TRANSIENT CLEARING OF AIR IN A LOOP SEAL

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1. EXECUTIVE SUMMARY

A quasi-steady filling assumption leaves an air void in a loop seal. Transient filling at high rate might project water at high momentum into the loop seal, thereby sweeping out most of the air. Tests were performed and confirmed that, for specified flow rates, the quasi-steady model was relatively accurate. Of the air estimated by the quasi-steady model, approximately 85% remains trapped.

2. SITUATION AND TEST BASIS

The situation arises in consideration of potential air entrapment at Millstone Station Unit #3 in the RSS System. Following a large-break LOCA, all air may not be fully cleared during filling of the piping to the containment spray header, leaving a small air void in a dead-end loop seal to valves MV8837A/B. When these valves are subsequently opened, this air tends to be transported toward the charging and safety injection pumps. Although the amount of air arriving at pump inlets is small, NU has performed a detailed evaluation of the inlet void fraction as a function of time, so as to assess the risk to pump integrity.

If the air was not trapped in the first place, then there would not be a need for detailed evaluation of air transportation. Accordingly, deterministic analysis and model tests were performed to assess the filling transient. Figure 1 is a normalized elevation schematic of the geometry; dimensions are given in Table 1.

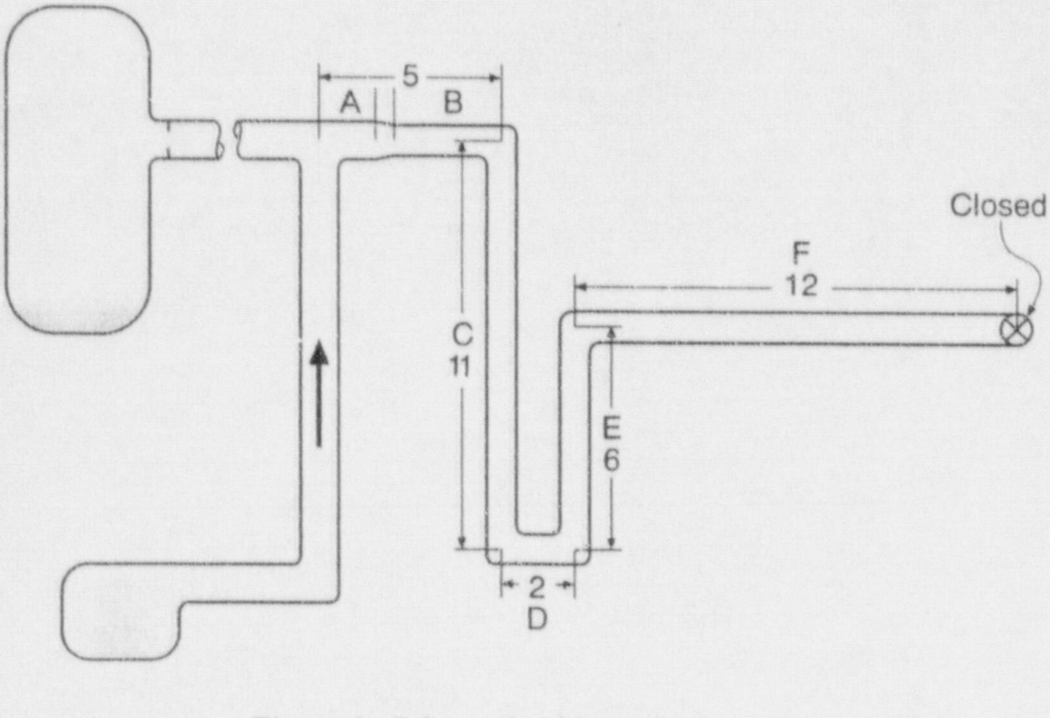

Figure 1. Schematic of Loop Seal
(All lengths are normalized in pipe diameter.)

Table 1. Millstone Station Pipe Section Descriptions				
Pipe Section	**Length L (inches)**	**L/D**	**Diameter D (inches)**	**Segment Orientation**
A	15	1.5	10	Run
B	24	3	8	Run
C	87	11	8	Downcomer
D	16	2	8	Run
E	50	6	8	Riser
F	92	12	8	Run

3. TEST FINDING

Slow filling of a loop seal to a dead-end pipe, at constant pressure, will fill the seal with water only to the high point of the seal, as in Figure 2. Based on preliminary screening tests, we find that rapid filling leads to nearly the same result.

