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In Situ Void Fraction and Gas Volume in Hanford Tank 241-SY-101 as Measured with the Void Fraction Instrument

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

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Abstract

The void fraction instrument (VFI) was deployed in Tank 241-SY-101 three times in 1998 to confirm and locate the retained gas (void) postulated to be causing the accelerating waste level rise observed since 1995. The design, operation, and data reduction model of the VFI are described along with validation testing and potential sources of uncertainty. The test plans, field observations and void measurements are described in detail, including the total gas volume calculations and the gas volume model. Based on 1998 data, the void fraction averaged 0.013 ± 0.001 in the mixed slurry and 0.30 ± 0.04 in the crust. This gives gas volumes (at standard pressure and temperature) of 87 ± 9 scm in the slurry and 138 ± 22 scm in the crust for a total retained gas volume of 221 ± 25 scm. This represents an increase of about 74 scm in the crust and a decrease of about 34 scm in the slurry from 1994/95 results. The overall conclusion is that the gas retention is occurring mainly in the crust layer and there is very little gas in the mixed slurry and loosely settled layers below. New insights on crust behavior are also revealed.

Summary

The Void Fraction Instrument (VFI) has now been operated five times in Tank SY-101: twice in the winter of 1994/95 and thrice in the summer of 1998. Tests were conducted in riser 11B on December 21, 1994 and in riser 4A on January 17, 1995. In 1998, the VFI was operated in riser 11B on June 29 and July 22, and in riser 1C (after temporary removal of the Enraf® level gauge) on September 11. The June 29 test was 12–18 hours after a pump run aimed approximately at 11B, while the July 22 test was three days after a similarly aimed pump run. The September 11 test was about 12 hours after a pump run aimed at riser 1C. Both of the 1994/95 tests were conducted approximately one day after a pump run aimed roughly perpendicular to the riser. One void fraction measurement was obtained in the crust on June 29, and several were made on September 11. Below is a brief synopsis of all the VFI tests in SY-101.

The first VFI measurements in 1994 and 1995 were performed to assess the effectiveness of the mixer pump in preventing gas retention. The VFI found a void fraction of less than 0.01 from under the crust down to about 80 inches from the bottom. This region was characterized as a convective solid-liquid slurry with very little trapped gas. From 80 down to 40 inches the void fraction increased to about 0.04 in a loosely settled solids region. Below 40 inches, the void abruptly increased to 0.08–0.15 in an apparently undisturbed sludge layer. The average void fraction under the crust was 0.016. These trends were observed in both risers 4A and 11B. No attempt was made to measure the void fraction in the crust layer.

In the June 29, 1998 (VFI #1) test in riser 11B, the crust was lanced approximately a week before the test. A pump run aimed within 30 degrees of the riser was made 12–18 hours before the test. The first activity was to detect the bottom of the crust by raising the VFI into the crust and then lowering it in six-inch increments until the lower arm could be rotated manually. This occurred at about 54 inches below the crust surface. This process appears to have dislodged gas-containing material from the crust that descended during subsequent VFI measurements in the slurry layer and invalidated the results.

During the July 22, 1998 (VFI #2) test, also in 11B, no disturbance of the crust layer was attempted, and the crust was not lanced. A pump run aimed within 30 degrees of the riser was made three days before the test. The measured void fraction varied from 0.003 to 0.016, with an average of 0.012. These results are consistent with the 1994/95 void profile for the slurry layer.

The third VFI test, on September 11, 1998 (VFI #3), was conducted in riser 1C. The crust was not lanced because the area around 1C had been flushed with water periodically over the years. On the first traverse, four void measurements were made in the mixed slurry shortly after a pump run but without any prior disturbance of the crust. The measured void fraction for these tests ranged from 0.010 to 0.032, with an average of 0.014. These results are consistent with the 1994/95 and July 22, 1998, void fractions and confirm that that the void fraction below the crust is generally quite low.

Next, several VFI measurements were made within the crust layer where void fractions ranged from 0.210 to 0.433 with an average of 0.30. Following this, three void measurements were made in the slurry layer to confirm that crust disturbance dislodged gas-bearing material

that would be detected in subsequent samples. Void fractions for the three samples were 0.226, 0.122, and 0.084, following about the same profile as those of VFI #1. This confirms that the VFI #1 results were due to the crust disturbance and do not represent general tank conditions.

The gas volumes calculated from these data are summarized in Table S.1. The results of the three 1998 VFI tests confirm that most of the gas is stored in the crust with a relatively low void fraction in the waste from near tank bottom to just under the crust. There is no significant gas retention in the loosely settled solids, and there is no evidence of any remaining undisturbed sludge.

Table S.1. Results of Gas Volume Calculation

Crust	
Void fraction	0.30 ± 0.04
In situ volume (m^3)	145 ± 24
Standard volume (scm)	149 ± 24
Mixed Slurry	
Void fraction	0.013 ± 0.001
In situ volume (m^3)	48 ± 5
Standard volume (scm)	84 ± 9
Total	
In situ volume (m^3)	193 ± 24
Standard volume (scm)	233 ± 26

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1.0 Introduction

The flammable gas hazard in Hanford waste tanks was first recognized in the behavior of double-shell tank (DST) SY-101.[a] The waste level in this tank began periodically rising and suddenly dropping shortly after it was filled in 1980. The large, "sawtooth" level drops were taken as an indication of episodic gas releases that might pose a safety hazard. A period of intense study of this tank's behavior in 1990–1992 involving two core samples, headspace gas monitoring, and computational simulation revealed that these releases were, in fact, hazardous. The gas released from the waste was indeed flammable, and the releases were quite large. Some of them had sufficient volume to exceed the lower flammability limit (LFL) in the entire headspace and would probably have damaged the tank had the gas been ignited.

The historic gas releases in SY-101 were buoyancy-induced waste displacement events, at one time called "rollovers" (Allemann et al. 1993). In a buoyant displacement, a portion, or "gob," of the nonconvective layer near the tank bottom accumulates gas until it becomes buoyant enough to overcome the weight and strength of material restraining it. At that point, it suddenly breaks away and rises through the supernatant liquid layer. The stored gas bubbles expand as the gob rises, failing the surrounding matrix so a portion of the gas can escape from the gob into the headspace (Meyer et al. 1997).

The potential for buoyant displacements in SY-101 was mitigated in October and November 1993 by mixing the waste with a pump installed on July 4 of that year, following a large gas release event (Event I) on June 26 (Allemann et al. 1994). Mixing prevents gas retention by suspending solid particles that would have settled to form the nonconvective layer and dislodging bubbles from those particles that do settle temporarily between pump runs. For the past five years, the SY-101 mixer pump has kept the waste mobilized and prevented the buildup of flammable gas while operating only a three times a week for 25 minutes (Stewart et al. 1994; Brewster et al. 1995).

1.1 SY-101 Waste Configuration

Prior to mixer pump installation, the waste in SY-101 comprised the typical DST configuration of a crust layer floating on a convective liquid with a nonconvective, settled solids layer on the bottom. The layers are denoted as convective or nonconvective because of their characteristic temperature profiles. In a convective layer, convection circulates the waste and keeps its temperature uniform. The temperature profile in a nonconvective layer is dominated by conduction; in the nonconvective layer on the bottom, heat generation typically creates a parabolic temperature profile; heat flow through the crust into the dome space produces a nearly linear profile. This configuration is exemplified by the February 1, 1993 temperature profile in SY-101, just prior to gas release Event H, as shown in Figure 1.1.

(a) Hanford radioactive waste tanks are formally referenced as 241-SY-101, for example. However, this report will follow the common practice of dropping the 241- prefix.

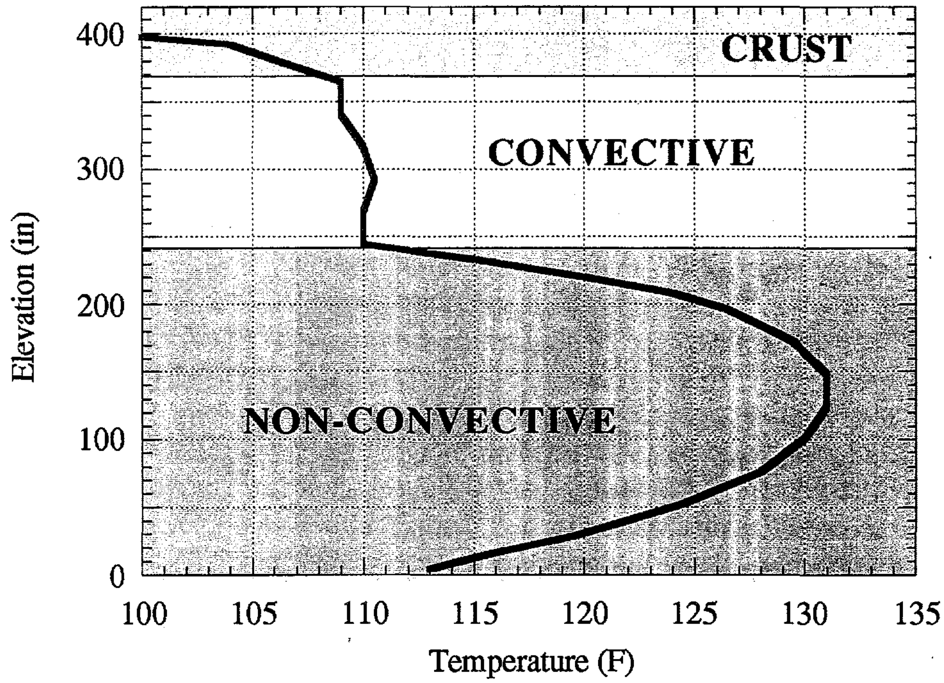

Figure 1.1. SY-101 Waste Configuration Prior to Mixing

The mixer pump mixed the convective and nonconvective layers together to prevent formation of a deep nonconvective layer and the associated large gas releases. The solids remain suspended between mixer pump runs in this convective mixed slurry layer. In fact, the Full Scale-Tests showed that only a limited amount of settling occurs after 30 days of much reduced pump operation (Stewart et al. 1994). However, some of the larger heavier solid particles apparently settle out quickly between pump runs and become nonconvective, though the solids are mobilized each time the pump is run in the region of the jet. This behavior gives rise to the title, "loosely settled layer." This post-mixing configuration is shown in Figure 1.2 along with temperature profiles from July 1994 to July 1997. Note that the temperature profiles are plotted as differences from the mixed slurry layer temperature.

For approximately two years after initial mixing, a thin, (18–24 inches) nonuniform layer of waste remained on the bottom that had not been mobilized by the mixer pump. This "undisturbed sludge" layer was the object of the first void fraction instrument (VFI) deployment in 1994 and remained of potential interest in the 1998 VFI runs as well.

The floating crust layer is not disturbed by mixer pump operation. In fact, the last major disturbance to the crust occurred during a moderate gas release event on August 27, 1993. The crust layer has been basically intact for the more than five years since then. This has been an important factor in the level rise issue discussed in Section 1.2.

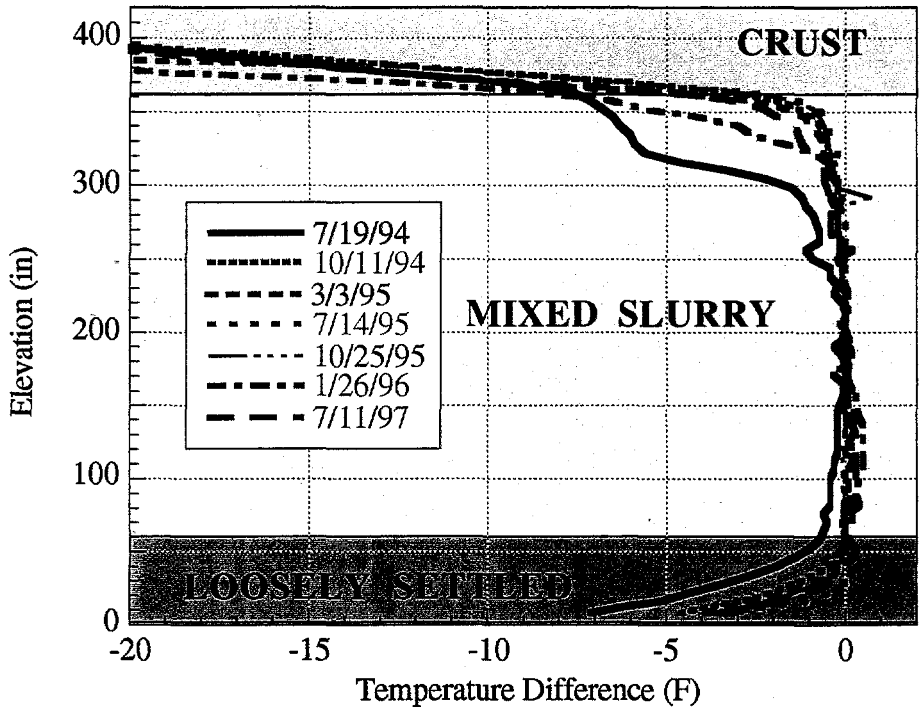

Figure 1.2. SY-101 Post-Mixing Waste Configuration

Mixer pump operation is a "fact of life" for SY-101 and dominates all other activities in and around the tank. Each time the pump is run the hydrogen concentration in the headspace rises from a background level of 20–30 ppm to 15–250 ppm for several hours before declining slowly back to the background. The gas release induced by a typical pump run is estimated as 30 to 50 cubic feet compared with the total gas generation rate of about 90 scf/d.

1.2 The Level Rise Issue

Beginning in December 1994 with the installation of the Enraf level gauge in riser 1A, a slow but inexorable increase has been observed in waste level. At the time this was not deemed significant, because no similar rise was noted on the Food Instrument Corporation (FIC) contact probe level gauge in riser 1C, which was the device used to evaluate the mixer pump safety controls (Sullivan 1995). The waste level history from December 1, 1994 to the present is shown in Figure 1.3.

However, the same level rise trend appeared at riser 1C when the FIC was replaced with a second Enraf gauge in December 1996, although it was periodically interrupted by water flushes that were required to remove waste that had adhered to the Enraf bob. At the same time the level rise at riser 1A was observed to be accelerating.

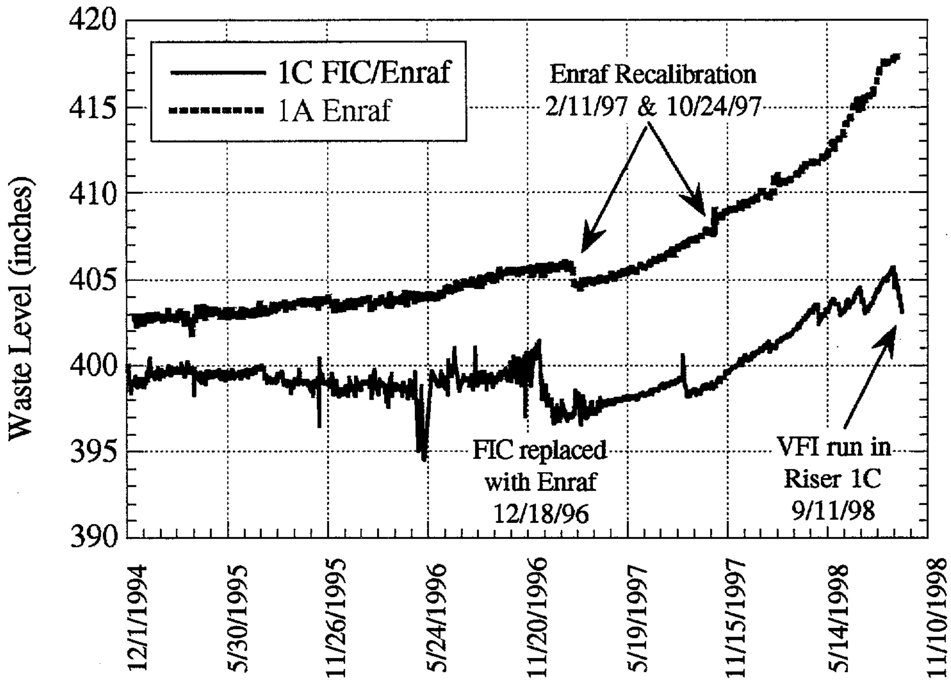

Figure 1.3. SY-101 Waste Level since December 1, 1994

The accelerating level rise was officially noticed in the fall of 1997, and a task group was formed to investigate the cause and recommend a plan for its further characterization and potential mitigation. At the same time, because it was obvious that the level rise was not due to gas buildup in a nonconvective layer but probably in the floating crust, it was recognized that the potential hazard (if any) was not covered by the Mixer Pump Safety Assessment (Sullivan 1995). This resulted in declaring an Unreviewed Safety Question (USQ) in late 1997.[a]

The task group concluded that the level rise was due to gas retention and recommended that inquiries begin to confirm that level rise indeed was occurring and to confirm the volume of retained gas.[b] The first activity confirmed the level measurements and determined that level rise was occurring over the entire tank (Benar 1998).

The second activity to confirm the gas location and inventory was based on operation of the VFI. The flammable gas hazard varies depending on whether the gas causing the level rise is stored in the crust, the mixed slurry, or the loosely settled layer (see Figure 1.2). The effect of the mixer pump on local gas content of the slurry was also of interest. Accordingly, the VFI was run three times in two risers during the summer of 1998. The results of these tests are the subject of this report.

(a) Waste Surface Level Growth in 241-SY-101, USQ No. TF-97-0975.
(b) PHMC. February 27, 1998. Interoffice memo, "Final Report from Task Team for Level Growth Issue in Waste Tank 241-SY-101."

1.3 Sampling History of SY-101

SY-101 and five other DSTs are on the 25-tank Flammable Gas Watch List (FGWL). The FGWL tanks were identified in response to Public Law 101-510, Section 3133 (the Wyden Amendment), as having a "serious potential for release of high level waste due to uncontrolled increases in temperature or pressure" from a flammable gas burn. This status has provided a powerful impetus for experiments, characterization, monitoring, and analytical studies sufficient to fully understand the risk involved. Accordingly, the VFI, ball rheometer, and retained gas sampler (RGS) were developed and deployed in the FGWL DSTs starting in December 1994.

The gas retention and release behaviors of Hanford DSTs AN-103, AN-104, AN-105, AW-101, SY-101, and SY-103 have been characterized in detail by the ball rheometer, VFI, and RGS during operations from December 1994 to May 1996. The results of this testing campaign include the following (Meyer et al. 1997; Shekarriz et al. 1997):

- Waste configuration (thickness of the crust, convective, and nonconvective layers)
- Rheology of the convective and nonconvective layers (viscosity and yield stress as a function of shear rate, and density)
- Retained gas volume and distribution (void fraction profile, effective pressure, and gas volume of each waste layer)
- Composition of the retained gas and concentration of ammonia dissolved in the liquid
- Gas release behavior (gas release history, distribution of release volume and release fraction).

Table 1.1 summarizes the waste sampling history of SY-101 (excluding headspace grab samples and crust auger samples) including the RGS samples planned for October 1998. The location of each of these events is shown in Figure 1.4. It should also be noted that gas generation tests were conducted on Window E sample material in 1995 (Person 1996).

Table 1.1. Waste Sampling History of SY-101 Through 1998

Riser	Core	RGS	VFI	Ball Rheometer
22A	5/91 (Window C) Planned 10/98	 Planned 10/98	-	-
11B	12/91 (Window E)	-	12/21/94 6/29/98 7/22/98	4/5/95
4A	-	-	1/17/95	3/28/95
1C	-	-	9/11/98	-
23A	Planned 11/98	Planned 11/98	-	-

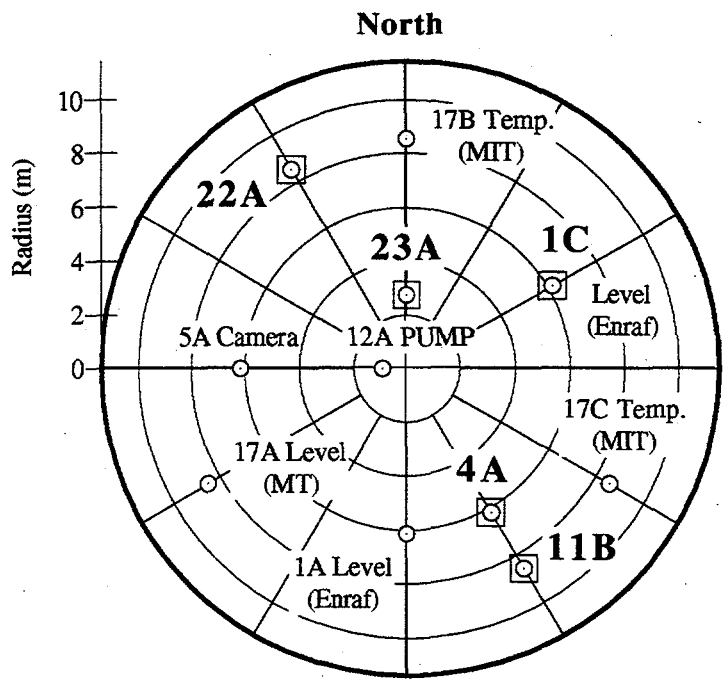

Figure 1.4. Sampling Locations in SY-101

1.4 Report Outline

This balance of the report describes the operation and the results of the VFI in the context of confirming the gas volume and location. Section 2 describes the design and operation of the VFI and the model by which the void fraction is computed from the measured temperatures and pressures. Section 3 discusses the test plans and the conduct of the actual tests including noteworthy observations on the in-tank video and the actual void fraction data. Section 4 covers the gas volumes derived from the void fraction profiles and the crust model, and Section 5 summarizes the conclusions of the work. Section 6 lists references cited.

