June 30, 2011

Appendix C

Review of "Air Water Transport in Large Diameter Piping Systems: Analysis and Evaluation of Large Diameter Testing Performed at Purdue University," WCAP-17271

C-1 Introduction and Summary

Two phase two component transient fluid flow data in pipes larger than two inches in diameter were essentially non-existent before the Purdue test program that is described in WCAP-17271. The two inch diameter is also important because, as stated in WCAP-17271, the transition to diameter not having an effect on the drift flux distribution coefficient for slug / froth flow is about two inches. Yet much of the concern with determination of fluid transport in nuclear power plants is in pipe diameters larger than two inches.

WCAP-17271 provides such data for 4, 6, 8, and 12 inch diameter piping in testing at Purdue University that was funded by the Pressurized Water Reactors Owners Group (PWROG). The configuration applies to many plant system suction pipe configurations and includes correlations for application of the data. It covers 84 transient air/water test conditions with two to four repeat runs for each test condition. System flow rates approximated startup and running of an emergency core cooling system (ECCS) pump.

Most tests were run at about 21 ºC. Some tests, termed "heated test section" tests, were conducted at 80ºC. In comparison to the low temperature tests, some cases resulted in a large increase in gas volume at the top of the vertical test section and it sometimes resulted in doubling the time it took for complete gas entrainment to occur. Rapid condensation occurred in the vertical test section as pressure increased with decreasing elevation due to the head of water. Assuming thermodynamic equilibrium for these cases appears reasonable.

The WCAP summary is as follows:

> In summary, the test program results documented in this report provided a good database that allowed characterization of several complex phenomena that occur in large diameter piping systems with 90˚ elbows. The cutoff between large diameter and small diameter behavior was identified as 3" from the available literature for the tested fluid conditions. Some of the results from the 4" testing could be characterized as small diameter phenomena. However, the larger diameter test results were, in general, consistent and can be characterized as large diameter behavior.
>
> The scaling analysis results provide general correlations for the dominant phenomena observed in the testing, which included flow initialization via a vertical kinematic shock and vertical down-comer to horizontal elbow distribution. The resulting empirical correlations from the scaling analysis are considered acceptable for pipe diameters ranging from 4" up to 30".
>
> The PIRT (Phenomena Identification and Ranking Table) process identified several other gaps that should be addressed to close out the GL issue. Before a final evaluation model is developed, it is likely that additional testing efforts will be needed in areas such as horizontal flow stratification that can lead to a build-up and surge in downstream gas flux. Furthermore, for conditions where large gas volumes exist, phenomena that were not investigated as part of this test program

> could occur. For instance, no information is available to determine what occurs when a kinematic shock reaches a downstream flow obstruction. As a result, care should be taken when analyzing conditions where large gas volumes exist. It is not clear at this point in time if additional efforts will be needed to address this and similar concerns.

The NRC staff finds the WCAP summary to be acceptable subject to the following comments:

1. Piping lengths shorter than used in the Purdue tests can result in hydraulic jump behavior propagating downstream that did not occur in the tests. This potentially causes a significant increase in downstream gas flux in comparison to the test results.

2. Empirical correlation predictions must be acceptably applied to experimental data before the NRC staff will accept their application for analysis of plant configurations. Further, scaling correlation uncertainties should be increased when applied due to the effect of the assumptions, the amount of data, and the stochastic nature of the experimental data.

3. The use of "evaluation model" in the PIRT paragraph should not be confused with the traditional "evaluation model" typical of such applications as analysis of design basis loss-of-coolant accidents. The requirements for assessing operability as less stringent than those associated with evaluation models.

WCAP Section 12 provides the following discussion that warrants repeating here:

> Phenomena related to the pump and piping configuration directly upstream of the pump should be considered as part of a pump testing program. Entrance geometries specific to the pump location which could lead to unfavorable pump entrance conditions should be reviewed and analyzed. An evaluation of these geometric impacts should be performed, which could potentially require additional testing. If the results of a pump test program that incorporates entrance effects indicate additional gas transport studies need (be) done in this area, this matter should be revisited.
>
> Flow stratification in horizontal pipes can lead to an accumulation of gas, for instance in an offtake or tee geometry. Once gas is accumulated, a subsequent instability can lead to a large surge in gas downstream. This phenomenon was not investigated as part of the test programs described in this report. Currently, there are not available modeling approaches that have been validated to account for this type of behavior. Therefore, flow stratification in horizontal pipes, leading to downstream surges in gas is the most significant knowledge gap.

These data weaknesses must be addressed in applying a void transport methodology.

Overall, the NRC staff finds that the Purdue tests provide a valuable addition to available data applicable to two-phase two-component transient pipe flow. Use of the data in acceptably verifying void transport methodologies is recommended subject to the qualifications identified in this safety evaluation.

C-2 Requirements for Determination of Current Operability[1]

The requirements for determining current operability differ from the traditional approach used for evaluating design basis requirements. This difference also extends to the data needed to support operability determinations. Consequently, coverage of these requirements is provided before discussing the WCAP.

