PRC-STP-00177 S
Revision 0

An Experimental Study of the Stability of Vessel-Spanning Bubbles in Cylindrical, Annular, Obround, and Conical Containers

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

Contractor for the U.S. Department of Energy
under Contract DE-AC06-08RL14788

CH2MHILL
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Revision 0

EDC #: PRC-EDC-10-44543

An Experimental Study of the Stability of Vessel-Spanning Bubbles in Cylindrical, Annular, Obround, and Conical Containers

Document Type: TR Program/Project: STP

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Date Published
January 2010

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P.O. Box 1600
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Printed in the United States of America

Total Pages: 80

1.0 Introduction

This report provides a summary of experiments that were performed by Fauske & Associates on the stability of vessel-spanning bubbles. The report by Fauske & Associates, *An Experimental Study of the Stability of Vessel-Spanning Bubbles in Cylindrical, Annular, Obround and Conical Containers*, is included in Appendix A. Results from the experiments confirm that the gravity yield parameter, Y_G, correctly includes container size and can be applied to full-scale containers to predict the possibility of the formation of a stable vessel spanning bubble. The results also indicate that a vessel spanning bubble will likely form inside the STSC for KE, KW, and Settler sludges if the shear strengths of these sludges exceed 1820, 2080, and 2120 Pa, respectively. A passive mechanism installed in the STSC is effective at disrupting a rising sludge plug and preventing the sludge from plugging the vent filter or being forced out of the container.

2.0 Background

The Sludge Treatment Project for Engineered Container and Settler Sludge (EC/ST) Disposition Subproject is being conducted in two phases. Phase 1 of the EC/ST Disposition Subproject will retrieve the radioactive sludge currently stored in the K West (KW) Basin into Sludge Transport and Storage Containers (STSCs) and transport the STSCs to T-Plant for interim storage. Phase 2 of the EC/ST Disposition Subproject will retrieve the sludge from interim storage, treat and package sludge for disposal at the Waste Isolation Pilot Plant. The STSC is a cylindrical container; similar to previously used large diameter containers. A STSC (Figure 1) with a diameter of 58 inches will be used to transport KE and KW originating sludge (located in Engineered Containers 210, 220, 240, 250, and 260) to T-Plant. A STSC with an annulus (Figure 2) will be used to transport Settler Tank sludge, located in Engineered Container 230.

An obround small canister design was previously considered to retrieve sludge from the basin. The obround design was selected in *Small Canister Design Selection*, PRC-STP-00052. However, the small canister was not selected for transporting the sludge. The STSC was selected for sludge loading and transport to T-Plant as discussed in *Decision Report for Direct Hydraulic Loading of Sludge into Sludge Transport and Storage Containers*, PRC-STP-00112. The STSC will be directly loaded with sludge as described in the *Preliminary STP Container and Settler Sludge Process System Description and Material Balance*, HNF-41051.

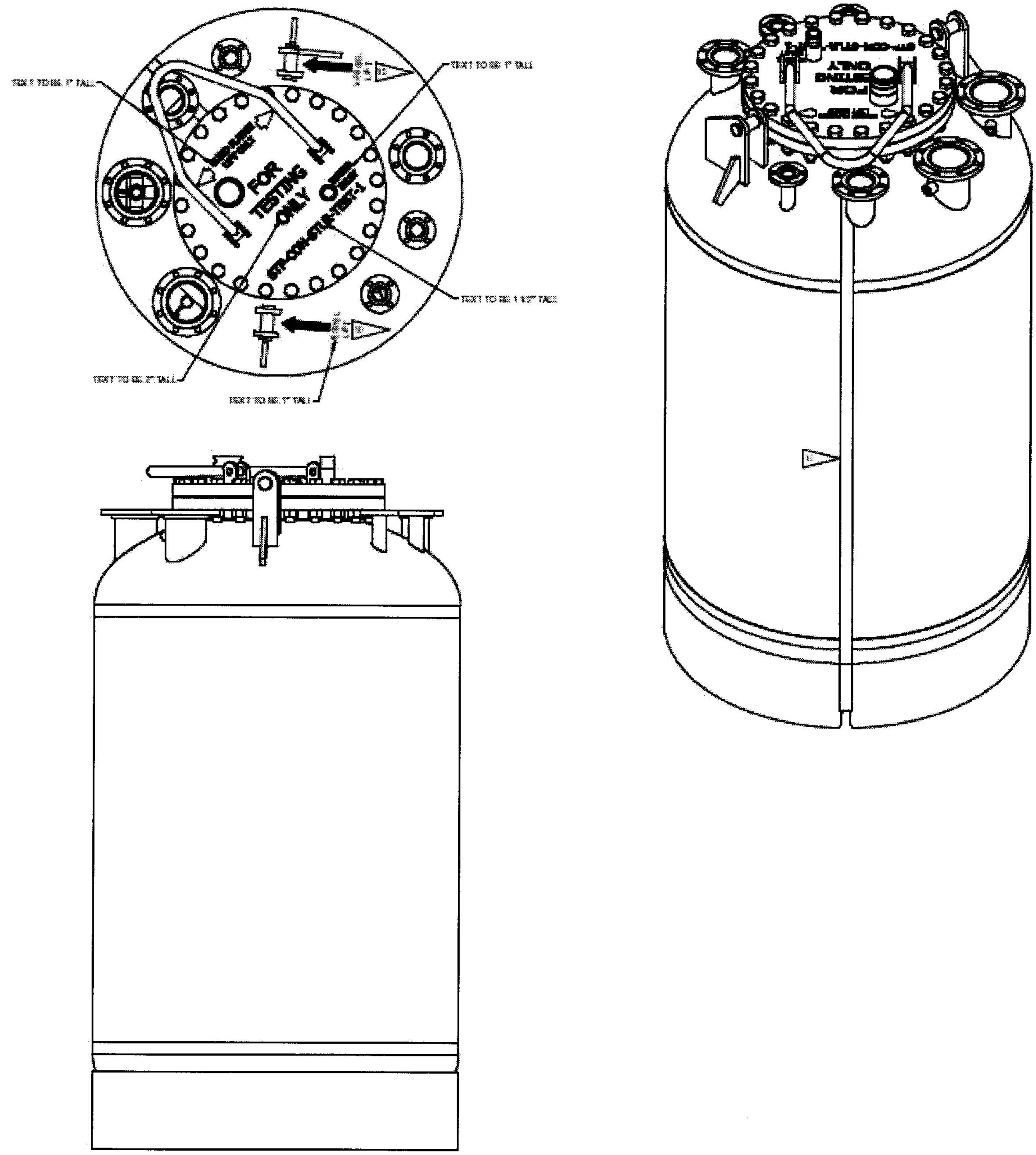

Figure 1 Sludge Transport and Storage Container (STSC)

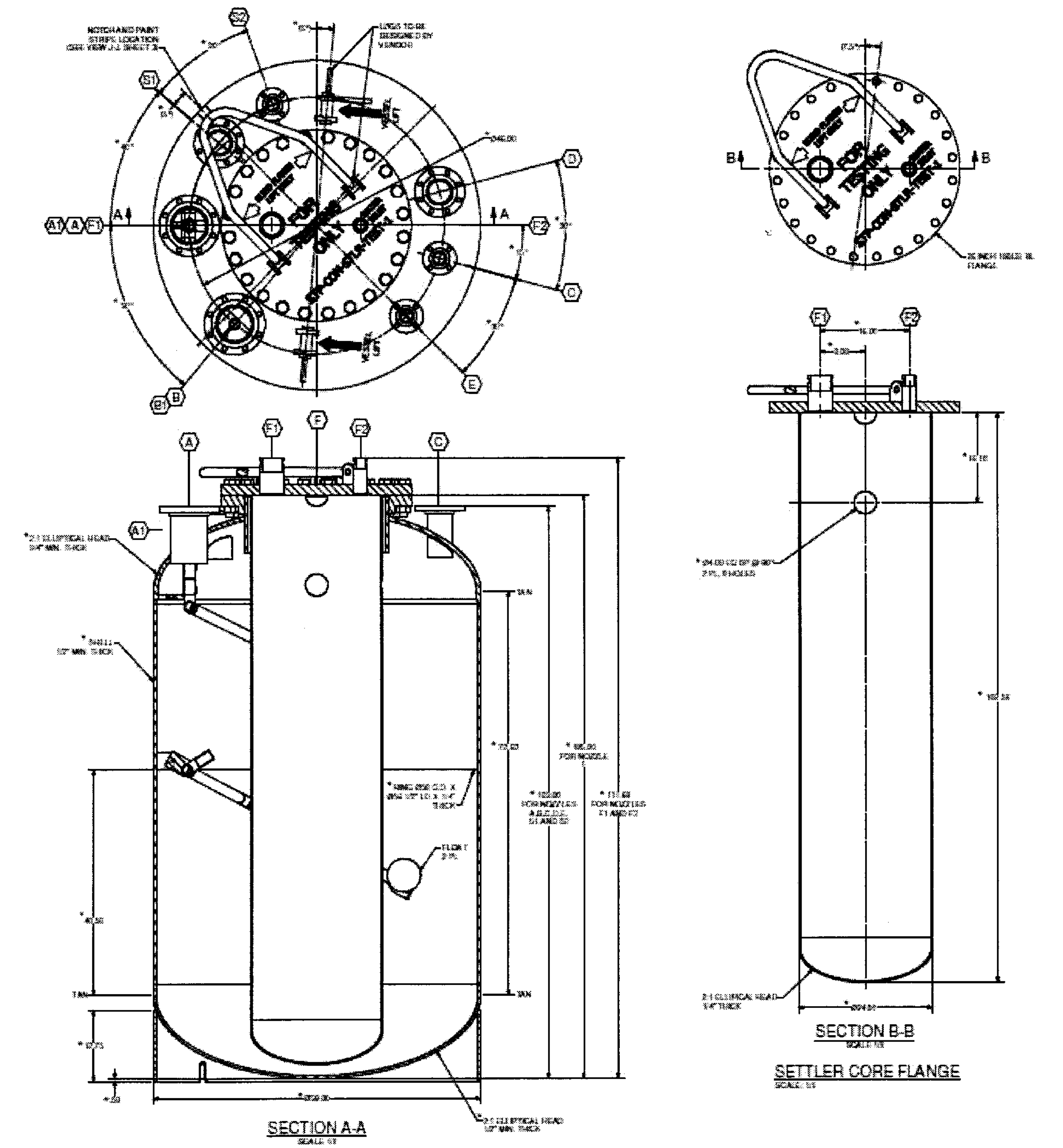

Figure 2 STSC with Annulus

3.0 Scope

The KW Basin sludge contains uranium metal particles that produce hydrogen gas due to oxidation with water. A vessel-spanning bubble may form inside a container if the sludge shear strength prohibits gas release. This vessel-spanning bubble may displace the sludge and overlying water. As the sludge layer rises it may plug the vent filter on a container or even expel the sludge from a container. Failure (collapse) of the sludge plug may occur due to Taylor instability. According to the Taylor instability theory a single dimensionless gravity-yield parameter Y_G defines the onset of a Taylor instability in the vessel-spanning composite and governs how the instability scales. The dimensionless gravity-yield parameter, Y_G, is defined below where τ_0 is the shear strength (Pa) of the sludge, ρ_{SL} is the density (kg/L) of the sludge, g is the gravitational constant (9.81 m/s^2), and D is the diameter (m) of the container.

$$\frac{\tau_0}{\rho_{sl} g D} \leq Y_G$$

The Fauske & Associates report, *An Experimental Study of the Stability of Vessel-Spanning Bubbles in Cylindrical, Annular, Obround and Conical Containers* (Appendix A), analyzes the stability of a sludge plug formed with relation to the sludge properties and diameter of a container.

The purpose of the work by Fauske & Associates was to (i) test the validity of the gravity yield parameter for predicting the breakup of vessel spanning bubbles in cylindrical, annular and obround containers and (ii) evaluate the performance of specific container-design features in terms of their ability to disrupt an otherwise stable vessel spanning bubble/sludge layer composite or to prevent the formation of a vessel spanning bubble.

4.0 Experiment Summary

The experiments in the Fauske & Associates report analyzed the stability of a sludge plug formed inside cylindrical STSCs, annular STSCs, obround canisters, and small scale vessels using an EPK Kaolin clay and water mixture. Different shear strengths of EPK Kaolin material were used as the simulant for the small scale and scaled container model experiments to observe the stability of the sludge plug. The shear strengths of the simulants were used in the gravity yield parameter relationship to determine the validity of the relationship in predicting the breakup of a vessel spanning bubble.

In these scaled container model experiments, an EPK Kaolin simulant mixture was placed inside the container with a porous plate bottom. The simulant sludge plug was forced upward by opening an air valve and injecting air through the porous plate at the bottom of the container, as shown in Figure 3. A vessel spanning bubble was established when the gas pressure was sufficient to overcome the weight of the sludge plug. The sludge plug was stable if it remained intact while rising in the test vessel. Failure of the sludge plug resulted in a complete collapse of the sludge column to the bottom of the container. The appearance of another vessel spanning bubble was not observed in any experiments with a failed sludge plug.

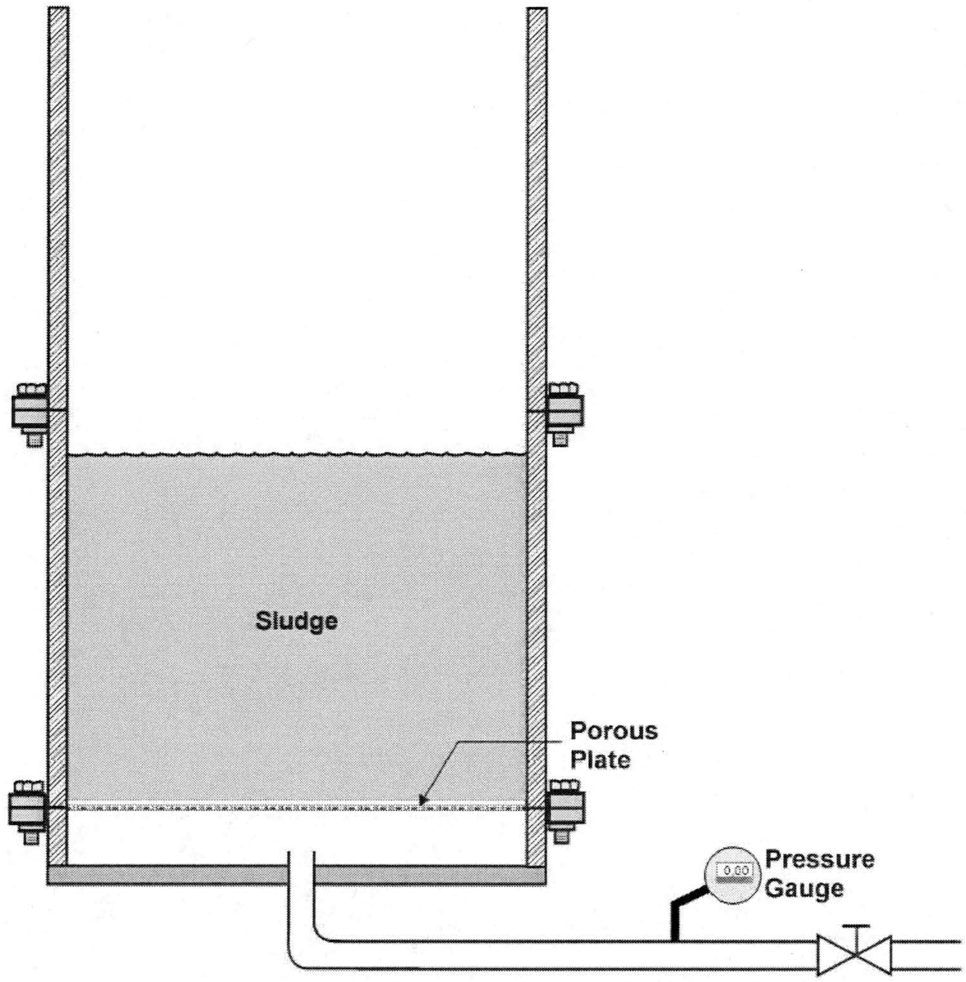

Figure 3 Illustration of Scaled Container Model Experiment Set-up

The small-scale experiments were performed by inverting beakers (vessel turnover) and observing the EPK Kaolin simulant. The small-scale tests were conducted to replicate the scaled container model tests using a simpler system. The small-scale tests use fewer materials than the scaled container model tests and were completed in a shorter time frame. Figure 4 shows the classification of the simulant based on behavior during the vessel turnover experiment.