2.0 Void Fraction Instrument

The VFI is designed to measure the volume fraction of free (undissolved) gas, or void, at specific locations in a tank. The VFI does not determine gas composition, and its response is very nearly independent of gas composition. The void fraction is measured by compressing the waste captured in a sample chamber of known size with nitrogen gas. This section describes the VFI in detail including its operation, measurement of pressures and temperatures, the void fraction calculation model, and uncertainty in the void calculation.

2.1 VFI Operation

The sample chamber is mounted on a rotating arm that is deployed vertically through a riser by means of a crane. The VFI can make measurements at a radius of 76 cm (30 in.) about the riser center about every 30 to 60 cm (12–24 in.) of elevation. Figure 2.1 is a sketch of the VFI deployed in a tank.

Typically, the waste has a floating "crust" layer with a hard surface that the VFI cannot penetrate without potential damage to the sample chamber. Before the VFI can be operated for the first time in a riser, a hole is made through the crust with a water lance, which is shown being lowered into the dome in Figure 2.2. Lancing was performed before the VFI was deployed in risers 11B and 4A in 1994/95 and before re-entering riser 11B in June 1998. Lancing was not done on the second test in 11B in July 1998 or on the third test in riser 1C in September 1998.

Once below the base of the crust layer, the arm is rotated 90 degrees to become horizontal and is lowered to the desired depth in the tank with the cover of the sample chamber open. Lowering the chamber with the cover open replaces the previous sample with fresh waste. At the measurement location the cover is closed to capture a waste sample, and the waste is compressed with nitrogen gas by opening a valve between the connecting line and the source volume. The void fraction is calculated from the initial and final pressures and temperatures and known system volumes as discussed in Section 2.3. The VFI is shown being lowered into the dome in Figure 2.3 and about to enter the waste in Figure 2.4. Figure 2.5 shows the elbow pivot pin and lower arm being raised from the waste, and Figure 2.6 shows the open sample chamber being decontaminated.

The reference or zero position for the elevation of the sample chamber is the waste surface directly under the test riser; it is located by observing the elbow pivot pin for the lower arm passing into the waste on the in-tank video camera (see Figure 2.5). The uncertainty in this observation is estimated as the radius of the pivot pin, which is about 4 cm. The uncertainty in relating the measured waste level elevation and the height of the liquid level penetrated by the VFI is also taken to be ±5 cm (±2 inches). The total uncertainty in the level is the square root of the sum of the squares, ±7 cm.

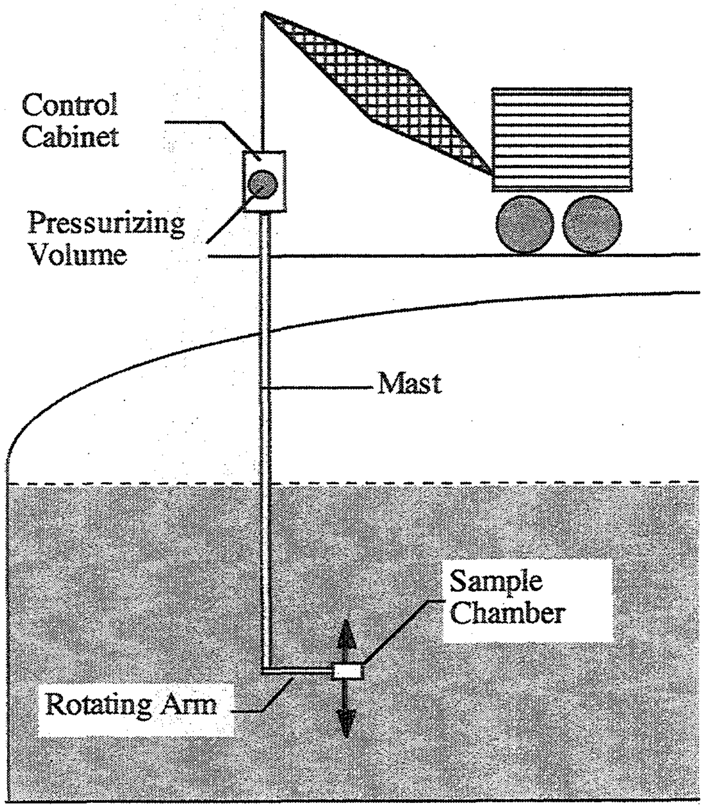

Figure 2.1. Void Fraction Instrument Deployed in a Tank

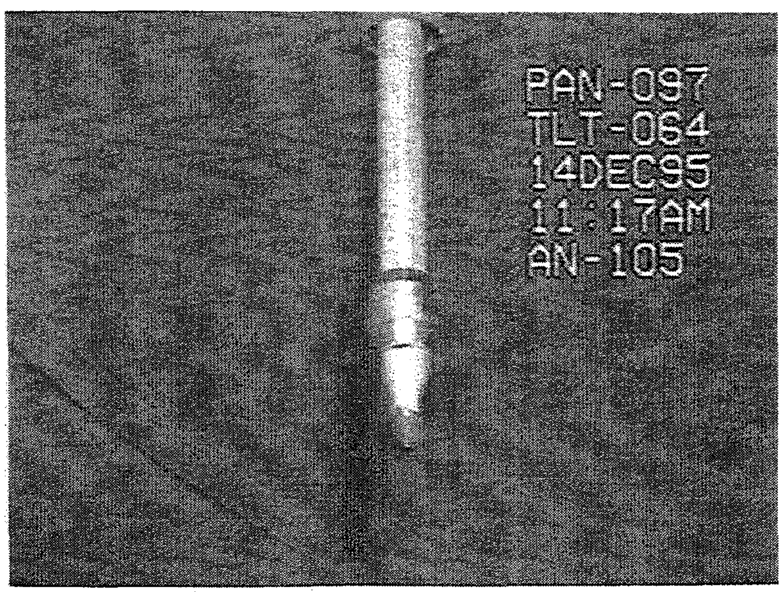

Figure 2.2. Water Lance Being Lowered into the Tank Dome

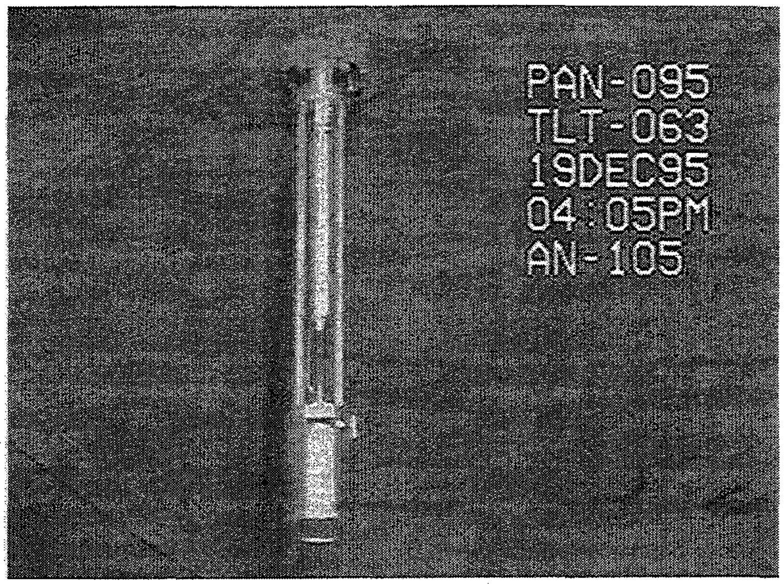

Figure 2.3. VFI Being Lowered into the Tank Dome

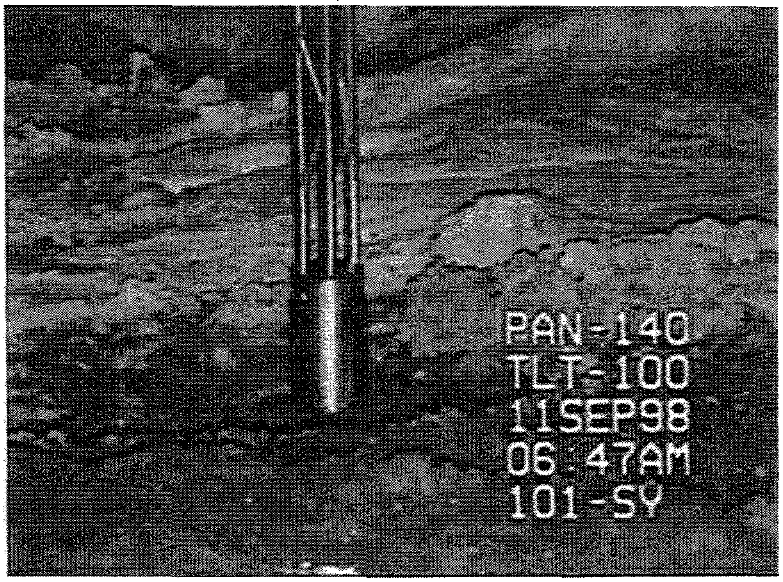

Figure 2.4. Closed Sample Chamber Approaching the Waste Surface

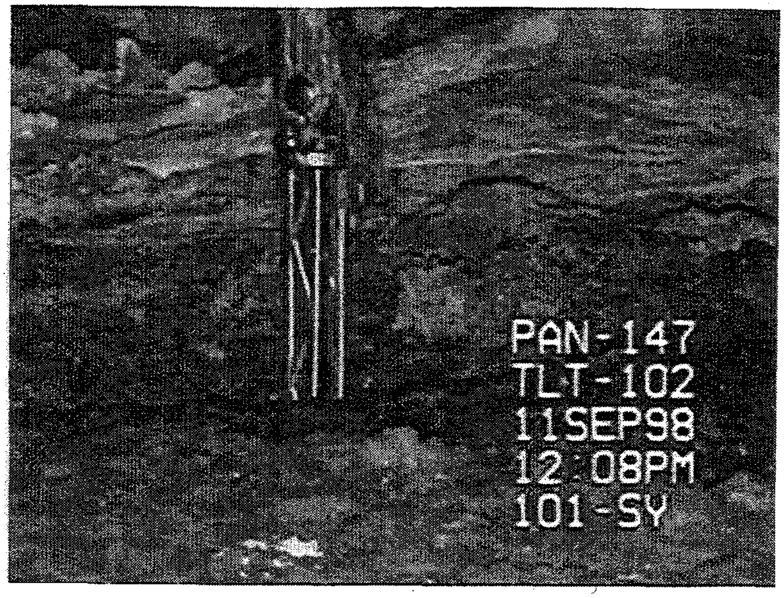

Figure 2.5. The VFI Being Withdrawn from the Waste

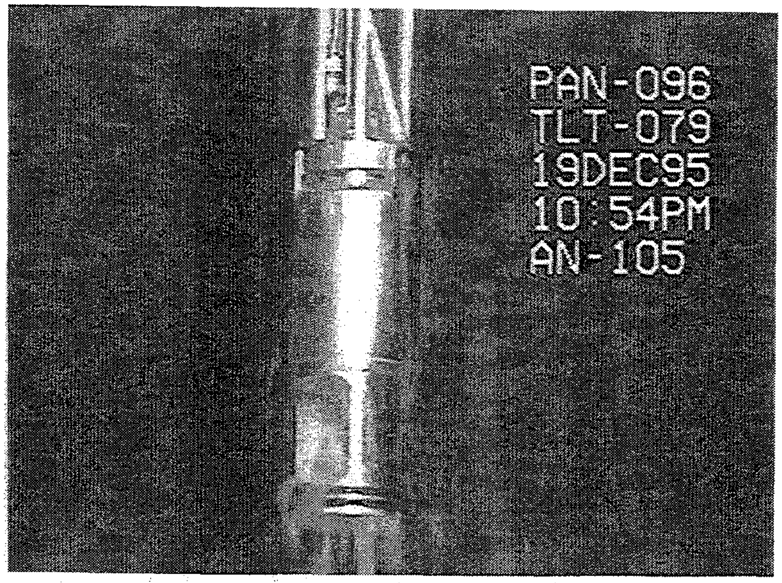

Figure 2.6. Open Sample Chamber During Decontamination

Sample locations are selected to provide the best possible understanding of the void fraction distribution for the available time in the tank. Three parameters describe the sample location in the tank: the selected riser, the angular orientation of the lower arm, and its elevation. The risers are selected based on availability and spatial distribution.

Up to four vertical traverses can be planned for each riser. On the first traverse, the lower arm is normally pointed toward the center of the tank. On the second traverse, the lower arm is rotated 180 degrees to point away from the center. On the third traverse the arm is rotated 90 degrees clockwise from the second, and the fourth is 180 degrees from the third. Because of limits on time and/or nitrogen gas supply, the fourth and sometimes the third traverses are dropped. The measurement elevations on later traverses are usually varied based on what is found during the first traverse. In the SY-101 tests a maximum of two traverses were made in any one deployment.

2.2 Pressure and Temperature Measurement

The VFI does not measure the void fraction directly. It is calculated from precisely measured volumes, pressures, and temperatures before and after the pressurization process. The calculation model is explained in Section 2.3. This section discusses how the various pressures and temperatures are measured.

The pressurizing chamber, connecting line, and sample chamber each have a measured temperature and pressure and a known volume. All of the pressure measurements are made inside the equipment enclosure, which is outside of the tank on top of the VFI mast; the only instruments inside the tank are temperature sensors. The pressure transducers are connected to the pressurizing chamber and to the connecting line near its upper end. The initial and final pressures and temperatures of the nitrogen gas charge in the pressurizing chamber are measured for each test. The pressures in the connecting lines, which extend from inside the equipment enclosures through the support masts to the sample chamber, are measured with a pressure transducer in the equipment enclosure.

The temperature of the gas in the connecting line varies along its length. The gas inside the connecting lines and fittings is at essentially the same temperature as the tube walls at equilibrium. Tube wall temperatures are measured at several locations along the lines and averaged to calculate the line temperature.

The temperature of the waste in the sample chamber is assumed to be represented by the temperature measured by an RTD located 76 cm from the sample chamber, near the lower arm pivot and, when the arm is oriented horizontally, at the same elevation as the sample chamber. The initial pressure in the sample chamber is assumed to be equal to the ambient hydrostatic pressure of the waste. At the end of each test, after the sample chamber is opened, the gas in the connecting line escapes through the check valve until equilibrium is reached. The line pressure, measured by a pressure transducer in the equipment enclosure, is then recorded as the initial waste pressure.

2.3 Void Fraction Calculation

The void fraction calculation assumes that the number of moles of gas in the system is conserved during pressurization. The initial amount of gas includes the gas in the pressurization chamber and the connecting line plus the free gas existing as bubbles or pockets in the waste sample. The total amount of gas in the system after a sample has been pressurized includes the gas in the pressurization chamber and the connecting line, the free gas remaining in the waste, a small amount that may have condensed or dissolved in the waste, and the nitrogen 'injected' into the sample chamber during pressurization. A detailed derivation of the model is given in Appendix A; this section summarizes the main features of the model.

The gas in the waste sample may also depart from ideal gas behavior for a number of reasons. Some of the species present, specifically ammonia, dissolve in the liquid as pressure increases; water vapor also condenses as pressure increases. These effects are included by conceptually allowing a small fraction of the gas in the sample chamber to be removed from the system.

The nitrogen in the system is modeled as a real gas. The Beattie-Bridgeman equation of state for nitrogen is used to account for departures from ideal gas behavior at high pressures (Moran & Shapiro 1988). Also, the elevation head is added to the line and sample chamber pressures. At a sample chamber pressure of 35 atm, the 18-m height of the VFI mast produced a head of about 1/30 atm, or 0.1% of the maximum pressure.

The pressurization chamber and the connecting line are essentially rigid; their volumes are essentially constant and do not change with pressure. The sample chamber, however, is less rigid; the cover undergoes hoop expansion, and the sample chamber length increases because the side ligaments stretch when pressurized. These effects have been included in the model by computing a change in sample chamber volume proportional to the pressure change and the volumetric compliance of the sample chamber.

The expression for the void fraction as a function of the measured system parameters is given by:

The expression for the void fraction as a function of the measured system parameters is given by:

$$\begin{aligned}\alpha = \{ & K_1[f(T_{1f},P_{1f}) - f(T_{1i},P_{1i})] + K_3[f(T_{3f},P_{3f}) - f(T_{3i},P_{i3})] \\ & + \beta \cdot (P_{2f} - P_{2i}) \cdot f(T_{2f},P_{2f})\}[f(T_{2i},P_{2i}) \cdot (1-k) - f(T_{2f},P_{2f})]^{-1}\end{aligned} \tag{2.1}$$

where the following nomenclature applies:

T	=	temperature
P	=	pressure
V	=	volume
N	=	number of moles of gas
f(T,P)	=	molar density given by the Beattie-Bridgeman state equation
K_1	=	V_1/V_2
K_3	=	V_3/V_2
β	=	volumetric compliance of the sample chamber
k	=	fraction of gas that vanishes from sample chamber due to condensation

Subscripts:
0 = gas bubbles in the waste
1 = pressurization chamber
2 = sample chamber
3 = connecting line
i = initial conditions
f = final conditions.

The void fraction calculation model captures the important physical effects of the VFI system. This results in very accurate estimates of the void fraction held in the sample chamber. The estimated uncertainty is discussed in the next section along with other concerns that have been raised over the years that could potentially affect the void calculation.

2.4 Void Fraction Model Uncertainty

Uncertainties in the void fraction measurements are of two types: errors associated with the uncertainties in the individual parameters used in calculating the void fractions and errors due to some of the trapped gases in the sample escaping from the waste before the sample chamber is closed. An analytic evaluation of the uncertainty due to parameter errors was performed, and the errors due to the sampling process were examined experimentally.

The linear combination of uncertainties in the individual parameters yields an overall measurement uncertainty of ±0.005 void fraction. The parameters with the largest contributions to the overall error are the connecting line volume, the parameter that models the real gas behavior of the trapped gases in the waste, and the compliance of the sample chamber. Other uncertainties and effects have also been considered.

If the increase in bubble pressure due to surface tension was significant, the VFI would underpredict the void fraction; however, calculations show that the pressure added by surface tension is significant only for bubbles less than one micron in diameter, and free bubbles that size do not exist. Studies of gas release signatures and photomicrographs of core samples from SY-101 (Brewster et al. 1995) indicate that the volume-average bubble size is on the order of a few hundred microns. In any event, if the overpressure due to surface tension were sufficiently large to cause an error in VFI measurements, it would also be sufficient to drive the gas in the bubble back into solution (Peurrung et al. 1998). Small bubbles can only exist attached to particles in such a way as to increase their radius of curvature and minimize surface tension pressure.

In a similar way, the strength of the waste could cause the void fraction to be under-predicted. As the sample is compressed, the pressure inside the bubbles may be slightly less than the pressure measured by the pressure transducer because the surrounding material supports some of the load. However, the ball rheometer indicates waste yield stresses less than 500 Pa, which is insignificant compared with the 3.5 MPa sample chamber pressure.

The temperatures inside the gas bubbles are not necessarily the same as those measured by the transducers. The bubble temperature will tend to increase temporarily upon compression until heat transfer to the waste reestablishes equilibrium. But bubbles have negligible thermal mass compared with the waste and system hardware, so the transient time is short, and the *initial* and final temperatures are essentially equal. Thermal equilibrium of the sample due to gas compression is not an issue, even for the largest bubbles.

However, thermal equilibrium between the waste and the VFI structure must be considered, particularly for the first void fraction measurement after the VFI enters the waste. Transient heat transfer calculations indicate that a 10-minute wait is sufficient to reduce the maximum temperature difference to below 0.6°C (1°F). A 20-minute wait is used in actual testing to ensure thermal equilibrium.

There is also a sample capture error that was first quantified approximately in experiments conducted at LANL with both gassed SY-101 chemical simulant and neutrally buoyant spheres to investigate capture of bubbles in non-Newtonian fluids. Although the resemblance of those tests and analyses to actual VFI measurements in general tank waste is questionable, the results showed the void of the sample to be less than that of the undisturbed waste by a factor of around 0.1 with an uncertainty of ± 0.04.[a] Analysis of the RGS also raised the possibility of incomplete capture due to shear stress of the sludge on the container walls.[b] However, a zero error is predicted for shear strength below 1,500 Pa (0.2 psi), which is the case in all the tanks tested. In any event, to approximately account for this effect we assume a 10% sample capture error in non-fluid waste. That is, the indicated void is multiplied by a factor of 1.1 to give the assumed correct value. In SY-101 this correction is only applicable for measurements in the crust layer in 1998 and in the undisturbed sludge in 1994/95.