Realistic or bounding approaches may be used to address operability issues. The objective is to "reasonably ensure that subject system operability" is achieved and a "reasonable expectation" test applies. This means that a high degree of confidence applies but absolute assurance is not necessary. The determination can be based on analyses, test or partial test, experience, and/or engineering judgment. This is particularly applicable to determination of void transport behavior, pump response to voids, and vortexing where the reliance on judgment will vary depending upon the depth of understanding that has been developed. Consequently, a strong reliance on engineering judgment will sometimes be necessary to support a finding regarding current operability[2]. Future improvements regarding application of data and development of void behavior methodologies will allow operability findings to be more solidly based on analyses and tests and the need for engineering judgment will be diminished although there will likely remain circumstances where solidly based engineering judgment is both appropriate and acceptable.

A bounding analysis considers the phenomena, "but does not require analytical models for each phenomenon."[3] Implementing a bounding "approach requires applying appropriate limitations which conservatively bound high ranked phenomena that are not directly modeled. For instance, since little is known about gas phase separation at tees, a bounding analysis would assume all gas flowing into a tee junction flows down the worst case branch. Also, since little is known about flow distribution around various geometries, no distribution is assumed."

The WCAP provides some coverage of the previous paragraph's last sentence:

> If appropriate limitations are applied, a homogenous flow model can be used to evaluate two phase flow through a piping system. An initial distribution of the gas phase can be calculated using empirical correlations ... (and) the gas is (then) assumed to transport homogenously through the system, and the only change in gas volumetric flux is due to compression (or evaporation and condensation if temperature gradients exist). Using this approach, the assumption that the downstream volumetric flux of gas is never greater than the initial volumetric flux of gas, corrected for pressure changes, is critical." For example, "since a well defined evaluation model for flow through tees does not exist, (Reference C-3 that is reviewed in Appendix E) suggests assuming all gas flows down the worst case tee branch. In addition, several other limitations associated with separated flow and slug flow regimes are important to assure large volumetric fluxes of gas are not transmitted downstream.

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[1] "Currently operable" is a determination made on the basis of currently available information with the understanding that later information may affect the conclusion.

[2] Additional information on regulatory requirements for assessing operability is provided in References C-4 through C-6.

[3] Quotes are from the WCAP.

WCAP Section 10.3.3 provides a proprietary correlation to address gas distribution behavior in an elbow connecting a vertical downcomer to a horizontal pipe. (See Section C-8, below.) Although this is claimed to provide some benefit when evaluating pump suction void fraction, the WCAP states that other issues must still be addressed. It continues with:

> Under some circumstances, a re-accumulation of gas may occur. The re-accumulation may not necessarily lead to slug formation, such as would occur as gas accumulates upstream of a kinematic shock. However, a re-accumulation and subsequent instability may lead to a large gas flux downstream. In essence, a low upstream gas flux, over a sufficient time period, could lead to a greater downstream gas flux over a shorter time period. This could potentially occur under the following circumstances:
>
> 1.) Separated flow region upstream of a kinematic shock extends to a downstream flow disturbance, causing the separated flow region to detach and move downstream resulting in a surge of gas.
>
> 2.) Flow stratification in a tee or offtake geometry resulting in an accumulation and subsequent downstream surge of gas.
>
> This is of particular importance, if a constant gas source exists in the piping system, such as would occur during recirculation operation when pump suctions are aligned to the sump. Under these conditions, a steady, low void fraction, stream of gas could exist due to gas coming out of solution from the saturated sump fluid. Unfortunately, there are currently no bounding approaches to addressing item 2 above. Reference 3.20[4] documents a detailed review of offtake geometry, but the studies were performed with a low velocity in the header pipe, and are not applicable to a wide range of flow regimes; for instance, when a wavy stratified flow exists in the header pipe.
>
> As a result, current bounding analysis methods are forced to assume that following a tee or offtake geometry, an unfavorable gas volumetric flux exists downstream of the geometry. At very low offtake flow rates, an assumption could be made that the gas remains attached at either the tee or offtake, or a downstream elbow, and the flow redistributes through the same kinematic shock mechanism as described in Section 7.2.2. Unfortunately, there is no test data available to evaluate under what conditions this assumption is reasonable.

The NRC staff believes the examples may be insufficient to bound behavior and additional care should be taken when examining potential conditions. For example, as stated above, assuming all gas is flowing into the worst case tee junction (offtake) may not bound behavior if the assumption is that the gas flows into the tee as it reaches that location as opposed to the gas accumulates and then enters the tee as a slug or with a void fraction that is higher than would be expected had the gas not accumulated. And it is known that gas will preferentially concentrate on the inside of a horizontal elbow and if there is an appropriately oriented tee immediately downstream of the elbow, a homogeneous flow model may be inappropriate for

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[4] Andreychek, T. S., el al,. “Loss of RHRS Cooling while the RCS is Partially Filled,” Westinghouse Electric Company LLC, WCAP-11916, Rev. 0, July, 1988. This document provides information applicable to the issues identified in Generic Letter 88-17.

that configuration. Such possibilities should be addressed in both bounding approaches and better estimate modeling.

