PNNL-11200
UC-721

Retrieval Process Development and Enhancements FY96 Pulsed-Air Mixer Testing and Deployment Study

M. R. Powell
C. R. Hymas

August 1996

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest National Laboratory
Richland, Washington 99352

DISCLAIMER

Summary

This document describes work conducted during fiscal year 1996 to evaluate the potential application of pulsed-air mixers to the slurry-mixing needs of the U.S. Department of Energy's waste-retrieval programs. Pulsed-air mixers offer considerable cost and operational advantages compared to the baseline slurry-mixing approach (i.e., jet mixer pumps), so the deployment of pulsed-air mixers should be pursued where it can be shown that the mixing performance will be adequate. This work was funded through the EM-50 Tanks Focus Area as part of the Retrieval Process Development and Enhancements (RPD&E) project at the Pacific Northwest National Laboratory (PNNL). The mission of RPD&E is to understand retrieval processes, including emerging and existing processes, gather performance data on those processes, and relate the data to specific tank problems such that end users have requisite technical bases to make retrieval and closure decisions.

Pulsed-air mixing uses large air bubbles introduced near the tank floor to induce slurry mixing. The bubbles are produced by horizontal, circular plates positioned just above the tank floor. Pipes deliver gas to the center of each plate from specially designed gas-pulsing valves, which are commercially available. Pulsed-air mixing differs from conventional air sparging in that single, large bubbles are introduced into the tank fluid periodically (e.g., once every 15 seconds) instead of small bubbles injected on a continuous basis. The rapid growth of the pulsed-air bubbles near the tank floor and their subsequent rise through the fluid serve to both suspend solids from the tank floor and maintain those solids in a uniform suspension.

Measurements of the fluid velocities produced by pulsed-air mixers near the tank floor were made using a hot-film anemometer. The observed peak velocities were correlated with gas pressure, plate diameter, gas-line diameter, and the distance between the plate and the tank floor. These data allow the design of pulsed-air mixing systems using the conservative assumption that the plates operate independently with respect to waste mixing.

The fluid velocity versus mixer design correlations were used to develop a pulsed-air mixer using full-scale mixing plates. This mixer was tested in a 1/4-scale mockup of a Hanford double-shell tank. This test demonstrated that the large-scale circulation patterns induced by the rising bubbles result in better mixing performance than that expected based on the fluid velocity correlations. Resuspension of the settled solids following a mixer outage was also demonstrated.

Mixer deployment was addressed by the University of Washington Applied Physics Laboratory (APL/UW) through a subcontract with PNNL. A feasible concept was developed for deploying the required number of pulsed-air mixing plates into an underground, horizontal waste tank similar to the V-tanks at the Idaho National Engineering Laboratory (INEL) and the Melton Valley tanks at Oak Ridge National Laboratory (ORNL). A detailed description of the mixer-deployment process and required equipment is included in this document.

The pulsed-air mixer testing conducted by PNNL, with assistance from Pulsair Systems, Inc. (Bellevue, Washington), substantially improved our ability to predict the capability of pulsed-air mixers to mobilize tank sludge and maintain solids in suspension. The key findings of the testing are:

- Slurry mixing applications where the goal is to maintain solids in suspension can be addressed by far fewer plates than are needed for cohesive sludge mobilization. The capability of a single, centrally located mixing plate in the 1/4-scale tank (18.75 ft diameter) to maintain approximately 80 wt% of the solids in suspension demonstrates that the large-scale circulation patterns induced in the slurry by the rising bubbles effectively maintain solids in suspension.

- The fluid velocities produced by the rapidly expanding gas bubble near the tank floor are sufficient to stir up cohesive tank sludge. The sludge will be mobilized by the pulsed-air bubble out to a distance from the center of the plate that is characterized by the bubble pulse radius (R_{pulse}). The bubble pulse radius has been correlated with mixing plate diameter, gas pressure, gas line diameter, and plate standoff distance. Thus, pulsed-air mixers can be designed to mobilize sludge by distributing the mixing plates such that the plates are spaced roughly $2R_{pulse}$ apart.

- Due to the number of mixing plates required to cover the tank floor, there is a challenge for the deployment of pulsed-air mixers in large-diameter, flat-bottomed waste tanks. Too many mixing plates are required to cover the tank floor. However, sludge mobilization is probably feasible in other tanks where the tank geometry is different. For example, the sludge in the INEL V-tanks can be resuspended by deploying only 4 mixing plates along the tank bottom. Deployment of 4 mixing plates into a horizontal tank design is addressed in this document. A similar mixer and deployment design should be applicable to the Melton Valley tanks at ORNL.

In short, pulsed-air mixers should be applied to slurry-mixing problems where either the tank is relatively small, the sludge is flocculent and soft, or mixing will be facilitated by gravity either through tank design (e.g., V-tanks and Melton Valley tanks) or through slurry density gradients (e.g., gas mitigation in Hanford tanks 101-SY and 103-SY). Large-diameter tanks require the deployment of an unrealistically high number of mixing plates to bring about sludge mobilization.

Several issues must be addressed before pulsed-air systems can be installed in radioactive-waste tanks. First, when the mixing plates are operated using a relatively high gas pressure to generate the bubble (e.g., 100 psig), a considerable shock wave can be produced within the waste. The effect of the shock on the mechanical integrity of the tank must be examined to ensure that the tank is not damaged. Shock-wave intensity can be reduced by operating the mixer at a lower pressure, but this decreases the bubble pulse radius. It may be possible to alleviate much of the shock wave by making small changes to the pulse valve and gas line designs.

The second issue to be addressed is aerosol generation. A fine mist of waste slurry is formed when the large bubbles break the waste surface. Whether the rate of aerosol generation is large enough to be of concern is not yet known. This is primarily an operating cost issue; that is, a higher aerosol-generation rate requires that the tank ventilation system be designed with greater capacity. It is expected that the pulsed air aerosol generation rate is similar to or smaller than that for tank sluicing, so it is unlikely that the pulsed air aerosol generation rate will require prohibitively expensive tank-ventilation systems.

It is recommended that pulsed-air mixing be used to mobilize and mix the solids in tanks V-3 and V-4 at INEL in preparation for retrieval of the waste slurry. Before deployment, it will be necessary to address tank vibration and aerosol effects, but neither issue is expected to be unresolvable. An additional application of pulsed-air mixing may be flammable-gas mitigation in selected Hanford double-shell waste tanks, such as 101-SY. A single, centrally located mixing plate pulsed at a low frequency at low gas pressure (to avoid shock-wave effects) may effectively prevent the accumulation of flammable gases within the layer of non-convective waste. A pulsed-air mixer in tank 101-SY would not be susceptible to mechanical failure as is the existing gas-mitigation mixer pump.

Acknowledgments

This work was funded by the EM-50 Tanks Focus Area as part of the Retrieval Process Development and Enhancements Project at PNNL. Pulsair Systems, Inc. provided assistance with both the experimental work and the deployment study as well as a mixer controller and all of the mixing plates used. The pulsed-air mixer deployment concept was developed by the University of Washington Applied Physics Laboratory. Section 3.0 of this report was prepared by Applied Physics Laboratory personnel as part of a subcontract issued by PNNL to the University of Washington.

Nomenclature

C	empirical constant
D_{hole}	diameter of hole in upper mixing plate, cm
D_{pipe}	inside diameter of gas pipe, cm
D_{plate}	pulsed air mixing plate diameter, cm
FY95	fiscal year 1995
FY96	fiscal year 1996
h	standoff distance, cm
h_{min}	minimum standoff distance, cm
INEL	Idaho National Engineering Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
RPD&E	Retrieval Process Development and Enhancements
r	radial position measured from mixing plate centerline, cm
r_i	radial position of the air/liquid interface, cm
R_p	pulsed air mixing plate radius, cm
R_{pulse}	bubble pulse radius, cm
R_{plate}	pulsed air mixing plate radius, cm
t	time, sec
U_o	fluid exit velocity at edge of mixing plate, cm/s
U_{max}	maximum downstream fluid velocity, cm/s
USDOE	United States Department of Energy
W_{init}	initial weight percent solids in slurry, %
ΔP	pressure difference between compressed air and liquid head, psi
ρ	liquid density, g/cm^3
ρ_{kaolin}	particle density of kaolin clay, 2.64 g/cm^3
ρ_{slurry}	slurry density, g/cm^3
ρ_{water}	density of water at slurry temperature, g/cm^3

Contents

Figures

Tables

1.0 Introduction

Millions of gallons of radioactive waste resides in underground tanks at U.S. Department of Energy (USDOE) sites. The waste was generated primarily by the processing of nuclear fuel elements to remove fissile radionuclides for use in atomic weapons. Plans call for the waste to be removed from the tanks and processed to create immobile waste forms, which will be stored to prevent release to the environment.

The consistency of the waste ranges from liquid, to slurry, to sticky sludge, to hard saltcake. A variety of waste-retrieval and processing methods are being evaluated and implemented. One such method is pulsed-air mixing, which is the subject of this report.

Pulsed-air mixing equipment has been successfully applied to a number of difficult mixing applications in various chemical-process industries. Most previous applications, however, involved the mixing of particle-free viscous fluids. The study described in this report was performed to improve the understanding of how pulsed-air mixing applies to slurries. Pulsed-air mixing technology is patented by Pulsair Systems, Inc. (Bellevue, Washington). Throughout this report, the phrase "pulsed-air mixing" refers exclusively to the mixing technology marketed by Pulsair Systems, Inc.

This document describes work conducted during fiscal year 1996 to evaluate the potential application of pulsed-air mixers to the slurry-mixing needs of the U.S. Department of Energy's waste-retrieval programs. Pulsed-air mixers offer considerable cost and operational advantages compared to the baseline slurry-mixing approach (i.e., jet mixer pumps), so the deployment of pulsed-air mixers should be pursued where it can be shown that the mixing performance will be adequate. This work was funded through the EM-50 Tanks Focus Area as part of the Retrieval Process Development and Enhancements (RPD&E) project at the Pacific Northwest National Laboratory (PNNL). The mission of RPD&E is to understand retrieval processes, including emerging and existing processes, gather performance data on those processes, and relate the data to specific tank problems such that end users have requisite technical bases to make retrieval and closure decisions.

1.1 Description of Pulsed-Air Mixing

The pulsed-air mixing technique uses discrete pulses of air or inert gas to produce large bubbles near the tank floor, which rise to the surface of the liquid, thereby inducing mixing. An array of horizontal, circular plates is positioned a few centimeters from the tank floor. Pipes connected to each plate supply the pulses of gas to the underside of each plate. Control equipment and gas-pulsing valves available from Pulsair Systems, Inc. are used to control the pulse frequency, duration, gas pressure, and plate sequencing to create a well mixed condition within the tank.

Figure 1.1 is a sketch showing the growth of a pulsed-air bubble. When compressed air is supplied to the underside of the mixing plate (also called the accumulator plate), the growing bubble expels liquid radially outward from under the plate. This is shown in the upper-left sketch in Figure 1.1. Bubble growth continues radially outward beyond the edge of the accumulator plate, out to a distance of R_{pulse} from the plate center. The air/liquid interface reaches R_{pulse} quickly; stop-action video reveals that R_{pulse} is reached about 0.1 sec after gas-pulse initiation. After this point, the bubble collapses radially inward and moves up toward the liquid surface.

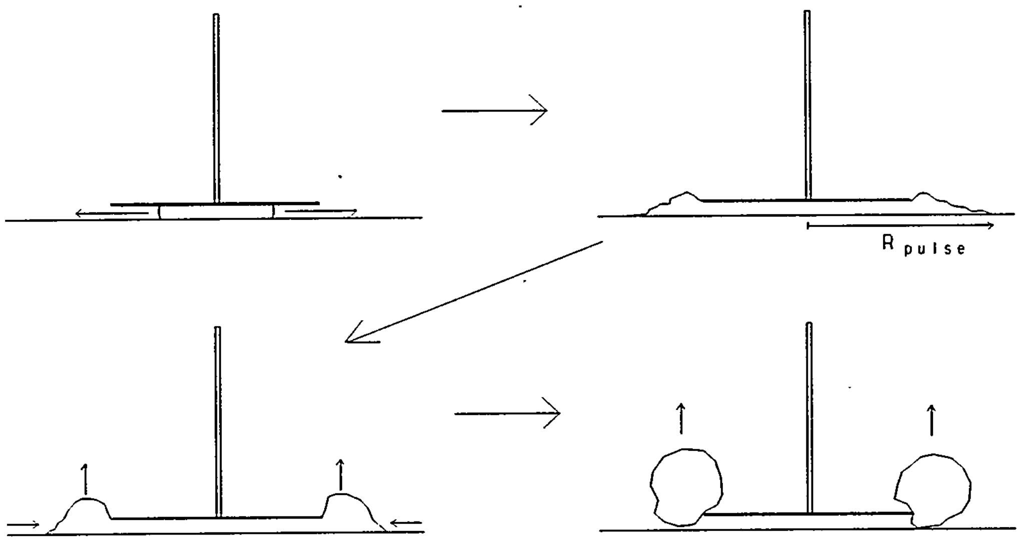


Figure 1.1. Sketch of Gas Bubble Growth Showing R_{pulse}

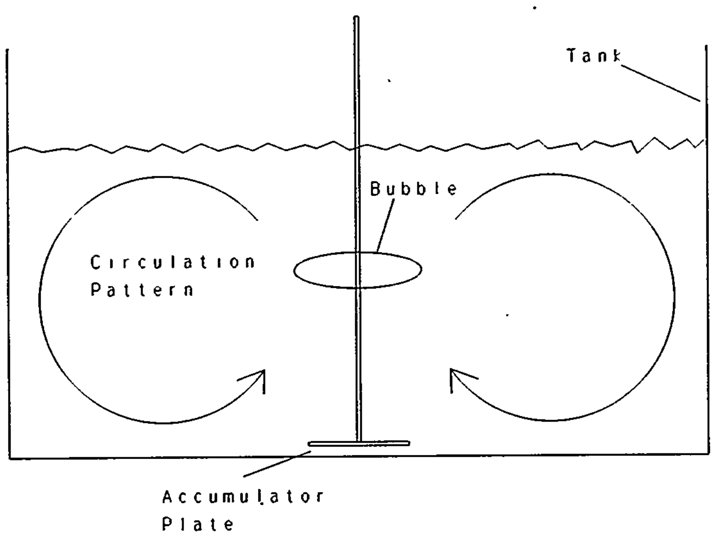


Figure 1.2. Bubble-Induced Fluid Circulation Pattern

For slurry mixing, both the rapid growth of the bubble to R_{pulse} and its subsequent rise to the liquid surface are relevant. The fluid velocities produced by the rapid radial growth of the bubble out to a distance of R_{pulse} are high enough to sweep settled solids off the tank floor. The rising bubble induces large-scale fluid-circulation patterns within the tank that maintain slurry uniformity and keep solids in suspension. The circulation pattern generated by bubbles from a centrally located plate is shown schematically in Figure 1.2.

Pulsed-air mixing has a number of advantages over other waste mixing approaches (e.g., jet mixer pumps): reduced equipment cost, reduced risk of equipment failure, easier equipment decontamination, very low operating costs, no minimum liquid level required for operation, and minimal heat addition to the waste. Of these advantages, the reduced risk of equipment failure is probably the most significant. Pulsed-air mixers require no moving mechanical parts within the tank. Mixer pumps, by contrast, have shaft seals, impellers, and motors potentially submerged in the waste. Failure of these components could necessitate replacement of the mixer pump. The only pulsed-air mixer components within the tank are stainless-steel pipes and plates.

1.2 Review of Previous Pulsed-Air Testing

In fiscal year 1995, a study of pulsed-air mixing for application at Hanford was conducted by PNNL.[a] This study was funded by EM-30 through Westinghouse Hanford Company. Pulsed-air mixing had been identified as a potential low-cost substitute for jet mixer pumps. The 1995 study was undertaken in an effort to determine whether the mixing performance expected from pulsed-air mixers would fulfill some of Hanford's slurry-mixing needs.

Two series of tests were conducted in a 1/12-scale tank. The first test was designed to determine whether pulsed-air mixers could maintain waste slurries in suspension. Given an initially well mixed slurry in a tank, a determination was to be made of whether a pulsed-air mixer could maintain an acceptable fraction of that slurry in suspension (i.e., not allow it to settle to the tank floor). The second test series was designed to evaluate the capability of pulsed-air mixers to resuspend the sludge that is known to have accumulated in many of the Hanford double-shell tanks.

A 13-plate pulsed-air mixer array was designed for these tests. The slurry suspension-maintenance tests were conducted using two different-sized plates, each at two standoff distances. A view of the array of mixing plates looking down into the tank before waste simulant was added is shown in Figure 1.3. A schematic representation of the experimental arrangement is given in Figure 1.4. The mixing-plate sizes used were 15.2-cm- and 7.6-cm-diameter plates, each operated at both 0.6-mm and 0.2-mm standoff distances. The capability of each of these configurations to maintain solids in suspension was evaluated at both 50 and 100 psig.

---

[a]Powell, MR, MA Sprecher, CR Hymas, D Winkel, RM Andrews, and RE Parks. 1995. *1/12-Scale Testing of a Pulsair™ Mixing Array: An Evaluation of Pulsed-Bubble Mixing for Hanford Waste Retrieval and Processing Applications.* A letter report prepared for Westinghouse Hanford Company by Pacific Northwest Laboratory (Richland, Washington) and Pulsair™ Systems (Bellevue, Washington).

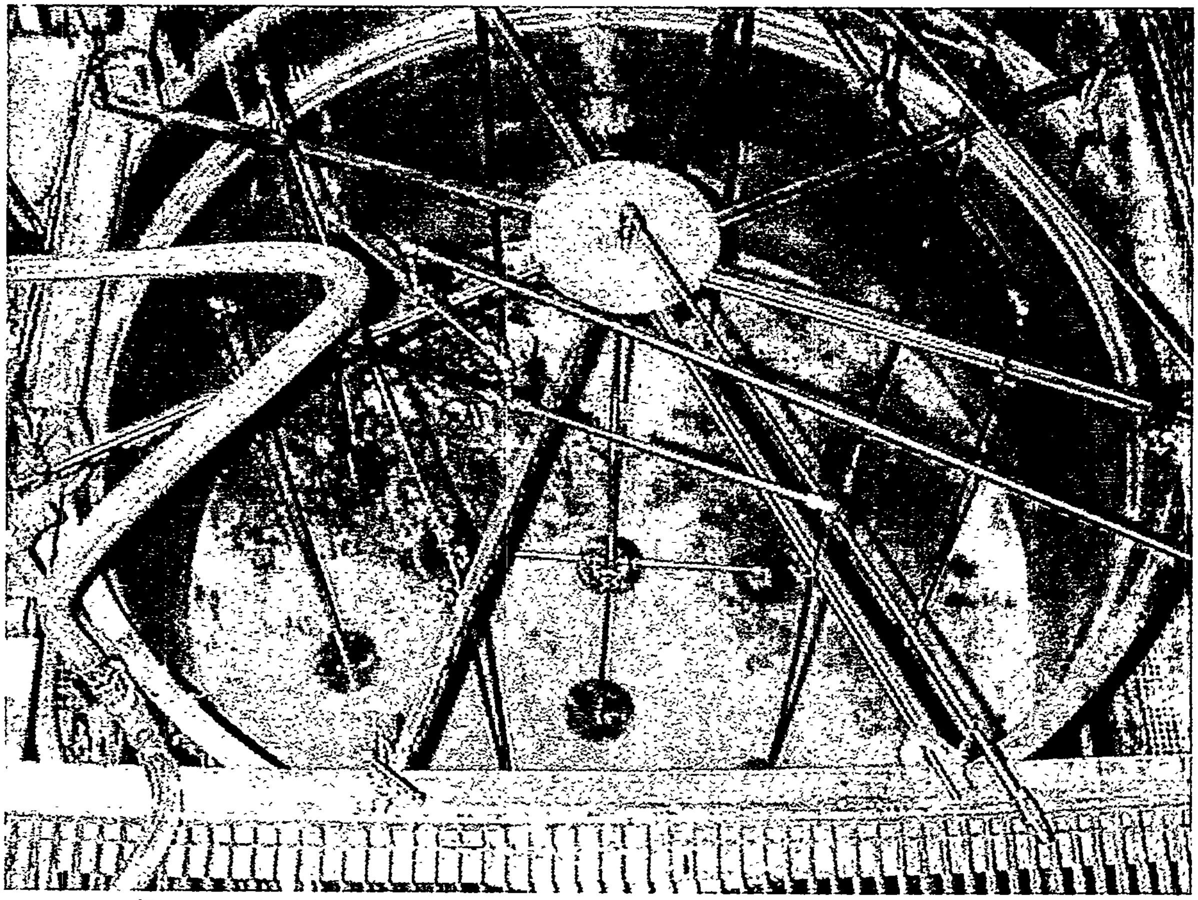


Figure 1.3. Fiscal Year 1995 Pulsed-Air Mixing Array in 1/12-Scale Tank

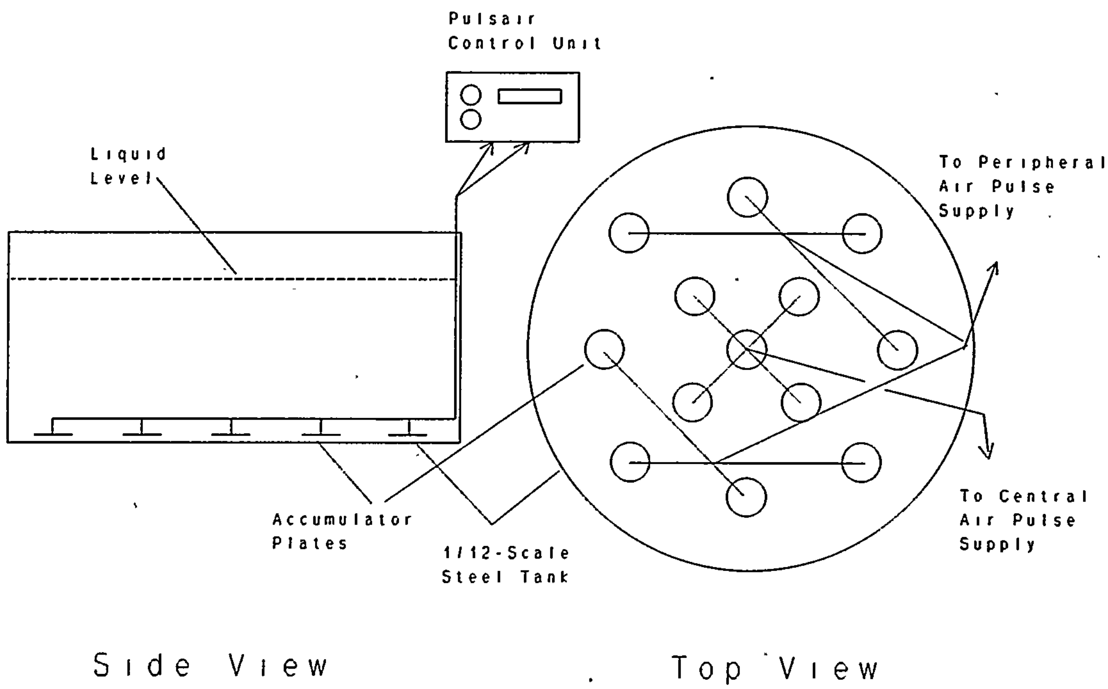


Figure 1.4. Sketch of 1/12-Scale Mixing Array Used for FY95 Testing

The slurry-suspension tests used a scaled slurry simulant; that is, the settling velocities of the solids selected for testing were approximately 3.5 times faster than the actual waste-settling velocities. The factor of 3.5 was determined by an analysis of the expected fluid velocity scaling.[a]

The simulant used for the sludge-mobilization test was a mixture of water and kaolin clay. The wt% clay was high enough that the mixture had a consistency similar to that of room-temperature margarine (shear strength about 5.0 $kdyn/cm^2$). This simulant was not scaled; that is, its properties were designed to be directly comparable to those of actual Hanford double-shell tank sludge. Because of this, the amount of sludge suspended in the 1/12-scale test was expected to be significantly greater than that expected from a full-scale deployment.

