Appendix D
Review of "Technical Basis for Gas Transport to the Pump Suction,", Fauske &Associates, LLC, FAI/09-130, ML110480451 and ML110480452 (Non-Proprietary), ML110480456 (Proprietary), December, 2010

D-1 Introduction and Summary

The stated purpose of the Fauske report "is to develop a technical basis and a criterion for the conditions that are sufficient to prevent significant volumes that are formed in the piping high points from being transmitted to the pump suction location as gas slugs." The approach is to establish conditions that reasonably ensure bubbly flow will exist at the pump suctions, a condition that precludes transport of gas slugs into the pumps. Fauske addresses this by establishing the conditions where gas in a horizontal pipe high point is transported to the top of a downward vertical pipe or downcomer where it initially accumulates. The gas is then gradually carried downward where a well-developed essentially homogeneous bubbly flow is postulated to leave the bottom of the downcomer and this flow condition is stated to continue to the pump suction.

The report acceptably addresses the conditions necessary to establish that homogeneous bubbly flow will be achieved at the bottom of the downcomer provided the horizontal pipe leading from the bottom of the downcomer to the pump does not influence the upstream behavior. It does not acceptably establish that flow conditions at the bottom of the downcomer continue to the pump suction.

The initial step in the process is to determine the conditions where gas initially accumulates to fill the top of the downcomer. This accumulation causes a kinematic shock to form with a water column below the gas void. Water flowing from the upper horizontal pipe then falls through the void and impacts on the water column. This causes gas to be entrained in the water below the kinematic shock as the water plunges into the top of the water column. The report then acceptably establishes that a downcomer volume that is four times as large as the initial gas volume will provide a sufficient downcomer length for homogeneous bubbly flow to be established at the bottom of the downcomer assuming that downstream conditions have no effect on the downcomer.

If this volume criterion is met, Fauske next assumes that the behavior will propagate into the pump and the gas volume that could enter the pump is:

$$V_{gp} = Q_S \alpha_p \Delta t$$

where: Q_S = pump suction flow rate
α_p = average gas void fraction entering the pump
Δt = duration of the event that is acceptable
and the last two terms are know from a pump acceptance criterion table.

This is the acceptable volume at the pump suction. It is then adjusted for any elevation pressure change between the pump suction and the location of the gas void. If the adjusted acceptable gas volume, V_{gp}, is greater than the initial gas volume, Fauske concludes that the initial gas volume does not jeopardize operability. Observe that gas slug flow downstream of the downcomer is not a concern with the Fauske approach as long as homogeneous flow occurs.

This process has not been shown to be acceptable because homogeneous behavior has not been shown to propagate unchanged from the bottom of the downcomer to the pump. Closely related to this is that the maximum void fraction has not been shown to be less than the 1.7 times α_p criterion that precludes momentary large void fractions from entering the pump.

D-2 Objective

The starting point of a prediction of an acceptable void fraction at the suction to a pump is the acceptance criteria. The report's Table 1 provides acceptable pump entrance void fractions that are consistent with the following NRC staff void fractions:

	$\% \frac{Q}{Q_{BEP}}$	Φ for BWR Typical Pumps	Φ for PWR Typical Pumps		
			Single Stage	Multi-Stage Stiff Shaft	Multi-Stage Flexible Shaft
Steady State Operation	40%-120%	0.02	0.02	0.02	0.02
Steady State Operation	< 40% or > 120%	0.01	0.01	0.01	0.01
Transient Operation	70%-120%	0.10 for ≤5 sec	0.05 for ≤20 sec	0.20 for ≤20 sec	0.10 for ≤5 sec
Transient Operation	< 70% or > 120%	0.05 for ≤5 sec	0.05 for ≤20 sec	0.05 for ≤20 sec	0.05 for ≤5 sec

where: Q = water volumetric flow rate
BEP = best efficiency point
Transient Φ is averaged over the specified time span
Instantaneous Φ < 1.7 times the listed value

The transient operation criteria are based on the premise than full head will be recovered after the gas has passed through the pump as substantiated by pump operation experience and the judgment that the short times associated with the transients will not result in pump damage. Further, the most likely condition that would result in pump damage would be associated with an insufficient flow rate during the transient time, a condition that is not judged to occur during the listed transient times in conjunction with the Φ < 1.7 criterion that precludes momentary large void fractions and precludes slug flow with respect to applying the criteria.

