June 19, 2019

Ms. Frances Pimentel, Sr. Project Manager,
Risk and Technical Support
Nuclear Energy Institute
1201 F Street, NW, Suite 1100
Washington, DC 20004

SUBJECT: FINAL NONPROPRIETARY SAFETY EVALUATION OF PWROG-15060, "PUMP SUCTION GAS ACCUMULATION OPERABILITY CRITERIA GUIDANCE" (CAC NO. MF8075; EPID L-2016-TOP-0006)

Dear Ms. Pimentel:

By letters dated May 5 and 9, 2016 (Agencywide Documents Access and Management System (ADAMS) Accession Nos. ML16147A079 and ML16147A123, respectively), the Nuclear Energy Institute (NEI) and Pressurized Water Reactor Owners Group (PWROG) submitted nonproprietary and proprietary versions of topical report (TR) PWROG-15060, "Pump Suction Gas Accumulation Operability Criteria Guidance." By letter dated June 25, 2018, the Nuclear Regulatory Commission (NRC) staff issued its draft safety evaluation (SE) on PWROG-15060 (ADAMS Accession No. ML18072A002).

In a September 10, 2018, letter (ADAMS Accession No. ML18297A054) the PWROG requested that the NRC staff hold its review in abeyance. The letter also requested that the NRC staff issue a revised, draft SE. By letter dated March 25, 2019 (ADAMS Accession No. ML18267A319), the NRC staff issued a revised draft SE.

The PWROG provided comments on the second, draft SE via letter dated May 9, 2019 (ADAMS Accession No.: ML19135A072) the PWROG provided comments on the second, draft SE. The comments addressed inconsistencies and typographical errors.

The NRC staff has found that PWROG-15060 is acceptable for referencing in licensing applications for nuclear power plants to the extent specified and under the limitations delineated in the TR and in the enclosed final SE. The final SE defines the basis for our acceptance of the TR.

Our acceptance applies only to material provided in the subject TR. We do not intend to repeat our review of the acceptable material described in the TR. When the TR appears as a reference in license applications, our review will ensure that the material presented applies to the specific plant involved. License amendment requests that deviate from this TR will be subject to a plant-specific review in accordance with applicable review standards.

In accordance with the guidance provided on the NRC website, we request that NEI publish accepted proprietary and non-proprietary versions of PWROG-15060 within three months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed final SE after the title page. Also, they must contain historical review information, including NRC requests for additional information (RAIs) and your responses. The accepted versions shall include a "-A" (designating accepted) following the TR identification symbol.

As an alternative to including the RAIs and RAI responses behind the title page, if changes to the TRs provided to the NRC staff to support the resolution of RAI responses, and the NRC staff reviewed and approved those changes as described in the RAI responses, there are two ways that the accepted version can capture the RAIs:

1. The RAIs and RAI responses can be included as an Appendix to the accepted version.
2. The RAIs and RAI responses can be captured in the form of a table (inserted after the final SE) which summarizes the changes as shown in the approved version of the TR. The table should reference the specific RAIs and RAI responses which resulted in any changes, as shown in the accepted version of the TR.

If future changes to the NRC's regulatory requirements affect the acceptability of this TR, NEI will be expected to revise the TR appropriately. Licensees referencing this TR would be expected to justify its continued applicability or evaluate their plant using the revised TR.

If you have any questions or require any additional information, please feel free to contact the NRC Project Manager for the review, Joseph Holonich at (301) 415-7297 or joseph.holonich@nrc.gov.

Sincerely,

/RA/

Dennis C. Morey, Chief
Licensing Processes Branch
Division of Licensing Projects
Office of Nuclear Reactor Regulation

Docket No. 99902028

Enclosure:
Final Safety Evaluation

SUBJECT: FINAL NONPROPRIETARY SAFETY EVALUATION OF PWROG-15060, "PUMP SUCTION GAS ACCUMULATION OPERABILITY CRITERIA GUIDANCE" (CAC NO. MF8075; EPID L-2016-TOP-0006) DATE: JUNE 19, 2019

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SAFETY EVALUATION OF PWROG-15060-P, "PUMP SUCTION GAS ACCUMULATION OPERABILITY CRITERIA GUIDANCE"

Issue Date: June 2019

Principal Contributors: Warren C. Lyon, Terrence C. Brimfield

PREFACE

The purpose of Topical Report (TR) PWROG-15060-P and PWROG-15060-NP (W, December 31, 2015) is to describe methodologies to predict the volumetric flux of a non-condensable gas at a pump inlet based on the gas volume at an upstream accumulation location. Predicted volumetric flux is then compared to pump inlet criteria to assess operability. Other downstream effects, such as vortexing and water hammer, are not within the scope of the TR. The purpose of this safety evaluation (SE) is to provide an in-depth evaluation of the TR. This includes evaluation of data and correlations provided in WCAP-17271-P (W, October 2010) and WCAP-17276-P (W, January 2011) that, in general, evaluate upstream gas accumulation without discussion of secondary downstream effects.

