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Retrieval Process Development and Enhancements Pulsed-Air Mixing DOE Site Assessment

M. R. Powell

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

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Summary

The purpose of this report is to document 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). Pulsed-air mixers should be deployed wherever it can be shown that their 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 to provide end users with the requisite technical bases to make retrieval and closure decisions.

Pulsed-air mixing is a commercially available technology (from Pulsair Systems, Inc. of Bellevue, Washington) and is used extensively in the lube oil mixing industry, municipal wastewater treatment plants, and other applications. 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 being injected on a continuous basis. The rapid expansion of the pulsed-air bubbles near the tank floor and their subsequent rise through the fluid serve to both lift solids from the tank floor and maintain those solids in a uniform suspension.

The strengths and weaknesses of the pulsed-air mixing approach were identified to determine where pulsed-air mixing is appropriate and where it is not. A decision logic diagram that describes the procedure used to conduct this evaluation is provided in the body of this report (Figure 2.1). Pulsed-air mixing is expected to be effective for the mobilization and mixing of sludges in horizontal cylindrical storage tanks like those at the Idaho National Engineering and Environmental Laboratory (INEEL) and at Oak Ridge National Laboratory (ORNL). The geometry of such tanks is particularly conducive to effective pulsed-air mixing. However, pulsed-air mixing is not a good choice for the mobilization and mixing of cohesive sludge in large-diameter, flat-bottomed tanks (e.g., the double-shell tanks at Hanford).

Pulsed-air mixing is also expected to be effective for the mixing of salt solutions like those in the Hanford low-level waste Phase I Privatization feed tanks (AP Farm); and for the mixing of waste slurries where some solids settling is permissible, as in Tank W-9 at ORNL or in Hanford Tanks 101-SY and 103-SY. Application of pulsed-air mixing to these mixing challenges is being evaluated.

The mixing of grout with residual waste heels is another potential niche for pulsed-air mixing, but the feasibility of this has not yet been demonstrated. Some proof-of-principle testing is needed to determine whether this application should be pursued.

Several issues must be addressed before pulsed-air systems can be installed in radioactive-waste tanks. First, when the plates, which are known as accumulator plates, are operated with a relatively high gas pressure to generate the bubble (e.g., up to 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 radius of the bubble pulse, and makes mixing less effective. 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 aerosol handling 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 pulsed-air mixing will require prohibitively expensive tank ventilation systems.

Other issues to be resolved include mixer scaleup for certain applications, and whether pulsed-air mixers can be used to mix grout slurries with waste heels. Work currently underway will help to resolve the scaleup issues. Grout mixing proof-of-principle tests are not currently part of the RPD&E work scope.

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Nomenclature

CSEE	confined sluicing end-effector
D_{pipe}	compressed air delivery pipe inside diameter, cm
D_{plate}	accumulator plate diameter, cm
DOE	U.S. Department of Energy
GAAT	Gunite and Associated Tanks
h	accumulator plate standoff distance, cm
h_{min}	minimum accumulator plate standoff distance to avoid choked flow, cm
INEEL	Idaho National Engineering and Environmental Laboratory
MVST	Melton Valley Storage Tank
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
RPD&E	Retrieval Process Development and Enhancements Project
R_{pulse}	air bubble pulse radius, cm
SRS	Savannah River Site
UW/APL	University of Washington Applied Physics Laboratory
ΔP	air pressure difference between air supply and static head, kPa

1.0 Background

Millions of gallons of radioactive waste reside in underground tanks at U.S. Department of Energy (DOE) 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.

The purpose of this document is to examine the liquid and slurry mixing needs at the DOE waste sites and determine which of these needs can potentially be met by pulsed-air mixers. 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 their 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 to provide end users with the requisite technical bases to make retrieval and closure decisions.

1.1 Description of Pulsed-Air Mixing

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. A study was performed in fiscal year 1996 to improve the understanding of how pulsed-air mixing applies to slurries (Powell and Hymas 1996). 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 provided by Pulsair Systems, Inc.

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 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 and 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 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.

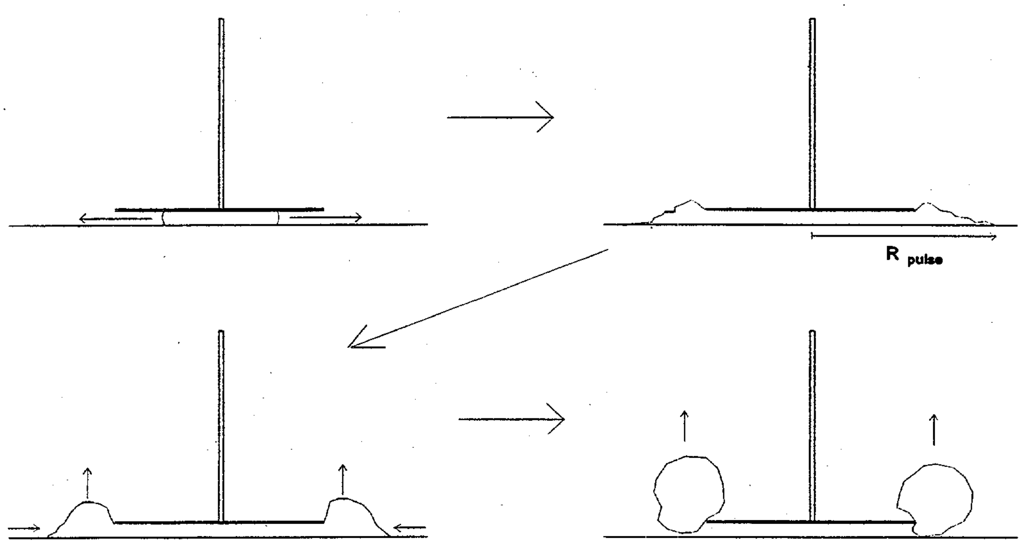

Figure 1.1. Sketch of Gas Bubble Growth Showing R_{pulse}

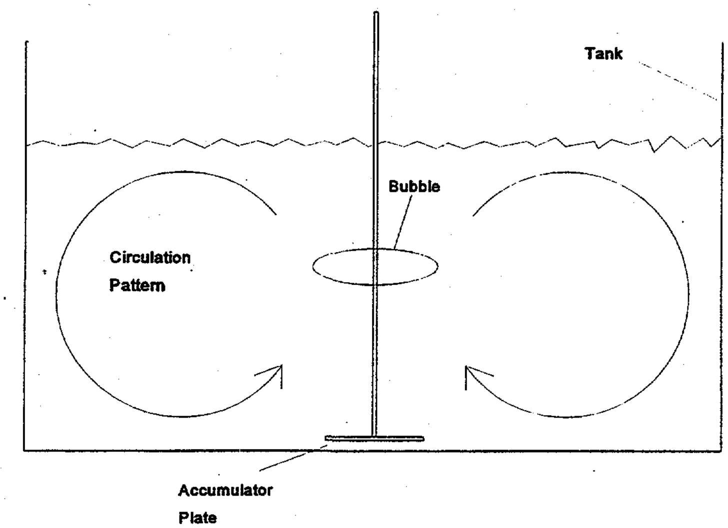

Figure 1.2. Bubble-Induced Fluid Circulation Pattern

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 any 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 Previous Pulsed-Air Testing

Tests of pulsed-air mixing systems were conducted by PNNL during fiscal years 1995 and 1996. The purpose of the 1995 test, which was funded by EM-30, was to determine whether pulsed-air mixing was likely to have applications at any of the DOE sites. The proof-of-principle tests were encouraging and, in 1996, a more extensive set of tests funded by EM-50 were performed so that the performance of pulsed-air mixers in DOE waste slurries and sludges could be more accurately predicted. Also, the fiscal year 1996 effort included the development of pulsed-air mixer deployment concepts for remote entrance into a horizontal waste tank. These tests are described briefly in Sections 1.2.1 through 1.2.3. A more extensive description of the fiscal years 1995 and 1996 testing can be found in Powell and Hymas (1996).

In early fiscal 1997, a test was conducted in which a single pulsed-air accumulator plate mobilized and mixed a layer of settled waste simulant at the Oak Ridge National Laboratory. This test and its implications are described in Section 1.2.4.

1.2.1 FY95 Proof-of-Principle Tests

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 performance expected from pulsed-air mixers would meet some of Hanford's slurry-mixing needs.

Two series of tests were conducted in a 1/12-scale mockup (1.9-m diameter, 0.8-m liquid depth) of a Hanford double-shell tank using a 13-plate mixing array (see Figure 1.3). The first test series 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 as to whether a pulsed-air mixer could maintain an acceptable fraction of that slurry in suspension (i.e., not allow solids to settle to the tank floor). The second test series was designed to evaluate the capability of pulsed-air mixers to resuspend the type of sludge that is known to have accumulated in many of the Hanford double-shell tanks.

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 using only a 13-plate mixing array. The data implied that a much larger number of accumulator plates would be required to mobilize more than 90% of the sludge in a full-scale Hanford double-shell tank (22.9-m = 75-ft. diameter).

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[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).