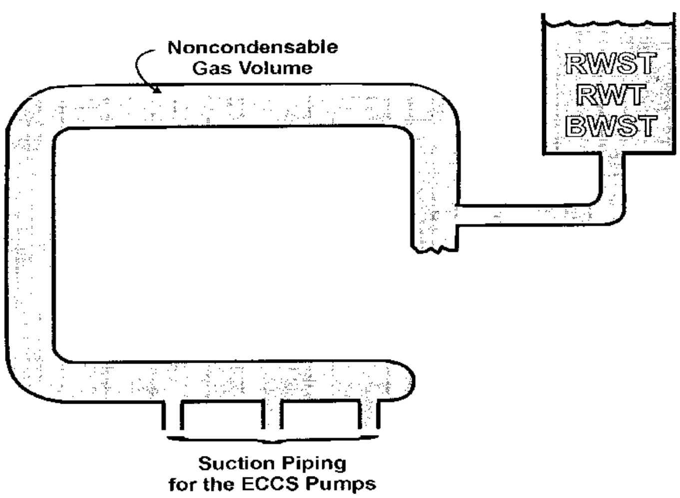
Meeting the steady state criteria should preclude pump damage provided pump miniflow requirements are met so that pump cooling is ensured. Further, the steady state criteria will reasonably ensure that operability requirements will be met if the difference between the pump head required to meet operability requirements and the un-degraded pump head is greater than three percent. If required pump head is within three percent of un-degraded head, then degradation due to gas should be addressed.

The pump void criteria are applicable and acceptable when the upstream suction piping has a circular cross section and the velocity is generally parallel to the pipe centerline as flow enters the pump unless acceptable qualifications are provided.

With the acceptance criteria determined, the next step is application of an analysis methodology that predicts how a suction piping void behaves as it is transported to a pump suction. The Fauske report describes a methodology for accomplishing this.

D-3 Piping Configuration and Transient Response to Flow Initiation

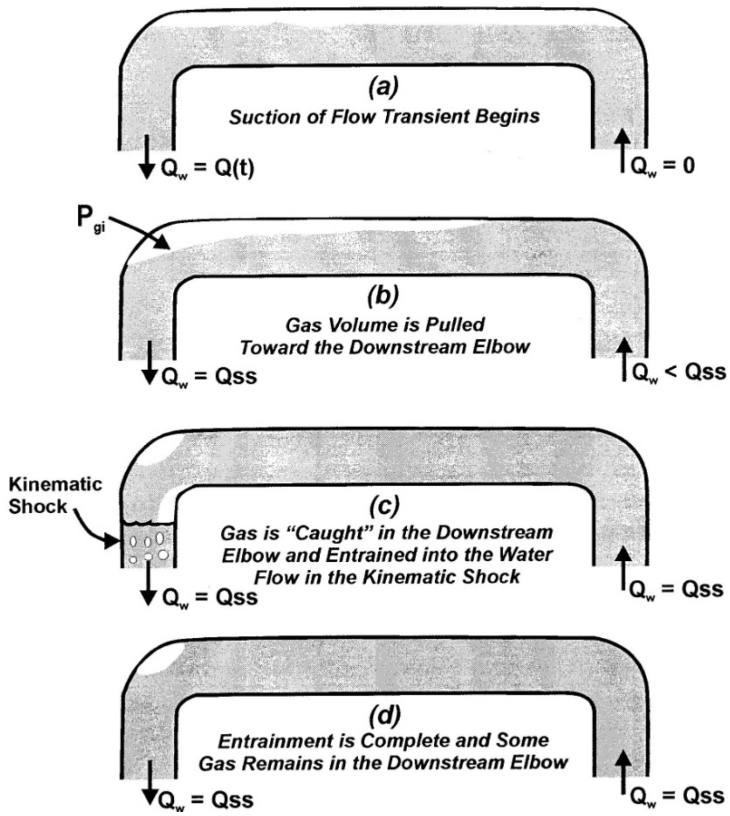
Fauske introduces its methodology with an illustration of generic suction piping typical of pressurized water reactors (PWRs) :



where RWST = refueling water storage tank, RWT = refueling water tank, and BWST = borated water storage tank, terminology used by industry to describe the same tank; and ECCS = emergency core cooling system.