Other than the sample capture error, the other uncertainties in the system are ±0.005 void fraction. This is confirmed by the results of validation tests described in Appendix B. The system error is generally small compared with the variability of the measured void fraction in non-fluid waste, which is typically 1/5 to 1/3 of the average void fraction. However, it needs to be considered in measurements of void in the mixed slurry layer of SY-101, where the void fraction is only 0.01 to 0.02.

(a) Abbott JR and C Unal. November 16, 1994. *Sampling Ability of the In-Situ Voidmeter Instrument.* LANL letter report TSA-6-94-316 (M110), Los Alamos National Laboratory, Los Alamos, New Mexico.
(b) Shekarriz A, and JD Norton. September 15, 1995. *Retained Gas Sampler System Analysis.* Letter report PNL-FG-091595, Pacific Northwest Laboratory, Richland, Washington.

3.0 Test Conduct and Field Observations

VFI operation is an intense waste-intrusive activity that offers many unique opportunities to gain insight about the waste. The entire operation is captured on in-tank video, which allows observation of any notable gas releases or waste movement around the VFI mast. The load on the crane supporting the VFI is monitored (though not recorded as data) so that large increases in waste strength can be detected. Because the VFI mast is rotated in the horizontal plane by hand, operators can actually "feel" the waste. This ability was used to advantage in two of the 1998 tests in determining the elevation of the base of the crust layer. At the same time, the headspace gas monitors and waste level gauges track the tank for any changes that might result from the waste disturbance caused by VFI insertion.

This section summarizes all these observations in the context of the test plan and test conditions. The void fraction data is also given. Each VFI run that has been performed in SY-101 to date is included. Except for the 1994/95 runs, which are combined together, each deployment is described individually in Sections 3.1 through 3.4. The measured pressure and temperature profiles from all tests are discussed in Section 3.5; the void data are also tabulated in Appendix C.

3.1 Initial VFI Tests in 1994/95

SY-101 was the first tank in which the VFI was operated. The main objective was to confirm that the mixer pump had, indeed, prevented a nonconvective layer from forming and that no significant gas volume was stored in the slurry. The test also investigated the ability of the mixer pump to excavate sludge off the tank bottom. Risers 4A and 11B were selected mainly because they were unused and unobstructed for crane access.

The first test was in riser 11B on December 21, 1994, approximately one day after a mixer pump run aimed at a location about 60 degrees counter-clockwise from the riser, as shown in Figure 3.1. A hole had been water-lanced through the crust several weeks prior to the test. Notwithstanding the long time since lancing, VFI penetrated the crust with little resistance. The crane load decreased by approximately 890 N (200 lb) as the VFI passed through the crust.

The first traverse confirmed that the mixed slurry layer held very little if any trapped gas. Therefore, the first measurement location for the second traverse was set at about four feet from the bottom. The crane began unloading at about 76 cm (30 in.), indicating increased resistance to the sample arm. At the lowest sample location, about 56 cm (22 in.) elevation, the sample chamber would not hold pressure, and testing in riser 11B was terminated.

The second test was in riser 4A on January 17, 1995. The water lance had been run only a few days before, and no decrease in crane load was detected as the VFI penetrated the crust. As in the previous test in riser 11B, the mixer pump was run about one day before the test, with the jet aimed roughly perpendicular to the riser, as shown in Figure 3.2.

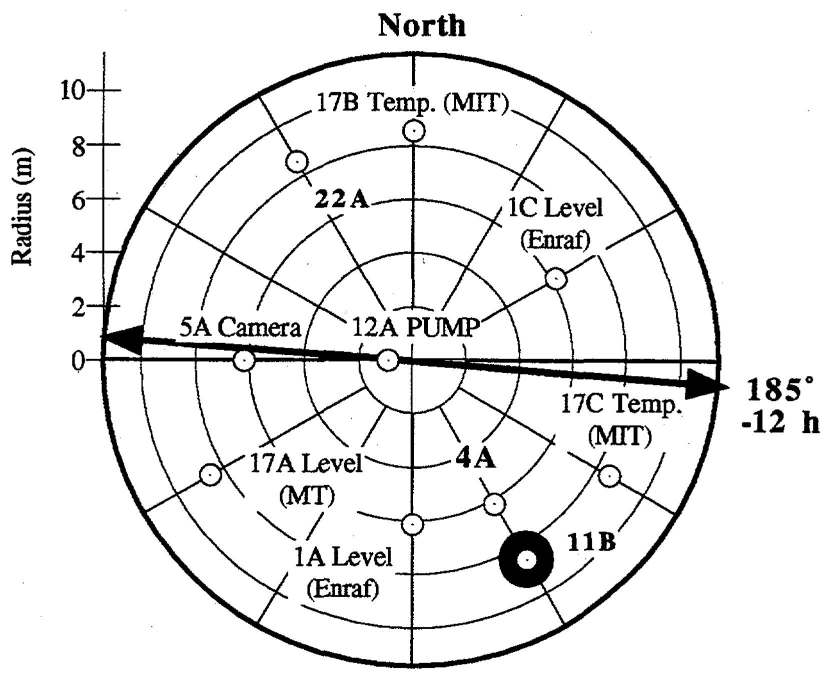

Figure 3.1. Pump Run Prior to VFI Test December 21, 1994

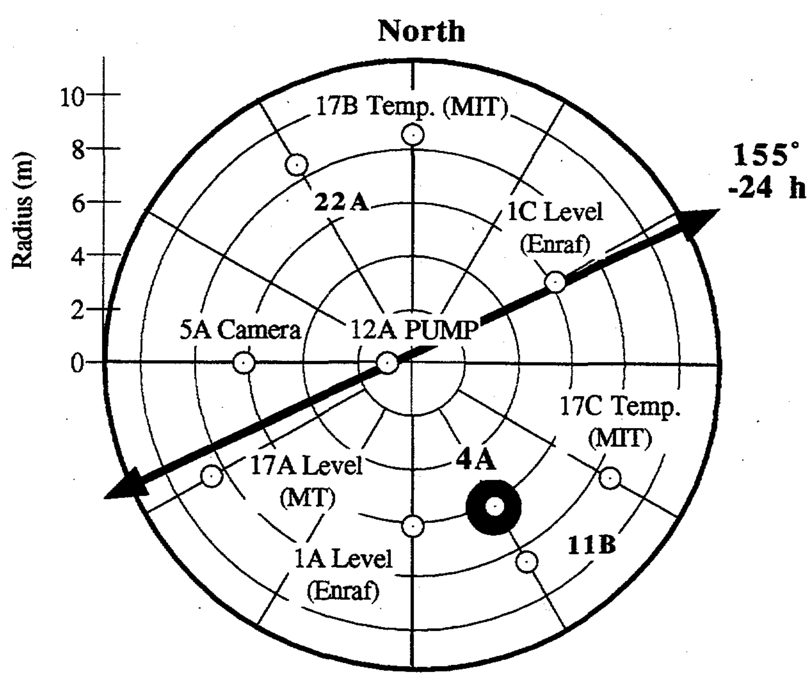

Figure 3.2. Pump Run Prior to VFI Test on January 17, 1995

Based on the data from riser 11B, the test plan for riser 4A was modified to increase the number of orientations from two to four and eliminate double pressurization because both the first and second pressurization measured virtually the same void values in every instance. The first and second traverses proceeded uneventfully. Testing was terminated near the end of the third traverse when the load-measuring device on the crane became unreliable.

The same trends in void fraction were observed in both risers 4A and 11B, as shown in Figure 3.3. The void fraction was less than 0.01 in the mixed slurry layer from under the crust to about 80 inches from the bottom. From 80 inches down to 40 inches, the void fraction increased to about 0.04 in the loosely settled layer. Below 40 inches, the void abruptly increased to 0.08–0.15 in an apparently undisturbed sludge layer. The average void fraction under the crust was only 0.016.

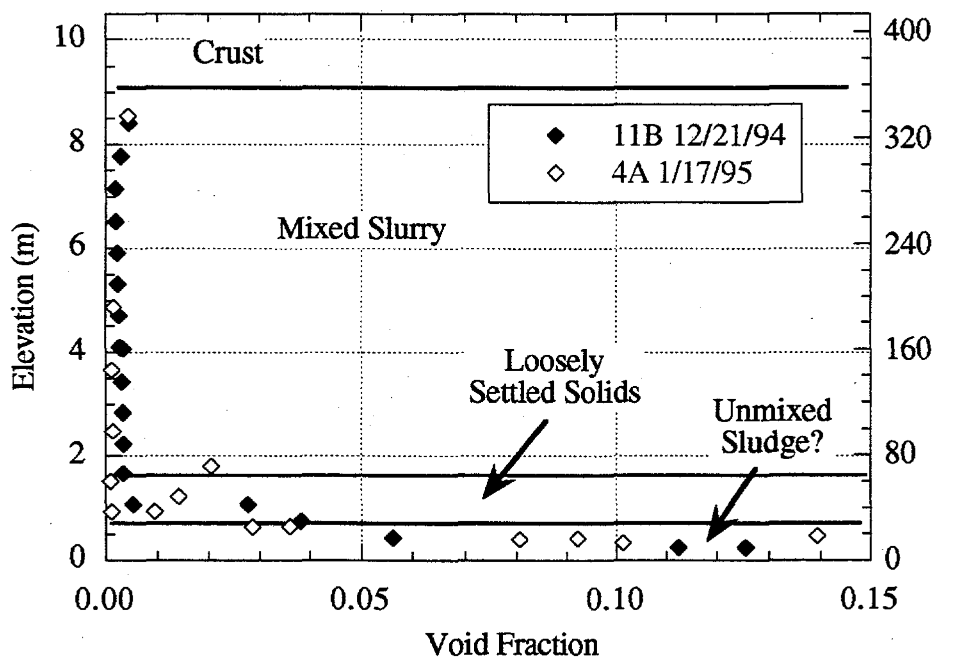

Figure 3.3. Void Fractions Measured in 1994/95 Tests

3.2 VFI #1, June 29, 1998

The VFI tests initially planned for 1998 were intended to measure the void fraction profile just below the crust and in the assumed soft lower portion of the crust. This area was of interest because this region was considered the most likely location for the gas to accumulate and cause the level to rise.

Void measurements were desired in the crust itself but had not been attempted previously, so one of the objectives of the VFI #1 test was to determine whether crust measurements were practical. However, because of the small risk of O-ring damage or failure to seal and maintain pressure in the sample chamber while operating in nonconvective waste, and because a detailed void fraction profile through the entire waste depth was the priority, crust void measurements were planned only after the void profile was established. If crust layer sampling proved practicable, crust layer void measurements were planned to be done first in the second deployment.

The June 29 test followed the test matrix in "Data Acquisition Plan for Void Fraction Measurements in Tank 241 SY-101," Revision C (attached as Appendix D), on the first traverse. The riser was water lanced several days before testing. The test began 12 to 18 hours after a pump run aimed approximately at riser 11B, as shown in Figure 3.4.[a] Almost all of the data were collected with the lower arm pointed toward the tank center.

The first activity was to detect the bottom of the crust using the lower arm so that void measurements could be made as high in the waste as possible, short of the crust itself. This was done by raising the VFI into the lower portion of the crust with the lower arm in the horizontal position and then lowering it until the arm could be rotated manually. The VFI had to be lowered to approximately 54 inches below the surface in order to rotate the mast. The VFI was then lowered 6 inches more, and the first void fraction measurement was taken. Though not recognized at the time, this operation dislodged material from the base of the crust that created spuriously high void fractions on the subsequent traverse.

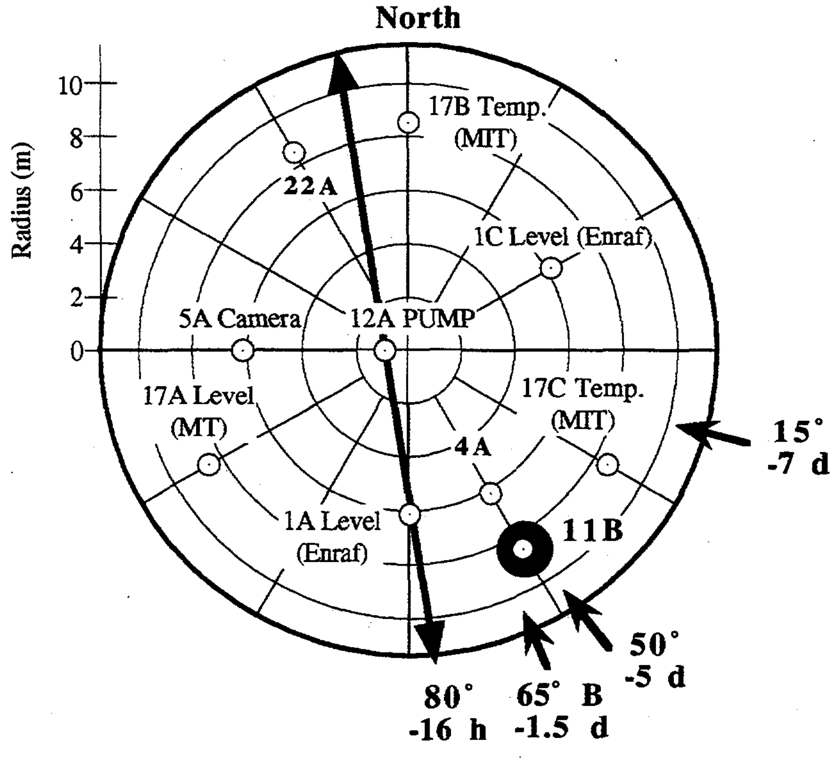

Figure 3.4. Pump Runs Prior to VFI Test #1, June 29, 1998

(a) The "B" notation following the angle (65°) indicates that the run was a "bump"—five minutes at 1000 rpm—rather than a normal run of 25 minutes at 1000 rpm.

Nineteen void fraction measurements were taken on the first traverse, with the lowest reading about 386 inches below the surface, 18 inches off the bottom. The VFI was then raised and the lower arm rotated to 180 degrees away from the tank center. Two void measurements were taken near the top at this orientation. The arm was then rotated 90 degrees and the VFI slowly raised until the pressure on the arm cylinder increased, indicating that the lower arm was pushing into the crust with some force. A void fraction measurement was taken here, about 31 inches below the surface and midway through the crust layer. The VFI was then removed from the tank.

The void fractions in the June 29 test ranged from 0.178 at 60.5 inches below the surface to 0.048 about 18 inches from the tank bottom, averaging 0.084. Two void measurements made on the second traverse were approximately 0.03 lower than those at a similar depth on the first traverse. (The high void in this test is attributed to disturbance of the crust as observed in VFI #3.) The data are plotted in Figure 3.5. Error bars represent system error only.

The one void measurement in the crust of 0.032 is probably valid based on results from VFI #3. However, the measurements from below the crust do not represent the general distribution of gas in the tank as the crust disturbance apparently dislodged gas-bearing material that compromised the data on the subsequent traverse.

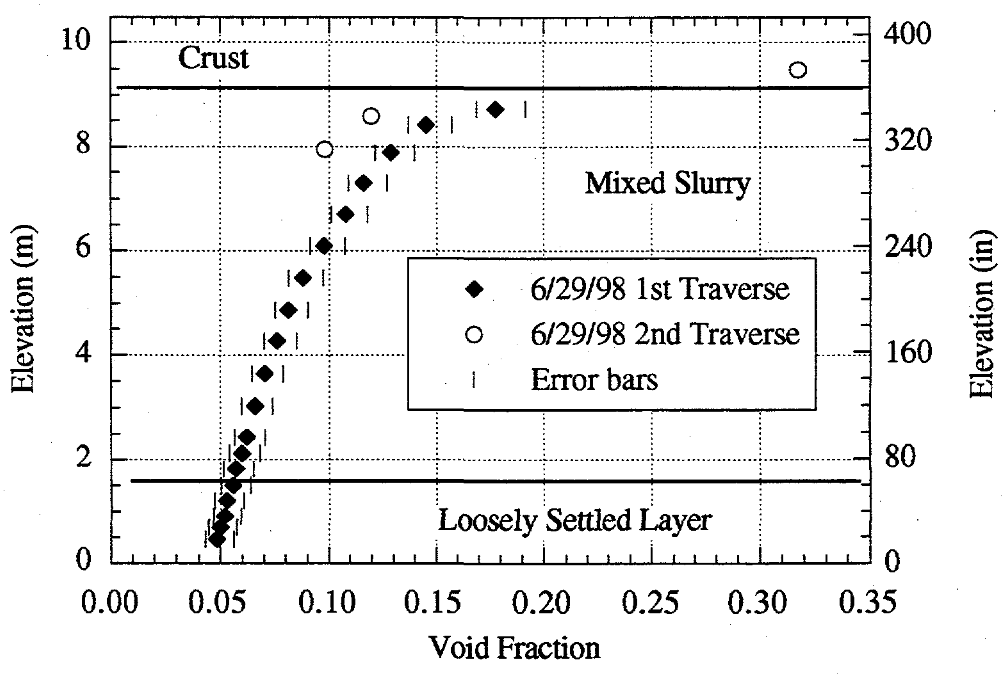

Figure 3.5. Void Fractions Measured in 6/29/98 Test in Riser 11B

3.3 VFI #2, July 22, 1998

Because a much different void fraction profile was measured in VFI #1 than those obtained in December 1994 and January 1995, the second deployment of 1998 was intended to confirm whether these data were representative and to improve our understanding of the gas retention processes.

Instead of riser 4A as originally planned, riser 11B was used again. A longer time was specified between the last mixer pump run and VFI testing, anticipating that, if the high void fraction in VFI #1 was due to the pump, the void should decrease if given a longer time for bubbles to rise. The mixer pump was also to be aimed directly at riser 11B some time before VFI #2 to re-mix the waste and avoid the potential for data contamination from the prior VFI test in 11B. The actual pump run schedule is shown in Figure 3.6.

The July 22 test followed the test matrix in "Data Acquisition Plan for Void Fraction Measurements in Tank 241 SY-101," Revision D (attached as Appendix E). The crust was not water lanced again after VFI #1. No crust measurements were performed during this deployment because it was believed that the source of gas accumulation responsible for level rise had already been found in VFI #1. Therefore, the amount of gas trapped in or just below the crust was not as interesting as it had been, and the relatively risky crust void measurements were not deemed justified.

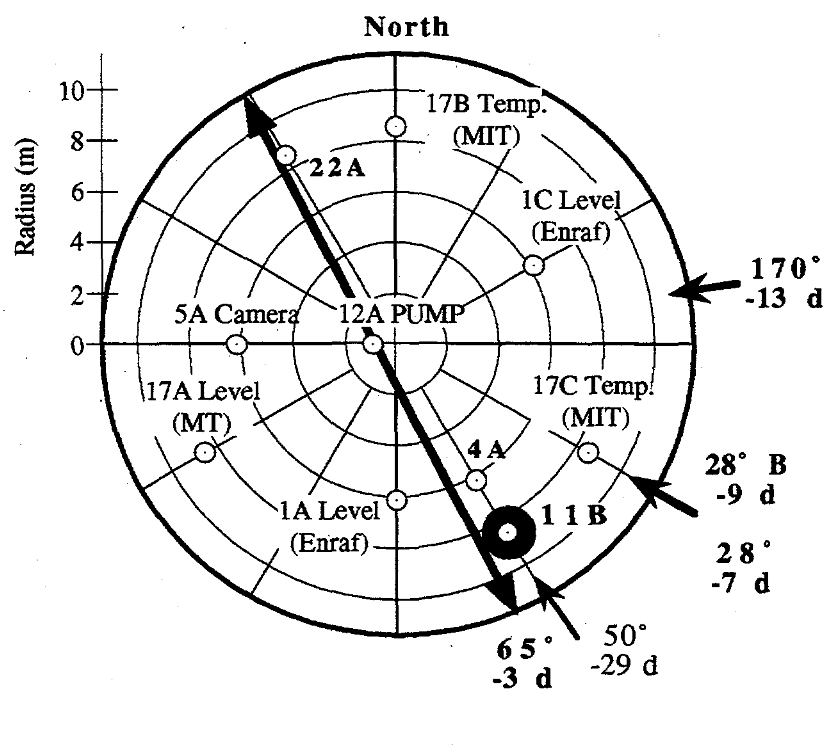

Figure 3.6. Pump Runs Prior to VFI Test #2, July 22, 1998

Only one full traverse was made, starting as high in the tank as possible. However, it is important to note that the base of the crust was not located by rotating the VFI as it was during the first test because the base elevation was already known. Therefore, there was no crust disturbance to dislodge gas-bearing material and contaminate subsequent measurement.

The void fraction measured on July 22 was much more uniform and much lower in magnitude than that found on June 29. The profile is closer to the 1994/95 data except for the high void fractions near the bottom in the early tests. The void fraction varied from 0.012 near the bottom to a maximum of 0.016 from 270 to 300 inches. The average void fraction was 0.012. The measured void profile is plotted in Figure 3.7. One additional void measurement of 0.013 was taken deep in the waste while the VFI was being raised to be removed from the tank with the arm rotated; it was consistent with the others taken at a similar depth from the downward traverse.