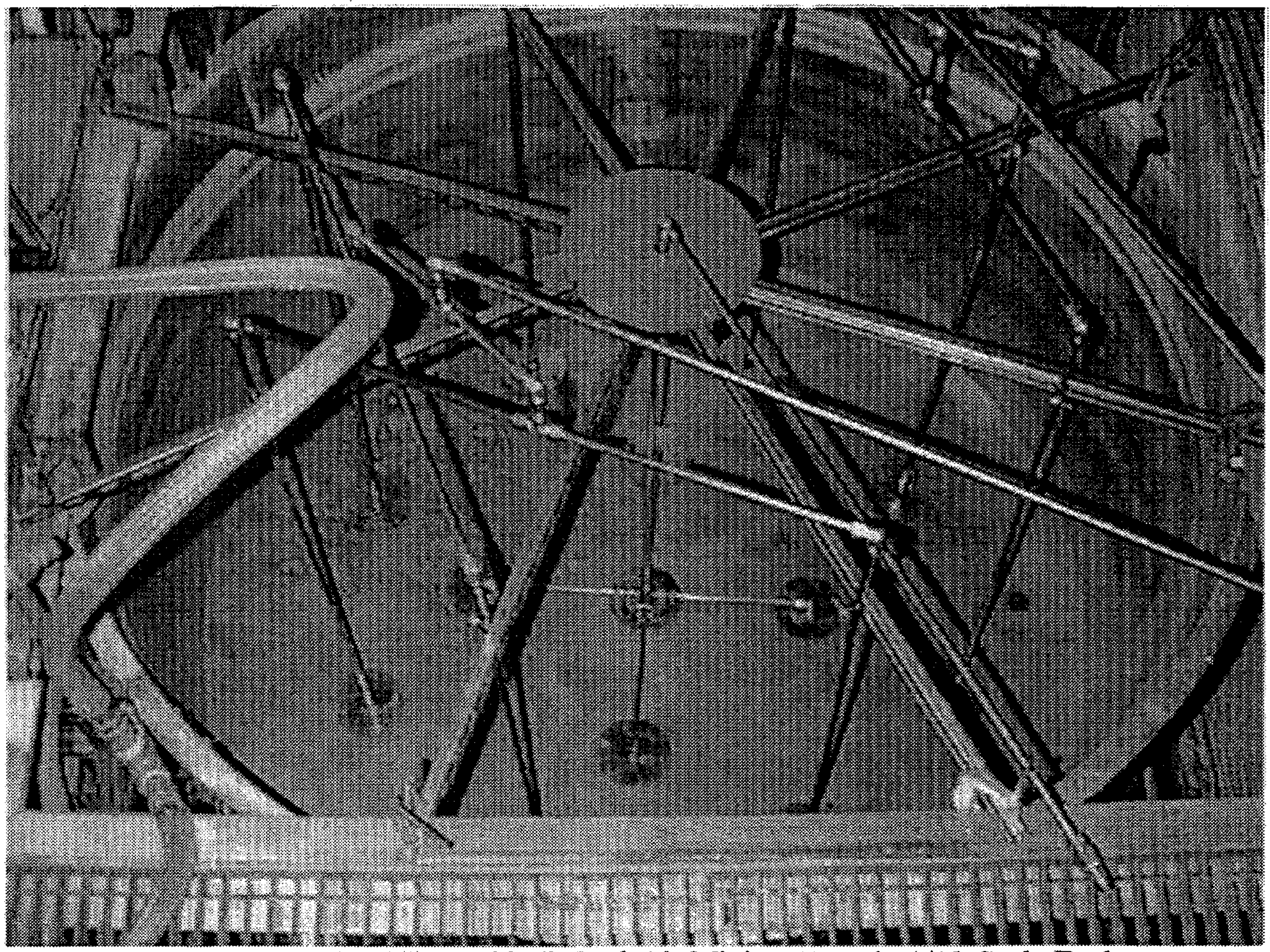

Figure 1.3. Fiscal Year 1995 Pulsed-Air Mixing Array in 1/12-Scale Tank

1.2.2 FY96 Correlation Development Testing

The goal of this series of tests was to determine the fluid velocities produced near the tank floor by pulsed-air accumulator plates. Knowledge of these velocities is needed to predict how effectively a pulsed-air mixer will mobilize settled solids from the tank floor.

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.

This testing revealed that the fluid velocities produced by the rapidly expanding gas bubble near the tank floor are sufficient to stir up cohesive tank sludge, but only out to a limited distance from the plate. 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}), which is shown in Figure 1.1. The bubble pulse radius was successfully correlated with accumulator plate diameter, gas pressure, and gas line diameter. The bubble pulse radius correlation is:

$$R_{pulse} = 0.8\, D_{plate}^{0.31}\, \Delta P^{0.39}\, D_{pipe}^{0.51} \qquad (1.1)$$

where R_{pulse} = predicted bubble pulse radius, cm
D_{plate} = accumulator plate diameter, cm
ΔP = compressed air pressure minus static head pressure, kPa
D_{pipe} = inside diameter of compressed air pipe, cm

The data and procedure used to develop this correlation are provided in Appendix A of this report. Note that Equation 1.1 applies only when the plate standoff distance is larger than the minimum acceptable value, which is a function of the plate design and pipe diameter as described in Appendix A. Data that can be used to estimate air consumption rates are also provided in Appendix A.

Equation 1.1 is used to design pulsed-air mixers for sludge mobilization applications or where little or no solids settling can be tolerated. The accumulator plates and air line sizes are sized to meet the tank access constraints (e.g., riser sizes and locations) and gas pressure is set by the capacity of the available air supply balanced against any tank damage concerns in fragile tanks (e.g., ORNL Tank W-9). Establishing these mixer design parameters determines the magnitude of R_{pulse}, which is estimated using Equation 1.1. The required number and location of accumulator plates is determined. To ensure sludge mobilization and prevent particle settling, the plates are must be spaced roughly $2R_{pulse}$ apart.

1.2.3 FY96 1/4-Scale Tank with Full-Scale Accumulator Plates

The fluid velocity versus mixer design correlations described in Section 1.2.2 were used to design a pulsed-air mixer using full-scale accumulator plates. This mixer was tested in a 1/4-scale (5.7-m, 18.75-ft diameter) 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 solely on the fluid velocity correlations. Resuspension of the settled solids following a mixer outage was also demonstrated.

The key finding of these 1/4-scale tests was that the slurry mixing performance of the pulsed-air mixer was better than expected. Slurry mixing applications where the goal is to maintain solids in suspension can be addressed by far fewer plates than are needed to mobilize cohesive sludge. A single, centrally located accumulator plate in the 1/4-scale tank maintained approximately 80 wt% of the solids in suspension, demonstrating that the large-scale circulation patterns induced in the slurry by the rising bubbles can effectively maintain solids in suspension.

1.2.4 FY97 ORNL Rectangular Tank Sludge Simulant Mixing

In December of 1996, a single pulsed-air accumulator plate was installed in a rectangular, open-topped, simulant holding tank at ORNL. The tank contained about 18 m^3 (4800 gal.) of tank waste simulant being used for confined sluicing end-effector (CSEE) retrieval testing as part of the Oak Ridge EM-40 Gunite and Associated Tanks (GAAT) remediation project. This waste simulant was prepared from kaolin clay, sand, gravel, and water. This test served two purposes. First, the GAAT retrieval testing required that the settled waste simulant be remixed and pumped back to the retrieval testbed so that CSEE testing could continue. Second, because pulsed-air mixing was being considered for use in the gunite waste receiver tank (W-9), it was useful to provide a demonstration of pulsed-air mixing for the engineers working on the gunite waste retrieval project.

A dual-plate pulsed-air mixer was used to resuspend and mix a 1.2-m (4-ft) deep layer of waste simulant that had settled in the 6m x 2.4m x 2.4m (20ft x 8ft x 8ft) rectangular tank at ORNL. As shown in Figure 1.4, the pulsed-air mixer consisted of two 36-cm (14-in.) diameter steel plates separated by about 0.64 cm (0.25 in.). The mixer was designed so that pulses of compressed air could be delivered either between the plates or to the underside of the lower plate. Air was first pulsed beneath the lower plate to allow the mixer to excavate its way down through the sludge to the tank bottom. Then air pulses were applied between the plates. The large rising air bubbles effectively mixed roughly one-third of the settled sludge even though the mixer was only operated in one region of the tank (roughly 1.5 m from one end of the tank, see Figure 1.5). It is expected that adding two or three more accumulator plates to this tank would effectively resuspend and homogenize all the settled waste simulant.