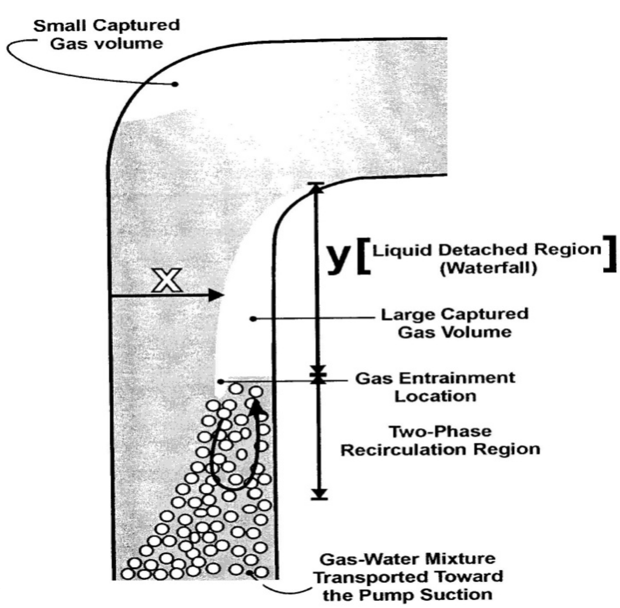
Note that some ECCS suction connections are from the side or top of the horizontal header so that behavior differs from that associated with the figure. This difference does not affect the Fauske conclusions when it is correctly addressed.

Fauske illustrates the transient by the following figure:



where Q = flow rate, w refers to water, t = time, P_{gi} = gas pressure, SS refers to steady state, and $0 \leq t \leq$ time at SS.

Fauske states that for significant initial gas volumes and a high enough flow rate, Configuration (c) will occur and a kinematic shock will occur with detail shown in the following figure:



An essential feature of the shock is entrainment of air by the waterfall as the water plunges into the top of the water column. Fauske concludes that "as long as the downcomer is sufficiently tall to establish the kinematic flow pattern for the conditions of interest, the gas void fraction that will be transported to the pumps, will be in a bubbly flow configuration." This is correct with respect to flow from the bottom of the downcomer as long conditions downstream of the downcomer do not affect the bubbly flow configuration, conditions that are not substantiated by test data.

Ignoring this aspect for now, Fauske describes the sequence of events as follows:

1. Pump starts.

2. Initial flow begins to expand and depressurize the gas space (P_{gi}).

3. Gas depressurization initiates the supply flow.

4. A small depressurization (generally about 1 psi) is sufficient for the supply flow to be provided. The extent of the depressurization is configuration specific, but the suction systems are typically designed such that only a small change is needed from the "no flow" condition to supply the steady-state pump flow.[1]

5. Gas volume is pulled to the downturned downstream elbow until a configuration is developed that can deliver the supply flow.

6. All gas that is not consistent with the water delivery configuration is pulled into the top of the downcomer.

7. The gas volume in the top of the downcomer develops a kinematic shock (waterfall) region that experiences gas entrainment, recirculation, disengagement and downward transport of a bubbly flow.

Next we examine the Froude number predicted behavior :

$$N_{FR} = \frac{V}{\sqrt{\dfrac{Dg_c(\rho_L - \rho_g)}{\rho_L}}}$$

D = pipe diameter
V = liquid velocity based on total pipe flow area
g_c = gravitational constant
ρ = density
subscript L indicates liquid
subscript g indicates gas

In an initially stagnant condition where flow is initiated, little gas movement will occur in a horizontal pipe for $N_{FR} \leq 0.31$. As N_{FR} is increased above 0.31, the interaction of gas and liquid will increase and gas will move more rapidly toward the downstream end of a horizontal pipe.

[1] This is plant-specific and should be confirmed during a plant analysis to ensure that frictional pressure drop does not significantly affect void.

We agree with the above Section D-3 discussion with the following exceptions:

1. "As long as the downcomer is sufficiently tall to establish the kinematic flow pattern for the conditions of interest, the gas void fraction that will be transported to the pumps, will be in a bubbly flow configuration." This does not address behavior from the downward end of the vertical pipe to the pump suction.