During the June 29 deployment, there was considerable bubbling around the VFI mast during the initial insertion and moving the VFI to the first test location. There was less bubbling as the VFI moved lower into the tank. There was an associated increase in the measured hydrogen concentration in the dome space. During the July 22 deployment there was very little or no bubbling around the VFI mast except while moving to the first measurement location. The hydrogen concentration in the tank did not increase measurably.

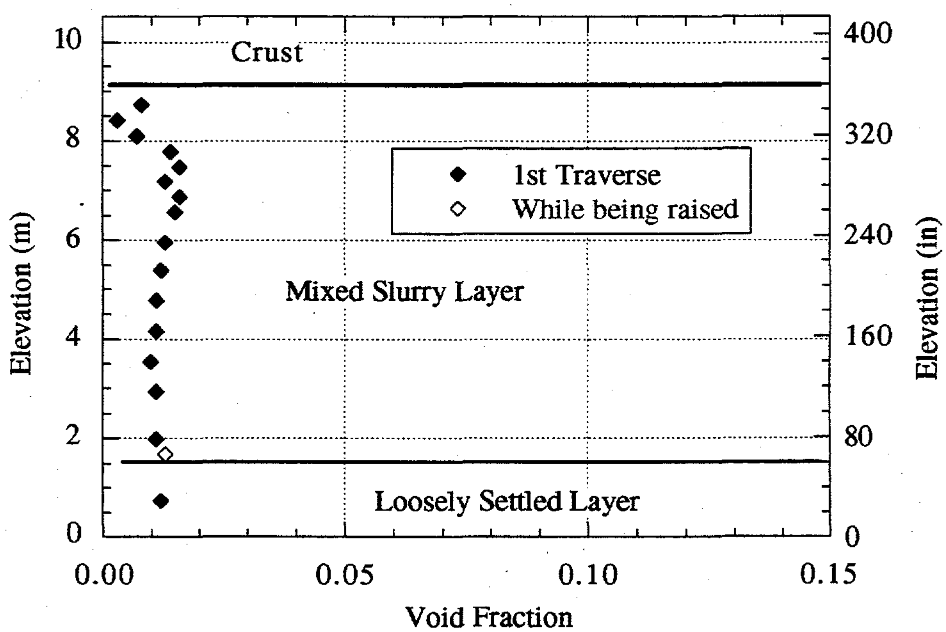

Figure 3.7. Void Fractions Measured on the 7/22/98 Test in Riser 11B

3.4 VFI #3, September 11, 1998

For the September 11 test, the "Data Acquisition Plan for Void Fraction Measurements in Tank 241 SY-101," Revision F, was followed (attached as Appendix F). Riser 1C was selected, and the Enraf level gauge was removed from this riser to provide access for the VFI. The pump was run approximately 14 hours before testing with the nozzle pointed almost directly at riser 1C, as indicated in Figure 3.8.

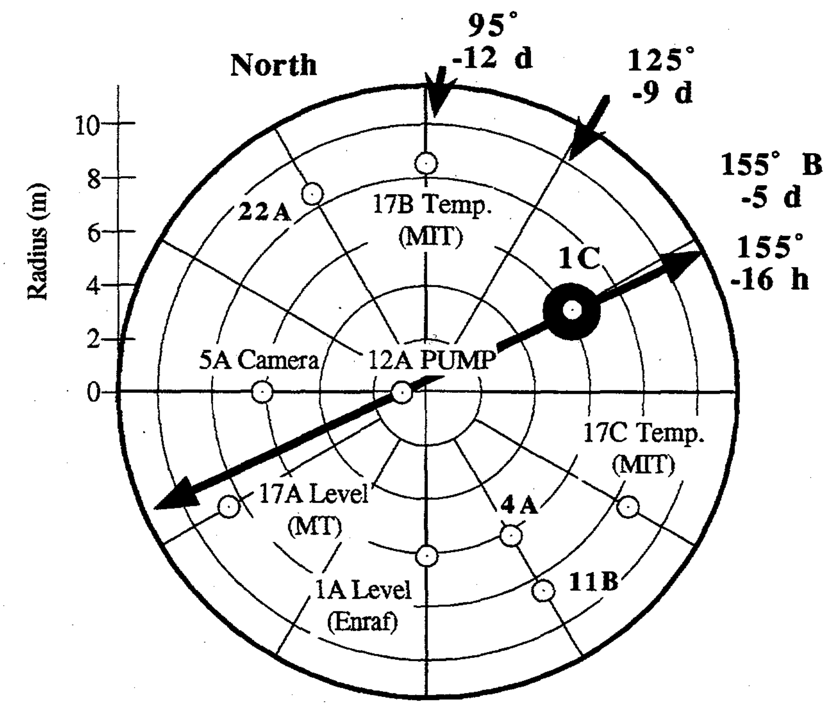

Figure 3.8. Pump Runs Prior to VFI Test #3, September 11, 1998

The purpose of this series of tests was to determine which, if either, of the void fraction profiles measured on June 29 or July 22 is representative of the entire tank and to find out whether a disturbance of the lower portion of the crust may have caused the high void fractions in VFI #1. The test plan was therefore based on three hypotheses that were to be tested with the logic sketched in Figure 3.9.

The first hypothesis is that **gas is generally absent** in the waste below the crust, though pump runs and spontaneous releases may temporarily elevate the void fraction locally. Hypothesis #1 was tested by making a few void measurements where a high void fraction would be likely due to recent pump operation. If a low void is found, the hypothesis is proven true.

If a relatively high void fraction were found, Hypothesis #1 would not be proven but may still be true. A second hypothesis, that **the gas is a local transient event** due to pump operation, was posed. To test this hypothesis, a second set of void measurements would be made two days after the first ones to allow entrained bubbles to rise and solids to settle after the pump run. If a low void fraction were found, Hypothesis #2 would be true, as would be Hypothesis #1, and we could conclude that **gas is generally absent,** except locally, after a pump run. However, if the void fraction were relatively high after the two-day wait, Hypothesis #2 would be false, which would also confirm that Hypothesis #1 is false. We would then have to conclude that **gas is generally present** and that VFI #2 test results were somehow anomalous.

To examine a possible mechanism for the high void measured in VFI #1 on June 29, we posed Hypothesis #3—that the high void in **VFI #1 is due to a local crust disturbance.**[a] This hypothesis was tested by making an abbreviated traverse to the bottom immediately after several crust void measurements to deliberately disturb the lower portion of the crust. If a high void fraction similar to that of VFI #1 were found, it could be attributed to the crust disturbance, and Hypothesis #3 would be true. However, if the void fraction remained low, our hypothesis would be false, and the results of VFI #1 would appear to be produced by neither a pump run nor a crust disturbance; it would be a local event and not evidence of a generally high void fraction.

The highlighted logic blocks on Figure 3.9 trace the outcome of the tests and therefore list the conclusions. A low void fraction was found in the first measurements, which confirmed that gas is generally absent from the mixed slurry layer and that high void does not persist more

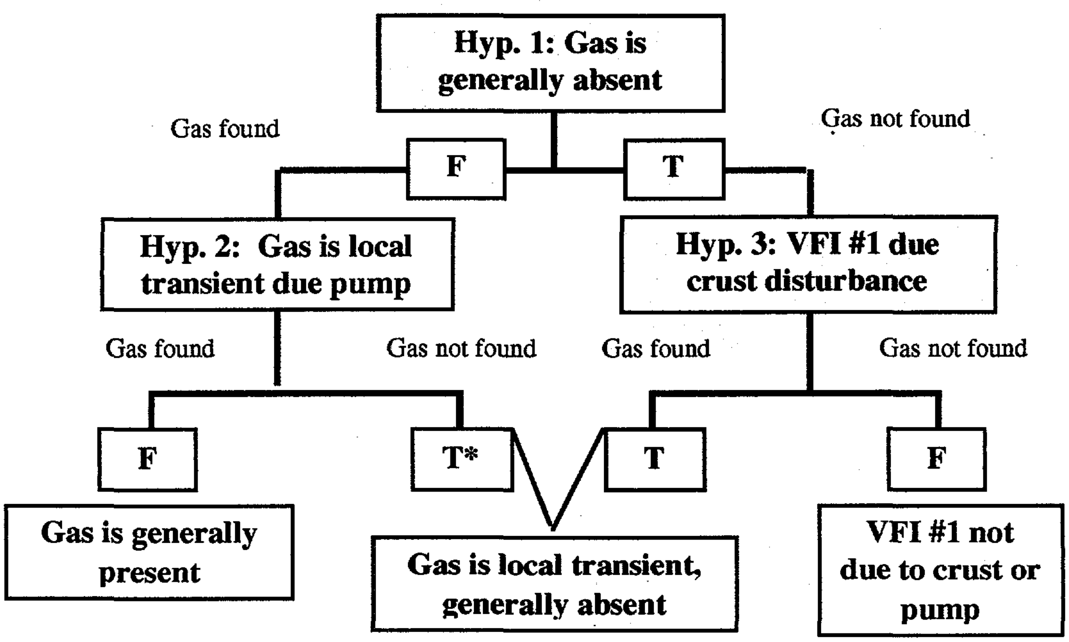

Figure 3.9. Hypotheses and Conclusions for VFI #3, September 11, 1998

(a) It has also been suggested that material trapped in the sample volume might cause a high void in subsequent tests. However, the raw VFI pressure and temperature data do not support this theory.

than a few hours after a mixer pump run. A high void fraction with a profile similar to that of VFI #1 was found after the crust disturbance and confirms that VFI #1 was, indeed, caused by locating the bottom of the crust by attempting to rotate the VFI mast.

The overall conclusion is that gas is generally absent in the waste from the base of the crust to the tank bottom, and that any high void measurement there is a local transient. A discussion of specific test observations and the void fractions is given below.

The crust was not water lanced before testing on September 11. Lancing was not deemed necessary because the area under 1C had been repeatedly flushed with water over the past year (due to Enraf flushings). No detectable crane load reduction was observed as the VFI penetrated the crust. A first traverse of four measurements was done to characterize the mixed slurry layer. The void fraction was between 0.01 and 0.02 except for the first measurement near the base of the crust, which was about 0.03. The VFI was then moved upward and a single sample taken just below the crust that matched the prior four data points. This measurement was intended to determine whether bubbling of released gas (N_2 from VFI operations) from below tended to increase or decrease the measured void fraction.

The VFI was then raised up into the crust until the load on the crane increased from about 1600 pounds (approximately the weight of the VFI) to about 2000 pounds, the maximum permitted crane load. At this point, the sample chamber was about two feet below the waste surface. Five crust void measurements were made, each at a different depth and lower arm orientation.[a] After each crust measurement, the VFI was lowered to 36–44 inches below the top of the crust to open the sample chamber and rotate the arm to the next sample azimuth and minimize the disturbance to the waste at the next measurement location.

Following the crust measurements, a second traverse of three samples was made through the mixed slurry layer to see whether the crust disturbance changed the measured void fraction in the waste below on the subsequent traverse. It did. Void fractions ranged from 0.23 down to 0.08, roughly paralleling the profile seen in VFI #1.

On both the first and second traverse, a noticeable drop in the crane load was observed at approximately mid-depth in the waste. This did not appear to be due to riser interference, but no bubbling or other indications of gas release were observed during any of the tests.

The measured void fractions are shown in Figure 3.10. The profile measured in the first traverse on September 11 corresponds almost exactly to the July 22 data. Note that the earlier data were taken three days after a pump run aimed at the test riser, while the later data were taken less than one day after a similar pump run. This supports the conclusion that the void fraction in the waste is generally very low.

(a) The lower arm was deliberately rotated within the lowest part of the crust to test the hypothesis that the crust disturbance created a high void fraction, as discussed above.

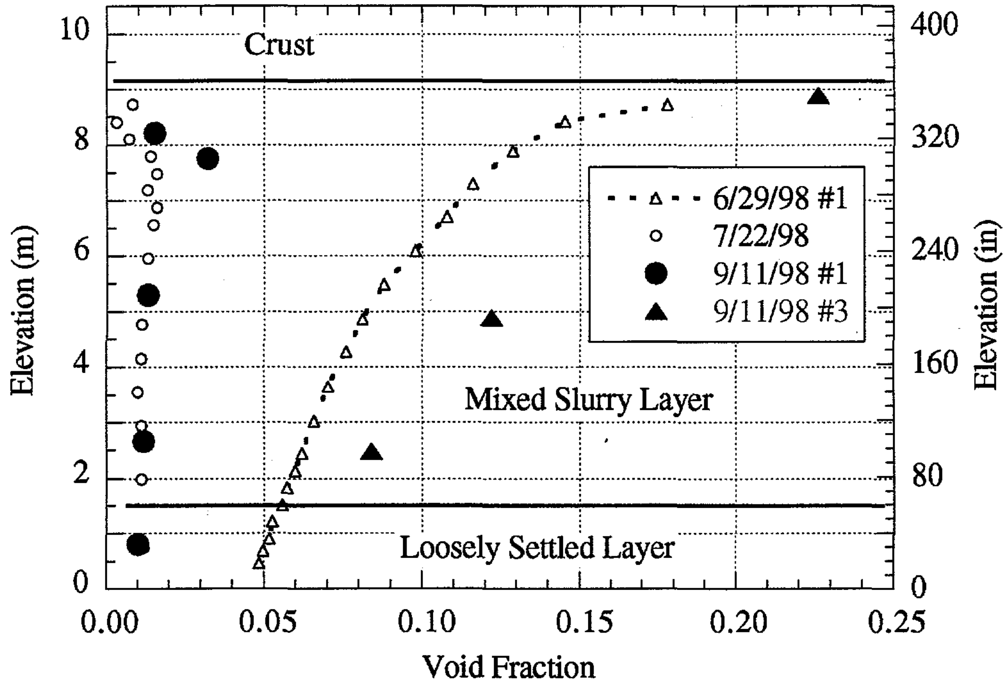

Figure 3.10. Void Fractions Measured on the First Traverse on 9/11/98 in Riser 1C

The high void fractions on the third traverse were measured immediately after a series of crust layer measurements that disturbed the crust layer similar to the disturbance in the June 29 tests. This supports the conclusion that the high void fractions do not represent the general waste condition.

One void fraction measurement was made in the crust layer on June 29, and several more were obtained September 11. All crust layer void measurements are summarized in Figure 3.11. The void fractions range from 0.21 to 0.43 with an average of 0.30. There may be a trend present with the highest void fraction at the base of the crust and decreasing upward.

3.5 Pressure and Temperature Profiles

After the VFI sample chamber is opened, the gas is released from the chamber and the connecting line until the pressure in the connecting line drops to approximately the same as the local pressure of the waste. A check valve (nominally 1/3 psig cracking pressure) at the bottom end of the connecting line prevents waste from being drawn back up the line. The final pressure measured in the connecting line is used in the calculation of the void fraction as the initial pressure of the sample.

The local pressure profile in atmospheres is shown in Figure 3.12. The pressure profiles are very nearly linear, which indicates a fairly uniform density. The increased scatter in the July deployment is more consistent with the 1994/95 tests in SY-101 and other tanks. There is

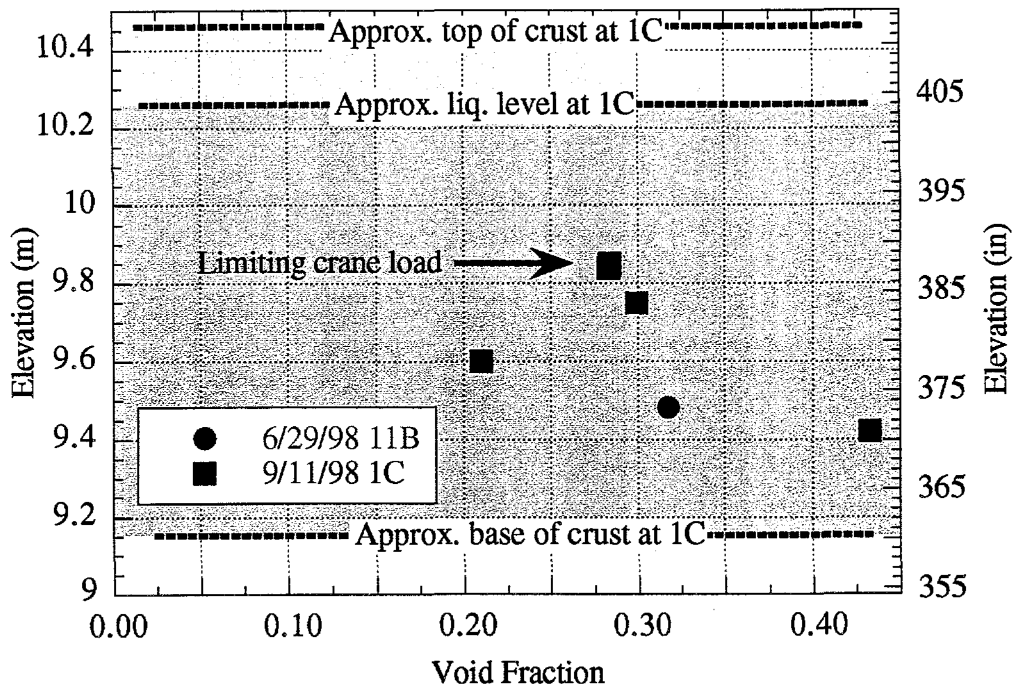

Figure 3.11. Void Fractions Measured in the Crust in Risers 11B and 1C

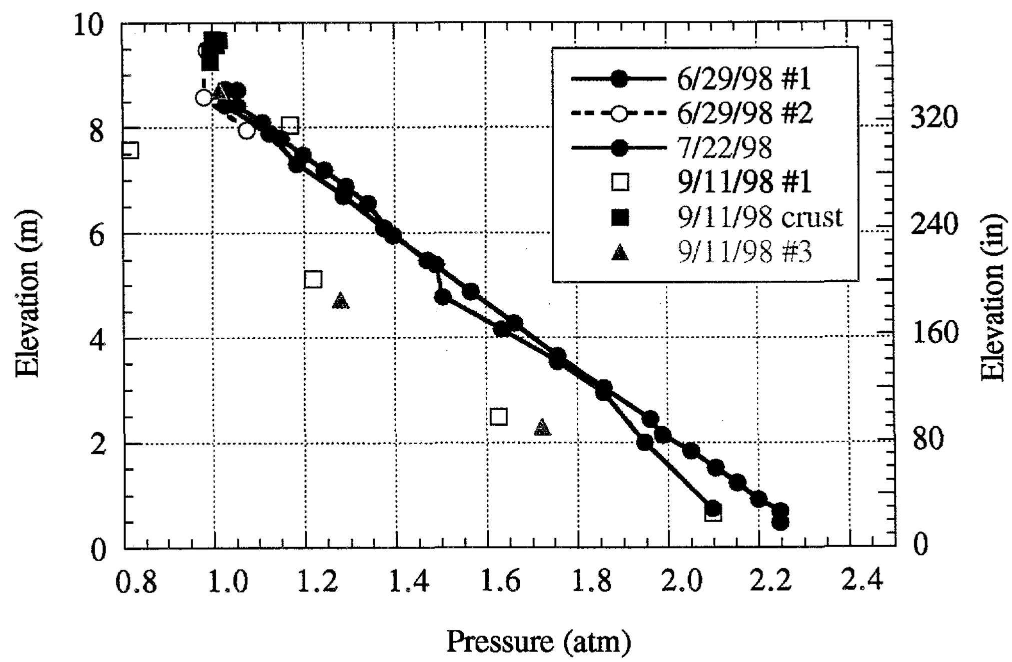

Figure 3.12. Measured Pressure Profiles from 1998 VFI Tests

currently no explanation for the low pressures measured in the September 11 tests. However, any errors in void fraction due to pressure error of less than half an atmosphere is less than 0.001 void fraction.

Two temperature sensors near the elbow pivot are used to measure the local waste temperature for calculating the void fraction. The temperature profile is shown in Figure 3.13. The temperature profile from July 22 is about 1.5°C higher near the surface and 0.5°C higher near the bottom. The temperatures in all tests are a few degrees C lower than the 323K (120°F) measured at the multifunction instrument trees (MITs). The lower temperatures measured on September 11 are the result of the VFI mast not reaching thermal equilibrium due to the wide spacing of sample locations. Again, the void fraction error caused by incomplete thermal equilibrium is calculated to be less than 0.001 void fraction.