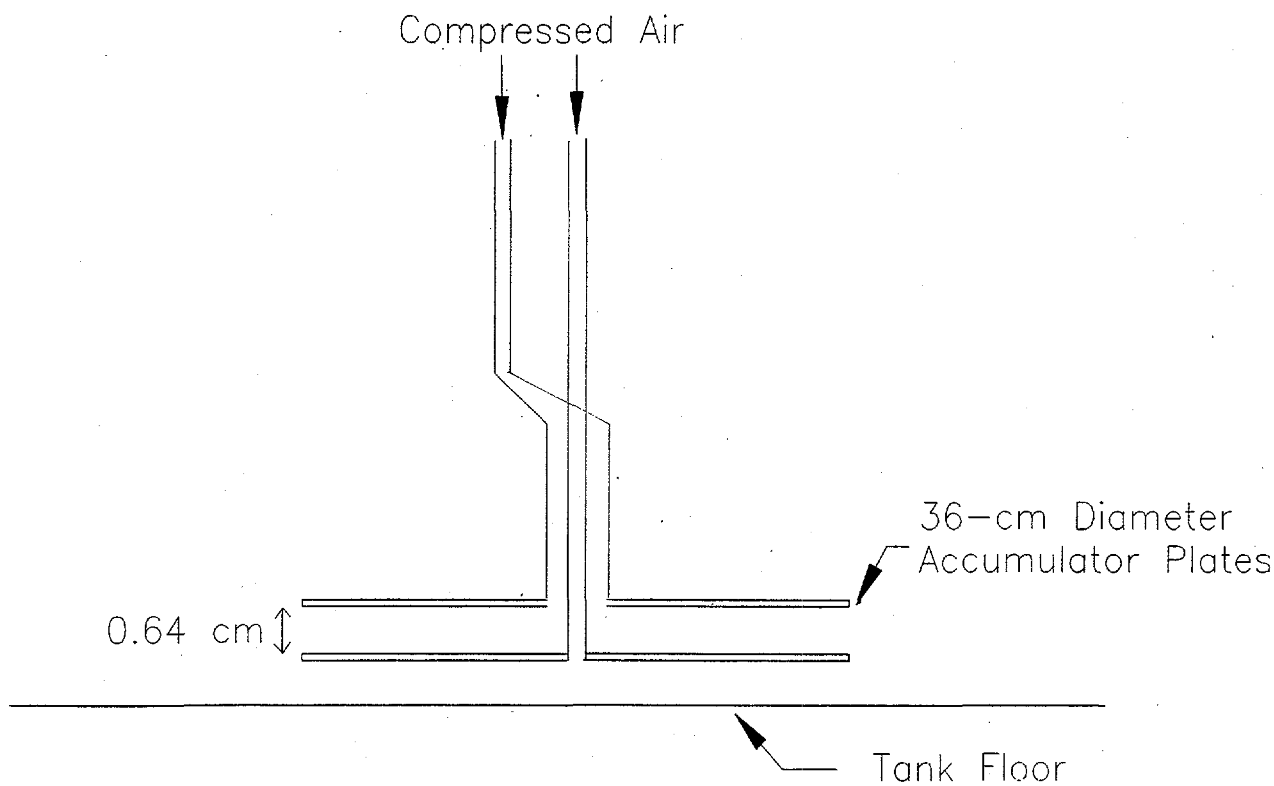

Figure 1.4. Sketch of Double-Plate Mixer used in ORNL Simulant Tank

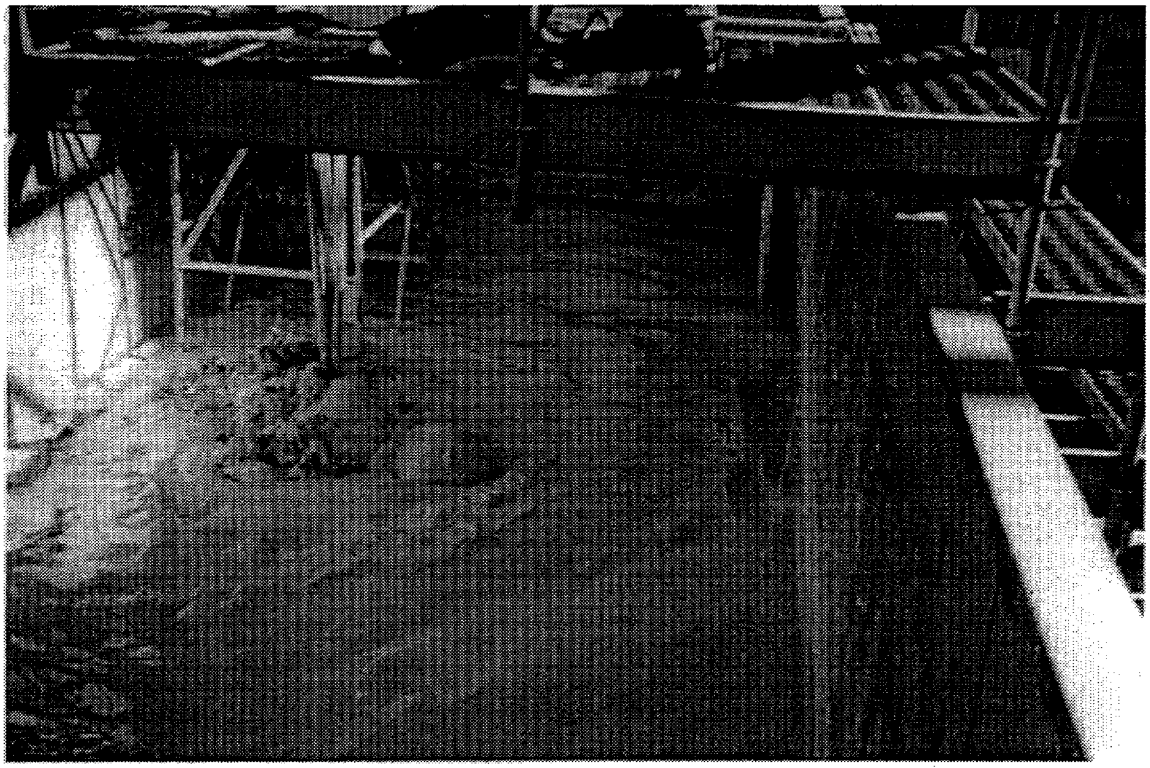

Figure 1.5. Pulsed-Air Mixing Action in ORNL GAAT Simulant Tank (accumulator plate is located roughly 1.5 m from the far end of the tank and 1 m from the tank wall on the left side of the photo).

This pulsed-air mixer was mounted such that it could be positioned anywhere inside the rectangular tank. Moving the plate to various locations within the tank, the majority of the settled solids were resuspended and transferred back to the GAAT retrieval testbed. Since the initial mixer demonstration in December, the pulsed-air mixer has been used periodically to resuspend and mix the simulant as needed to support GAAT retrieval project testing. The mixer has suffered no operational breakdowns during this time.[a]

This mixer demonstration was witnessed by key staff on the GAAT remediation project, who subsequently indicated a strong interest in using a pulsed-air mixer for slurry suspension in ORNL Tank W-9.

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[a]During the initial mixer demonstration in December 1996, the air line leading to the underside of the bottom plate became plugged with gravel. This problem was quickly remedied by enlarging the hole in the plate so that it was of the same diameter as the air line leading to the plate.

2.0 Conclusions and Recommendations

Pulsed-air mixing is expected to be applicable to a variety of mixing challenges at the DOE waste sites. Because of the financial and operational advantages of pulsed-air mixers compared to other mixing approaches, pulsed-air mixing should be considered for use wherever it can be shown that adequate mixing will be achieved. Several specific applications for pulsed-air mixing are identified and described in detail in Section 3.0. These include:

- Mixing in ORNL Tank W-9, which is the waste receiver tank for the gunite tank waste retrieval project. Mixer design for this application is underway.

- Mobilization and mixing of sludge waste in selected INEEL V-tanks. A mixer deployment concept for the V-tanks has already been developed.

- Mixing of low solids content salt liquors for the Hanford AP farm low-level waste vendor feed tanks. A scaleup analysis is underway to allow the prediction of expected mixing times for this application. Preliminary results indicate mixing times will be sufficiently short.

- Any new processing or storage tanks to be built. Installation of pulsed-air mixers during tank construction is inexpensive, and a sufficient number of accumulator plates to ensure adequate mixing can be easily installed.

- Mixing of grout with waste heels for tank closure. Although this application of pulsed-air mixing has not yet been demonstrated, it is expected to be effective provided that the tank geometry is favorable (e.g., horizontal storage tanks). It is recommended that some proof-of-principle tests be conducted to determine whether pulsed-air grout mixing should be pursued.

In general, pulsed-air mixing can be applied to those mixing applications where it is not required that stiff, cohesive sludge be mobilized or that large particles be maintained in suspension. In some instances, however, pulsed-air mixing can be used for sludge mobilization and mixing of large particles, but it is necessary that the tank geometry be favorable. A favorable tank geometry is one that allows the development of large-scale fluid circulation patterns; and that has sloping tank walls, which direct sludge and settling particles into the effective reach of the accumulator plates. Horizontal cylindrical tanks (e.g., INEEL V-Tanks, ORNL Melton Valley Storage Tanks, and ORNL Bethel Valley evaporator service tanks) have favorable geometries for pulsed-air mixing. Cone-bottomed tanks are also easily mixed by pulsed-air mixers. Unfavorable tank designs are typically large-diameter flat-bottomed tanks such as the Hanford double-shell and single-shell tanks. Pulsed-air mixers can still be employed in these unfavorable tank geometries, but the mixing is less efficient and more particle settling may result.

Figure 2.1 was developed to assist potential users in assessing whether pulsed-air mixing can be applied to a given waste mixing problem. This same logic was used to develop the list of recommended pulsed-air mixer applications given at the beginning of this section. Figure 2.1 is not intended to address all possible applications of pulsed-air mixing, just those typical of the mixing challenges in the DOE waste tanks.

Several of the decision points in the logic diagram require that decisions be made based on waste property measurements or on the desired mixer performance. For example, if the sludge shear strength is less than 50 Pa, the mixer is designed according to the "Slurry Maintenance" pathway instead of the "Sludge Resuspension" pathway. The specific values used for these decision points in Figure 2.1 are approximate. If the sludge shear strength is, for example, 60 Pa, a successful mixer design might result from following the Slurry Maintenance path instead of the Sludge Resuspension path. The approximate nature of these decision criteria should be considered when using Figure 2.1.

Values for the numeric decision criteria were selected based on a combination of literature data and previous mixer system testing. Sludge with a shear strength of less than about 50 Pa tends to flow under its own weight. Mobilization this kind of sludge, therefore, does not require that the plates be spaced close enough to ensure overlap of bubble pulse radii. As discussed in Section 1.2.2, the bubble pulse radius (R_{pulse}) was correlated with mixer design and operation parameters as part of the fiscal year 1996 testing (see Appendix A). Equation 1.1 is used to estimate the magnitude of R_{pulse} for any given mixer design.

Another decision point in Figure 2.1 indicates that the "Liquid Mixing" design is used when the solids settling rate is less than about 1 cm/h. This slow settling rate is characteristic of very small (typically submicron) particles or of particles suspended in either a very dense or very viscous liquid. The large-scale fluid circulation patterns established in the tank by the pulsed-air mixer yield fluid velocities near the tank floor that are significantly faster than 1 cm/h.

When more than 90% of the waste solids must be maintained in suspension and the particle settling rate is greater than about 1 cm/h, a more robust design approach is required. As shown in Figure 2.1, this situation is handled by using a design approach similar to the Sludge Resuspension approach. The less-than-10%-allowable-settling criterion is approximate and was selected based on the pulsed-air mixer performance observed during the 1/4-scale tank tests (see Section 1.2.3).