2. The behavior at large N_{FR} where a kinematic shock occurs in the upper horizontal pipe with a slug of gas in front of the shock in not mentioned. This could occur with the initial gas volume small enough that the kinematic shock would not develop in the upper part of the downcomer if N_{FR} were smaller, or at a large enough N_{FR} for the gas to pass through the elbow and the downcomer as a slug. The potential concern is that this slug continues through the piping and reaches the pump. However, if this occurs, the kinematic shock will not develop in the upper downcomer and the method will not be applicable.

3. Fauske also states that "It is emphasized that a waterfall would only form for the larger gas volumes since the small volumes would likely be transported as continuous bubble flow. Continuous downstream bubble flow has not been established to occur.

D-4 Methodology Development

Fauske develops the mathematical methodology by first showing that the effect of friction pressure drop on void volume is generally negligible while cautioning that "this can, and should be evaluated for the plant specific design. The pump run-up flow to the steady state is assumed to be linear, an assumption we have verified by examining pump startup data, and an approximation of the bubble volume that can exist in the top of the elbow, as illustrated in the previous figure, is developed. This volume is shown to be small so that the assumptions involved in its determination are relatively unimportant since the volume does not significantly perturb the predicted downstream behavior. Further, it will eventually be entrained in the flowing water and removed if $N_{FR} > \sim 1$.

Fauske addresses behavior in the upper downcomer assuming that the kinematic shock has developed as illustrated in the above figure.[2,3] The report notes that the water will tend to remain attached to the outside pipe wall and the water velocity will increase as it falls through the upper downcomer void thus decreasing its cross sectional area. This characteristic is used to develop the x dimension that in turn allows calculation of the upper downcomer height, y. With these developed, "the time dependent erosion history of the gas volume can be calculated."

The report then develops a relationship between flow rate, waterfall velocity and the upper downcomer length. It references two correlations that provide the volumetric flow rate of gas bubbles entrained in water due to impact by a known flow rate of a jet of water of known initial

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[2]Not addressed yet is that the gas volume must be large enough that the kinematic shock develops as illustrated in the previous figure and the flow rate must be small enough that the gas volume is not transported as a slug down the vertical pipe.

[3]Appendices B and D to the Fauske report cover experiment information applicable to this concept. These are addressed in Section D-6, below.

diameter that has fallen a specified distance before impacting the surface of a pool of water. The behavior in the elbow and upper part of the downcomer is stated to be expected to cause more gas entrainment than a free-falling jet and the correlation with the smaller coefficient is used "for assessing the conditions that would prevent a gas slug from penetrating through the downcomer volume." Stated differently, the approach minimizes the gas bubble entrainment rate and hence the calculated rate of gas bubble transport toward the bottom of the downcomer. This maximizes the gas volume in the waterfall region thus maximizing the length of the liquid detached region as well as extending the time it takes to remove the gas volume in the waterfall region by bubble flow from the bottom of the region. The report does not mention that the jet of water has an initial velocity due to flow through the elbow in contrast to the assumed initial velocity of zero. Neglecting this effect also contributes to maximizing the upper downcomer volume. Although this approach conservatively maximizes the upper downcomer gas volume, it appears to non-conservatively underestimate the maximum void fraction associated with gas bubbles being transported toward the bottom of the downcomer. As discussed in Section D-6.1, below, comparison with the Palo Verde data is consistent with maximizing the upper downcomer gas volume but the prediction of void fraction at the bottom of the downcomer is conservative with respect to the test data.

Fauske then notes that the water jet velocity, and the entrained gas bubble velocity, in the location of impact is greater than the velocity associated with flow through the full area of the pipe that will be developed in the lower downcomer - at the bottom of the figure. Further, the water and gas bubble velocities toward the bottom of the downcomer will be different due to bubble buoyancy. This is addressed by introducing the effect of slip ratio to obtain the void fraction in the lower downcomer as related to the flow rate being transported to the pump.

As an example of the behavior, the report assumes a water velocity of 7 ft/sec and the velocity of the gas bubbles relative to the water velocity as 1 ft/sec. The slip ratio is 6/7 = 0.86. Substituting this into the calculation developed as described above results in a calculated homogeneous void fraction of 0.23 and a void fraction at the bottom of the downcomer of 0.27. Fauske then states that as this flow turns into a horizontal leg, it can "be expected to accelerate to essentially a homogeneous condition and possibility even develop a slip ratio that may be larger than unity. In any case, the horizontal flow would have a lower void fraction; the maximum value of which would be 0.23. As stated in Item 1 at the end of Section D-3, above, we have reservations concerning the assumed behavior as flow enters the lower horizontal pipe.