Proprietary information that meets Title 10 of the *Code of Federal Regulations* (10 CFR) 2.390 requirements is identified by a vertical bar located to the left of the proprietary information and by a yellow highlight. Where necessary, brackets (**[ ]**) are additionally used to enclose proprietary information. This evaluation is non-proprietary when the information identified by the bars and brackets is removed although references to proprietary documents will remain.

When equations, tables, or figures are copied from a WCAP, the equation, table, or figure numbers are included in the copy to facilitate referencing the sources.

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NOMENCLATURE

A	averaged void fraction measurement device, pipe area
AEC	Atomic Energy Commission
AIMP	averaged void fraction measurement device
BOP	balance of plant
BWR	boiling water reactor
BWROG	Boiling Water Reactor Owners Group
BWST	borated water storage tank
CFR	code of federal regulations
CHR	containment heat removal
d	pipe inside diameter, inches
D	pipe inside dimeter, usually ft
DAIMP	instrument designation
DB	current design basis
DC	vertical down-comer
ECCS	emergency core cooling system
EPRI	Electric Power Research Institute
FR	Federal Register
G	gas, mass flow rate
G_G	gas mass flow rate
G_L	liquid mass flow rate
g_c	gravitational constant, ft/sec^2
GDC	general design criterion
GL	Generic Letter
GI	generic issue
H	pump head
IMC	designation for NRC inspection manual
JHF	Flowserve pump model
L	liquid, pipe length
LCO	Limiting Conditions of Operability
L_R	required shock length (upper DC length to achieve homogeneous bubbly flow)
$L_{S,id}$	ideal shock length (DC length that is totally voided at time zero)
MFM	magnetic flow meter
N_{FR}	Froude number
N_{Re}	Reynolds number
NRC	Nuclear Regulatory Commission
NEI	Nuclear Energy Institute
OGC	Office of General Council
P_M	static pressure at void fraction measurement location (psia) during time Δt
$P_{t,i,}$	top header initial pressure (psia)
$P_{R,out}$	pressure in down-comer where homogeneous bubbly flow is established
PW	parallel wire void measurement device
PWR	pressurized water reactor
PWROG	pressurized water reactor owners group
Q	flow rate
Q_g	average gas volumetric flow rate entering pump (gpm) during time Δt
Q_ℓ	average liquid volumetric flow rate entering pump (gpm) during time Δt
Q_{mix}	average mixture volumetric flow rate (gpm) during time Δt
R	Statistical measure of the fit of a line to data
RCS	reactor coolant system

RHR	residual heat removal
RIMP	volume averaged void fraction measurement device
RW	volume averaged void fraction measurement device
RWT	refueling water tank
RWST	refueling water storage tank
SE	safety evaluation
SR	surveillance requirement
SSC	structure, system, or component
TS	technical specification
TSTF	Technical Specification Task Force
TR	topical report PWROG-15060
U	liquid velocity
u_ℓ	liquid velocity
u_{mix}	mixture velocity
V	volume of horizontal pump inlet pipe, pipe volume
V_g	volume at L_R
$V_{gas,\ max}$	volume that must exist in upper horizontal pipe for shock to occur in lower pipe
V_i	initial gas volume in upper horizontal pipe (ft^3)
VM	void meter
WCAP	a Westinhouse document
W_e	Weber Number
<u>W</u>	Westinghouse
X	horizontal coordinate value
Y	vertical coordinate value, vertical elevation
z	water depth required for flow from upper horizontal pipe into elbow
α	void fraction
α_e	measured void fraction near end of data file
α_m	maximum measured void fraction
α_{te}	void fraction at end of transient
β	volumetric flux ratio
β_{ave}	average volumetric flux ratio
$\beta_{el,out}$	average β at exit from lower elbow
β_{max}	maximum β that occurs at time zero
$\beta_{min\ reqd}$	minimum lower horizontal pipe β for occurrence of a shock in lower horizontal pipe
β_p	pump-specific allowable flux ratio
$\beta_{R,out}$	average gas volumetric flux ratio over the initialization process
Δt	time for gas to be transported past location of interest (sec)
$\Delta t_{el,in}$	time over which fluid enters lower elbow, from the lower elbow holdup correlation
Δt_p	maximum transient time or pump-specific allowable transient time
Φ	planned or actual void fraction, initial void fraction
ρ_ℓ	liquid density
ρ_g	gas density
σ	viscosity

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1.0 INTRODUCTION

Plants typically are designed and licensed so that systems, such as the emergency core cooling system (ECCS) and the residual heat removal (RHR) system, are to be in a water-solid condition. Consequently, for most licensees, whether stated or not, the current design basis (DB) for the subject systems is a water-solid condition. The Nuclear Regulatory Commission (NRC) and the Nuclear Energy Institute (NEI) reiterated this by stating, "If there is no specified design limit then the design limit is no gas present" (NEI/NRC, April 2013). It is also identified in Technical Specification (TS) Task Force (TSTF)-523 Revision 2 (TSTF, February 21, 2013) by such statements as "The NRC was concerned that the design condition, with some exceptions, is water-solid and the system may not be restored to this condition."