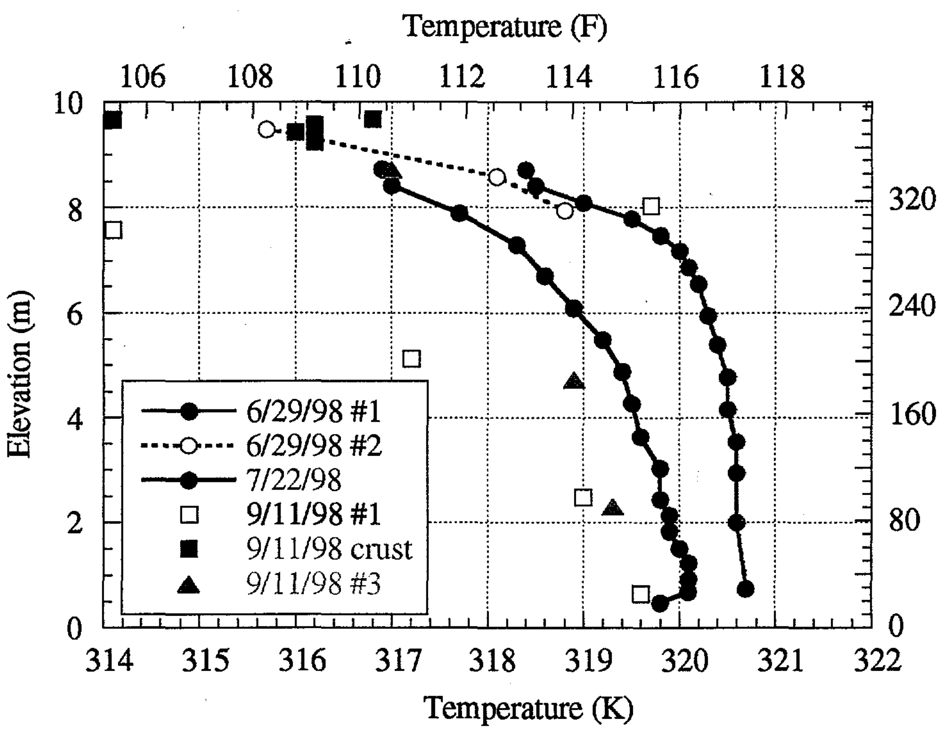

Figure 3.13. Measured Temperatures

4.0 Gas Volume

Based on the results of the September 11 tests compared with the prior two 1998 runs, the void fractions that best represent the general waste condition are those from the July 22 test and the first traverse on September 11. The crust void fractions from June 29 and September 11 can also be used (see Figures 3.7, 3.10 and 3.11).

The gas volumes and uncertainties in the crust and the mixed slurry layer (including the loosely settled layer below) were computed from the measured void fractions by a Monte Carlo simulation technique. This model and the expressions for the gas volumes in terms of the void measurements are derived in Appendix G.

4.1 Crust Thickness and Buoyancy

Besides the void fraction, the gas volume calculation requires a measure of the crust thickness and submergence. The elevation of the base of the crust can be determined at two locations from the MIT validation probe temperature profiles in risers 17B and 17C. The temperature profiles from the most current and 1995 validation probe data from 17B and 17C are shown in Figures 4.1 and 4.2, respectively. The temperature profiles show a crust base elevation of 360 inches within the uncertainty of the measurement. The crust base elevation observed when attempting to rotate the VFI mast in both risers 11B and 1C was also about 360 inches. The top of the crust can be assumed with a potentially high uncertainty to be given by the Enraf gauge in riser 1A and the free liquid level by the Enraf in riser 1C. On July 22, these two levels were 417.7 and 404.5 inches, respectively. This makes the crust thickness about 58 inches, of which about 44 inches is submerged; the fraction of the crust that is submerged is 44/58 = 0.76.

The crust submergence fraction, f_S, can also be derived from Archimedes' Principle. Given the crust void fraction and densities, the submergence fraction is given by

$$f_S = \frac{\dfrac{1}{1-\alpha_{NB}} - (1-\psi)\phi}{\dfrac{1}{1-\alpha_{CR}} - (1-\psi)\phi} \tag{4.1}$$

where ϕ is the porosity of the material above the liquid level and ψ is its liquid saturation (ψ=1.0 means the porosity is filled with liquid), and α_{CR} is the average crust void fraction. α_{NB} is the neutral buoyancy void fraction, which is computed as

$$\alpha_{NB} = 1 - \frac{\rho_L}{\rho_{CR}} \tag{4.2}$$

where ρ_L is the liquid density and ρ_{CR} is the ungassed bulk density of the submerged portion of the crust. Equation (4.1) can be used to predict waste level if crust thickness and void fraction

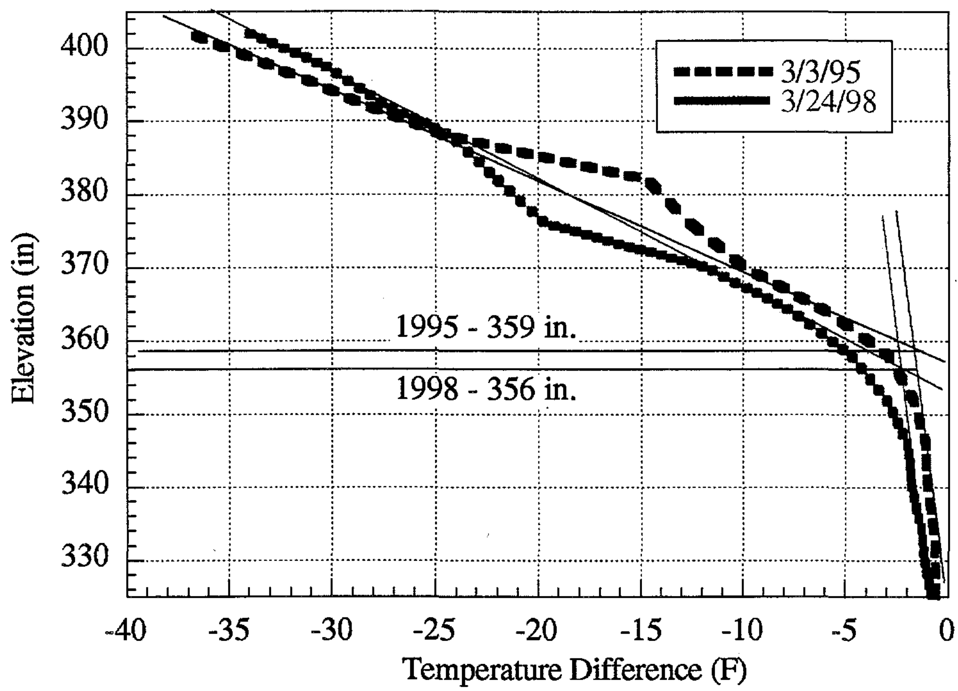

Figure 4.1. Crust Base Elevation Indicated by the Temperature Profile in Riser 17B

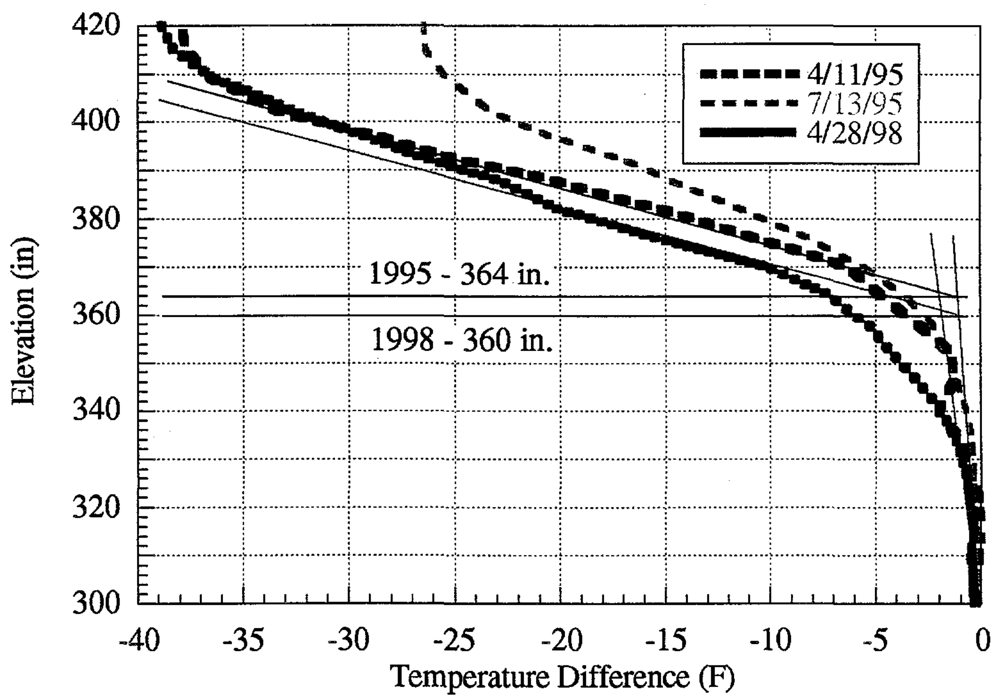

Figure 4.2. Crust Base Elevation Indicated by the Temperature Profile in Riser 17C

are known. For example, using the measured crust average void fraction of 0.3, porosity of 0.4, and average freeboard saturation of 0.4, the equation gives a submergence fraction of 0.79, which closely matches the measured value.

4.2 Gas Volumes

Assuming gas is retained only in the submerged portion, the crust in situ gas volume is given by

$$V_{CR} = AF_A \alpha_{CR} f_S H_{CR} \tag{4.3}$$

where A is the tank cross-sectional area, and F_A is a factor to account for the fact that the crust occupies slightly less than the total tank area.

The in situ gas volume contained in the mixed slurry layer is computed similarly as

$$V_{SL} = A\alpha_{SL}(L_W - H_{CR}) \tag{4.4}$$

where α_{SL} is the average slurry layer void fraction, L_W is the waste surface level (Enraf 1A level), and H_{CR} is the total crust thickness. The average void fractions in the crust and slurry layers and their uncertainties are computed as outlined in Appendix G.

The gas volumes computed from the measured void fractions is listed in Table 4.1 including a comparison with the corresponding values from the 1994/95 void data (Meyer et al. 1997). The waste levels predicted by the simple hydrostatics crust model "tuned" to conditions on 1/1/95 are summarized in Table 4.2, and the parameter values used in both calculations are given in Table 4.3.

The average void fraction computed below the crust determined from the combined data from July 22 and the first traverse from September 11, 1998 is 0.013 ± 0.001. This gives a total in situ gas volume in the slurry layer of 48 ± 5 m^3 (1,700 ft^3) at an average pressure is 1.8 atm or 84 ± 9 m^3 (3,000 ft^3) at one atmosphere. The VFI data from 1994/95 indicated 60 ± 21 m^3 (2,100 ft^3) of gas below the crust in situ at an average pressure of 2 atm, or 118 ± 35 m^3 (4,200 ft^3) at one atmosphere, most of which was stored near the bottom.

The average void fraction in the crust based on the void fraction measurements from June 29 and September 11, 1998 is 0.30 ± 0.04, which gives a gas volume of about 145 ± 24 m^3 (5,120 ft^3) or 149 ± 24 m^3 (5,260 ft^3) at one atmosphere. The estimated gas volume in the crust in 1995 was 62 ± 41 m^3 (2,100 ft^3) or 64 ± 40 m^3 (2,300 ft^3) at one atmosphere based on a void fraction of 0.16. The crust gas volume compares with the prediction of the simple hydrostatic model, which also predicts the surface level and liquid level almost exactly.

Table 4.1. Results of Gas Volume Calculation

Parameter	1998	1994/95	Difference
Crust			
Void fraction	0.30 ± 0.04	0.16 ± 0.1	
In situ volume (m^3)	133 ± 22	62 ± 41	71
Standard volume (scm)	138 ± 22	64 ± 40	74
Effective pressure (atm)	1.03 ± 0.02	1.03 ± 0.02	
Mixed Slurry			
Void fraction	0.013 ± 0.001	0.016 ± 0.006	
In situ volume (m^3)	48 ± 5	60 ± 21	-12
Standard volume (scm)	84 ± 9	118 ± 35	-34
Effective pressure (atm)	1.76 ± 0.04	1.97 ± 0.1	
Total			
In situ volume (m^3)	181 ± 22	122 ± 46	59
Standard volume (scm)	221 ± 25	182 ± 53	39
Effective pressure (atm)	1.22 ± 0.03	1.49 ± 0.22	

Table 4.2. Results of Crust Hydrostatic Model Prediction

Input Values	1/1/95	7/22/98
Crust height (cm)	110	150
Crust void fraction	0.16	0.30
Computed Values		
Submergence (cm)	101.1	116.9
Freeboard (cm)	8.9	33.1
Submergence fraction	0.92	0.78
Crust gas volume (m^3)	61	132
Predicted Levels (in.)		
Surface	402.5	417.8
Liquid	399.0	404.7
Actual Levels (in.)		
Surface	402.5	417.7
Liquid	399.0	404.5

Table 4.3. Parameter Values Used in Gas Volume Calculations

Parameter	Value
Crust porosity	0.4
Freeboard saturation	0.2
Liquid S.G.	1.5
Submerged crust S.G.	1.7
Crust area fraction	0.92

The estimated total retained gas volume currently in SY-101 from the 1998 void fraction data is 181 ± 23 m^3 (6,400 ft^3) in situ or 221 ± 25 m^3 (7,800 ft^3) at one atmosphere, most of which is stored in the crust layer. This represents an increase of 59 m^3 (2,100 ft^3) of gas in situ or 39 m^3 (1,400 ft^3) at one atmosphere, compared with the 1995 total of 122 ± 46 m^3 (4,300 ft^3) in situ or 182 ± 53 m^3 (6,400 ft^3) at one atmosphere, about a third of which was stored in the crust.

4.3 Relating Level Growth to Gas Volume

Between December 1994 and July 1998, the waste level indicated by Enraf buoyancy gauge 1A has increased from just under 403 inches to about 418 inches, a growth of 15 inches. At the same time, the approximate free liquid level[a] indicated by Enraf 1C has increased almost five inches, from 399 inches to 404.5 inches.

The net increase in the in situ volume of 59 m^3 (2,100 ft^3) between the 1995 and 1998 VFI tests (see Table 4.1) accounts for only 5.7 inches of direct growth. This represents a loss of about 1 inch in the mixed slurry and a gain of almost seven inches in the crust. No gas retention is attributed to the postulated "undisturbed ring" of waste outside the radii of the MITs and VFI test risers (27–29 ft.). The nonconvective layer yield stress is too low to allow a significant height of waste in this region.

The missing level growth is accounted for by the increased buoyancy of the crust layer, which causes it to float higher in the liquid, as well as a small increase in the crust solids mass. The simple crust hydrostatic model accurately predicts the 1998 liquid and surface level changes from January 1995 conditions when given the recent void fraction and crust thickness measurements.

(a) The Enraf 1C level is kept close to the free liquid level by periodic flushing. This has been confirmed by lancing the crust under the manual tape and inserting the VFI in riser 1C. A true measurement of free liquid level is very difficult because of the tendency for a foam and a soft crust layer to form within hours after the crust is penetrated.

5.0 Conclusions

The best characterization of the void fraction in the mixed slurry layer in 1998 is obtained from the July 22 test and the first traverse of the September 11 tests. The crust void fraction is characterized by the five September 11 measurements plus the one taken on June 29. The void fractions in the region beneath the crust are uniformly low. There is no significant gas retention in the loosely settled solids, and there is no evidence of any remaining undisturbed sludge. The crust void fraction ranges from 0.22 to 0.43 with an average of 0.30.

The gas volumes calculated from these data, when combined with a simple hydrostatics model for crust buoyancy, accurately reflect the waste level changes from January 1995 to July 1998. This confirms that the SY-101 level growth is mainly due to gas accumulation in the crust. The 1998 VFI campaign also revealed that a disturbance to the crust dislodges gas-bearing material that artificially elevates the void fraction measured on a subsequent traverse.

6.0 References

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Appendix A

Void Fraction Model

Appendix A

Void Fraction Model

The following nomenclature is used to describe the volumes and properties in the model:

T	= temperature
P	= pressure
V	= volume
N	= number of moles of gas.

Subscripts:

0	= gas bubbles in the waste
1	= pressurization chamber
2	= sample chamber
3	= connecting line
i	= initial conditions
f	= final conditions.

The pressurizing gas in the system is nitrogen and is treated as a real rather than an ideal gas. If the volume, pressure, and temperature of the gas in each volume are all known, the number of moles of gas can be calculated using standard relationships. For real gases, it can be shown that the number of moles of gas held within a volume is directly proportional to the volume, to very good approximation. The relation is given by

$$N = V \cdot f(T,P) \tag{A.1}$$

where

$$f(T,P) = \frac{N}{V} = \frac{P \cdot Z(T,P)}{RT} \tag{A.2}$$

In Equation (A.2), R is the universal gas constant, and Z(T, P) is the compressibility of nitrogen, which is obtained from the Beattie-Bridgeman equation of state for nitrogen. The Beattie-Bridgeman equation of state is expressed as (Moran and Shapiro 1988)

$$f(T,P) = \frac{(1-\varepsilon)}{v^2}(v+B) - \frac{A}{v^2RT} \tag{A.3}$$

where

$$A = A_0(1 - a/v)$$

$$B = B_0(1 - b/v)$$

$$\varepsilon = \frac{c}{vT^3}$$

and A_0, a, B_0, b and c are constants, P is the pressure, T is the temperature, v is the molar specific volume, and R is the universal gas constant. In application, the standard Beattie-Bridgeman constants were changed slightly to obtain a more accurate correlation over the pressure range of 1 to 40 atm and temperatures of 250 to 350K, the ranges over which the VFI is expected to operate. The model is accurate to well within 0.1% of published gas tables (Keenan and Kaye 1965) over this range of operating conditions.

Equating the initial and final amount of gas in the system results in the following expression for conservation of moles of gas between initial and final states:

$$N_{1i} + N_{2i} + N_{3i} = N_{1f} + N_{2f} + N_{3f} + N_z \tag{A.4}$$

where N_z is the number of moles of gas originally in the sample chamber that condenses or otherwise disappears. We define N_z as a simple fraction, k, of the initial number of moles in the sample chamber so that

$$N_z = kN_{2i} \tag{A.5}$$

Substituting Equations (A.2) and (A.5) into Equation (A.4) yields

$$\begin{aligned} &V_1 \cdot f(T_{1i},P_{1i}) + V_0 \cdot f(T_{2i},P_{2i}) + V_3 \cdot f(T_{3i},P_{3i}) = \\ &V_1 \cdot f(T_{1f},P_{1f}) + V_0 \cdot f(T_{2f},P_{2f}) + \Delta V_2 \cdot f(T_{2f},P_{2f}) \\ &+V_3 \cdot f(T_{3f},P_{3f}) + k \cdot V_0 \cdot f(T_{2i},P_{2i}) \end{aligned} \tag{A.6}$$

Expansion of the sample chamber during pressurization is included by computing a change in sample chamber volume proportional to the pressure change:

$$\Delta V_2 = \beta \cdot (P_{2f} - P_{2i}) \cdot V_2 \tag{A.7}$$

where β is the volumetric compliance of the sample chamber.

Now define the volume ratios, $K_1 = V_1/V_2$ and $K_3 = V_3/V_2$ and the void fraction, $\alpha = V_0/V_2$. Substituting these definitions for the volume ratios and Eq. (A.7) in Equation (A.6) and solving for the void fraction yields

$$\begin{aligned} \alpha = &K_1[f(T_{1f},P_{1f}) - f(T_{1i},P_{1i})] + K_3[f(T_{3f},P_{3f}) - f(T_{3i},P_{i3})] \\ &+ \frac{\beta \cdot (P_{2f} - P_{2i}) \cdot f(T_{2f},P_{2f})}{f(T_{2i},P_{2i}) \cdot (1-k) - f(T_{2f},P_{2f})} \end{aligned} \tag{A.8}$$

Equation (A.8) can be used to calculate void fraction from the initial and final pressures and temperatures, system volumes, compliance of the sample chamber, and assumed properties of the trapped gas.

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Appendix B

Validation Tests

Appendix B

VFI Validation Tests

As part of its post-fabrication qualification testing in October 1994, "known" void fractions were measured by placing carefully machined plastic blocks in the sample chamber to represent void fractions ranging from 0.05 to 0.50. The "true" void volume was found by submerging the sample chamber under water, closing the cover, and capturing the water trapped in the sample chamber between the blocks. The weight of the trapped water was used to determine the void volume. Tests were also conducted at zero (chamber filled with water) and 100% void (chamber empty).

Because there is uncertainty in the actual void fraction obtained with the plastic blocks, only the data for zero and 100% void fraction can be used to assess system accuracy. The plastic block void fraction data are valid primarily for assessing repeatability. It must also be noted that, the void fractions for these tests were calculated with an earlier model that did not account for non-ideal gas behavior in the pressurization chamber (Stewart 1995).

In spite of all these concerns, the difference between the measured and true void fraction was within 0.02 void fraction in all cases. The zero and 100% void tests were within 0.01 void fraction of the true value. Double pressurization was used for all of the tests. In all cases the void fractions calculated from the first and second pressurizations were equal within one tenth of one percent void fraction. See Stewart et al. (1995) for a full description of these tests.

An indirect source of validation is comparison of void fractions measured by the VFI with those derived from the RGS. Because the measurements were made several months apart in different risers, it is not possible to quantify the difference. However, it is clear that both devices are giving consistent measurements. A typical example of the comparison is shown for AW-101 in Figure B.1 (see Meyer et al. 1997 for similar comparisons in AN-103, AN-104, and AN-105).