D-5 Effect of Elevation Head

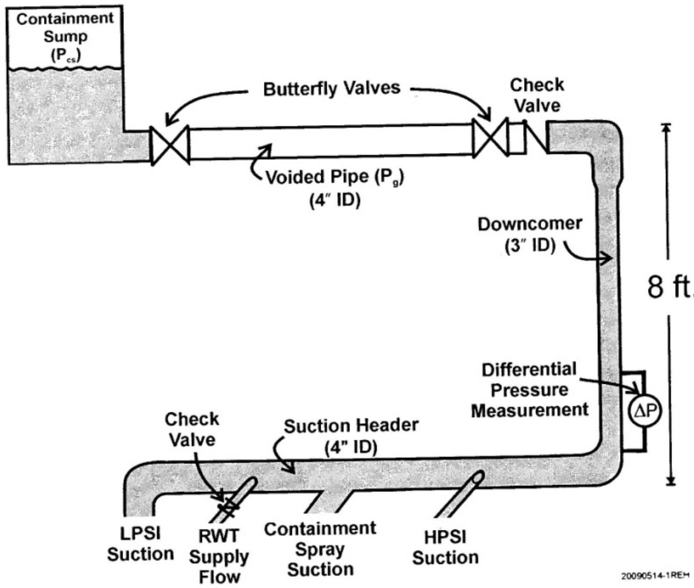
The above Section D-4 methodology did not include the effect of elevation change on the void fraction and this can be significant for some plant configurations. With the downcomer void distribution developed as discussed in Section D-4, above, this calculation is straightforward assuming ideal gas law and will not be addressed further here.

D-6 Comparison with Experimental Data

There are numerous approximations in the above methodology and comparisons with experimental data are necessary to evaluate applicability. Fauske describes the tests and provides comparisons with Palo Verde, Purdue, and Beaver Valley test data.

D-6.1 Palo Verde Test Information

A schematic of the Palo Verde test is shown in the following sketch that was provided as Figure B-1:



The initially voided 4 inch pipe was 5 ft long and the butterfly valve opening times ranged from 10 to 20 seconds depending upon the test. At about 3 seconds the valves were sufficiently open to pressurize the void to the upstream pressure and gas would begin to transport into the downcomer. The downcomer length was sufficient for development of a kinematic shock with transition to bubbly flow at the bottom of the downcomer.

The difference in horizontal and vertical downcomer diameters is stated to have been "done to ensure the downward water velocity exceeded the bubbly rise velocity as would be the case for the plant suction piping." This was achieved at the expense of distorting behavior in the vicinity of the ends of the horizontal pipes. We consider failure to address phenomena in the lower horizontal pipe to be an important weakness in both the test and its application to modeling of plant behavior.

No length information was provided for the 4 inch downcomer before the reducer. We note this will perturb the flow behavior and the kinematic shock in the upper downcomer but the downcomer length appears to be long enough that bubble behavior was fully established by the time bubbles reached the bottom of the downcomer.

N_{FR} was used when discussing results but the report did not clearly indicate whether it was calculated for the 4 inch or the 3 inch pipe. It did state that for N_{FR} = 0.6, the velocity in the 4 inch pipe was 2 ft/sec and in the 3 inch pipe it was 3.6 ft/sec. Using these velocities, we calculate N_{FR} = 0.61 and 1.27 for the 4 and 3 inch pipes, respectively. The difference is a factor of two, in agreement with the report description and an important difference when considering results within the downcomer and at both ends where the diameter of both horizontal pipes is 4 inches. This probably means that bubbles will be more likely to concentrate at the top of the 4 inch upper horizontal pipe immediately downstream of the elbow than would be the case with a 4 inch diameter downcomer and it will be more difficult for bubbles to re-enter the bottom of the downcomer from the lower horizontal pipe than would be the case for 4 inch pipe throughout.

Reported N_{FR} ranged from 0.10 to 0.60 and peak void fraction at the bottom of the downcomer ranged from 0 to 0.62. Void fraction was 0 with N_{FR} = 0.10. This is consistent with expectations since N_{FR} of at least 0.31 is needed to pull a significant air quantity down the downcomer. The next lowest N_{FR} were 0.34 and 0.39 where void fractions were 0.17 and 0.24 with observation of agglomeration of downward flowing air bubbles. The N_{FR} at the observation location was 0.68 and 0.78, respectively. All other N_{FR} were greater than 0.46 (0.92) and no correlation of N_{FR} versus void fraction appeared to exist.