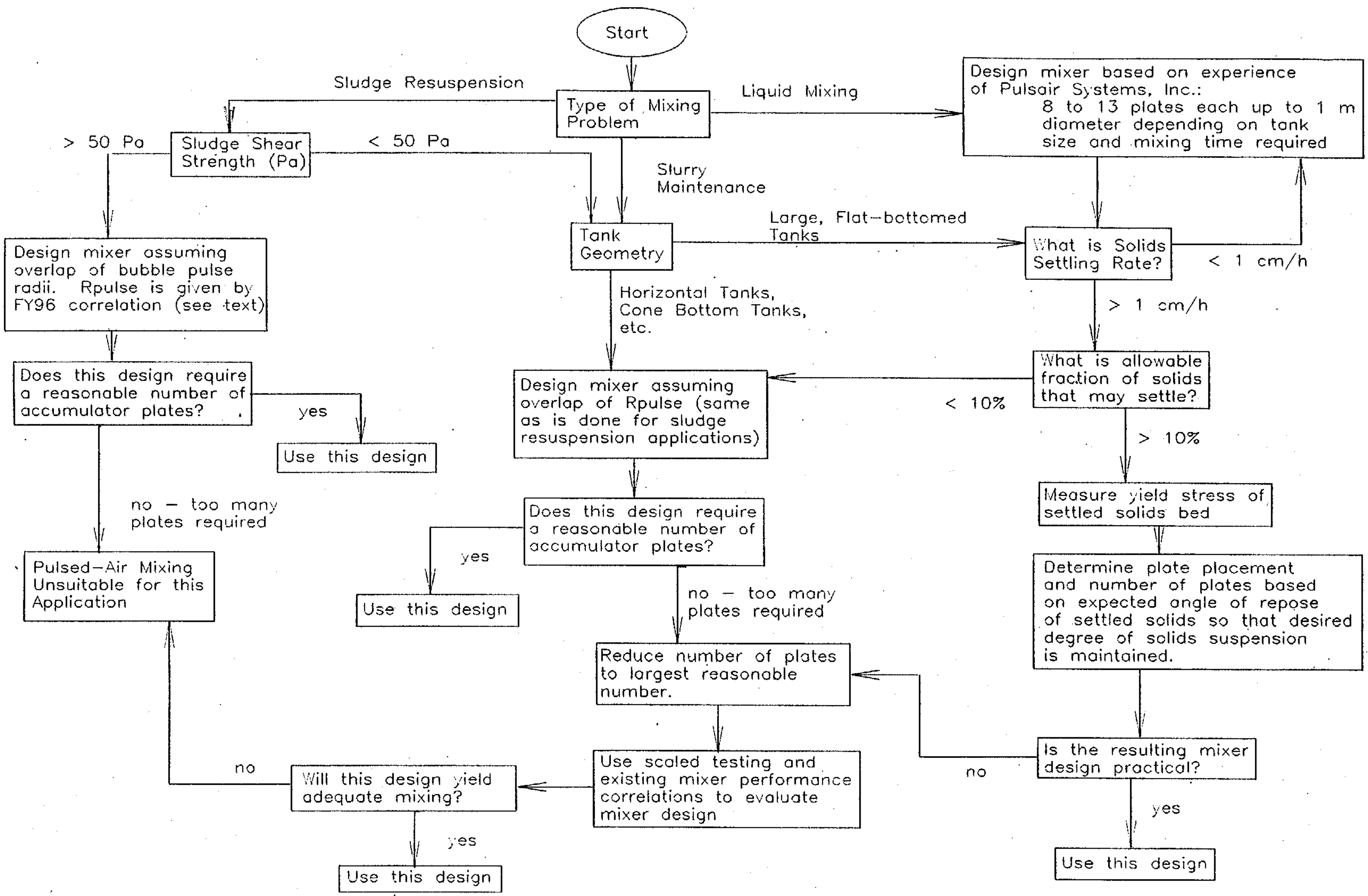


Figure 2.1. Pulsed-Air Mixer Applicability Assessment Flow Diagram

3.0 Applicability of Pulsed-Air Mixing to DOE Mixing Challenges

Testing of pulsed-air mixers at PNNL and the proven mixer performance in industrial mixing applications imply that pulsed-air mixing can be used to address some of the DOE mixing challenges. The advantages of pulsed-air mixing (e.g., low cost and high reliability) are attractive enough that it should be used wherever it can be shown that adequate mixing will be obtained.

Despite the encouraging test results for pulsed-air mixing, it is clear that there are applications where pulsed-air mixing is not the right choice. For example, the mobilization of stiff, cohesive sludge in large-diameter, flat-bottomed tanks is not well-suited for pulsed-air mixing. The effective range of each accumulator plate for the mobilization of strong sludge is small, so a very large number of accumulator plates would be required for such an application.

Some of the slurry mixing challenges at the DOE waste sites are reviewed in this section, with the aim of performing a preliminary evaluation of whether pulsed-air mixing should be applied. The decision logic shown in Figure 2.1 was used in this evaluation. In some cases, pulsed-air mixing can be recommended, based on existing test data. In other cases, it is clear that pulsed-air mixing should not be considered because mixing performance would be inadequate. Some mixing challenges remain, however, where it cannot yet be determined whether pulsed-air mixing would be adequate. In these cases, suggestions are made for further work to resolve the remaining issues.

The mixing challenges discussed in this section are categorized by site. Many DOE sites have similar mixing problems, so even though the following discussions focus on specific tanks at specific sites, the conclusions and recommendations can be applied to similar mixing problems in other tanks at other sites.

3.1 Oak Ridge National Laboratory

Potential applications for pulsed-air mixing technology at the Oak Ridge National Laboratory are described below.

3.1.1 Gunite Receiver Tank W-9

As mentioned in Section 1.2.4, a pulsed-air mixing array is currently being considered for use in gunite Tank W-9 at ORNL. Tank W-9 will be used to receive the waste retrieved from the other gunite storage tanks. Waste will accumulate in Tank W-9 until waste transfers are made to the Melton Valley Storage Tanks (MVSTs). The pulsed-air mixer will be used to mobilize and mix some fraction of the accumulated waste, which will then be pumped through a pipeline to the MVSTs.

Along with Pulsair Systems, Inc. and the University of Washington Applied Physics Laboratory (UW/APL), the Retrieval Process Development and Enhancements Project is currently designing a pulsed-air mixing system for use in ORNL tank W-9. This system must be deployed through the existing tank risers. There will be a total of five large risers in Tank W-9, three of which may be used for deploying the pulsed-air mixer. Three of the risers are 0.6 m (2 ft) in diameter and the remaining two are 0.76 m (30-in.) in diameter. Only the 0.6-m diameter risers are to be used for pulsed-air mixer deployment.

The pulsed-air mixer design parameters (i.e., number and size of plates) have not yet been determined, but it is expected that multiple plates will be deployed in each of the three available risers. These plates will each be a 28 cm (11 in.) in diameter and will be affixed to a yet-to-be-designed deployment mechanism, which will distribute the plates inside the tank. A sketch of a pulsed-air mixer deployed in Tank W-9 through three tank risers is shown in Figure 3.1.

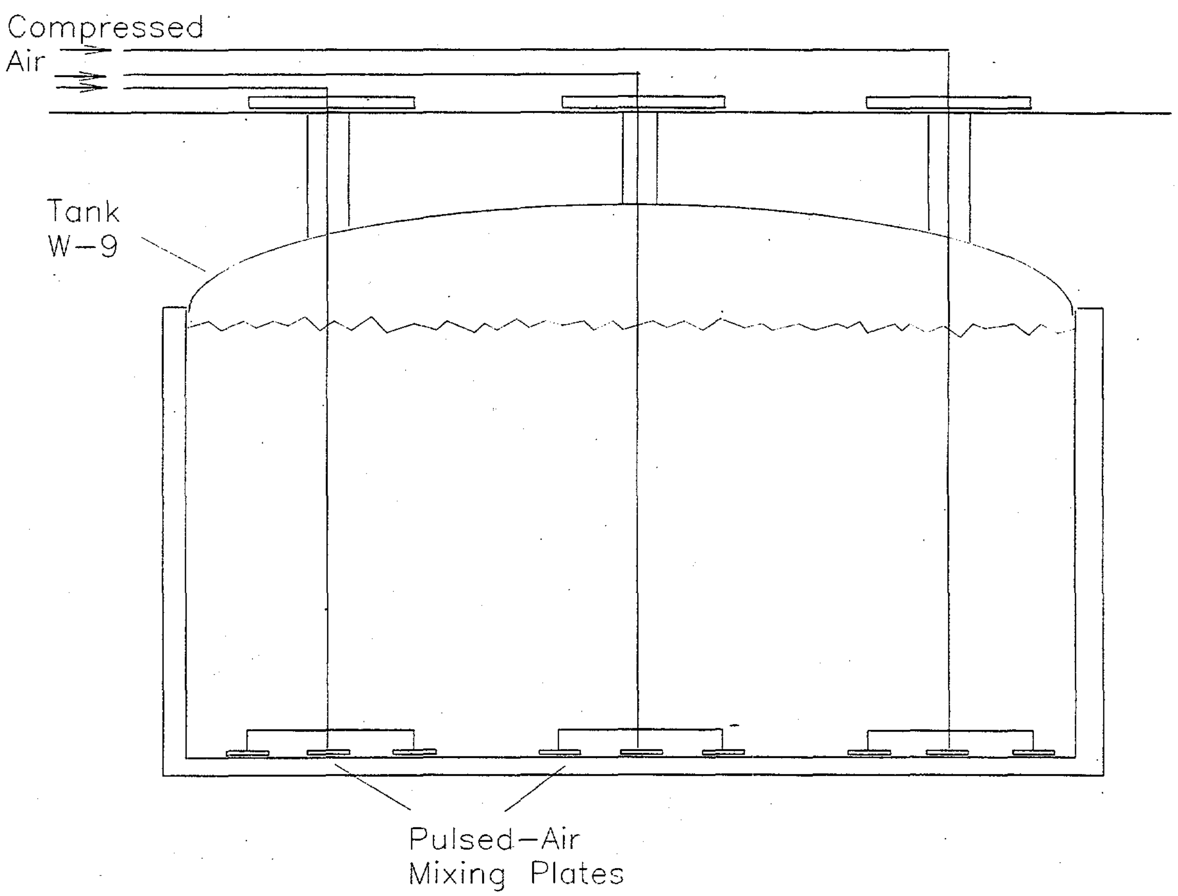


Figure 3.1. Sketch of Pulsed-Air Mixer Deployed in ORNL Tank W-9

ORNL personnel request that the mixer be designed to produce a slurry containing about 10 wt% solids for transfer. This slurry will be transported via pipeline to the MVSTs. It is not required that all of the solids in Tank W-9 be suspended. Some settling of particles is allowable and expected. The waste heel remaining in Tank W-9 after the last pulsed-air mixing and waste transfer cycle will be retrieved with the waste retrieval system that will be used for the other gunite tanks (i.e., CSEE and tracked vehicle). Therefore, the W-9 pulsed-air mixer will be designed for eventual removal from the tank.