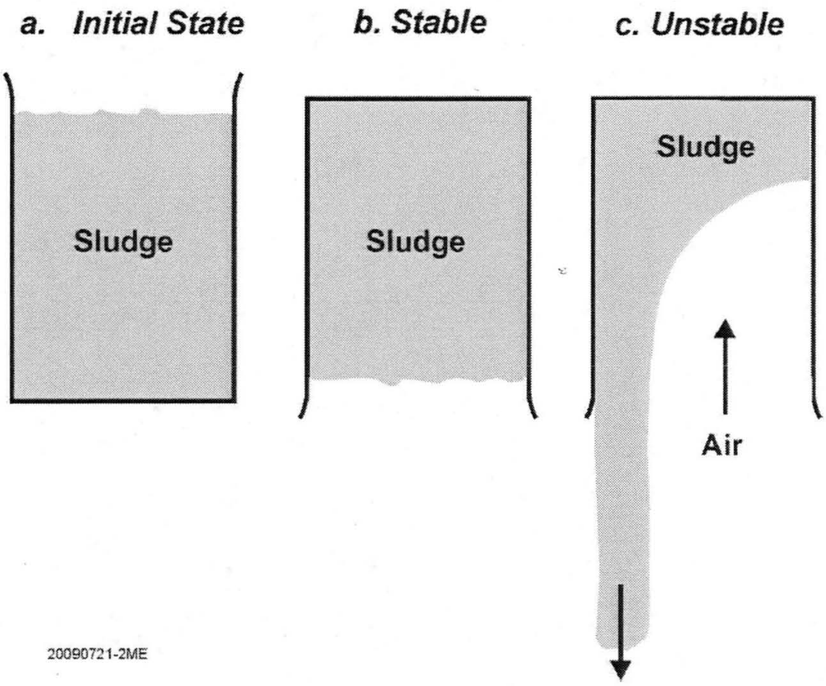

Figure 4 Illustration of stable and unstable results during vessel turnover experiments

If only a small amount of sludge drained out of the vessel in the small-scale tests, the system was classified as "marginally unstable." The small scale experiments were performed to prove the dimensionless gravity-yield parameter is scale independent. Turnover experiments were also conducted in small-scale cylindrical vessels to confirm the previous unpublished turnover experiments in cylindrical geometry (Gauglitz, 2002) and to provide a direct comparison to the annular turnover experiments with identical simulants.

Apart from the difference in the container sizes used, the major difference between the small scale and scaled container model experiments was time for the experiment. In the small scale experiments the simulant sludge was inverted abruptly. While in the scaled container model experiments a vessel spanning bubble slowly developed beneath the sludge plug over a period of 10 minutes. The different time periods did not affect the test results as discussed in Section 5.0.

In the Fauske & Associates report, sludge plug failure and the prevention of a vessel spanning bubble were investigated through the use of a sludge buster design where a rim (or circular shelf) is attached to the wall of the container and also through the use of angle-walled or cone shaped containers. One test was also performed with a bag material liner as a vessel spanning bubble suppressor.

5.0 Experimental Results

The results of the experiment are:

(1) The results confirm that the dimensionless groups $Y_G = 0.06$ and $Y_G = 0.09$ adequately describe the transition between stable and unstable vessel spanning bubbles in annular and cylindrical container geometries, respectively. Accordingly, these results confirm

that the dimensionless group Y_G correctly includes container size and can be applied to full-scale containers.

(2) When comparing an annulus with an outer diameter equal to that of a cylinder, the results show that the annular geometry provides more resistance to sludge plug failure by Taylor instability.

(3) The presence of a deep column of water on top of a rising cylindrical sludge plug having a stable Y_G value did not result in sludge plug instability.

(4) Assuming that $Y_G \cong 0.09$ for all container geometries, the obround sludge plug stability experiments indicated that the appropriate characteristic dimension for insertion into Y_G is the diameter of the cylindrical ends of the container or, equivalently, the width of the rectangular section of the container. The occurrence of Taylor instability in the obround container was always confined to the cylindrical ends of the obround sludge plug, suggesting that the diameter of the cylindrical ends is the controlling dimension.

(5) The circular rim (shelf) of 0.0191 m or 0.197 m shelf width proved to be an effective sludge buster in a 0.445-m diameter cylindrical test vessel. Rising sludge plugs of strengths 759 and 1600 Pa, the two sludge plug strengths investigated that were stable in the absence of the sludge buster, broke and collapsed upon attempting to flow past the sludge buster shelf.

(6) The obround rim (shelf) of width 0.0191 m proved to be an effective sludge buster in the obround container. Rising sludge plugs of strength 1600 Pa that were stable in the absence of the sludge buster collapsed either upon pressing up against the shelf or after about ¼ depth of the sludge plug rise past the shelf.

(7) A conical container of half angle 14.2° proved to be very effective in eliminating vessel spanning bubbles over the entire range of shear stresses investigated (170 to 974 Pa) and for the two sludge depths investigated (0.3 and 0.51 m).

(8) The angled walls attached to the straight sections of the obround container prevented vessel spanning bubble formation beneath high-strength 1600 Pa obround sludge plugs.

(9) The bag material liner in the 0.445 m diameter cylindrical container prevented vessel spanning bubble formation beneath a high-strength 1600 Pa cylindrical sludge plug.

(10) In all cases when a rising plug was unstable, a rising plug never again formed after failure, and gas was continuously released at the rate it was supplied.

6.0 Application of Experimental Results to Full-Scale Small Canister and STSC

Sludge densities and shear strengths from SNF-7765, *Supporting Basis for SNF Project Technical Databook*, were used to solve for the dimensionless gravity-yield parameter, Y_G. Y_G values were calculated for the STSC and small canister (Appendix B). The diameter of the cylinder was used as D in the definition of the gravity yield parameter, and the diameter of the cylindrical ends of the obround container was used as D in the definition of the gravity yield parameter. Separate calculations were not performed for the annular STSC since Fauske & Associates concluded that it is correct to use the diameter of the outer cylinder of the annular container to be D in the definition of the gravity-yield parameter:

$$\frac{\tau_0}{\rho_{sl} g D} \leq Y_G$$

The calculated Y_G values were graphed with the measured sludge shear strength. Based on the results of the Fauske & Associates report, $Y_G = 0.06$ and $Y_G = 0.09$ adequately describe the transition between stable and unstable vessel spanning bubbles in annular and cylindrical container geometries, respectively. Y_G values higher than 0.06 for annular containers and higher than 0.09 for cylindrical containers would result in a stable sludge plug. The region between $Y_G = 0.06$ and $Y_G = 0.09$ is indicated on the graph by the bold rectangle in Figure 5. Table 1 lists the values for shear strength, τ_0, and the gravity yield parameter, Y_G, used to generate the graph in Figure 5.

Table 1 Values for Shear Strength and Gravity Yield Parameter for Figure 5

Sludge Sample	τ_0 (Pa)	Y_G (STSC)	Y_G (Small Canister)
KES-M-13 Top	2.2	1.37E-04	3.98E-04
KES-T-20 Top	0.9	3.89E-05	1.13E-04
96-04 U/L	99	6.28E-03	1.82E-02
96-06 U/M	230	9.36E-03	2.71E-02
96-06 M	170	6.13E-03	1.78E-02
96-06 M/L	500	1.38E-02	4.01E-02
96-06 L	470	1.09E-02	3.15E-02
96-11 U/L	130	8.18E-03	2.37E-02
96-21 Rec	40	8.39E-04	2.43E-03
96-24 Rec	30	7.86E-04	2.28E-03
KC-2/3 M250	390	1.27E-02	3.67E-02
KC-4 P250	3600	1.92E-01	5.56E-01
KC-4 M250	310	1.79E-02	5.18E-02
KC-5 P250	3100	1.43E-01	4.15E-01
KC-5 M250	290	1.67E-02	4.85E-02

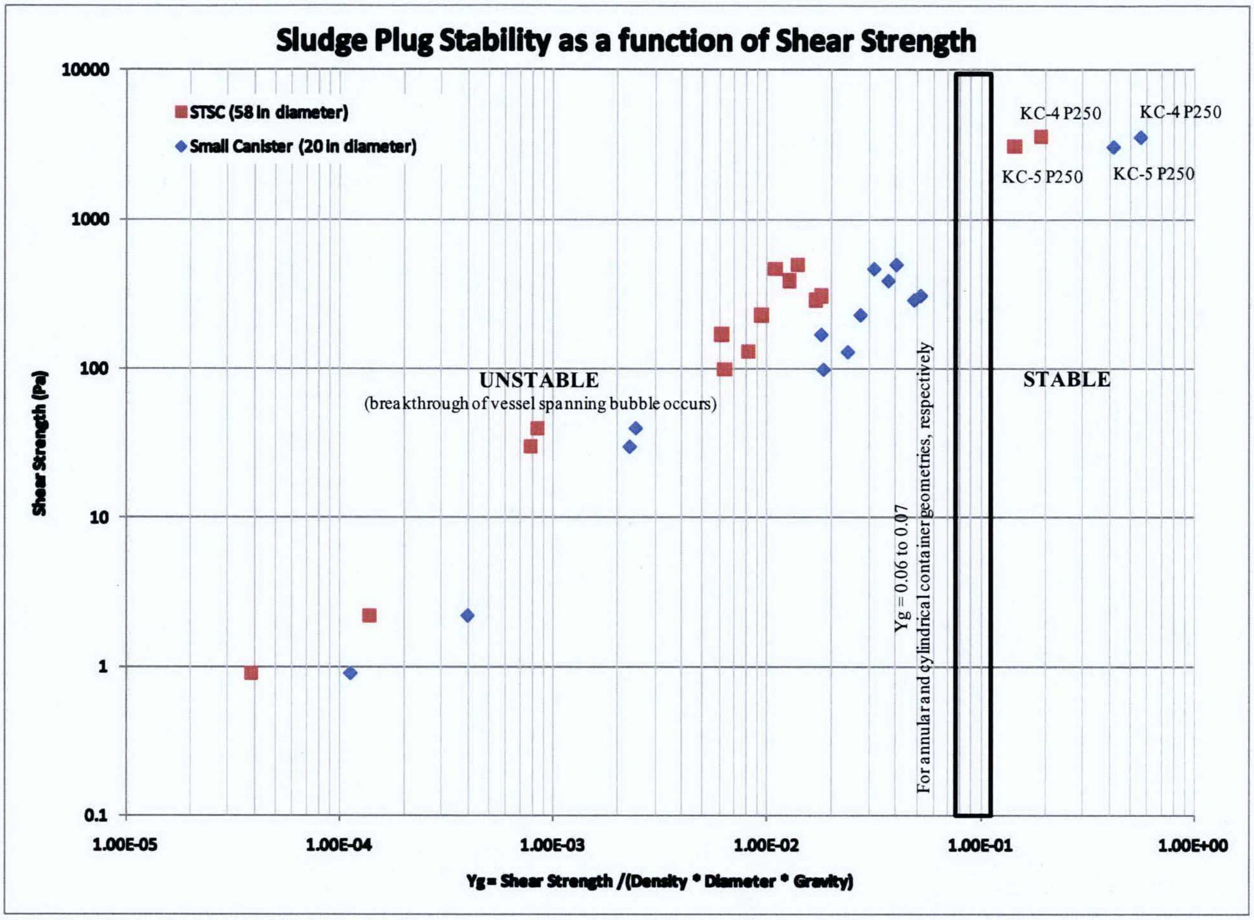

Figure 5 Graph of Sludge Plug Stability as a function of Shear Strength

As indicated by Figure 5, some of the K Basin sludge will likely form a stable vessel spanning bubble inside the STSC and small container. A smaller diameter results in a larger Y_G value, therefore, the small canisters are more likely to form a stable vessel spanning bubble. Table 2 shows the minimum shear strengths required for each of the K Basin sludges for a stable vessel spanning bubble to form in either a 58" diameter STSC or a 20" diameter small canister. The design basis densities of the sludges[1] are 1400, 1600, and 2450 kg/m^3 for KE originating, KW originating, and Settler sludge, respectively.

Table 2 Minimum Shear Strength, τ_0, that causes a Stable Sludge Plug

	STSC	Small Canister
KE Sludge	1820 Pa	628 Pa
KW Sludge	2080 Pa	718 Pa
Settler Sludge	2120 Pa*	1100 Pa

*Annular STSC used for Settler Sludge

[1] HNF-41051, Rev 5, 2010, Preliminary STP Container and Settler Sludge Process System Description and Material Balance, CH2MHill Plateau Remediation Company, Richland, Washington

Fauske and Associates recommend that sludge stability tests should be performed with higher shear strength materials because settler sludge gains strength during aging. Figure 5 indicates that higher shear strength material is more likely to form a stable vessel spanning bubble. However, Fauske and Associates' experiment shows that a passive mechanism installed in the STSC is effective in disrupting a stable sludge plug. Activities have been scheduled (STP schedule, Activity ID ECD00180, Verify Sludge/Bubble Buster Concept – Small Scale and Activity ID ECD00190, Verify Sludge/Bubble Buster Concept – Large Column) to test the effectiveness of a fin (or triangular shape) installed in the test vessel as a passive mechanism to disrupt a stable sludge plug. Higher shear strength sludge simulants will be used in these tests.

Fauske and Associates expressed concern about the formation of vessel-spanning bubbles in rectangular containers and the uncertainty in evaluating the stability of rectangular sludge plugs. Rectangular containers will not be used as a part of STP; however sludge in the basin is currently stored in rectangular Engineered Containers. There is a Surveillance Requirement, SR 3.10.1[2], currently in place that requires verification twice weekly that Engineered Container sludge level is less than or equal to 9 ft to ensure that upward level trends (i.e., formation of a vessel-spanning bubble) will be observed in a timely manner.

7.0 Conclusions

The Fauske & Associates report confirms that the dimensionless gravity yield parameter, Y_G, correctly includes container size and can be applied to full-scale containers to predict the possibility of the formation of a stable vessel spanning bubble. The Fauske & Associates report also identified $Y_G = 0.06$ and $Y_G = 0.09$ to describe the transition between stable and unstable vessel spanning bubbles in annular and cylindrical container geometries, respectively. An analysis performed by using the dimensionless gravity yield parameter, characterization data for K Basin sludge, and dimensions of the STSC showed that a stable vessel spanning bubble will likely form inside the STSC if the KE, KW, or Settler sludge shear strengths exceeds 1820 Pa, 2080 Pa, and 2120 Pa, respectively. Also, a stable vessel spanning bubble is more likely to form in a smaller diameter canister at lower sludge shear strengths. However, the project has already selected the Direct Loading option to retrieve sludge into STSCs instead of the small canisters per PRC-STP-00112.

A passive mechanism installed in the STSC is effective at disrupting the rising sludge plug and preventing the sludge from plugging the vent filter or being forced out of the container. The current STSC design incorporates a sludge buster ring attached to the inside of the STSC. Another mechanism being considered to disrupt a rising sludge plug in the STSC is a fin (or triangular shape) that will be attached to the outer wall.

[2] HNF-SD-SNF-TSR-001, Rev 10, 2009, 105-KW BASINS TECHNICAL SAFETY REQUIREMENTS, CH2MHILL Plateau Remediation Company, Richland, Washington

Appendix A FAI/09-272: An Experimental Study of the Stability of Vessel-Spanning Bubbles in Cylindrical, Annular, Obround and Conical Containers

FAUSKE & ASSOCIATES, LLC

WORLD LEADER IN NUCLEAR AND CHEMICAL PROCESS SAFETY

FAI/09-272

An Experimental Study of the Stability of Vessel-Spanning Bubbles in Cylindrical, Annular, Obround and Conical Containers

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January, 2010

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1.0 PURPOSE AND SUMMARY

A vessel-spanning bubble may form in any sludge container when heavy, gas-generating particles are embedded in sludge of suitability high yield stress. The consequence of such a bubble is to displace sludge and overlying water with the possibility to plug filters and even release sludge from a container.

An overlying sludge layer/underlying vessel-spanning bubble composite is subject to failure by Taylor instability. According to Taylor instability theory a single dimensionless gravity-yield parameter Y_G (see Eq. 3-1) defines the onset of a Taylor instability in the vessel-spanning composite and governs how the instability scales. If sludge container conditions are not favorable for a Taylor instability it may be possible to break the vessel-spanning composite with passive design features.

The purpose of the experimental work reported here is to (i) test the validity of the gravity yield parameter for predicting the breakup of vessel spanning bubbles in cylindrical, annular and obround containers and (ii) evaluate the performance of specific container-design features in terms of their ability to disrupt an otherwise stable vessel spanning bubble/sludge layer composite or to prevent the formation of a vessel spanning bubble. The design features investigated are a rim that occupies a portion of the container's cross section and an angled container wall. Also investigated is the flexible material that will be formed into a bag to hold the sludge in small storage containers. The bag material is constructed of a rough, woven polymer that when pressed up against the container wall by the sludge layer may serve as an unintended vessel-spanning bubble suppressor by providing gas escape channels along the container wall.

The results of the experimental program reported here may be summarized as follows:

(1) The results confirm that the dimensionless groups $Y_G = 0.06$ and $Y_G = 0.09$ adequately describe the transition between stable and unstable vessel spanning bubbles in annular and cylindrical container geometries, respectively. Accordingly, these results confirm

that the dimensionless group Y_G correctly includes container size and can be applied to full-scale containers.

(2) When comparing an annulus with an outer diameter equal to that of a cylinder, the results show that the annular geometry provides more resistance to sludge plug failure by Taylor instability.