The report states that "These tests provide the most extreme conditions to enable the transmittal of a gas slug to the bottom of the downcomer, i.e. the tests were initiated with ...(b) a sufficient Froude number to pull the gas into the top of the downcomer and (c) a downward velocity that is sufficient to entrain the gas thereby pulling it through the downcomer pipe to the suction header." This is true of many tests but not all. For example, N_{FR} = 0.10 (0.20 in the downcomer) did not move gas as shown in the test data. This observation does not affect our conclusions regarding the report.

Fauske states that the measured void fraction is never one and that this demonstrates the most important observation from the tests "that, as a result of the kinematic shock, the two-phase flow regime is bubbly flow, not slug flow." This is inconsistent with some of the Purdue test results where slug flow was observed at void fractions of less than one.

Figure B-3 provides void fraction at the bottom of the downcomer as a function of time for Test PVA22. This starts at 0, maximizes at about 0.21 and the transient is over in about 30 seconds. Yet the void fraction remains at about 0.02 for the remainder of the plot that ends at 120 sec. Figure 9 provides the same information for Test PVA21 where the behavior is similar although the maximum void fraction is about 0.13 and void fraction is zero after about 30 seconds. Table B-1 does not identify any difference between the tests. We do not understand the Figure B-3 non-zero behavior since the void source is finite unless for some reason the void is circulating in the bottom of the downcomer. Figure B-4 is stated to provide a comparison of gas transport to the pump compared to the initial gas inventory and may provide some insight, but the figure in our copies of the report is a solid black rectangle and provides no information.

Fauske reported that the kinematic shock was about 1 ft below the bottom of the piping high point for N_{FR} = 0.6 and the void fraction at that location was about 0.23. With a slip ratio of 0.72, "the void fraction of the flow being transported to the pump would be approximately 0.29." It continues with "Figure B-5 shows that this represents the upper limit of values observed for Froude numbers of 0.6 (velocity of 0.61 m/s) (2 ft/sec). As the Froude number decreases, the buoyancy influence increases and some large values of local void fraction can occur. Nonetheless, this method of assessing the void fraction at the bottom of the downcomer is demonstrated to be consistent with experiments and if anything conservatively biases to the maximum value." Figure 10 is identical to Figure B-5 except the line labeled "Calculated Peak Void Fraction @ 0.25" is at elevation 0.32 in Figure 10 and is at elevation 0.25 in Figure B-5. This appears to be an error in one or both figures.

In Figure 9, the initial gas volume passes through the downcomer in 15 to 20 seconds. Fauske states that the approximation of the behavior predicts 7.1 seconds and hence is conservative with respect to the rate of gas transport to the pump. Other comparisons of test versus prediction are respectively, maximum depth of the kinematic shock = 4.8 ft versus 1 ft, and void fractions of 0.09 to 0.31 with one point at 0.34 (from Figure 10) versus 0.32.

The prediction results are generally conservative for these comparisons.

D-6.2 Purdue Test Information

Most of the Purdue test information in this Fauske report is identified as proprietary. We discussed the Purdue tests in the non-proprietary Appendix C on the basis of non-proprietary information. The two reports are inconsistent in identifying proprietary information. Please see Appendix C for a test description and our evaluation of the Purdue tests.

Fauske Section 5.2 states that "Currently, this large scale testing program is still ongoing and thus is not addressed further in this report." This is inconsistent with the Fauske report date of December, 2010 and the same report date for the Purdue tests that describes the test program and results. However, we agree that for practical purposes no useful additional information is provided in Section 5.2. This is a weakness in the report since representative data for all Purdue tests should be considered.

D-6.3 Beaver Valley Test Information

Most of the Beaver Valley information is stated to be proprietary and the intent of this review is to provide a non-proprietary assessment.

Unit 1 and Unit 2 test configurations were involved that replicated the Beaver Valley HPI suction piping. Both involved a horizontal header that initially contained a gas layer above water and a downcomer. In one, a short downcomer of smaller diameter than the header connected from the upper horizontal pipe to a lower horizontal pipe followed by another short downcomer. In the other, the downcomer was an extension of the horizontal pipe similar to the Purdue configurations although the downcomer was shorter.

