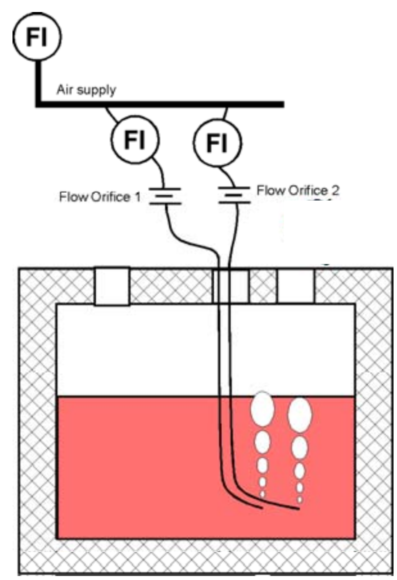


Test 1.A Test 1.B Test 1.C thru 1.F

Figure 11. Bubbler configurations for Test 1, Baseline test and test of orifice size for two orifices with a single air supply.



Test 2 configuration



Test 3 configuration

Figure 12. Bubbler configuration for Test 2, single bubbler with a double orifice.

Figure 13. Bubbler configuration for Test 3, two bubblers with a single air supply with balancing restrictors.

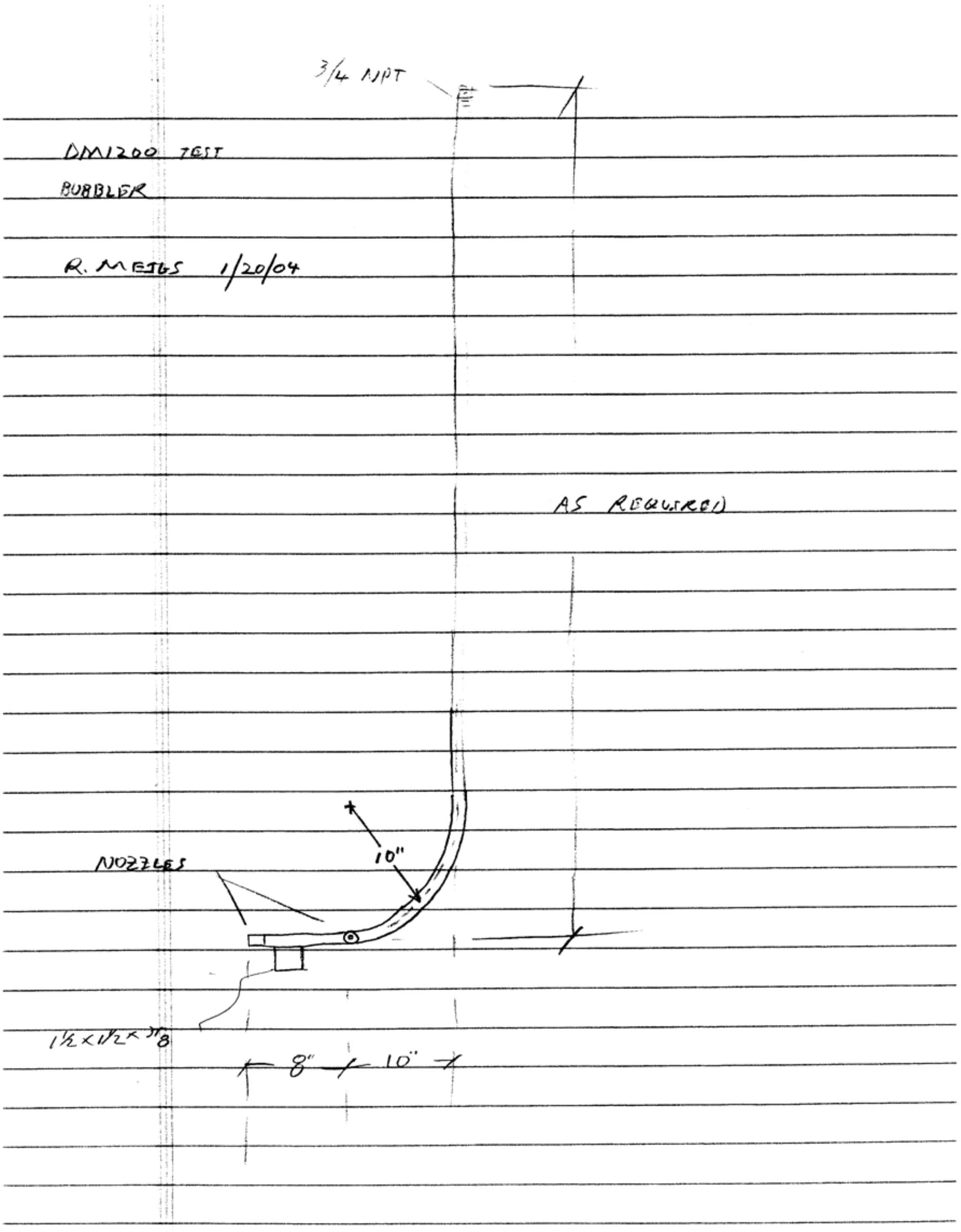


Figure 14. Design sketch of the double nozzle J bubbler.

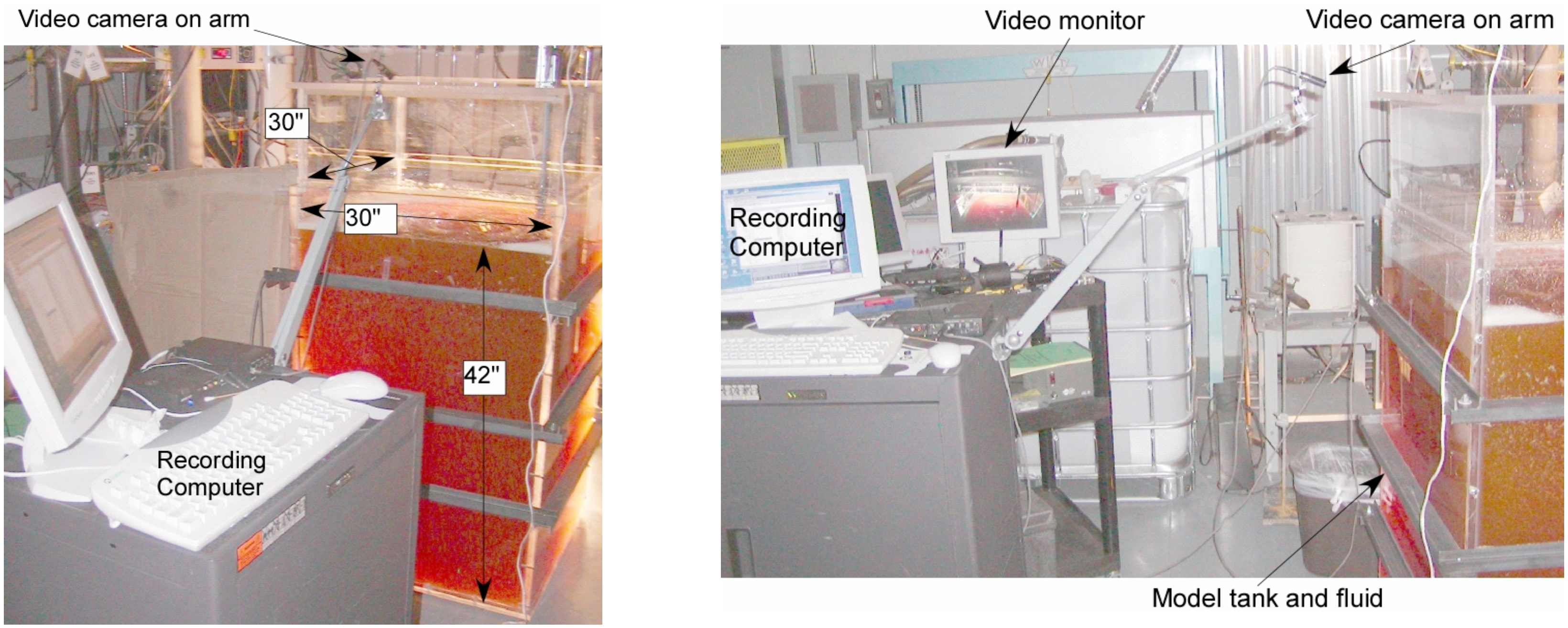


Figure 15. Front and side views of the physical model test apparatus. The tank and video recording equipment are indicated.