(3) The presence of a deep column of water on top of a rising cylindrical sludge plug having a stable Y_G value did not result in sludge plug instability.

(4) Assuming that $Y_G \cong 0.09$ for all container geometries, the obround sludge plug stability experiments indicated that the appropriate characteristic dimension for insertion into Y_G is the diameter of the cylindrical ends of the container or, equivalently, the width of the rectangular section of the container. The occurrence of Taylor instability in the obround container was always confined to the cylindrical ends of the obround sludge plug, suggesting that the diameter of the cylindrical ends is the controlling dimension.

(5) The circular rim (shelf) of 0.0191 m or 0.197 m shelf width proved to be an effective sludge buster in a 0.445-m diameter cylindrical test vessel. Rising sludge plugs of strengths 759 and 1600 Pa, the two sludge plug strengths investigated that were stable in the absence of the sludge buster, broke and collapsed upon attempting to flow past the sludge buster shelf.

(6) The obround rim (shelf) of width 0.0191 m proved to be an effective sludge buster in the obround container. Rising sludge plugs of strength 1600 Pa that were stable in the absence of the sludge buster collapsed either upon pressing up against the shelf or after about 1/4 depth of sludge plug rise past the shelf.

(7) A conical container of half angle 14.2° proved to be very effective in eliminating vessel spanning bubbles over the entire range of shear stresses investigated (170 to 974 Pa) and for the two sludge depths investigated (0.3 and 0.51 m).

(8) The angled walls attached to the straight sections of the obround container prevented vessel spanning bubble formation beneath high-strength 1600 Pa obround sludge plugs.

(9) The bag material liner in the 0.445-m diameter cylindrical container prevented vessel spanning bubble formation beneath a high-strength 1600 Pa cylindrical sludge plug.

(10) In all cases when a rising plug was unstable, a rising plug never again formed after failure, and gas was continuously released at the rate it was supplied.

2.0 INTRODUCTION

This report documents the results of an experimental program designed to determine the behavior of vessel spanning bubbles in sludge containers. The sludge is a mixture of particles and water and some of the particles are reactive uranium metal particles. If most of the reactive uranium metal particles settle out at the bottom of the container a container-spanning reaction-product gas layer may form above the metal and may expand against the overlying, relatively deep layer of inert sludge. Indeed small-scale experiments performed by Baker et al. (2000) showed an expanding gas pocket beneath a K-Basin sludge sample. The gas pocket occupied the entire cross section of the test vessel and displaced the sludge layer upward. In their experiment most of the uranium metal particulate was at the bottom of the sludge layer. The major concern is that such a "vessel spanning bubble" may form in an actual sludge container and may drive the overlying sludge material to the vents at the top of the container, through which the sludge may be released from the container. The potential for vessel spanning bubbles increases for small storage containers (see below).

A sludge plug overlying a vessel spanning bubble is subject to failure by the well-known Taylor instability if the diameter of the vessel is larger than some critical value. It is envisioned that during the instability the vessel spanning bubble penetrates the sludge plug, breaks through the surface of the plug and the plug slumps back to the bottom of the vessel. An important and convenient product of the Taylor theory when applied to a yield stress fluid is a dimensionless gravity yield parameter Y_G that (i) dictates whether or not a sludge plug will fail and (ii) governs how the instability scales (Epstein, 2002). The theoretical finding of a gravity yield parameter for describing the stability of sludge plugs displaced by vessel spanning bubbles was tested by Gauglitz (2002) in a series of limited unpublished experiments with small cylindrical vessels. In these experiments vessels initially filled with kaolin simulant sludge were turned upside down and the response of the simulant sludge was observed. If the simulant did not drain out of the vessel the system was classified as Taylor stable and if draining occurred the system was classified as Taylor unstable. The measured threshold boundaries between stable and unstable sludge plugs were reasonably well-correlated by a single gravity yield parameter value.

Two of the goals of the experimental program reported here are to observe the Taylor instability and to determine the value of the gravity yield parameter when a sludge plug is being displaced upward by a vessel spanning bubble. The desired and realistic configuration of a gas column trapped beneath a plug of simulant sludge was established in a cylindrical container, in an annular-geometry-container and in a container with a rectangular midsection and cylindrical ends. The latter oblong design is referred to as an "obround container". In the annular container design the sludge is confined to a region between the vessel wall and an inner circular cylinder. The annular region may be employed in very large sludge containers to reduce the radial heat conduction path out of the container and prevent the reactive sludge from entering a thermally unstable regime. The obround design may be used for the small containers that will be placed in larger transport and storage containers.

The tests reported here involving a sludge plug overlying a vessel spanning bubble were performed with a single cylindrical container, with a single annular container and with a single obround container. Therefore, while these tests are capable of establishing the magnitude of the threshold gravity yield parameter value Y_G for a realistic sludge layer/vessel-spanning-bubble-morphology, they can not prove that Y_G is useful for scaling, particularly with respect to the annular and obround geometries for which no previous data on sludge plug stability exists. To remedy this situation smaller-scale annular geometry turnover-tests were performed as part of the present study to investigate the effect of container size. Turnover experiments were also conducted in small-scale cylindrical vessels to confirm the previous unpublished turnover experiments in cylindrical geometry (Gauglitz, 2002) and to provide a direct comparison to the annular turnover experiments with identical simulants. Small scale turnover tests were not performed with obround containers. It is felt that the threshold yield parameter measured in the one-half scale laboratory container should be applicable to the full size obround container.

Very strong sludges in large containers and sludges of moderate strength in small containers are predicted to be stable to Taylor instability. In these cases the containers must be designed in a way that promotes the destabilization of the sludge plug and underlying gas column. Two container designs have been identified that may destabilize an otherwise "Taylor stable" vessel-spanning bubble. These are (i) a container with an internal rim fitted to the container wall midway between the top and bottom of the container that presumably forces the yield-stress-material-sludge-plug flow to contract and fail (Epstein and Plys, 2002) and (ii) a container with an angled wall (e.g. a truncated-cone-shaped-container) within which the vessel spanning bubble is released as soon as the overlying sludge plug moves up and, hopefully, separates from the wall (Gauglitz and Schmidt, 2009). The internal rim design was investigated experimentally in both cylindrical and obround containers as part of this study. A truncated-cone-shaped container was fabricated specifically to test the angled wall concept. Slightly angled walls on the straight sections of the obround container were also tested for their ability to prevent the formation of a vessel spanning bubble in the obround design.

A flexible bag will hold the sludge in the actual small storage containers. When the bag is filled with sludge it will press up against the inside bottom and wall of the container. The bag is constructed of woven polymer material and it has been suggested that its rough-open-weave structure will serve as a path for the upward flow of reaction product gas and thereby preclude the growth of a vessel spanning bubble. This possibility was tested in a cylindrical container at the end of this study.

3.0 SLUDGE PLUG FAILURE BY TAYLOR INSTABILITY IN CYLINDRICAL, ANNULAR AND OBROUND CONTAINERS

3.1 Theoretical Considerations

A sludge plug overlying a vessel spanning bubble may fail by the well-known "Taylor instability". This instability occurs when there is acceleration from a lighter fluid to a heavier fluid (or deceleration of a heavier fluid by a lighter one). Since gravity acting downward from a heavier fluid to a lighter fluid is equivalent to a system accelerating upward with the acceleration from the lighter to the heavier, this phenomenon readily occurs when one turns over a glass of water and columns of air interpenetrate the water. The rising sludge plug above a container-spanning bubble is obviously subject to Taylor instability.

Based on available experimental and theoretical work on Taylor instability in solids (Miles, 1966 and Barnes et al., 1974), Epstein (2002) concluded that the appropriate criterion for predicting the collapse of a sludge plug in a cylindrical vessel of diameter D takes the form of a gravity -yield parameter

$$\frac{\tau_0}{\rho_{sl} g D} \leq Y_G \qquad (3\text{-}1)$$

where τ_0 is some stress that characterizes the strength of the sludge, ρ_{sl} is the density of the sludge, g is the gravitational constant and Y_G is an empirical constant. Gauglitz (2002) confirmed experimentally that Eq. (3-1) describes the onset of sludge instability in laboratory scale cylindrical vessels when τ_0 is identified with sludge shear strength measurements. Epstein and Plys (2002) examined his data and selected the value $Y_G \cong 0.08$.

The experimental results presented later on (in Section 3.4) show that Eq. (3-1) describes sludge plug instability in an annular-shaped sludge container as well as in a cylindrical container, with D taken to be the diameter of the outer cylindrical wall of the annular container. The selection of the outer diameter is consistent with experiments on the rise velocity of Taylor-bubbles in a vertical annular channel containing water (Griffith, 1963). To calculate the rise velocity the outer diameter of the channel is used in the bubble rise velocity equation. The experimental results also show that Eq. (3-1) describes sludge plug instability in an obround container with D identified with the diameter of the cylindrical ends or, equivalently, the width of the rectangular section dimension of the container. The rest of this section summarizes the experimental work that was performed to evaluate the utility of the gravity yield parameter, Eq. (3-1), for predicting the behavior of vessel-spanning bubbles in circular, annular and obround sludge storage container geometries.

3.2 Experimental Techniques and Apparatuses

Both small-scale and larger-scale Taylor instability experiments were performed. The small-scale experiments were simple hand-held vessel turnover experiments. In the small-scale tests the diameters of the cylindrical vessels and the outer diameters of the annular test vessels varied in size from 0.017 to 0.16 m. The different size vessels in the annular tests were geometrically scaled by having an essentially identical value of $\cong 0.5$ for the ratio of the inner and outer diameters. This diameter ratio was also used in the larger scale annular tests described later on. A turnover experiment is illustrated in Fig. 3-1. From a Taylor instability point of view, the upside down beaker in Fig. (3-1b) contains a stable sludge plug overlying atmospheric air, or, equivalently, a vessel spanning bubble of infinite depth. Figure (3-1c) illustrates an unstable result with air from the underlying atmosphere (or from a vessel spanning bubble of infinite depth) penetrating and displacing the sludge plug. Turnover experiments are most convenient for studying Taylor instability in fluids in small-scale vessels when the only acceleration force is gravity. Obviously as the scale of the experiment increases and the weight of the fluid and its container increases the turnover experiment becomes more difficult to implement and to control.

In the larger scale annular, cylindrical and obround geometry experiments (hereafter referred to as the large scale tests or the injected bubble tests) a simulant sludge plug was forced upward by opening an air valve and establishing a vessel spanning bubble with a gas pressure sufficient to overcome the weight of the sludge plug. A schematic diagram of the apparatus for

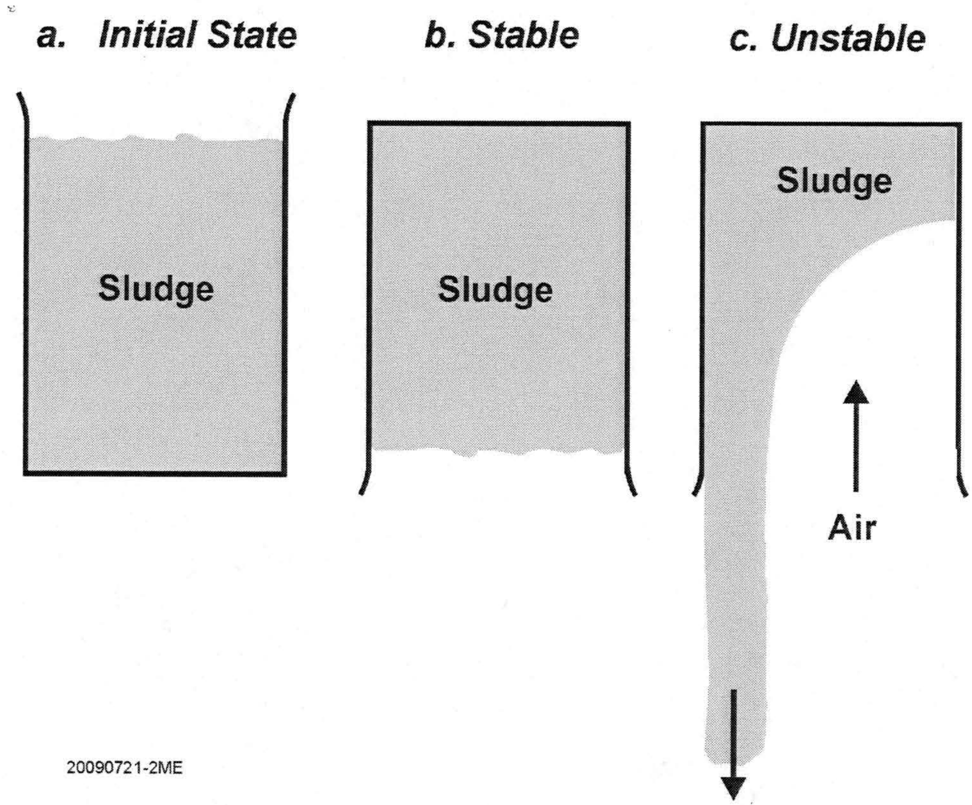


Figure 3-1 Illustration of stable and unstable results during vessel turnover experiments.

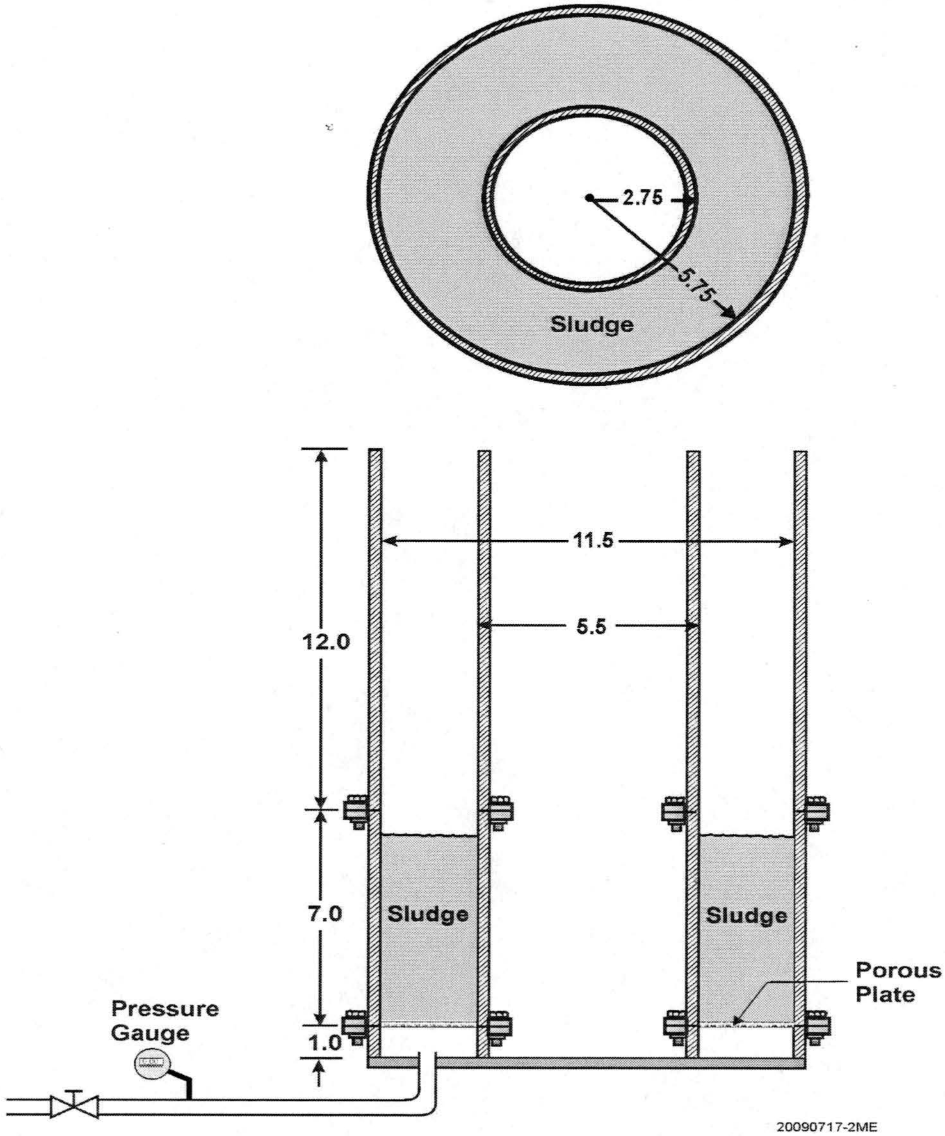


Figure 3-2 Schematic diagram of experimental apparatus for the investigation of sludge plug stability in an annular container (all dimensions are in inches). Sludge plug position just after thin vessel spanning bubble lifts it off porous plate. Note that the air plenum region below the porous plate occupies the entire annulus.

studying sludge plug instability in an annular geometry is shown in Fig. 3-2. The main component of the apparatus is a plexiglas annular column constructed of an outer cylinder of 0.292 m ID (11.5 in.) and an inner cylinder of 0.14 m OD (5.5 in.). Three sections comprise the column: a lower gas manifold section that measures 0.0254 m (1.0 in.) in height, a middle 0.178 m (7.0 in.) long section and an upper 0.305 m (12.0 in.) long section. The lower section receives air from a high pressure line that is directed to a throttle valve just upstream of the test section. The middle section contains the simulant sludge plug which is initially supported by a porous plate that separates the lower gas manifold from the annular sludge plug.