A plot of the maximum void versus the initial void fraction was provided for the Unit 1 upper downcomer that includes the kinematic shock model prediction and the experimental void data over a range from 0 to 1. The predicted void fractions are significantly larger than the data. In a similar plot for the lower downcomer, the data exceed the prediction over the larger void fraction conditions but all of these cases were outside the criterion for use of the simplified equation.[4]

Similar comparisons for the upper and lower regions of the Unit 2 downcomer were essentially a realistic fit of the prediction to the data although there were few experimental points at a small void fraction. With the exception of one data point, all of the lower region data points were outside of the criterion for use of the simplified equation.

The two data comparisons are consistent with use of the simplified equation limited to conditions where it provides conservative results.

D-7 Gas Transport Methodology

The initial consideration to a simplified approach to prediction of gas transport to pumps is to determine if the Froude number is large enough so that gas will be moved by flowing water. If this determination results in no gas transport, then the issue does not need to be pursued further since the gas will not impact pump operation.

[4] This criterion is discussed in Section D-7, below.

If gas is transported, then Fauske considers formation of a kinematic shock in the top of a downcomer to be key to development of a simplified approach to prediction of transport of a suction pipe void to pumps. Once developed at an acceptable distance from the bottom of a downcomer, Fauske concludes that bubbly flow will exit from the bottom of a downcomer and that this ensures there will be no slug flow entering a pump.

Completion of the simplified methodology involves determining the acceptance criteria that must be met to apply the methodology.

D-7.1 Criterion to Reasonably Ensure a Kinematic Shock is Formed.

Fauske's Section 6.0 states that the comparisons with Palo Verde and Purdue system tests show that the maximum value of the kinematic shock is about half the height of the downcomer. Further, it states that this height "is important in providing the transition to a water continuous, bubbly flow pattern and this is critical to the assurance of the transient pump performance, i.e. no transmittal of a slug flow configuration to the pump suction. To ensure that there is always a sufficient downcomer height to establish the necessary kinematic shock, the criterion recommended for application to plants is that the downcomer volume should be at least four times the volume of the maximum gas accumulation in the high point piping. For those piping geometries that have several steps in the vertically downward direction, the largest of these steps should have a volume that is at least four times that of the maximum accumulated gas volume."

If one applies the factor of four criterion to the Palo Verde and Purdue test facilities, the maximum initial void fraction that meets the criterion is 0.28 and 0.29, respectively. Although the Palo Verde void fraction is one before the valves are opened to initiate a test, the effective initial void fraction is smaller due to compression from the simulated containment sump. For example, with a sump overpressure of zero, Fauske's Table B-1 provides an initial void fraction of 0.3. With the test facilities meeting the criterion and the statement "that the maximum value of the kinematic shock is about half the height of the downcomer" for these facilities, applicability of the factor of four criterion is acceptably established with respect to the waterfall effect. However, as discussed in Section C-6, at $N_{FR} = 2.5$ in the 6 and 8 inch tests, co-current slugs moved down the vertical pipe and the Purdue report stated that "Trailing slugs were observed near the end of the transient and were characterized by complete flushing of the gas held up in the top horizontal header, elbow and kinematic shock region." The effect of this behavior on the factor of four criterion needs further explanation.

Certainly, establishment of the kinematic shock and bubbly flow toward the bottom of a vertical downcomer is important, but it is not sufficient to ensure no slug flow into a pump suction. As stated in Section C-6, horizontal slug flow was observed in the lower horizontal pipe in both the 8 and 12 inch tests. In the 8 inch tests, it only occurred at $N_{FR} = 1.65$ and an initial void fraction of 20%. In the 12 inch tests, it occurred at $N_{FR} = 1.0$ and an initial void fraction of 5%. Counter-current slug flow was observed after a large portion of the void had passed through the system for $N_{FR} < 1.0$. This type of behavior has not been acceptably addressed with respect to development of the basis for pump suction behavior.

D-7.2 Use and Application of a Simplified Equation

As discussed above, the first step is to determine if suction pipe gas will move toward a pump by determining the Froude number, N_{Fr}. If $N_{Fr} \leq 0.31$ and the average void fraction in a plane perpendicular to the pipe centerline, Φ, is ≤ 0.20, then there is no need to perform a further assessment because the gas will not move into the pump suction.