Finally, zero and 100% void tests were run in the field on July 7, after the first VFI test of 1998. As before, the zero void test filled the sample chamber with water and the 100% void test were made on an empty sample chamber. The results are given in Table B.1. The average error for the zero void tests was 0.005 void fraction. The 100% void test measured 1.08. This is consistent with instrument uncertainties at this high void, which is far beyond the design range of 0–30% void. We believe that the VFI system accuracy has been adequately demonstrated and there can be no serious doubt that its measurement truly represents the gas content of the waste in the tank.

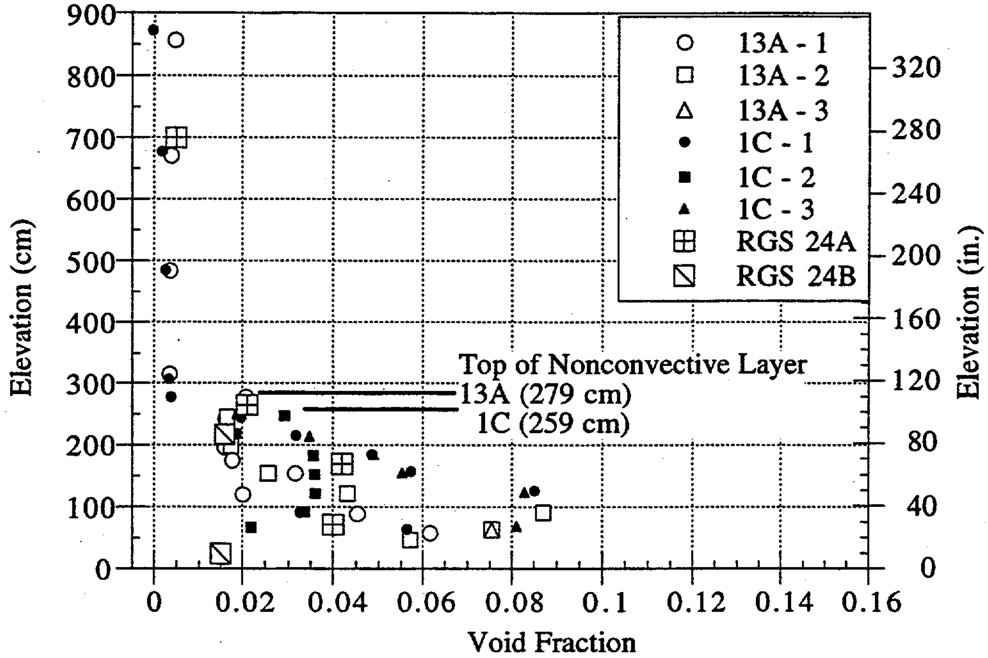

Figure B.1. Void Fraction Measured by VFI and RGS in AW-101

Table B.1. Results of July 7, 1998 Field VFI Verification Tests

Zero Void Tests	100% Void Test
Void Fraction	Void Fraction
0.0021	1.088
0.0048	
0.0036	
0.0086	

References

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Appendix C

Tabulation of VFI Data

Appendix C

Tabulation of VFI Data

The data for each void measurement taken in SY-101 from December 1994 to September 1998 are summarized in Tables C.1 through C.5. The average void fraction is listed for double pressurizations. The reference elevation is the assumed elevation at which the lower arm pivot entered the waste. This is taken to be the waste level indicated by the FIC or Enraf gauge in riser 1C except for the September 11, 1998 test. In that test, the camera angle and waste surface ridges prevented observation of actual waste penetration, so the reference was defined as the point at which the pivot pin disappeared from view. Videotapes of the Enraf bob being lowered to the waste surface indicate that the reference is about 7 inches above the actual level, which was 405 inches on September 11—hence the reference elevation of 412 inches.

Table C.1. VFI Data from December 21, 1994, Riser 11B

Reference elevation 399.2 in.

Depth (in)	Elev. (in)	Elev. (m)	Void Frac.	Press. (atm)	Temp. (K)
68	331	8.41	0.0045	0.91	318.2
93	306	7.77	0.0029	1.17	319.3
117	282	7.16	0.0018	1.34	319.8
142	257	6.53	0.0019	1.42	320.0
166	233	5.92	0.0021	1.46	320.2
190	209	5.31	0.0022	1.53	320.4
214	185	4.70	0.0025	1.63	320.5
238	161	4.09	0.0026	1.74	320.5
239	160	4.06	0.0033	1.82	320.4
264	135	3.43	0.0030	1.83	320.4
287	112	2.84	0.0033	1.93	320.4
311	88	2.24	0.0034	2.02	320.4
333	66	1.68	0.0035	2.12	320.4
357	42	1.07	0.0053	2.21	320.3
382	17	0.43	0.0560	2.33	319.7
390	10	0.25	0.1124	2.42	318.6
390	10	0.25	0.1256	2.45	318.2
357	42	1.07	0.0276	0.99	320.1
369	30	0.76	0.0382	2.36	319.9

Table C.2. VFI Data from January 17, 1995, Riser 4A

Reference elevation 399.2 in.

Depth (in)	Elev. (in)	Elev. (m)	Void Frac.	Press. (atm)	Temp. (K)
62	337	8.56	0.0043	0.93	317.7
207	192	4.84	0.0015	1.48	319.5
255	144	3.63	0.0011	1.85	318.8
301	98	2.46	0.0014	1.96	318.8
339	60	1.49	0.0009	2.07	318.9
362	37	0.90	0.0011	2.22	319.7
386	13	0.31	0.1014	2.32	319.1
328	71	1.78	0.0205	2.16	319.6
351	48	1.19	0.0142	2.17	319.7
373	26	0.62	0.0359	2.30	319.7
374	25	0.61	0.0286	2.36	319.6
380	19	0.44	0.1393	2.38	319.3
362	37	0.91	0.0095	2.14	319.5
383	16	0.39	0.0922	2.35	319.2
383	16	0.38	0.0806	2.42	319.0

Table C.3. VFI Data from June 29, 1998, Riser 11B

Reference elevation 404 in.

Depth (in)	Elev. (in)	Elev. (m)	Void Frac	Press. (atm)	Temp. (K)
60	344	8.74	0.178	1.03	316.9
73	332	8.42	0.145	1.03	317.0
93	311	7.89	0.129	1.12	317.7
117	287	7.30	0.116	1.19	318.3
140	264	6.70	0.108	1.29	318.6
164	240	6.10	0.098	1.38	318.9
188	216	5.48	0.088	1.47	319.2
212	192	4.87	0.081	1.57	319.4
236	168	4.26	0.076	1.66	319.5
260	144	3.65	0.070	1.76	319.6
285	120	3.04	0.066	1.86	319.8
308	97	2.45	0.062	1.96	319.8
320	84	2.14	0.060	1.99	319.9
332	72	1.84	0.057	2.05	319.9
345	60	1.51	0.056	2.10	320.0
356	48	1.22	0.053	2.15	320.1
368	36	0.91	0.052	2.20	320.1
377	27	0.69	0.050	2.25	320.1
386	18	0.46	0.048	2.25	319.8
66	338	8.58	0.120	0.98	318.1
91	313	7.95	0.098	1.08	318.8
31	373	9.48	0.317	0.99	315.7

Table C.4. VFI Data from July 22, 1998, Riser 11B

Reference elevation 404 in.

Depth (in)	Elev. (in)	Elev. (m)	Void Frac.	Press. (atm)	Temp. (K)
60.5	344	8.72	0.008	1.06	318.4
72.9	331	8.41	0.003	1.06	318.5
85	319	8.10	0.007	1.11	319.0
97.2	307	7.79	0.014	1.15	319.5
109.4	295	7.48	0.016	1.20	319.8
120.7	283	7.20	0.013	1.25	320.0
133.2	271	6.88	0.016	1.29	320.1
145.4	259	6.57	0.015	1.34	320.2
169.8	234	5.95	0.013	1.40	320.3
191.8	212	5.39	0.012	1.49	320.4
216	188	4.78	0.011	1.51	320.5
240.4	164	4.16	0.011	1.63	320.5
264.6	139	3.54	0.010	1.76	320.6
288.3	116	2.94	0.011	1.86	320.6
325.6	78	1.99	0.011	1.95	320.6
374.6	29	0.75	0.012	2.10	320.7
337.7	66	1.68	0.013	2.13	320.7

Table C.5 VFI Data from September 11, 1998, Riser 1C

Reference elevation 412 in.

Depth (in)	Elev. (in)	Elev. (m)	Void Frac.	Press. (atm)	Temp. (K)
107	306	7.76	0.032	0.82	314.1
204	209	5.30	0.013	1.22	317.2
307	105	2.66	0.012	1.63	319.0
380	32	0.81	0.010	2.10	319.6
88	324	8.22	0.015	1.17	319.7
25	387	9.84	0.283	1.02	314.1
24	388	9.85	0.284	1.00	316.8
28	384	9.75	0.299	1.01	316.2
34	378	9.60	0.210	0.99	316.0
41	371	9.42	0.433	0.99	316.2
62	350	8.90	0.226	1.02	317.0
219	193	4.89	0.122	1.28	318.9
314	98	2.48	0.084	1.72	319.3

Appendix D

Data Acquisition Plan for Void Fraction Measurements in Tank 241 SY-101

Revision C

Jim Alzheimer

June 1998

Pacific Northwest National Laboratory
Richland WA 99352

Data Acquisition Plan for Void Fraction Measurements in Tank 241 SY-101

D.1 Introduction

This plan describes where and in what order void fraction measurements should be taken in Tank 241-SY-101. At each chosen location, the local void fraction will be determined from pressure and temperature data.

Additional VFI testing in Tank 241-SY-101 is desired because the waste level is increasing at a slow but steady rate without an accepted explanation. The planned VFI deployments are intended to measure the void fraction in the waste using the same equipment and procedures as were used for the earlier deployments, in December 1994 and January 1995, except for minor variations in the locations where the VFI measurements will be taken. For the current tests, the void fraction profile just below the crust and in the assumed soft lower portion of the crust are of interest because one possible explanation for the level increase is accumulation of gas in this region. Therefore, the original test matrix is expanded to include measurements taken higher in the waste.

A detailed void fraction profile is desired through the entire waste depth to compare with the earlier data. While using the VFI in the lower portion of the crust, there is a small risk of O-ring damage or getting a hard piece of waste stuck in the seal area and not being able to maintain pressure in the sample chamber. Also, successful sampling in the crust layer is not ensured because it has not been attempted before. Therefore, in the first riser, testing will be performed to confirm the ability to make VFI measurements in the crust only after the measurements have been completed in the remainder of the tank. If crust layer sampling proves practicable, crust layer measurements will be performed first in the second riser, followed by normal vertical traverses through the remainder of the tank.

In the past, up to three traverses have been conducted through the waste depth. However, due to the additional time required for the measurements in the crust layer, only one full traverse and a partial second traverse of eight measurements are planned if time and nitrogen supply permit. The elevations of the measurements in the second traverse are not specified and will be selected based on the preliminary void fraction data obtained during the first traverse. More data can be taken at locations where unexpected or unusual void fraction measurements were obtained.

D.2 Data Acquisition Strategy

Except for crust layer sampling, the same test strategy is planned for both selected risers, 4A and 11B. In the first riser, measurements are performed in the crust as a test after at least one normal traverse to the bottom of the tank has been completed. In the second riser, if crust sampling is successful, it will be performed first, followed by at least one normal traverse to the bottom. In any event, the test plan for the second riser should be modified as necessary based on the results from the first riser, as was the normal procedure in past tests.

D.2.1 Sample Locations

Three parameters describe the individual sample location in the tank. These are 1) selected riser, 2) angular orientation of the pivot arm, and 3) elevation from the tank bottom. By selecting appropriate combinations of these three parameters, the best understanding of the void fraction distribution can be made for the available time in the tank. The angular orientation is measured in degrees clockwise from the reference orientation with the arm pointed toward the tank center as illustrated in Figure D.1. The test matrix for the first riser is given in Table D.1 and described in Section D.2.1.1. If crust sampling is not successful, the test locations for the second riser are the same as in the first riser as described in Section D.2.1.2. If void measurements are to be performed in the second riser, the test matrix is given in Table D.2 and described in Section D.2.1.3.

D.2.1.1 First Riser

The VFI will be inserted into the waste until the pivot arm is well below the crust with the pivot pin for the arm at approximately 336 inches above tank bottom (approximately six feet below the waste surface and two feet below the bottom of the crust). **The cover will then be opened before rotating the arm to the horizontal. This is a change from previous procedures to minimize the disruption of the waste above the sample chamber.** The arm will be held in the vertical orientation at this location for ten minutes to begin reaching thermal equilibrium with the waste. The arm will then be rotated to the horizontal with the arm pointed 45 degrees clockwise from the tank center. This location will be held for another ten minutes for final thermal equilibration.

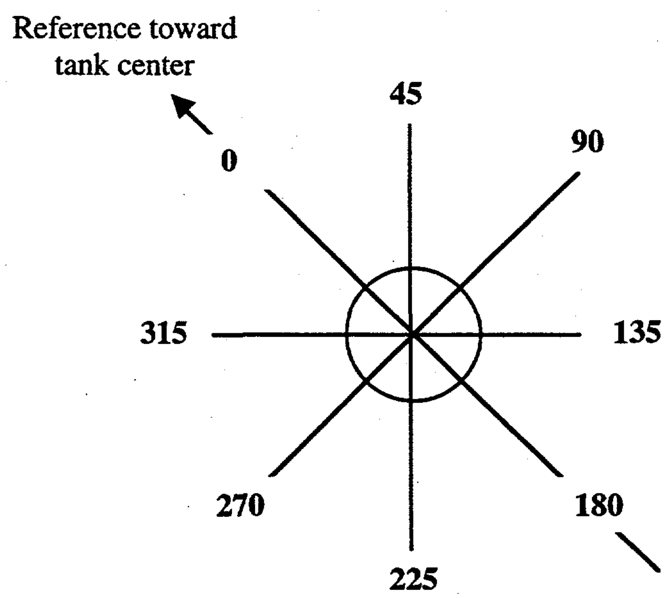

Figure 1. Reference for VFI Test Orientations

Table D.1. Void Fraction Matrix for SY-101, First Riser (or second riser without crust tests)

Test Number	Test Elevation (inches from bottom)	Arm Orientation (degrees clockwise from reference direction toward tank center)	Description
NA	366	45	Initial setup
1.	360	0	First traverse
2.	336	0	"
3.	312	0	"
4.	288	0	"
5.	264	0	"
6.	240	0	"
7.	216	0	"
8.	192	0	"
9.	168	0	"
10.	144	0	"
11.	120	0	"
12.	96	0	"
13.	84	0	"
14.	72	0	"
15.	60	0	"
16.	48	0	"
17.	36	0	"
18.	24	0	"
19.	12	0	"
20.	TBD	180	Second Traverse
21.	TBD	180	"
22.	TBD	180	"
23.	TBD	180	"
24.	TBD	180	"
25.	TBD	180	"
26.	TBD	180	"
27.	TBD	180	"
28.	372	270	Crust sampling test
29.	378	90	"
30.	384	225	"
31.	390	315	"

For the first test **the sample cover will be closed to protect the O-rings,** and the VFI will be raised very slowly until the sample chamber or arm contacts the bottom of the crust, or the sample chamber reaches 366 inches from tank bottom, whichever is lower. The crane load and the pressures in the VFI pneumatic cylinders must be monitored carefully as the VFI is raised to ensure compliance with the safety assessment. The pivot arm will be rotated to the reference orientation, pointing toward the tank center, without lowering the VFI, if possible. If there is excessive resistance to rotation, the VFI will be lowered in 6-inch increments until it can be safely rotated. The sample chamber cover will then be opened and the VFI lowered an additional six inches to fill the sample chamber with waste for the first void fraction measurement. A normal traverse will then be made to the bottom of the tank, as indicated in the test matrix in Table D.1.

When the last test in the first traverse is completed, the VFI will be raised to the elevation at which the VFI was rotated to begin the first traverse, or to a lower elevation. Then the sample chamber will be rotated 180 degrees clockwise to point away from the tank center and lowered at least six inches to begin the second traverse. Sample elevations for the second traverse will be determined based on the results of the first traverse. The schedule and nitrogen supply must be monitored carefully and the second traverse terminated if necessary to allow for crust layer testing.

After completing the last test in the second traverse to the bottom of the tank, the VFI will be raised so that the sample chamber is below the crust and a series of void fraction measurements taken just below and as far into the crust as possible. After each void fraction measurement, the sample chamber is opened and a gas bubble released that disturbs the waste around and above the sample chamber. Sampling of the crust will have to start at the bottom and progress upward. Therefore, crust layer sample locations are each at different orientations. The first crust sample will be six inches above the uppermost sample of the first traverse and with the arm oriented 90 degrees counterclockwise from the first traverse (270 degrees clockwise from reference). This attempts to minimize the disturbance from previous testing.

Several additional crust tests will be attempted at other orientations and depths, as shown in Table D.1. After each test in the crust, the VFI will be lowered to the depth at which the arm was able to rotate on the very first test (nominally 360 inches), the arm will be rotated to the desired orientation, and the VFI raised to the next test elevation. Testing will thus proceed with six-inch upward increments, with the VFI lowered and rotated between tests, until the load on the arm approaches the safety assessment limits or data is obtained at 390 inches from tank bottom.

D.2.1.2 Second Riser Excluding Crust Layer Measurements

If crust layer sampling was not successful in the first riser, and the decision is made not to attempt it in the second riser, the initial VFI setup and testing will proceed exactly as described for the first riser. The test matrix is listed in Table D.1, **excluding tests 28 through 31**. The test matrix may be modified based on the results from the first riser.

D.2.1.3 Second Riser Including Crust Layer Measurements

If the decision is made to perform crust layer sampling in the second riser, the VFI is positioned initially at 45 degrees as described in Section D.2.1.1 for the first riser, **except that a**

Table D.2. Void Fraction Matrix for SY-101, Second Riser with Crust Tests

Test Number	Test Elevation (inches from bottom)	Arm Orientation (degrees clockwise from reference direction toward tank center)	Description
NA	336	45	Initial setup
1.	366	180	Crust sampling
2.	372	270	"
3.	378	0	"
4.	384	90	"
5.	390	225	"
6.	396	315	"
7.	330	0	First traverse
8.	312	0	"
9.	288	0	"
10.	264	0	"
11.	240	0	"
12.	216	0	"
13.	192	0	"
14.	168	0	"
15.	144	0	"
16.	120	0	"
17.	96	0	"
18.	84	0	"
19.	72	0	"
20.	60	0	"
21.	48	0	"
22.	36	0	"
23.	24	0	"
24.	12	0	"
25.	TBD	180	Second Traverse
26.	TBD	180	"
27.	TBD	180	"
28.	TBD	180	"
29.	TBD	180	"
30.	TBD	180	"
31.	TBD	180	"
32.	TBD	180	"

lower elevation of 336 inches is used to minimize waste disturbance near the crust layer. The test matrix is given in Table D.2. The test matrix may be modified based on the results from the first riser.

After initial setup and thermal equilibration, the VFI will be rotated to the first orientation for crust testing and raised to the test elevation with the sample chamber open to capture a sample for the first void fraction measurement. The sample chamber is then opened, and the VFI lowered back to 336 inches before the arm rotated to the next crust sample location. Crust tests will continue in six-inch upward increments, with the VFI lowered and rotated between tests, until the load on the arm approaches the safety assessment limits or data are obtained 396 inches from tank bottom.

When the last crust layer measurement is completed, the VFI will be lowered back to 336 inches and the arm rotated to the orientation of the first traverse down the tank. At least one normal traverse will be completed using the test matrix in Table D.2, including any modifications based on the results from the first riser.

D.2.2 Sample Pressurization

The source pressure used to pressurize the samples will be held constant. The error analyses have shown that the higher the pressurization pressure, the more accurate the results. Therefore, a source pressure of approximately 3.4 MPa (500 psi) is recommended for all tests. No double pressurizations will be performed to conserve time and nitrogen.

D.2.3 Parameters Not To Be Varied

The VFI will be lowered as slowly as is reasonably possible with the crane. If it is moved too quickly, there is a potential for releasing unacceptable amounts of the trapped gas from the waste. Slow speeds were used in all previous VFI deployments and should be used again.

The sample chamber has a finite thermal mass. Time is required for the sample chamber to come to thermal equilibrium if moved between locations of different temperatures. The same hold times used for the previous tanks are appropriate for this test plan.

D.2.4 Additional Operational Items

Because a major objective of this test series is to measure the void fraction in and just under the crust layer, it is recommended that the waste disturbance during lancing be held to a minimum and that minimum water volume be used. However, crust penetration should NOT be attempted with the VFI without first lancing through the upper hard surface and ensuring that minimal force is required to complete the penetration.

The weight of the VFI on the crane is measured and monitored to ensure that neither the device nor the tank is damaged. For this series of tests, the load measured by the crane mounted load cell will be used to assist in positioning the VFI sample chamber at the bottom side of the hard crust. Without the crane load data, it will not be possible to complete the complete test sequence.

It is important to be sure that the setup for the VFI tests permits the VFI to probe the tank waste as deeply as possible. The scaffolding and plastic contamination containment sleeve should receive special attention.