It is not always practical to maintain a water-solid condition in existing nuclear power plant systems and some short-term void accumulation is acceptable although where a void is found that exceeds the DB condition, the void must be removed as soon as is practical. In all cases, operability must be reasonably maintained[1]. TR PWROG-15060-P provides methodologies for predicting the impact of void accumulation at high points in suction pipes on pump operability due to void passage into pump suctions. Other phenomena, such as water hammer and vortexing, are not addressed. The NRC staff has determined that the topical report (TR) methodologies are acceptable when voids have been discovered that exceed the DB value during the time when the voids cannot be removed and the cause of the void formation is addressed. The TR methodologies have not been approved for determination of DB values.

The NRC staff provided insight into "as soon as is practical" in Generic Letter (GL) 91-18 Revision 1 (NRC, October 8, 1997), subsequent rewrites, and IMC-0326 (NRC, January 31, 2014) that states, "The TSs require that an SSC [(structure, system, or component)] be operable given the plant condition (operational mode); thus there should be a reasonable expectation that the SSC in question is operable while an operability determination is being made, or an appropriate TS action requirement should be entered."

Regulatory Guide 1.160 (NRC, May 2012) states that 10 CFR 50.65(b) includes safety-related and non-safety-related SSCs. And, in regard to "Applicability of Appendix B to 10 CFR Part 50," "Each licensee's maintenance efforts should minimize failures in both safety-related and BOP [(balance of plant)] SSCs that affect safe operation of the plant."

Most of the gas transport methods referenced in the TR provide proprietary methodologies to assess the impact of accumulated gas on pump operability. These methods were developed to predict the gas volumetric flux fraction, β, at a pump inlet based on the gas volume at an upstream accumulation location. These are documented in WCAP-17276-P (W, January 2011) and WCAP-17271-P (W, October 2010). Some of the TR information may not be available to licensees that did not provide support for development of the WCAP-17276-P and WCAP-17271-P methodologies. Such licensees are expected to provide equivalent coverage of void assessment.

The methods are acceptable for operability determinations following discovery of a void subject to the limitations that (1) applicability is limited to evaluation of gas movement in pump suction

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[1] Voids that have no effect on operation, such as isolated bubbles or voids in heat exchangers that cannot be removed and will not affect operation, may be considered to exist under water-solid conditions if properly evaluated and dispositioned (e.g., using 50.59 or via a license amendment).

pipes, (2) to determine if a system, although degraded, would have continued to perform its specified function[2], and (3) other limitations apply as addressed in this safety evaluation (SE). Note that acceptability is limited to the initial discovery and 10 CFR Part 50, Appendix B, Criterion XVI would require that recurrence is precluded. PWROG-15060-P includes discussion that aspects of the WCAP-17271-P method could be repetitively applied to elbows at the exits from additional vertical down-comers (DCs). This is acceptable. If, after restoration, one cannot preclude recurrence the SSC will need to be modified or amended or compensatory actions such as more frequent venting or monitoring performed to ensure that restoration is maintained.

When pump inlet voiding is identified on an SSC the condition should be entered into the licensee's 10 CFR Part 50, Appendix B, corrective action program, the cause identified, and actions to preclude recurrence taken. The resolution of the condition will likely be accomplished by one or a combination of the following: (1) restore the SSC to the as designed condition, (2) modify the SSC, or (3) amend the license to adopt a new current design basis (DB) void limit. For all of these methods the cause of the voiding requires identification so that the condition can be promptly corrected and recurrence precluded or the license amended appropriately. As an example, simple venting to restore the SSC to the DB condition would be insufficient if the cause is not identified and the venting frequency modified to address the causal mechanism and preclude recurrence.

It is not the intent that licensees continue to use this process for assessing recurrences of pump voiding. However, the NRC staff acknowledges that on occasion an attempt to correct a condition or identify the cause is unsuccessful in precluding recurrence. For occurrences where the initial attempt to correct the problem was unsuccessful this method may be used again to demonstrate operability. This allowance does not preclude the necessity to re-enter the issue into the Appendix B corrective action process and reinvestigate the issue to identify the cause and preclude repetition for each subsequent occurrence.

The TR methods apply to a configuration that consists of an upper horizontal pipe where gas is assumed to have accumulated, a DC[3], and a lower pipe that leads to a pump. The modeled behavior assumes that at time zero a pump has started and all of the gas has moved into the upper DC.

With the exception of offtakes, the TR does not address vortexing, localized level reduction, or air ingestion during flow from tanks, sumps, or large pipes such as during residual heat removal operation when taking suction from a pressurized water reactor (PWR) hot leg during mid-loop operation.

A key aspect of addressing transient void transport correlations is comparison to test data. It has been impractical to simulate entire systems and it has been necessary to use scaled test

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[2]Specified Function/Specified Safety Function associated with operability refers to the capability to perform the "specified function" at non-improved TS plants or "specified safety function" at improved Standard TS plants. The specified function/specified safety function of an SSC is that specified safety function(s) in the licensing basis for the facility. In addition to providing its specified safety function(s), an SSC is expected to perform as designed, tested, and maintained. When system capability is degraded to a point where the system cannot perform with reasonable expectation or reliability, the SSC should be judged inoperable, even if at this instantaneous point in time the SSC(s) could provide the specified safety function(s).