The steady and gradual introduction of air into the lower manifold sections forces the sludge plug to lift off the porous plate and a growing vessel spanning bubble is formed that slowly displaces the sludge plug upward into the upper section of the apparatus. The sludge lift-off process is remarkably "clean" in that very little sludge residue is left behind on the porous plate and the bottom surface of the sludge plug just after lift off is flat and free of large scale indentations. Note that the presence of the porous plate together with the slow introduction of air ensures that the air flow and pressure through the porous plate is spatially uniform over the plane of the plate. A photograph of a stable-rising-annular-sludge plug is shown in Fig. 3-3.

The circular test section is illustrated in Fig. 3-4. Much like the annular column, the circular column consists of three sections. The height of the lower gas manifold section is 0.0254 m (1.0 in.) and the middle and upper sections are 0.33 m (13.0 in.) high. The diameter of the circular column is 0.445 m ID (17.5 in.). Initially the sludge layer rests on a porous plate which caps the gas manifold. The sludge layer is set into motion and an underlying vessel spanning bubble is formed by slowly pressurizing the gas manifold at the bottom of the column. A photograph of a stable-rising-cylindrical-sludge plug is shown in Fig. 3-5.

Figure 3-3 Stable rising annular sludge plug.

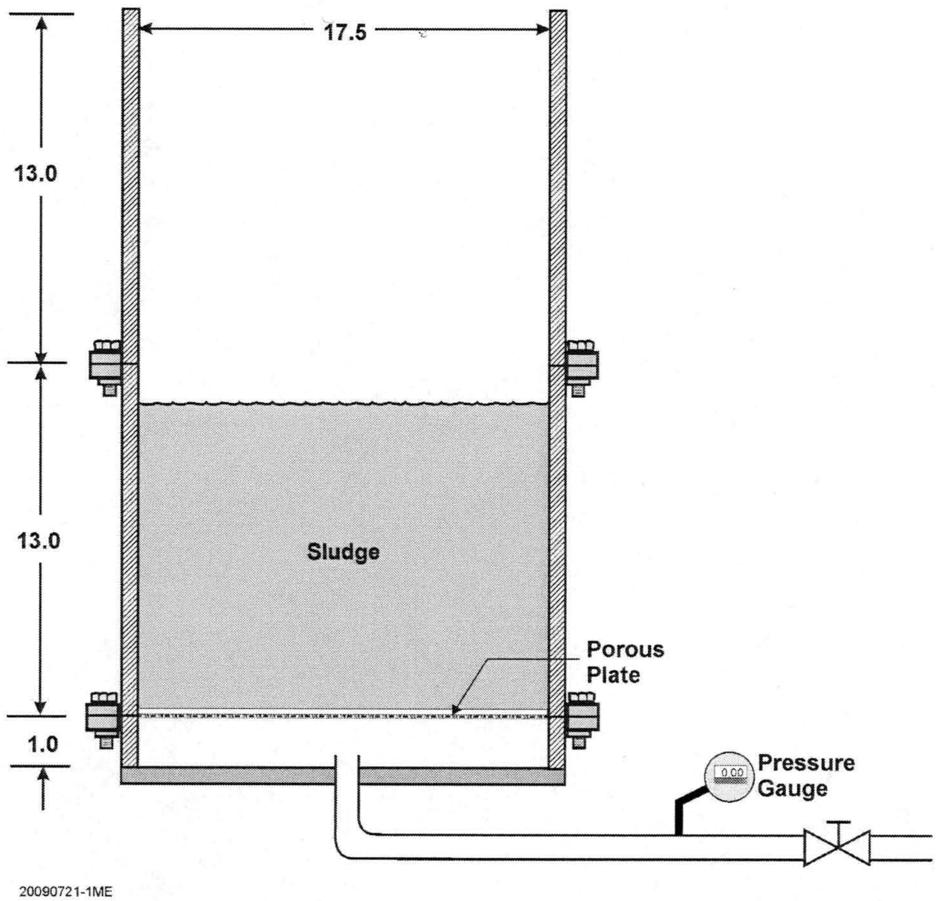


Figure 3-4 Schematic diagram of experimental apparatus for the investigation of sludge plug stability in a large-scale cylindrical container (all dimensions are in inches). Sludge plug position just after thin vessel-spanning bubble lifts it off porous plate.

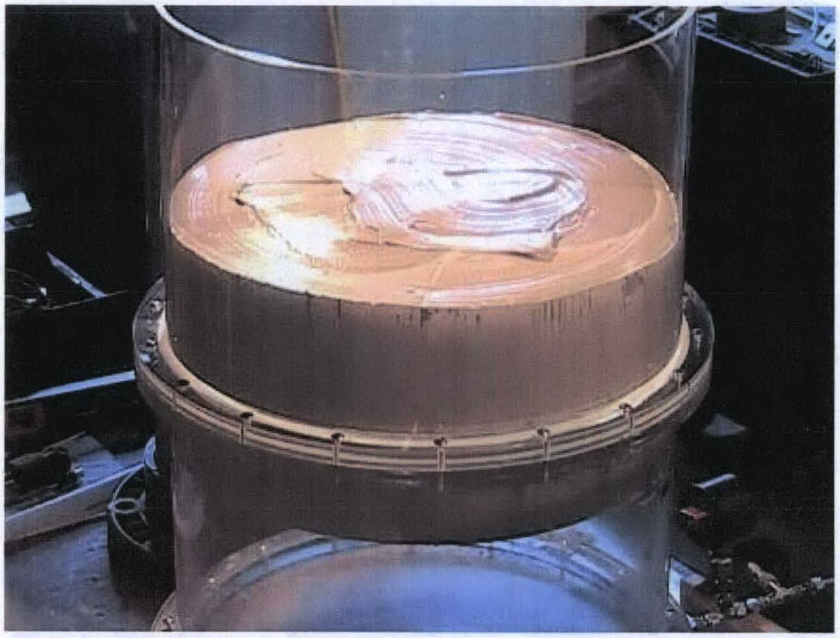


Figure 3-5 Stable rising cylindrical sludge plug.

The three sections of the obround container are illustrated in Figs. 3-6 and 3-7. The lower gas manifold section is 0.75 in. (1.905×10^{-2} m) in height. The heights of the middle and upper sections are 7.0 in. (0.1778 m). The side view in Fig. 3-7 shows the 11.0 in. (0.2794 m) width of the container, the lower air plenum section with the air supply tube and the initial position of the sludge layer. It follows that the radii of the circular ends of the container are 1/2 (11.0) = 5.5 in. (0.1397 m). The lengths of the straight sides of the container are 7.81 in. (0.1984 m) and the end-to-end length of the container is 18.81 in. (0.4778 m). A photograph of a stable-rising-obround-sludge plug is shown in Fig. 3-8.

Mixtures of deionized water and industrial grade pulverized EPK kaolin (obtained from Edgar Minerals Inc., Edgar, FL) were used to represent the sludge material. Kaolin was added to the water and mixed in separate containers using a large drywall mixing blade rotated by an electrical drill motor until a uniform bubble free consistency was obtained. Depending on the strength of the mixture, the mixture was then poured and/or scraped from the mixing container(s) into the middle section of the test container and on top of the porous plate. To accomplish this the upper section of the apparatus was separated from the middle section. The mixture was then stirred again in the test container with the motor-driven impeller to lift the trapped gas pockets (introduced during loading of the vessel) to the surface of the sludge. The mixture was allowed to rest undisturbed for a period of 1.0 to 1.5 hours before a stability test was performed. The upper section of the apparatus was then reconnected to the sludge plug-containing middle section, and the experiment was initiated by turning on the air flow to the lower manifold section.

The same EPK kaolin material used in the large-scale gas injection tests was used in the small-scale turnover tests, and the sludge mixtures of desired strengths were prepared with deionized water. The kaolin and water were vigorously mixed with a motor-driven impeller, mixed again by hand in the small-scale test containers, and the mixture was kept still in the container for about an hour before conducting a turnover test. The roughly one hour mixture rest period is motivated by the fact that available kaolin simulant sludge shear strength measurements (see below) were made after a mixture aging period of one hour.

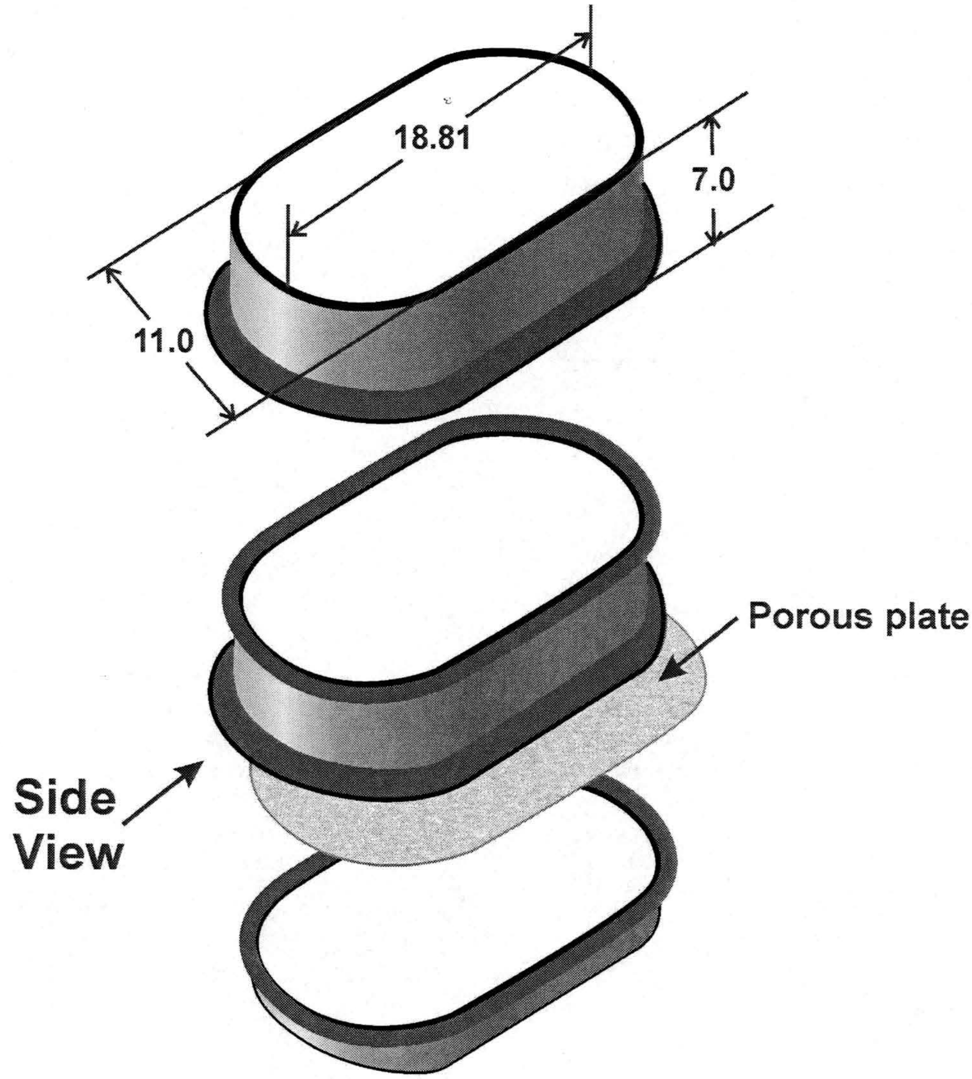


Figure 3-6 Disasssembled view of experimental apparatus for the investigation of sludge plug stability in an obround container (all dimensions are in inches).

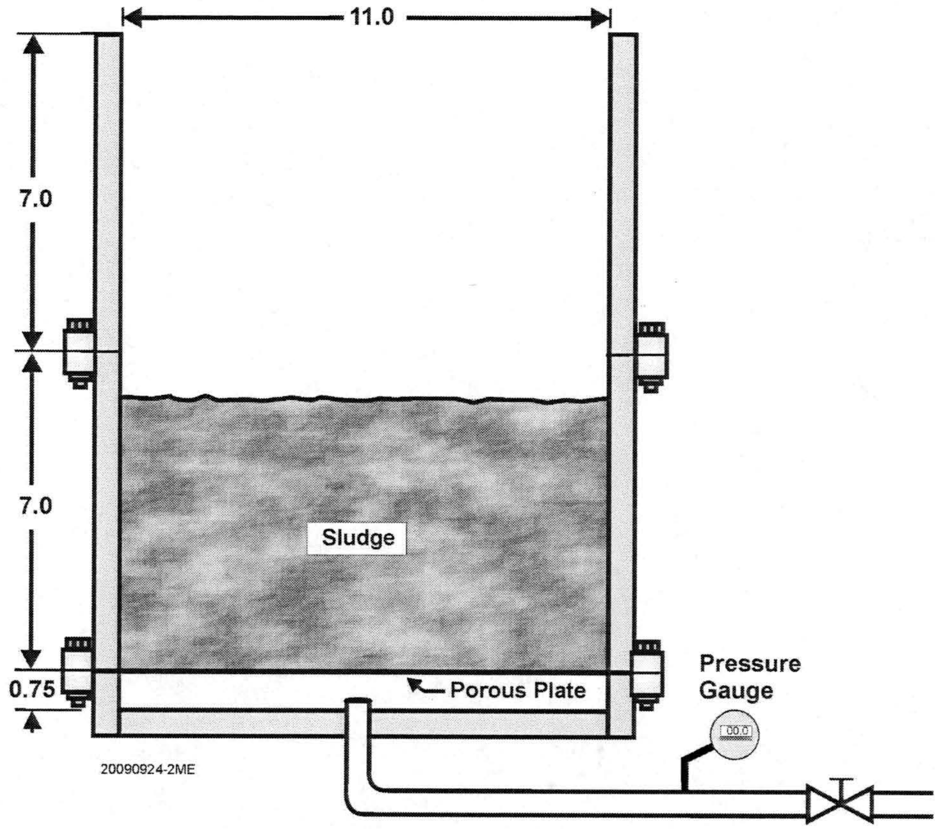


Figure 3-7 Side view of obround container (see Fig. 3-6) showing sludge plug resting on porous plate (all dimensions are in inches).

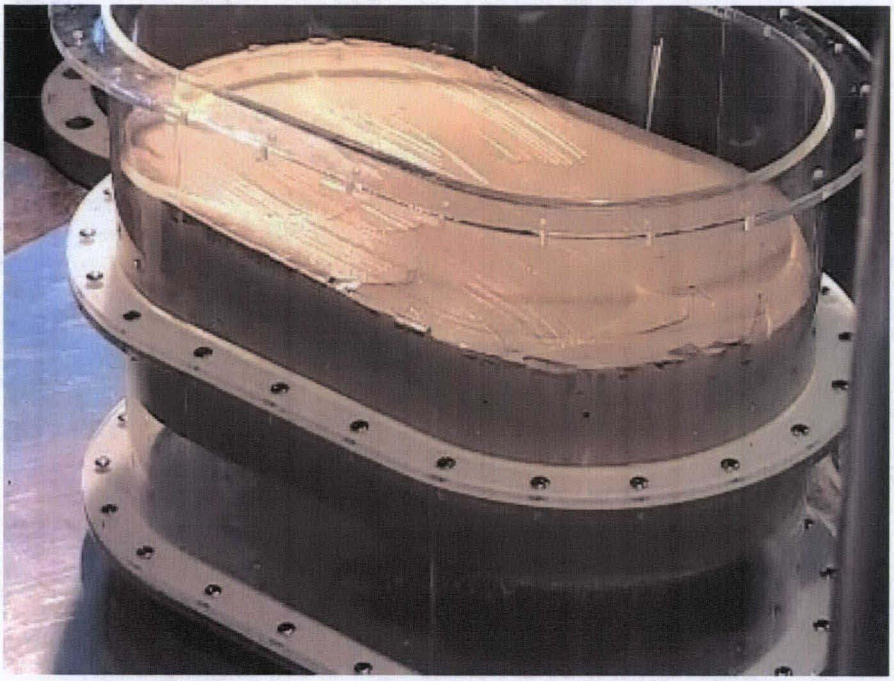


Figure 3-8 Stable rising obround sludge plug.