Appendix E

Data Acquisition Plan for Void Fraction Measurements in Tank 241 SY-101

Revision D

Jim Alzheimer

July 1998

Pacific Northwest National Laboratory
Richland WA 99352

Data Acquisition Plan for Void Fraction Measurements in Tank 241 SY-101

E.1 Introduction

This plan describes where and in what order void fraction measurements should be taken in Tank 241-SY-101 for the second deployment of 1998. At each chosen location, the local void fraction will be determined from pressure and temperature data.

During the first deployment June 29, 1998, a much different void fraction profile was measured than the December 1994 and January 1995 deployments. This test plan for the second deployment of 1998 is intended to maximize our understanding of the gas retention processes in the tank.

Instead of deploying into a different riser at a different distance from the tank center for the second set of tests as was originally planned, the same riser (11B) will be used again. The parameters that will be varied will be related to the operation of the mixer pump. Whereas the mixer pump had been run only about 14 hours before the deployment on June 29, a longer time between mixer pump operation and testing is desired for this testing. In addition, it is desired to have the mixer pump aimed approximately at riser 11B for the last pump run before deployment. The intent is to re-mix the waste and avoid the potential for data contamination from the prior VFI test in 11B.

No crust tests are planned for this deployment. Because the amount of gas trapped in or just below the crust is not as much of interest as it had been before the last deployment, the relatively risky crust void measurements will not be made.

E.2 Data Acquisition Strategy

Because of the higher average void fraction in the tank, fewer void fraction measurements than normal will be possible before exhausting the nitrogen supply bottle. Therefore, only one full traverse is planned. This traverse will start as high in the tank as possible and continue in to the bottom. For this traverse, the lower arm will be pointed toward the tank center. Slightly more data will be taken near the top of the tank on this traverse than for the previous deployment to better characterize this part of the tank. A limited number of measurements may be taken on a second traverse if the nitrogen supply permits.

E.2.1 Sample Locations

Three parameters describe the individual sample location in the tank. These are 1) selected riser, 2) angular orientation of the pivot arm, and 3) elevation from the tank bottom. By selecting appropriate combinations of these three parameters, the best understanding of the void fraction distribution can be made for the available time in the tank. The angular orientation

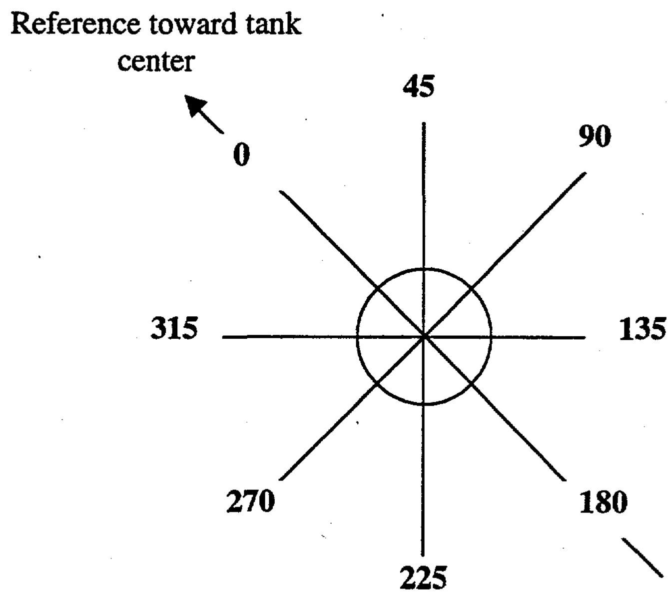

Figure E.1. Reference for VFI Test Orientations

is measured in degrees clockwise from the reference orientation with the arm pointed toward the tank center as illustrated in Figure E.1. The test matrix for this deployment is given in Table E.1 and described below.

The VFI will be inserted into the waste until the pivot arm is well below the crust with the pivot pin for the arm at approximately 336 inches above tank bottom (approximately six feet below the waste surface and two feet below the bottom of the crust). **The cover will then be opened before rotating the arm to the horizontal. This is a change from previous procedures to minimize the disruption of the waste above the sample chamber.** The arm will be held in the vertical orientation at this location for ten minutes to begin reaching thermal equilibrium with the waste. The arm will then be rotated to the horizontal with the arm pointed 90 degrees clockwise from the tank center. This location will be held for another ten minutes for final thermal equilibration.

For the first test, **the sample cover will be closed to protect the O-rings,** and the VFI will be raised very slowly until the sample chamber or arm contacts the bottom of the crust or the sample chamber reaches 350 inches from tank bottom (54 inches below surface), whichever is lower. The crane load and the pressures in the VFI pneumatic cylinders must be monitored carefully as the VFI is raised to ensure compliance with the safety assessment. The pivot arm will be rotated to the reference orientation, pointing toward the tank center, without lowering the VFI, if possible. If there is excessive resistance to rotation, the VFI will be lowered in six-inch increments until it can be safely rotated. The sample chamber cover will then be opened and the VFI lowered an additional 6 inches to fill the sample chamber with waste for the first void fraction measurement. A normal traverse will then be made to the bottom of the tank, as indicated in the test matrix in Table E.1.

Table E.1. Void Fraction Matrix for SY-101, Riser 11B Second Deployment

Test Number	Test Elevation (inches from bottom)	Test Distance (inches below surface)	Arm Orientation (degrees, see Figure D.1)	Description
NA	350	54	45	Initial setup
1.	344	60	0	First traverse
2.	332	72	0	"
3.	320	84	0	"
4.	308	96	0	"
5.	296	108	0	"
6.	284	120	0	
7.	272	132	0	"
8.	260	144	0	"
9.	236	168	0	"
10.	212	192	0	"
11.	188	216	0	"
12.	164	240	0	"
13.	140	264	0	"
14.	116	288	0	"
15.	92	312	0	"
16.	78	326	0	"
17.	66	338	0	"
18.	54	350	0	"
19.	42	362	0	"
20.	30	374	0	"
21.	18	386	0	"
22.	TBD	TBD	180	Second Traverse
23.	TBD	TBD	180	"
24.	TBD	TBD	180	"
25.	TBD	TBD	180	"
26.	TBD	TBD	180	"
26.	TBD	TBD	180	"
27.	TBD	TBD	180	"

If a second traverse is desired when the last test in the first traverse is completed, the VFI will be raised to the elevation at which the VFI was rotated to begin the first traverse or to a lower elevation. Then the sample chamber will be rotated 180 degrees clockwise to point away from the tank center and lowered at least six inches to begin the second traverse. Sample elevations for the second traverse will be determined based on the results of the first traverse. The schedule and nitrogen supply must be monitored carefully and the second traverse terminated if necessary.

E.2.2 Sample Pressurization

The source pressure used to pressurize the samples will be held constant. The error analyses have shown that the higher the pressure, the more accurate the results. Therefore, a source pressure of approximately 3.4 MPa (500 psi) is recommended for all tests. No double pressurizations will be performed to conserve time and nitrogen.

E.2.3 Parameters Not To Be Varied

The VFI will be lowered as slowly as is reasonably possible with the crane. If it is moved too quickly, there is a potential for releasing unacceptable amounts of the trapped gas from the waste. Slow speeds were used in all previous VFI deployments and should be used again.

The sample chamber has a finite thermal mass. Time is required for the sample chamber to come to thermal equilibrium if moved between locations of different temperatures. The same hold times used for the previous tanks are appropriate for this test plan.

E.2.4 Additional Operational Items

The weight of the VFI on the crane is measured and monitored to ensure that neither the device nor the tank is damaged. For this series of tests, the load measured by the crane mounted load cell will be used to assist in positioning the VFI sample chamber at the bottom side of the hard crust. Without the crane load data, it will not be possible to complete the complete test sequence.

It is important to be sure that the setup for the VFI tests permits the VFI to probe the tank waste as deeply as possible. The scaffolding and plastic contamination containment sleeve should receive special attention.

Appendix F

Data Acquisition Plan for Void Fraction Measurements in Tank 241 SY-101

Revision F

Jim Alzheimer

August 1998

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Richland WA 99352

Data Acquisition Plan for Void Fraction Measurements

in Tank 241 SY-101

F.1 Introduction

This plan describes where and in what order void fraction measurements should be taken in Tank 241-SY-101 for the third deployment of 1998. During the first deployment of 1998 on June 29 into riser 11B, a much different void fraction profile was measured compared to the December 1994 and January 1995 deployments. The second 1998 deployment on July 22, also in riser 11B, was much different than that of June 29 and more consistent with the early tests. This test plan for the third deployment of 1998 is intended to confirm hypotheses developed to explain the difference between them and to determine which best represents gas retention in the entire tank. The riser selected is 1C.

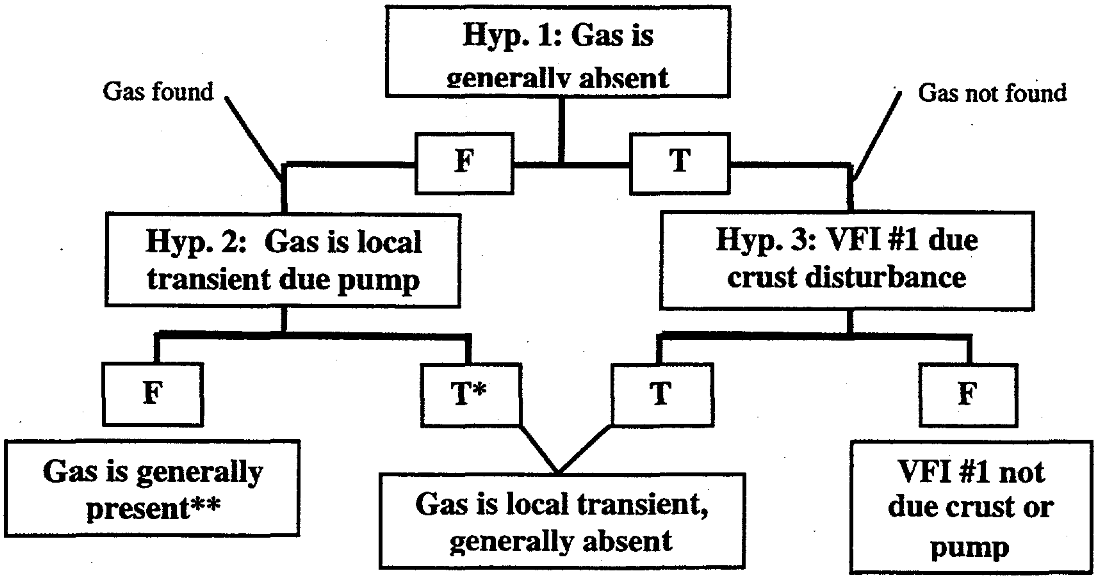
F.2 Data Acquisition Strategy

The purpose of the third set of tests is to determine which, if either, of the void fraction profiles measured on June 29 (Test 1A and 1B) or July 22 (Test 2) is representative of the entire tank. We also intend to find out whether a disturbance of the lower portion of the crust caused the high void fractions in Test 1. The VFI test plan is based on three hypotheses that will be tested with the logic sketched in Figure F.1. The three-part test plan is illustrated in Figure F.2.

The first, and we believe most likely, hypothesis is that **gas is generally absent** in the slurry layer and below, though pump runs and spontaneous releases may temporarily elevate the void fraction locally. Hypothesis #1 will be tested by making a few void measurements in a situation where it would be more likely to find a high void fraction. If a low void is found, the hypothesis is true. Accordingly, Test 3A will be performed less than 24 hours after a pump run aimed within 30 degrees of the test riser (155° azimuth overlies 1C).

If the void fraction found in Test 3A is minimal, Hypothesis #1 is true and we conclude that gas is generally absent. However, we wish also to examine a possible mechanism for the high void measured in Test 2. Accordingly, we pose Hypothesis #3 that the high void in **VFI #1 is due to a local crust disturbance.** This hypothesis will be tested by performing Test 3C, in which several crust void measurements will be made, followed by a deliberate disturbance of the lower portion of the crust. Then an abbreviated traverse will be made.

If a high void fraction similar to that of Test 1A is found on the traverse, it is a result of the crust disturbance and Hypothesis #3 is true. However, if the void fraction remains low, our hypothesis is false, and the results of Test 1 appear to be produced neither by a pump run nor crust disturbance, but is still confirmed to be a local event and not evidence of a generally high void fraction.



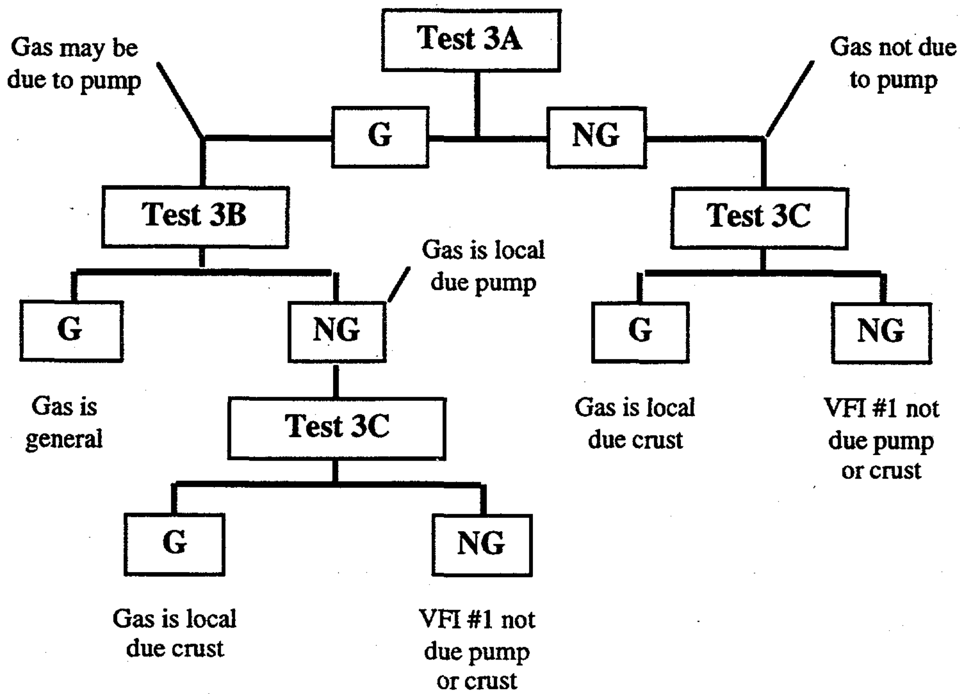
* Hyp. 3 also to be tested here, not shown. See Figure 2.
** VFI #2 may also be anomalous, but more tests are needed to prove it.

Figure F.1. Logic Flow - Hypotheses and Conclusions

If a void fraction greater than a few percent is found Test 3A, Hypothesis #1 is not proven but may still be true. To confirm this, we pose a second hypothesis that **the gas is a local transient event** due to pump operation. To test this hypothesis we perform a second set of void measurements. Test 3B will be an abbreviated traverse two days after Test 3A to allow entrained bubbles to rise and solids to settle after the pump run.

If the void fraction in Test 3B is greater or equal to that of Test 3A, Hypothesis #2 is false. This also confirms the Hypothesis #1 is false and we can conclude that **gas is generally present**. The results of Test 2 may be anomalous, but an additional test(s) would be required to confirm that. If the void fraction found in Test 3B is low, Hypothesis #2 is true, as is Hypothesis #1, and we can conclude that **gas is generally absent** except locally after a pump run. In this case, because the conclusions point to the level rise being caused by gas accumulation in the crust layer, Test 3C will be performed as described above to obtain crust void data and to confirm whether the Test 1A results were due to crust disturbance.

In summary, when this test plan is completed, we expect to have confirmed whether or not the mixed slurry layer generally contains a high or low void fraction and whether or not a disturbance of the lower portion of the crust layer cause the high void fraction of Test 1. The details of test operation and sample locations are described for each test described in the following sections.



Test 3A: Three void measurements <24 hrs after a pump run aimed within 30 degrees of riser.
Test 3B: Short traverse 2 days after Test 3A.
Test 3C: After Test 3A, crust void measurements & crust disturbance followed by short traverse.
G: High void fraction measured
NG: Low void fraction measured

Figure F.2. Test Plan

F.2.1 Sample Locations

Three parameters describe the individual sample location in the tank. These are 1) selected riser, 2) angular orientation of the pivot arm, and 3) elevation from the tank bottom. By selecting appropriate combinations of these three parameters, the best understanding of the void fraction distribution can be made for the available time in the tank. The angular orientation is measured in degrees clockwise from the reference orientation with the arm pointed toward the tank center as illustrated in Figure F.3.

Test 3C is intended to follow Test 3A or 3B in the same deployment. Because test 3B requires a two-day wait after Test 3A, the VFI should be removed during the waiting period. All three tests may be performed as separate deployments if necessary.

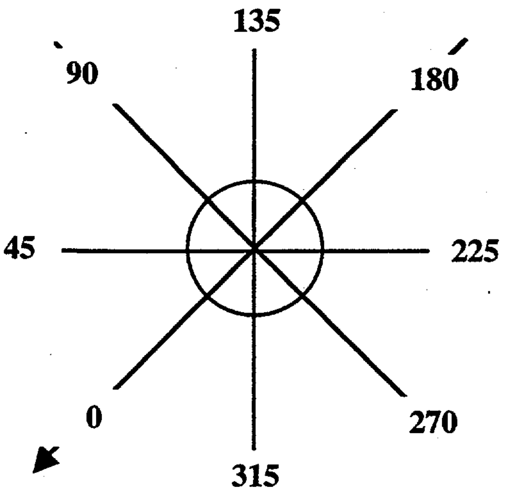


Figure F.3. Reference for VFI Test Orientations

The decisions to make the fourth measurement in Test 3A and to perform Test 3B depend on the first three void fraction measurements in Test 3A. The void fractions to be used with the criteria listed below are field values corrected by the offset shown in Figure F.4.

F.2.1.1 Test 3A

The objective of this series of measurements is to establish the void profile prior to any major disturbance of the crust layer in anticipation of the crust void measurements planned for Test 3C. Test 3A will be performed not more than 24 hours following a 25-minute pump run at 140, 155, or 170°. The results of this test will determine whether to conduct Test 3B or 3C next.

The VFI will be inserted into the waste until the pivot arm is well below the crust with the pivot pin for the arm approximately 320 inches above tank bottom (approximately seven feet below the waste surface and three feet below the bottom of the crust). **The cover will then be opened before rotating the arm to the horizontal. This is to minimize the disruption of the waste above the sample chamber.** The arm will be held in the vertical orientation at this location for ten minutes to begin reaching thermal equilibrium with the waste. The arm will then be rotated to the horizontal with the arm pointed 90 degrees clockwise from the tank center. This location will be held for another ten minutes for final thermal equilibration.

Four void measurements will be made in an abbreviated traverse with the arm oriented 90 degrees clockwise from the tank center. The lowest sample elevation will be more than 60 inches above tank bottom. The last sample will be taken on the way back up, above previously sampled locations. This sample will check whether 1) rising bubbles from lower tests

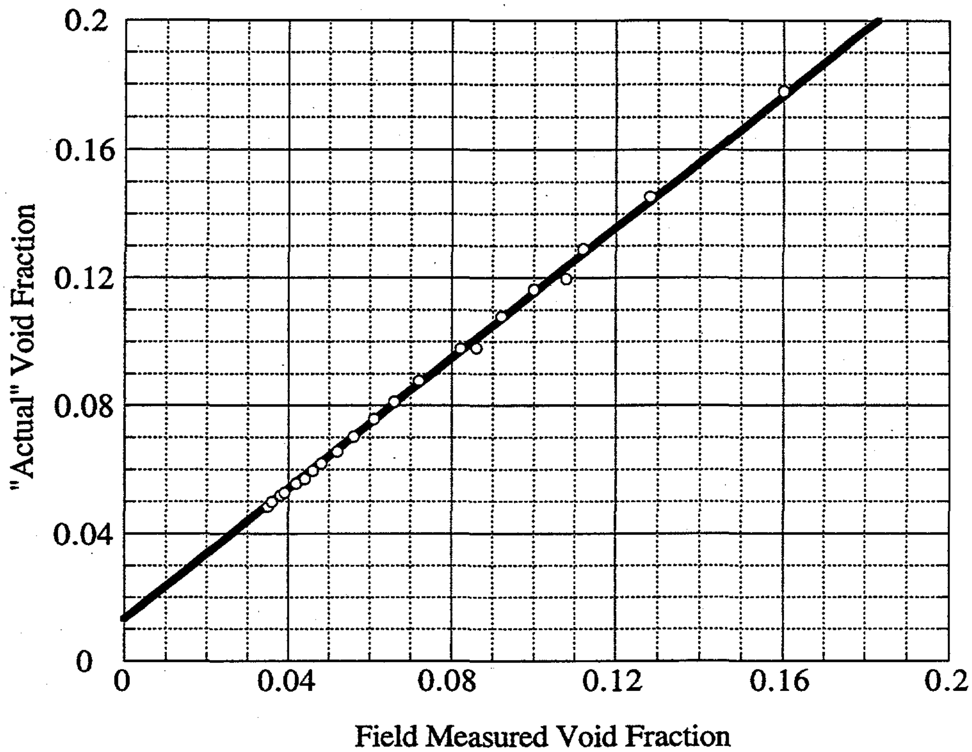


Figure F.4. Void Fraction Correction Chart

remove gas from above if high void is present or 2) rising bubbles from lower tests could increase the void fraction above if low void is present. The desired elevations are given in Table .F.1. If the corrected void fraction is less than 0.02 in all three tests, a fourth sample will be taken as low as practicable in the waste, approximately 18 inches above the tank bottom.