The slurry suspension-maintenance test demonstrated that up to 80 wt% of the solids could be maintained in suspension by the pulsed-air mixer array (largest plates at the highest pressure). Because the simulant properties were scaled to account for the difference in size between the 1/12-scale mixer and a full-scale mixer, it was predicted that a full-scale mixer of similar (but 12 times larger in all dimensions) design could maintain roughly 80 wt% of the solids in suspension. This prediction was contingent upon the validity of the scaling analysis, which has since been found to be inaccurate (see Section 2.1.2).

The sludge-mobilization test was conducted by first loading an 8-cm-thick layer of sludge simulant into the bottom of the tank. Simulated supernate (water) was added carefully to avoid disturbing the sludge layer. The pulsed-air mixer array was then lowered into the tank until the plates came to rest on the sludge layer. When the air pulsing started, the mixing plates slowly lowered themselves into the sludge (due to the combination of erosion and the weight of the mixer array) until the tank floor was reached. The test was continued until no further sludge mobilization occurred (as evidenced by stable slurry density). At this point, 54 ± 2 wt% of the sludge had been suspended.

The tank was drained to reveal the remaining sludge layer; it was found that the performance of the center mixing plate far exceeded that of the other 12 mixing plates in the array. Figure 1.5 shows the sludge bank remaining after this test. It is clear that the effective radius for mobilization of the center plate exceeded that of the other plates. The center plate cleaned sludge away out to a distance of about 22 cm from its center. The other plates only managed to clear sludge to about 12 to 15 cm from their respective centers. It was estimated that if the performance of the center plate could be obtained by the other 12 plates in the array, then mobilization of about 80 wt% of the sludge would have been obtained in the 1/12-scale test. Had the scaling analysis developed for this previous testing been valid, the observed 80 wt% sludge mobilization at 1/12-scale would predict a rather dismal 20 wt% of the sludge mobilized for the corresponding full-scale mixer.

---

[a]The factor of 3.5 was derived from the scaling analysis, which assumed that the primary mechanism for keeping particles off the tank floor was the generation of a radial wall jet of tank fluid as the liquid was expelled from beneath the accumulator plates by the pressurized gas. The testing conducted in FY96 has demonstrated that this assumption is incorrect.

Figure 1.5. Remaining Sludge Following FY95 Pulsed-Air Mobilization Test

The reason for the much greater performance of the center plate was traced to the fact that the air supply was not sufficient to deliver full gas pressure to the other plates. The experimental layout was such that only the center-most plate received near-full gas pressure during each pulse. This knowledge was used to help design the pulsed-air mixing systems tested in FY96. The present system designs include compressed-air accumulator tanks upstream of the pulsing valves to ensure sufficient air flow.

Based on the 1/12-scale test results, it was concluded in FY95 that pulsed-air mixing may provide sufficient mixing intensity to maintain solids in suspension, but not enough to mobilize cohesive sludge from the tank floor. These two conclusions were made with the caveat that the scaling analysis had yet to be verified. The recent testing, described in Section 2.0, has shown the previous scaling analysis to be in error. These two conclusions, however, remain largely unchanged despite the problems with the previous scaling analysis. This is addressed fully in Section 2.0.

1.3 Objectives of Current FY96 Work

Following the pulsed-air testing conducted in fiscal year 1995, two major uncertainties remained to be overcome before a decision could be reached as to whether pulsed-air mixing should be pursued for Hanford tanks. The first uncertainty, mixer performance scaleup, was detailed in Section 1.2. The second uncertainty was mixer deployment. To mix the waste in a Hanford double-shell tank, it seemed clear that a dozen or more mixing plates might need to be deployed into the tank. It was not clear how this could be done because all the mixing plates must be installed through the pre-existing tank risers, the largest of which are only 1.07 m (42 in.) in diameter.

The fiscal year 1996 work, described in this report, was undertaken to address both of these uncertainties. Funding for the present work was provided by the EM-50 Tanks Focus Area through the Retrieval Process Development and Enhancements project.

The issue of pulsed-air mixer scaleup was addressed through a series of tests in both 1/12-scale and 1/4-scale tanks (based on Hanford double-shell tank dimensions). Mixer performance was quantified as a function of plate diameter, gas pressure, gas-line size, and plate-standoff distance. These data were used to develop correlations that provide a design basis for full-scale pulsed-air mixers. The testing done to address the pulsed-air mixer scaleup issue is described in Section 2.0.

Mixer deployment was addressed by the University of Washington Applied Physics Laboratory (APL/UW). APL/UW has extensive experience designing and deploying equipment similar to the pulsed-air mixers. For example, APL/UW has deployed large-scale sensor arrays through boreholes in arctic ice for the U.S. Navy. A subcontract was placed with APL/UW for this portion of the work. The mixer-deployment concept developed by APL/UW for the INEL V-tanks is described in Section 3.0 of this report.

2.0 Pulsed-Air Scaleup Testing

Two series of tests were conducted to determine how the performance of pulsed-air mixers changes with mixer size, design, and operation. This knowledge of mixer scaleup was needed to ensure that the conclusions drawn from the fiscal year 1995 testing were valid. The first test series was conducted in a 191-cm- (75-in.-) diameter tank with the goal of correlating peak fluid velocities with mixer design and operation parameters. This tank is 1/12-scale with respect to a Hanford double-shell tank. The second test series used an array of four full-scale plates installed in a 5.72-m- (18.75-ft-) diameter tank. This tank is 1/4-scale with respect to a Hanford double-shell tank. The purpose of the second test series was to ensure that the full-scale plate performance was consistent with that predicted based on the correlations developed in the first test series. The first test series is described in Section 2.1; the second test series is described in Section 2.2.

2.1 Scaleup Correlation Development

The purpose of the testing described in this section was to correlate the maximum fluid velocities near the tank floor produced by pulsed-air mixing plates with mixer design and operation parameters. The greatest challenge for pulsed-air mixers with respect to slurry mixing is expected to be the prevention of solids accumulation on the tank floor. The rising bubbles promote excellent vertical mixing, so it is unlikely that slurry homogeneity is a realistic concern.[a] The prevention of solids settling, however, requires that sufficient fluid velocity be present near the tank floor. The maximum fluid velocities produced by pulsed-air mixing plates were measured in an effort to characterize the capability of each mixer design to prevent solids settling. The velocity measurements were made at four radial positions (all 1 cm above the tank floor) for four different plate diameters, four different standoff distances, and five different gas pressures. The resulting correlations will be used to design full-scale pulsed-air mixers.

The scaleup correlation development testing is described in this section. A description of the experimental procedure and apparatus is followed by a presentation of the data collected. The full-scale plate testing in the 5.72-m (18.75-ft) tank is addressed in the Section 2.2.

2.1.1 Experimental Procedure and Equipment

A schematic of the 1/12-scale tank and the single, centrally-located Pulsair mixing plate is shown in Figure 2.1. The tank used during the testing was a 191-cm- (75-in.-) diameter, 91-cm- (36-in.-) high, stainless-steel tank. Pulsair Systems, Inc. provided the accumulator plates (various sizes), the plate support structure, and the Pulsair control equipment. The Pulsair control equipment was used to regulate the pulse frequency, pulse duration, plate sequencing, and gas pressure. Compressed air was supplied from the building compressed air line, which has a maximum pressure of about 100 psig.

---

[a]No evidence of vertical concentration gradients was found during either the fiscal year 1995 slurry suspension tests or the current FY96 tests using kaolin clay.

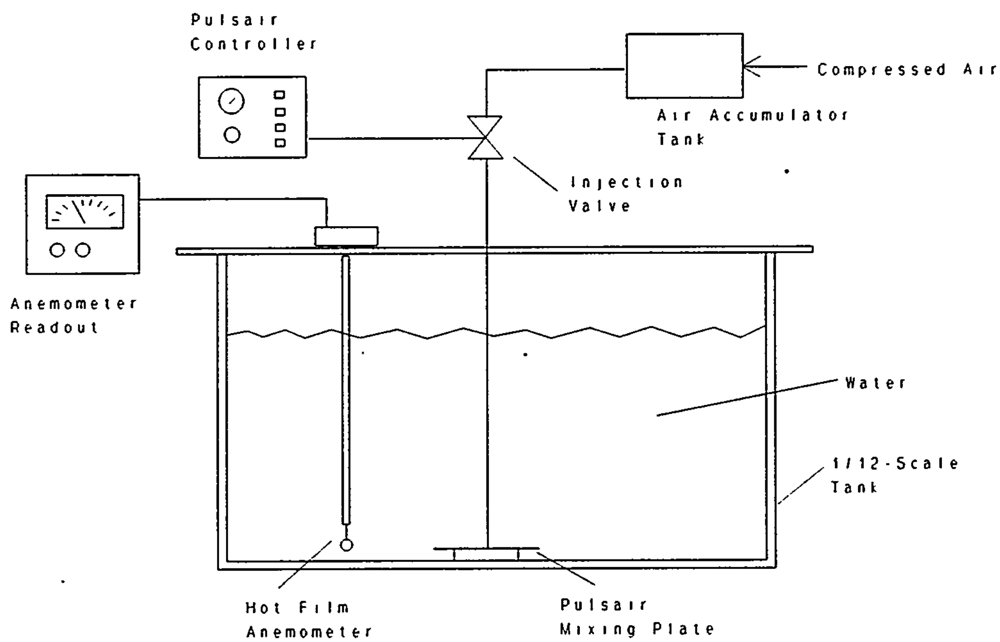


Figure 2.1. Scale-Up Correlation Development Test Fixture Schematic

Table 2.1. Test Parameters for Scaleup Correlation Development Testing

Test Parameter	Values Tested
plate diameter (cm)	6.1, 14.2, 23.9, 36.6 cm
standoff distance (cm)	0.32, 0.64, 1.27, 2.54 cm
gas pressure (psig)	20, 40, 60, 80, 100 psig
distance from plate centerline at which velocity measurements taken (cm)	≥ 4 locations (variable)
gas pipe diameter (cm)	6.1-cm plate: 0.32, 0.51, 0.68, 0.92 cm
	14.2-cm plate: 1.58 cm
	23.9-cm plate: 1.25, 2.1, 2.66, 3.5 cm
	36.6-cm plate: 4.09 cm

Four different plate diameters were tested. The mixing plates were made from stainless-steel plate. A double-plate arrangement was used so that the plate standoff distance[a] could more easily be controlled. The bottom plate was held a fixed distance from the top plate by three bolts. The plates, gas lines, and valves used for the testing are shown in Figure 2.2. The plate diameters tested were 6.1 cm, 14.2 cm, 23.9 cm, and 36.6 cm. Each of these plates was tested at standoff distances of 0.32 cm, 0.64 cm, 1.27 cm, and 2.54 cm. For the 6.1-cm and 23.9-cm plates, additional tests were conducted in which the gas-line diameter was varied. Four different gas delivery-pipe diameters were tested for each of these plate diameters. A single standoff distance was used for these tests.[b] The full suite of mixer design and operation parameters tested are listed in Table 2.1. All possible permutations of the listed plate diameters, standoff distances, and gas pressures were tested. For all tests, the tank contained clean water to a depth of 60 cm.

The fluid velocities produced by the pulsed-air mixing plates were measured using a Thermo-Systems, Inc. (TSI) model 1210-20W hot-film anemometer probe with a TSI model 1054B probe controller. The analog voltage output of the probe controller was routed to a peak-measuring digital multimeter (Fluke Model 87) to measure the maximum fluid velocity produced by each gas pulse. The hot-film anemometer was calibrated by inserting the anemometer into the middle of a pipe through which a known water flow rate was passed. Corrections were made for the turbulent velocity distribution profile in the pipe and for variations in water temperature.

---

[a]Plate standoff distance is defined as the vertical distance between the upper and lower plates. The plate standoff distance (*h*) is shown schematically in the lower-left portion of Figure 2.4.

[b]A standoff distance of 0.64 cm was used for the 6.1-cm plates, and a standoff distance of 1.27 cm was used for the 23.9-cm plates.

Hot-film anemometers provide instantaneous, local fluid velocity measurements.[a] A thin quartz cylinder (typical diameters are 25 to 100 μm) is suspended between two epoxy-coated supports roughly 0.5 cm apart. The quartz cylinder is sputter-coated with a thin platinum film. Feedback-control electronics pass electrical current through the platinum between the epoxy-coated supports. The current is maintained such that the platinum film is maintained at a constant temperature that is higher than that of the flowing liquid surrounding the film. The probes used in this study were maintained at roughly 67°C. The liquid temperature ranged from 9°C to 15°C. Higher liquid flow rates across the platinum film remove more heat by forced convection. The amount of electrical current required to maintain a constant probe temperature is a function of the liquid flow rate at the probe surface and the temperature difference between the probe film and the liquid. The hot-film anemometer controller used in this study outputs a voltage that is indicative of the flow experienced at the surface of the platinum film on the probe. The peak voltage was recorded during these tests.

The hot-film anemometer probe was held in position within the tank using a rigid support structure affixed to the tank. The probe support slides along a rail. This enabled fluid-velocity measurements to be made at selected radial distances from the mixing plate. All measurements were made at a vertical distance of 1.0 cm above the tank floor. Vibration-dampening material was placed between the probe and the probe support to ensure that the peak voltages reported by the anemometer did not reflect the effects of the tank vibration induced by the gas pulses.

Each test was conducted by first configuring the mixing plate. The appropriate plate diameter, gas-line diameter, standoff distance, and pulsing-valve size were selected and assembled. The mixing plate was then affixed inside the tank with the centerline at the tank center. The 14.2-cm mixing plate positioned in the tank is shown in Figure 2.3. No water had yet been added to the tank when this photograph was taken.

Once the mixing plate and gas-delivery system were properly configured, testing would begin at the lowest gas pressure. The pulsing frequency was set low enough to enable the fluid motion to decay to low levels between pulses (usually 15-20 seconds between pulses). Eight successive peak-voltage readings were then recorded from the anemometer output using the voltmeter set to detect voltage peaks of 0.001-sec duration or more. The average peak voltage was computed and adjusted to account for differences between the water temperature during the test and during calibration. The peak voltage was then translated into peak fluid velocity based on the calibration data. The standard deviation of the eight voltage readings was used to estimate the 95% confidence interval on the mean peak velocity. This procedure was repeated for the remaining gas pressures. The anemometer probe then was moved to a new radial position and testing resumed at the lowest gas pressure. Data for the five gas pressures tested were taken at a minimum of four different radial positions.

The magnitude of R_{pulse} (see Figure 1.1) was quantified by watching the tank floor during the gas pulses. The radial distance reached by the bubble/water interface during the gas pulse was recorded. The recorded value was the average of at least 4 observed pulse radii. Gas pulse radius measurements were made for each pressure for each of the mixer configurations tested. The 95% confidence intervals for the mean R_{pulse} values were estimated based on the standard deviation of the R_{pulse} measurements for each configuration.

---

[a] A general discussion of hot-film anemometry is given in Comte-Bellot (1976).

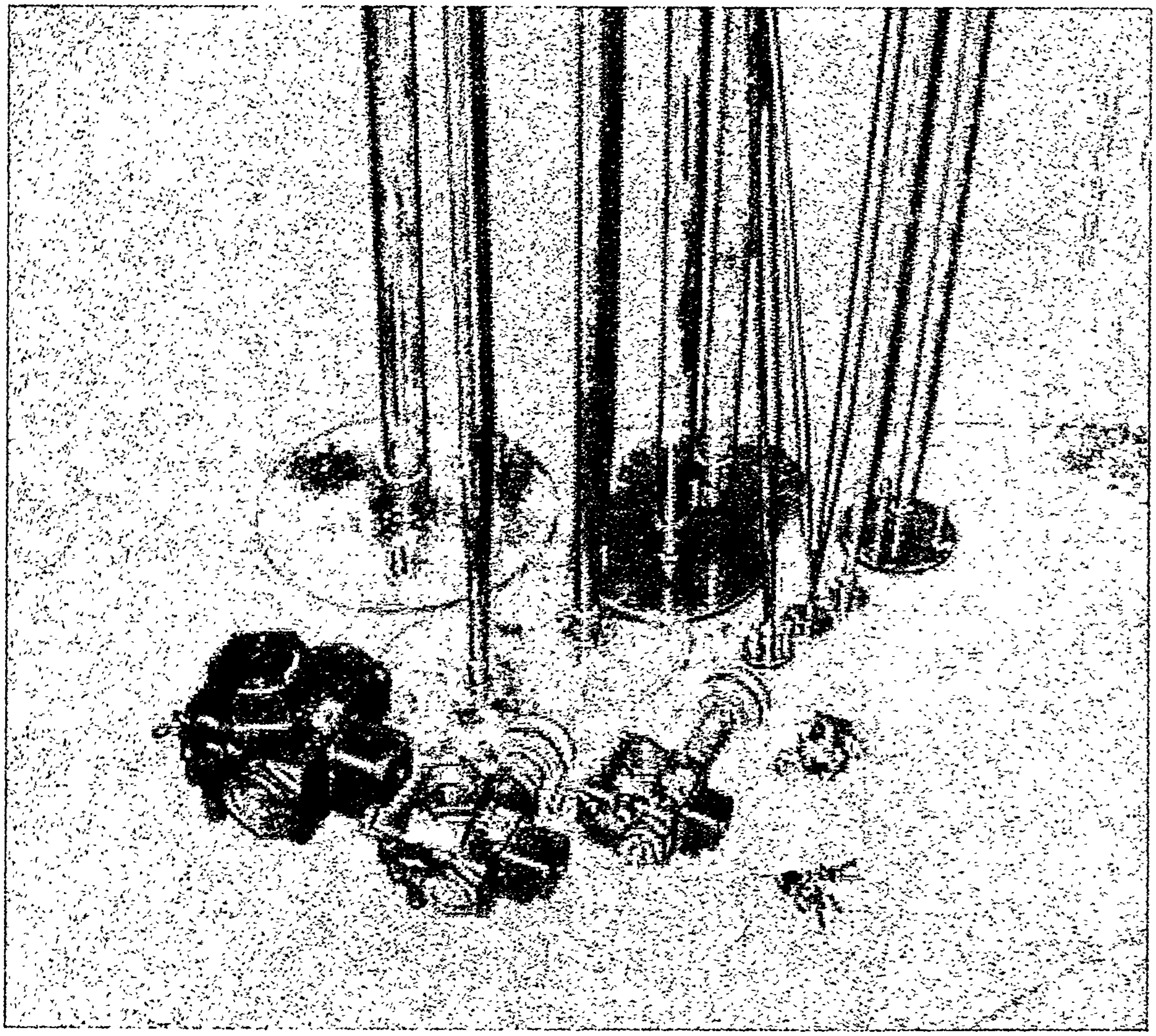


Figure 2.2. Plates, Valves, and Gas Lines Used for Scale-Up Testing

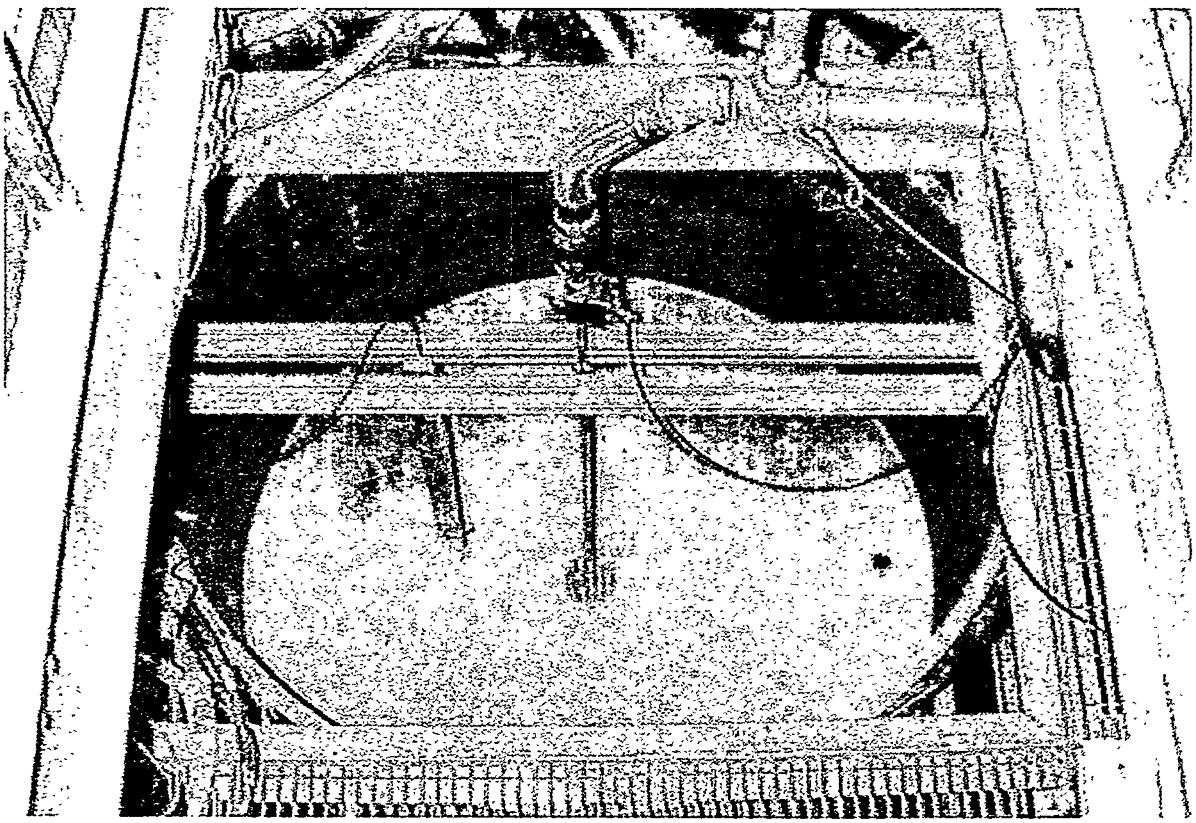


Figure 2.3. Scale-Up Correlation Development Test Set-Up

2.1.2 Scaleup Testing Results

The results of the scaleup correlation development testing conducted in the 1/12-scale tank are presented in this section. Measurements of the peak fluid velocities produced near the tank floor by pulsed air mixing plates were made as described in Section 2.1.1. The data collected revealed that the previous understanding of pulsed-air mixer scaleup was in error. A brief discussion of the previous scaleup methodology will be given and followed by a discussion of the recent data that show that methodology to be incorrect.