The report's Section 5.2, "CRITICAL ASSESSMENT OF SYSTEM CODE MODELING METHODS," addresses simplifying assumptions and associated issues. It states that "The impact of geometry on a system code's applicability is very important in two phase applications. If geometry dependent phenomena play a significant role in the transport process they must be accounted for when extrapolating test data to a significantly different geometry." And "the validity of ... the ... codes, for a particular application, is dependent on the test data used to validate the code and the built in closure relationships and transfer terms. As a result, if the impact of dominant phenomena on the built in closure relations has not been addressed, the model should not be extended." It continues by stating that "an empirically based approach would most likely yield similar accuracy to a system computer code utilizing mass, momentum, and energy equation solutions." These statements support our approach for using computer codes or correlations where we require validation through comparison of predictions and applicable test data.

C-3 State of Liguid / Gas Flow Behavior Information

WCAP Sections 3.1.3 and 3.1.4 summarize the status of available data. In general, data for large diameter (> ~ 3 inches) elbows is insufficient to support modeling of horizontal elbows, data obtained from the Purdue tests provides support for transient modeling of elbows in a horizontal to vertically downward orientation and limited support of vertically downward to horizontal configurations. Some vortexing and tee information is stated to exist but is not addressed in the WCAP, "the available models are not yet adequate in all situations," and " there is a significant knowledge gap in these areas." For example, some of the phenomena of potential concern were observed during the Arizona public service test program that is summarized in WCAP Section 3.2. The staff concludes that modeling of two phase, two component transient flow must be conducted with allowance for these data weaknesses.

WCAP Section 4 summarizes the conclusions of an expert panel that addressed the state of knowledge.[5] Areas identified where an improved understanding of phenomena is necessary to perform a best estimate evaluation where a bounding approximation may be inadequate include:

a. Kinematic shock at vertical plane elbows.
b. Vortexing at offtakes.
c. Phase separation at tees.
d. Flow stratification in horizontal pipes.
e. Pump entrance phenomena / piping entrance configuration.

Phenomena that need to be well understood "to assure that re-accumulation of gas and subsequent formation of slug flow does not occur" are

[5] The work is addressed in Swartz, M., "Phenomena Identification and Ranking Table (PIRT) to Evaluate Void Fraction / Flow Regime at ECCS, RHR and CS Pump Suctions," Westinghouse Electric company LLC, WCAP-17167-NP, Rev. 0, December, 2009. The report was not provided to the NRC although members of the NRC staff have read the report and judge it to provide excellent coverage of the state of knowledge. The WCAP Section 4 summary is sufficient for the review being reported here.

a. Flow stratification in horizontal pipes.

b. Pump entrance phenomena (piping entrance configuration).

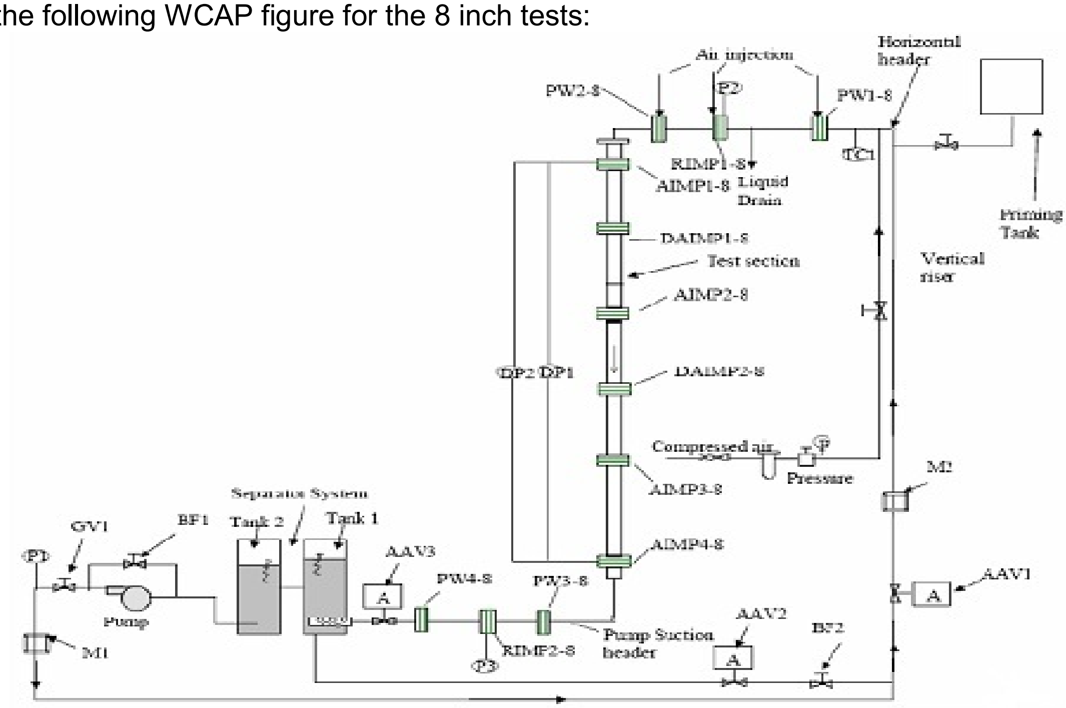
The WCAP concluded the discussion with “phenomena related to the pump and piping configuration directly upstream of the pump should be considered as part of ongoing pump gas intrusion tolerance investigations and any future pump testing efforts. Flow stratification in horizontal pipes can lead to an accumulation of gas, for instance in an offtake or tee geometry. Once gas is accumulated, a subsequent instability can lead to a large surge in gas downstream. Currently, no modeling approaches exist that can account for this type of behavior.” And “flow stratification in horizontal pipes, leading to downstream surges in gas is the most significant knowledge gap identified by the PIRT panel.”