There are differences between the cylindrical and annular containers turnover tests and the large scale cylindrical and annular containers injected bubble tests that should be noted here. In the turnover tests the simulant sludge was moved abruptly into an inverted sludge over gas configuration, while in the large scale tests a vessel spanning bubble slowly developed beneath the sludge plug over a period of about 10 minutes. In the turnover tests the unstable behavior of sludge distortion and draining out of the container occurred essentially immediately after the container was turned upside down. When sludge plug failure was observed in the large scale tests the instability was delayed for minutes or tens of minutes following the formation of an initially thin vessel spanning bubble. Finally, based on the theory cited in Section 3.1, the instability should be independent of the depth of the simulant sludge above the vessel-spanning bubble. All of the large scale annular experiments and most of the large scale cylindrical experiments were conducted with the ratio of the simulant sludge depth to the container outer diameter being approximately 0.5. Two tests with the large scale cylindrical containers employed sludge layers having depth to diameter ratios of about 0.26 and 0.29. The ratio of the sludge depth to the diameter of the circular ends of the obround container was approximately 0.5. The ratio of simulant sludge depth to container outer diameter varied from 0.6 to 1.0 in the small-scale tests.

3.3 Sludge Shear Strength and Density Estimates

The most important parameter that relates the behavior of the simulant sludge to actual sludge waste is the shear strength. Therefore it is important to know the shear strength of the simulant kaolin/water mixtures employed in the tests. Three samples of simulants (50, 54 and 57 wt% kaolin) used in the stability experiments were collected to make shear strength measurements. The results of these measurements are reported by Burns et al. (2010). Three repeat measurements were taken on each sample and the average strength for each sample was used to develop the following correlation relating shear strength to the kaolin mass concentration

$$\tau_0 = 0.0005 \exp[0.2497(\text{wt\% kaolin})] \qquad (3\text{-}2)$$

In these tests, all the individual measurements were within 10% sample average, showing good reproducibility of the measurements. The three data points were also well correlated with an exponential equation, as expected based on previous work, and the correlation coefficient was 0.997 (Burns et al. 2010). Burns et al. (2010) also compared the results for these three kaolin samples with previous data and correlations for EPK kaolin/water mixtures (Powell et al., 1995; Gauglitz et al., 2001; and Rassat et al., 2003). The most appropriate results to compare with are those reported by Gauglitz et al. and Rassat et al. The correlation of data reported by Gauglitz et al. is

$$\tau_0 = 0.0119 \exp\left[0.1921(\text{wt\% kaolin})\right] \tag{3-3}$$

and the data of Rassat et al. is well represented by

$$\tau_0 = 0.0297 \exp\left[0.1715(\text{wt\% kaolin})\right] \tag{3-4}$$

In the above equations τ_0 is in Pa.

While the shear strength estimates given by these three correlations are reasonably similar between 30 and 2000 Pa, there are some notable differences. The correlation based on the clay samples used in testing (Eq. 3-2) has a stronger dependence on the kaolin concentration than both the correlations of Rassat et al. (2003) and Gauglitz et al. (2001). The rheology of kaolin slurries is known to depend on pH and ionic concentration, so it is likely that the difference is due to differences in the water used in each study, though differences in how the samples are mixed and aged and perhaps lot-to-lot variation of EPK kaolin over the years may play a role. The three clay samples tested span only a portion of the range of kaolin concentrations used in this study, but the uncertainty in the repeat measurements was small and the correlation coefficient for Eq. (3.2) was very good (Burns et al. 2010). Even though it is based on a limited data set, Eq. (3-2) will be used to estimate τ_0 and to calculate Y_G from Eq. (3-1) because this correlation gives the best determination of shear strength for the samples used in testing.

There is uncertainty in the strengths estimated from Eq. (3-2). Both Burns et al. (2010) and Powell et al. (1995) reported uncertainties for repeat shear strength measurements of about 10% on identical samples. In addition, estimating the strength of samples outside the kaolin concentrations where data were collected is an extrapolation, and higher uncertainties are expected for extrapolations. Based on these uncertainties and the difference between correlations of different studies, we will assume for the current work that shear strength given by Eq. (3-2) has an uncertainty of ± 25%. This is the dominant uncertainty in the gravity-yield parameter discussed above, so the error on the gravity-yield parameter for each instability experiment will also be ± 25%.

The density of the mixture is calculated assuming that both the kaolin and the water do not contain a significant amount of entrained air or other gas (Rassat et al., 2003). The density ρ_{sl} of the kaolin simulant is then

$$\rho_{sl} = \frac{1}{\frac{[1.0 - (\text{wt\% kaolin})/100]}{\rho_w} + \frac{(\text{wt\% kaolin})/100}{\rho_k}} \qquad (3\text{-}5)$$

where ρ_w (998 kg m^{-3}) and ρ_k (2650 kg m^{-3}) are, respectively, the intrinsic densities of the water and kaolin components of the mixture. Using Eq. (3-5) to determine the simulant sludge density should only result in a minor uncertainty in the gravity-yield parameter.

3.4 Experimental Observations and Results from the Annular and Cylindrical Geometry Experiments

As mentioned previously, in the small-scale-turnover tests, the vessels (cylindrical and annular) were turned upside down and the kaolin simulant was observed. If the simulant sludge did not move the sludge column was classified as stable. If most of the simulant drained from the vessel the sludge column was classified as unstable. If only a small quantity of sludge fell from the vessel the system was classified as "marginally unstable". The results of the small scale experiments are tabulated in Tables 3-1 and 3-2 and are plotted as points in a vessel diameter versus gravity yield parameter coordinate system in Figs. 3-9 and 3-10 for the annular

Table 3-1

Experimental Conditions and Results for Instability Tests of Vessel Spanning Bubbles in an Annular Geometry

Kaolin (wt %)	Density (kg/m³)	Shear Strength[1] (Pa)	Annulus Outer Diameter (m)	Annulus Inner Diameter (m)	Ratio of Depth to Outer Diameter	Y_G	Stability	Apparatus[2,3]
45.0	1387	67	0.050	0.027	~ 1	0.098	stable	Invert
45.0	1387	67	0.120	0.063	~ 0.6	0.041	unstable	"
45.0	1387	67	0.160	0.073	~ 0.6	0.031	unstable	"
50.0	1450	157	0.050	0.027	~ 1	0.221	stable	"
50.0	1450	157	0.120	0.063	~ 0.6	0.092	stable	"
50.0	1450	157	0.160	0.073	~ 0.6	0.069	stable	"
50.0	1450	157	0.292	0.140	~ 0.5	0.038	unstable	Inj Bub
50.0	1450	157	0.292	0.140	~ 0.5	0.038	unstable	"
53.0	1490	263	0.292	0.140	~ 0.5	0.062	unstable	"
54.0	1504	312	0.292	0.140	~ 0.5	0.073	stable	"

1) Shear strength from correlation in Figure 4.13 of Rassat et al. (2003)
2) Invert - Apparatus inverted by hand to observe stability
3) Inj Bub - Air bubble injected from below to observe stability

Table 3-2

Experimental Conditions and Results for Instability Tests of Vessel Spanning Bubbles in a Cylindrical Geometry

Kaolin (wt %)	Density (kg/m^3)	Shear Strength[1] (Pa)	Vessel Diameter (m)	Ratio of Depth to Diameter	Y_G	Stability	Apparatus[2,3]
45.0	1387	67	0.017	~ 1	0.289	stable	Invert
45.0	1387	67	0.025	~ 1	0.196	stable	"
45.0	1387	67	0.050	~ 1	0.098	marginal	"
45.0	1387	67	0.060	~ 1	0.082	unstable	"
45.0	1387	67	0.070	~ 1	0.070	unstable	"
45.0	1387	67	0.120	~ 0.6	0.041	unstable	"
50.0	1450	157	0.050	~ 1	0.221	stable	"
50.0	1450	157	0.060	~ 1	0.185	stable	"
50.0	1450	157	0.070	~ 1	0.158	stable	"
50.0	1450	157	0.120	~ 0.5	0.092	stable	"
50.0	1450	157	0.160	~ 0.5	0.069	unstable (just barely)	"
54.0	1504	312	0.160	~ 0.6	0.132	stable	"
56.0	1533	440	0.444	~ 0.5	0.066	unstable	Inj Bub
56.0	1533	440	0.444	~ 0.5	0.066	unstable	"
57.0	1548	523	0.444	~ 0.5	0.078	stable	"
57.0	1548	523	0.444	~ 0.5	0.078	stable	"
57.0	1548	523	0.444	~ 0.5	0.078	unstable	"
60.0	1594	874	0.444	~ 0.5	0.126	stable	"
60.0	1594	874	0.444	~ 0.5	0.126	stable	"
60.0	1594	874	0.444	~ 0.26	0.126	stable	"
60.0	1594	874	0.444	~ 0.29	0.126	stable[4]	"

1) Shear strength from correlation in Figure 4.13 of Rassat et al. (2003)
2) Invert - Apparatus inverted by hand to observe stability
3) Inj Bub - Air bubble injected from below to observe stability
4) 0.25-m deep overlying water layer

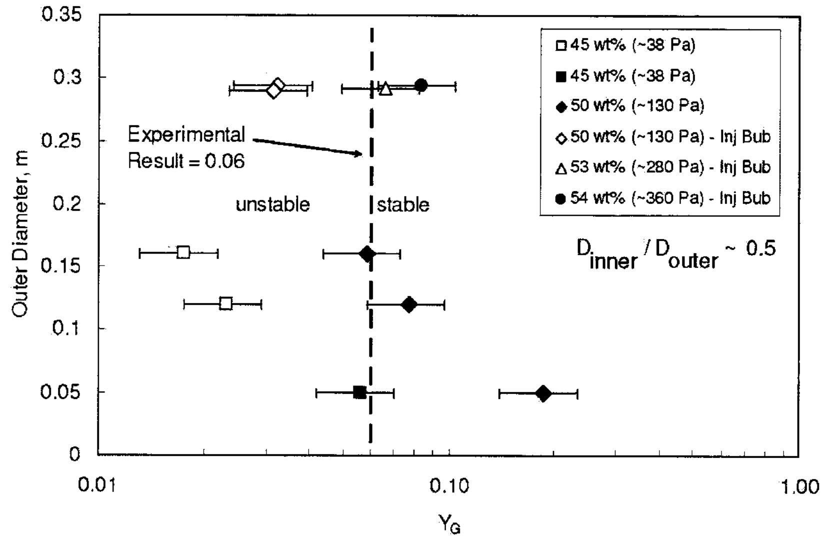


Figure 3-9 Results for the instability of vessel spanning bubbles in an annular geometry. Unstable configurations are noted with "open" symbols and stable configurations are noted with "closed" symbols.

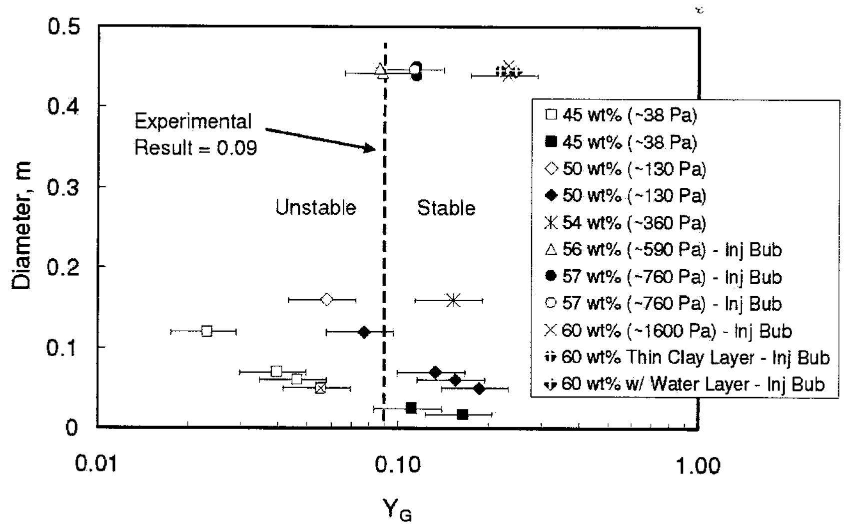


Figure 3-10 Results for the instability of vessel spanning bubbles in a cylindrical geometry. Unstable configurations are noted with "open" symbols, stable configurations are noted with "closed" and "cross" symbols, and a marginally stable system is an open symbol with a "cross". For repeat experiments at identical Y_G values, the positions of the symbols are adjusted slightly so each experiment can be represented.

experiments and the cylinder experiments, respectively. The open data points refer to unstable sludge columns and the solid data points (and "cross" symbols in Fig. 3-10) refer to stable sludge columns. The open symbol with a cross identifies the one test in Fig. 3-10 that was classified as marginally stable.

The larger-scale experiments were performed in a more controlled manner by slowly injecting air below the simulant sludge column through a porous plate and observing if a sustained vessel spanning bubble formed or if the system was unstable. The sludge plug was classified as stable if it remained intact while rising completely from the middle section of the test vessel into the upper section. Sludge plug failure always resulted in the complete collapse of the sludge column back to the porous plate. In all the experiments involving a failed sludge plug, collapse of the sludge plug was not followed by the appearance of another vessel spanning bubble. Bubbles were observed to grow and burst at one or more sites at the surface of the collapsed sludge column indicating that the injected air was passing through the weakened (or liquefied) regions of the sludge and these regions prevented the accumulation of air beneath the sludge column.

All the sludge plug failures in the large-scale tests seem to begin at the lower surface of the sludge column, either from a crack that spreads across the bottom surface of the sludge column or from an elongated bubble that separates the bottom of the sludge plug from the container wall. The crack or bubble begins to grow, slowly at first, in the circumferential and radial directions, and ultimately develops into a rather wide gas bubble that rises to the surface of the sludge column at an accelerating rate. A photograph of such a bubble is shown in Fig. 3-11.

Figures 3-9 and 3-10 show the results of the large scale annular geometry and cylindrical geometry experiments (see also Tables 3-1 and 3-2). These experiments are noted as injected bubble (Inj Bub) experiments. Again, the open symbols are for unstable sludge plugs and the solid symbols are for stable sludge plugs. Five of the large-scale data points in Fig. 3-10 for cylindrical containers were obtained from the experiments performed to evaluate how internal structures ("sludge busters") can disrupt an otherwise stable sludge plug (see Section 4.0). The

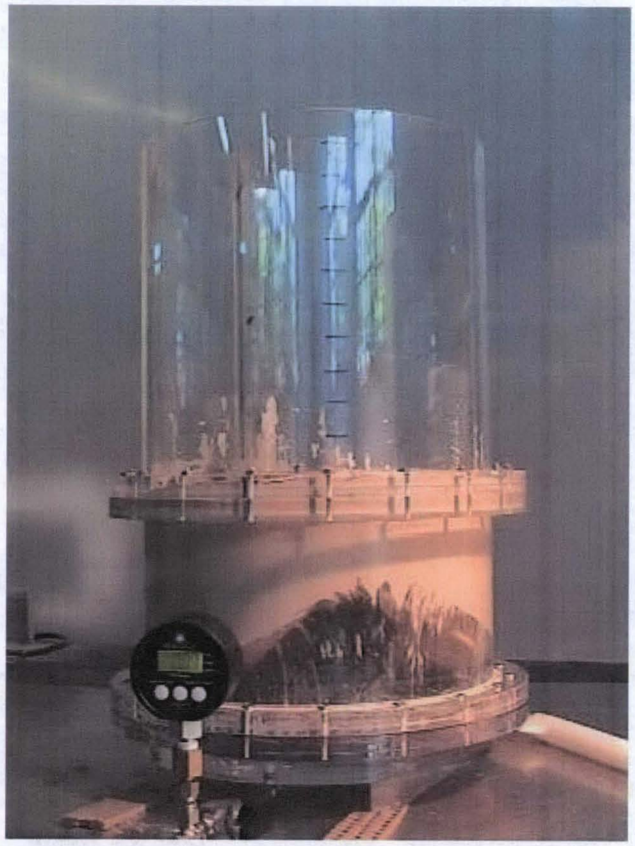


Figure 3-11 Taylor bubble growing from below and penetrating annular sludge plug.

sludge plugs that made contact with the sludge buster were classified as stable and those sludge plugs that failed before reaching the sludge buster were classified as unstable.

The last two entries in Table 3-2 pertain to the two large-scale cylindrical container experiments that were performed with shallow sludge layers of depth-to-diameter ratios of 0.26 and 0.29. Implicit to the theory is that sludge plug stability is independent of depth so that stable behavior was anticipated for these 1600 Pa sludge layers and this is what was observed. The second of the shallow layer tests was performed with a water layer on top of the sludge layer to replicate actual sludge storage conditions. The depth of the overlying water layer was approximately 10.0 in (0.25 m) which was about two times the 5.0-in. (0.13 m) depth of the simulant sludge layer. The three layer composite configuration (vessel spanning bubble + sludge layer + water layer) was observed to be stable (see Fig. 3-12). The vessel spanning bubble continued to expand until the surface of the water layer was displaced upward a distance of approximately 10.0 in. (0.25 m) to the top of the container whereupon the test was terminated. The observed stable light water layer/heavy sludge layer interface is consistent with instability theory.