[3] All reference to a DC is to a vertical DC.

models. Therefore, it is generally necessary to apply methodologies that have been established to reasonably predict or bound test behavior.

The most comprehensive transient void data available are provided by tests conducted at Purdue University (W, October 2010). Phase I tests of 6- and 8-inch diameter pipes were completed in 2006. Phase II tests of 4- and 12-inch diameter pipes were completed in 2010. Other tests included tests at the Westinghouse (W) thermal hydraulic laboratory (W, December 31, 2015).

Aspects that apply to assessment of void accumulation are discussed in the following SE sections.

1.1 Froude Number, N_{FR}

N_{FR} may be calculated from a simplification of TR Eq. 4-7:

$$N_{FR} = \frac{u_{mix}}{\sqrt{g_c\, d\, /12}} \tag{1}$$

Where: u_{mix} = mixture velocity, ft/sec
g_c = gravitational constant, ft/sec^2
d = pipe inside diameter, inches

Gas movement as a function of N_{FR} is illustrated in Table 1 (NEI/NRC, April 2013).

Table 1 Gas movement as a Function of NFRN_{FR}	Effect
≤ 0.31	No gas movement in horizontal pipe if void fraction, Φ, ≤ 0.20. [4]
0.31 < N_{FR} ≤ 0.65	Some gas may be transported depending on pipe geometry
> 0.54	Gas will move toward the downstream end of a horizontal pipe that has no local high points. Some bubbles may move downward in an attached DC.
< 0.8	Dynamic venting, the use of water flow to remove voids, is not effective.
0.8 < N_{FR} < ~2.5	Time to clear gas is a function of flow rate and piping geometry. Time to clear is not well characterized. Previous NRC publications provided an upper bound of 2.0. This is changed to ~2.5 to better reflect the erratic data scatter observed in testing.
≥ 1	Gas will be removed from an inverted "U" tube heat exchanger for steady state flow lasting several minutes.
> 1.2	A horizontal pipe that is open at the downstream end will run full.
≥ ~2.5	All gas will be removed from pipe but localized gas pockets may remain where full flow conditions may not exist such as in the vicinity of valves or orifices.

If assessment of N_{FR} results in a prediction of no gas transport, there is no immediate operability concern since the gas will not impact pump operation unless there is a perturbation that affects flow. Note, however, that accumulated gas may exceed the DB and gas accumulation may still need to be addressed.

[4] The Φ ≤ 0.20 criterion reasonably ensures there is sufficient flow area for liquid transport.

1.2 Acceptable Pump Inlet Characteristics

The NRC staff previously accepted for use the TR Table 3-1 criteria (NEI/NRC, April 2013) (W, December 31, 2015) that apply to pump inlet conditions that do not jeopardize operability.[5]

The last four columns were originally the void fraction, α. However, α is the void fraction that exists at a location. With the exception of homogeneous flow where there is no slip between phases, α is not a measure of what is flowing. This requires consideration of the slip that occurs between phases. The gas acceptance criteria must be based on criteria that include slip unless there is homogeneous flow. These criteria are described by the volumetric flux ratio, β, defined by:

$$\beta = \frac{Q_g}{Q_g + Q_\ell} \tag{2}$$

Or:

$$\beta = \frac{Q_g}{Q_{mix}} = 448.8\,\frac{V_i\left(\frac{P_{t,i}}{P_M}\right)}{Q_{mix}\,\Delta t} \tag{3}$$

where: Q_g = average gas volumetric flow rate entering the pump (gpm) during time Δt
Q_ℓ = average liquid volumetric flow rate entering the pump (gpm) during time Δt
Q_{mix} = average mixture volumetric flow rate (gpm) during time Δt
P_M = average static pressure at the void fraction measurement location (psia) during Δt
$P_{t,i,}$ = top header initial pressure (psia)
Δt = time for gas to be transported past the location of interest (sec)
V_i = initial gas volume in upper horizontal pipe (ft^3)

In the Purdue tests, Δt is the time between the leading and trailing edges of the gas to pass a sensor location. W calculated the start time by determining the beginning of a void fraction measurement and finding the time where the void fraction was equal to 10 percent of the maximum void fraction. The transient end time was calculated by starting from the end of each vertical and bottom horizontal time series void fraction measurement and finding the time where the void fraction was equal to $0.15(\alpha_m - \alpha_e) + \alpha_{te}$ where α_m is the maximum void fraction, α_e is the void fraction near the end of the data file, and α_{te} is the void fraction at the end of the transient (See Section 8.2.2 of WCAP-17271-P, Volume 1). The last term was added to account for the void fraction not decreasing to zero at the end of some transients. In effect, after a time Δt, all of the void was considered to have passed the location. The method for determining Δt is acceptable.