The existing gunite tank waste characterization data, tank design drawings, and planned gunite tank waste retrieval and transfer procedures are being studied in an effort to develop a defensible pulsed-air mixer design for Tank W-9. Once the number, size, and location of the accumulator plates is established, work will begin on the design of a deployment system for the mixer.

Pulsed-air mixing is well suited for application in Tank W-9. The slurry formed in Tank W-9 will be relatively weak and easy to resuspend. Furthermore, the mixer is not required to mobilize and mix all the sludge. The mixer need mobilize only enough solids to meet the desired limit of 10 wt%.

3.1.2 Melton Valley Storage Tanks

Other mixing challenges at ORNL may be amenable to pulsed-air mixing. These include the retrieval of waste from and the closure of some of the horizontal storage tanks at ORNL (e.g., the Melton Valley Storage Tanks). The horizontal cylinder geometry of these tanks facilitates mixing by the pulsed-air approach. The pulsed-air plates will be distributed along the bottom of the tank, and spaced such that minimal solids settling occurs between the plates. The sloping sides of the tank direct any settled solids downward into the effective range of the accumulator plates.

The MVSTs have a single manway for access into the tank, along with multiple smaller (i.e., 10-cm diameter) openings. Deployment system concepts have been developed for placing pulsed-air mixers into similar horizontal storage tanks (see Section 3.2), and the mixer performance correlations predict that mixing will be satisfactory. It is recommended, therefore, that pulsed-air mixers be considered for use in the retrieval of waste from horizontal storage tanks at ORNL.

3.1.3 Grout Mixing for Closure

Some tank closure plans call for mixing any waste remaining inside the tanks with a grout mixture, which will solidify and trap the waste within its matrix. Mixing the waste heel with the grout slurry is not easily accomplished using conventional mixing technologies. Pulsed-air mixing, however, is expected to be capable of efficiently mixing the waste heel with grout. This concept has not yet been demonstrated, so it cannot be stated with certainty that pulsed-air mixing of grout will be successful. A proof-of-principle test using a scaled pulsed-air mixer in a scale model horizontal waste tank would reveal whether pulsed-air mixing is as effective for mixing grout as it is for mixing waste slurries.

Pulsed-air mixing is not likely to be applicable to the problem of retrieving cohesive sludge from the large-diameter, flat-bottomed tanks (i.e., the gunite tanks). It has been estimated that perhaps more than one hundred 0.9-m-diameter (3 ft) accumulator plates would need to be deployed inside the tank to ensure complete sludge mobilization (see calculations in Powell and Hymas, 1996). The deployment of such a large number of plates is not likely to be cost effective. For this reason, the use of pulsed-air mixing for the retrieval of waste from the gunite tanks at ORNL is not recommended at this time.

3.2 Idaho National Engineering and Environmental Laboratory

The potential applications for pulsed-air mixing technology at the Idaho National Engineering and Environmental Laboratory are described in this below.

3.2.1 V-Tanks Waste Retrieval

One of the most promising potential applications of pulsed-air mixing technology is the retrieval of waste from the INEEL V-tanks. The V-tanks are horizontal, cylindrical tanks roughly 6.7-m (22-ft) long and 3-m (10-ft) inside diameter. A schematic of Tank V-3 is shown in Figure 3.2.

As part of the fiscal year 1996 RPD&E pulsed-air mixing studies, a pulsed-air mixer deployment concept for Tank V-3 was developed by the University of Washington Applied Physics Laboratory (UW/APL), based on mixer design data provided by PNNL. The INEEL V-tanks contain a fluffy, flocculent sludge beneath a supernatant liquid layer. Based on the pulsed-air mixer correlation development testing (see Section 1.2.2) and on the descriptions of the Tank V-3 sludge, it was determined that four pulsed-air accumulator plates could mobilize and mix the V-3 waste.

UW/APL developed a deployment concept in which each of the four accumulator plates is individually installed through the 50-cm (20-in.) manway near one end of the tank. The procedure for mixer installation and operation is outlined in Powell and Hymas (1996). A schematic of the deployed mixer is shown in Figure 3.3 and a plan view is shown in Figure 3.4.

Pulsed-air mixing is recommended for the mobilization and mixing of INEEL V-tank waste. Testing with waste simulants implies that mixer performance will be adequate, and mixer deployment can be accomplished without undue difficulty. Aerosol generation and vibration issues remain to be addressed (see Section 4.0), but these are not expected to be difficult to resolve, based on preliminary analyses.