The small-scale and large-scale results of the annular and cylindrical geometry experiments confirm that the dimensionless gravity yield parameter Y_G, Eq. (3-1), derived from Taylor instability theory, accounts for vessel size and simulant sludge strength. From the experimental results in Figs. 3-9 and 3-10 we infer a gravity yield parameter of $Y_G = 0.06$ for annular containers and $Y_G = 0.09$ for cylindrical containers, respectively. These Y_G values for the stability boundaries (see vertical dashed lines in Figs. 3-9 and 3-10) were selected where the data give high confidence that systems would be unstable at these conditions. This was done because the application of these criteria is to determine conditions when large-scale vessels will certainly have unstable vessel-spanning bubbles for a specific material. The Y_G selections were also based on the large scale gas injection experiments, since these experiments were performed in a controlled manner and it is felt that they best represent actual vessel-spanning bubble/sludge plug morphology. It is also evident from the results in Figs. 3-9 and 3-10 that a sludge plug in an annular container of outer diameter D is more stable than a sludge plug in a cylindrical container of diameter D.

Figure 3-12 Stable three layer configuration in cylindrical container (vessel spanning bubble + sludge layer + water layer).

3.5 Experimental Observations and Results from the Obround Container Experiments

Table 3-3 summarizes the results of the obround sludge plug/vessel spanning bubble stability experiments. These stability experiments were performed after the obround angled-wall experiments were performed (see Section 4.5). In the angled wall experiments vessel spanning bubble formation was precluded by gas escape in the "corners" of the container where the circular sections are attached to the straight sections and where the edges of the angled walls are located. In order to ensure that the angled walls were responsible for vessel spanning bubble prevention and not the corners themselves a number of stability tests were performed with relatively strong simulant sludges of weight percent 56 to 60. Over this range the obround sludge plug/vessel spanning bubble composites are predicted to be stable to buoyancy forces based on the stability criterion $Y_G \gtrsim 0.09$ and the end-to-end length of the obround container, 0.4778 m (18.81 in). As indicated in Table 3-3 these obround sludge plugs were stable and we may conclude that the angled walls prevented the sludge plugs from rising in the angled wall experiments.

The first test performed with 53 wt% kaolin resulted in a stable obround sludge plug. This observation proved to be puzzling since subsequent tests with 53 and 54 wt% kaolin revealed unstable obround sludge plug behavior. All the failures were the same in that they were initiated by a bubble rising up through the sludge about midway between the center of the circular ends and the far ends of the container (see Fig. 3-13). No bubble rise was observed in the rectangular section of the container indicating perhaps that the rectangular section does not get involved in the instability. Indeed by selecting the diameter of the circular ends as the appropriate characteristic length for insertion into the gravity yield parameter we get the expected value $Y_G \cong 0.09$ for the stable/unstable transition yield parameter that was derived from the experiments with cylindrical containers. Of course one cannot rule out the possibility that the width of the rectangular section of the container is the correct length scale since the width and diameter of the circular ends are numerically identical. If this is the case one may say that for rectangular containers the width dictates the onset of Taylor instability, although this conclusion should be verified by experiment (see Section 5.2).

Table 3-3

Experimental Conditions and Results for Instability Tests of Vessel Spanning Bubbles in the Obround Container Using the Air Bubble Injection Method

Kaolin (wt%)	Density (kg/m^3)	Shear Strength$^{(1)}$ (Pa)	Ratio of Depth to Diameter$^{(2)}$	$Y_G^{(2)}$	Stability
52.0	1477	222	~ 0.5	0.054	unstable
52.0	1477	222	~ 0.5	0.054	unstable
53.0	1490	262	~ 0.5	0.064	stable
53.0	1490	262	~ 0.5	0.064	unstable
54.0	1504	312	~ 0.5	0.076	unstable
54.0	1504	312	~ 0.5	0.076	unstable
54.5	1512	340	~ 0.5	0.082	stable
55.0	1518	370	~ 0.5	0.089	stable
56.0	1533	440	~ 0.5	0.105	stable
57.0	1548	523	~ 0.5	0.123	stable
58.0	1563	620	~ 0.5	0.145	stable
59.0	1579	736	~ 0.5	0.170	stable
60.0	1594	874	~ 0.5	0.200	stable

(1) – Shear strength from correlation in Fig. 4.13 of Rassat et al. (2003).

(2) – Based on 0.28-m (11.0 in) diameter of circular ends or, equivalently, width of rectangular section.

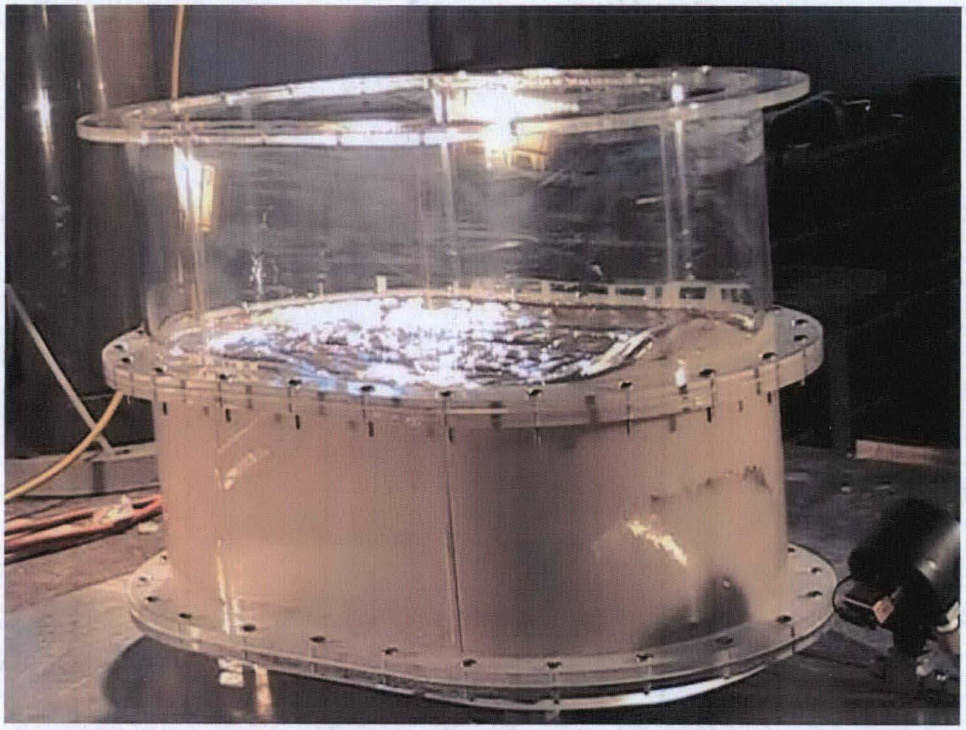


Figure 3-13 Taylor bubble rising to the surface of sludge plug in the cylindrical section on the right-hand side of obround container. Bubble has expanded to the lower wall (dark triangular shadow at bottom of container) and is about to break through surface where sludge dome has formed.

3.6 Video Camera Recordings

All the experiments on sludge plug failure by Taylor instability were recorded using a video camera and the videos are available on a DVD upon request.

4.0 SLUDGE PLUG FAILURE AND PREVENTION OF A VESSEL SPANNING BUBBLE BY DESIGN

4.1 Introduction

When the gravity yield parameter exceeds the threshold values for sludge plug stability, container-internal structural designs dedicated to fail (bust) the rising sludge plug or prevent the vessel-spanning bubble from forming in the first place should be considered. Two designs were tested as part of the present study: (i) a shelf (or rim) attached to the wall of the container to fail (bust) an otherwise stable rising sludge plug and (ii) an angled wall to prevent the formation of a vessel-spanning bubble.

The actual small sludge storage containers, as opposed to the laboratory model containers tested and described here, include an internal polymer bag for holding the sludge. When the bag is filled with sludge it will press up against the container floor and wall(s). It is anticipated that the woven bag material will provide escape paths along the wall for the metal-particle generated gas and thereby prevent the formation of a vessel-spanning bubble. Thus, while the primary purpose of the bag is to hold the sludge, it was tested as a potential vessel spanning bubble suppressor and is included here under the heading of vessel spanning bubble prevention by design.

4.2 Sludge Buster Experiments in Cylindrical Container

The "sludge buster design" tested is illustrated in Fig. 4-1; it is simply a rim (or circular shelf) attached to the wall of the 0.445 m ID circular test container at the flange where the middle section of the container is fastened to the upper section of the container. Four sludge-buster-shelves were constructed from 0.513-m diameter, 0.453-cm thick Plexiglas discs. Each shelf was formed by cutting a hole in a disc whose center coincided with the center of the disc. The widths of the shelves produced in this manner are 0.0191 m (0.75 in), 0.0699 m (2.75 in), 0.146 m (5.75 in) and 0.197 m (7.75 in). Only the narrowest (0.0191 m) and widest (0.197 m)

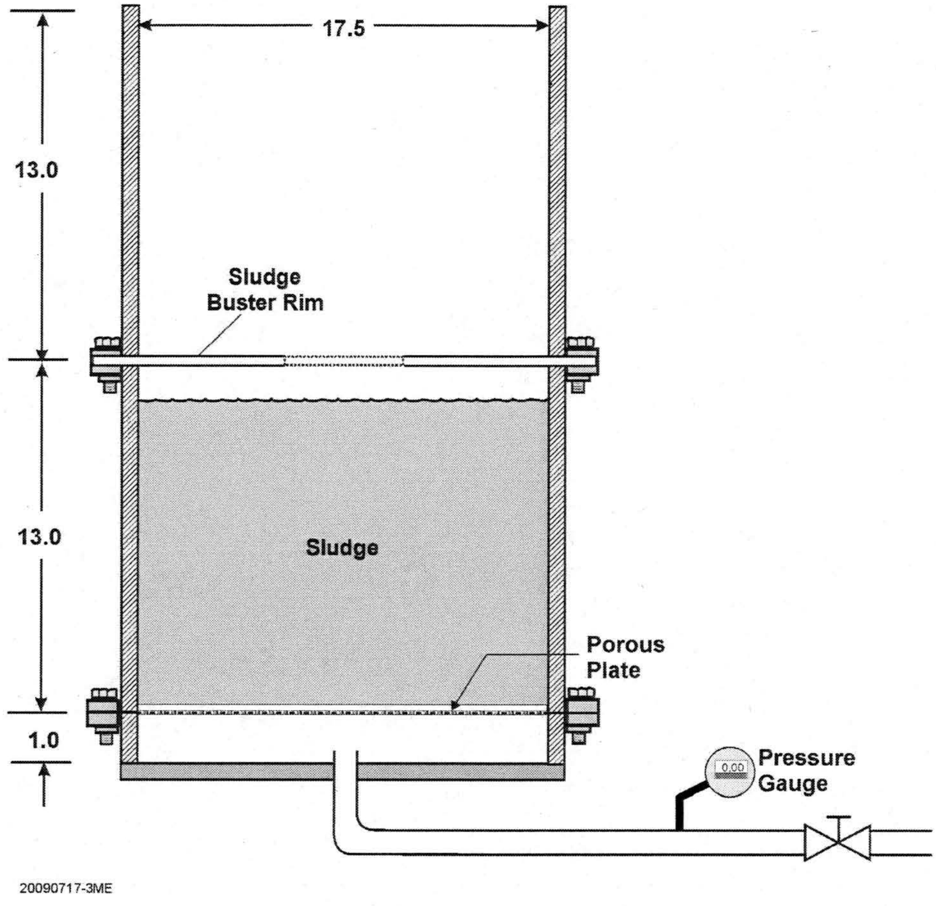
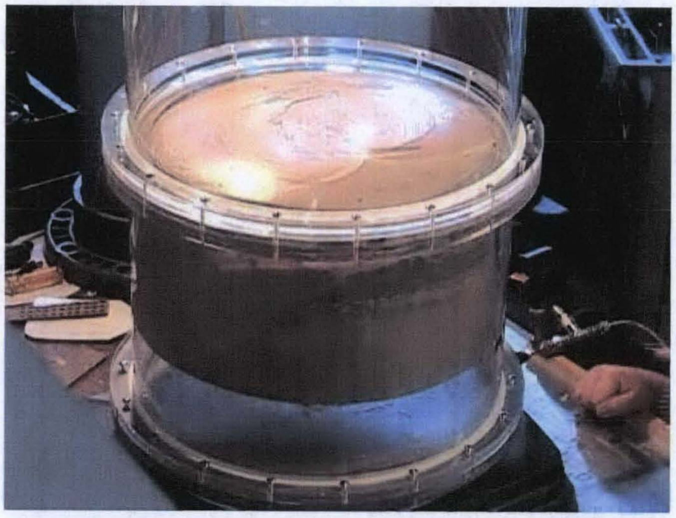


Figure 4-1 Schematic diagram of cylindrical container with sludge buster rim (all dimensions are in inches).

shelves were used in the tests. The purpose of the shelf is to cause the sludge-plug flow to contract and, hopefully, destabilize the plug by shear.

Five tests were performed, three with 57 wt% kaolin/water mixtures (Y_G = 0.113) and two with 60 wt% kaolin/water mixtures (Y_G = 0.231). In all but one of the sludge buster tests, the kaolin sludge layers were left undisturbed on the porous plate for about one hour before conducting the tests. The exception was a sludge buster test with 60 wt% kaolin which was allowed to age for about 18 hours. The evidence in the literature suggests that the effect of aging the kaolin simulant for this length of time is to increase its strength by as much as a factor of two (Van Kessel and Blom, 1998). According to the results displayed in Fig. 3-10, the 57 wt.% mixture is just inside the stable regime while the 60 wt% mixture is definitely stable. In one of the tests with the 57 wt% mixture the sludge plug did not rise to the sludge buster shelf but, instead, failed naturally shortly after it lifted off the porous plate, indicating that the 57 wt% mixture in the 0.445-m diameter cylindrical container is borderline unstable. In three other sludge buster tests with the 57 and 60 wt% mixtures aged for about one hour the sludge plug reached the shelf and failed, either upon pressing up against the bottom of the shelf or after flowing a short distance (~ 4.0 cm) past the shelf. The mode of failure was the same in all three experiments (see Fig. 4-2). A gas film spread out circumferentially between the bottom of the sludge column and the container wall and then propagated with considerable speed (compared with the rate of rise of the sludge plug) to the top of the plug whereupon the sludge plug collapsed. Unlike during the sludge plug failures by Taylor instability, the thin penetrating gas film did not grow into a large bubble.

The mode of failure of the 60 wt% kaolin sludge plug which was aged for 18 hours was different than the presumably weaker sludge plugs discussed in the foregoing. The sludge plug did not fail until about two-thirds of the sludge column passed through the opening formed by the sludge buster shelf. Just prior to failure the bottom surface of the sludge plug changed from flat to concave and large cracks developed on the bottom and top surfaces of the plug. Plug failure was indicated by the slow depressurization of the underlying gas column. While the actual location of the gas leak could not be found, it was obvious from the declining pressure gage readings that gas was penetrating the vertical thickness of the sludge plug probably through



(a) Just before failure.

(b) After failure.

Figure 4-2 Sludge plug morphology in cylindrical container with sludge buster shelf: (a) just after pressing up against sludge buster shelf and (b) after failure and collapse. The circumferential "shadow" in Fig. (a) is the top portion of the spreading gas film that ultimately breaks through the surface of the plug. Note in Fig. (b) the path that remains for sustained gas flow to the surface after failure.

one or more cracks that traversed the thickness of the plug. About 15 minutes after the leak was detected the sludge plug collapsed back to the porous plate. Unfortunately, the video camera stopped recording before the sludge plug collapsed. Figure 4-3 shows the last frame of the video when about one-third of the sludge column was above the shelf.

The results of the sludge buster experiments in the large cylindrical container are summarized in Table 4-1.

4.3 Sludge Buster Experiments in Obround Container

The ledge-shaped sludge buster design used in the cylindrical container and described in Section 4.2 was also employed in the obround container. The ledge is illustrated in Fig. 4-4 which shows a side view of the obround container (see Fig. 3-6). The ledge is actually an obround-shaped 'ring" of plastic material of width 0.0572 m (2.25 in.). It is attached to the container wall over the entire inside peripheral length of the container by the bolts that hold the middle and upper sections of the container together, thereby forming a ledge that protrudes 0.0191 m (0.75 in.) into the container.

Two tests were performed with 0.15-m (6.0 in.) deep sludge layers made up of 60 wt% kaolin/water mixtures. The initial location of the surface of the sludge layer was approximately 0.025 m (1.0 in.) below the sludge buster ledge. We know from our previously discussed sludge stability tests that 60 wt% obround sludge plugs are stable in an obround container with smooth vertical walls (see Section 3.5).

In the first test the sludge plug collapsed immediately after pressing up against the ledge (see Fig. 4-5). In the second test sludge plug collapse occurred after a distance of about 1/4 depth of sludge plug rise past the shelf. Much like in the cylindrical vessel with a sludge buster ledge, the reason for collapse was the intrusion of gas between the wall and the sludge to the top of the sludge plug.

Figure 4-3 Strong sludge plug (> 1600 Pa) rising through contraction established by sludge buster shelf located at flange. The extruded portion of the sludge plug above the shelf has separated from the container wall. Failure occurred after about two-thirds of the plug was extruded.