The NRC staff's previously stated three stipulations are re-written as follows in recognition that bubbles may re-enter the DC exit from the downstream elbow and a flow regime other than a dispersed bubbly flow regime may have been demonstrated to meet the pump entrance criteria:

(1) If a DC exists downstream of the gas accumulation location that is credited to contribute to meeting the pump entrance criteria, then verify sufficient DC volume to ensure bubbly flow at the highest DC level where the waterfall no longer affects α or β. See SE Section 1.6 for calculation of DC length.

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[5] TR tables and figures are not reproduced in this SE. The reader is guided to refer to the TR while using the SE.

(2) Identify and address if any other configuration exists between the gas accumulation location and the pump which may result in a transition from a dispersed bubbly flow regime to a flow regime that affects the pump entrance characteristics.

(3) Demonstrate that an acceptable flow regime exists at the pump entrance throughout transients and that β meets the acceptance criteria.

The TR Table 3-1 criteria are conservative. TR Table 3-2 from the Electric Power Research Institute (EPRI) Roadmap program (EPRI, August 2012) provides more realistic criteria. The difference between the TR Table 3-1 and TR Table 3-2 criteria may be credited as a conservatism when performing an operability determination if the TR Table 3-1 criteria are satisfied.

The TR stated that stratified flow regimes could not be tolerated if located at a pump suction. Note also that typical pump entrance configurations include a reducer immediately upstream of the pump entrance. The reducer and a short length of associated pipe between the reducer and the pump entrance are considered to be part of the connected pump.

1.3 Operating Procedures

Voids should be treated as conditions adverse to quality and addressed in the licensee's corrective action program. Typically, operating procedures will identify void volumes that will not jeopardize operability and the voids will be addressed as soon as is practical so that the DB is satisfied. Such volumes must be founded on test data, on approved methodologies, or on other acceptable information since acceptable theoretical methods have not been established. Operating experience may be credited as test data.

Occasionally, a void may be identified that exceeds the volume allowed in operating procedures. It is acceptable to address operability under this condition by analyses, test or partial test, experience, and/or engineering judgment.

1.4 The TR Model

The modeling approach is to average parameters over the time it takes for the gas to be moved past an observation location and into a pump. This effectively starts with the pump void acceptance criteria and is followed by correlations that use averaged parameter values.

The TR WCAP-17271-P and WCAP-17276-P models are based on the following event sequence:

(1) One or more pumps start.

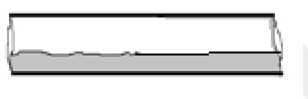
(2) Initial flow begins to expand and depressurize the gas space. The suction systems are typically designed so that a small pressure change will supply the steady-state pump flows although this is plant-specific and should be confirmed to ensure that frictional pressure drop does not significantly affect the void movement analysis.

(4) The gas volume is pulled from the upper horizontal pipe to the downturned elbow that leads to a DC until a configuration is developed that can deliver the supply flow.

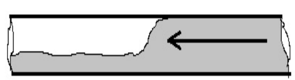
(5) All gas that is not consistent with the water delivery configuration is pulled into the top of the DC

(6) The gas volume in the top of the DC develops a kinematic shock (waterfall) region that experiences gas entrainment and downward transport of bubbly flow. If the DC is sufficiently long, homogeneous bubbly flow will exist immediately below the DC region that is affected by the waterfall.

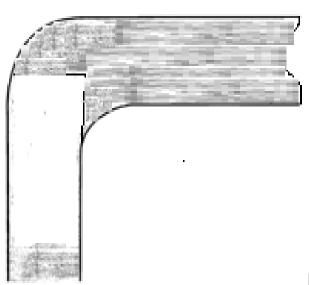
(7) There may be some large bubble return from the vertical to horizontal elbow located at the DC exit. The Purdue test data illustrate that these bubbles rapidly break up and do not travel a significant distance up the DC. This behavior is neglected since it tends to reduce the quantity of gas moving toward a pump.



The model for the suction pipe behavior initially assumes there is a stagnant water layer in an upper horizontal pipe elevation as illustrated in the sketch to the left.

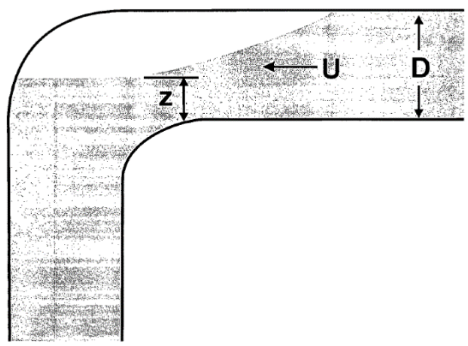


When one or more pumps start, typically the water flow rate and N_{FR} (see Table 1) will be large enough to cause a hydraulic jump (kinematic shock) in the upper horizontal pipe as shown in the sketch to the left and gas will rapidly move toward the downstream end of the pipe while the pipe is water-solid upstream of the jump. Note that the kinematic shock behavior also applies if the upper horizontal pipe is initially voided. This process will usually continue until most of the gas has moved into the DC.