Previously Developed Pulsed-Air Scaling

As part of the pulsed-air mixer testing conducted during fiscal year 1995 (described in Section 1.2) an analysis of the expected mixer scaleup was performed. The basis of this analysis was the assumption that particle settling is prevented primarily by the fluid velocities produced as the bubble progresses outward between the plates. As the bubble grows, the fluid between the plates is forced radially outward at high speed. The radially flowing fluid, it was assumed, was responsible for preventing particle settling (or resuspending particles) out to a distance where the velocity had decayed to a low level. It was hypothesized that the velocity profile produced by the expelled fluid was similar to that of a fully developed radial-wall jet, which is given by Rajaratnam (1976) as

$$U_{max} = U_o C \frac{\sqrt{R_p h}}{r - R_p} \qquad (2.1)$$

where U_{max} = maximum downstream fluid velocity, cm/s
U_o = fluid velocity at the edge of the plate, cm/s
C = empirical constant in the range of 1.5 to 2.0
R_p = plate radius, cm
h = plate standoff distance, cm
r = radial distance from the plate center, cm

Development of the radial wall fluid jet is shown schematically in Figure 2.4. The figure shows the growing bubble pushing water radially outward from under the plate toward the settled solids.

A simple force balance was employed to predict the relationship between the downstream fluid velocities and the mixer design and operation parameters (e.g., R_p, h, and gas pressure). The force available at the air/water interface of the growing bubble (while under the plate) was applied toward the radial acceleration of the liquid remaining under the plate to estimate the fluid velocity at the plate exit (U_o) as a function of time. The U_o versus time relationship was found by numerically solving the differential equation:

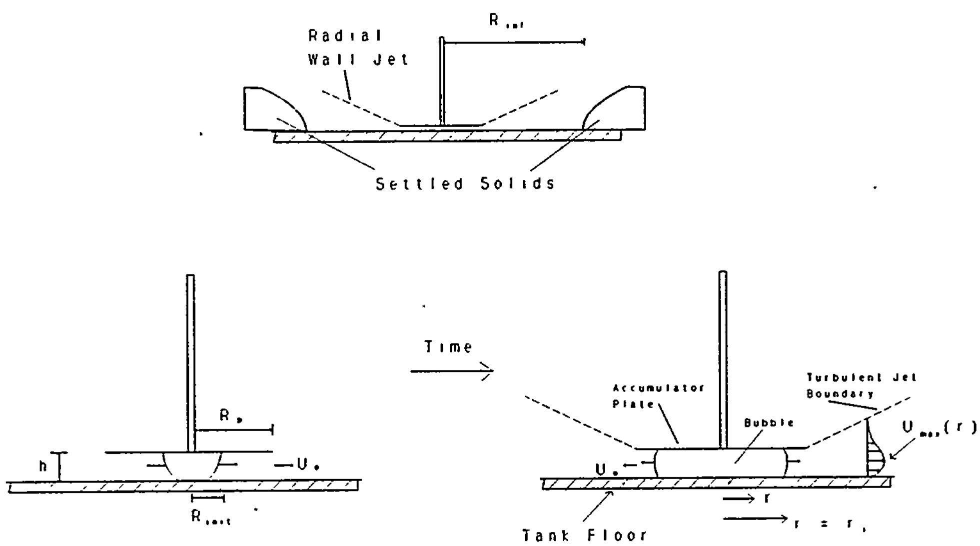


Figure 2.4. Development of Radial Wall Jet During Bubble Growth

$$\frac{\Delta P}{\rho} = \frac{d^2 r_i}{dt^2} (R_p - r_i) \qquad (2.2)$$

where ΔP = gas pressure minus head pressure, Pa
ρ = liquid density, kg/m^3
r_i = radial position of the air/water interface beneath the plate, cm
t = time, s

Once this differential equation was solved, the fluid exit velocity was computed as a function of time using the following equation:

$$U_o = \left(\frac{dr_i}{dt}\right)\frac{r_i}{R_p} \qquad (2.3)$$

Applying the results of equation 2.3 to equation 2.1 allowed the downstream velocities to be computed as a function of time, radial distance, gas pressure, plate diameter, and standoff distance.

The previously developed scaling methodology was based on the predictions of equations 2.1 through 2.3. The equations predict that geometrically scaled plates will produce equal exit velocities (U_o) distances, provided that the same ΔP is used at both scales and standoff distances are equal. Because the standoff distance was assumed to not be scaled, it was predicted that the maximum downstream velocities (U_{max}) produced by a 1/12-scale plate would be $(12)^{1/2}$ = 3.5 times greater than those at full-scale for the same scaled downstream velocities. For this reason, the slurry simulant chosen for the slurry suspension maintenance test in fiscal year 1995 was designed to require 3.5 times more fluid velocity than tank waste.

Based on the fiscal year 1995 testing and the scaling methodology outlined above, it was concluded that pulsed-air mixers should be capable of maintaining solids in suspension in large tanks, but may have difficulty mobilizing consolidated sludge. While these conclusions are still considered valid, the present (fiscal year 1996) testing has demonstrated that the scaling methodology was incorrect largely because the maximum downstream fluid velocities are not produced by the flow of liquid out from between the plates, but instead by the rapid extension of the bubble along the tank floor.[a] This is explored further in the next section.

---

[a]It should also be noted that the previously developed scaling methodology made several simplifying assumptions that were expected to affect its predictions. For example, the momentum of the fluid surrounding the plate was neglected. The effect of choking flow on the availability of gas for bubble growth was also not considered.

Fluid-Velocity Measurement Results

Fluid-velocity measurements were made using a hot-film anemometer and a single mixing plate as described in Section 2.1.1. Based on the scaling analysis described above, it was expected that the maximum fluid velocities would be inversely proportional to the distance from the edge of the mixing plate; however, it was discovered that the peak fluid velocities are not produced by the radial wall jet of liquid (see Figure 2.4). Instead, the rapid growth of the bubble *beyond* the edge of the plate is responsible for the peak velocities observed (recall Figure 1.1, which shows the effective pulse radius of the bubble near the tank floor). The fluid-velocity measurements demonstrated that at radial distances less than R_{pulse} the fluid velocities are typically high (about 200 to 300 m/s). At distances beyond about R_{pulse}, however, the fluid velocities very quickly decay to low levels (less than 50 cm/s).

A typical fluid-velocity profile is shown in Figure 2.5. The 100 psig data, for example, show velocities on the order of 250 cm/s between 30 and 42 cm from the plate centerline. Between 42 and 48 cm, however, the average peak velocity falls to under 150 cm/s; by 54 cm the velocity is down to about 70 cm/s. During this test, the bubble pulse was visually observed to reach a radial distance of about 51 $\pm$ 3 cm. Similarly, at 60 psig R_{pulse} was observed to be about 42 cm, which is consistent with the peak-velocity data. In all the velocity profile tests conducted, this same relationship was observed. That is, the fluid velocities were on the order of 200 to 300 cm/s out to a radial distance of about 5 to 10 cm less than R_{pulse}. At radial distances approximately equal to R_{pulse}, the peak velocity undergoes a rapid decline to values less than about 50 cm/s within about 5 cm beyond R_{pulse}.

The exact distances below and above R_{pulse} at which this transition takes place are dependent on the size of the mixing plate; the transitions for smaller diameter plates occur over shorter radial distances. This is illustrated in Figure 2.6, which shows peak velocity profile data for the smallest plates tested (6.1 cm). The R_{pulse} values observed visually for the 6.1-cm plate at a 0.635-cm standoff distance were 7, 8, 9, 11, and 12 $\pm$ 2 cm (estimated 95% confidence interval based on observed variation in consecutive measurements) for 20, 40, 60, 80, and 100 psig pressures, respectively. Once again the visually determined R_{pulse} values are consistent with the fluid-velocity measurements. Further, the transition from high velocities to low velocities occurs over a shorter distance for the smaller-diameter plates.

The solids suspension performance of pulsed-air plates apparently can be adequately characterized by R_{pulse}. The fluid velocities within R_{pulse} of the plate center are high enough to prevent the settling of waste solids and are probably high enough to mobilize soft to moderately strong cohesive sludge. Beyond R_{pulse}, however, the fluid velocities are not sufficient for sludge mobilization or to maintain large particles in suspension. Because the effective mixing radius of the pulsed-air plates is essentially equal to R_{pulse}, the remainder of the plots provided in this section will use R_{pulse} to describe the observed mixer performance rather than plots of peak velocity versus radial distance.

As described earlier, R_{pulse} was measured by viewing the pulse from directly above the tank. The radial distance reached by the bubble was recorded for multiple pulses and averaged to obtain a single R_{pulse} value. High-speed photography was used to capture the bubble growth for illustration purposes. Figures 2.7 through 2.10 show the rapidly growing bubble, which reaches a distance of R_{pulse} in Figure 2.9.

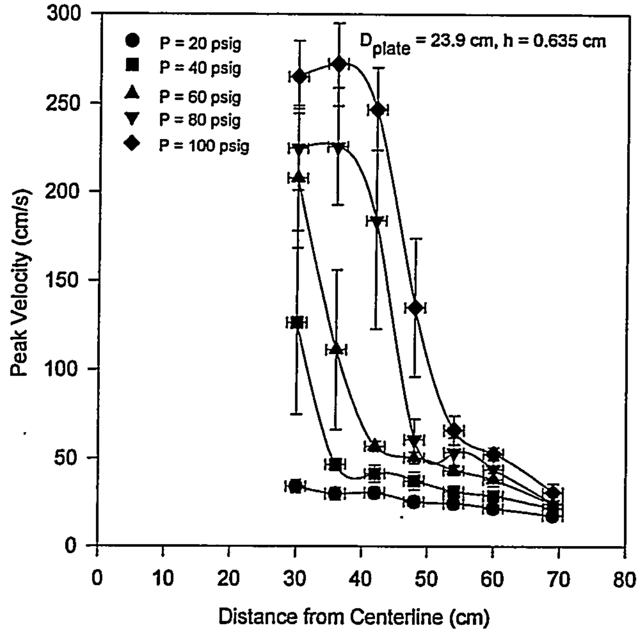


Figure 2.5. V_{max} vs. Pressure and Distance (23.9-cm Plate)

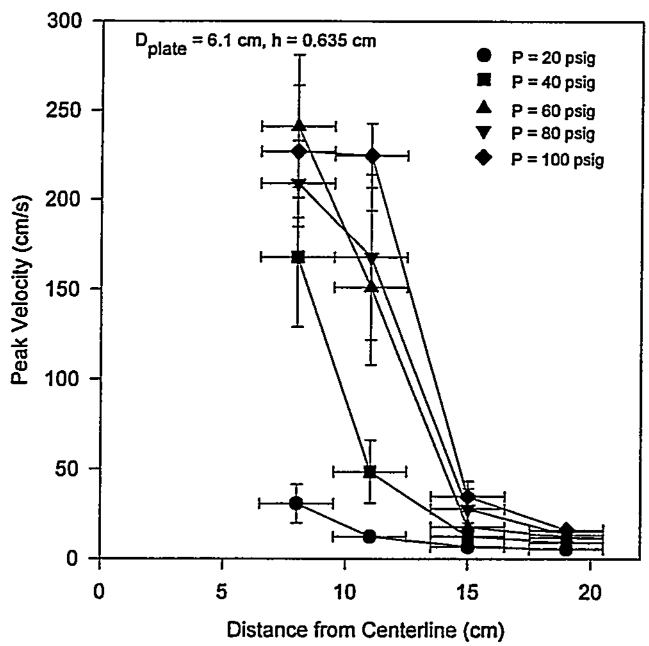


Figure 2.6. V_{max} vs. Pressure and Distance (6.1-cm Plate)

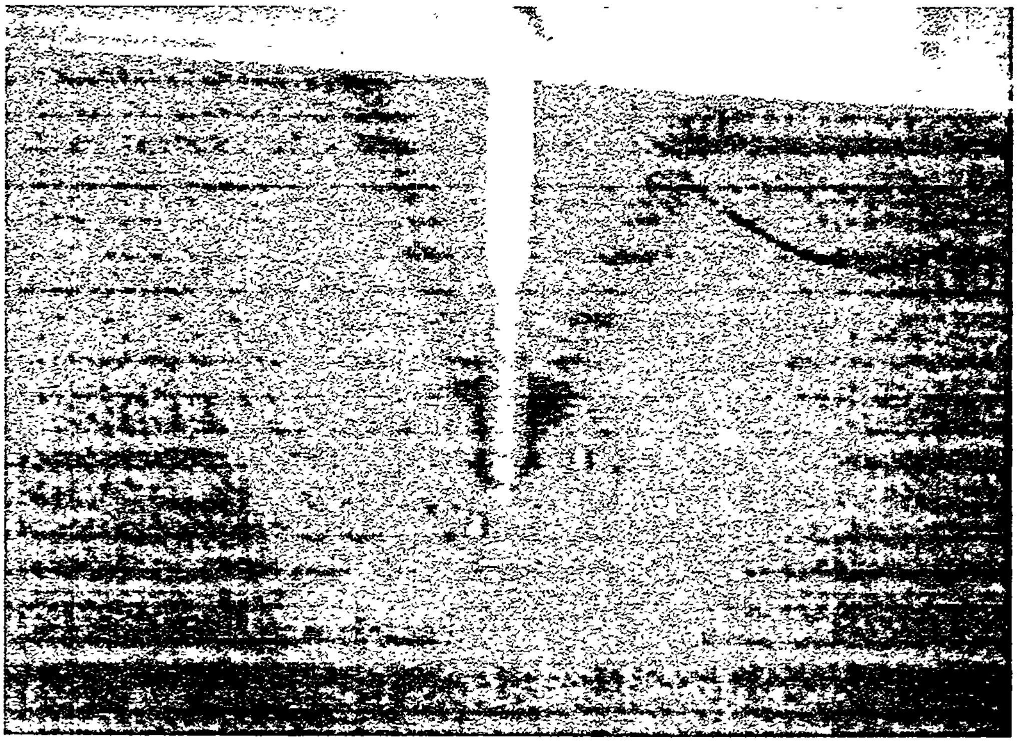


Figure 2.7. 23.9-cm Mixing Plate Before Gas Pulse at 100 psig

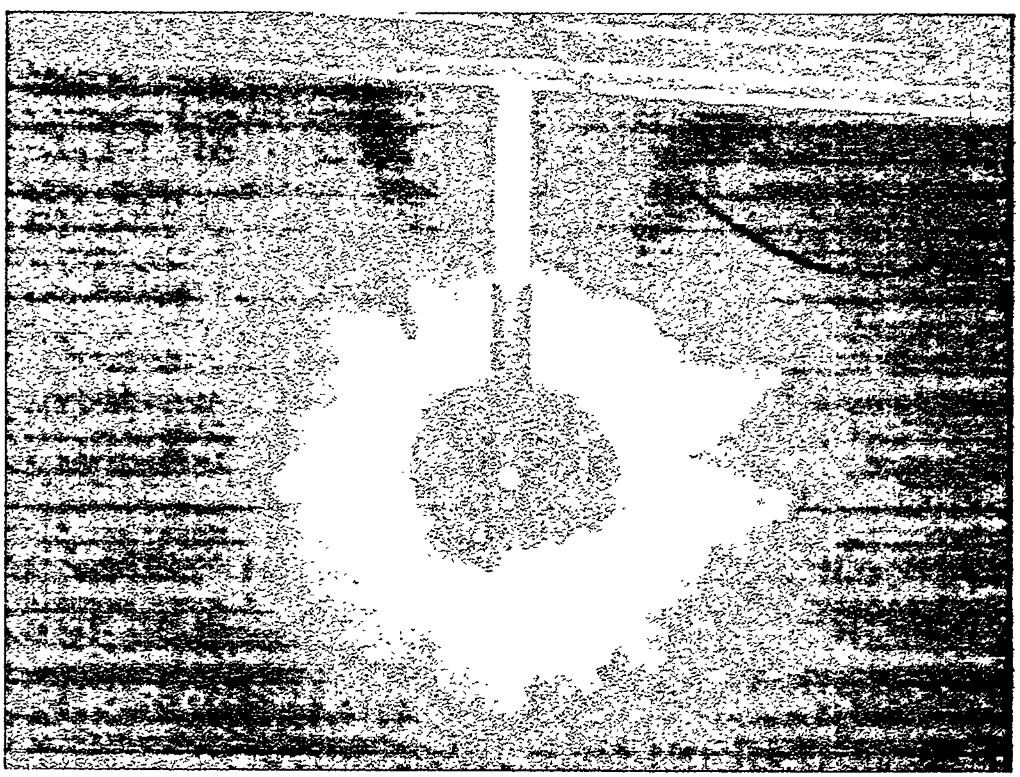


Figure 2.8. Bubble 17 ms After Beginning of Pulse

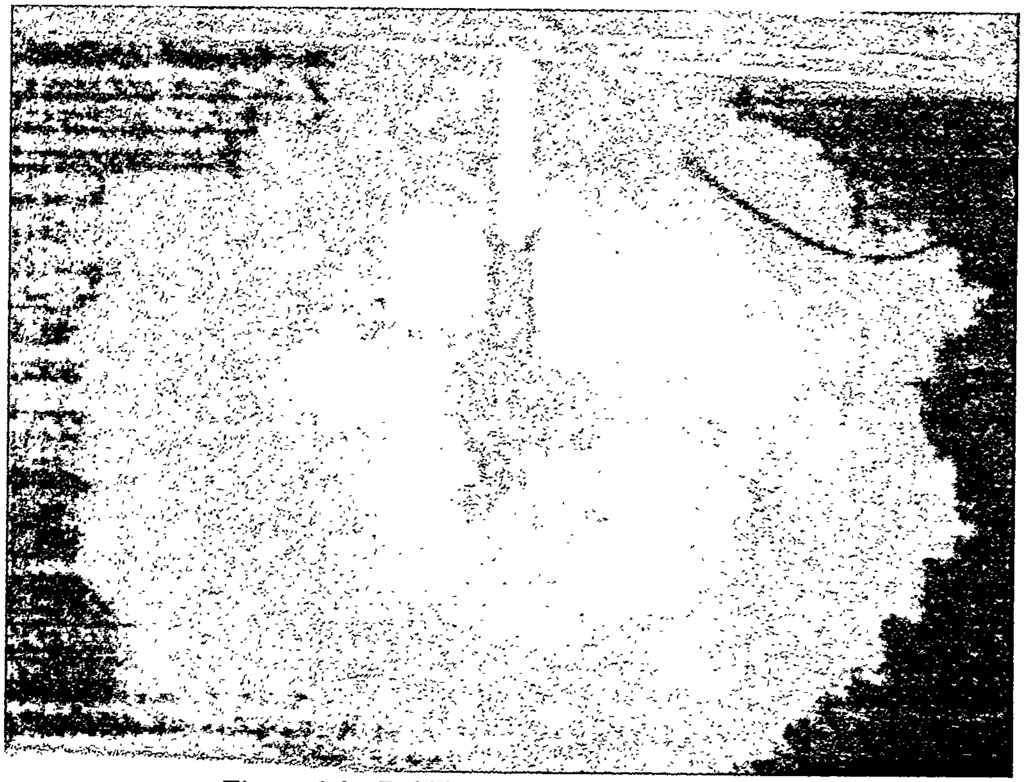


Figure 2.9. Bubble 128 ms, Bubble is at R_{pulse}

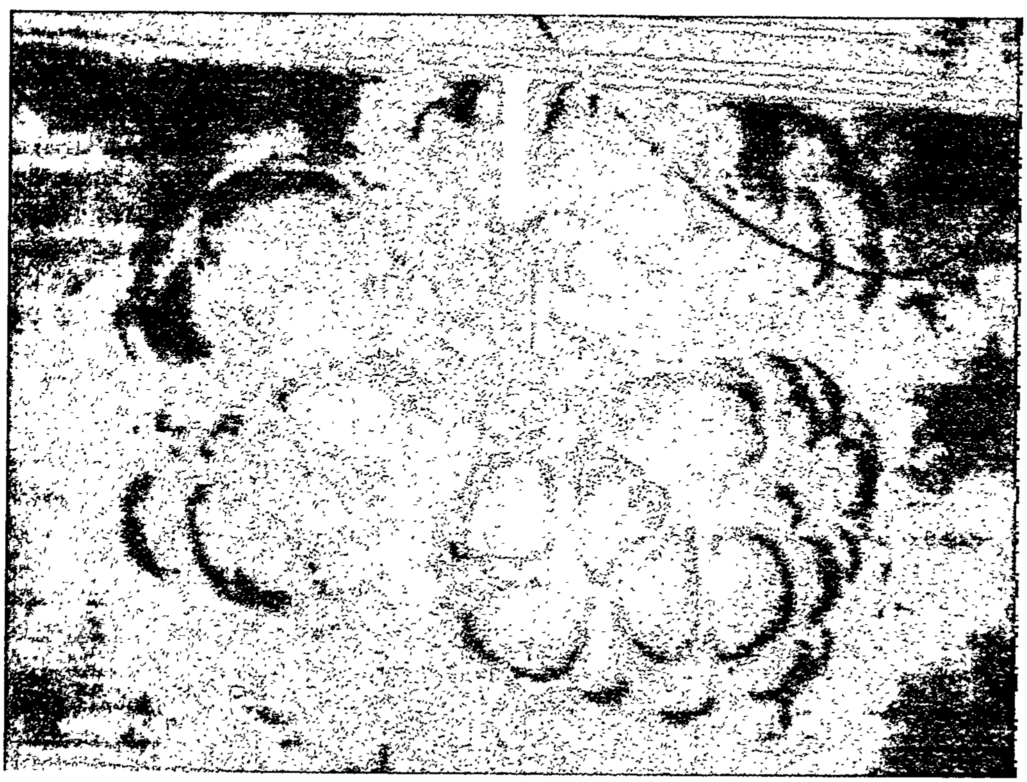


Figure 2.10. Bubble at 268 ms

Effect of Gas Pressure on Velocity and R_{pulse}

Fluid velocity and gas bubble pulse radius measurements were made for each mixer configuration at five gas pressures ranging from 20 to 100 psig in 20 psig increments. Increases in gas pressure resulted in systematic increases in bubble-pulse radii. For given plate and gas pipe sizes, the pulse radius was independent of standoff distance provided that the standoff distance was greater than some minimum value, which is dependent on the gas-pipe diameter. The effect of standoff distance is described below. Considering only those cases where the standoff distance was larger than the minimum, it is found that the pulse radius increases with both plate diameter and gas pressure. The increase in pulse radius with pressure is roughly linear over the range studied, as shown in Figure 2.11. The data shown here are all for plates with a plate-diameter-to-gas-line-diameter ratio of 9.0. The effect of varying this ratio is considered in a later section.