Table 4-1

Experimental Conditions and Results of Sludge Buster

Tests in 0.445-m Diameter Cylindrical Container

Kaolin (wt.%)	Density (kg m^{-3})	Shear Strength (Pa)	Y_G	Shelf Width (m)	Aging Time (hr)	Sludge Plug Failed
57.0	1548	523	0.078	0.197	1.0	Yes[2]
57.0	1548	523	0.078	0.0191	1.0	Yes[2]
57.0	1548	523	0.078	0.0191	1.0	Taylor[1] Unstable
60.0	1594	874	0.126	0.0191	1.0	Yes[2]
60.0	1594	> 874	0.126	0.0191	18.0	Yes[3]

1) Sludge plug did not rise to sludge buster shelf; failed by Taylor instability.
2) Failed shortly after contact with shelf by gas penetration along container wall.
3) Failed long after contact with shelf, probably by gas penetration through internal cracks.

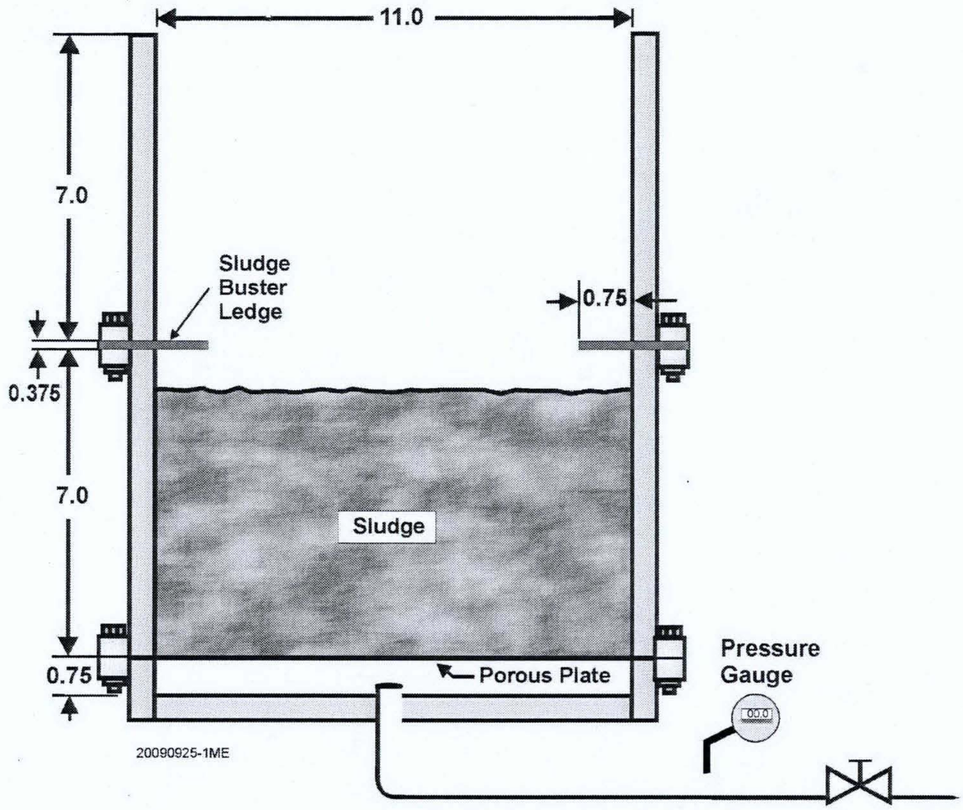


Figure 4-4 Side view of obround container (see Fig. 3-6) with sludge buster ledge (all dimensions are in inches).

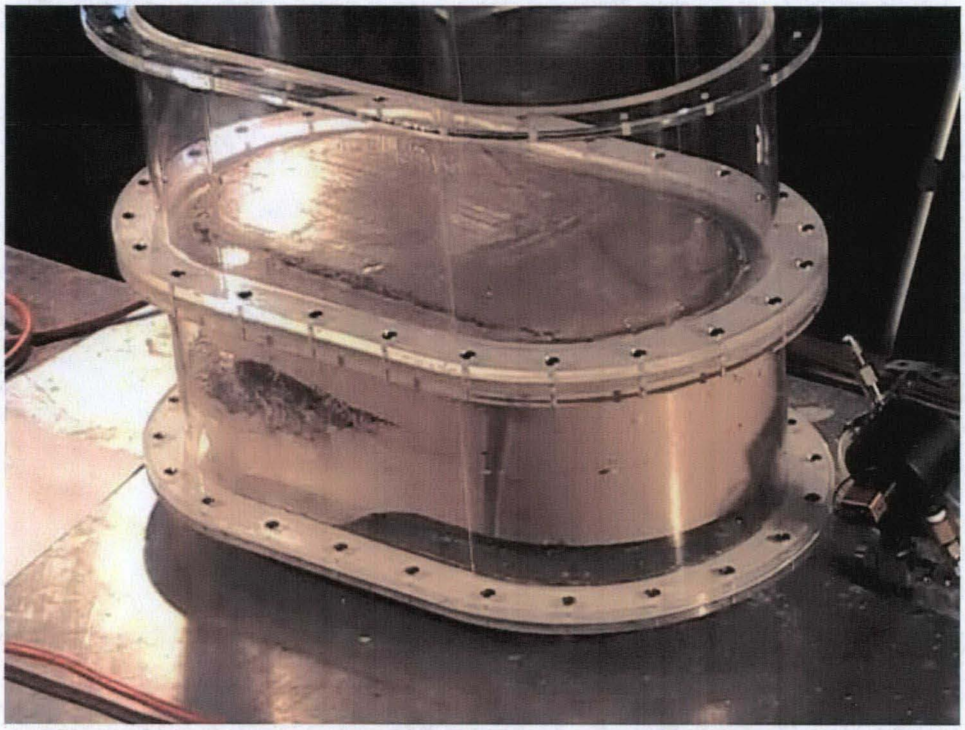


Figure 4-5 Sludge plug failure and collapse just after pressing up against sludge buster shelf. Sludge plug collapse "wave" propagating from left where collapse has occurred to right where the sludge plug is still suspended above vessel spanning bubble. The crack at the surface of the sludge plug coincides with the edge of the shelf.

4.4 Cone Shaped Containers for Vessel Spanning Bubble Prevention

Based on the behavior observed during the sludge-buster-shelf experiments described in the foregoing, particularly the sludge plug's inability to conform to small obstructions in its path, the idea of an angled-wall or cone-shaped sludge storage container which by itself may preclude the formation of a vessel spanning bubble seems rather appealing (Gauglitz and Schmidt, 2009). A truncated cone shaped container was fabricated and experiments on the response of initially truncated-cone-shaped simulant sludge plugs to gas injection from below were performed.

The laboratory model, plastic truncated cone-shaped container is shown schematically in Fig. 4-6. The base of the cone which coincides with the floor of the lower plenum section is 0.2 m (7.9 in.) in diameter. In the middle section of the container the sludge plug initially rests on an 0.22-m (8.66 in.) diameter porous plate. The wide opening at the top of the container is 0.549 m (21.6 in.) in diameter. The height of the conical container not counting the air plenum is 0.648 m (25.5 in.). The angled wall of the conical container is 14.2 degrees from a vertical line. Six "cone tests" were completed and the results are presented in Table 4-2.

Referring to Table 4-2 we note that in five of the tests the criterion for Taylor instability, namely Eq. (3-1) with D equal to the diameter of the base of the sludge cone (0.22 m), was not satisfied. Nevertheless the sludge plugs did not rise a measurable distance off the porous plate. Even when the instability criterion was satisfied (last entry in Table 4-2) no sludge plug upward displacement followed by Taylor instability was observed. Instead, in all the cone tests, a gas front was observed to gradually propagate upward from the porous plate to the top of the sludge cone along one side of the container wall. Behind the front was a continuous gas film through which the injected gas ultimately escaped to the atmosphere.

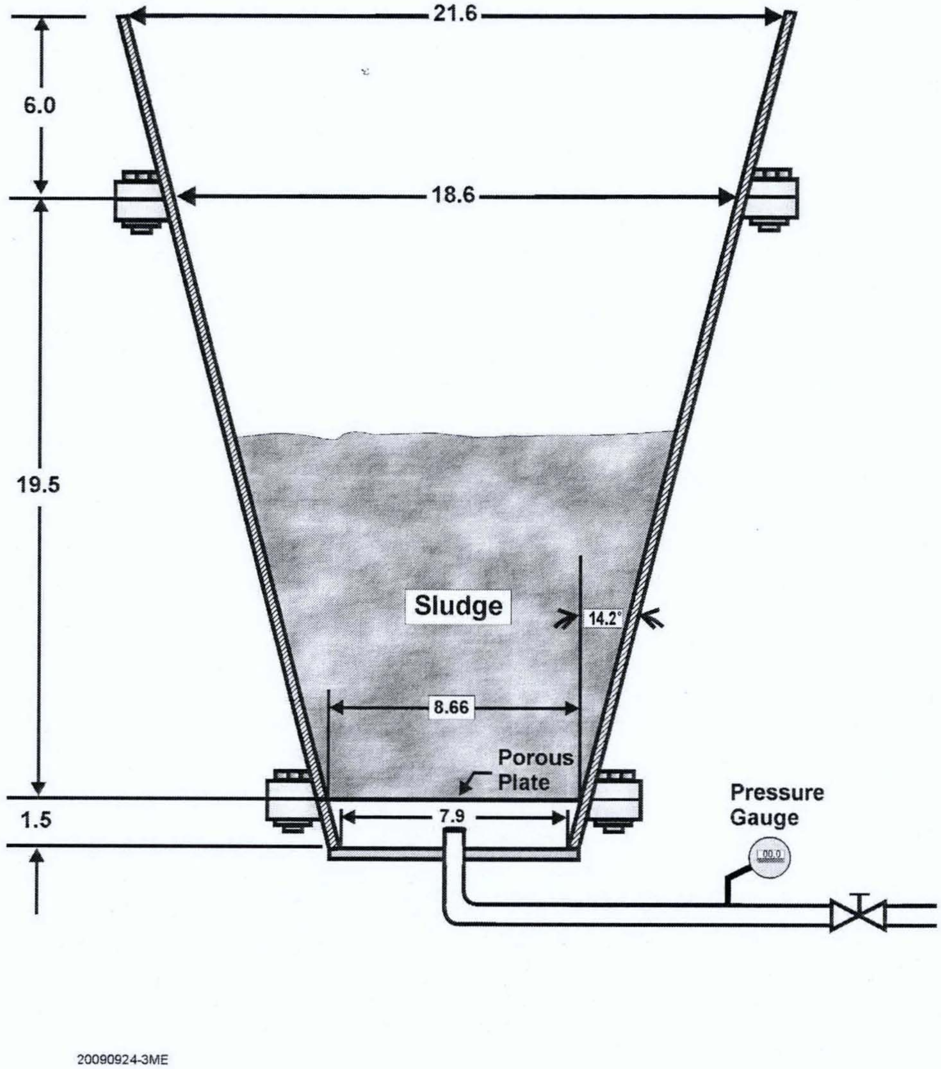


Figure 4-6 Schematic diagram of conical container holding sludge cone (all dimensions re in inches).

Table 4-2

Experimental Conditions and Results of Sludge Behavior Tests in Conical Container

Kaolin (wt.%)	Density (kg m^{-3})	Shear Strength (Pa)	Y_G	Sludge Depth (m)	Controlled Gas Flow (cm^3 min^{-1})	Vessel-Spanning Bubble
55.0	1519	371	0.133	0.3	No	No
55.0	1519	371	0.133	0.3	No	No
55.0	1519	371	0.113	0.3	1.0	No
58.0	1563	620	0.184	0.3	1.0	No
58.0	1563	620	0.184	0.51	1.0	No
51.0	1463	187	0.0593	0.3	1.0	No

In the first two cone tests the gas injection rate was not monitored and the elapsed time for pressure buildup in the plenum and gas film breakthrough along the wall at the top of the sludge cone was about 30 min. A concern was raised that if the gas injection rate was very slow and/or the sludge cone was taller the sludge material may have sufficient "relaxation time" under the influence of gravity to remain in contact everywhere with the container wall and prevent the intrusion of gas into the sludge/container wall interfacial region. To address this concern, in the remaining four cone tests (see Table 4-2) the gas flow rate was measured and maintained at the very slow injection rate of about 1.0 cm^3 min^{-1}, and in one of these tests the sludge depth was increased from 0.3 to 0.51 m. Even at this slow rate of injection gas front penetration and breakthrough was observed after about 2.0 to 3.0 hours of operation depending on the depth of the sludge. The only difference between the fast and slow gas injection experiments was that in the former case gas release to the atmosphere was continuous whereas in the latter case periodic gas release behavior was observed due to the sealing and reopening of the gas release path. This periodic behavior was inferred from the plenum pressure readings which were observed to slowly oscillate about the hydrostatic pressure established by the overlying sludge cone.

Figure 4-7 is a photograph of the 0.51-m deep simulant sludge cone resting on the porous plate in the conical model container after gas breakthrough. The dark patches that can be seen through the container wall are segments of the gas film pathway from the air plenum to the surface of the sludge cone.

Figure 4-7 Photograph of conical container with sludge cone. The dark patches are segments of the gas escape path.

4.5 Obround Container with Angled Walls

Encouraged by the results of the cone shaped container experiments, a middle section for the obround container was fabricated with slightly angled walls of about 4.1° from the vertical. Recall that the corresponding angle of the cone container was 14.2°. A side view of the obround container with the angled walls is illustrated in Fig. 4-8. The angled walls were attached to the straight sides of the obround container and lengthwise extend short distances (4.0 mm) into the cylindrical ends. The length and height of each of the two angled walls are, respectively, 0.206 m (8.125 in.) and 0.178 m (7.0 in.). The angled wall thickness at its base is 12.7 mm (0.5 in.).

Two tests were performed with the angled walls. In each test a 0.15-m (6.0-in.) deep layer of 60 wt% kaolin (shear strength 1600 Pa) was used. In both tests the sludge plugs were displaced upward by gas injection a short distance of about 6.4 mm (0.25 in.) when a pressure decrease in the air plenum was signaled by the gauge, indicating that air was escaping around or through the sludge plug to the atmosphere. In the first test air bubble release at the surface of the sludge layer at the vertical edge of one of the angled walls was observed shortly after the plenum pressure started to decrease. Some time later another bubbling site appeared at the other edge of the same angled wall. No gas columns or films were observed along the container wall at these locations. Either it was difficult to see the gas columns in the corners formed by the edges of the angled wall or the gas columns penetrated the interior of the sludge a short distance away from the wall. In the second test a gas escape path was observed through the container wall in the vicinity of one of the edges of the angled wall on the opposite side of the container from where the gas was escaping during the first test. Bursting gas bubbles were visible at the surface where the air penetrated the sludge. Interestingly enough, shortly after the first gas escape path was observed another path opened up, but this time in the center of the container about midway between the two angled walls. In both tests, while the air flow remained on, the obround sludge plugs remained suspended above the porous plate at the initial liftoff distance of about 6.4 mm (0.25 in.).

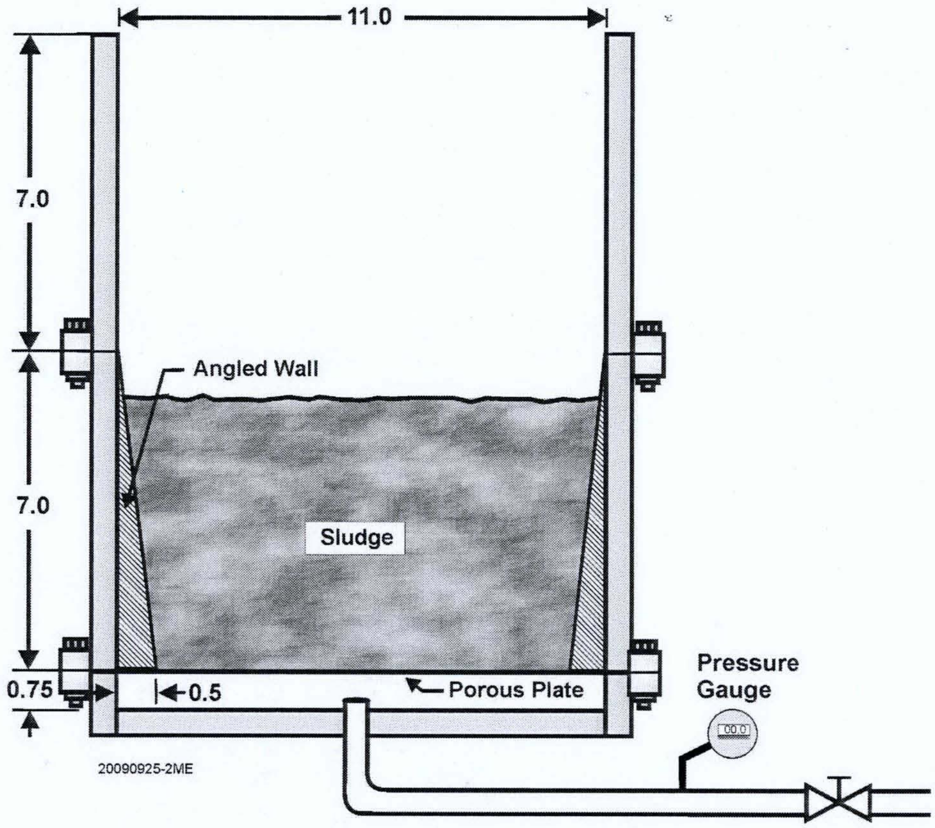


Figure 4-8 Side view of obround container (see Fig. 3-6) with angled walls (all dimensions are in inches).