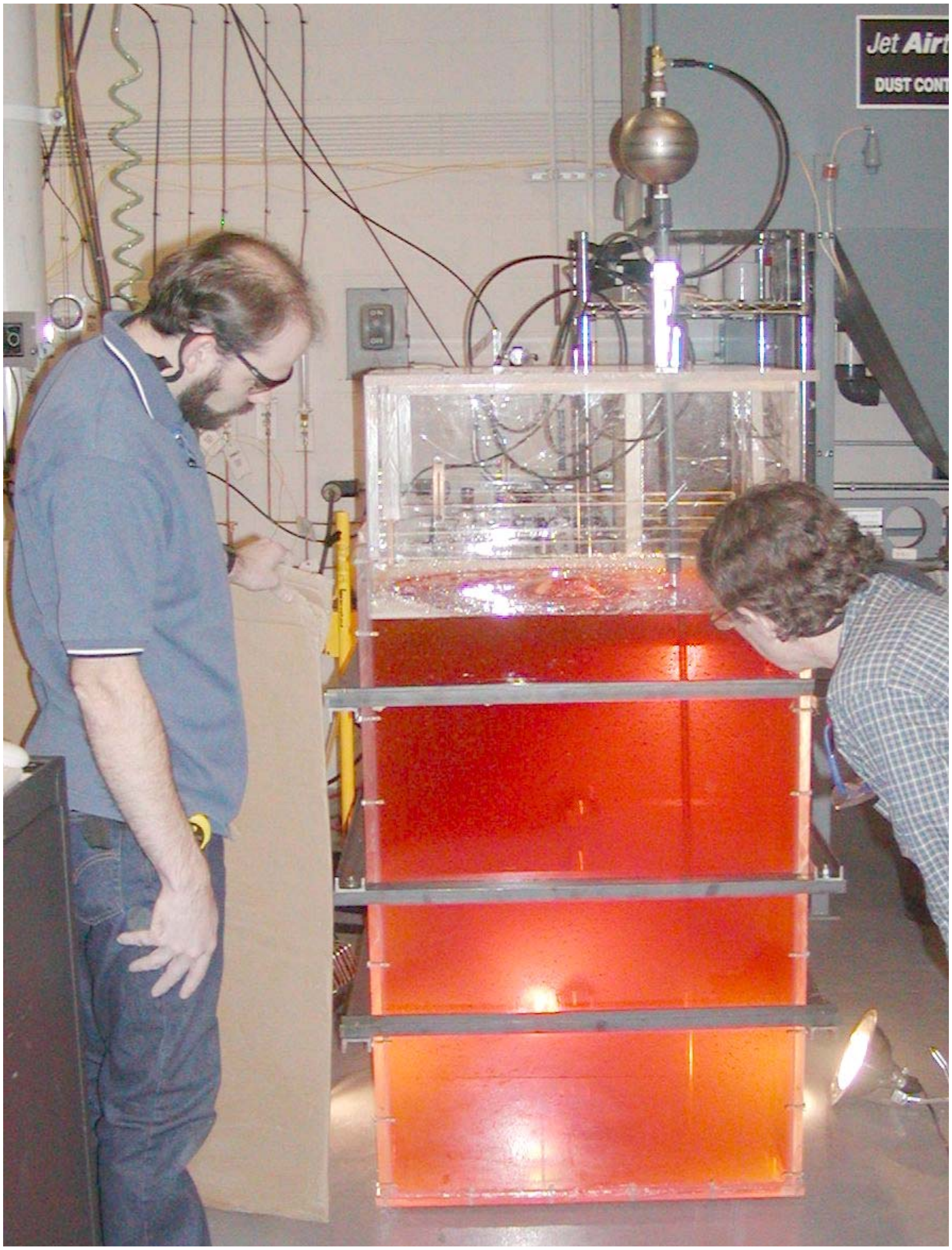


Figure 16. Front view of physical model. Several rising bubbles are visible. The cloudy appearance of the liquid is due to scattering from an accumulation of tiny air bubbles.

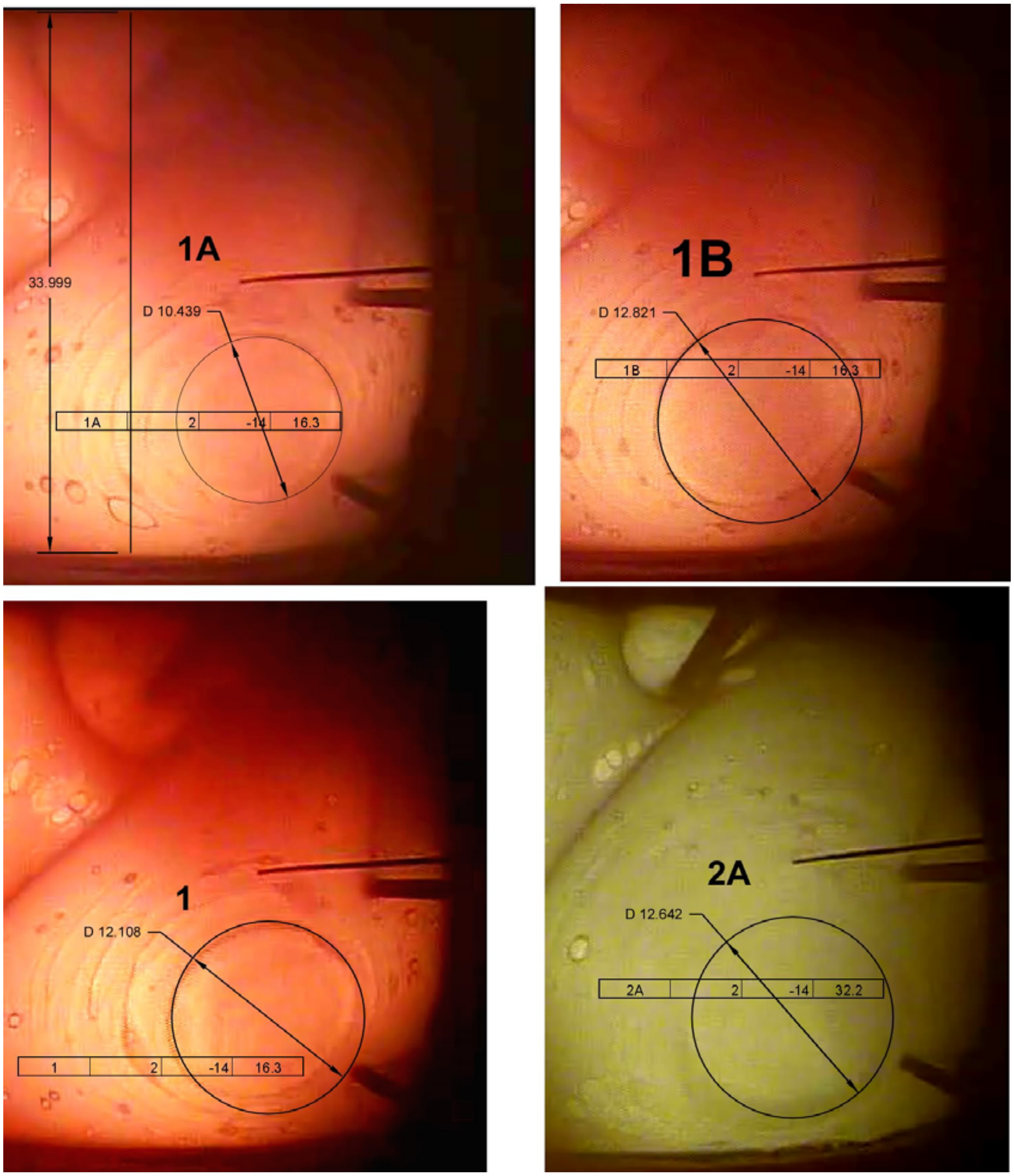
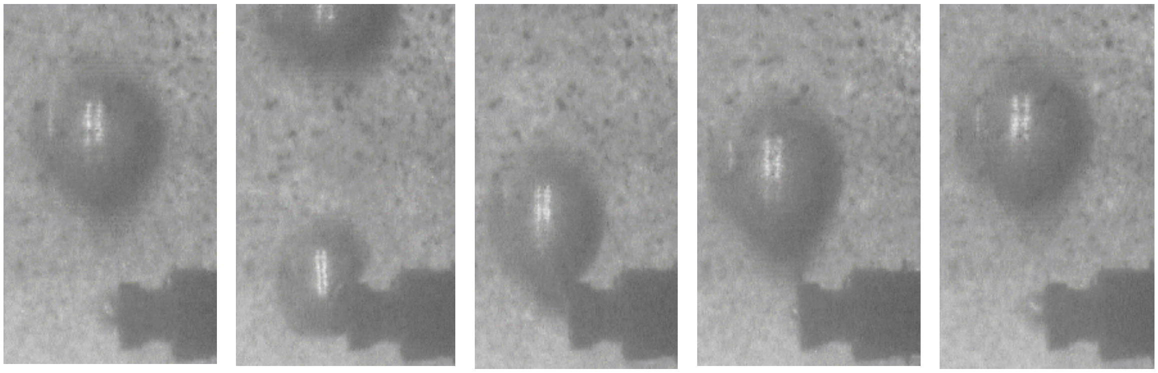
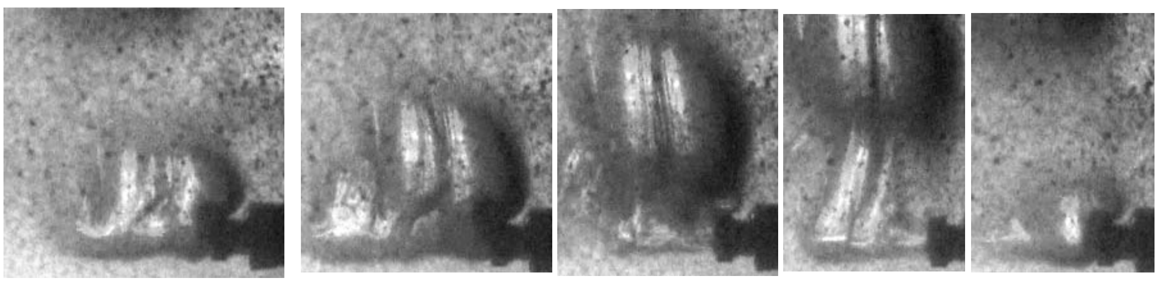