These tests were performed in a one-quarter scale model. Our opinion is that there is low potential to alter this conclusion even if elaborate tests were performed at various scales. Accordingly, we abandoned further tests.

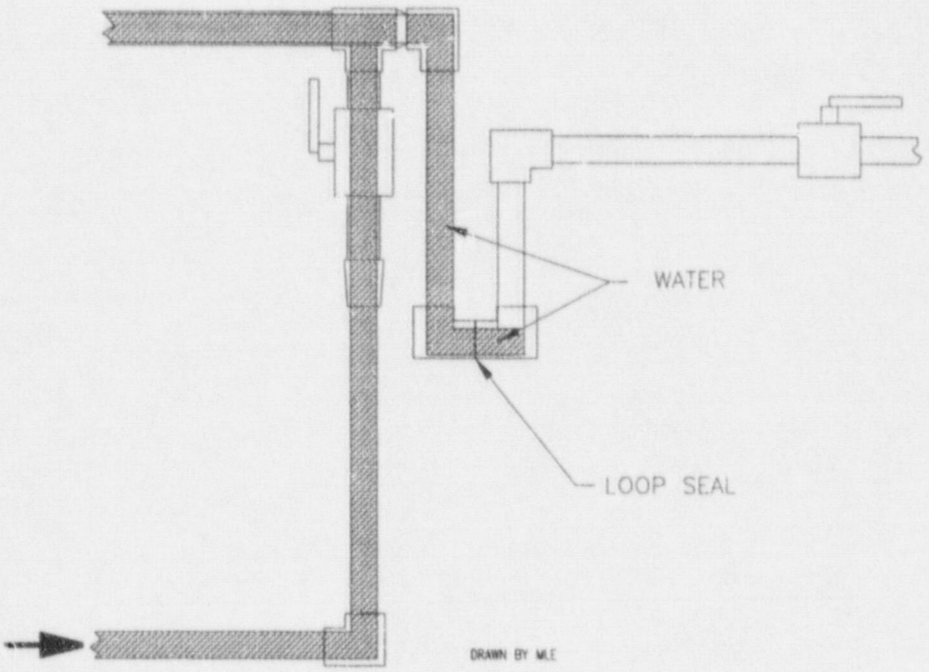

Figure 2. Slow Filling of a Loop Seal

4. TEST MODEL AND DATA

The physical model constructed at Creare is shown in Figure 3 and was based on 2 inch piping. The normalized dimensions are given in Figure 4. Both the actual and the normalized dimensions are listed in Table 2. The prototype is primarily 8 inch diameter. The scaling analysis of Section 5 indicates similitude for 3 inch piping. It was less expensive and faster to perform the early screening tests with somewhat undersized 2 inch pipe. Our intention (if the results were promising) was to step up to 4 inch pipe thereby both bounding the design basis for similitude and also providing data at two scales to confirm scaling to full size.

The mixing tee was appropriately scaled with 2.5 inch pipe. The exhaust side (modeling the piping to the containment spray header) was also appropriately scaled as 2.5 inch piping. This exhaust was to one atmosphere pressure in a relatively short length of pipe. The estimated frictional pressure drop in this piping is negligible as an adjustment to system (one atmosphere) pressure. The exhaust pipe rose approximately 7 inches to its exit. The imposed head of 7 inches of water is negligible in comparison with one atmosphere system pressure (approximately 34 ft).

To preserve Froude number, the model flow rate was approximately 160 gpm. (See calculation sheet in Section 6.) A rotameter was installed to measure this flow rate with approximately 5% accuracy. The flow rate was checked independently by catching the exhaust flow in a tank for a time metered by stopwatch. Though less precise, this second measurement of flow rate by a second, independent means provides considerable confidence in the accuracy of the primary measurement.

Tests were performed at the model flow rate to preserve similarity, and also at a higher flow rate closer to the full scale value of 21 ft/sec.

Operation of the facility, Figure 3, proceeded as follows. Initially all of the valves and drain plugs were closed with the system void of water. Valve 2 was then cracked open slightly; the pump was turned on; and valve 1 was opened slowly. As water began to flow through the flow meter, valve 2 was opened fully, and the system was flushed of air. After flushing, valve 2 was adjusted to achieve the desired flow; valve 1 was closed; and then the pump was turned off.

With the pump off, the piping after the Tee was drained through V3. To aid this process, valves 4, 5, 6 and 7 were opened. Once drained, valves 3, 4, and 7 were closed; the graduated cylinder was filled with water; and then, valves 5 and 6 were also closed.