The pulse radius is not expected to continue increasing linearly with pressure. A pressure will be reached beyond which further increases in R_{pulse} will not be observed. This is a consequence of the fact that compressible fluids (air) can flow no faster than their sonic velocities (about 330 m/s for air). It is not presently known, however, at what pressure the gas-pulse radii will stop increasing.

A plot of pulse radius versus plate diameter and pressure is shown in Figure 2.12; Figure 2.13 contains the same data except that R_{plate} has been subtracted from each of the respective R_{pulse} values. This shows that the increase in pulse radius with increasing plate radius is not due just to the increasing plate radius. It is not clear from Figure 2.13 whether the quantity R_{pulse} - R_{plate} is directly proportional to R_{plate} (for a given pressure) or if it is proportional to $(R_{plate})^x$, where x is a constant between zero and one.

Effect of Plate-Standoff Distance

For a plate of given diameter operating at a given pressure, the pulse radius depends on how quickly the high-pressure gas moves through the gas line, pulsing valve, and mixing plate. This flow rate, it appears, is determined largely by the minimum cross-sectional area for flow in the compressed air flow path. When the standoff distance is small, the minimum cross-sectional area for flow is at the point where the compressed-air flow exits the gas pipe and begins flowing radially outward between the plates. This area is defined by a cylinder with a diameter approximately equal to the outside diameter of the gas pipe (for the plate designs used during the testing) and a height equal to the standoff distance. It is the outside diameter of the gas pipe that is important because this equals the inside diameter of the pipe fitting welded to the plate into which the gas pipe fits. Figure 2.14 shows the relationship between the pipe outside diameter and the minimum cross-sectional area for gas flow between the mixing plates.

Tests were conducted at standoff distances (distance between the upper and lower plate) of 0.32 cm (0.125 in), 0.64 cm (0.25 in.), 1.27 cm (0.5 in), and 2.54 cm (1.0 in). Figures 2.15 through 2.18 show the effect of standoff distance on the pulse radius for each of the plate sizes tested. It was determined that plate-standoff distance has only a minor effect on the pulse radius provided that the standoff distance is greater than a minimum value, which is established by the gas pipe line diameter.

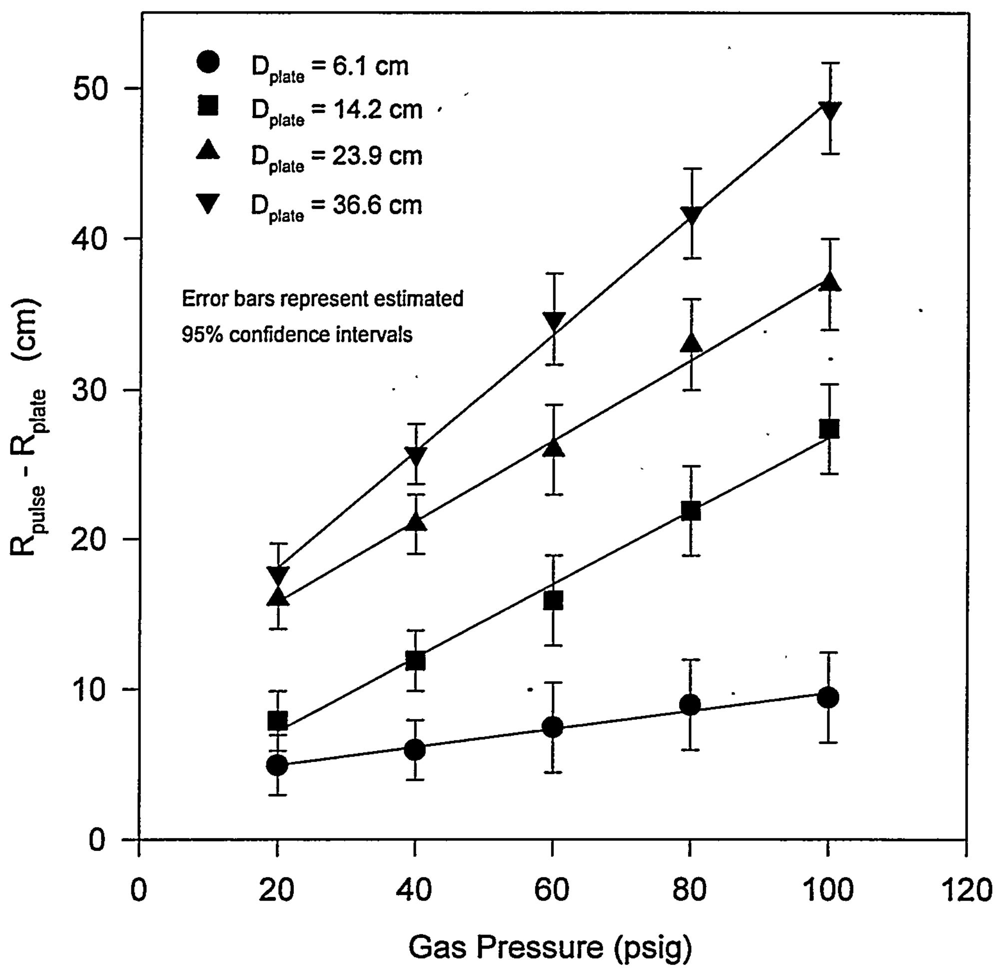


Figure 2.11. Pulse Radius Beyond Plate versus Pressure and Plate Diameter

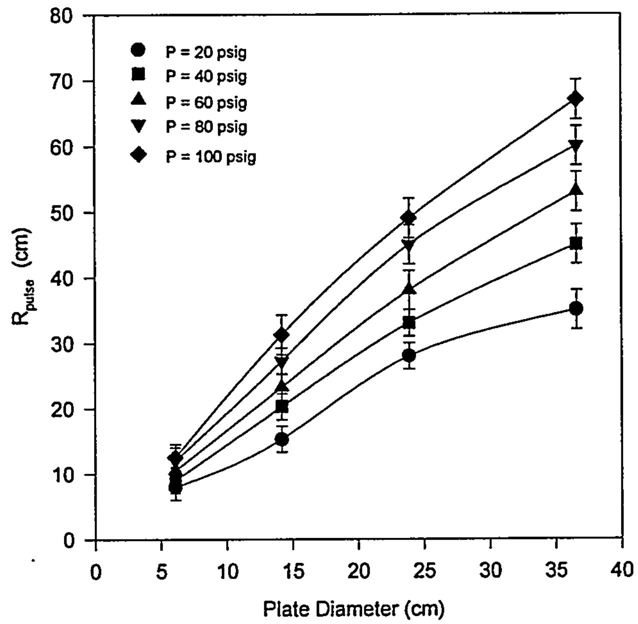


Figure 2.12. Effect of D_{plate} and Pressure on R_{pulse}

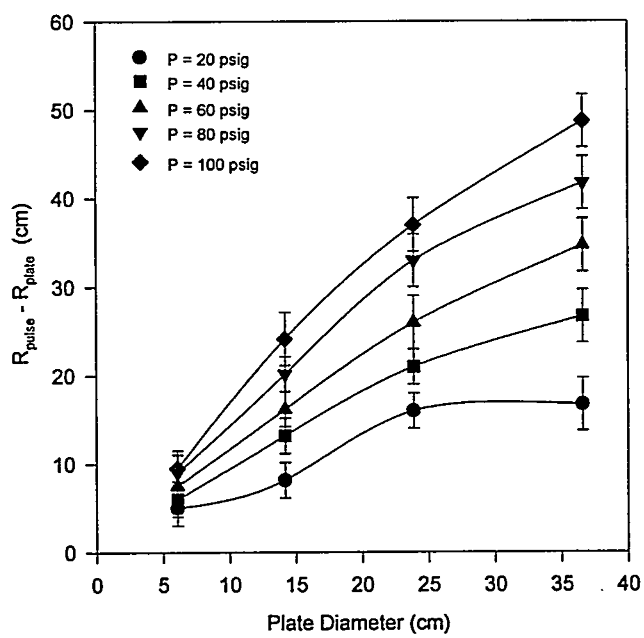


Figure 2.13. Incremental R_{pulse} vs. D_{plate} and Pressure

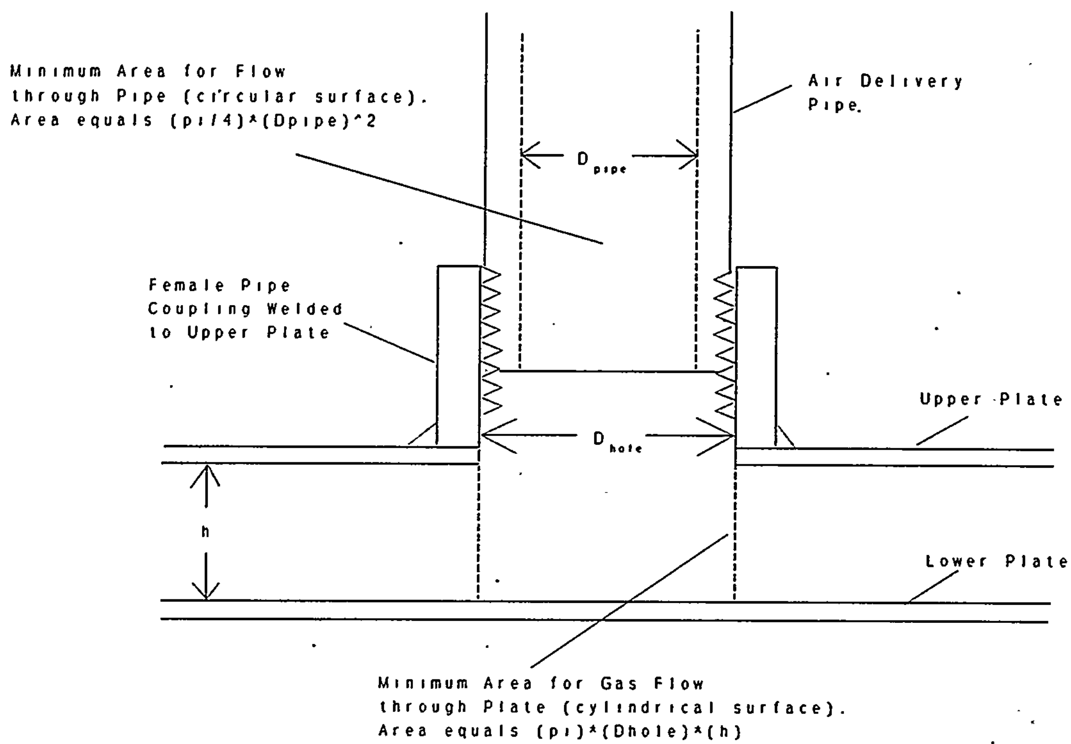


Figure 2.14. Sketch Showing Air Flow Areas in Pipe and Entrance to Plates

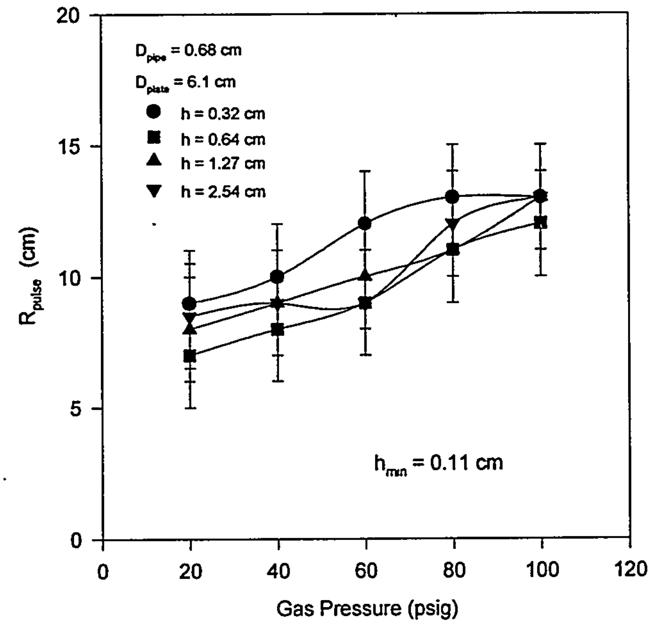


Figure 2.15. Pulse Radius versus ΔP and h for 6.1-cm Plate

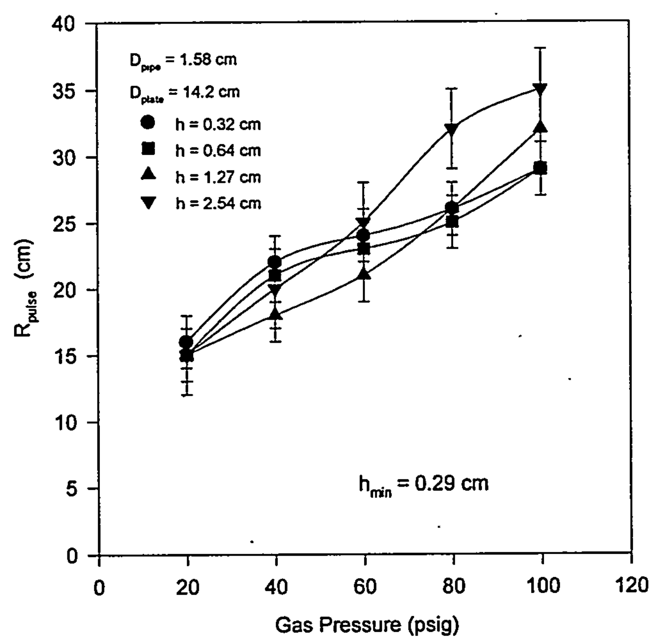


Figure 2.16. Pulse Radius versus ΔP and h for 14.2-cm Plate

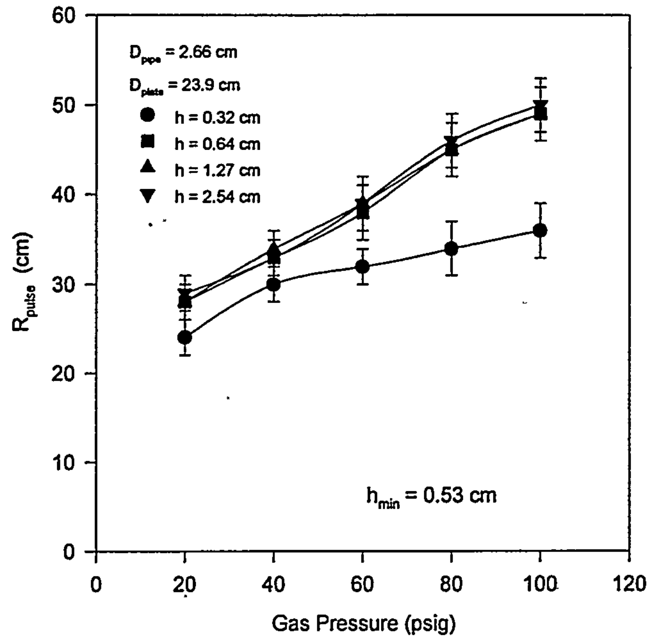


Figure 2.17. Pulse Radius versus ΔP and h for 23.9-cm Plate

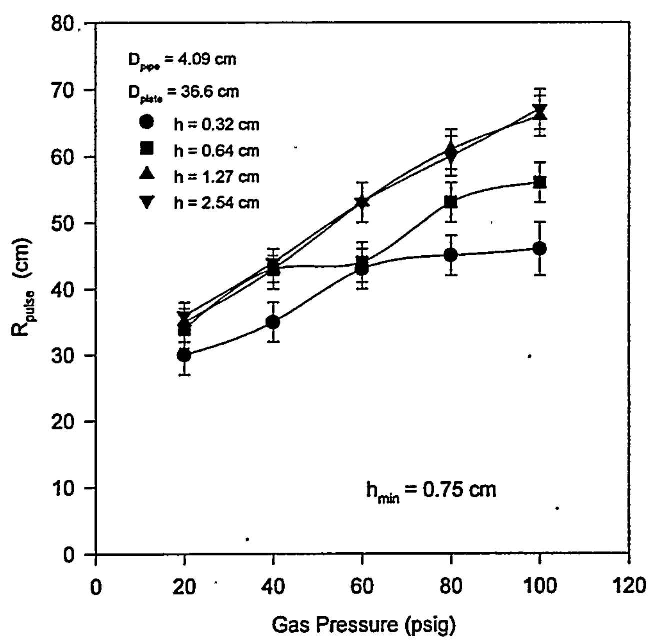


Figure 2.18. Pulse Radius versus ΔP and h for 36.6-cm Plate

Because it is desired that R_{pulse} be maximized, the standoff distance should be set large enough to ensure that the minimum cross-sectional area for gas flow is upstream of the interface between the plate and the gas pipe (whether this be the gas-pipe area itself, inside the pulsing valve, or elsewhere). The minimum standoff distance that meets this criterion is given by

$$h_{\min} = \frac{D_{pipe}^2}{4(D_{hole})} \tag{2.4}$$

where D_{pipe} = inside diameter of the gas pipe, cm
D_{hole} = diameter of hole in the upper mixing plate through which the gas flows. This is about equal to the outside diameter of the gas pipe as shown in Figure 2.14, cm
h_{min} = minimum recommended standoff distance, cm

Figures 2.15 through 2.18 show that when the standoff distance is less than h_{min}, then the gas bubble pulse radius is systematically smaller than for the standoff distances larger than h_{min}. The value of h_{min} that applied for each test is shown on the plots. No significant difference is seen between the pulse radius measurement data for the different standoff distances in Figures 2.15 and 2.16. In both cases, all the standoff distances used for testing were greater than h_{min}. The pulse-radius data in Figures 2.17 and 2.18, however, show a dependence on standoff distance. Again, it is seen that when the standoff distance is less than h_{min}, then the pulse radii are smaller. It is expected that mixer performance will be degraded when the standoff distance is increased beyond some distance larger than those tested here (up to 2.54 cm). Determination of the upper standoff distance limit, however, was not a goal of this test program.

This result is significant because it allows the defensible selection of plate-standoff distance based solely on the size of the pipe used to deliver compressed air to the mixing plate. Again, it is assumed in the derivation of Equation 2.4 that the gas pipe inside diameter gives the minimum cross-sectional area for gas flow upstream of the mixing plate. If there are other, smaller constrictions of the gas flow (e.g., inside the pulsing valve), then the actual h_{min} will be smaller than that given by Equation 2.4 by a factor equal to the ratio of the area of the constriction to the gas pipe cross-sectional area.

Effect of Gas-Pipe Diameter

Experiments were performed in which four different gas-line sizes were tested on a 6.1-cm plate and a 23.9-cm plate. The 6.1-cm plate was tested using a standoff distance of 0.64 cm; the 23.9-cm plate test used a 1.27-cm standoff distance. The larger standoff was used for the 23.9-cm plate because a 0.64-cm standoff is smaller than h_{min} for the largest diameter gas pipe tested. The results of these tests are shown in Figures 2.19 and 2.20. Increases in gas line cross-sectional area are seen to result in increases in pulse radius for both the 6.1-cm plates and the 23.9-cm plates. The pulse radii for the largest pipe used in Figure 2.20 are not much larger than those for the second-to-largest pipe. This implies there may be a limit to the increases in R_{pulse} with increasing gas pipe area. In all these experiments, the minimum gas-flow area was that of the pipe cross-section.

For the purpose of pulsed-air mixer design, Figures 2.19 and 2.20 imply that gas-line diameter should be maximized (at least to a point) to maximize R_{pulse}. Mixer installation logistics and

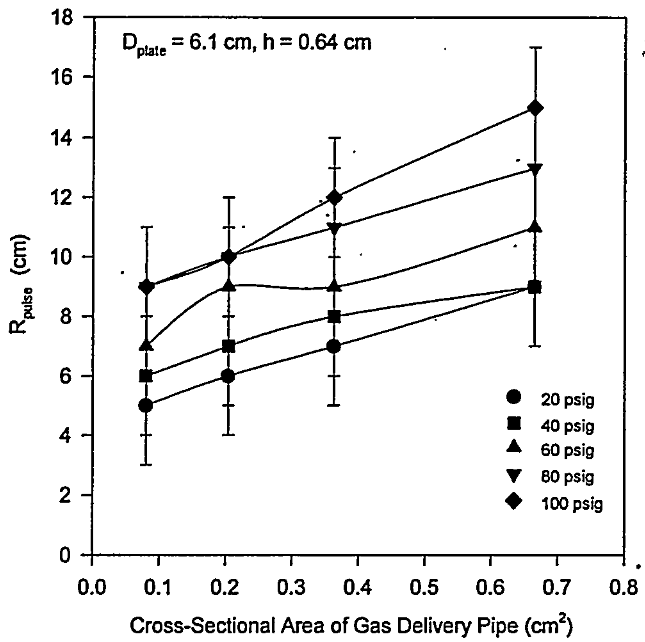


Figure 2.19. R_{pulse} vs. Gas Pipe Area (6.1-cm Plate)

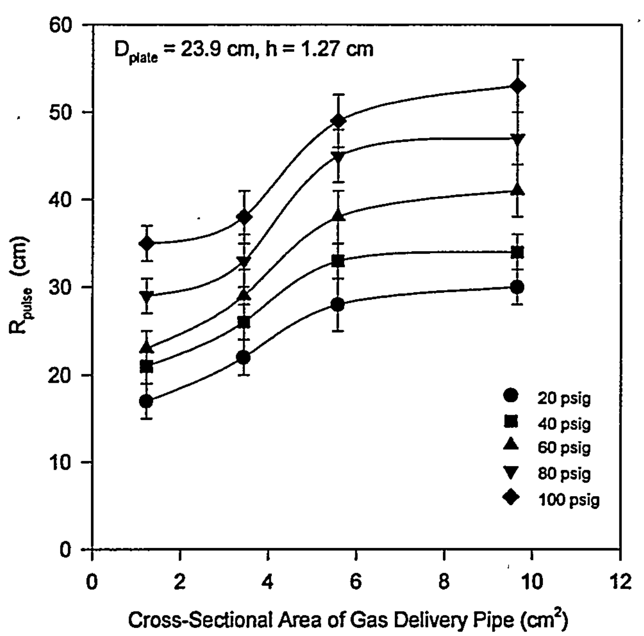


Figure 2.20. R_{pulse} vs. Gas Pipe Area (23.9-cm Plate)

the capacity of the upstream compressed-air supply should be used to establish the maximum practical line diameter. Plate standoff distance is then determined according to Equation 2.4.