Figure 17. Estimates of bubble diameter at the melt surface. The bubble diameter was scaled from captured frames of the videos. Due to the near-saturated image intensity with limited contrast, these results are subject to considerable interpretation and variance but indicate the correct general magnitude of the diameter.



Time, sec. 0.00 0.10 0.13 0.20 0.23



Time, sec. 0.00 0.03 0.10 0.13 0.17

Figure 18. Frames of 0.125" diameter nozzle with low flow rate, upper series, and high flow rate, lower series.

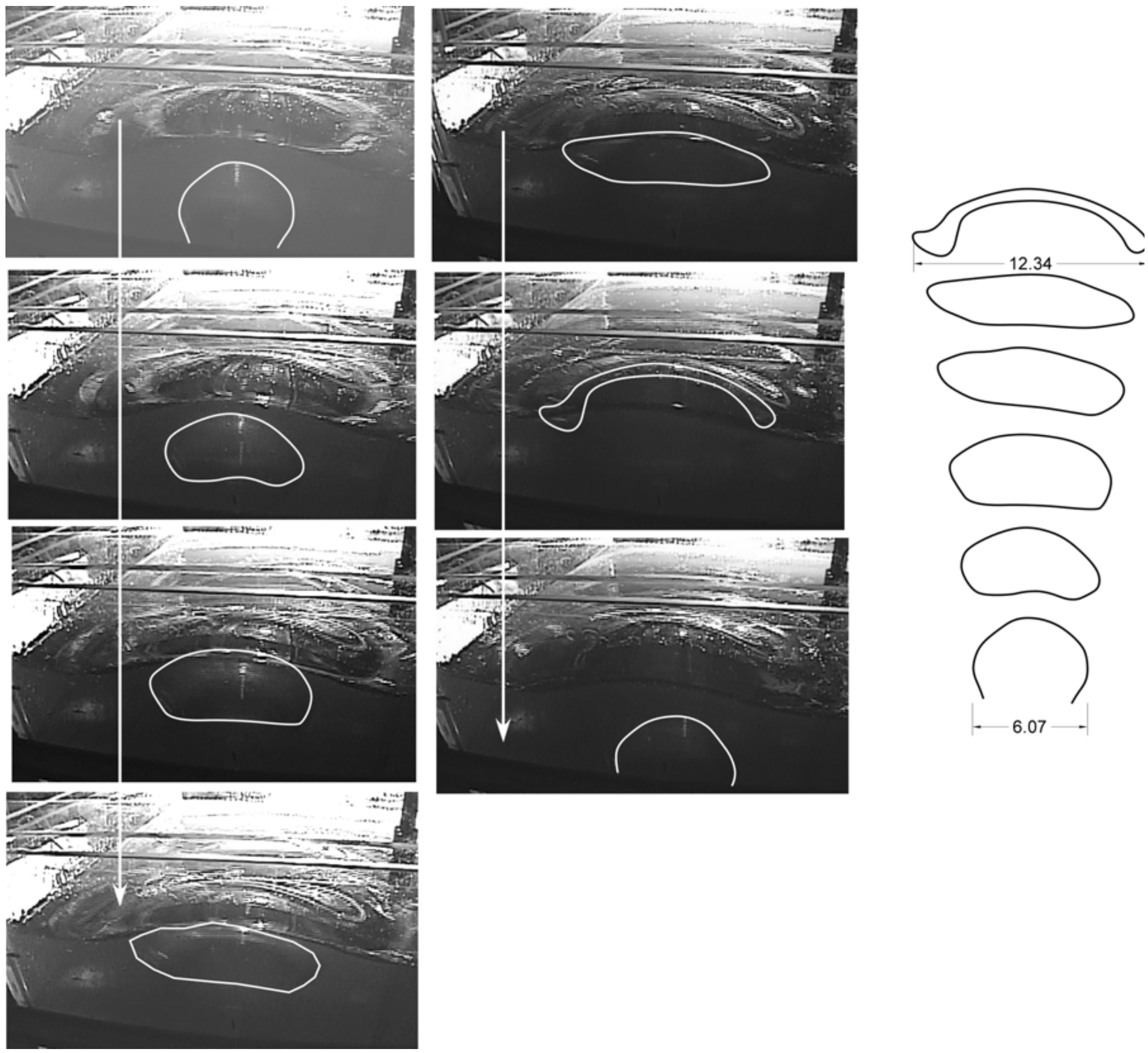


Figure 19. Sequence of video clips showing the morphology of a bubble as it nears the surface of the fluid. The arrows indicate the sequence of clips. The sketches at the right summarize the shape changes and indicate a diameter change of about a factor of two.

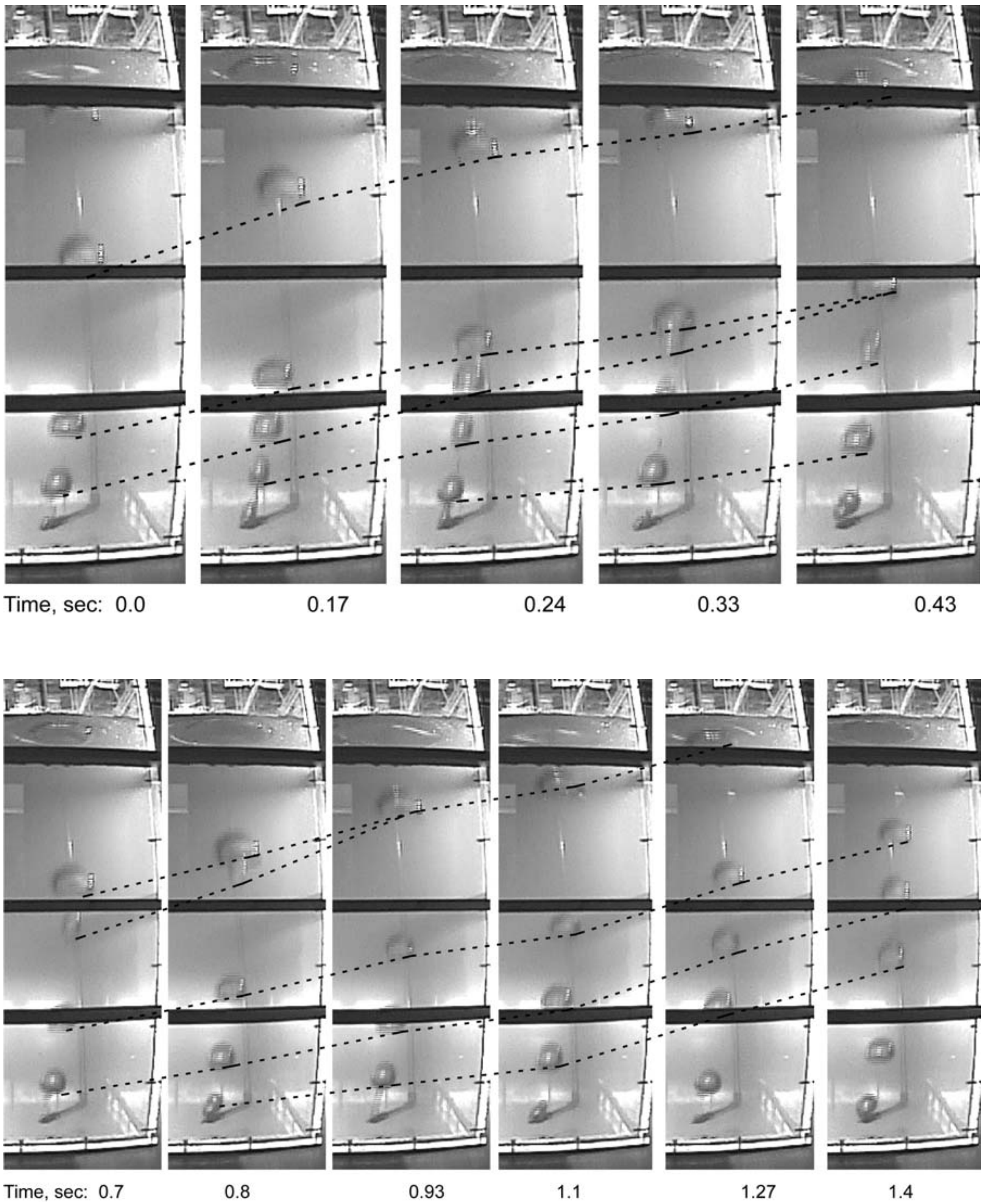


Figure 20. Sequence of video clips showing the capture of two bubbles by a third. The dashed lines track the bubbles from one frame to the next.