The condition illustrated in the sketch to the left is observed to be established immediately in the start-up transient and is assumed at time zero for analysis purposes, consistent with observed Purdue test observations (W, August 2010). The DC upper void level is taken as the centerline of the upper horizontal pipe to model the curved elbow. The length of the totally voided DC region is referred to as the “ideal shock length,” $L_{S,id}$.

Water from the upper horizontal pipe is assumed to fall through the DC gas and to impact on water at the bottom of the void. This waterfall is observed to drive gas bubbles some distance into the water. The distance from the top of the DC where the impact effects no longer occur so that homogeneous bubbly flow is established is the minimum DC length necessary to achieve homogeneous bubbly flow immediately below the region affected by the waterfall, the “required shock length,” L_R. This distance has been established from the Purdue test data. Homogeneous bubbly flow is assumed to continue below this length when the flow rate is sufficient to carry the bubbles out of the DC. The downward flow in the DC carries bubbles out of the DC and gradually removes the large captured gas volume.



The sketch to the left illustrates the condition when the large gas volume has been removed. A small volume that was not removed remains where the distance z is established by the water flow into the DC. The illustrated gas volume size is typically small and of no consequence.

The initial high point pressure and the pressure during gas movement are important considerations when calculating the initial high point volume that will not jeopardize pump operability. The Purdue tests (W, October 2010) involved an initial pressure that decreased upon transient initiation. The analysis model described in the Purdue test reports (WCAP-17271-P) and in the TR assumed the pressure was constant at the decreased value.

The TR did not address that reactor coolant system (RCS) water contains chemicals that may change the water flow characteristics, yet the analysis methods are based on tests that used clean water. The NRC staff concluded the potential flow differences could be neglected based on published regulatory guidance (NRC, January 31, 2014).

1.5 Initial Pressure Transient

There was a ramp-up transient at the beginning of each Purdue test to simulate pump start-up. This is not addressed in the TR. In some cases, all gas had passed through the test facility before the startup transient had completed. This resulted in an N_{FR} that differed from the N_{FR} used in the correlations. This ramp-up was neglected which meant that the N_{FR} used to correlate the results was not equal to the average N_{FR} obtained during the tests. The NRC staff accepted this inconsistency since the correlations were acceptably correlated with the data and a plant pump startup transient was simulated by each of the Purdue tests.

Some plant conditions have a completely voided high point volume in contrast to the maximum void in the Purdue tests of 20 percent. This is not a concern because the modeled configuration has all the void moved into the upper DC at time zero.

1.6 DC Length Requirement

The TR correlations require a DC that is long enough to provide homogeneous bubbly flow where water falling through the initial void at the top of the DC no longer affects the void volume. This is the required shock length, L_R, that, when there is no diameter change between the upper horizontal pipe and the DC, is acceptably determined by TR Eq. 5-6. An older specification that the DC volume must be greater than four times the original gas volume is also acceptable. Further, since TR Eq. 5-6 is based on average properties, L_R must be at least equal to several pipe diameters.

1.7 WCAP-17276-P, the Simplified Equation

The NRC's NEI 09-10 SE stated that the simplified equation is acceptable subject to the following **conditions** modified as specified below to reflect the present NRC staff assessment:

(1) **Either $N_{FR} \leq 2.5$ or flow rate ≤ $10D^{2.5}$ gpm.** The maximum N_{FR} during Purdue testing did not exceed ~2.5; therefore, to use the simplified equation it is necessary that $N_{FR} \leq 2.5$. The $10D^{2.5}$ gpm limitation is no longer needed.

(2) **DC volume must be greater than four times the gas volume.** This requirement resulted from the need to satisfy the simplified equation homogeneous flow assumption in the lower DC. Stated differently, the DC must be large enough to contain the kinematic shock region including behavior below the waterfall impact elevation. The factor of four criterion to calculate volume and the TR Eq. 5-6 to calculate DC length are both acceptable.

(3) **4 inches ≤ pipe diameter ≤ 30 inches.** The simplified equation is acceptable for use in pipe diameters from four inches to 30 inches on the basis of the scaling analysis reported in WCAP-17271-P.

(4) **Maximum transient time, Δt_p, taken from TR Table 3-1 or Table 3-2, must be modified as discussed in WCAP 17276-P** (W, January 2011). This limitation results from the requirement that the calculated Δt_p must be consistent with the pump criteria.

(5) **Flow rate must be low enough that gas is not transported from its original location into the pump suction as a slug.** The Item 1 $N_{FR} \leq 2.5$ stipulation covers this.

(6) **Any DC off-take or other configuration change must be located below the elevation corresponding to a vertical DC volume that is four times the gas volume.** As discussed in Item 2, the four times DC volume stipulation has been modified and TR Eq. 5-6 may be used to predict the minimum DC length.

(7) **Licensees are expected to identify (and address) any configuration that exists between the gas accumulation location and the pump which may result in a transition from a dispersed bubbly flow regime to a separated flow regime.** The Purdue tests exhibited a hydraulic jump in the lower horizontal pipe during some of the tests. Flow downstream of the jump transported gas towards the pump, and the TR provided methods to evaluate the acceptability of the gas transport.