Typical HPI pump suction configurations include downward flow in a vertical pipe with an elbow to a horizontal pipe that has a small length to diameter ratio with a reducer immediately upstream of the pump entrance. This configuration may be inconsistent with pump vendor recommendations and is not replicated in the Purdue testing, as is discussed below. Further, typical pump suction headers include offtakes / tees that are also not replicated in the testing. Consequently, modeling of such configurations must be done with care and a safety factor will likely be necessary to compensate for the lack of knowledge and supporting data. Further, in some circumstances, simply assuming all of the gas passes in one direction as a worst case may be inadequate to address the gas surge concerns, a potential condition that should be addressed as part of the overall modeling.

No information was included that addressed industry plans to address these weaknesses.

C-4 Test Description

Although there were variations in test configurations, the general configuration is illustrated in the following WCAP figure for the 8 inch tests:



The pipes of interest are the upper horizontal header that is connected to a vertical downward-oriented test section that is connected to a lower horizontal pump suction header. Lengths are about 31, 27, and 17 feet, respectively. The RIMP, AIMP, and DIMP designations are for void instrumentation. A typical test may be described as consisting of the following steps[6]:

1. With Valves AAV1 and AAV3 closed and AAV2 and the priming tank valve open, adjust the void fraction to the desired value in the upper horizontal header and close the priming tank valve.

2. With the pump running at the desired flow rate as determined by Valve BF2, initiate flow through the headers and the vertical test section by closing Valve AAV2 and opening AAV1 and AAV3.

3. The void in the upper horizontal header is swept toward the pump and the instruments indicate the system void, pressure, and flow rate behavior.

Tests included a range of system flow rates to cover startup and running of an emergency core cooling system (ECCS) pump. The 4, 6, 8, and 12 inch pipe diameter tests were run at about 21 ºC. Additional 4 inch diameter pipe tests were run at about 80 ºC to obtain insight into the mass transfer and transport process associated with the steam vapor partial pressure that was a significant percentage of atmospheric pressure. 84 tests were conducted and each test was repeated two to four times.

Test pressure was lower than generally occurs in plant ECCSs and an initial upper horizontal header pressure decrease was not typical of plant systems. The former causes voids to be a stronger function of elevation than in an ECCS. The latter introduces a transient that is not present in an ECCS, as discussed in the next paragraph. We do not judge these to detract from the data usefulness because if an analysis methodology predicts the challenging test conditions it should also be applicable to similar configurations in plant applications.

Standard Temperature Test conditions were set by closings Valves AAV1 and AAV3 with AAV2 open, BF2 set to simulate the resistance of the test section, and GV1 adjusted to obtain the desired flow rate as indicated on M1. Then the desired amount of air was introduced into the upper horizontal header at 14.7 psia. A test was initiated by opening AAV1 and AAV3 and closing AAV2. Since the separation system was at 14.7 psia, pressure in the upper horizontal header decreased to < 10 psia within a few seconds due to the difference in the head of water in the vertical test section and in the separation system. This caused the upper horizontal header air volume to expand in a manner atypical of flow initiation in a plant. Most tests were of this type.

Modified tests, termed Flow Initialization Tests, were run with AAV3 open so that the initial upper horizontal header pressure was reduced to minimize the initial pressure change. The WCAP compares the results from the Standard Temperature and Flow Initialization Tests and concludes that "the trends are very similar. Therefore, the effect of the flow initiation transient on the gas transport process is negligible." If void factions are compared on a graph with ordinates adjusted to overlay one set of data with the other, the WCAP conclusion regarding similar trends is substantiated. However, the peak void factions differ by a factor of two and the time span

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[6]This description illustrates the general testing approach. Actual step details are provided in WCAP Section 6.2.1..

when voids are observed differs by about 25 percent. This does not support the conclusion that the effect of the flow initiation on the gas transport process is negligible.

Most of the tests were conducted at room temperature where the initial upper horizontal header depressurization at test initiation did not result in significant water evaporation. However, some tests, termed "heated test section" tests, were conducted at 80ºC and water evaporation "resulted in a dramatic increase in the gas volume (in the upper horizontal header) compared to the low temperature" tests. In some cases, this resulted in a large increase in gas volume at the top of the vertical test section and it sometimes resulted in doubling the time it took for complete gas entrainment to occur. Interesting, at the highest Froude Number tested, 2.5, there was little difference and "it is unclear whether the evaporation process occurred at these conditions."