Figure 21. Video still showing a jet of fluid that results when a trailing bubble joins another bubble at the surface of the fluid.

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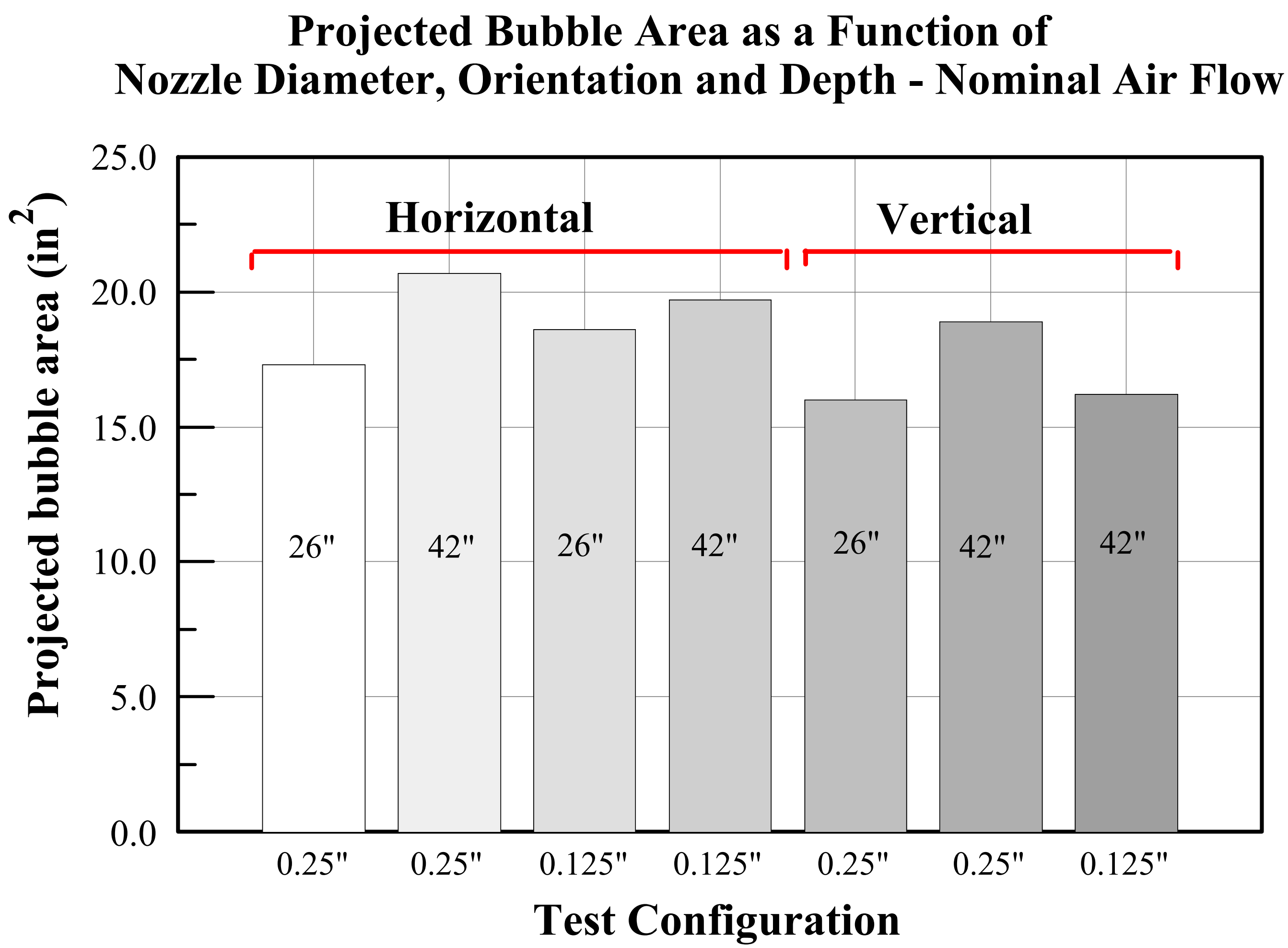

Figure 22. Results from Test 4.A. The projected bubble area as a function of nozzle diameter, orientation, and depth at nominal air flow.

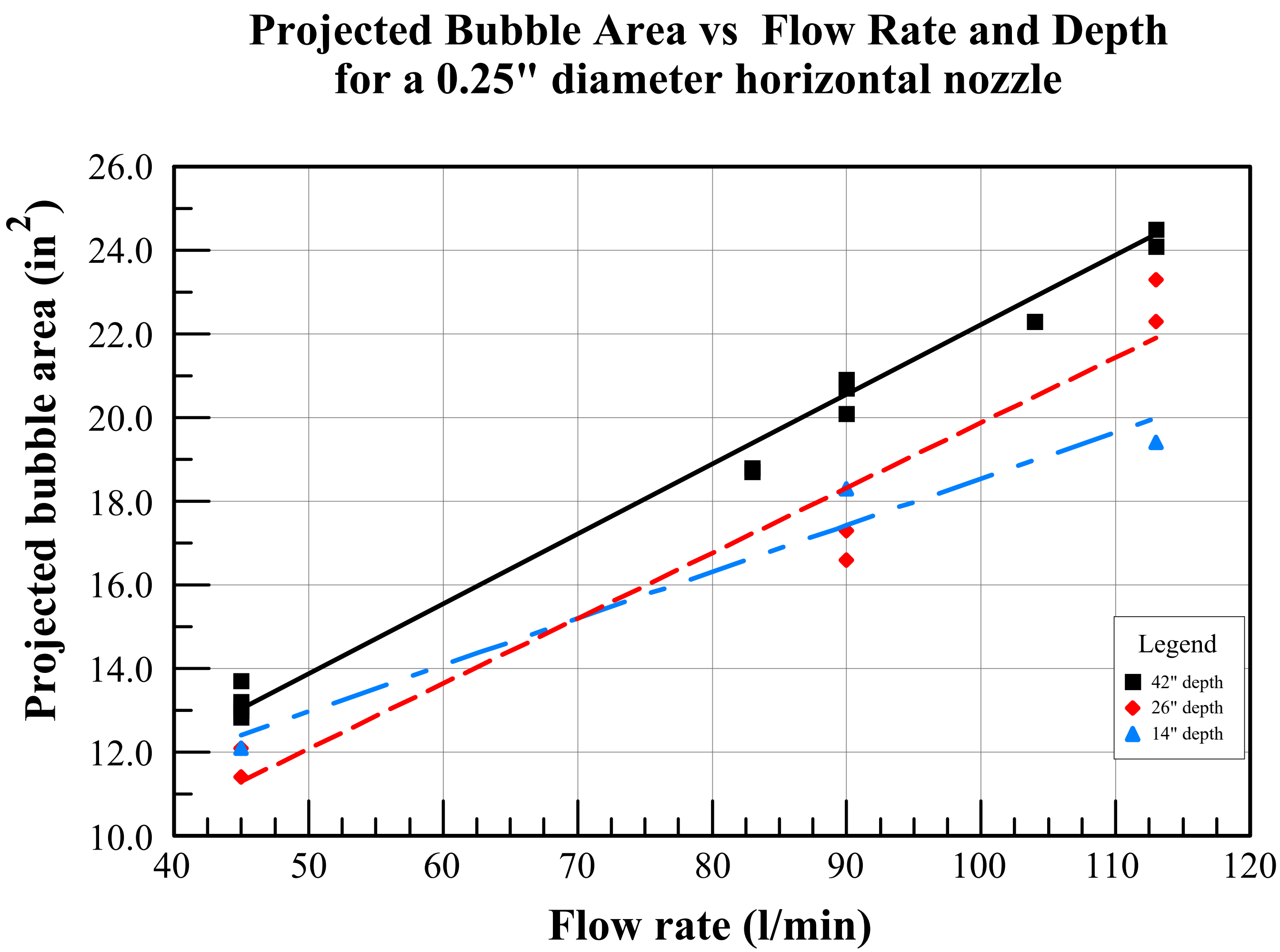

Figure 23. Results from Test 4.B. The projected bubble area as a function of depth and flow rate for a 0.25" horizontal nozzle.