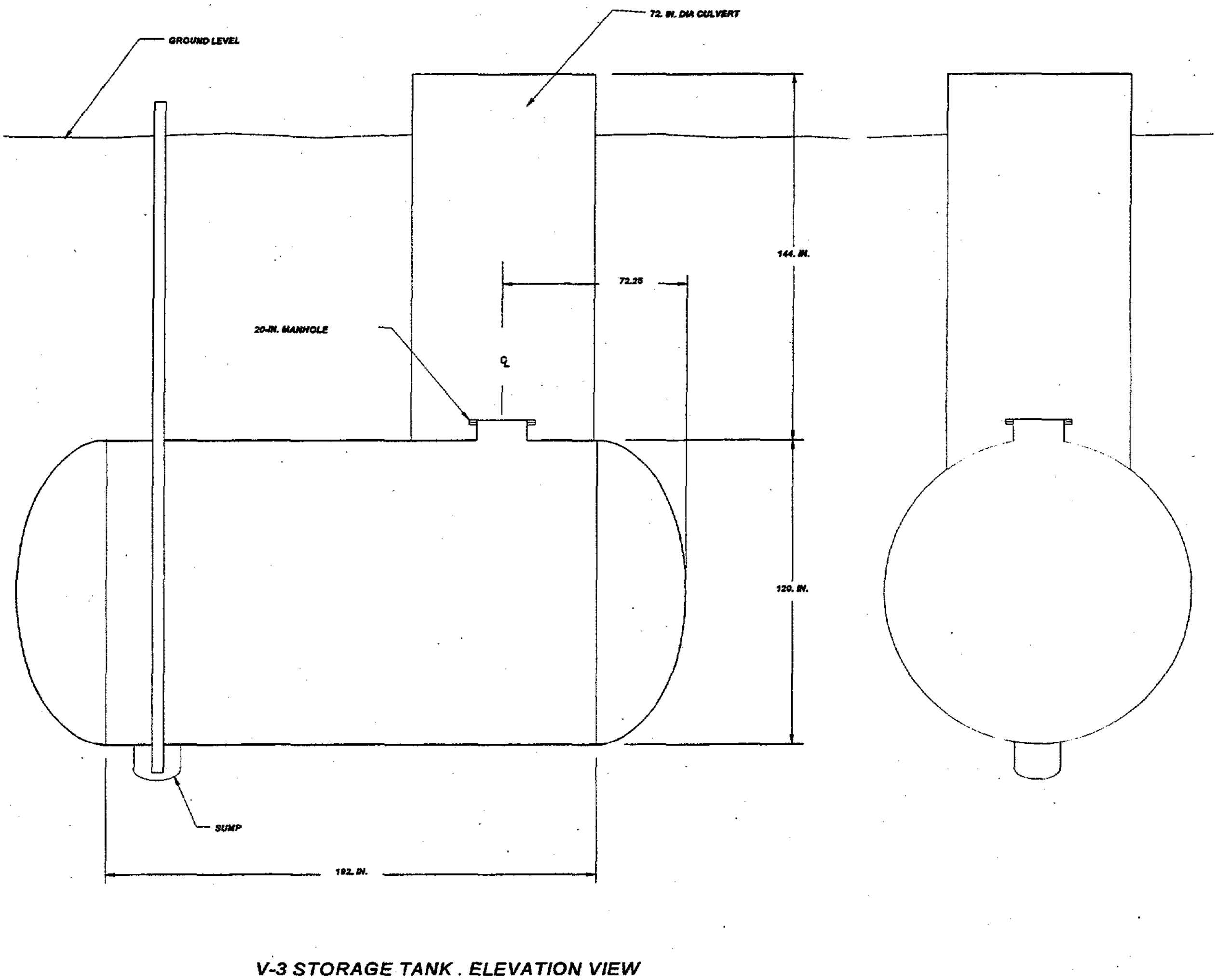


Figure 3.2. Sketch of INEEL Tank V-3

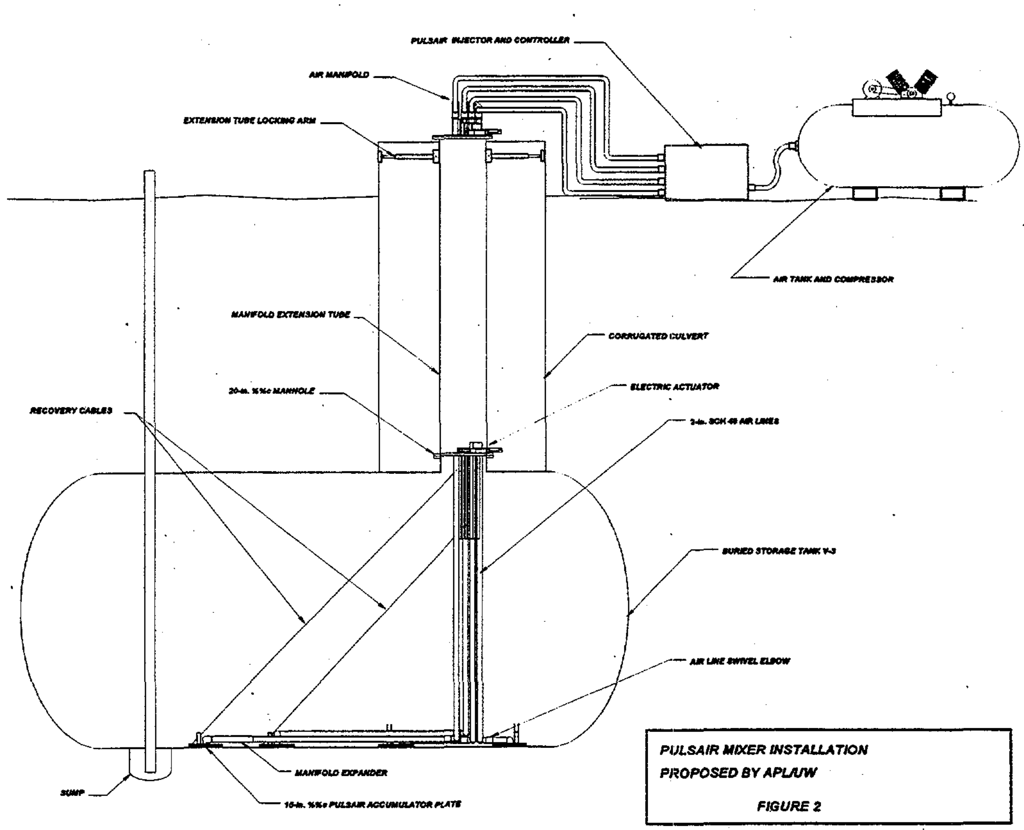
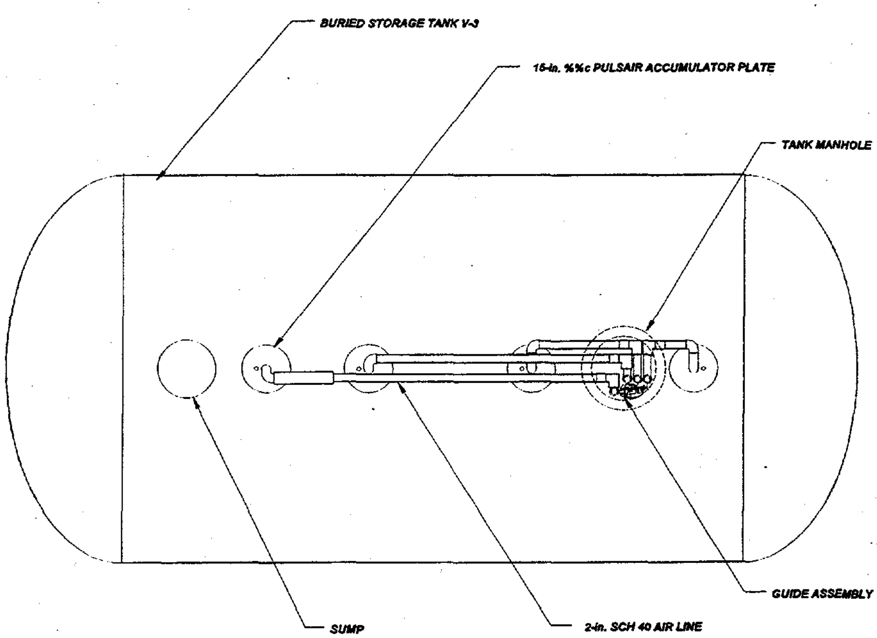


Figure 3.3. Installed Pulsed-Air Mixer in INEEL V-Tank



V-TANK, PLAN VIEW OF INSTALLATION

FIGURE 4

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

3.2.2 V-Tanks In-Situ Grouting

Another potential application of pulsed-air mixing at INEEL is in the closure of tanks via in-situ grouting. This application is identical to that described in Section 3.1 for the closure of ORNL tanks. Though mixing of grout with pulsed-air mixers has not yet been demonstrated, the tank geometry and grout slurry rheology are favorable, so mixer performance is expected to be adequate. Some small-scale proof-of-principle testing could be done to establish whether pulsed-air mixing should be considered for the in-tank mixing of grout with tank waste heels.

3.2.3 High-Level Liquid Waste Tanks

As discussed earlier, pulsed-air mixing does not appear to be a good choice for the mobilization of sludge in large-diameter, flat-bottomed tanks. Thus, pulsed-air mixing is not recommended for use in the 15.2-m (50-ft) diameter, 1135 m^3 (300 kgal) underground storage tanks at the INEEL Idaho Chemical Processing Plant tank farm. In addition to having an unfavorable tank geometry, these tanks are lined with banks of cooling coils near the tank walls. These cooling coils would adversely affect the performance of a pulsed-air mixer.

3.3 Hanford Site

The great majority of Hanford waste is contained within large-diameter, flat-bottomed tanks. Therefore, it is not likely that pulsed-air mixers are a feasible option for the mobilization and subsequent mixing of Hanford waste. However, there are several niche applications of pulsed-air mixing that should be considered at Hanford.

3.3.1 Low-Activity Waste Feed Tanks

The most promising of these potential applications at Hanford is the mixing of low-activity waste solutions in the AP tank farm. Some of the AP farm tanks will be used to supply the feed material to low-activity waste treatment/immobilization facilities.

Even though these tanks are 22.9-m (75-ft) diameter, flat-bottomed tanks, pulsed-air mixing is expected to be effective, because the waste properties are favorable. The low-level waste stream contains primarily salts dissolved in water, and only a small amount of particulate. Furthermore, any particles that are present will be very small and therefore will settle slowly. The waste will be added to the tank as a slurry, so it will not be necessary for the pulsed-air mixer to mobilize a layer of cohesive sludge.

A preliminary analysis indicates that two or three pulsed-air accumulator plates positioned in the center of the tank near the floor will provide adequate mixing. The waste must be mixed so that a uniform feed is supplied to the treatment/immobilization facility. Deployment of only a few accumulator plates can be accomplished through the central tank riser.

The fiscal year 1997 RPD&E pulsed-air mixing work includes an examination of the existing mixer performance data to allow the prediction of mixing times in the full-scale AP farm tanks, assuming that only a few pulsed-air accumulator plates will be used. A preliminary analysis predicted that a full-scale mixing time on the order of one hour should be obtained. A more thorough calculation of the expected mixer performance is on-going, but clearly, pulsed-air mixing shows considerable promise for AP farm mixing. The baseline mixing technology for these tanks is jet mixer pumps, which are considerably more expensive to procure and operate.

3.3.2 Hydrogen Mitigation

One possible application of pulsed-air mixing that has received relatively little attention is in waste tanks such as 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 accumulator plate in the center of the tank may be capable of maintaining the tank waste in a mixed condition, to prevent such 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, but because there are significant financial and operational advantages to using a pulsed-air mixer, these analyses should be conducted.

3.3.3 Single-Shell Tank Salt Removal

Another potential pulsed-air mixing application is in the facilitation of saltcake retrieval from single-shell tanks. In some of the non-leaking single-shell tanks, sluicing may be used to break up and dissolve the sludge and saltcake wastes. Pulsed-air accumulator plates could be used inside the tank to accelerate the dissolution of saltcake by providing nearly continuous fluid motion.

Finally, pulsed-air mixing should certainly be considered for use in any new waste holding or processing tanks. Installation of large numbers of accumulator plates (should they be required) is easy if it is done during tank construction.

3.4 Savannah River Site

Few specific potential applications for pulsed-air mixing have been identified at the Savannah River Site (SRS). For reasons already discussed, pulsed-air mixing is unlikely to be feasible for the mobilization and mixing of sludge in the large-diameter flat-bottomed tanks. As at the other sites, though, pulsed-air mixing should be considered for use in any waste processing or storage tanks that may be built in the future.

3.4.1 Alternative Salt Removal

Pulsed-air mixing may be of use in the enhancement of saltcake dissolution, as described earlier for the Hanford tanks. Pulsed-air accumulator plates could be used to speed up the dissolution of saltcake until enough waste is removed from the tank that jet mixer pumps can take over and finish the removal. Whether pulsed-air mixing is feasible for this application has yet to be evaluated.

3.5 Summary

The potential pulsed-air mixing applications discussed in Sections 3.1 through 3.4 are summarized in Table 3.1. Key points for each application are listed along with a judgement regarding the potential success of pulsed-air mixing.

Table 3.1. Pulsed-Air Mixing Assessment Summary

Application	Type of Problem	Pros/Cons	Pulsed-Air Applicability
ORNL Tank W-9	Maintenance of slurry suspension	P: complete suspension not required. C: large diameter, flat bottomed tank.	likely
ORNL MVSTs	sludge mobilization and mixing	P: horizontal cylinder tank shape facilitates mixing	likely
ORNL grout mixing for tank closure	slurry mixing	P: pulsed-air mixing effective for viscous slurries C: number of plates required for adequate mixing may be high because of tank is large diameter w/flat bottom	unknown
INEEL V-Tanks	sludge mobilization and mixing	P: horizontal cylinder tank shape facilitates mixing P: deployment concept already developed	likely
INEEL high-level liquid waste tanks	sludge mobilization and mixing	C: large diameter, flat bottomed tank - number of plates required probably high C: cooling coils cover tank floor and sides	unlikely

Application	Type of Problem	Pros/Cons	Pulsed-Air Applicability
Hanford low-activity waste feed tanks	salt solution mixing (low solids conc.)	P: few plates required because solids settling not likely to be a problem P: considerable cost reduction compared to current baseline (mixer pumps)	likely
Hanford double-shell tanks	sludge mobilization and mixing	C: large diameter, flat bottomed tank - number of plates required too high	unlikely
Hanford tank hydrogen mitigation	sludge/slurry mixing	P: possibly just a few plates required for effective mitigation P: no spark source in tank C: untested application	unknown
Hanford single-shell tank salt removal	salt solution and slurry mixing	P: may improve efficiency of water-based recovery methods (e.g., sluicing). C: effectiveness unknown - untested application	unknown
SRS high activity waste tanks	sludge mobilization and mixing	C: large diameter, flat tanks - too many plates required.	unlikely
SRS alternative salt removal	salt solution and slurry mixing	P: may improve efficiency of water-based recovery methods C: effectiveness unknown - untested application	unknown

4.0 Remaining Issues and Uncertainties

Before any pulsed-air mixing is attempted in radioactive waste tanks, two key issues must be addressed. First, operation of the accumulator plates at high gas pressures can produce a significant shock wave. The concern is that the induced vibration may be of sufficient magnitude to damage tanks whose structural integrity is uncertain (e.g., the gunite tanks at ORNL). Pulsair Systems, Inc. has not noted any tendency toward tank damage while operating their pulsed-air mixers in commercial applications. If induced tank vibrations are determined to be a problem in any given application, the accumulator plates can be operated at lower pressures to decrease the intensity of the shock wave. Operation at the higher pressures would be used only 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 design changes in the pulsing valve and accumulator plate.