Where significant evaporation occurred in the upper horizontal header, rapid steam condensation occurred in the vertical test section as the steam-gas void progressed down the test section as the pressure increased due to the head of water. As a result, the WCAP concluded that the "evaporation and condensation processes occur rapidly, and this could potentially result in a non-conservative analysis if not considered" and "assuming mixture thermodynamic equilibrium throughout the transport process is suggested." This is acceptable.

C-5 Pump Air Ingestion Criteria

The test is designed to provide transient air-water data that is applicable to ECCS suction piping. Considerations of suction pipe voids begin with the following interim criteria for the void fraction entering a pump, Φ, that we will accept without further justification for not jeopardizing operability of a pump, as qualified in the discussion following the table, or with similar characteristics that must be acceptably justified by the licensees:

	$\% \frac{Q}{Q_{BEP}}$	**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[7]

The transient operation criteria are based on the premise that the initial void fraction in the pump does not exceed 0.05, that 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 (1) preclude pump damage provided pump miniflow requirements are met so that pump cooling is ensured and (2) reasonably ensure that operability requirements will be met if the pump head, H, satisfies the following:

$$(H_{\text{un-degraded}} - H_{\text{required to meet operability requirements}}) / H_{\text{un-degraded}} > 0.03$$

Head degradation due to gas should be addressed if this relationship is not satisfied.

The pump void criteria are applicable 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.

The WCAP's Table 1 is consistent with the above table but it is incomplete since it does not identify exclusion of slug flow. As stated above, the maximum transient void fraction must be less than a factor of 1.7 times the Table 1 average gas void fraction criteria.

The WCAP states that the Table 1 void fractions, α, are typically based on the liquid and gas volume flow rates Q_l and Q_g, respectively, according to the formula $\alpha = Q_g / (Q_g + Q_l)$. This is a homogenous flow definition of void fraction and is consistent, for example, with the NUREG/CR-2792 (Reference C-2) definition of α. If slip occurs between phases, then α must be defined by $\alpha = V_g / (V_g + V_l) = A_g / (A_g + A_l)$ where the V's are the pipe volumes occupied by the fluid when defining a volume averaged void fraction and the A's are the pipe areas occupied by gas and liquid for an area averaged void fraction. The report uses α according to the volume or area averaged values and defines a volumetric flux ratio, $\beta = Q_g / (Q_g + Q_l)$ that is determined from measured quantities that is consistent with and can be used with Table 1 criteria.

C-6 Flow Phenomena and Froude Number[8]

Equation 8-8 defines the Froude Number as $N = u_m / (g D)^{1/2}$ where u_m = average mixture velocity during the transient time, g = gravitation constant, and D = pipe inner diameter.
The usual definition of Froude Number is:

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[7] The table and the 1.7 represent mutual judgment of industry and SRXB representatives following the June, 2010, meeting at NEI's Washington, DC location. See ML101650201, ML102080675, and ML101590268.
[8] This section addresses WCAP Sections 3, 6, and 7.

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

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

and, since $\rho_L >> \rho_g$, this reduces to $N_{FR} = V / (Dg_c)^{1/2}$ which is identical to Equation 8-8 except for the velocity term. The actual liquid velocity is V / (1 – Φ) and, for homogeneous flow, this is also u_m. Hence, as long as Φ is small, there is little difference in the two definitions.