If $N_{Fr} > 0.31$, then the gas is assumed to move toward the pump and further evaluation is necessary. Fauske's next step is to apply the factor of four criterion to determine if the configuration will reasonably ensure formation of a kinematic shock in the downcomer so that homogeneous bubbly flow exits the downcomer. If this criterion is met, Fauske next assumes that the behavior will propagate into the pump and the gas volume that could acceptably enter the pump is:

$$V_{gp} = Q_S \, \alpha_p \, \Delta t$$

Where: Q_S = pump suction flow rate

α_p = average gas void fraction entering the pump that is acceptable via the above Section D-2 table

Δt = duration of the event that is acceptable via the above Section D-2 table

Since this is the acceptable volume at the pump suction, it is then adjusted for any elevation pressure change between the pump suction and the location of the gas void. If the adjusted acceptable gas volume, V_{gp}, is greater than the initial gas volume, Fauske concludes that the initial gas volume does not jeopardize operability.

With respect to multiple pumps such as illustrated in the Palo Verde test configuration, the process is repeated assuming all of the void enters each pump using the pump-specific characteristics unless there is experimental evidence or detailed analyses that demonstrate the distribution.

With respect to local high points between the initial gas void and the pump suction that are initially filled with water, Fauske states the if $N_{Fr} > \sim 0.5$, "there is no significant potential for the gas to separate out" and "if the gas is transported to the high point as a bubbly mixture, it would remain as a bubbly mixture.

This is an acceptable process with the exception of the conclusion that there are no issues associated with behavior downstream of the lower end of the downcomer.

D-7.3 Flow Characteristics in the Lower Horizontal Pipe that leads to the Pump

In response to a question related to flow behavior in the vicinity of the downcomer to lower horizontal pipe, Fauske stated that "The transition from the vertical downcomer to a horizontal pipe certainly generates flow patterns that are not homogeneous in character. Specifically, conditions are observed with gas tending to move back up the downcomer. These behaviors would act to 'stretch-out' the gas void being transmitted toward the pump and therefore reduce the average void fraction being ingested by the pump during the two-phase flow transient. Therefore, it is conservative to evaluate the gas transport as a homogeneous mixture because it maximizes the gas transport rate to the pumps(s)."

We agree that if conditions occur with gas moving back up the downcomer, it would stretch out void transmission to the pump since it would eventually be re-entrained in the downcomer downward flow. Further, there would be a tendency for the upward moving gas volume to decrease due to breakup with the smaller bubbles again moving downward simultaneous with a tendency for the upward moving gas volume to increase due to decreasing pressure. We do not consider this behavior to be of significant concern since it will likely be occurring later in the transient after the maximum upper void volume has diminished with a corresponding reduction in gas entrainment below the kinematic jump. However, the Fauske response does not address two aspects of the concern:

1. Can the accumulated gas move as a slug downstream into the pump? Some of the Purdue test results appear to indicate this can occur.

2. What happens if the lower horizontal pipe in a plant is short so that the non-homogeneous behavior occurs at the pump suction?

Another area that is not addressed in the Fauske report is the potential case where the Froude number is so large that a hydraulic jump occurs in the upper horizontal pipe and the water continues to move as a piston forcing the gas slug to travel into the pump as a slug.

D-8 Conclusions

There are three unresolved issues that prevent NRC concurrence with the simplified equation approach:

1. The assumption is made that a homogeneous bubbly flow mixture that leaves the bottom of a downcomer will remain in this configuration. The Purdue test data show this assumption is incorrect. A significant void volume can accumulate in the end of the lower horizontal pipe near the junction with the downcomer and a hydraulic jump can occur downstream of the void where stratified flow occurs with water flowing under the gas. Some of the void can dissipate via this process and move toward the pump and some can return to the downcomer where it progresses upward as a countercurrent slug. One possibility is that the void suddenly moves toward the pump as a slug. Another concern is that the lower horizontal pipe may be short in a plant and the large void region may occur at the entrance to the pump. These possibilities are not identified in the Fauske report.

2. The maximum void fraction has not been shown to be less than the 1.7 times the average void fraction criterion that precludes momentary large void fractions from entering the pump.

3. The Fauske report does not address a potential case where the Froude number is so large that a hydraulic jump occurs in the upper horizontal pipe and the gas moves into the pump as a slug as though water behind the gas acted as a piston.