At this point, we were ready to begin testing. The pump was turned on, and valve 1 was opened for 15 seconds. The flow rate was recorded, and the spill water was timed and gathered in a tank as a rough check on the flowmeter. The test was ended by closing valve 1, then turning off the pump.

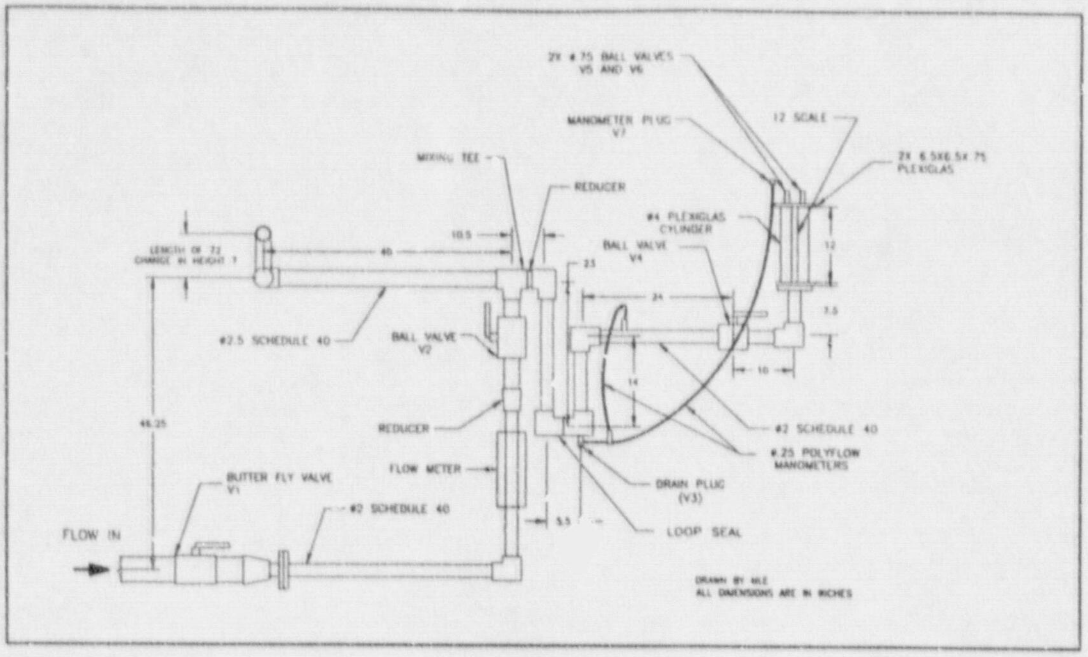

Figure 3. As Built Test Facility
(Numbers are in inches)