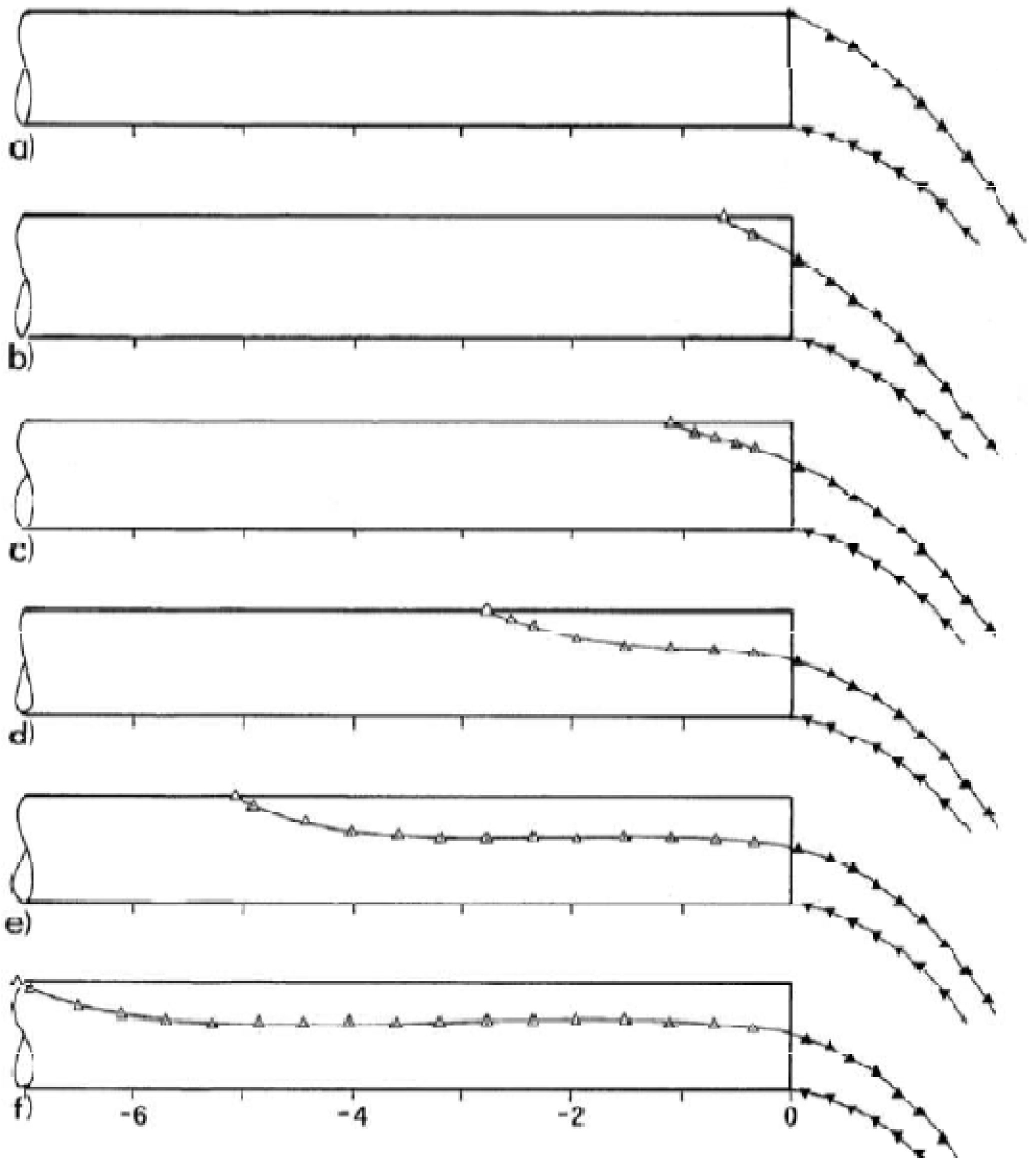
WCAP-17271 states that there is general agreement in the literature that a pocket of air located in a horizontal pipe cannot be transported vertically downwards at a Froude Number that is less than 0.35. The NRC staff inspection guidance is that gas may be assumed to not move in a horizontal pipe if the Froude Number, N_{FR}, is ≤ 0.31 and the average void fraction in a plane perpendicular to the pipe centerline, Φ, is ≤ 0.20. The WCAP does not provide information that would support a change in staff position and the staff will continue to use the more conservative N_{FR} ≤ 0.31.

The WCAP states that an open-ended horizontal pipe will run full if N_{FR} > 1.16 and “all gas will be transported out of a horizontal piping section” if N_{FR} ≥ 1.0 provided the downstream piping is sloped vertically upward. WCAP Figure 1, reproduced on the next page, illustrates the behavior. The Figure 1 criteria are acceptable.

Reference C-1, as reviewed in Appendix A, states that “a Froude number in the piping highpoint of 0.54 is sufficient to sweepout an accumulated gas volume.” The NRC staff concluded that N_{FR} ≥ 0.54 will move gas toward the downstream end of a horizontal pipe that has no local high points provided gas can flow freely from the end of the pipe. The Purdue data indicate that gas holdup occurs in the region of the junction between the upper horizontal header and the vertically downward test section for N_{FR} = 0.6 and 0.8 after 50 seconds. At N_{FR} = 0.93, the gas appeared to be completely entrained down the vertical test section within 50 seconds.

These data, and other data from Section 7.2 of the WCAP, provide proprietary void fraction data as a function of time, initial void fraction in the horizontal header, and N_{FR} for the Purdue test section. These data substantiate that N_{FR} ≥ 1 is sufficient to sweep air out of a vertical pipe under steady state downward-flow conditions. This is important for "dynamic venting" where gas is removed by flushing from the system provided sufficient time is allowed for the flushing to be completed. The steady state qualification is also important with respect to other transient behavior as discussed in the following paragraphs.

Figure 1 Cavity Profiles for Fr=(a) 1.16; (b) 0.794; (c) 0.700; (d) 0.641; (e) 0.628; (f) 0.602



The data show that higher Froude Numbers result in a hydraulic jump or kinematic shock in the upper horizontal header where the void is pushed ahead of solid water and air is moved more rapidly through the elbow from the upper horizontal header into the top of the downward flow vertical test section. This establishes a void fraction of close to one at the top of the vertical test section that is larger (longer) as Froude Number and horizontal header void fraction are increased. The WCAP attributes the behavior "to gas holdup in the upper portion of the vertical pipe and an abrupt flow regime transition from annular or falling film (separated) to a churn-turbulent flow regime, termed a kinematic shock." The transition is furthest from the elbow early in the transient so that water falling through the voided length falls further and impacts the transition at a higher velocity, causing the entrained air to move further below the transition and apparently moving air volume through the transition at a greater rate early in the transient.