4.6 Bag Material Liner as a Vessel Spanning Bubble Suppressor

One test with bag material liner (TENCATE Geo tube® GT500 woven polypropylene) was performed. The large cylindrical test container was used (see Fig. 3-4 and Fig. 4-9). A continuous sheet of bag material was attached to the inside wall of the container at the porous plate with a thick bead of silicon sealant. The bottom edge of the liner was essentially submerged in the sealant bead. Sealant was also applied to the bottom of the porous plate at the air plenum wall to protect the overlying bead from the elevated plenum pressure. The bag material sheet covered the entire inside wall of the container up to the top of the container where it was attached to the wall with clamps. The sludge layer consisted of 60 wt% kaolin (shear strength 1600 Pa) and it pressed the bag material against the container wall over the 0.13-m (5.0-inch) height of the sludge layer.

Upon pressurizing the plenum the injected air was observed to flow around the silicon seal and up along the bag material liner to the top of the sludge plug. Apparently the bag material liner, which is a 1.8-mm thick weave, provided numerous microchannels (or gaps) for gas flow between the sludge column and the container wall. No lifting of the sludge plug was observed.

4.7 Video Camera Recordings

All the sludge plug failure by design tests were videotaped and the videos are stored on a DVD which is available upon request.

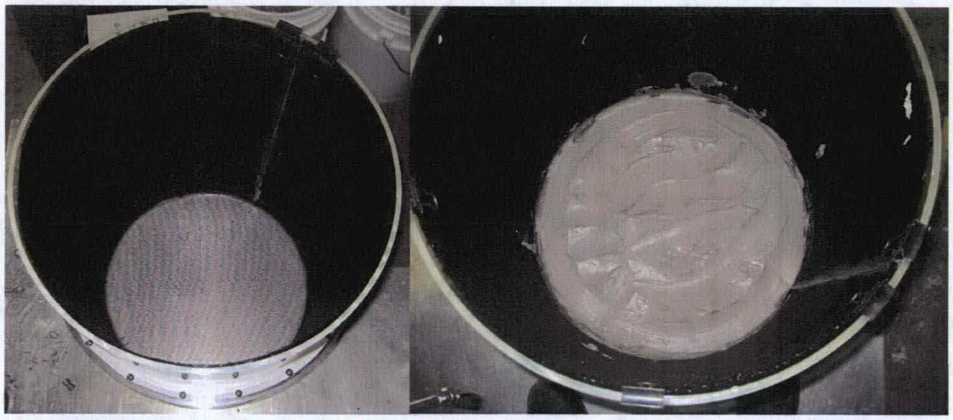


Figure 4-9 Cylindrical test container lined with woven polypropylene material before and after simulant sludge was added to the container.

5.0 RECOMMENDATIONS FOR FUTURE WORK

5.1 High-Shear-Strength-Sludge Simulant

To test very high shear strength sludge materials in the range, say, 2 x 10^3 to 5 x 10^3 Pa sludge stability tests should be performed with Settler sludge simulant. Settler sludge gains strength during aging (consolidation) and can readily be mixed and stirred initially when it is relatively weak. These strengths can not be achieved with in-vessel kaolin simulant due to the difficulty of mixing and stirring the kaolin/water pair, which reaches full strength immediately upon mixing.

5.2 Rectangular Container

Some sludge storage containers are rectangular in shape and concerns have been raised regarding the potential for vessel-spanning bubbles in these containers (Plys et al., 2009). The major uncertainty in evaluating the stability of rectangular sludge plugs is the unknown characteristic length for insertion into the gravity yield parameter. Is the appropriate length the longer or shorter side of the container? Stability experiments in rectangular Plexiglas containers should permit unambiguous determination of the correct length scale.

6.0 REFERENCES

Baker, R. B., Makenas, B. J., and Pottmeyer, J. A., 2000, "Observations of K Basins Sludge Behavior in Relation to Sludge Container Design and Storage at T Plant," HNF-6705 Rev. 0, Fluor Hanford, Inc., Richland, Washington.

Barnes, J. F., Blewitt, P. J., McQueen, R. G., Meyer, K. A. and Venable, D., 1974, "Taylor Instability in Solids," J. Appl. Physics 45, pp. 727-732.

Burns, C. A., Gauglitz, P. A., and Russell, R. L., 2010, "Shear Strength Correlations for Kaolin/Water Slurries: A Comparison of Recent Measurements with Historic Data," Pacific Northwest National Laboratory Report PNNL-19094.

Epstein, M., 2002, "Taylor Instability of a High-Strength Sludge Plug in a Storage Container," Appendix in "Vessel-Spanning Bubble Formation in K Basin Sludge Stored in Large-Diameter Containers," by G. Terrones and P. A. Gauglitz, Pacific Northwest National Laboratory Report PNNL-13805 (March).

Epstein, M. and Plys, M. G., 2002, "Hydrodynamic and Thermal Behavior of Reactive Sludge in Storage Containers," Fauske & Associates Report FAI/02-39 (May).

Gauglitz, P. A., Terrones, G., Muller, S. J., Denn, M. M., and Rossen, W. R., 2001, "Mechanics of Bubbles in Sludges and Slurries," Pacific Northwest National Laboratory Report PNNL-13748.

Gauglitz, P. A., 2002, "Simple Experiments to Confirm Taylor Instability Criterion," E-mail to M. Epstein (February 7).

Gauglitz, P. A. and Schmidt, A. J., 2009, "Cone-Shaped Vessel Concept," oral presentation at Bubble Management Workshop, Richland, WA (March 19).

Griffith, P., 1963, "Bubble Rise Velocity in Tubes of Noncircular Cross Section," ASME Paper No. 63-HT-20, Nat. Heat Transfer Conf., Boston, Mass.

Miles, J. W., 1966, "Taylor Instability of a Flat Plate," General Dynamics, General Atomic Division Report GAMD-7335 (August).

Plys, M. G., Lee, S. J. and Epstein, M., 2009, "Settler Sludge Behavior During Retrieval," Fauske & Associates Report FAI/08-30 (February).

Powell, M. R., Gates, C. M., Hymas, C. R., Sprecher, M. A. and Morter, N. J., 1995, "Fiscal Year 1994 1/25th-Scale Sludge Mobilization Testing," Pacific Northwest National Laboratory Report PNNL-10582.

Rassat, S. D., Bagaasen, L. M., Mahoney, L. A., Russell, R. L., Caldwell, R. L., and Mendoza,

D. P., 2003, "Physical and Liquid Chemical Simulant Formulations for Transuranic Wastes in Hanford Single-Shell Tanks, 2003," Pacific Northwest National Laboratory Report PNNL-14333 (July).

Van Kessel, T. and Blom, C., 1998, "Rheology of Cohesive Sediments: Comparisons Between a Natural and an Artificial Mud," J. Hydraulic Research 36, pp. 591-611.

Appendix B Calculation Sludge Plug Stability as a Function of Shear

CHPRC Calculation Cover Sheet and Revision Summary

Section 1: Identification		
1. Project Identifier ~~A-21C~~ TD 1/28/10	2. Modification Description Title/Subject Calculate Sludge Plug Stability as a Function of Shear Strength	3. Page B-3 of B-6

4. Use of Form

[X] Calculation [ ] Engineering Analysis [ ] Software Installation [ ] Technical Basis [ ] Other

5. Job Title	6. WBS Number	7. Department/Organization
N/A	N/A	PF340000

8. Calculation Number	9. Affected Building Numbers	10. Room	11. Floor
PRC-STP-00177 Revision 0	N/A	N/A	N/A

12. Independent Verification Required?	13. Performance Category (PC)
[X] Yes [ ] No	[ ] 0 [ ] 1 [ ] 2 [ ] 3 [ ] N/A

Section 2: Preparation, Review, and Approval

14. Rev. No.	15.	16. Originator	17. Checker	18. Approver: Design Authority or System Engineer	19. Supersedes Calc. No. or Rev. No.	20. Field Confirmation Required?
0	Print Name	Tarandeep Dhaliwal	Michael E. Johnson	Michael E. Johnson	N/A	[ ] Yes [X] No
	Sign	TD Dhaliwal	Michael E. Johnson	Michael E. Johnson		
	Date	1/20/10	1/20/10	1/20/10		
	Print Name					[ ] Yes [ ] No
	Sign					
	Date					
	Print Name					[ ] Yes [ ] No
	Sign					
	Date					

Section 3: Revision Summary

21. Rev. No.	22. Description/Reason for Revision	23. Affected Pages
0	Initial Release of Calculation	

Registration Stamp (as applicable):	Classification Review:
Signature/Date: ______________________	Signature/Date: ______________________

A-6004-793 (REV 0)

Prepared by:	Tarandeep Dhaliwal			
Date:	6-Jan-10			
Revision:	0			
Reviewed by:	Michael E Johnson			
Date:	7-Jan-10			

Purpose: Determine if the KW Basin sludge will form stable vessel spanning bubbles in cylindrical and annular STSC and cylindrical small canisters.

Approach: Use the density and shear strength of sludge and diameter of container to calculate the value of the Taylor instability single dimensionless gravity-yield parameter in order to determine if a stabel vessel spanning bubble forms.

Assumptions

1 The diameter, D, of the annular STSC used to calculate the Taylor instability single dimensionless gravity-yield parameter is taken to be the diameter of the outer cylindrical wall of the annular container. (See Fauske & Associates Report, p13)

Inputs

1 Diameter of container

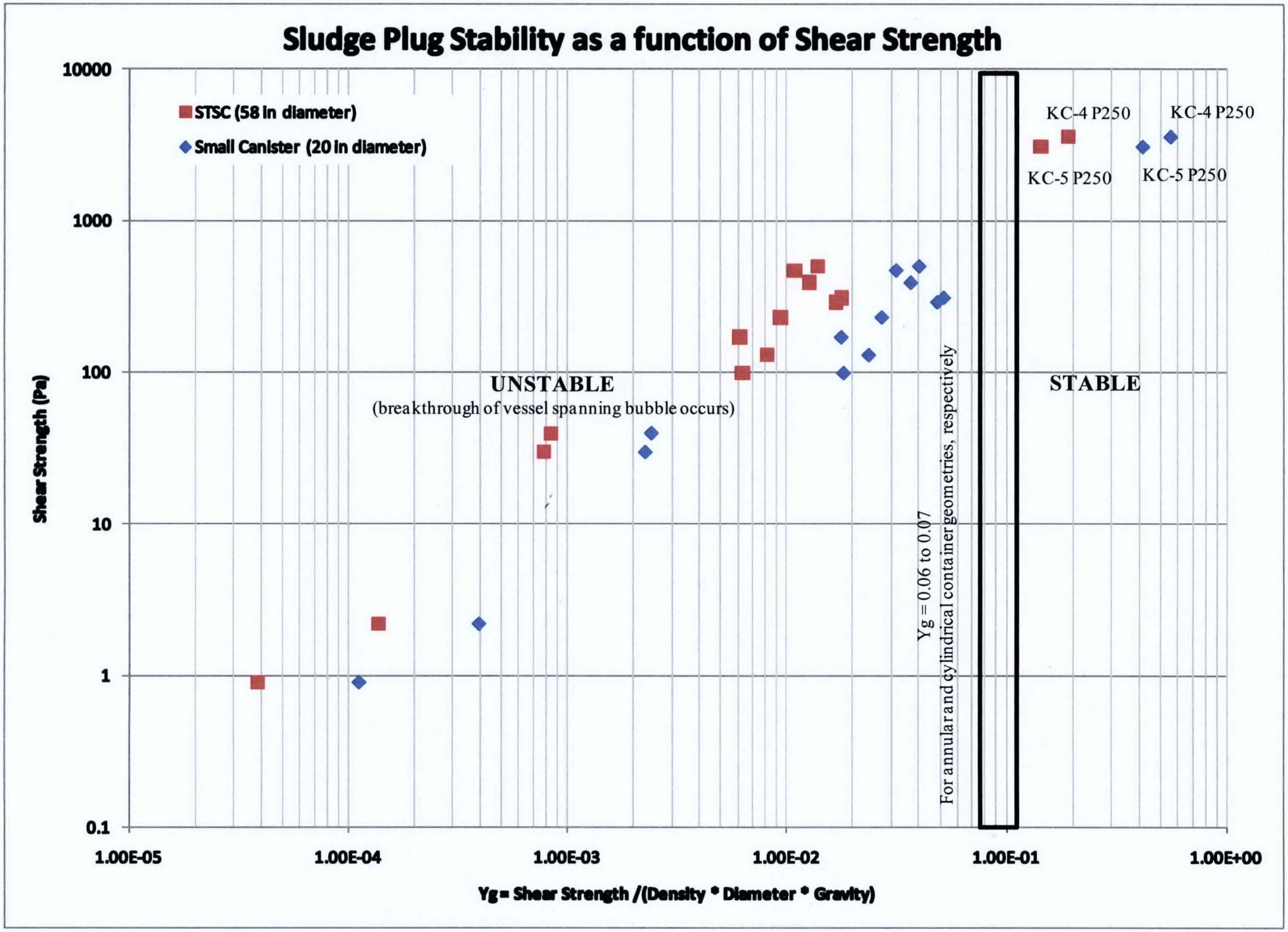
Diameter (annular and non-annular STSC):	58" =	1.4732	m
Diameter (Small Canister):	20" =	0.508	m

2 Density and Shear Strength of sludge samples

	Shear Strength, Pa	Settled Density, g/cm3	Settled Density, kg/m3
1995 KE Floor and Pits Sludge			
KES-M-13 Top	2.2	1.11	1110
KES-T-20 Top	0.9	1.6	1600
1996 KE Canister Sludge			
96-04 U/L	99	1.09	1090
96-06 U/M	230	1.7	1700
96-06 M	170	1.92	1920
96-06 M/L	500	2.5	2500
96-06 L	470	2.99	2990
96-11 U/L	130	1.1	1100

			1996 KW Cansiter Sludge			
			96-21 Rec	40	3.3	3300
			96-24 Rec	30	2.64	2640
			1999 Consolidated Sludge Samples			
			KC-2/3 M250	390	2.13	2130
			KC-4 P250	3600	1.3	1300
			KC-4 M250	310	1.2	1200
			KC-5 P250	3100	1.5	1500
			KC-5 M250	290	1.2	1200
		Basis:	SNF-7765, Revision 3C, Supporting Basis for SNF Project Technical Databook, 2006, Appendix C, Section C.5.0, Table C-2			
	3	g =	9.81	m/s2		
Equations						
	1	Dimensionless gravity-yield paramter, YG				
			$Y_G \ge \frac{\tau_0}{\rho_{sl} g D}$			
			The dimensionless yield parameter is greater than or equal to the shear strength of the sludge divided by the product of density of the sludge, gravity, and the diameter of the container.			
Calculations						
	1	Dimensionless gravity-yield parameter, YG				
				YG, STSC [Pa]	YG, Small Canister [Pa]	
			1995 KE Floor and Pits Sludge			
			KES-M-13 Top	0.00013714	0.0003977	
			KES-T-20 Top	3.8922E-05	0.0001129	
			1996 KE Canister Sludge			
			96-04 U/L	0.0062846	0.0182254	
			96-06 U/M	0.00936156	0.0271485	
			96-06 M	0.00612656	0.017767	
			96-06 M/L	0.01383883	0.0401326	
			96-06 L	0.01087667	0.0315423	
			96-11 U/L	0.00817749	0.0237147	

		1996 KW Cansiter Sludge							
		96-21 Rec	0.00083872	0.0024323					
		96-24 Rec	0.0007863	0.0022803					
		1999 Consolidated Sludge Samples							
		KC-2/3 M250	0.01266935	0.0367411					
		KC-4 P250	0.19161453	0.5556821					
		KC-4 M250	0.01787515	0.0518379					
		KC-5 P250	0.14300121	0.4147035					
		KC-5 M250	0.01672192	0.0484936					


Sludge Plug Stability as a function of Shear Strength
STSC (58 in diameter)
Small Canister (20 in diameter)
KC-4 P250
KC-4 P250
KC-5 P250
KC-5 P250
UNSTABLE
(breakthrough of vessel spanning bubble occurs)
STABLE
Yg = 0.06 to 0.07
For annular and cylindrical container geometries, respectively
10000
1000
100
10
1
0.1
Shear Strength (Pa)
1.00E-05
1.00E-04
1.00E-03
1.00E-02
1.00E-01
1.00E+00
Yg= Shear Strength /(Density * Diameter * Gravity)