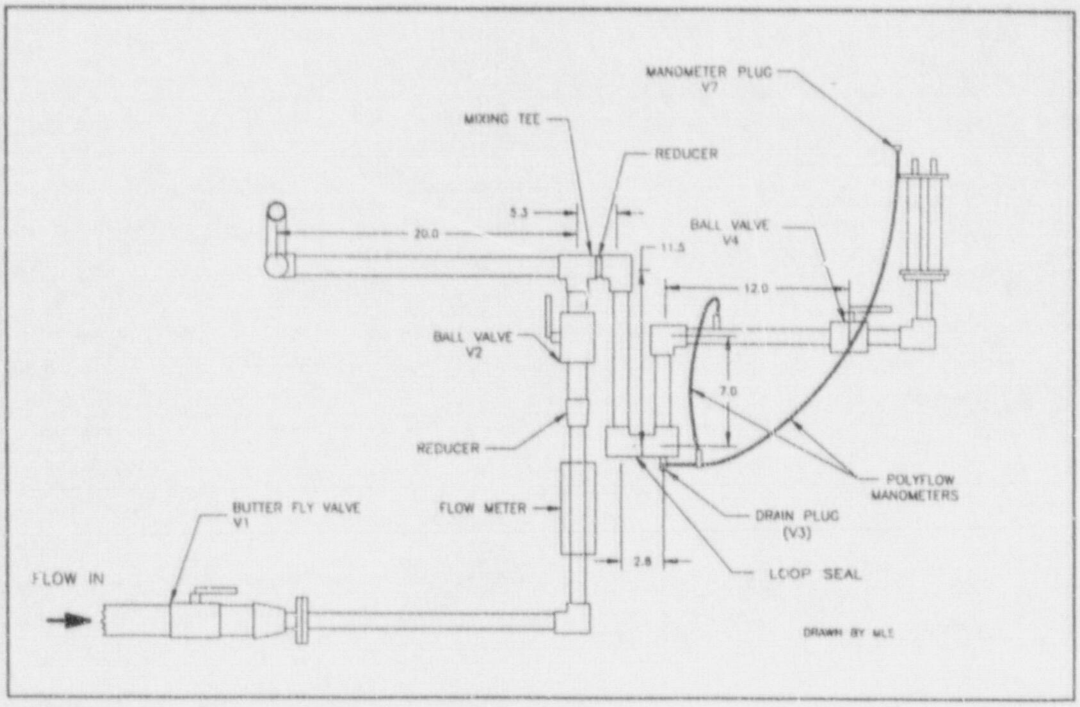

Figure 4. Normalized As Built Test Facility
(Dimensions are divided by Pipe Diameter)

Table 2. Test Facility Normalized Dimensions				
Pipe Section	**Length L (inches)**	**L/D**	**Diameter D (inches)**	**Segment Orientation**
A	5.5	2.2	2.5	Run
B	3.5	1.7	2	Run
C	23	11.5	2	Downcomer
D	5.5	2.7	2	Run
E	14	7.0	2	Riser
F	24	12.0	2	Run

The void volume in the dead end loop seal was determined two different ways. First, one could simply observe on the loop seal manometer the water level in the loop seal. This measure is highly accurate for the actual situation, with water limited to Section E and not filling Section F. For the preferred situation, water substantially in Section F, the manometer would have been a backup measurement.

Secondly, valves 4 and 7 were opened, allowing the void to flow into the measuring cylinder. The volume of air in the cylinder was recorded. The air pressure in the cylinder is nearly atmospheric pressure and can be determined by a hydrostatic balance or by direct measurement L using a second manometer on the top of the cylinder.

To repeat the test, the test section was drained, the measuring cylinder refilled with water and another test was run.

We ran a total of 6 tests as shown in Table 3. The first four were run through the facility as shown in Figure 3.

Table 3. Transient Clearing of Air In a Loop Seal					
Test Number	Flow Rate GPM	Void Volume Ft^3	Void Length Inches	L/D_{void}	Void Fraction
1.	170	0.0623	32.07	15.5	0.87
2.	190	0.0618	31.83	15.4	0.86
3.	160	0.0591	30.43	14.7	0.82
4.	190	0.0568	29.43	14.2	0.80
Mean	177	0.0600	30.94	15.0	0.84
5.	250 (approx.)	0.0623	32.07	15.5	0.87
6.	275 (approx.)	0.0605	31.11	15.1	0.84

For the last two tests, we removed the 2 inch inlet pipe and the flow meter to obtain higher flows and determine their effect. For these last two tests, the flow rate was estimated by timing and catching the exhaust water. The results consistently showed that the vast majority of the air beyond the loop seal remained trapped after filling. In the table, the void volume is the volume of air left in the piping down stream of the loop seal after a filling cycle (the fraction of the volume of pipes E and F). The void length is the length of the void in a 2 inch pipe. There are approximately 37 inches of 2 inch pipe after the loop seal in the test facility. Dividing the void length by the pipe length after the seal gives us the L/D_{void} ratio. The final column of data is the void fraction in the pipe section after the loop seal. The air pressure in the cylinder is not given, in that it was an inconsequential (1 to 2 inches of water).

It is quite evident that transient filling of the dead end loop seal does not effectively clear the air beyond the seal. Approximately 85% of the air remains trapped, or, alternatively, only 15% of the air is cleared. Additionally, there is no evidence that flow rate has an appreciable effect on the trapped void fraction.

5. TEST BASIS --- PREDICTION OF TRANSIENT CLEARING OF A LOOP SEAL

Consider the loop-seal geometry in Figure 1. The prototype has an eight inch diameter pipe except in the region of the tee where the piping is ten inches in diameter. The length dimensions are approximately 39, 87, 16, 50, and 92 inches which for an eight inch (sch 40) pipe equates to 5,11, 2, 6, and 12 inch multiples of pipe diameter. (The first pipe run is in fact two sections, A and B, of slightly different diameter.)

The tank to the upper left of Figure 1 is intended to represent containment. At the time of the subject filling transient, it is at a pressure of approximately 38 psia (23 psig). Because the containment is large, pressure is relatively constant during the critical portion of this filling transient. In particular, volumetric addition of water from this system, as well as condensation on the moving front in the piping, can both be neglected as factors altering containment pressure.