Thus, if the vertical pipe is short, this behavior may result in greater gas movement exiting the bottom of the vertical pipe.

At N_{FR} = 2.5 in the 6 and 8 inch tests[9], co-current slugs moved down the vertical pipe. "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." These co-current slugs tended to break up after traversing several diameters in the vertical pipe.

In the 4 inch tests, co-current slugs "occurred sporadically, sometimes occurring in one repetition of a test case, but not the next." The WCAP attributes this stochastic behavior to the maximum stable slug diameter that is a larger percentage of the pipe diameter for the 4 inch pipe tests. This resulted in large data uncertainty

Kinematic shocks were observed in the 8 inch tests downstream of the elbow between the vertical test section and the horizontal pump suction header with a substantial void fraction reduction downstream of the shock. The entrainment rate exiting the shock was relatively constant irrespective of distance from the elbow to the shock.

Horizontal slug flow was observed 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.

In some cases, the void fraction in the pump suction header was significantly greater than the initial void fraction in the top horizontal header and could jeopardize pump operation if it moved into the pump before it dissipated or if the kinematic shock did not develop before reaching the pump so that a high void faction entered the pump as a slug. We believe this, and the significant data scatter, will be particularly challenging when the test results are used for verification of void movement methodologies.
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C-7 Data Analysis Considerations

WCAP Section 8.1 addresses incorrect void fraction instrumentation indications and Section 8.2 covers calculation of initial air volume, the transport time interval, the average void fraction, the pressure distribution within the test facility, the maximum shock transition length in the vertical test section, characteristic mixture flow rate and velocity, characteristic gas flow rate and velocity, the volumetric flux fraction, and slip ratio. Many of these calculation methods are straightforward and will not be addressed further here although users of the test data should be aware of the methods. A few comments on others are provided in the remainder of this report section.

Section 8.2.4 describes pressure determination with respect to it being measured only in the horizontal headers. With respect to position, frictional effects are assumed negligible in comparison with other contributors to pressure changes. This is generally acceptable although it should be confirmed during plant-specific investigations. A linear pressure distribution is assumed from top to bottom in the vertical test section. The WCAP concludes "that the linear approximation of the pressure distribution results in minimal error in comparison to other errors associated with the two phase flow measurements and analysis." While we agree that the

[9] Limited pump capability kept the test facility from reaching N_{FR} = 2.5 for the 12 inch pipe.

proprietary bounding determination of pressure error is small, it may introduce a bias that should be addressed as part of the uncertainty considerations when using the data.

Uncertainty was estimated using simplifying assumptions that may be non-conservative for low flow rate conditions. The combination of simplifying assumptions and the effect due to low flow rate, among other behaviors, leads us to conclude that the proprietary uncertainty information may be used as part of the guidance when selecting a safety factor for void transport predictions using methodologies that rely in part on the Purdue data, but other considerations also contribute to determination of a safety factor.

The WCAP provides extensive discussion to correlate the observed data with physical understanding. We have not discussed this subject in detail since our primary focus is on application of the Purdue data to verify void transport methodologies where the Purdue and plant configurations are comparable. It would be of enhanced interest where the configurations or operating conditions differ and we will expect licensees to address such differences as part of the justification for application of void transport methodologies that rely upon the Purdue data for part of their acceptance criteria.

WCAP Section 9.5 addresses differences between the 6 inch and all other Purdue test results. Purdue and Westinghouse believe the 6 inch piping may have been tilted and the 5% initial void fraction cases were not used in the scaling analysis. In light of this observation, care must be taken in using the 6 inch test results since the effect was likely to have an initial void fraction that was less than believed.

C-8 Scaling Analysis

ECCS piping can be as large as 24 inches in diameter and cooling water system suction piping can be 30 inches in diameter. Therefore, the WCAP reports on development of empirical correlations to demonstrate that the dominant phenomena are applicable to the larger diameter piping. The WCAP considerations applied to the scaling study and the NRC staff observations are as follows:

1. The 4 inch slugging behavior was not considered since it was not observed in larger diameter pipe testing and it was believed to not be applicable to larger diameter pipes. We agree that neglecting aspects unique to the 4 inch tests is acceptable in extrapolating to pipes larger than 12 inches. We note, however, that slugging was also observed in pipes larger than 4 inches.

2. Phenomena near the elbows resulted in gas phase distribution. We observe that the distribution is not always beneficial and this must be considered with care. For example, a tee downstream of an elbow will be exposed to either higher or lower gas concentration with respect to the upstream concentration depending upon its orientation, a configuration not directly addressed by the Purdue tests.

3. The entrainment that occurred at the kinematic shock interface in the vertical test section resulted in distribution of the gas and, with the exception of slug flow behavior under some conditions, little distribution occurred following the shock. The void fraction reduction below the shock could be attributed to compression. This is correct when considering a suitable distance below the shock location for the tested configuration. It would be incorrect for a shorter vertical pipe section where the shock phenomena were not fully developed over the length of pipe.