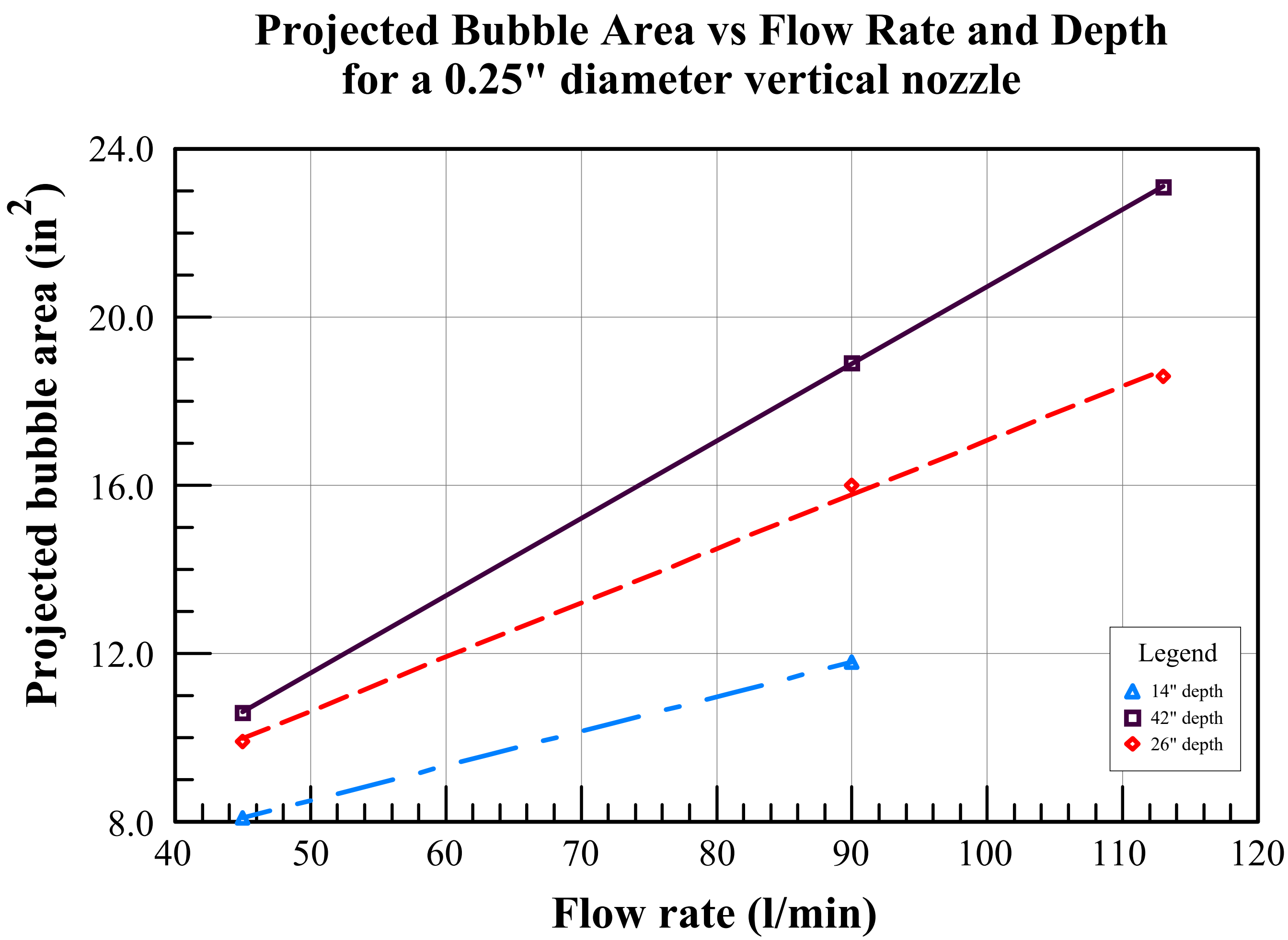

Figure 24. Results from Test 4.Ba. The projected bubble area as a function of depth and flow rate for a 0.25" vertical nozzle.

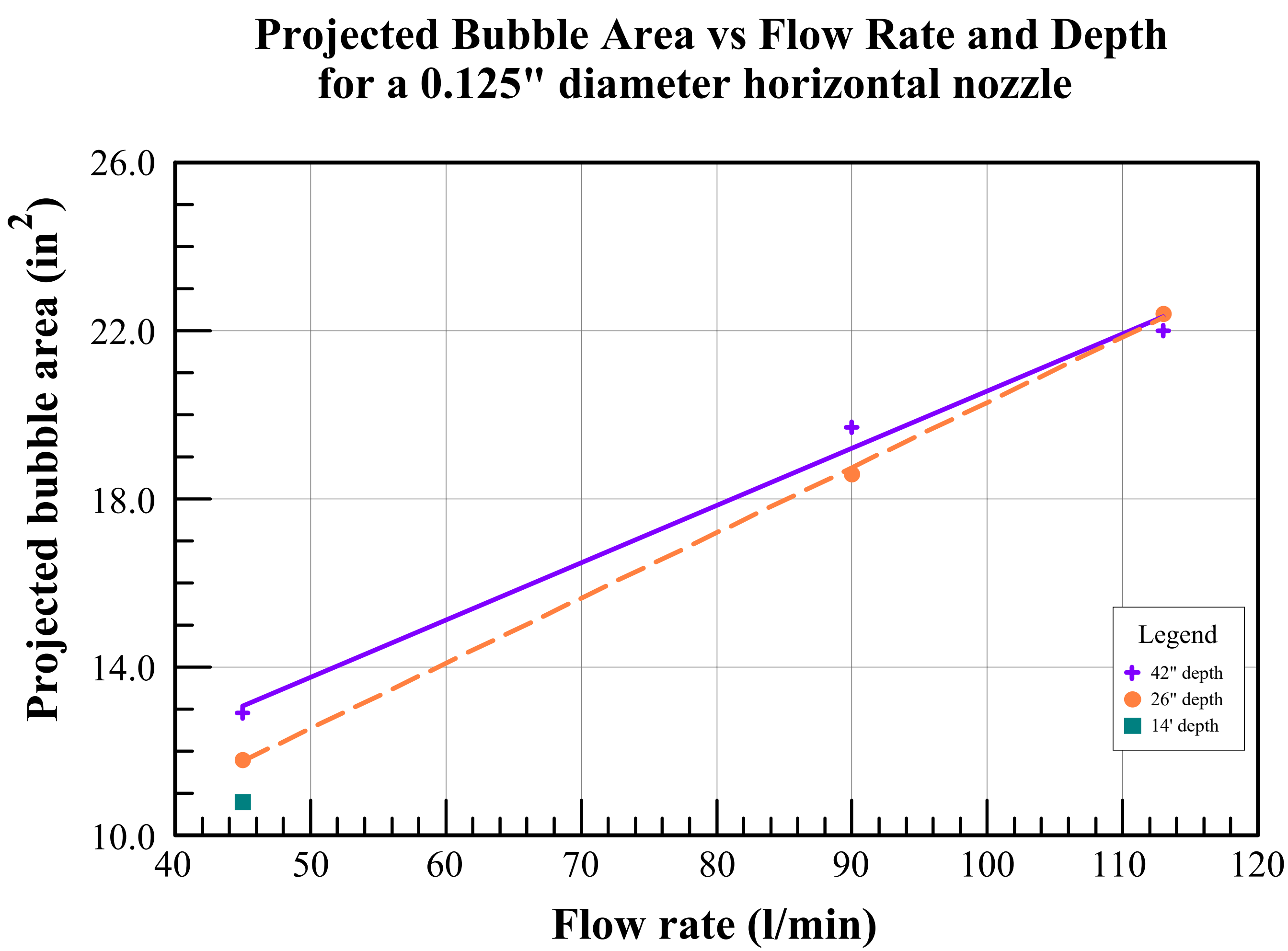

Figure 25. Results from the Test 4.Bb. The projected bubble area as a function of depth and flow rate for a 0.125" diameter horizontal nozzle.