The second issue that must be addressed before implementation is aerosol generation. Figure 4.1 shows the surface agitation observed when operating the pulsed-air mixer at 550 kPa (80 psig) in the 1/4-scale tank (5.7-m diameter). Depending on the pulse rate and number of accumulator plates used, the aerosols 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.

Resolution of both the shock wave and aerosol issues is part of the on-going fiscal year 1997 RPD&E pulsed-air mixing study. Results of these studies will be published in a report later this fiscal year.

Before pulsed-air mixing can be recommended for use in the Hanford AP farm tanks for the mixing of low-activity waste treatment/immobilization feed, a scale-up analysis must be completed. This analysis will determine whether mixing is expected to be adequate in the full-scale tank. Preliminary analyses indicate that adequate mixing will be achieved. This scale-up analysis is also part of the fiscal year 1997 RPD&E work scope.

Finally, some proof-of-principle testing is needed to determine whether pulsed-air mixing should be used to mix grout slurry with the waste heels in horizontal storage tanks like those at INEEL and ORNL. Grout mixing in this tank geometry is problematic for conventional mixing approaches, but pulsed-air mixing should be well suited to this application. Proof-of-principle grout mixing studies are not currently part of the RPD&E work scope.

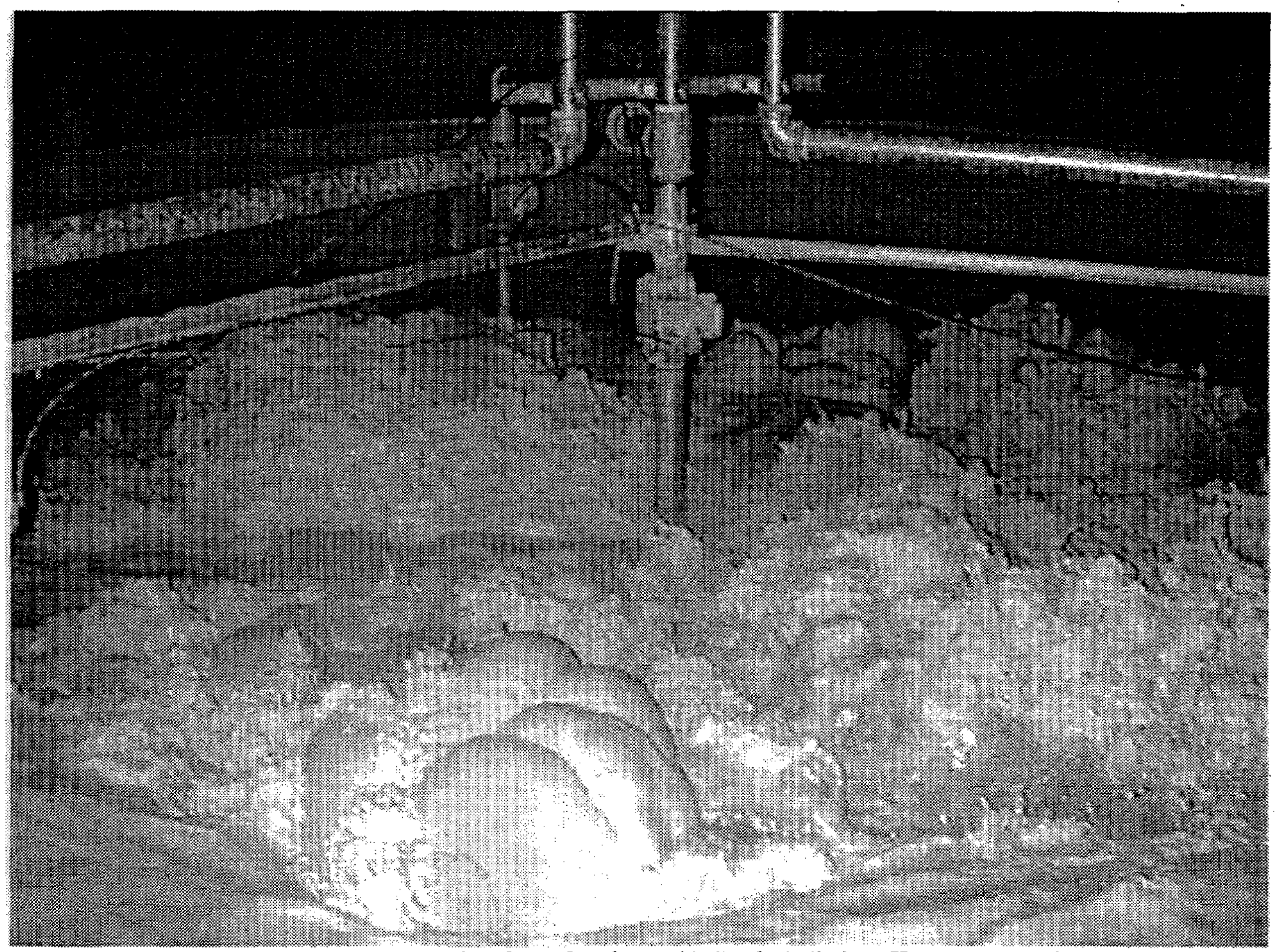


Figure 4.1. Slurry Surface During 1/4-Scale Mixing Test at 80 psig

5.0 References

Powell, M. R. and C. R. Hymas. 1996. *Retrieval Process Development and Enhancements FY96 Pulsed-Air Mixer Testing and Deployment Study.* PNNL-11200. Pacific Northwest National Laboratory, Richland, Washington.

Press, W. H., B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling. 1986. *Numerical Recipes.* Cambridge: Cambridge University Press.

Appendix A

Pulsed-Air Mixer Design Correlations

Appendix A: Pulsed-Air Mixer Design Correlations

As part of the fiscal year 1996 pulsed-air mixer testing, the bubble pulse radii produced by various combinations of plate diameter, compressed air pressure, and compressed air pipe diameter were measured. For the purpose of designing pulsed-air mixers, these data were correlated to allow the prediction of bubble pulse radius (R_{pulse}). The usefulness of the bubble pulse radius data is addressed in Section 1.2.2.

The pulse radius data gathered in fiscal year 1996 were used to develop a correlation between R_{pulse}, and plate diameter (D_{plate}), pressure differential (ΔP), and air pipe diameter (D_{pipe}). Plate standoff distance (h) was also varied as part of the 1996 testing, but it was determined that R_{pulse} was insensitive to standoff distance up to the largest h tested (2.5 cm) provided that the standoff distance was larger than a minimum value (h_{min}) as given by the equation:

$$h_{\min} = \frac{D_{pipe}^{2}}{4(D_{hole})} \qquad \text{(A.1)}$$

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 usually approximately equal to the outside diameter of the gas pipe, cm
h_{min} = minimum recommended standoff distance, cm

The R_{pulse} data where standoff distance was less than h_{min} were not included in the correlation described below. All the data that were included in the correlation are provided in Table A.1, which were fit to a correlation of the form:

$$R_{pulse} = K\,(D_{plate})^{a}\,(\Delta P)^{b}\,(D_{pipe})^{c} \qquad \text{(A.2)}$$

where K, a, b, and c are empirically determined constants. There is no particular reason to suppose that the relationship is of this form, but no theoretically based correlation form has yet been developed and the form of Equation A.2 is found to fit the data well. A Marquardt-Levenberg algorithm (Press et al. 1986) was used to perform the fit of the data and determine the values of the empirical constants. The least-squares fit yielded the following correlation:

$$R_{pulse} = 0.8\,D_{plate}^{0.31}\,\Delta P^{0.39}\,D_{pipe}^{0.51} \qquad \text{(A.3)}$$

where distances are measured in centimeters and pressure in kPa. A plot of predicted R_{pulse} vs. measured R_{pulse} values is given in Figure A.1. Equation A.3 is seen to fit the data well.

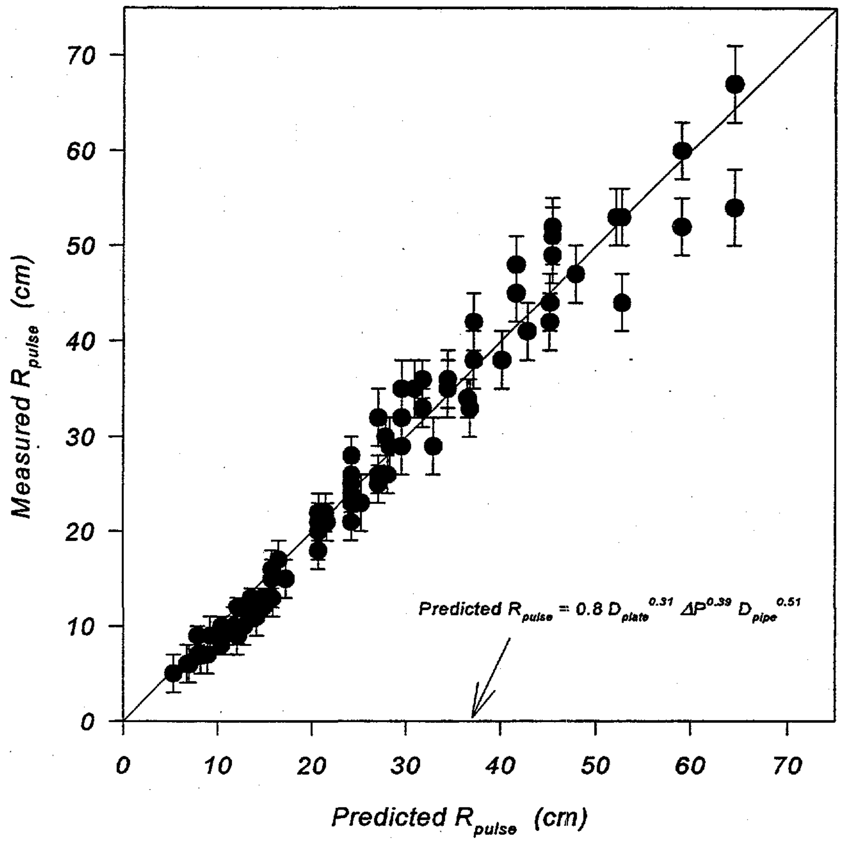


Figure A.1. Measured and Predicted R_{pulse} Values

There is some significant deviation between the correlation and the measured values for the larger R_{pulse} values. In some cases, Equation A.3 over predicts the bubble pulse radius. This may be an artifact of the experimental design, however, as the compressed air reservoir used in the testing was not large enough to ensure a maximum R_{pulse} for the largest accumulator plates.