Comparison of Results with Previous Test Data

Previous tests of the pulsed-air mixing approach were conducted in fiscal year 1995 and are described in Section 1.2 of this report. One of the tests demonstrated the capability of a pulsed-air mixer to mobilize a cohesive sludge simulant. Operation of the mixer at 100 psig using 15.2-cm diameter mixing plates with a 0.64-cm standoff distance mobilized sludge out to a radial distance of about 22 ± 3 cm from the plate center (see Figure 1.5). This performance was attained only for the center mixing plate. As discussed in Section 1.2, the performance of the other mixing plates in the array was adversely affected by the lack of sufficient air supply. The minimum area for gas flow supplying the center plate was in the 0.95-cm inside-diameter gas-supply tube.

The pulse-radius data generated as part of the present testing can be used to estimate the pulse radius expected from a mixing plate of similar design. Figure 2.12 indicates that a 15.2-cm plate operated at 100 psig will give a bubble-pulse radius of about 34 cm from the plate center, provided that $h \geq h_{min}$ and $D_{plate}/D_{pipe} \approx 9.0$. In the case of the fiscal year 1995 test, the pressure was 100 psig and the standoff distance used (0.64 cm) was greater than h_{min} (0.14 cm). The plate-diameter-to-pipe-diameter ratio, however, was about 16.0. To correct for this difference, the data in Figure 2.20 are used. In the D_{plate}/D_{pipe} range of interest, the bubble-pulse radius increases linearly with gas-pipe area at 100 psig. A 23.9-cm mixing plate with a D_{plate}/D_{pipe} ratio of 16.0 falls in between the two smallest gas pipes tested, which have ratios of 19.1 and 11.4. Interpolating linearly between these points gives a predicted pulse radius of 35.8 cm for a 23.9-cm plate. This is compared to the 49-cm pulse radius obtained using the 23.9-cm plate with a D_{plate}/D_{pipe} ratio of 9.0. The pulse radius for the mixing plate used during the fiscal year 1995 study is then predicted to be (35.8/49)*(34 cm) = 24.8 cm. This prediction agrees well with the observed effective radius of the mixing plate for sludge mobilization of 22 ± 3 cm.

The good agreement between the predicted and observed sludge-mobilization capabilities of the pulsed-air mixing plate provides added assurance of the reliability of the peak-velocity measurements made as part of the present study.

Effect of Exhaust Port Removal

A small portion of the mixing plate velocity testing involved comparing the performance of mixing plates with and without the exhaust-port plug in place on the gas-pulsing valves. When the exhaust port is open, then the gas volume downstream of the pulsing valve is open to the atmosphere while the valve is closed. This allows the tank fluid (water in this case) to fill the gas pipe up to the liquid level in the tank. When the pulsing valve activates, the connection between the downstream portion of the valve and the atmosphere is closed and pressurized air is forced down the gas pipe to the plate. With the exhaust port plugged, the connection to the atmosphere is closed all of the time. With the port plugged, then, the tank fluid does not rise up inside the gas pipe between gas pulses.

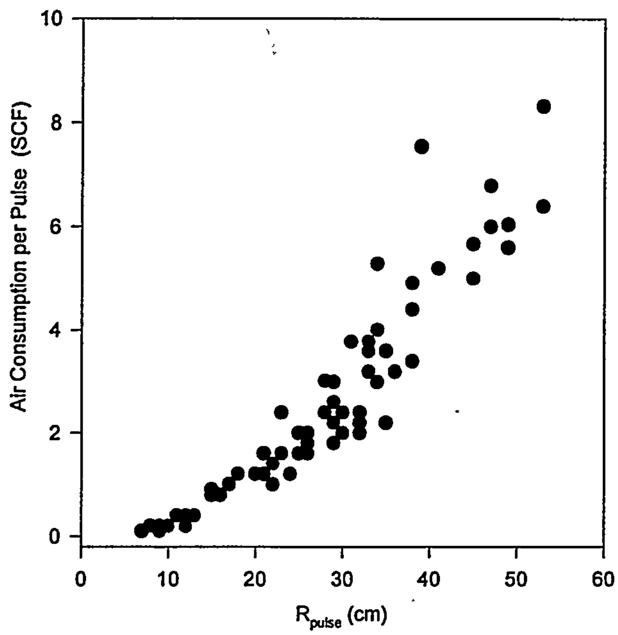


Figure 2.21. Air Consumption per Pulse

Based on the previously developed scaling methodology, it was expected that allowing the gas pipe to fill between gas pulses would result in enhanced performance. The added liquid volume expelled radially at the beginning of the pulse would be larger (by the amount inside the gas pipe), and this, it was hypothesized, would result in a more fully developed radial-wall jet of liquid. Peak fluid velocity and R_{pulse} measurements were compared both with and without the exhaust port plugged. No measurable differences in either peak velocity or pulse radius were found.

This result is consistent with the observation that the peak velocity is determined by the bubble-pulse radius. Further, it is clear that the momentum of the radial-wall jet does not appreciably affect the pulse radius. Increasing the wall-jet momentum (by increasing amount of fluid expelled from between the plates) did not affect the mixing-plate performance.

Air-Consumption Rate

The air-consumption rate per pulse versus observed bubble-pulse radius is plotted in Figure 2.21. These data were gathered by noting the magnitude of the pressure decrease in the 20-gallon accumulator tank during each gas pulse. The data for all the plate sizes and configurations tested are shown in Figure 2.21. It may be possible to reduce the amount of scatter in the plot by considering the individual effects of the other relevant test parameters (e.g., plate diameter and gas-line size). No attempt has yet been made to develop such a correlation. The correlation apparent between air consumption and pulse radius is fairly strong, though, so such an expanded correlation development effort may be of only limited use.

The data in Figure 2.21 can be used to estimate the air consumption rate of full-scale plates by extrapolation. The agreement between the extrapolated value and the observed air-consumption rate is described in Section 2.2.

Design of Full-Scale Mixer for a Horizontal Tank

The data presented here were used to develop a pulsed-air mixer design for possible future use in a horizontal tank like the INEL V-tanks or ORNL Melton Valley Tanks. It has been suggested that a pulsed-air mixer might aid in cleanup efforts by resuspending the soft sludge known to have formed on the bottom of tanks, such as INEL V-tanks V-3 and V-4. The resulting slurry can be maintained in suspension while a small pump sends the waste to downstream processing facilities. The pulsed-air scaleup correlation data indicate that an array of 4 mixing plates positioned along the tank floor should provide adequate resuspension of the sludge.

Each mixing plate will be 38 cm (15 in) in diameter so that the entire array can be deployed through a 51-cm (20-in) manway leading into the tank. Gas-line size is to be maximized to ensure that large pulse radii are obtained. Deployment of this mixer array using 2-inch schedule 40 gas pipes is addressed in Section 3.0 of this report. Sketches of the deployed mixer array are also included in Section 3.0. Each mixing plate will be of the double-plate arrangement similar to that used for the testing described in this document. Single-plate mixers cannot be used because the horizontal tanks do not have flat bottoms.

The scaleup correlation data predict that each mixing plate will have a pulse radius of about 70 cm when operated at 100 psig. The deployed plates are positioned such that they are about 1.2 m (4 ft) apart (center to center). This will allow for some overlap of the pulse radii to ensure that all the solids are mobilized. It may also allow the mixer to mobilize all the sludge when operated at a lower gas pressure. Lower gas pressures may help alleviate vibration and aerosol-generation concerns.

If each plate is pulsed at a frequency of about once per minute, the gas-consumption rate for this 4-plate mixer is estimated from Figure 2.21 to be about 40 to 50 SCFM, which is easily generated by a small, gas-powered air compressor.

Pulsed-Air Mixers for Sludge Mobilization in Large-Diameter, Flat-Bottomed Tanks

The scaleup testing revealed that the sludge mobilization characteristics of pulsed-air plates are more favorable at large scale than was predicted by the previously developed scaling methodology. However, a large number of plates would be required to mobilize a layer of consolidated, cohesive sludge successfully from the bottom of a typical Hanford double-shell tank. Taking a maximum reasonable plate diameter of 91 cm (3 ft), the number of plates required to mobilize cohesive sludge in a Hanford tank can be estimated. Extrapolating the data in Figure 2.13 for 100 psig pressure, the pulse radius for these full-scale plates is estimated to be about 100 cm. It is unlikely that sludge will be mobilized away from the plate to a distance greater than R_{pulse} unless the sludge is favorably affected by the gas pulse shock wave. Assuming that each plate is only effective to a distance of 100 cm, it is predicted that more than 500 mixing plates would need to be distributed on the tank floor and operated at 100 psig to mobilize all the sludge.[a] This large number of mixing plates poses significant challenges for the mobilization of cohesive sludges in large-diameter, flat-bottomed tanks.

2.2 Slurry Mixing/Mobilization Test Using Full-Scale Mixing Plates

A slurry mixing and resuspension test was performed in a 5.72-m (18.75-ft) diameter tank using full-scale-sized pulsed-air mixing plates. The dimensions of this tank are 1/4-scale with respect to the 1-million gallon double-shell tanks at Hanford. This test was performed to verify that the mixing action produced by large plates is consistent with that expected, based on an extrapolation of the scaleup correlation data presented in Section 2.1.

It was recognized that the scaleup correlation testing provides only a measure of the mixing produced by a single mixing plate. With multiple plates operating simultaneously or according to a predetermined sequence, large-scale circulation patterns can be established within the tank, which help to prevent solids from settling on the tank floor. Investigation of the importance of the large-scale circulation patterns for slurry-suspension maintenance was one of the purposes of the test in the 1/4-scale tank. Another purpose was to identify any additional operational concerns that might not have been apparent when the mixers were operated at smaller scales.

2.2.1 Test Description

The 1/4-scale tank and pulsed-air mixing plate array used for this series of tests is shown in Figure 2.22. Four mixing plates, each 91 cm (3 ft) in diameter, were positioned in the tank and stabilized as shown in Figure 2.22 (3 of the 4 plates are shown) and schematically in Figure 2.23. The plates were connected to gas-pulsing valves using 2.5-inch schedule 40 pipe. Compressed air was supplied by a diesel-powered air compressor capable of delivering up to 185 SCFM of air at 100 psig. The compressed air was routed into two 80-gallon air tanks, which were piped together to form a single air reservoir. Compressed air to the gas-pulsing valves was supplied through 2.5-inch schedule 40 pipe from the air tanks. A sketch of the 1/4-scale mixer arrangement is shown in Figure 2.23.

The bases used to select this mixer design and the simulant used for testing are described in the remainder of this section. The testing procedure and results are described in Section 2.2.2.

Mixer Design Basis

The full-scale mixing-plate diameter was chosen to be 91 cm (3 ft) because it was judged unlikely that plates of larger size could be inserted successfully into a waste-storage tank through one of the tank risers, the largest of which are about 107 cm (42 in.) in diameter. The gas-pipe size was selected similarly. Considering how many plates are likely to be needed within a tank, the use of pipe sizes larger than about 2.5 inches was judged to be unrealistic by staff at PNNL, Pulsair Systems, Inc., and the University of Washington Applied Physics Laboratory (APL/UW). Further, the largest gas-pulsing valves typically used by Pulsair Systems are designed for use with 2.5-inch pipe.

---

[a]This estimate is made by comparing the effective area of each mixing plate (0.785 m^2) with the total tank floor area (410 m^2). The total number of plates required to mobilize all the sludge will be approximately 410/0.785 = 522 plates.

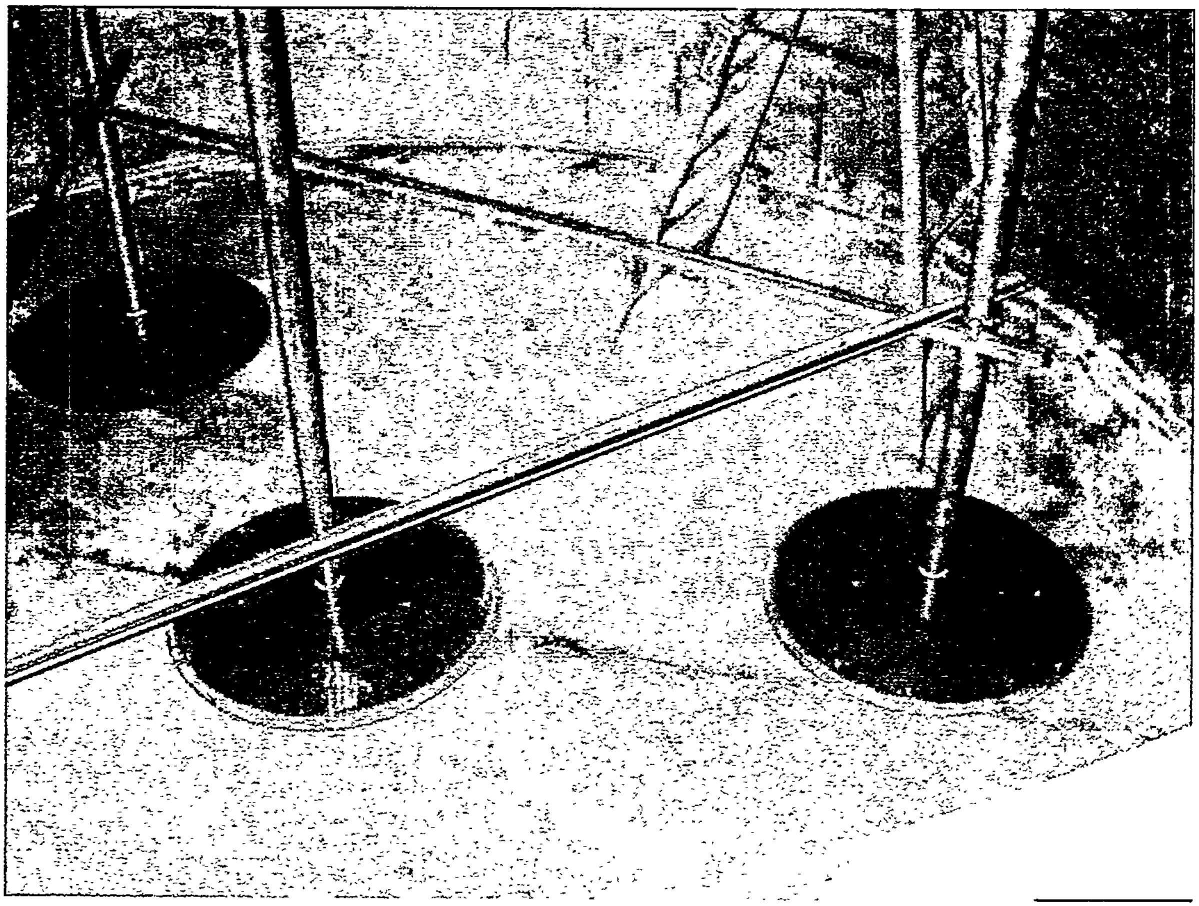


Figure 2.22. Mixing Plates Installed in 1/4-Scale Tank

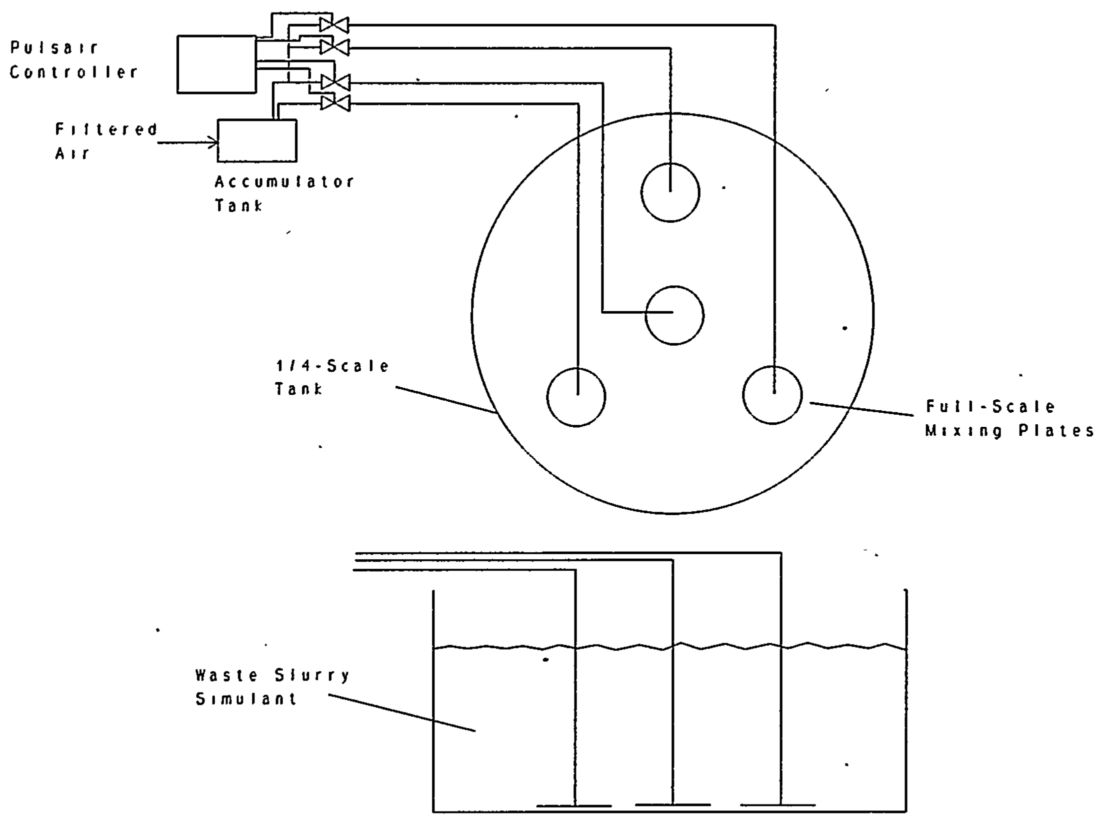


Figure 2.23. Sketch of Pulsed-Air Mixer in 1/4-Scale Tank

Once the plate diameter and gas-line size were determined, the minimum standoff distance was calculated using Equation 2.4 to be 1.35 cm. A slightly larger standoff distance was used for the plates (1.9 cm). Like the plates used for the scaleup correlation development testing, these mixing plates were each actually two plates held apart by spacers. The bottom plate rested directly on the tank floor and spacers were welded between the plates to maintain the desired 1.9-cm (0.75-in.) standoff distance.

Four mixing plates were selected based on the expected bubble-pulse radii from these plates and on the maximum number of plates thought to be reasonable in a full-scale application. If it is assumed that the number of mixing plates required in a given application is proportional to the surface area of the tank floor, a 4-plate mixer in a 1/4-scale tank is predicted to be similar to a 64-plate array in a full-scale tank. Deployment of 64 plates through existing tank risers is judged to be a significant challenge. Considering the tank-riser and mixing-plate sizes, it seems unlikely that any more than 20 to 25 mixing plates could be deployed into a full-scale (23-m = 75-ft diameter) tank.

The assumption that the number of plates required is proportional to floor area, however, is justified only if the mixer is to be used to mobilize consolidated, cohesive tank sludge. For slurry-suspension maintenance applications, the fluid velocities generated by large-scale circulation patterns are significant and scaling the number of plates by the floor area is not appropriate. The exact scaling relationship for determining the number of mixing plates required for slurry-suspension maintenance is not yet known, but it is expected that the number of plates required is considerably smaller than predicted based on a floor area proportionality.

Four mixing plates were used for this testing even though floor-area-based scaling would predict that a large number of plates would be required at full-scale ($4 \times 4^2 = 64$ plates). The tests conducted were primarily designed to evaluate slurry-suspension maintenance, though, so it is expected that the performance of 4 plates in the 1/4-scale tank is indicative of the performance of considerably fewer than 64 plates in a full-scale application. How many fewer plates would be required is not known. Further work, which may include computer modeling, will be required to resolve the true scaling relationship for determining the number of plates needed for slurry-suspension maintenance. Four plates were selected because this was the fewest number of plates that could be arranged in a symmetrical pattern with a single plate in the tank center. The plates were arranged in the tank with one plate in the center and the three remaining plates spaced at 120° and about 60% of the tank radius from the tank center. This arrangement, in the experience of Pulsair Systems, Inc., provides excellent mixing action when the center and peripheral plates are pulsed in an alternating sequence.[a]

Waste Simulant

The simulated waste slurry used for this test was a 4.5 wt% slurry of kaolin clay in water. This simulant was selected because it mimics the settling behavior observed in actual waste samples and because it can be prepared and safely used in large quantities. A total of about 46.9 m^3 (12,400 gal) of slurry was prepared by adding a more concentrated slurry (about 14.5 wt%) to roughly 30 m^3

[a]The center plate is pulsed, then after a time all the peripheral plates are pulsed simultaneously. After another delay the center plate is pulsed again, thereby continuing the cycle.

(8,000 gal) of water contained in the 1/4-scale tank. Before adding the concentrated slurry, the pulsed- air mixer was activated. All 4 plates were used with a gas pressure of 80 psig and a pulse cycle time[a] of about 30 seconds. This was done to ensure that the slurry was well mixed at the beginning of the test.

Tests conducted in support of the Hanford waste-pretreatment program have shown that the particle-settling characteristics of kaolin clay are similar to those of tank waste solids.[b] For a 5 wt% slurry, the particle-settling velocity[c] for a sample of solids from Hanford tank C-107 is approximately 10-15 cm/h. A 5 wt% kaolin clay in water slurry was observed (using the same apparatus) to settle at roughly 3 times this rate (30-45 cm/h). From the standpoint of these measurements, the use of kaolin clay as a simulant for waste solids is conservative in that the kaolin clay should provide a greater challenge to the pulsed-air mixer than would the C-107 solids. It should be noted that particle-settling behavior cannot be described completely simply by the particle-settling velocity as quantified by the rate at which the supernate/slurry interface settles. The settling velocity of the interface tends to provide a measure of the settling rates of the smaller particles in the slurry rather than the average settling rate or, more importantly, the settling rate distribution for a slurry.

The settling rate distribution characteristics can be inferred by examining the slurry particle size distribution. It is desirable for the waste simulant to possess a particle settling rate distribution that is similar to that of the waste. In particular, the fraction of large particles in the waste and simulant slurries should be similar because it is the large particles that will settle to the tank floor during a mixing test. If the simulant has no large[d] particles while, for instance, 20% of the waste solids mass is contained in the large particles, then the mixing test using the simulant might predict 100 wt% of the solids will be maintained in suspension while only 80 wt% of waste solids actually will be.