The piping is initially full of air. A column flow enters the tee at a flow rate of approximately 5200 gpm which is specified as a velocity of 21 ft/sec[1]. This is a Froude number in the riser to the tee of approximately

$$F = \frac{V}{\sqrt{gD}} = \frac{21}{\sqrt{32(10/12)}} = 4.1\,. \qquad (1)$$

5.1 A Model of Clearing Flow at a Simple Tee

The region of a mixing tee is quite complex when water is injected in an air-filled pipe[2]. However, at distances of 10 diameters or greater from the tee, open channel flows tend to be either stratified or column flow, according to the Froude number.

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[1] Craffey, J.J.; *Millstone 3 - Northeast Utilities Purchase Order 02041608, RSS Air Pocket Issue*; Northeast Utilities, October 15, 1997.

At the tee, the pressure loss due to friction is initially small and equal. So, initially the flow splits equally between the two directions, a Froude number of about two in each direction. If the pipe proceeded in each direction at constant size, to an open end at least ten diameters away from the tee, then we would expect a simple column flow in each direction. All of the air would soon clear in a simple manner. Assume that in fact this is the behavior in the left leg toward the tank in Figure 1.

The dynamic head in the flow toward the tank at velocity 10.5 ft/sec is

$$V^2/2g = (10.5)^2/(2)(32) = 1.7\ ft = 21\ in\,. \tag{2}$$

This is of the order of the loop seal elevation (though smaller) and tiny compared with pump-head or static pressure in the pipe. Therefore, the problem can be analyzed as a transient balancing inertia and hydrodynamics, with friction treated as a refinement.

Approximately two diameters from the tee, the loop seal piping reduces to eight inches. If the flow were equally split at the tee, the local Froude number would increase slightly to 2.3 and would still be prone to column flow. Therefore, the slight change of diameter is only a refinement.

5.2 A More Realistic Model of a Tee to a Dead End

If a column were to form in the eight inch run from the tee, and if it were to proceed toward the first elbow at a Froude number over 2 (a velocity over 10 ft/sec), then the air in the loop seal would be compressed. In the prototype, this air is initially at a pressure of approximately 38 psia. The loop seal has a total length from the tee of approximately 36 diameters. Each diameter of column motion corresponds with approximately 3% of the pipe volume. There is a like 3% increase of pressure, approximately 1 psia, or over 2 ft of water. That is, as the column attempts to advance eight inches into the pipe, it must overcome a transient pressure change greater than its dynamic head. It cannot do so. Therefore, column flow cannot persist.

In fact, column flow does not occur at all in the run (Section B) and downcomer (Section C) of the loop seal during the initial transient clearing of air. Thus, water enters the dead-ended loop seal as a separated flow. The water is mainly on the pipe wall as air escapes through the core in counter-flow. (The water is driven to the pipe wall by the transverse momentum of its injection at the tee.) As a result, the water approximately preserves its velocity as it turns in the tee then flows along the pipe into the loop seal.

The volume flow of air out is approximately equal to that of water in, preserving pressure in the loop seal. The void fraction may be approximately 50%. This air must escape through the left branch of the tee and into the tank. Thus the left branch also flows two phase for a time, probably bubbly flow.

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[2] Rothe, P.H. and Wallis, G.B.; *Water Plug Formation in Mixing Tees; Polyphase Flow and Transport Technology*, R.A. Bajura, ed, Publication H00158 of the American Society of Mechanical Engineers, 1980, pp 57-64.

The air clearing in the run from the tee and in the downcomer (Sections B and C in Figure 1) is inherently messy. A column flow of liquid attempts to form, but is slowed by air pressurization and punctured by a counterflow of escaping air. Inevitably, some air will be entrained by the approaching water while some water droplets will be retained by the counterflowing air. However, as a thought exercise, conceive this downcomer flow as a clean counterflow of water in an annulus on the pipe wall and air escaping in the core at the center. Further, imagine that the water preserves the velocity it had at the mixing tee.

5.3 A Model of Flow in the Loop Seal

Comes now a swirling annular flow of water moving at 20 ft/sec more or less into the downcomer of the loop seal. The water falls 11 diameters in the downcomer (Section C), but need rise only 6 diameters in order to pass the loop seal and enter Section E and F. Moreover, it carries momentum equal to another 4 diameters of pipe elevation, more or less. Thus, the loop seal may not establish initially.