The fiscal year 1996 testing also involved estimating the quantity of compressed air consumed each time a bubble was generated. The decrease in air pressure in the compressed air reservoirs during each pulse was used to estimate the air consumption rate. Figure A.2 shows the estimated air consumption per pulse in standard cubic feet of air (60 deg. F and 1 atm. pressure) as a function of R_{pulse}. For any given bubble pulse radius, there will be a range of air consumption rates that depend on how long the compressed air valve delivers air to the accumulator plate. In the fiscal year 1996 testing, the air injection times were set to be conservatively large to ensure that adequate air was available for maximum bubble growth. Consequently, the actual air consumption rate for a pulsed-air mixer will be somewhat lower than implied by Figure A.2. The data in Figure A.2 can, however, be used to establish a conservative upper limit for air consumption per pulse. The total air consumption rate will then vary linearly with the number of plates and with the gas pulsing rate, which is adjustable.

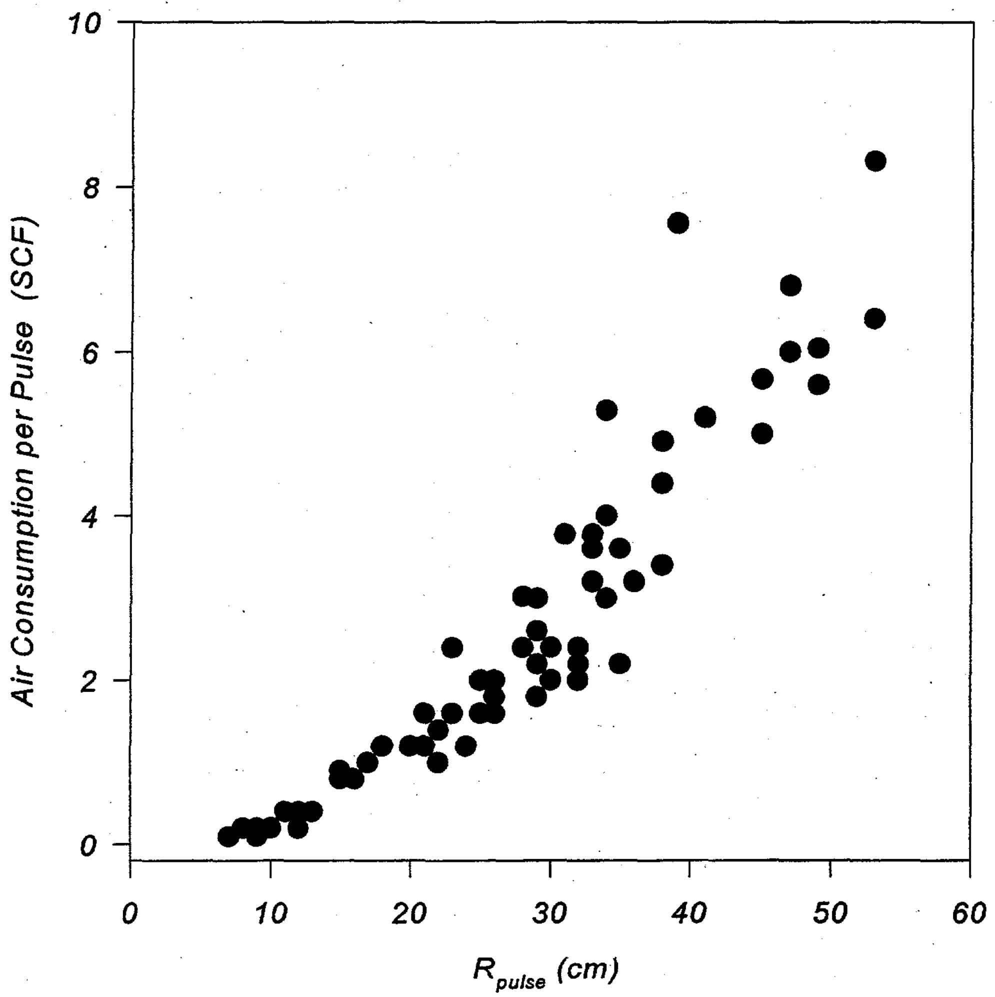


Figure A.2. Air Consumption per Bubble for Pulsed-Air Mixers

Table A.1. R_{pulse} Correlation Development Data					
D_{plate} (cm)	h (cm)	D_{pipe} (cm)	ΔP (kPa)	R_{pulse} (cm)	95% C.I. (±cm)
6.1	0.318	0.68326	137.8947	9	1
6.1	0.318	0.68326	275.7893	10	1
6.1	0.318	0.68326	413.684	12	1
6.1	0.318	0.68326	551.5787	13	1
6.1	0.318	0.68326	689.4733	13	1
6.1	0.635	0.68326	137.8947	7	1
6.1	0.635	0.68326	275.7893	8	1
6.1	0.635	0.68326	413.684	9	1
6.1	0.635	0.68326	551.5787	11	1
6.1	0.635	0.68326	689.4733	12	1
6.1	0.635	0.32	137.8947	5	2
6.1	0.635	0.32	275.7893	6	2
6.1	0.635	0.32	413.684	7	2
6.1	0.635	0.32	551.5787	9	2
6.1	0.635	0.32	689.4733	9	2
6.1	0.635	0.51	137.8947	6	2
6.1	0.635	0.51	275.7893	7	2
6.1	0.635	0.51	413.684	9	2
6.1	0.635	0.51	551.5787	10	2
6.1	0.635	0.51	689.4733	10	2
6.1	0.635	0.92	137.8947	9	2
6.1	0.635	0.92	275.7893	9	2
6.1	0.635	0.92	413.684	11	2
6.1	0.635	0.92	551.5787	13	2
6.1	0.635	0.92	689.4733	15	2
14.2	0.318	1.57988	137.8947	16	2
14.2	0.318	1.57988	275.7893	22	2
14.2	0.318	1.57988	413.684	24	2
14.2	0.318	1.57988	551.5787	26	2
14.2	0.318	1.57988	689.4733	29	3
14.2	0.635	1.57988	137.8947	15	2
14.2	0.635	1.57988	275.7893	21	2
14.2	0.635	1.57988	413.684	23	2
14.2	0.635	1.57988	551.5787	25	2
14.2	0.635	1.57988	689.4733	29	3
14.2	1.27	1.57988	137.8947	15	2
14.2	1.27	1.57988	275.7893	18	2
14.2	1.27	1.57988	413.684	21	2
14.2	1.27	1.57988	551.5787	26	2

Table A.1. R_{pulse} Correlation Development Data					
D_{plate} (cm)	h (cm)	D_{pipe} (cm)	ΔP (kPa)	R_{pulse} (cm)	95% C.I. (±cm)
14.2	1.27	1.57988	689.4733	32	3
14.2	2.54	1.57988	137.8947	15	3
14.2	2.54	1.57988	275.7893	20	3
14.2	2.54	1.57988	413.684	25	3
14.2	2.54	1.57988	551.5787	32	3
14.2	2.54	1.57988	689.4733	35	3
23.9	0.635	2.66446	137.8947	24	2
23.9	0.635	2.66446	275.7893	36	2
23.9	0.635	2.66446	413.684	42	3
23.9	0.635	2.66446	551.5787	48	3
23.9	0.635	2.66446	689.4733	51	3
23.9	1.27	2.66446	137.8947	28	2
23.9	1.27	2.66446	275.7893	33	2
23.9	1.27	2.66446	413.684	38	3
23.9	1.27	2.66446	551.5787	45	3
23.9	1.27	2.66446	689.4733	49	3
23.9	2.54	2.66446	137.8947	26	2
23.9	2.54	2.66446	275.7893	36	2
23.9	2.54	2.66446	413.684	42	3
23.9	2.54	2.66446	551.5787	48	3
23.9	2.54	2.66446	689.4733	52	3
23.9	1.27	1.25222	137.8947	17	2
23.9	1.27	1.25222	275.7893	21	2
23.9	1.27	1.25222	413.684	23	3
23.9	1.27	1.25222	551.5787	29	3
23.9	1.27	1.25222	689.4733	35	3
23.9	1.27	2.09296	137.8947	22	2
23.9	1.27	2.09296	275.7893	26	2
23.9	1.27	2.09296	413.684	29	3
23.9	1.27	2.09296	551.5787	33	3
23.9	1.27	2.09296	689.4733	38	3
23.9	1.27	3.5052	137.8947	30	2
23.9	1.27	3.5052	275.7893	34	2
23.9	1.27	3.5052	413.684	41	3
23.9	1.27	3.5052	551.5787	47	3
23.9	1.27	3.5052	689.4733	53	3
36.6	1.27	4.0894	137.8947	35	3
36.6	1.27	4.0894	275.7893	42	3
36.6	1.27	4.0894	413.684	44	3

Table A.1. R_{pulse} Correlation Development Data					
D_{plate} (cm)	h (cm)	D_{pipe} (cm)	ΔP (kPa)	R_{pulse} (cm)	95% C.I. (±cm)
36.6	1.27	4.0894	551.5787	52	3
36.6	1.27	4.0894	689.4733	54	4
36.6	2.54	4.0894	137.8947	36	3
36.6	2.54	4.0894	275.7893	44	3
36.6	2.54	4.0894	413.684	53	3
36.6	2.54	4.0894	551.5787	60	3
36.6	2.54	4.0894	689.4733	67	4

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