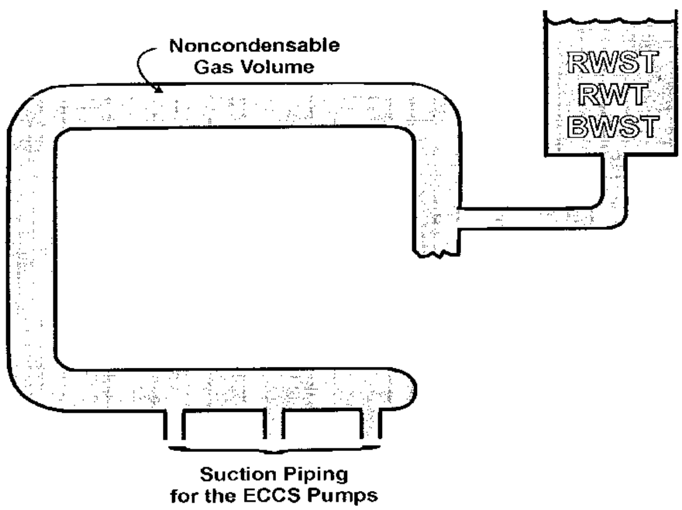
The simplified equation assumes the waterfall model and homogenous flow with corrections for system static pressure variations. This is a simplistic modeling approach that does not account for hold-up of gas at piping components. The TR gives the simplified equation as TR Eq. 5-1. The best fit for the transport time with respect to the Purdue data is given by TR Eq. 5-7.

In practice, the first step in applying the simplified equation is to obtain pump-specific allowable β_p and Δt_p from TR Table 3-1. This provides the maximum allowable V_g. Then a new Δt is obtained using Eq. 5-7. If the transport time predicted by Eq. 5-7 is less that the allowable transport time in the TR Table 3-1 pump acceptance criteria, then Eq. 5-7 is used for Δt_p in Eq. 5-1.

The WCAP-17276 methodology is acceptable subject to satisfying limitations and conditions provided in this SE.

1.8 The WCAP-17271-P Methodology

The WCAP-17271-P methodology is based on testing at Purdue University for $N_{FR} \geq 0.93$. The general suction pipe configuration was assumed to be as follows:



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

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

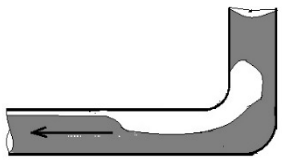
In the Purdue tests, kinematic shocks were observed in the eight-inch tests downstream of the elbow between the DC and the horizontal pump suction header with a substantial void fraction reduction downstream of the shock.

The start of the WCAP-17271-P methodology is described by the Weber Number (W_e), TR Eq. 4-4. The NRC staff will accept $W_e \geq 720$ and Reynolds number (N_{Re}) $\geq 10^5$ as lower bounding values for test facility scaling with the qualification that smaller values are acceptable when justified. Additional criteria are that minimum pipe diameter is four inches and the test scale can be no smaller than ¼ unless deviations are acceptably justified. Bubble size and bubble rise velocity do not scale.

In applying the WCAP-17271-P methodology, the next step is to calculate the average gas volumetric flow ratio over the initialization process (the flow initialization or upper elbow holdup correlation model) by TR Eq. 4-3. This is followed by application of the TR Eq. 4-6 elbow holdup correlation and the gas volumetric flux at the entrance to an elbow below a DC is then described by TR Eq. 4-8 where the pressures follow from use of TR Eq. 5-6 with the assumption of a DC linear pressure distribution. Next the TR Eq. 4-6 lower elbow holdup correlation is applied where $\Delta t_{el,in}$ is the time over which gas enters the elbow, given by TR Eq. 4-1, and the nomenclature has been changed from Δt_{init}.

Since gas holds up at the elbow, the gas transport time will increase at the elbow in accord with TR Eq. 4-9. This must be compared to the pump inlet acceptance criteria in TR Table 3-1 to determine which criteria are applicable.

1.9 Lower Horizontal Pipe



A horizontal pipe that is receiving a two-phase mixture from a DC may exhibit the behavior illustrated in the sketch to the left. Gas accumulates along the inside of the elbow and a shock is shown toward the left where the void fraction decreases, and the void fraction located to the left of the sketch is much less than the void fraction near the elbow. The gas near the elbow is stagnant, whereas the gas to the left of the jump is flowing towards the pump. Simultaneously, some of the gas may migrate upward in the DC where initially large bubbles break up and are then carried downward out of the DC. There is a significant difference in β if a pump is located upstream or downstream of the hydraulic jump.

Implications of the void are reported in three categories: (1) three dimensional behavior, (2) upper horizontal pipe void volume that can result in a hydraulic jump, and (3) location of a hydraulic jump if one occurs.

1.9.1 Two Component Lower Pipe Behavior

At pump and flow initiation the DC region below the region affected by the waterfall, the elbow between the lower end of the DC and the lower horizontal pipe, and the lower horizontal pipe will be water solid. Gas must accumulate near the entrance to the lower horizontal pipe for a kinematic shock to occur in the pipe.

The TR states that stratified flow regimes could not be tolerated if located at a pump suction. This is acceptable.