The question is how much air remains at the end of the filling transient in the riser of the loop seal (Section E in Figure 1) and in the run to the closed valve (Section F in Figure 1). Any water that enters this region, in any unsteady fashion, removes air that does not return.

An argument can be made that the injected water will penetrate fully to the valve, clearing air as it enters according to the void fraction (about half), then clearing more air as the water flow rebounds from the valve, another half. All air pockets will never be cleared by such a process. Yet, it would not be surprising if 80% of the air initially in the riser and run to the valve (Section E and F) were cleared by this transient filling process.

Working against this theory is the tendency of the flow to form a column at this Froude number. As the flow turns into the short riser, it may do so, thereby failing to clear the rest of the riser and the run. The behavior described above is complicated and specific to a particular geometry. Yet, it can be confirmed or denied readily by model tests.

5.4 Similitude Considerations

Assume a scale ratio, *S*, equal to the ratio of the full scale pipe diameter to the model pipe diameter.

Assume geometric similarity wherein all geometric ratios are preserved. For example, if *S* were precisely 4 (approximately that of the as-built model), then the downcomer (Section C) length would be 21.75 inches to preserve the length-to-diameter ratio at approximately 11.

Fluid dynamic similitude gives priority to preservation of the Froude number in a problem such as this one where inertia is balanced by hydrostatic elevation differences.

In the subject event, the pressure is not constant. Nonetheless, the pressure is approximately constant during the critical period. Containment pressure changes slowly by comparison with the very rapid refilling of the small section of piping of present interest. Also, the transient flow in the piping toward containment has low pressure loss. Thus, the refilling flow itself does not significantly alter pressure in the loop seal.

Subsequent to the brief period necessary to establish the loop seal, the entire system is pressurized substantially by the fluid dynamic loss at the containment spray nozzles. However, this effect occurs substantially after air is cleared (or not) from the loop seal. So the applicable pressure is that in containment at the time that water first arrives at the tee. This containment pressure has been calculated by NU to be approximately 38 psia.

The transient flow dynamics require preservation of the pressure coefficient $P/\rho gD$. Since the prototype is at 38 psia, whereas testing at atmospheric pressure (14.7 psia) is convenient, a scale ratio s = 2.6 results. Accordingly, tests in 3 inch pipe at atmospheric pressure are warranted to simulate 8 inch pipe at 38 psia.

Surface tension is generally not a significant parameter in air-water tests at sizes above 0.5 inch diameter. Prototype Reynolds number Re is high, of the order of 10^6. Model Reynolds number will be significantly less at three inch diameter both due to smaller size, and also due to velocity reduction to preserve the Froude number. Still, model Re will exceed 10^5 and be well into the turbulent range. Moreover, pipe friction is only a secondary parameter. Thus, Re distortion is likely to be irrelevant.

5.5 Multiphase Initial Flow to Tee

All of the above findings are for the case when only water is pumped into the pipe network and toward the tee and pipe section A. In fact, the RSS pump supplies an initially air-filled heat exchanger which may disperse some of its air as a column and later air in bubbly form. Creare has not analyzed this heat exchanger clearing. However, based on the high flow rate of water through its restricted passages, we believe that it will clear promptly and that air will advance first followed by nearly solid water. Moreover, our understanding is that such water will flow for a long period (many minutes) before MV8837 is open. For these reasons, the subject tests of impulsive clearing by a water-solid flow are believed to be a best estimate of the actual situation. There is no possibility that the present estimate is overly favorable by more than a few percent. Nor is it likely that the present estimate is overly conservative by more than a few percent.

6. CALCULATION SHEETS

6.1 Flow Rate Calculation for 1/4 Scale Model

From Equation 1, the Froude number is 4.1.

$$F = 4.1 = V/\sqrt{gD}\ . \qquad (3)$$

Preserving the Froude Number, the Flow velocity in our 2.5 inch standard schedule 40 riser will be

$$V = 4.1\sqrt{gD} = 4.1\sqrt{32.2(2.469/12)} = 10.55\ ft/s \qquad (4)$$

and hence, the scaled flow rate is

$$Q = 10.55(\pi/4)[2.469/12]^2 = 0.3509 \text{ CFS} \qquad (5)$$

or

$$Q = 157.5\ GPM \qquad (6)$$

6.2 Calculation of Initial Air Pocket

NU performed and documented various calculations. Among these, we employed their best estimate calculation of 1.27 cu ft based on the 85% finding reported in Table 3 above.