Table F.1. Void Fraction Matrix for Test 3A, SY-101, Riser 1C Deployment

Test Number	Test Elevation (in. from bottom)	Test Depth (in. below surface)	Arm Orientation (degrees, Fig. 3)	Description
1.	300	104	90	Short traverse
2.	200	204	90	"
3.	100	304	90	"
4.	18	386	90	Optional (low void 1-3)
5.	320	84	90	On the way out

If any of the three corrected void fractions are greater than 0.04 or if the average of the three measurements is greater than 0.02, Test 3B will be performed. This test requires a two-day waiting period, and the VFI will be removed from the tank. Otherwise, Test 3C will be performed. The void fraction criterion of 0.02 is chosen to distinguish significant gas retention in the slurry with respect to the sensitivity of the VFI system. An average void fraction below 0.02 accounts for under 40% of the measured level growth since 1995.

E.2.1.2 Test 3B

The objective of this test is to determine whether the gas found in Test 3A was a local event resulting from the prior pump run. The test will be performed not less than two days after Test 3A.

The VFI, removed from the tank after Test 3A, will be inserted into the waste until the pivot arm is well below the crust with the pivot pin for the arm at approximately 320 inches above tank bottom (approximately seven feet below the waste surface and three feet below the bottom of the crust). **The cover will then be opened before rotating the arm to the horizontal to minimize the disruption of the waste above the sample chamber.** The arm will be held in the vertical orientation at this location for ten minutes to begin reaching thermal equilibrium with the waste. The arm will then be rotated to the horizontal with the arm pointed 270 degrees clockwise (90 degrees counterclockwise) from the tank center. This location will be held for another ten minutes for final thermal equilibration.

Three tests will be conducted in an abbreviated traverse to the tank bottom with the arm oriented 270 degrees clockwise from the tank center. The desired elevations are given in Table F.2. If the void fractions measured in this test are similar to those found in Test 3A, it can be concluded that void fractions of this magnitude represent the entire slurry layer and the test series is terminated. If the average corrected void fraction in this test is less than 0.02, or is judged to be significantly lower than Test 3A, proceed to Test 3C.

Table F.2. Void Fraction Matrix for Test 3B, SY-101, Riser 1C Deployment

Test Number	Test Elevation (in. from bottom)	Test Depth (in. below surface)	Arm Orientation (degrees, Fig. 3)	Description
1.	320	84	270	Short traverse
2.	240	164	270	
3.	144	260	270	"
4.	36	368	270	"

F.2.1.3 Test 3C

The objective of this test is twofold: 1) to obtain several void measurements within the floating layer and 2) to determine whether a crust disturbance causes a high void fraction below it. After Test 3A or 3B is completed with a finding of minimal void, the VFI will be raised back to 320 inches above tank bottom, rotated to the zero degree azimuth (toward tank center) and then raised very slowly with the sample cover open until the sample chamber or arm is as high as practicable in the crust. This will be indicated by the sample chamber reaching approximately 12 inches below surface or when the crane and/or pneumatic pressure measurements indicate a load on the VFI lower arm, whichever is at a lower elevation. A single sample will be taken at this location. The crane load and the pressures in the VFI pneumatic cylinders must be monitored carefully as the VFI is raised to ensure compliance with the safety assessment and prevent damage to the VFI.

After the first crust void measurement is completed, the sample cover will be closed, the VFI will be lowered 12 inches, and an attempt will be made to rotate the pivot arm to 45 degrees clockwise from the tank center. If there is excessive resistance to rotation, the VFI will be lowered in 6-inch increments until it can be safely rotated. When the VFI can be rotated to the 45-degree azimuth, several more crust measurements will be made at other orientations and depths,as shown on Table F.3a. Fewer measurements may be made if the first is at a lower elevation than listed in the table.

After each test in the crust, the VFI will be lowered below the depth at which the arm was able to rotate after the first crust measurement (nominally 360 inches), the arm will be rotated to the desired orientation, and the VFI will be raised to the next test elevation. Testing will thus proceed with 6-inch downward increments, with the VFI lowered and rotated between tests.

After the lowering the VFI and opening the sample chamber after the last crust measurement, the arm will be oriented to zero degrees (toward tank center) and the sample chamber cover opened. The VFI will be lowered an additional six inches to fill the sample chamber with waste for the first void fraction measurement of an abbreviated traverse to the bottom of the tank, as indicated in the test matrix in Table F.3b. Additional measurements may be added to resolve trends in the void fraction profile, time and nitrogen supply permitting.

Table F.3a. Void Fraction Matrix for Test 3C Crust Samples, SY-101, Riser 1C Deployment

Test Number	Test Elevation (in. from bottom)	Test Depth (in. below surface)	Arm Orientation (degrees, Fig. F.3)	Description
1.	392	12	45	Crust measurement
2.	378	24	135	"
3.	372	30	180	"
4.	368	36	225	"
5.	362	42	315	"

Table F.3b. Void Fraction Matrix for Test 3C Traverse, SY-101, Riser 1C Deployment

Test Number	Test Elevation (in. from bottom)	Test Depth (in. below surface)	Arm Orientation (degrees, Fig. F.3)	Description
1.	344	60	0	Short traverse
2.	260	144	0	"
3.	180	224	0	"
4.	90	314	0	"
5.	54	350	0	"
6.	18	386	0	"

If high void is found in this traverse, it can be concluded that crust disturbance causes gas-bearing material to fall, increasing the void measured below the disturbed area. This, then is the most likely explanation for the high void found in Test 1. If low void is found following the crust disturbance, the results of Test 1 are shown not to be caused by the pump run or crust disturbance.

F.2.2 Sample Pressurization

The source pressure used to pressurize the samples will be held constant. The error analyses have shown that the higher the pressurization pressure, the more accurate the results. Therefore, a source pressure of approximately 3.4 MPa (500 psi) is recommended for all tests. No double pressurizations will be performed to conserve time and nitrogen.

F.2.3 Parameters Not To Be Varied

The VFI will be lowered as slowly as is reasonably possible with the crane. If it is moved too quickly, there is a potential for releasing unacceptable amounts of the trapped gas from the waste. Slow speed was used in all previous VFI deployments and should be continued.

The sample chamber has a finite thermal mass. Time is required for the sample chamber to come to thermal equilibrium if moved between locations of different temperatures. The same hold times used for the previous tanks are appropriate for this test plan.

F.2.4 Additional Operational Items

It is important to be sure that the setup for the VFI tests permits the VFI to probe the tank waste as deeply as possible. The scaffolding and plastic contamination containment sleeve should receive special attention prior to actual deployment.

Because the area around riser 1C has been repeatedly flushed with water, we believe lancing is not required prior to Test 3A. However, the VFI should be lowered through the crust very slowly and crane load should be monitored carefully to avoid high resistance. It is imperative to ensure the sample chamber and cover are not damaged. If lancing is determined necessary prior to Test 3A, it will not be required for the subsequent tests.

Appendix G

Gas Volume Calculation Model

Appendix G

Gas Volume Calculation Model

The most general expression for the gas volume contained in a cylindrical waste volume of depth, L, and radius, R, is given by the integral

EMBED Equation.2 (G.1)

where _ is the local instantaneous gas indicator function (Kataoka 1986; Zhang and Prosperetti 1993). The gas indicator function is defined as

_(x) = 1: gas is present at position x
_(x) = 0: gas is not present.

The area average gas fraction, _(z), which is the fraction of the total cross-sectional area occupied by gas in the plane z, is defined as

EMBED Equation.2 (G.2)

where A = _R2. The gas fraction is also often termed the 'void fraction'. Substituting Eq. (G.2) into Eq. (G.1) gives

EMBED Equation.2 (G.3)

In evaluating the flammable gas hazard and comparing tanks, we need to adjust the in-situ volume to standard pressure and temperature. Including the pressure and temperature correction in Eq. (G.1) gives the standard gas volume as

EMBED Equation.2 (G.4)

where p(r,_,z) and T(r,_,z) are the local pressure and temperature, respectively; EMBED Equation.2 is the standard atmospheric pressure of 101,320 Pa; and EMBED Equation.2 is the standard temperature, 298K. If we define the area average pressure, P(z), and temperature, T(z), in the same way as the area average gas fraction, the total gas volume at standard temperature and pressure is given by

$$\hat{V}_G = A\int_0^L \frac{p(z)}{\hat{p}}\frac{\hat{T}}{T(z)}\alpha(z)dz \tag{G.5}$$

The waste is actually composed of two main layers: a floating crust and a mixed slurry layer (the loosely settled layer is assumed to be part of the slurry for the purposes of the gas volume calculation). It is also necessary to subdivide the major waste layers further into sub-layers to resolve the profile of the local void fraction data and to perform the numerical analog of the integration in Eq. (G.3) and (G.5). Therefore it is most convenient to consider each layer and sublayer separately. Performing the integration for a layer or sublayer, i, of thickness, H_i, and average void fraction, α_i, the in situ volume, V_i, of the layer is

$$V_i = \alpha_i A H_i \tag{G.6}$$

and the standard volume, $\hat{V}_i$, is:

$$\hat{V}_i = V_i \frac{p_i}{\hat{p}} \frac{\hat{T}}{T_i} \tag{G.7}$$

where H_i is the layer thickness, p_i is the layer pressure, and T_i is the layer average temperature. Because the product of pressure and temperature ratios occurs often, we define the 'effective pressure ratio,' P_i, as

$$P_i = \frac{p_i}{\hat{p}} \frac{\hat{T}}{T_i} \tag{G.8}$$

G.1 Mixed Slurry Layer

The pressure in a sublayer i in the mixed slurry is calculated by

$$p_i = \hat{p} + g\rho_L f_S H_{CR} + g\rho_{SL}\left(\sum_{j<i} H_j(1-\alpha_j) + \tfrac{1}{2} H_i(1-\alpha_i) \right) \tag{G.9}$$

where ρ_L and ρ_{SL} are the liquid and degassed mixed slurry layer densities, respectively; H_{CR} is the crust layer thickness; f_S is the crust submergence fraction; H_i is the nonconvective sublayer thickness; and α_i is the sublayer void fraction.

The total in situ gas volume in the mixed slurry is the sum of the gas volumes in the respective sublayers:

$$V_{SL} = A \sum_{i=1}^{SL} \alpha_i H_i \tag{G.10}$$

The total standard volume is similarly computed, making use of the effective pressure ratio definition of Eq. (G.8) as

$$\hat{V}_{SL} = A \sum_{i=1}^{SL} \alpha_i H_i P_i \tag{G.11}$$

The overall average void fraction for the entire mixed slurry layer is calculated by

$$\alpha_{SL} = \frac{1}{H_{SL}} \sum_{i=1}^{SL} \alpha_i H_i \tag{G.12}$$

The average pressure ratio is defined as

$$P_{SL} = \frac{\hat{V}_{SL}}{V_{SL}} = \frac{1}{H_{SL}\alpha_{SL}} \sum_{i=1}^{SL} \alpha_i H_i P_i \tag{G.13}$$

G.2 Crust Layer

The effective pressure is the hydrostatic pressure at the midpoint of the submerged portion of the crust:

$$p_{CR} = \hat{p} + \frac{g}{2}\rho_L f_S H_{CR} \tag{G.14}$$

The in situ crust gas volume calculated from the measured void fraction and the thickness of the submerged portion of the crust. The crust submergence fraction, f_S, is derived from Archimedes' Principle in and is given by

$$f_S = \frac{\dfrac{1}{1-\alpha_{NB}} - (1-\psi)\phi}{\dfrac{1}{1-\alpha_{CR}} - (1-\psi)\phi} \tag{G.15}$$

where ϕ is the porosity of the material above the liquid level and ψ is its liquid saturation (ψ=1.0 means the porosity is filled with liquid), α_{CR} is the average crust void fraction and α_{NB} is the neutral buoyancy void fraction which is computed as

$$\alpha_{NB} = 1 - \frac{\rho_L}{\rho_{CR}} \tag{G.16}$$

where ρ_{CR} is the ungassed bulk density of the submerged portion of the crust. We must also apply an area factor, F_A, to account for the fact that the crust occupies slightly less than the total tank area.

The crust in situ and standard volumes are given, respectively, by

$$V_{CR} = AF_A \alpha_{CR} f_S H_{CR} \tag{G.17}$$

$$\hat{V}_{CR} = V_{CR} P_{CR} \tag{G.18}$$

The total in situ and standard gas volumes in the entire tank are the sums of the contributions of individual layers. They are given, respectively, by

$$V_G = V_{SL} + V_{CR} \tag{G.19}$$

$$\hat{V}_G = \hat{V}_{SL} + \hat{V}_{CR} \tag{G.20}$$

The overall tank effective pressure ratio is computed as the ratio of standard volume to in situ volume.

$$P_{EFF} = \frac{\hat{V}_G}{V_G} \tag{G.21}$$

G.3 Statistical Data Reduction Model

As indicated in Eq. (G.5), the total retained gas volume in a tank at standard temperature and pressure can be calculated by integrating the product of the local void fraction, hydrostatic pressure, and waste temperature, all of which vary with elevation. The spatial variability and measurement error associated with these quantities must be included in the uncertainty of the overall retained gas volume. The multiple sources of variability and the complex calculations make it difficult to calculate the uncertainty analytically. Instead, a Monte Carlo simulation technique is used to propagate the sources of variability through calculation numerically.

There are two key elements in this statistical simulation model: performing the numerical integration for the overall retained gas volume and combining the various sources of variability to obtain the overall uncertainty using a Monte Carlo simulation technique.

With the measurements of void, density, temperature, and waste configuration (i.e., layer thickness), the numerical integration is performed by dividing the tank waste into many very thin horizontal slices. If the slices are sufficiently thin, the void, hydrostatic pressure, and temperature within a slice can be considered uniform. Values of these quantities in a slice that does not contain a measurement are estimated as that of the nearest measurement. The retained gas volume in each slice can then be calculated as the integrand in Eq. (G.5). The summation of the gas volumes in all waste slices is a fair approximation of the integration in Eq. (G.5) for the total retained gas volume.

The numerical integration step does not assess the uncertainty of the gas volume estimate directly. The sample measurements vary spatially and are subject to measurement error. This implies that the measurements we have are just one set of values from a distribution of all possible values. If we took another set of measurements, we would obtain different values that would give a different total gas volume estimate. If this process were repeated many times, it would produce a distribution of the total gas volume that reflects the combined impact of the uncertainties from the multiple sources.

We can simulate the possible sampling results from estimated or assumed probability distributions of the input parameters and data. These distributions need to be set based on sample data, knowledge of the physical mechanisms of gas retention, and some assumptions. To ensure a reasonable coverage for all possible combinations of void, density, temperature, and waste configuration, a large number (e.g. 5000) of sets of measurements are simulated. The uncertainties of these derived quantities can then be estimated from the outputs of these simulations.

G.3.1 Input Probability Distributions

The following ascribes probability distributions to measurements of temperature, density, layer dimensions, and void fraction. The density and layer thickness are necessary to compute the hydrostatic pressure.

Temperature

The waste temperature is taken from MIT thermocouple measurements performed at approximately the time of the VFI tests. The temperature at each measuring elevation is assumed to be normally distributed. The measured value is taken as the mean and the standard deviation is assigned as 2°C. This distribution, which is applied to all tanks, is assumed to reflect both nominal measurement error and lateral variability of waste temperature.

Density

Mean and standard deviations of waste densities in the mixed slurry layer are based on density measurements with the ball rheometer in 1995 (Meyer et al. 1997). The submerged crust density is assumed equal to the nonconvective layer density determined from laboratory analysis of core samples (Reynolds 1993). The densities are assumed to be normally distributed with the same distribution applied to the entire mixed slurry or crust layer.

Waste Configuration

Normal distributions are assumed for waste surface level and crust thickness. Means and standard deviations are derived by averaging several kinds of measurements.

Void Fraction

Variability of void fraction is evaluated directly from VFI void fraction measurements. This variability mainly reflects the spatial variability within a tank. The measurement error associated with individual void measurement is not included in calculation because it is small compared with spatial variability.

The variability of void fraction is evaluated separately for the mixed slurry and crust layer. Each layer is divided into sublayers 48-cm (19-in.) thick. This thickness is chosen to match the length of an RGS segment for convenience in later combination of VFI and RGS data. This choice allows VFI and RGS data to be weighted equally when combined.

For each sublayer containing one or more void measurements, a sample mean is calculated as the average of all the measurements in the sublayer. A common lateral variability is assumed for all sub-layers in nonconvective layer. This lateral variability is estimated by a pooled sample variance, which is a weighted average of sample variance from all sublayers with more than one void measurement. The pooled sample standard deviation is calculated as

$$\hat{\sigma}_{\text{pooled}} = \sqrt{\frac{\sum_{i} n_i \hat{\sigma}_i^{\,2}}{\sum_{i} n_i}} \tag{G.22}$$

where n_i denotes the number of void samples in sublayer i, and σ_i denotes the sample standard deviation in sublayer i. The weighting emphasizes the sublayers containing the most measurements.

It is assumed that void measurements within a sub-layer are from a common normal distribution with the estimated mean void of the sub-layer and the pooled sampled standard deviation. The void measurements from the same riser are assumed to be correlated with a covariance equal to the riser to riser variability. The VFI data show that, in some tanks, void fraction measurements from one riser tend to be higher than the measurements from the other riser. The simulated sample measurements should reflect this tendency.

Void fraction measurements with this kind of riser-dependent structure can be simulated by imposing a covariance on a set of completely independent samples. Specifically, a covariance matrix is constructed with a dimension equal to the number of void fraction measurements in the main layer. The diagonal elements of the matrix are equal to the variance of the distribution from which the measurements are simulated. Because a common variance is assumed for all sublayers, all diagonal elements are all the same. The off-diagonal elements in the matrix represent covariance between two void measurements. If two measurements came from the same riser, the covariance is set equal to the riser-to-riser variability. Otherwise, the covariance is zero. Based on the properties of normal distributions, this matrix can be used to convert a set of completely independent random samples to a set of samples with the desired riser-to-riser structure.

The riser to riser variability was estimated through the following Analysis of Variance (ANOVA) model.

$$\alpha_{ijk} = \overline{\alpha} + R_i + L_j + \varepsilon_{ijk}$$

where

α_{ijk} = local void fraction measurement k in riser i at layer j
= mean void fraction in entire layer
R_i = deviation of void fraction at riser i from the mean
L_j = deviation of the void fraction in the jth sublayer
ε_{ijk} = sampling and measurement error

The riser effect R_I is considered as a random effect with zero mean and standard deviation σ_R. This standard deviation, which represents the riser-to-riser variability, was estimated by fitting the model to the VFI data for each tank.

G.3.2 Calculation Procedure

To numerically integrate the void fraction measurements and to propagate the sources of variability, the waste is divided into many very thin slices. We choose a 4.8-cm (1.9-in.) slice thickness, $1/10^{th}$ of the nominal 48 cm (19-in.) sublayer dimension. The idea is to simulate possible sample measurements (temperature, void, etc.); therefore, the waste condition in each thin slice can be evaluated from a given set of simulated measurements. Then the mean void fraction is estimated as the average void fraction in all the thin slices. The total retained gas volume is estimated as the sum of the gas volumes in each slice.

A set of measurements is simulated from the distributions described above using the following procedure:

1. Simulate a realization of waste level, crust thickness and submergence fraction, mixed slurry layer depth, and density from the pre-defined distributions.

2. Divide crust and mixed slurry layers into slices 1.9-in. thick based on the current realizations of waste configuration for the purpose of numerical integration.

3. Simulate a realization of temperature at each measuring location. If a waste slice does not contain any measuring location, the temperature of the slice will be the value of the realization at nearest elevation.

4. Simulate a realization of void fraction at each sampling location. Void fraction realizations at sampling locations within the same 19-in. sublayer are simulated from the same distribution. The void fraction value for each waste slice is calculated using the same procedure as for temperature.

For each simulation, one realization of average void fractions, gas volumes and effective pressures for crust, mixed slurry, and whole tank is calculated. Using i to index a waste slice, the following equations are used for the calculation:

$$\alpha_{mean} = \frac{1}{n_{slice}} \sum_i \alpha_i$$

$$V_G = A \sum_i \alpha_i h_i$$

$$\hat{V} = A \sum_i \alpha_i h_i \frac{p_i}{\hat{p}} \frac{\hat{T}}{T_i}$$

where n_{slice} is the number of slices in a layer; h_i is the height of a slice; α_i, p_i, and T_i denote void, pressure, and temperature, respectively, in i^{th} slice. The total gas volume is the sum of the gas volumes in the two waste layers.

A set of 5,000 realizations is obtained for each quantity of interest. A summary of the output distributions, including mean, median, standard deviation, percentiles, etc. is then calculated from these distributions.

G.4 References

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