The volume fraction particle size distributions for a sample of waste solids from Hanford double-shell tank 101-AZ are compared to the distribution for kaolin clay in Figures 2.24 and 2.25. While the distributions are similar, the kaolin particle size distribution (Figure 2.25) shows a higher concentration of larger particles. This also implies that kaolin clay presents a more difficult mixing challenge than do actual waste solids; thus, predictions of mixer performance based on tests using

---

[a]The cycle time is defined as the time required to complete one complete cycle of pulses in which first the center plate is pulsed and then the peripheral plates are simultaneously pulsed.

[b]The pretreatment program is conducting tests in which waste solids are settled in cylindrical chambers inside radioactive hot cells. This work is on-going and a cleared report has not yet been prepared. The data obtained thus far for both kaolin clay and solids from Hanford tank C-107 are reported here. A report describing the hot cell settling tests will be issued later this fiscal year by K. P. Brooks, who will be the primary author.

[c]These tests are actually measuring the speed of the interface between the supernate and the settling solids, which is a measure of the solids settling velocity.

[d]In this case, "large" particles are meant to be those that the mixer being tested is incapable of maintaining in suspension.

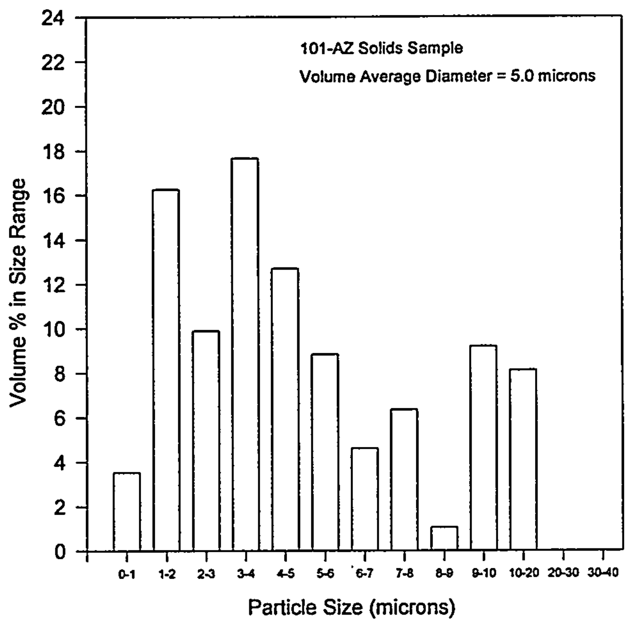


Figure 2.24. 101-AZ Solids Particle Size Distribution

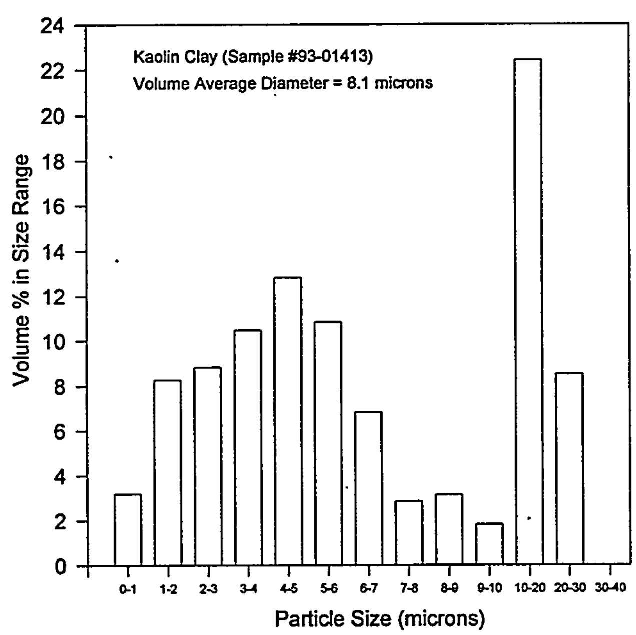


Figure 2.25. Particle Size Distribution for Kaolin Clay

kaolin clay should be conservative in that the actual mixer performance will exceed that predicted based on tests using kaolin-clay simulant.

The kaolin-clay concentration used for the pulsed-air mixer testing in the 1/4-scale tank was chosen to be 4.5 wt%. This concentration was chosen to be large enough to permit accurate quantification of the fraction of solids settled to the tank floor. The accuracy of this measurement is a function of the accuracy of the techniques used to measure slurry density, which are accurate to about ± 0.001 g/cm^3. This level of accuracy in slurry density yields an accuracy of about ± 3 wt% for estimates of the fraction of the solids maintained in suspension. It was desired that the slurry concentration be kept reasonably low, however, for two reasons. First, particle-settling rates are slower for higher-concentration slurries, so testing with a higher-concentration slurry makes the mixing predictions less conservative. Second, the resources required to both prepare and dispose the waste simulant are proportional to the total amount of solids used. Minimizing the solids concentration used for the testing keeps simulant preparation and disposal costs low.

2.2.2 Testing Procedure and Results

The first test began when the concentrated kaolin-clay slurry was added to the water in the 1/4-scale tank while the pulsed-air mixer was operating with all 4 plates at 80 to 100 psig and a cycle time of about 30 seconds. A sample of the initial slurry was withdrawn and analyzed to determine its density and wt% solids. Mixer operation continued uninterrupted for the next 36 hours.[a] The slurry density was monitored on an hourly basis to track the amount of solids remaining in suspension as a function of time.

Slurry density was quantified using two methods. First, a hand-held digital-density meter (Anton-Paar, Model DMA35) was used. This device calculates the slurry density based on the oscillation frequency of a small glass tube filled with the slurry. It is accurate to ± 0.001 g/cm^3; its calibration was verified using both water and known-concentration salt solutions. The second method for measuring slurry density involved collecting a slurry sample in a 100-mL pycnometer, which was then weighed to the nearest 0.01 g. Checks on the repeatability of this technique established that any single measurement was expected (to the 95% confidence level) to be within 0.0004 g/cm^3 of the average of multiple measurements. In general, the two density-measurement techniques agreed within the stated experimental uncertainties during all phases of testing.

Every 4 hours during testing, a sample of the slurry was withdrawn from the tank and dried to determine its weight-fraction solids. A Denver Instrument Company Moisture Analyzer was used to make this measurement. The moisture analyzer determines the mass loss of the slurry upon drying at 200°C for at least one hour. Repeatability to within about 0.03 wt% moisture was obtained using this instrument. The wt% moisture measurements were also used to estimate the fraction of solids remaining in suspension by comparing the measured slurry wt% solids to that of the initial slurry.

---

[a]The mixer was deactivated twice for about 15 minutes each in an effort to install a more sensitive pulse frequency controller. No change in the slurry density was noted in samples withdrawn both before and after the outage, so it is unlikely this affected the test results significantly.

Two slurry-suspension maintenance and 3 sludge-resuspension tests were conducted. The slurry-suspension maintenance quantified the fraction of solids maintained in suspension with all 4 plates operating at pressures of 80 psig and 20 psig. The slurry was then allowed to settle for 3 days before the mixer was reactivated and operated at a variety of pressures. Two more resuspension tests were then conducted, each after allowing the slurry to settle for 3 days. The test details and results are presented in the sections that follow.

Suspension Maintenance at 80 psig

The first test evaluated the capability of the 4-plate pulsed-air mixer to maintain the slurry simulant in suspension when operated at about 80 psig. At any given time during the test, the weight fraction of the total solids mass that was still in suspension could be determined from density measurements. The percentage of the initial solids in suspension is given by

$$\%\text{Suspended} = \frac{100\%}{W_{init}}\left(\frac{100}{\rho_{slurry}} - \frac{100}{\rho_{water}}\right)\left(\frac{1}{\rho_{kaolin}} - \frac{1}{\rho_{water}}\right)^{-1} \tag{2.5}$$

where ρ_{slurry} = measured slurry density, g/cm^3
ρ_{water} = density of water at the measured slurry temperature, g/cm^3
ρ_{kaolin} = density of kaolin particles, 2.64 g/cm^3 (Lambe and Whitman, 1969)

Equation 2.5 was used to compute the weight % of solids maintained in suspension during each of the pulsed-air mixing tests. Figure 2.26 shows that about 87 wt% of the solids were maintained in suspension when all 4 mixing plates were operated at 80 psig. The mixing plates were sequenced such that the center plate pulsed, followed by a pause, then the peripheral plates pulsed simultaneously, followed by a pause. The cycle time was approximately 30 seconds, so each plate was pulsed about twice per minute.

Compressed-air consumption was monitored by observing the pressure drop in the accumulator tanks during each pulse. The total compressed-air volume in the system is about 0.7 m^3 (180 gal). When the center plate pulsed, the pressure dropped about 20 psig. When the peripheral plates pulsed, the pressure dropped about 30 psig. This implies that the center plate was consuming about 30 SCF of gas per pulse, while each of the peripheral plates were consuming about 15 SCF per pulse. Gas consumption of about 15 SCF per pulse is consistent with the predicted gas-consumption rate based on Figure 2.21.

The center plate gas consumption was higher than expected because the injection time was set longer than was used in the scaleup correlation development testing. The injection time had to be set higher for the test in the 1/4-scale tank to get all of the peripheral plates to pulse for the desired amount of time. A pressurized-air signal is used to actuate the pulsing valves. The effective volume of the tubing leading to the center plate was smaller than that of the tubing leading to the peripheral plates. As a result, the center plate would open more quickly than the peripheral plates. This problem can be avoided by either using separate injection time controls for the center and peripheral plates, or by a more careful design of the control-valve tubing volumes.

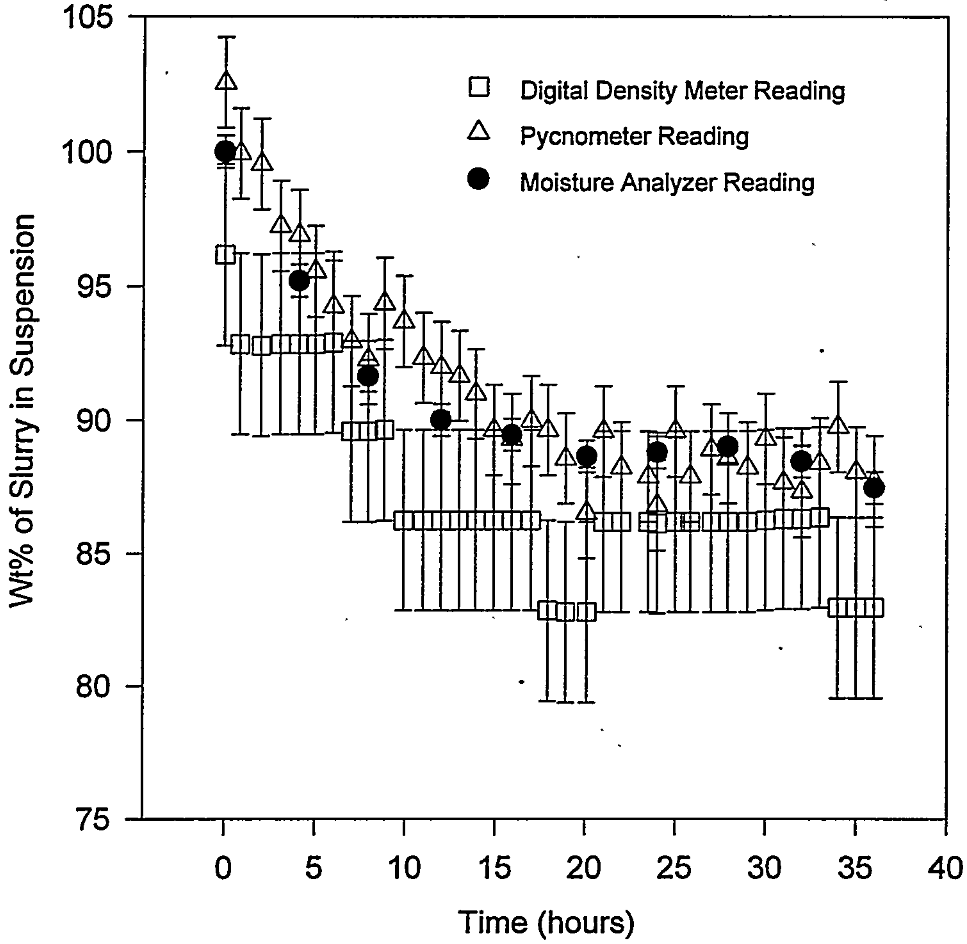


Figure 2.26. .Suspension Maintenance Test #1 Results

Suspension Maintenance at 20 psig

After operating the mixer for 36 hours at 80 psig, the gas pressure was decreased to 20 psig. Mixing continued for another 12 hours. During this time, the fraction of solids in suspension fell from about 87 wt% to about 82 wt%. A plot of the wt% in suspension versus time is given in Figure 2.27. The same pulse-cycle time was used for this portion of the test (30 seconds).

It is expected that the slurry density would not have decreased significantly had the test been continued beyond 12 hours. The data for the first suspension test (Figure 2.26) show that the final slurry density is reached in about 12 hours after the start of the test. Further, the slurry-resuspension test (discussed later in this section) conducted using the same mixer-operation parameters was found to resuspend about 78 wt% of the solids after the slurry had settled for 3 days. Based on this, the final wt% in suspension would have been expected to be between 78 and 82 wt% if the test had been conducted for a much longer time.

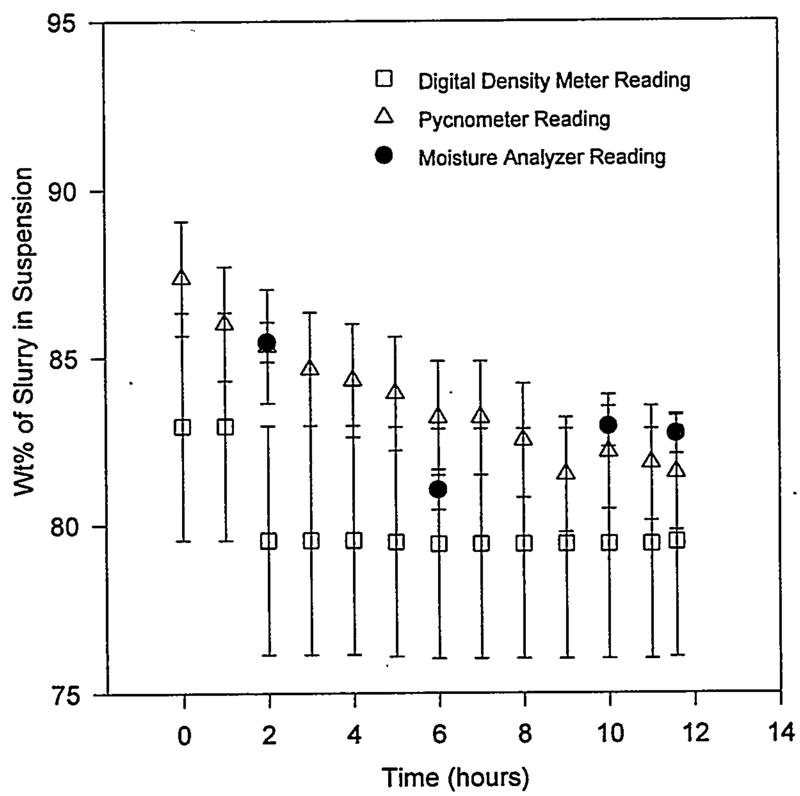


Figure 2.27. Slurry in Suspension vs. Time for 20 psig and 4 Plates

Resuspension Test #1

Following the completion of the second slurry suspension maintenance test, the mixer was deactivated. The slurry was allowed to settle for 3 days. At this point, the thickness of the settled solids layer was measured and found to be about 33 cm (13 in). A solids layer of this depth implies an average wt% kaolin of 20 to 25 wt% in the settled solids bed. Samples of the tank supernate were taken and analyzed. These samples contained less than 0.02 wt% solids, which implies that nearly all of the solids had settled to the tank floor.

The mixer was activated using all 4 plates and a pressure of 20 psig. The cycle time was 30 seconds. After the first 30 minutes of mixing, the slurry density stabilized. Operation continued at these settings for another 2 hours. The slurry samples indicated roughly 78 wt% of the solids were in suspension. The gas pressure was then increased to 80 psig and mixing continued for another 5.5 hours. Slightly more of the solids were mobilized. The slurry density stabilized at a level consistent with 83 wt% in suspension. The data for this test are shown in Figure 2.28.

Eight hours after the test started, the mixer operation was changed again. The pressure was reduced to 20 psig and only the single mixing plate in the center of the tank was operated. A cycle time of 6 seconds was used during this portion of the test. Testing continued for 8 hours using this configuration and the wt% in suspension was observed to stabilize at about 81 wt%.

The pressure was then decreased once again (16 hours after the start of the test), this time to 6 psig. Only the central plate was operating and a 6-second cycle time was used. No significant decrease in the wt% solids in suspension was observed over a 7-hour period. This result implies that the mixing action at low pressures is being controlled by the circulation patterns induced by the bubbles generated by the center plate. Increasing the gas pressure will increase the pulse radius, but apparently this is of little consequence.

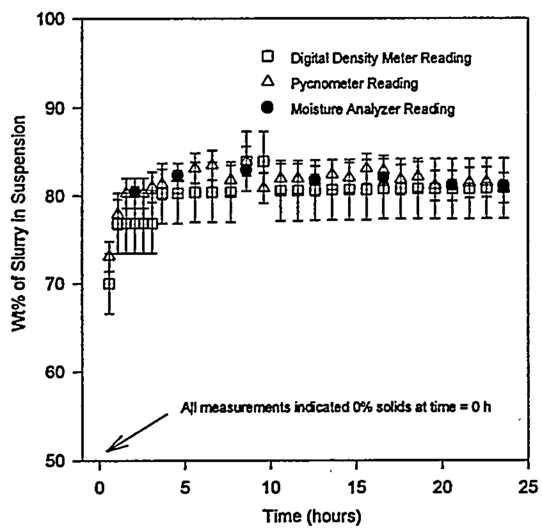


Figure 2.28. Resuspension Test #1

Resuspension Test #2

The slurry was again allowed to settle for 3 days after the completion of the first resuspension test. The sludge bed thickness and supernate solids concentrations were quantified and found to be identical to those at the beginning of the first resuspension test. The pulsed-air mixer was then activated with a gas pressure of 6 psig; only the center mixing plate pulsed one time every ten seconds. Mixer operation continued for 3 hours. As was observed before, the slurry density stabilized after only about 30 minutes of mixer operation. About 65 wt% of the solids were mobilized by the single mixing plate at 6 psig. The data for this test are shown in Figure 2.29.

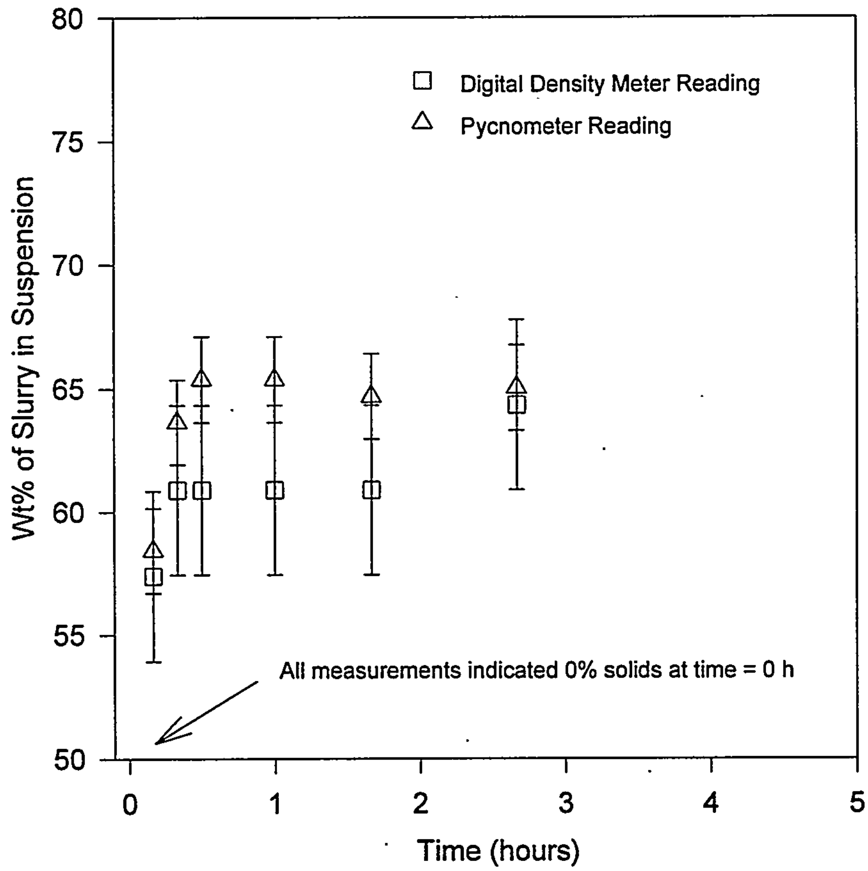


Figure 2.29. Resuspension Test #2 Data - Center Plate at 6 psig

Resuspension Test #3

The final slurry-resuspension test was conducted using all 4 plates operated at 6 psig with a cycle time of 11 seconds. Before the test, the slurry was allowed to settle for 3 days. Operation of all 4 plates at 6 psig resuspended about 72 wt% of the slurry from the tank floor. The data are shown in Figure 2.30.

The rate of air consumption during operation at 6 psig was found to be approximately 5 SCF per pulse for the center plate and about 3 SCF per pulse for each of the peripheral plates. Operation at 20 psig consumed air at rates of about 15 SCF and 5 SCF per pulse, respectively.