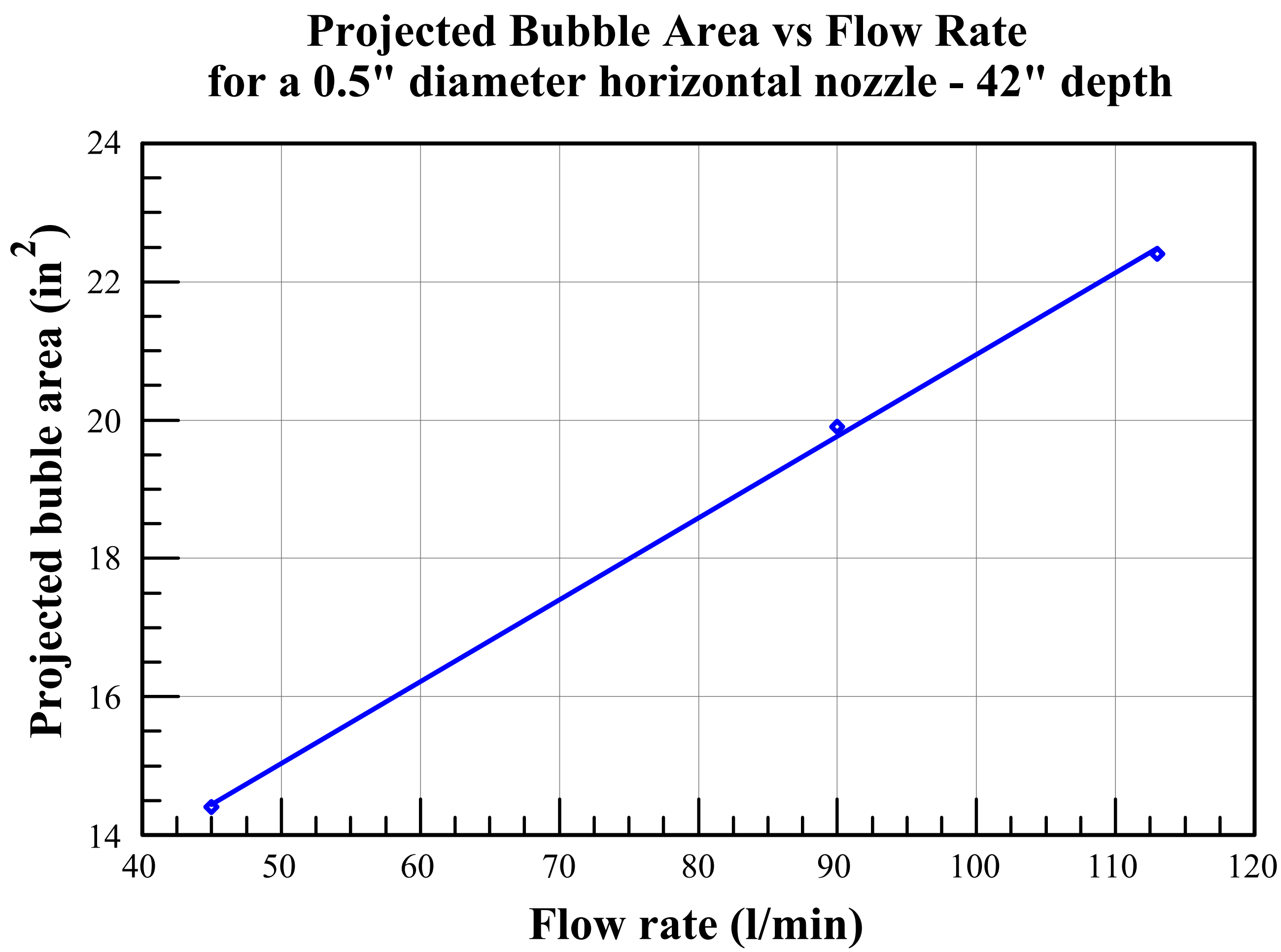

Figure 26. Results from Test 4.Bd. Projected bubble area as a function of flow rate for a 0.5” diameter nozzle at a depth of 42”.

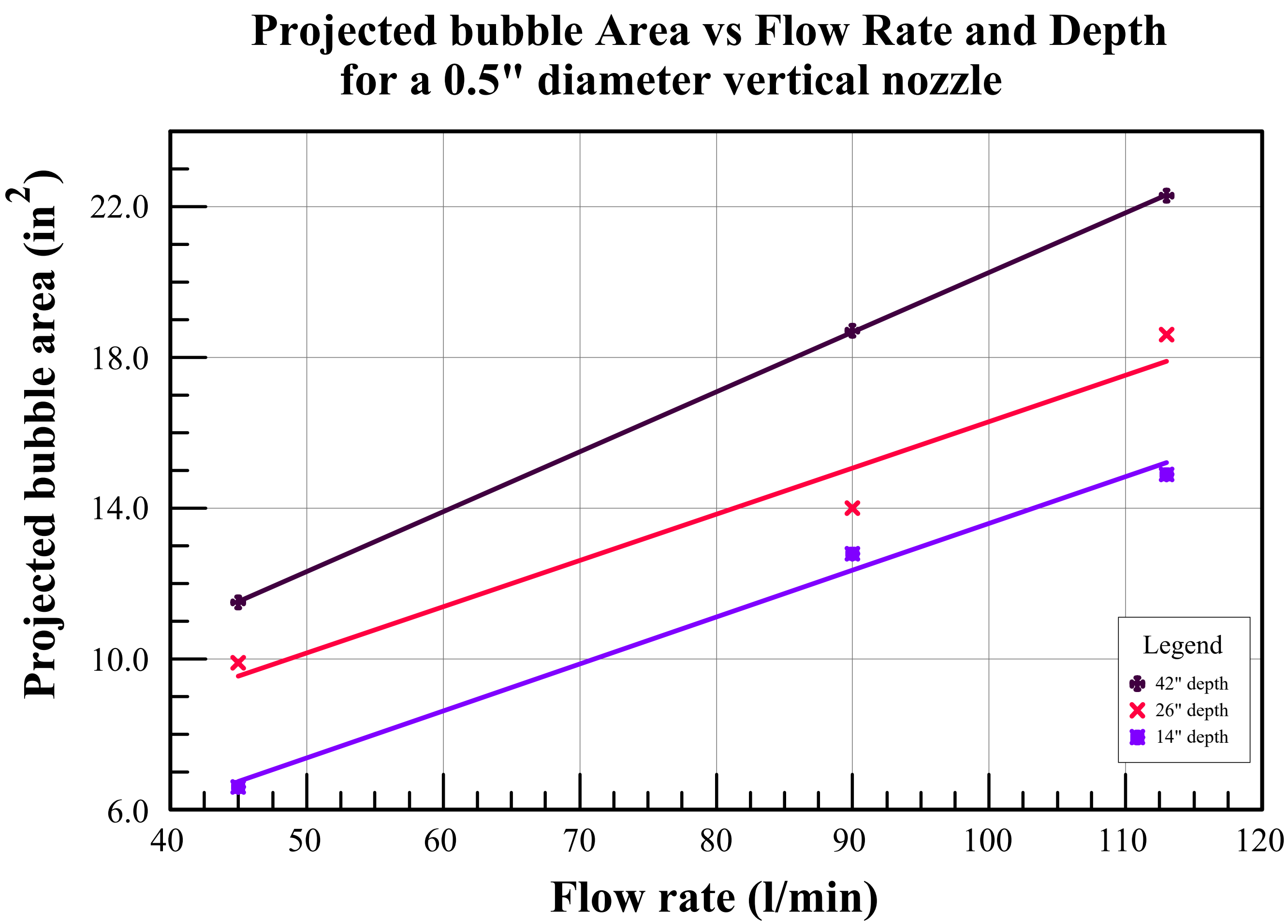

Figure 27 Results from Test 4.Be. The projected bubble area as a function of depth and flow rate for a 0.5" vertical nozzle.