4. Counter-current slugging was observed at the entrance of the lower elbow during the low Froude Number tests. It also occurred in the vertical test section. Counter-current slugging was neglected since it would reduce the downstream gas flux.

5. Void distribution occurred at the lower elbow exit due to kinematic shock entrainment in addition to distribution without a shock present. We agree that the shock affected the distribution and generally reduced the gas flux traveling downstream of the shock. However, if the pump suction header is too short, the behavior may be significantly different than observed in the Purdue tests and the gas flux entering the pump may be significantly larger.

6. Co-current slug flow was observed in the vertical test section. This was not addressed in the report because, although important to the gas transport process, it was stated to only occur at the highest flow rate conditions in the 6 and 8 inch tests and these were unlikely to be encountered during plant accident conditions. Further, the slugs tended to break up rapidly so that they did not increase downstream gas flux. We did not check the flow rates that would be encountered during accident conditions but note that design basis accident condition flow rates may be significantly smaller than would be encountered during realistic conditions. Further, the Item 3 pipe length comment also applies.

7. Co-current slug flow was observed in the bottom pump suction header in the 8 and 12 inch tests under specific test conditions but not enough data were available to develop a general correlation. Whether or not sufficient data were collected, co-current slug flow is an important phenomenon that cannot be neglected. Its being observed in the larger pipe tests is also important because the purpose of the scaling is to address pipes larger than those tested.

8. In addition, the general stochastic behavior of slug flow made development of correlations difficult due to insufficient data. We agree stochastic behavior complicates the picture. However, it appears to be real and may be encountered during plant operation. It cannot be neglected.

Based on the above considerations, the vertical test section kinematic shock and the lower elbow distribution phenomena were reported to be selected for the scaling study.

The WCAP sites references to support that the maximum stable bubble size is about 3 inches and stable full diameter slug flow should not exist, with the flow approaching pool flow, as diameters increase above the limit. The WCAP concludes that this supports that an acceptable range of pipe diameters was tested. This conclusion is supported by the test data where slug behavior was more pronounced in the 4 inch testing and in the larger diameters, vertical slug flow was random, unstable, and rapidly dissipated after forming.

A proprietary dimensional analysis was completed to define non-dimensional parameter groups for characterizing initialization of the vertical kinematic shock and the vertical test section to pump suction header elbow distribution. WCAP Section 12 provides the following regarding the scaling analysis:

> This scaling analysis provides an empirical relationship to evaluate the average volumetric gas flux exiting the vertical kinematic shock. However, detailed models allowing the calculation of volumetric flux fraction as a function of time have not been addressed in the scaling analysis. This information may be required to address peak pump air ingestion tolerances. However, arguments provided in this report suggest a flat characteristic gas flux profile far downstream of the initial kinematic shock. In addition, several parameters that are important in the kinematic shock entrainment process were not investigated. The main gap in this area is the pipe bend radius, which was not part of the test program's test matrix. The testing documented in this report was not intended to be a detailed experimental investigation of the kinematic shock phenomenon, and since this phenomenon is critical for performing a bounding analysis, it is recormnended that further investigation of this phenomenon be completed.

The NRC staff agrees that further investigation is warranted. It further notes that its previous comments regarding slug flow and the potential effect of differences between plant and test pipe lengths apply.

WCAP Section 13 demonstrates application of empirical correlations derived from the scaling analysis to an example geometry. Although this is useful in illustrating how to apply the correlations, it does not substantiate them. The NRC staff cannot accept these correlations until their applicability is acceptably established by comparisons to experimental data.

C-9 References

C-1 FAI/08-70, Rev.1, "Gas-Voids Pressure Pulsations Program", Fauske & Associates, LLC, for the PWR Owners' Group, ML090990426, September 2008

C-2 Kamath, P. S., et al, "An Assessment of Residual Heat Removal and Containment Spray Pump Performance Under Air and Debris Ingesting Conditions," Creare, Inc., NUREG/CR-2792, ML100110155, September, 1982.

C-3 "Investigation of Simplified Equation for Gas Transport", Westinghouse Electric Company, for the PWR Owners Group, WCAP-17276-P, Rev. 0, September 2010. Not received. Reviewed Revision 1, ML110480381, January 2011.

C-4 "NRC Regulatory Issue Summary 2005-20: Revision to Guidance Formerly Contained in NRC Generic Letter 91-18, 'Information to Licensees Regarding Two NRC Inspection Manual Sections on Resolution of Degraded and Nonconforming Conditions and on Operability,'" ML052020424, September 26, 2005.

C-5 "NRC Regulatory Issue Summary 2005-20, Rev. 1, Revision to NRC Inspection Manual Part 9900 Technical Guidance, 'Operability Determinations & Functionality Assessments for Resolution of Degraded or Nonconforming conditions Adverse to Quality or Safety,'" ML073440103, April 16, 2008.

C-6 "Operability Determinations & Functionality Assessments for Resolution of Degraded or Nonconforming conditions Adverse to Quality or Safety," NRC Inspection Manual, Part 9900: Technical Guidance, Attachment to Reference 6, April 16, 2008.