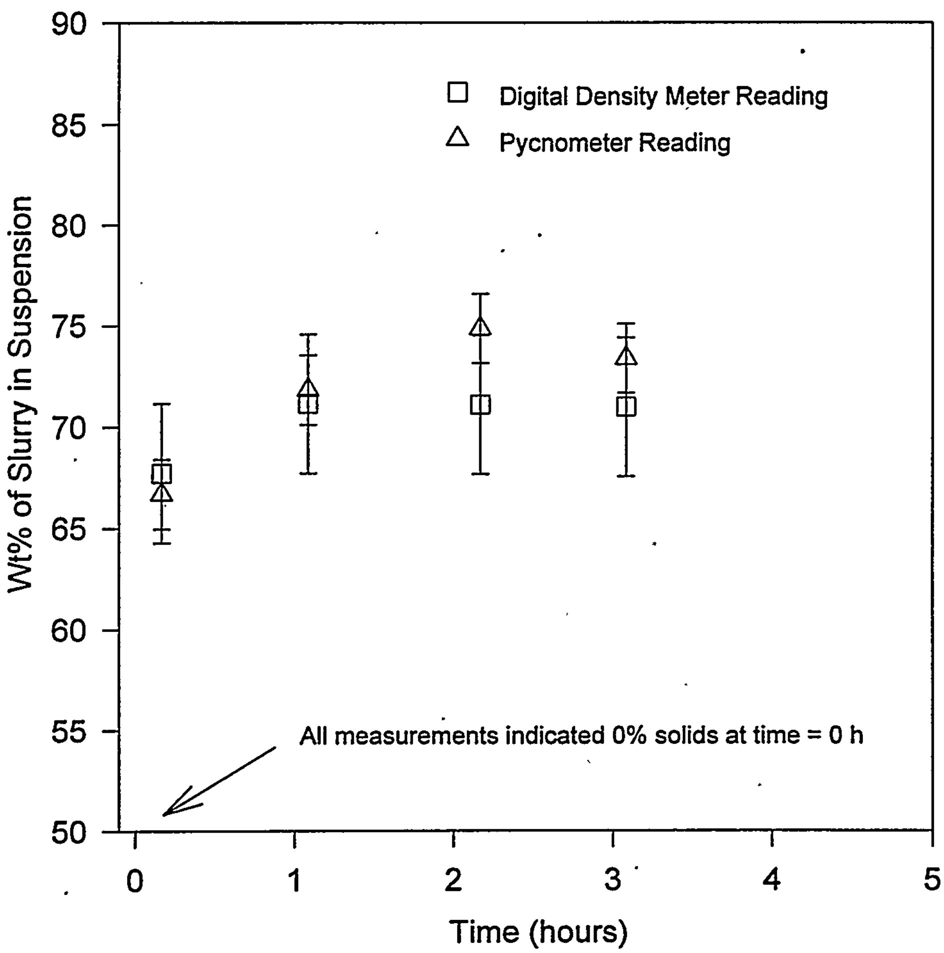


Figure 2.30. Resuspension Test #3 Data - 4 Plates at 6 psig

Implications of 1/4-Scale Test Results

The data gathered by testing full-scale mixing plates in the 1/4-scale tank demonstrate that mixing performance is better than would be expected, based on the previously developed scaling methodology. Rising bubbles induce large-scale circulation patterns within the tank that are sufficient to maintain tank-waste solids in suspension.

The test also demonstrated the reliability of the pulsed-air system. The mixer was operated for several days without an equipment problem. Following the completion of the testing, however, one of the pulsing valves stuck in the open position during a demonstration of the mixer being given for interested staff. This was easily remedied by a sharp blow to the side of the valve. It is important to note that although the gas-pulsing valves were mounted within the tank vapor space for this test, the valves can just as readily be mounted outside of the tank. Only the plates and gas lines need to be installed inside the tank. This is an important advantage over other mixing approaches where failure-prone equipment must come in contact with the radioactive waste. Simplicity of the pulsed-air mixer design avoids this problem.

Resuspension tests demonstrated that a pulsed-air mixer can recover from an unplanned mixer outage that results in slurry settling. It is not clear whether the simulant used for this test will consolidate at the same rate as tank waste, but the results provide evidence that short mixer outages might be of little concern.

Because the kaolin/water slurry is opaque, it was not possible to determine the pulse radii of the mixing plates visually. However, sludge-bed thickness measurements made shortly after mixer operation at 80 psig revealed that the tank floor was free of sludge out to a distance of about 85 $\pm$ 5 cm, which agrees reasonably well with the predicted pulse radius for these plates of about 90 cm (for operation at 80 psig).

2.3 Remaining Issues and Recommendations

The scaleup correlation development testing described in Section 2.1 of this report has provided a sound basis for the design of pulsed-air mixers for sludge-mobilization applications. The data indicate that pulsed-air mixers can be used for sludge mobilization whenever the tank floor area is relatively small or when the waste characteristics are such that it is not necessary to use a large number of mixing plates. For the mobilization of consolidated, cohesive sludge in large-diameter, flat-bottomed storage tanks, a prohibitively large number of pulsed-air mixing plates are needed. Mobilization of sludge in other types of tanks, such as the cylindrical, horizontal V-tanks at INEL, is practical because gravity tends to bring dislodged solids down near the mixing plates, which are located at the lowest point in the tank.

The mixer tests in the 1/4-scale tank (Section 2.2) demonstrated the importance of large-scale circulation patterns in mixing applications where the goal is to maintain solids in suspension. It is as yet unclear how to determine the number of mixing plates required at different scales to ensure similar slurry mixing. A combination of computer modeling and small-scale testing likely will be needed to develop this correlation. Whether such a correlation is needed will depend on whether slurry suspension maintenance applications for pulsed-air mixing can be identified.

One possible application of pulsed-air mixing that has received relatively little attention is in waste tanks like 101-SY at Hanford, which will periodically release a flammable gas mixture if the waste is left unmixed. The periodic gas releases have been mitigated through the use of a mixer pump in the center tank riser. It is suggested that a single pulsed-air mixing plate in the center of the tank may be capable of maintaining the tank waste in a mixed condition to prevent the problematic gas releases. The rising air bubble will effectively transport the dense slurry in the non-convective layer up into the supernate layer. Gravity will tend to collapse the non-convective layer slurry surrounding the plate into the void that is formed, and the next gas pulse will transport more of the solids upward. More analysis is certainly required before the pulsed-air mitigation approach can be judged feasible. Because there are significant financial and operational advantages to using a pulsed-air mixer, these analyses should be done.

Before any pulsed-air mixing in radioactive waste tanks is attempted, two key issues must be addressed. First, operation of the mixing plates at high gas pressures produces a significant shock wave. The concern is that the induced vibration may be of sufficient magnitude to damage the tank. Pulsair Systems, Inc. has not noted any tendency toward tank damage while operating their pulsed-air mixers in commercial applications. Their experiences should be reviewed to determine whether their data can be used to address this concern. If induced tank vibrations are determined to be a problem, the mixing plates can be operated at lower pressures to decrease the intensity of the shock wave. Operation at the higher pressures would only be used to mobilize the settled-solids layer. Once this is done, the pressure can be decreased to low levels and the solids will be maintained in suspension. It is also possible that the shock-wave magnitude can be decreased by altering the pulsing valve and mixing plate design.

The second issue that must be addressed before implementation is aerosol generation. Figure 2.31 shows the surface agitation observed when operating the pulsed-air mixer at 80 psig in the 1/4-scale tank. Depending on the pulse rate and number of mixing plates used, the aerosols generated may be of concern. Efforts should be made to determine whether the expected aerosol-generation rates will exceed the design limits of the tank-ventilation system. Ventilation system upgrades may be needed to handle the aerosol loading in some cases.

Based on the data collected to date, the following are recommendations for the future direction of radioactive waste pulsed-air mixing:

- Pursue deployment of a pulsed-air mixer array in a horizontal, cylindrical waste tank, such as tanks V-3 and V-4 at INEL. The data gathered indicate that adequate waste mixing will be achieved and deployment of the mixer is feasible (see Section 3.0).

- Examine the potential for tank damage in underground storage tanks exposed to the shock waves generated by pulsed-air mixing plates operated at high gas pressure. Investigate methods for reducing the shock-wave magnitude.

- Estimate the rate of aerosol generation as a function of pulsed-air mixer operating parameters and determine if existing tank-ventilation systems can handle the predicted aerosol load.

- Develop a revised scaling methodology for pulsed-air mixing that addresses both large-scale circulation pattern effects and the effect of liquid level.

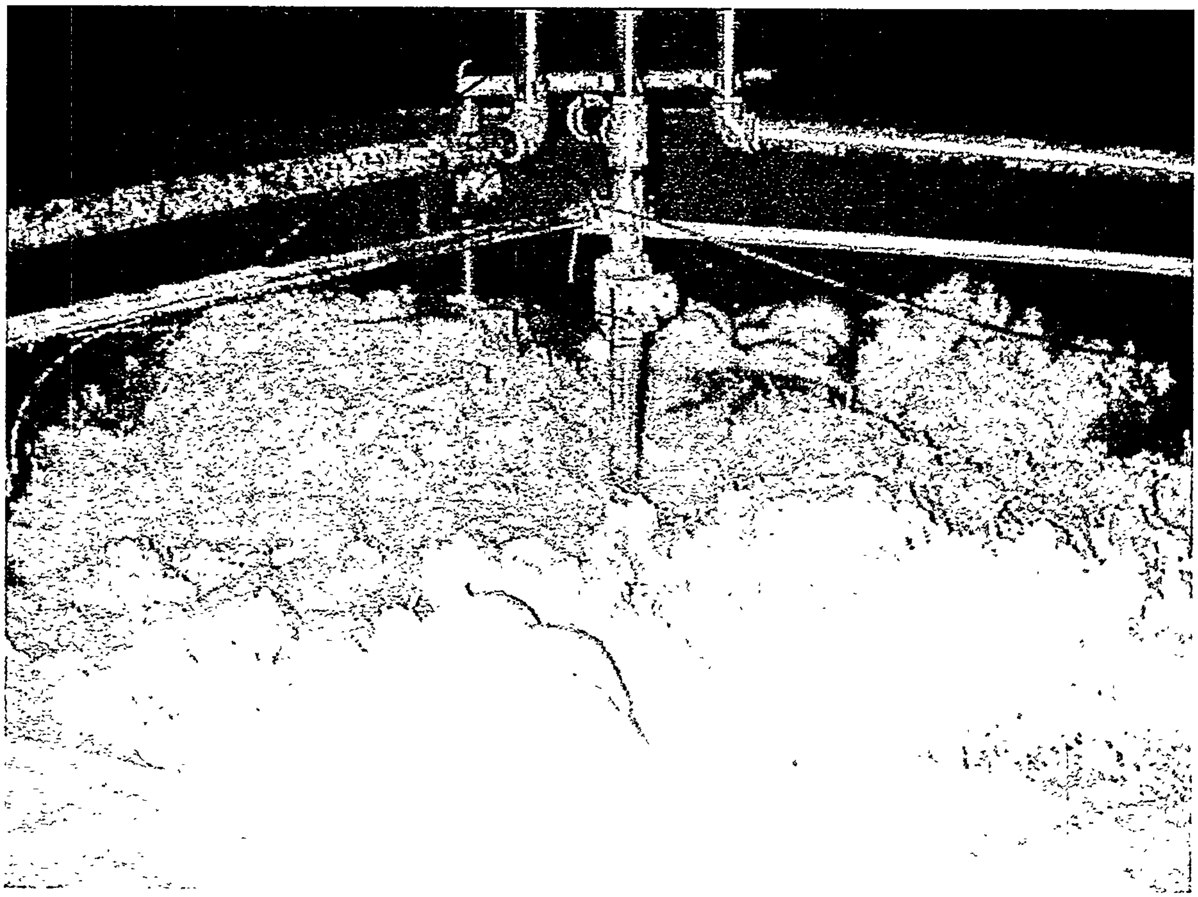


Figure 2.31. Slurry Surface During 1/4-Scale Mixing Test at 80 psig

3.0 Conceptual Design of Horizontal Tank Mixer Deployment

This section, which was prepared by the Applied Physics Laboratory of the University of Washington (APL/UW), describes proposed hardware to install Pulsair Systems, Inc. mixers in horizontal tanks such as the V-3 and V-4 radioactive-waste tanks at the Idaho National Engineering Laboratory (INEL). INEL V-tanks V-3 and V-4 were selected to provide a single tank design for the purpose of developing a mixer- deployment system. Tanks such as the ORNL Melton Valley tanks or Hanford miscellaneous underground-storage tanks could also have been used and the design concepts described here could be applied to any of these tanks. Horizontal tanks have been chosen for conceptual design purposes because they offer a simpler deployment than flat-bottomed tanks. Also, horizontal tanks offer reasonable demonstration options.

The mixer system consists of four pulsed-air accumulator plates spaced along the bottom of the tank. Bursts of high-pressure gas will be expelled from the accumulator plates to move and mix the sludge for resuspension in the settled solids into the tank supernate. Pulsair Systems, Inc. (Bellevue, Washington) will supply the patented technology of providing high-pressure air pulses to the accumulator plates to create the mixing action within the tanks. APL/UW engineers have developed a concept of how the equipment can be installed and removed, if necessary, through the 51-cm (20-in) diameter access port located near one end of the 3-m (10-ft) diameter by 6.7-m (22-ft) long tank.

3.1 Background

The Applied Physics Laboratory at the University of Washington has a long history of successfully developing equipment for remote and harsh environments. APL/UW engineers have designed, deployed, and retrieved many systems from the depths of the ocean and the far reaches of the Arctic. With this background, APL/UW was contracted under PNNL Task Order 307341-A-A2 to work with PNNL and Pulsair Systems, Inc. to develop concepts for reliable installation of a pulsed-air mixer system in a generic, radioactive-waste tank.

The initial intent of APL's involvement on the project was to use the information gained from testing pulsed-air mixing systems in the 1/12- and 1/4-scale model tanks at PNNL to develop concepts for installing the mixers in a full-scale waste-storage tank at Hanford.

After obtaining fluid-velocity results from the 1/12-scale tank testing at Hanford, PNNL personnel decided that the first demonstration of pulsed-air mixing in actual waste tanks should be proposed for relatively small, horizontal tanks such as the V-tanks at the Idaho National Energy Laboratory (INEL). PNNL personnel provided APL with the tank dimensions and the estimated size of pneumatic components to effect the breakup of radioactive sludge. APL was requested to develop a conceptual approach for installation of the equipment in the tanks, keeping in mind that the hardware may need to be removed from the tank after weeks of continual mixing. This conceptual equipment design was developed in parallel with the 1/4-scale tank testing from mid-April to mid-May 1996.

3.2 Objective

The main advantage of the Pulsair mixing system is its simplicity and absence of moving parts within the waste tank. In keeping with this simplicity, the installation equipment should have few moving parts in the tank, be highly reliable, safe to operate, and economical to construct. The main design difficulty is to install fairly large-sized components through a 51-cm (20-in) diameter access port, located at the bottom of a 3.7-m (12-ft) long culvert. A still tougher design constraint is to maintain the capability to remove the hardware after weeks of operation in a poorly characterized, hazardous waste slurry.

3.3 Design Constraints

INEL V-tank design drawings were used as the basis for the horizontal tank design. The required number and size of pulsed air mixing plates were determined based on the data presented in Section 2.1. The plate design, operation, and spacing were selected such that the gas pulse radius for each plate overlapped with the pulse radii of its neighboring plates. The constraints used to develop the mixer deployment design were:

1. V-tanks are 3-m (10-ft) inside diameter by 6.7-m (22-ft) long and buried 3 m (10 ft) underground with a 51-cm (20-in.) diameter access port (see Figure 3.1)

2. Pulsair accumulator plate assemblies are to be 38-cm (15-in.) in diameter.

3. Four Pulsair plate assemblies are required along the bottom of the tank. They are to be double plates separated vertically 1.3 cm (0.5 in.).

4. Pneumatic supply lines to accumulator plates are to be 2-in. schedule 40 steel pipe.

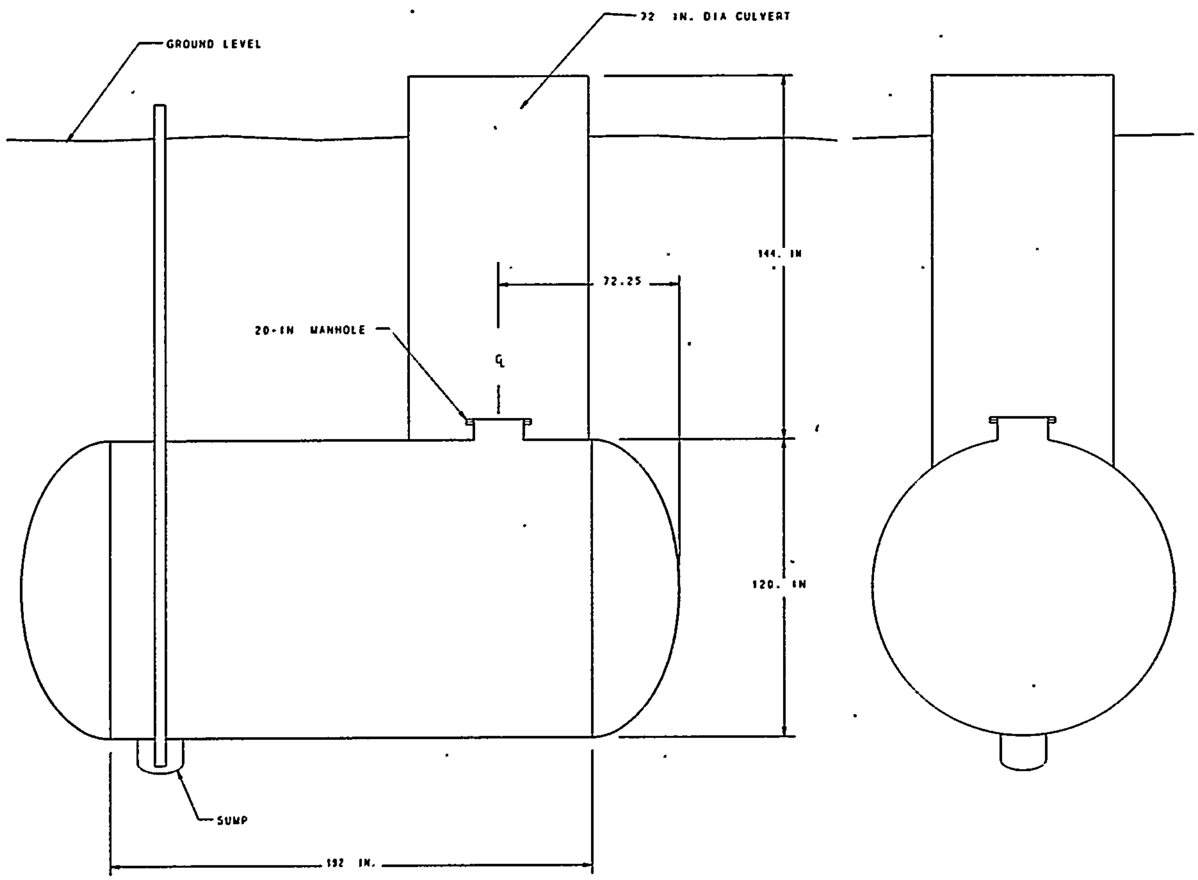
5. A Pulsair control unit with a separate injection valve on each line is required.

6. The Department of Energy facility will supply high-pressure gas and reservoir tanks to operate the pulsed-air mixer system at pressures up to 100 psig.

3.4 Installation Procedure

Information on the process to open the waste tank and seal it was not supplied to APL/UW. We assume that this procedure will allow a boom truck to back near the tank, lift and remove the manhole cover, install a 51-cm (20-in.) diameter extension tube to ground level and then lower the installation equipment into the tank. After the mixer is installed, an enclosure could be installed easily over the entire 1.8-m (6-ft) diameter conduit access to the tank.

Figure 3.2 shows the major components of the pulsed-air mixer system fully installed in a V-tank. Installation would be performed in five major stages: (1) remove manhole cover and install extension tube with attached guide and linear actuators; (2) lower first two pneumatic lines into the tank as an assembly, shift horizontally to the edge of the access hole and deploy the two pulsed-air



V-3 STORAGE TANK . ELEVATION VIEW

Figure 3.1. Sketch of INEL Tank V-3

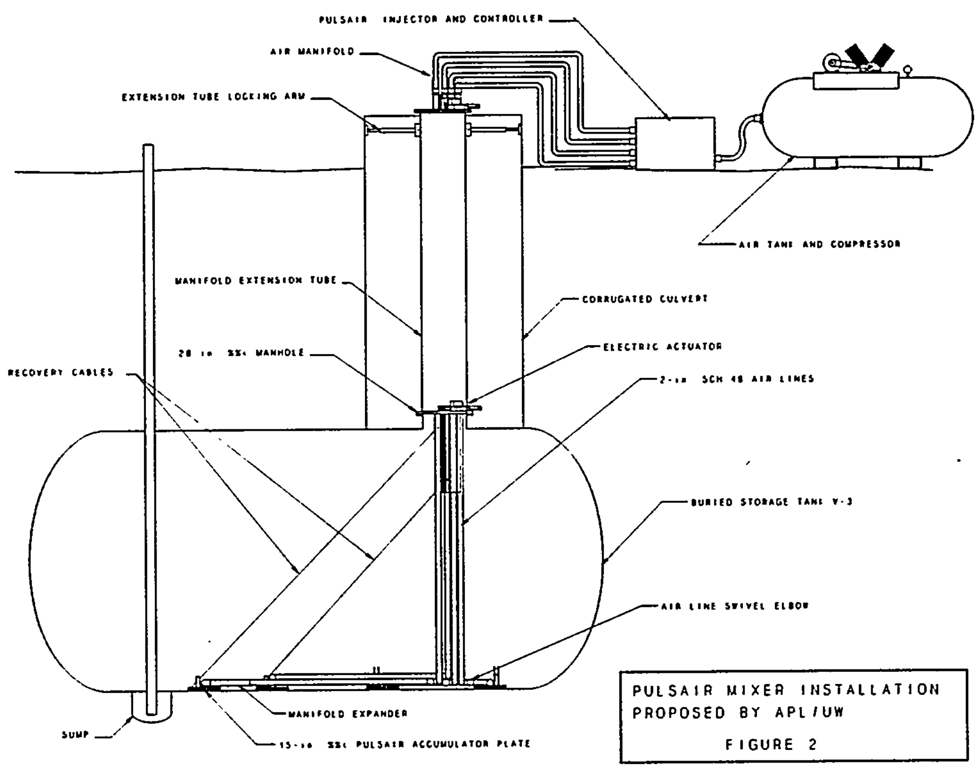


Figure 3.2. Installed Pulsed-Air Mixer in INEL V-Tank

accumulator plates; (3) lower third pneumatic assembly into the tank and deploy its accumulator plate; (4) lower the fourth pneumatic assembly into the tank and deploy its accumulator plate; and (5) attach the Pulsair Systems, Inc. controller and injection valves to mixer's pneumatic lines at the top of the extension tube and connect the gas supply.

3.5 Installation Details

A boom truck or crane with a minimum vertical reach of 9 m (30 ft) at a radius over the tank entrance will be required along with a 7.3-m (24-ft) flatbed truck nearby with the mixer equipment to be installed.

Each of the five installation stages listed in Section 3.4 are described in detail in the sections that follow.

3.5.1 Stage One

Remove the manhole cover from the tank access. Lower the 51-cm (20-in) inside diameter by 3.7-m (12-ft) long extension tube onto the manhole flange with tapered guide pins aligning it in at least two of the bolt holes. The top end of the tube is aligned and secured with expansion brackets against the surrounding 1.8-m (6-ft) diameter conduit. The extension tube has an internal guide for the first two pneumatic lines, as shown in Figure 3.3, along with linear actuators mounted at the top and bottom. The actuators position the pneumatic tubes horizontally after they are inside the tank. The internal guide contains two tee slots which accept the keys on the first two pneumatic-tube assemblies.