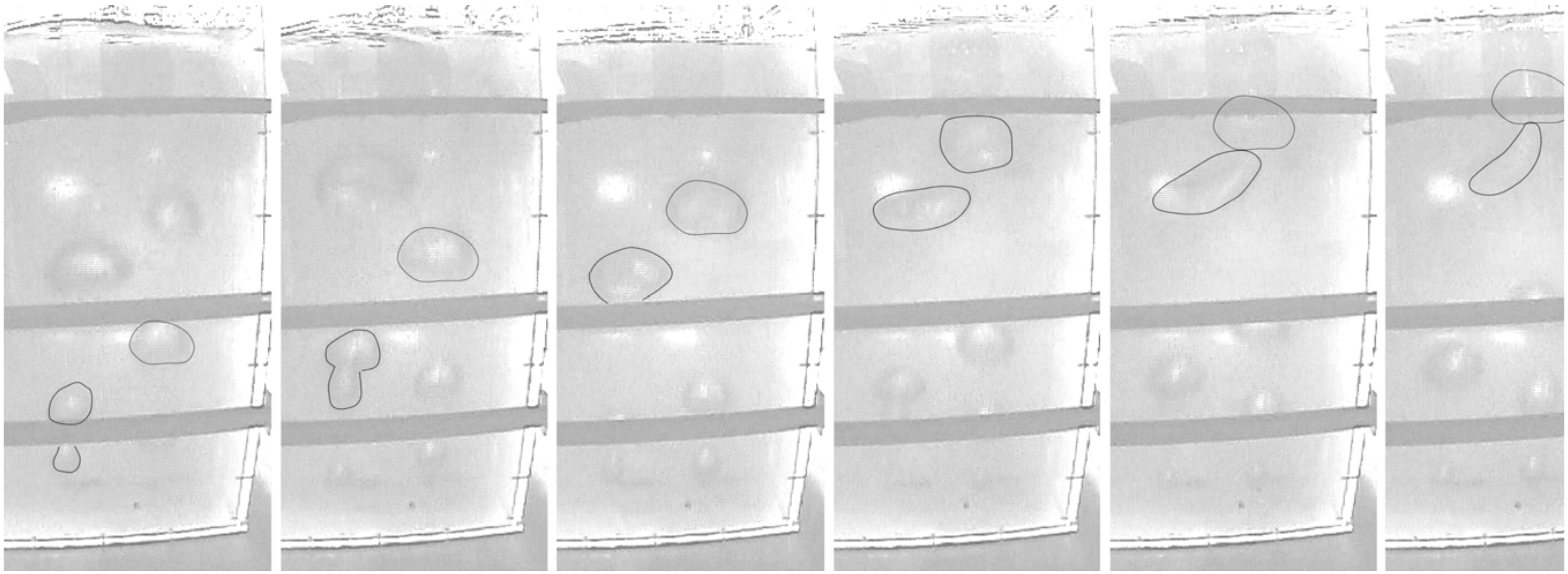

Figure 28. Sequence of video clips for the dual-nozzle bubbler illustrating the capture of a bubble from the left column of bubbles by a bubble from the right column.

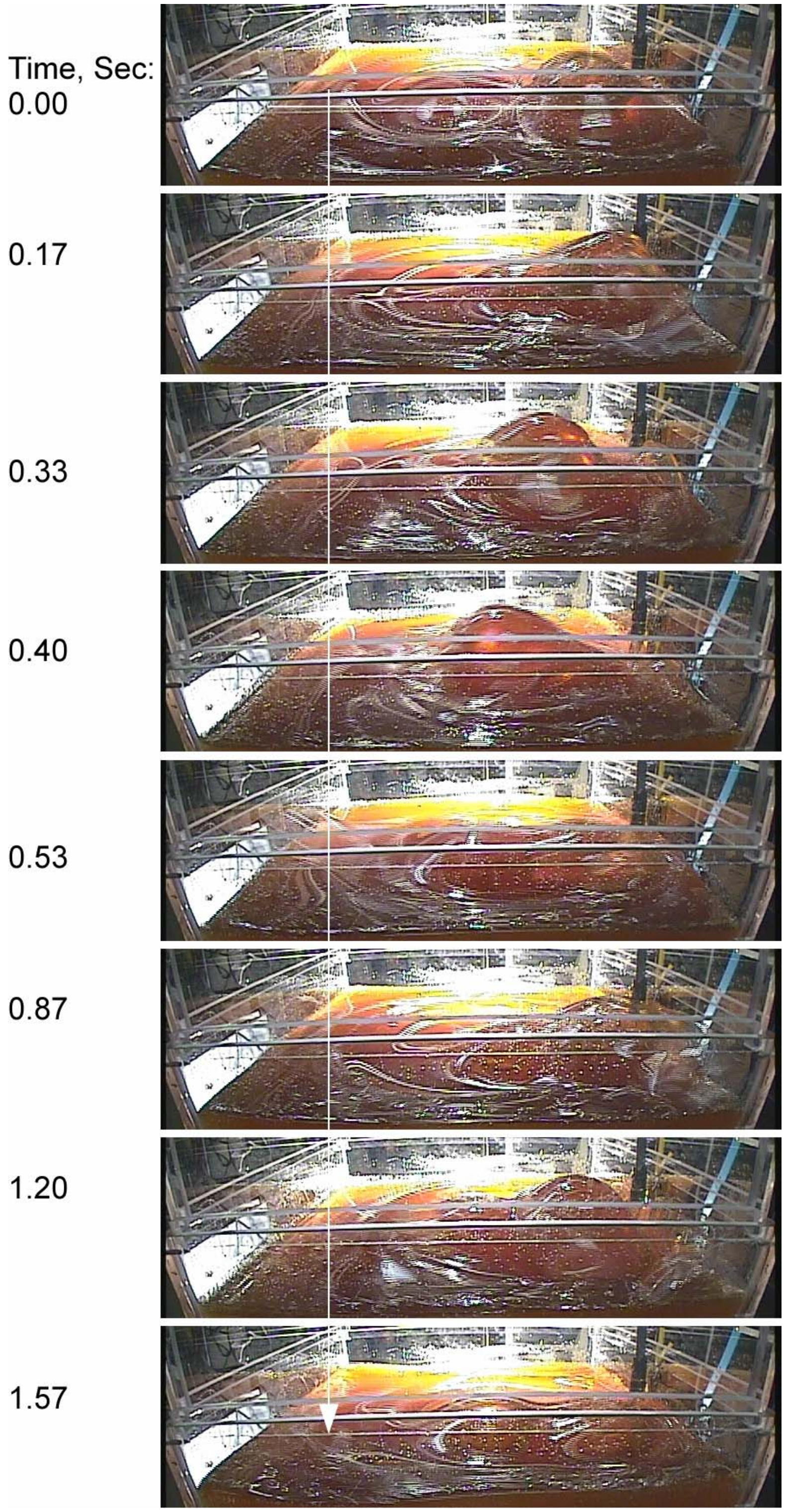

Figure 29. Sequence of video clips showing a lateral motion of the bubble mound at the surface, often associated with the capture of a bubble from one nozzle by a bubble from the other nozzle for the dual-nozzle bubbler.

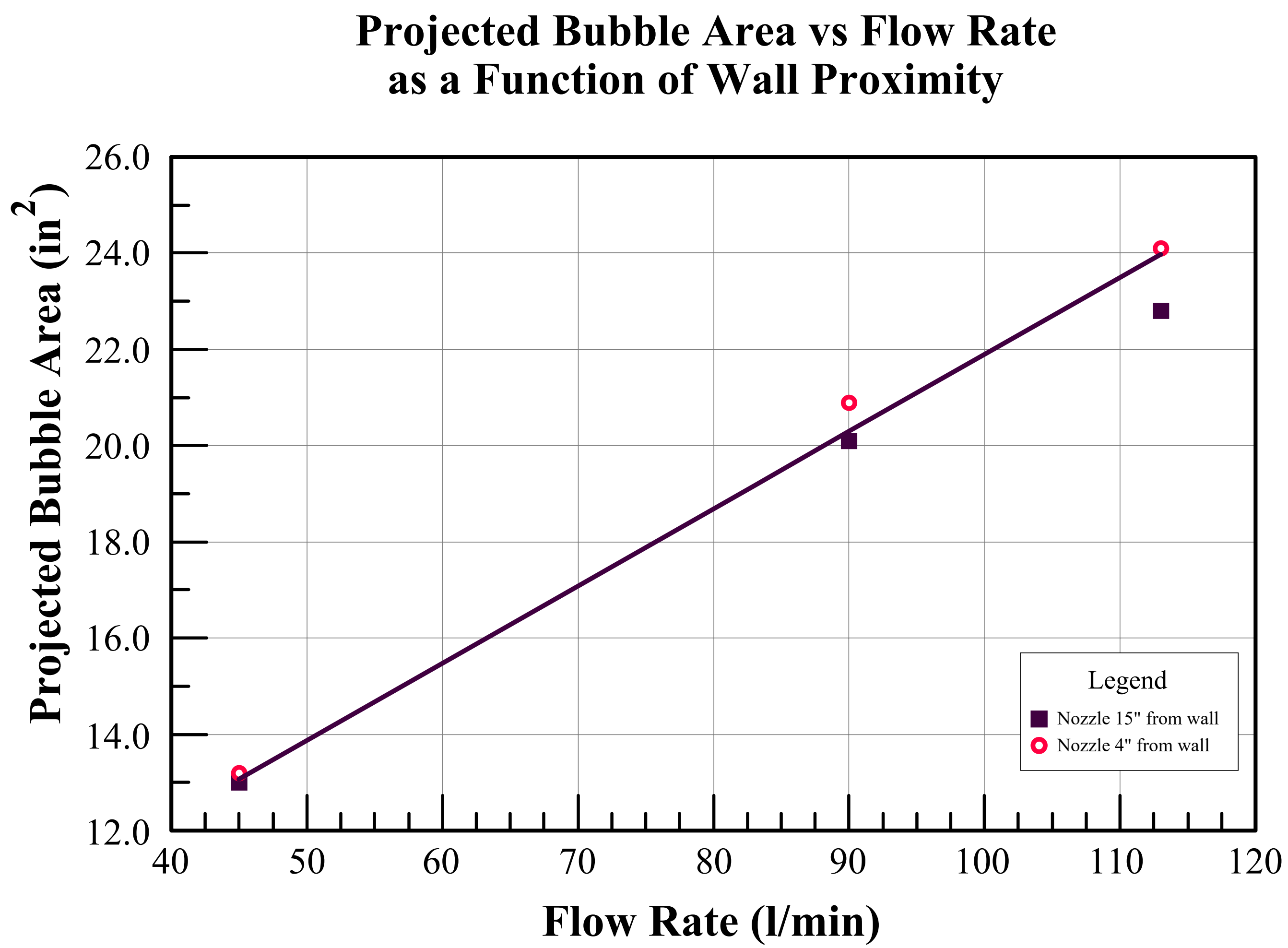

Figure 30. Results from Test 4.E. A comparison of bubble area for two values of the nozzle separation from the nearest wall.