3.5.2 Stage Two

The 7-m (23- ft) long assembly containing the number one and two pneumatic lines and pulsed-air accumulator plates is raised over the access tube to the tank. The tee guides are aligned manually and engaged as the assembly is lowered into the access-extension tube. The assembly is lowered roughly 5.5 m (18 ft) until the pulsed-air accumulator plates are inside the tank. The linear actuators securing the guide in the extension tube are electrically actuated to shift the entire assembly. This action positions the assembly against the edge of the access manhole and off-center to make room for the installation of the remaining pneumatic systems. The assembly is then lowered until the bottom end rests on the tank floor. A cable release is pulled to allow the two Pulsair accumulator plates to rotate to a horizontal position on the tank floor. The weight of the accumulator plates plus lead ballast is sufficient to cause the units to rotate at the swivel elbow joint after a 330-N (75-pound) spring gives them an initial impulse.

3.5.3 Stage Three

The 7-m (23-ft) long assembly of pulsed-air accumulator plate number three is raised over the access port. The tee guide is engaged manually into the tee-slot guide of the assembly installed in stage two. The number three accumulator plate assembly is lowered until the bottom end rests on the tank floor. A cable release is pulled manually, allowing the vertically oriented accumulator plate to fall horizontal to the tank floor at the end of its 2.1-m (6.8-ft) long pipe. This assembly also has a 330-N (75-pound) spring to give it an initial impulse in addition to the weight of the accumulator plate

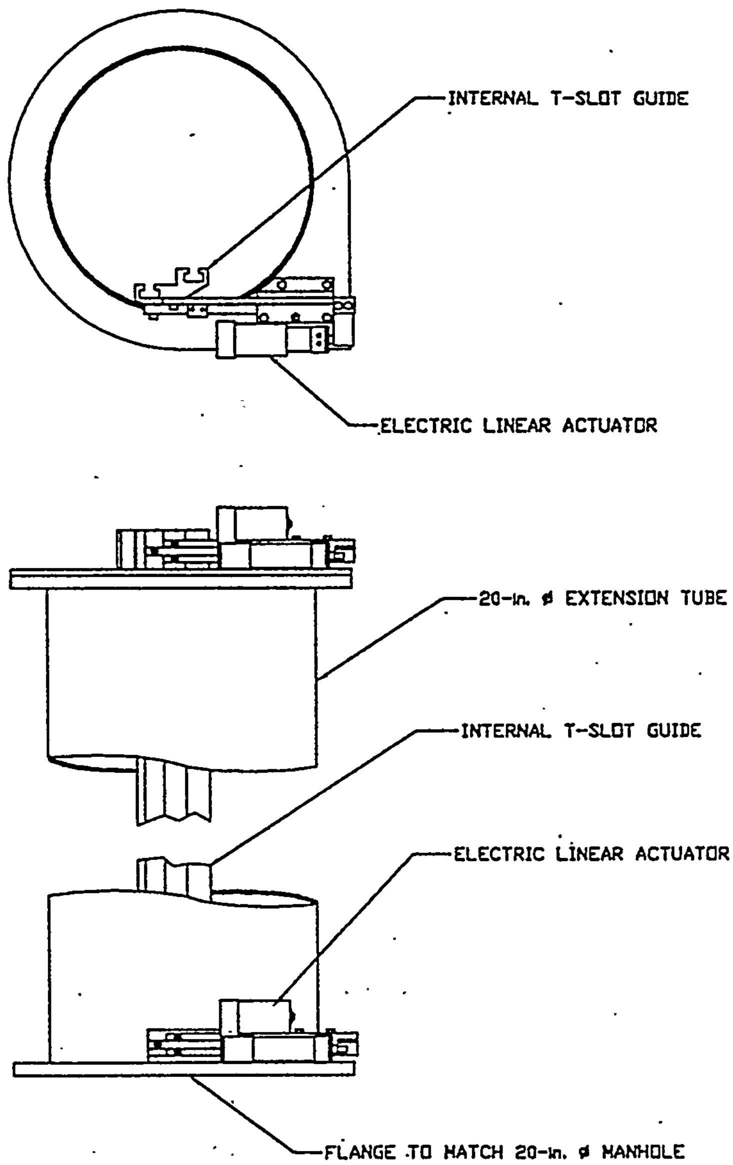


Figure 3.3. Extension Tube and Guide

and 23-kg (50-lb) lead ballast. The release cable is also attached to the accumulator plate so it can be used to raise the horizontal assembly back to vertical, in the event removal is required after the tank is empty.

3.5.4 Stage Four

Deployment of Pulsair accumulator plate assembly number four is an exact duplication of stage three except it is deployed down its own tee slot. After assembly four is lowered to the tank floor, the release device allows the accumulator plate assembly to rotate to the tank floor with an initial impulse from a spring. In this position the far edge of the accumulator plate will be roughly 18 cm (7 in) short of the tank sump. The inside diameter of the tank is the limiting factor on the length of this reach.

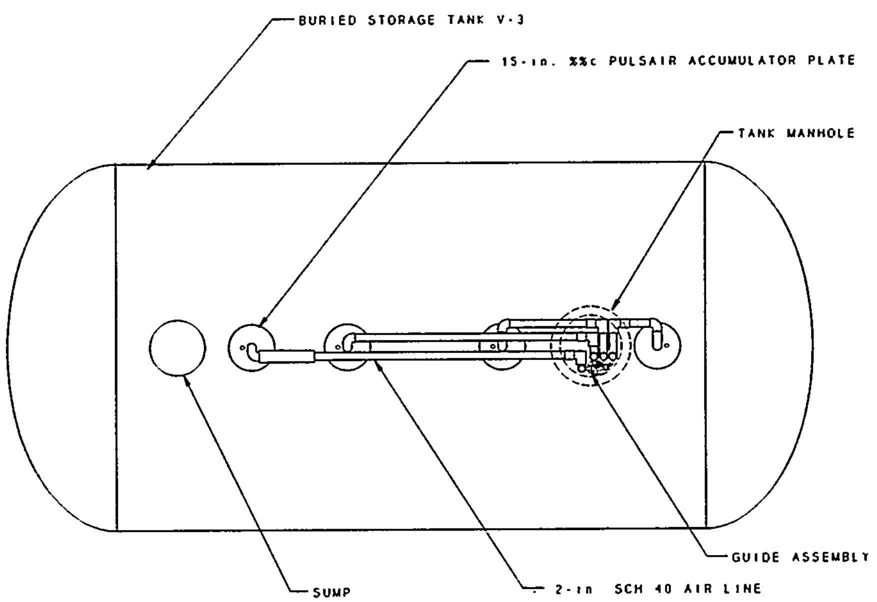
If the mixer system does not need to be removed after the tank is empty, a slip joint can be incorporated near the end of this fourth assembly. A 50-psi rupture disk on the 5-cm (2-in) orifice of the accumulator plate would allow low-pressure air pulses in the line to exert force on the joint. This force should extend the slip joint in the pneumatic tube. A 30-cm (1-ft) extension would position the edge of the accumulator plate near the 4-inch vertical sump pipe and out over part of the sump recess. The 4-inch vertical pipe into the tank sump prevents this Pulsair plate from getting closer than 0.8 m (2.5 ft) to the end of the tank floor. If the pipe in the sump can be removed, then the slip joint can easily accommodate more extension to position the plate closer to the end of the tank.

After applying the low-pressure bursts of air to extend the arm, 100 psi bursts of air will rupture the disk for normal operation. If the one hundred pounds of force does not move the sludge and allow the unit to extend, then the pulsing action of the unit under mixing conditions will let it work out into position.

The deployment concept takes into account that the waste sludge may not flow enough to let the pulsed-air plates initially contact the tank floor. However, if plate number two does not penetrate to the floor, then the horizontal pipe for plate number three will bear against it and apply additional force. Correspondingly, plate four can increase the pressure on both plates two and three as can be seen in Figure 3.4. This should ensure that plate two will be either on the bottom or that the pulsed-air actuation through accumulator plate two will put it there. The entire pulsed-air system can be operated even though the plates are not initially against the tank floor. Based on videos of an air lance in waste sludge and model testing, PNNL personnel are confident that the pulsed-air actuation will cause the plates to work down through the sludge.

3.5.5 Stage Five

The final stage of the mixer installation is to connect the gas supply, Pulsair Systems, Inc. controller, and injection valves to the top ends of the distribution lines in the tank. This is all done above ground where the 2-inch schedule 40 pipes come out of the manhole-extension tube. The exact details on this process will most likely be incorporated into the process of how the tank entrance will be covered or sealed. More information on safety and operating procedures will be required before this issue can be addressed in detail.



V-TANK, PLAN VIEW OF INSTALLATION
FIGURE 4

Figure 3.4. Plan View of Installed Pulsed-Air Mixer in INEL V-Tank

3.6 Equipment Description

Listed below are hardware to be installed inside the waste tank:

1. Four Pulsair accumulator plate assemblies with 23 kg (50 lbs) of lead ballast on each unit;

2. Four gas-delivery lines of 2-inch schedule 40 stainless-steel pipe (each consists of vertical pipe with 1 m [3 ft] of tee-section guide, custom swivel elbow with seals and ball races, horizontal pipe and two 90-degree elbows). Total length of four pipes is about 18.6 m (61 ft);

3. Guide-track assembly (total length about 1 m [3 ft]);

4. Four steel deployment springs; and

5. Three (3/16-inch-diameter 6 x 19 galvanized steel) recovery cables for a total of 10.7 m (35 ft).

Listed below are hardware outside a tank:

1. Manhole extension (steel tube 51-cm ID. x 3.7-m long) with flanges each end and containing a double tee-slot guide;

2. Pulsair controller and injection valves with 110 VAC power to controller;

3. Pneumatic plumbing, high-pressure gas supply and holding tank;

4. Two electric linear actuators requiring 110 VAC power;

5. 14.6 m (48 ft) of 2-inch schedule 40 stainless-steel pipe;

6. 13.7 m (45 ft) of 3/16-inch-diameter galvanized cable; and

7. 4.6 m (15 ft) of multiple tee-guide assembly.

3.7 Critical Component Description

A brief description of each key mixer system component is given in this section.

3.7.1 Custom Swivel Elbow

The rotary elbow joints of the pneumatic mixer lines in the waste tank would be constructed as depicted in Figure 3.5. They need to be custom-designed for compactness in this application, but they follow the proven design of commercial swivels. The double ball-bearing races provide smooth actuation in rotation. The balls of the bearing are loaded into a race with a groove in both parts so that the balls resist axial forces on the joint when the joint has internal pressure. The balls are

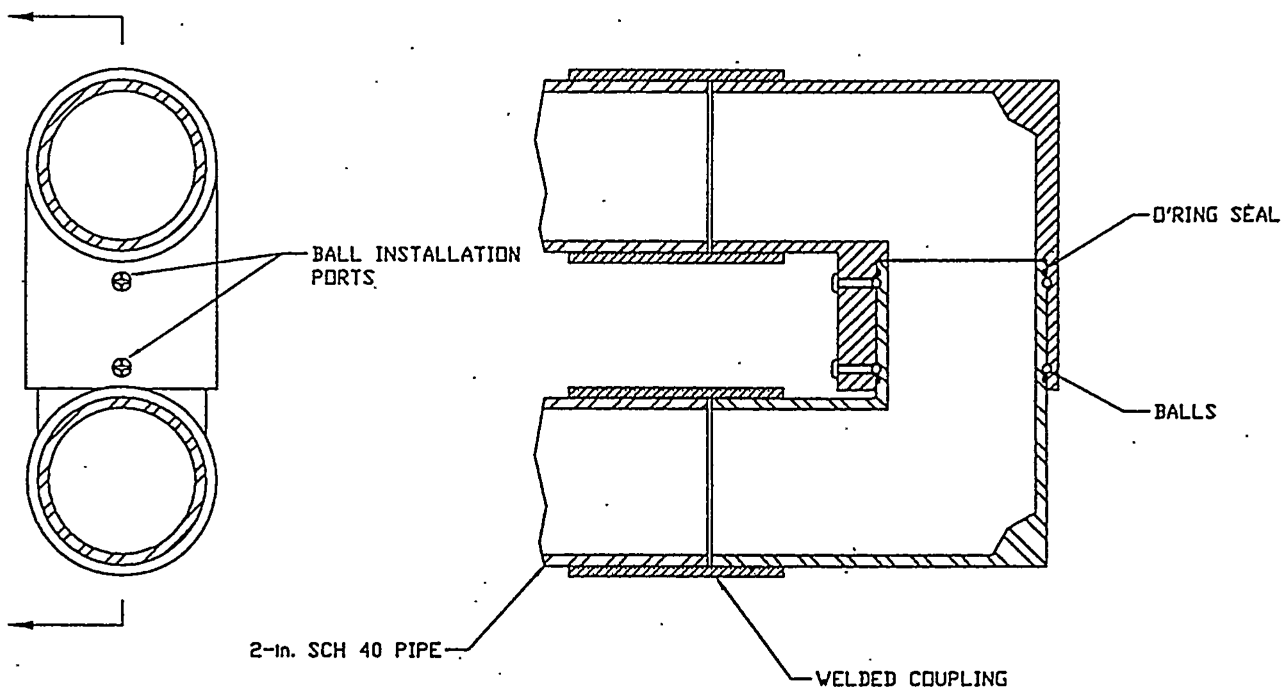


Figure 3.5. Air Line Swivel Elbow Sketch

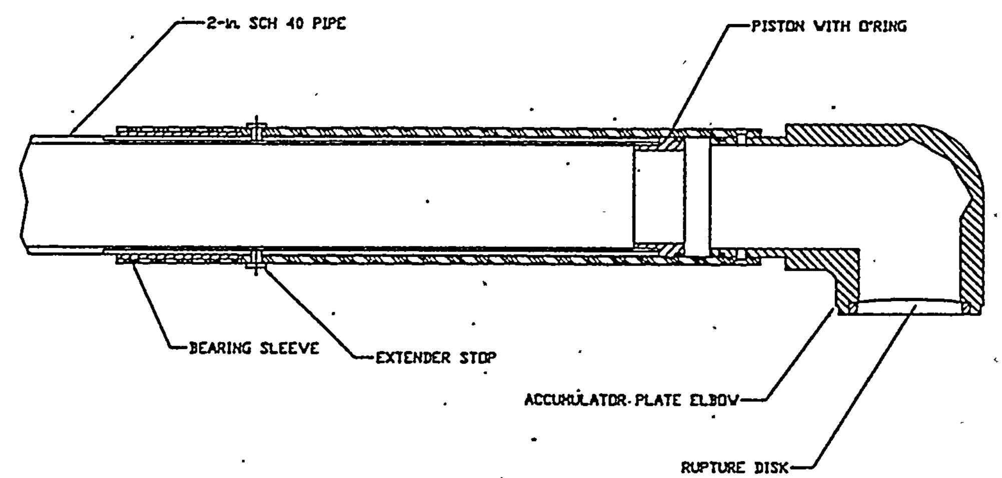


Figure 3.6. Air Line Slip Joint

installed into the races through the screw ports and retained by the screws. The bearings are sealed from contamination by an O-ring on either side of the double race and by O-rings under the heads of the ball retaining screws.

3.7.2 Slip-Joint Extension

A slip joint for extending the horizontal piping on mixer plate #4 is illustrated in Figure 3.6. The slip joint positions the mixer plate up to the tank's sump pipe. Longitudinal key ways, cut in the outside of the 2-inch stainless-steel supply pipe, serve as guides for the extender stop-screws in the outer, oversize pipe. The piston and bearing sleeve in the outer pipe are made of a material other than stainless steel; they are the sliding contact surfaces against the stainless-steel pipes to prevent possible galling. The rupture disk is designed to allow low-pressure air to extend the joint. This disk will blow out of the way when high-pressure pulsing is started.

3.7.3 Installation Guides

A horizontal cross-section of the manhole-extension tube with vertical guides is shown in Figure 3.7. The vertical guides for the mixer-system installation in the waste tank are shown with diagonal cross hatching in the lower right quarter of the figure. In this sketch, pulsed-air accumulator plates 1, 2 and 3 are already installed and are outside the view. Pulsair plate 4 is being lowered into the tank with the double mixer plate still vertical. The double-hatched tee-slot guide, next to the edge of the extension tube, is fastened to the linear actuators. This guide is constrained within the extension tube and does not extend into the tank. In this cross-section, the actuators have already shifted the assembly off the center of the extension tube. The finely cross-hatched tee guide shown as one piece is manufactured as several parts and bolted together into this shape. Pneumatic lines one and two are rigidly attached as part of this guide and would be installed as an assembly. This tee-guide section spans from the top of the manhole- extension tube to 1 m (3 ft) into the waste tank at full deployment and serves as a guide for the tee sections welded to the piping of mixer plates 3 and 4. To simplify the view the release cables, impulse springs and bearing plates for the springs are not shown in Figure 3.7.

3.8 Extraction Procedure

If the mixing system can be abandoned inside the tank after the tank is emptied, then the following extraction procedure could be applied. The Pulsair controller and injection valves would be removed from the system. The manhole-extension pipe, without the pneumatic-mixer pipes, would be lifted off the manhole flange and cleared by disengaging from the tee-slot guide. The 2-inch schedule 40 pipes, pipe guides and 3/16-in-diameter cables would be cut off below grade as required for the tank-sealing process.

If the Pulsair mixer system is to be removed from the tank after use, then the procedure could be nearly the reverse of installation, depending on the decontamination requirements. Removal would begin with accumulator plate number four. The retraction cable is tensioned by a winch clamped to the top of the number four supply pipe. This would raise the horizontal section with the accumulator plate to vertical. The number four unit is then hoisted vertically out of the tank until the tee slot disengages from the guide. The same process is followed for accumulator plate system three. Next, the assembly containing accumulator plates one and two is raised 2 m to 3 m vertically to enable the accumulator plates to hang vertically and the linear actuators in the extension tube shift the assembly to the center of the manhole. This allows the entire assembly to be raised out of the tank. The final step in removing the pulsed-air mixer system is to retract the extension-tube supports at the top end of the corrugated culvert and remove the manhole-extension tube.

3.9 Cost Estimate

The conceptual design of equipment to deploy a four-plate Pulsair Systems, Inc. mixer in a V-tank containing radioactive waste shows that the process can be accomplished with relatively simple hardware. All components are either off-the-shelf or easy to manufacture. We estimate that APL/UW can detail, construct, test in water, and deliver the conceptualized deployment equipment within six months for less than $155K. This estimate does not include any costs associated with an enclosure over the tank access, should one be required to address radioactive contamination concerns.

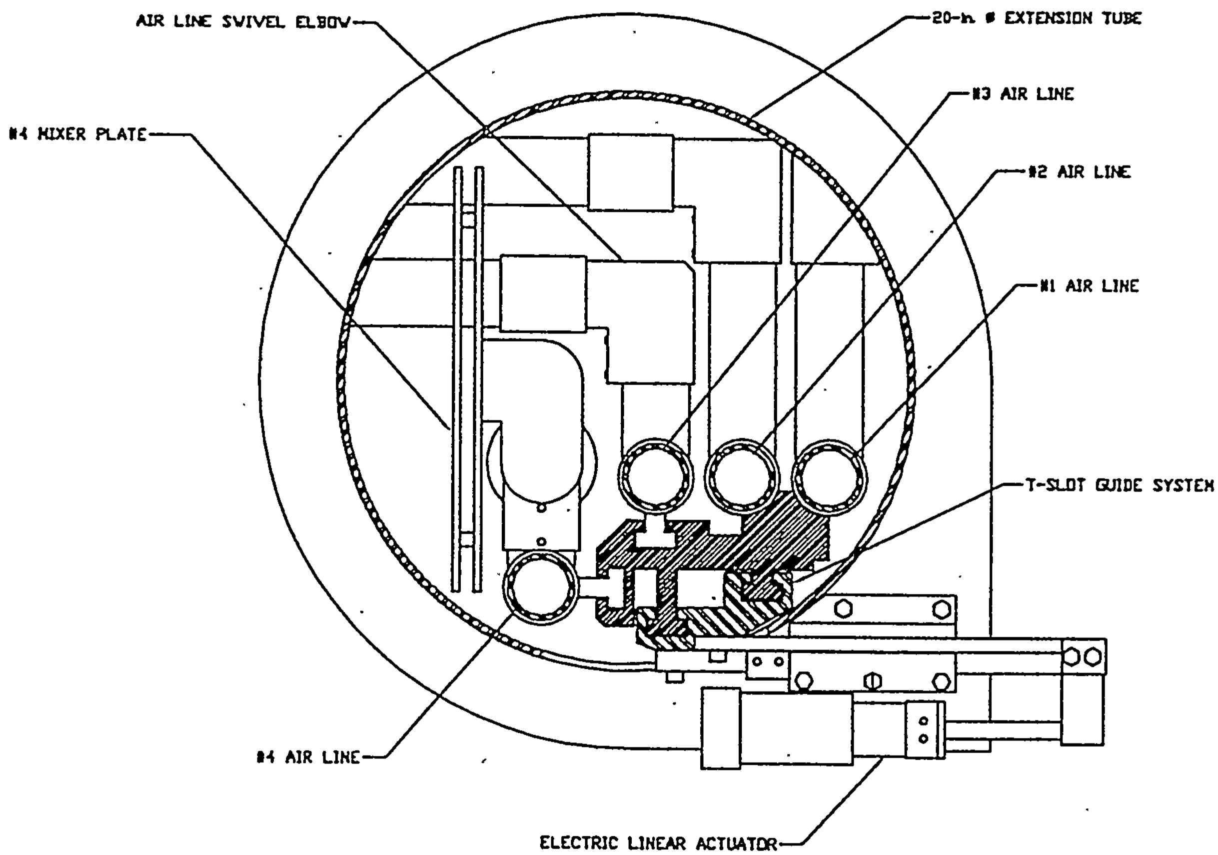


Figure 3.7. Installation Guides Viewed Down Extension Tube

Distribution

No. of
Copies

Offsite

2 DOE/Office of Scientific and Technical Information

Onsite

1 **DOE Richland Operations Office**

W. R. Wrzesinski, S7-53

40 **Pacific Northwest National Laboratory**

K. M. Airhart, K5-22 (10)
J. A. Bamberger, K7-15
W. F. Bonner, K9-14 (2)
G. R. Golcar, P7-19
C. R. Hymas, P7-19
L. M. Liljegren, K7-15
M. R. Powell, P7-19 (15)
J. H. Westsik, P7-19
M. W. Rinker, K5-22 (2)
P. A. Scott, R3-87
Technical Report Files (5)

No. of
Copies

2 **Westinghouse Hanford Company**

J. D. Galbraith, H5-49
P. W. Gibbons, H5-61