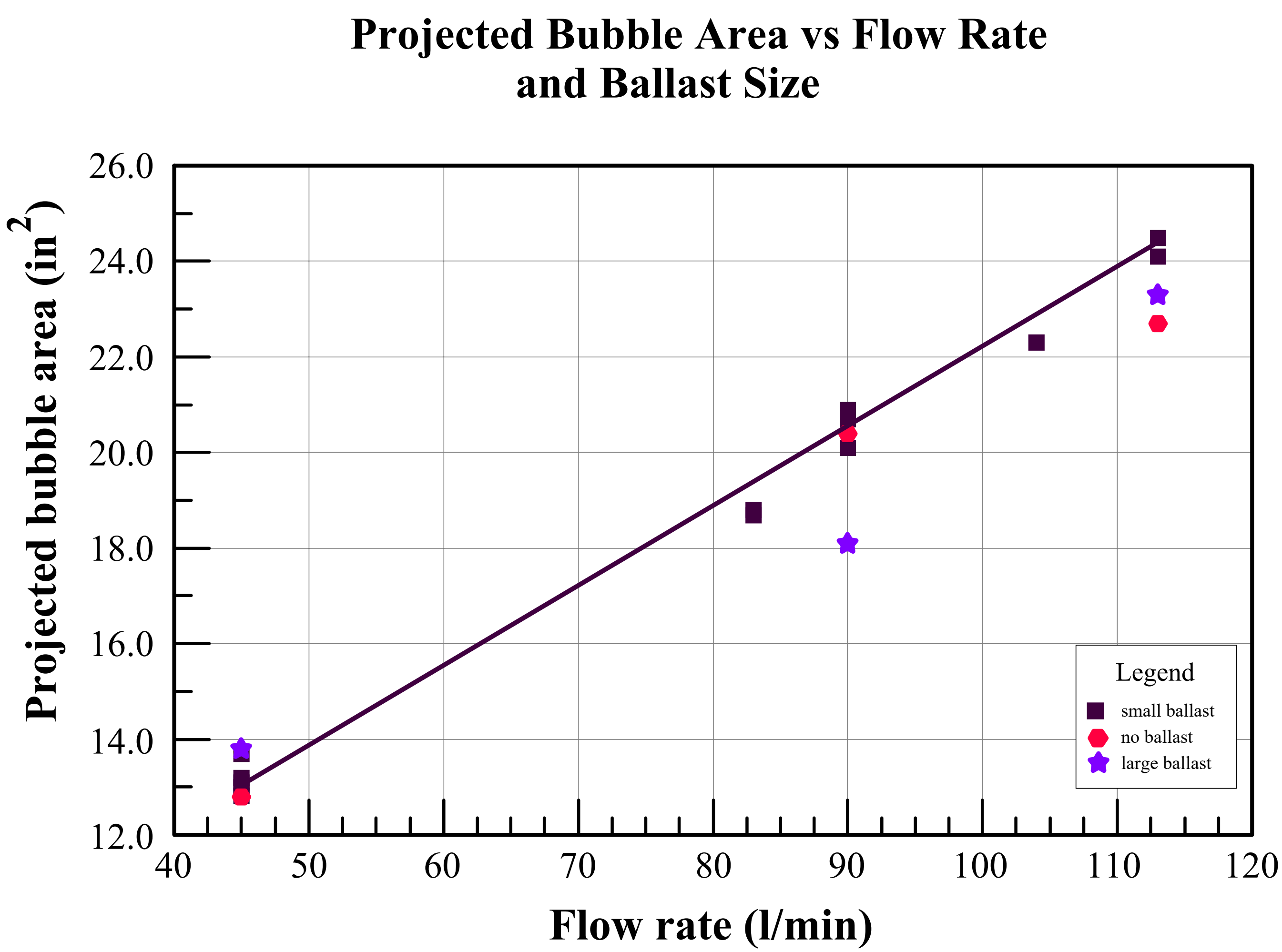

Figure 31. Projected bubble area versus flow rate for three air ballast volumes.

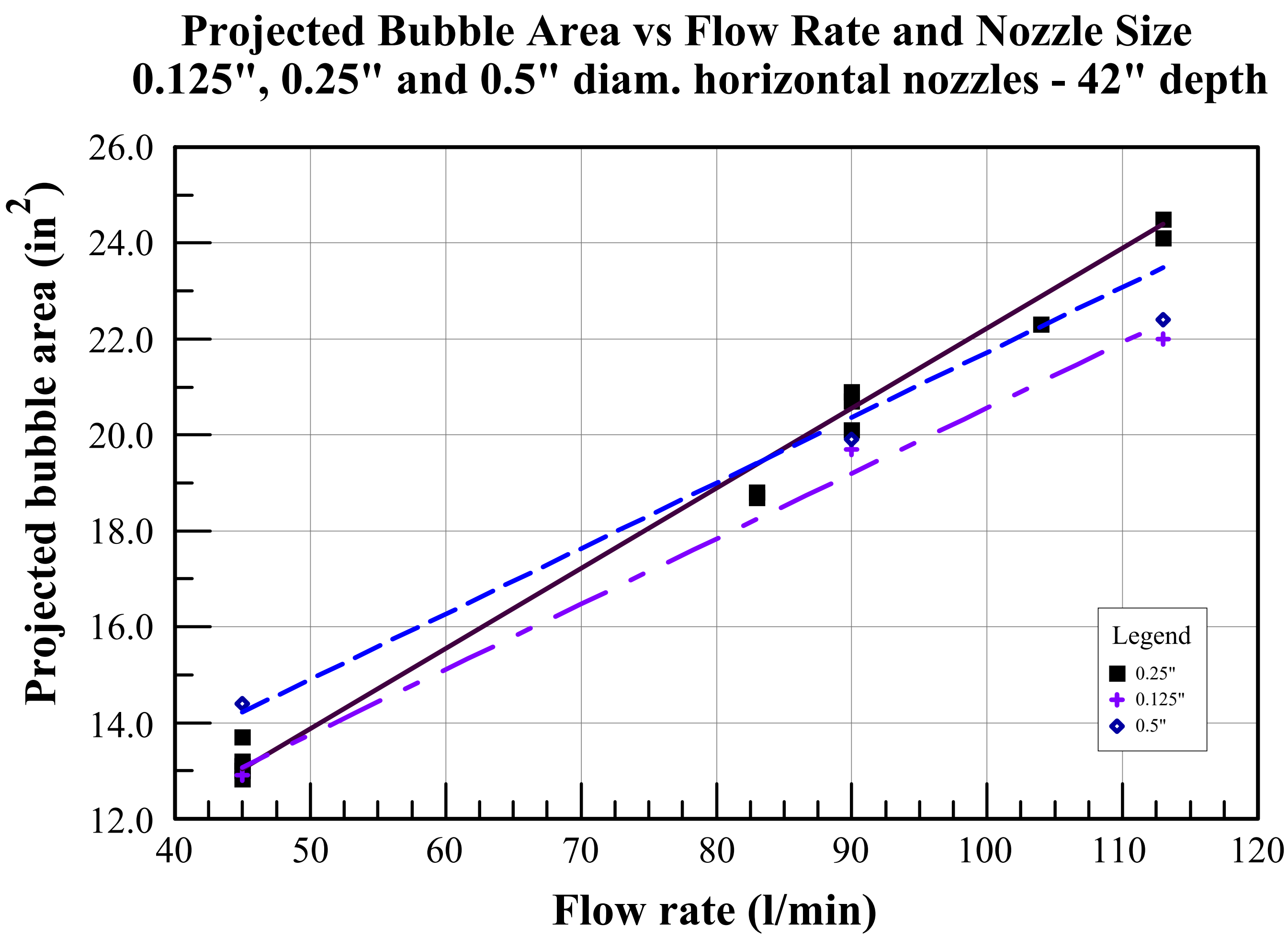

Figure 32. Comparison of projected bubble area vs. flow rate for 3 nozzle sizes at a 42" depth.