$\beta_{ave} \le$ **[ ]** represents the Purdue test information that indicates there is insufficient gas for a shock to exist.

If a pump is located in the gas accumulation region immediately downstream of a DC vertical to horizontal exit elbow and is removing gas as it accumulates downstream of the elbow due to gas exiting the elbow, it is questionable if a void or kinematic shock will form downstream of the elbow exit. If a pump is not removing gas and the DC length meets the TR Eq. 5-6 requirement, the average mixture flow rate can be determined at the DC exit. This does not, however, ensure that the mixture will be homogeneous when it leaves the elbow since centrifugal force will concentrate the gas on the inside of the elbow. For example, if a pump suction is on the bottom of the horizontal pipe the pump will experience a smaller void fraction than if located at the top and the void may continue to increase as a result. The TR is focused on average flow characteristics and does not identify this behavior.

It is acceptable to not address the case where a pump is removing gas as it leaves the elbow at the DC exit because neglecting the effect will result in over-predicting later gas movement toward the affected pump. When a pump is located close to the elbow exit and is removing gas at the rate that gas is leaving the elbow, the NRC staff will accept an assumption that a kinematic jump will not occur in the lower horizontal pipe provided the rate at which gas enters the pump meets the TR Tables 3-1 or 3-2 criteria.

If a horizontal pipe connects between the bottom of a DC and a pump entrance, and the acceptable methods identified in this SE cannot be shown to yield an acceptable pump entrance condition, applicable test data should be obtained or a methodology should be applied that has a multi-dimensional two-phase capability that has been verified by comparison to experimental data. Since phenomena in this region are not well understood, judgment may be a significant factor and a safety factor should be added to the predicted behavior to reasonably ensure the prediction encompasses behavior.

1.9.2 Allowable Initial Void to Avoid a Hydraulic Jump

The TR correlated the β required to form a kinematic shock from the W data for $1 \leq N_{FR} \leq 1.9$ with an R-squared value of 0.99 in TR Eq. 6-6. TR Eq. 6-6 was correctly assumed to hold for $1 \leq N_{FR} \leq 2.25$ with $\beta_{min\ reqd} = 0.188$ for $N_{FR} > 2.25$. In discussing TR Figure 6-12, the TR statement that β_{max} is less than 0.188 is incorrect.

The TR provided a comparison of β_{avg} and β_{max} by TR Eq. 6-9. Comparisons showed that β_{max} is more representative of the behavior than is β_{avg}.

TR Section 6.3.5.1.2 presents a TR Eq. 6-7 correlation of the maximum gas volumetric flux at the kinematic shock outlet where L_R is determined from TR Eq. 5-6 and d is the pipe diameter in inches. The β_{max} information is scattered but a comparison indicates that TR Eq. 6-7 is generally representative of the average of the information. TR Eq. 6-7 is acceptable when conservative assumptions, such as those reflected in TR Table 3-1, are used to bias the TR Eq. 6-7 predictions.

1.9.3 Hydraulic Jump Location

The Purdue tests established the jump magnitude in the lower horizontal pipe but only measured α upstream and downstream of the jump. It is necessary that either a kinematic shock does not form in the lower horizontal pipe or that the pipe length will contain the kinematic shock without allowing it to reach the pump inlet. If a kinematic shock should form in the lower horizontal pipe, TR Section 6.3.5.2 provides information to estimate the location of the shock.

TR Figures 6-10 and 6-11 illustrate that β_{max} provides better agreement between the W and Purdue results than β_{ave}.

Further the NRC staff conclusions include (1) Eq. 6-6 is acceptable for use significantly outside of $1.25 \leq N_{FR} \leq 2.25$ and remains constant for $N_{FR} > 2.25$, (2) no shock will form in the lower horizontal pipe if β_{max} < **[ ]**, (3) if a shock forms the TR provides a conservative method for predicting maximum shock length, (4) Eq. 6-7 is an acceptable description of void behavior when conservative assumptions are used, and (5) the kinematic shock will not form when the pump is located near the end of the lower elbow.

1.10 An Additional Concern for Boiling Water Reactors

Much of the concern involves gas accumulation at a high point in suction piping that can be addressed by the above methodologies. In some boiling water reactors (BWRs), gas could be entrained in water entering pump suctions due to blowdown of containment gases into the suppression pool/torus. This concern was acceptably addressed with closure of Generic Issue (GI)-193 (NRC, April 19, 2016).

1.11 WCAP-17271 Correlation Uncertainty Considerations

Model prediction discrepancies that were not identified in WCAP-17271 have been identified such as the initial transient flow rate, the experimental transit time associated with the Purdue tests, the linear DC pressure distribution, and the initial Φ and N_{FR} used to describe the Purdue test results. The NRC staff relies upon judgement as authorized in SE Section 2 when assessing operability and including safety factors when applying selected correlations. It does not rely upon uncertainty calculations since they are incomplete.

1.12 WCAP-17271 Acceptability

The WCAP-17271 methodology is acceptable subject to the limitations and conditions provided in this SE.

1.13 Conclusion Summary

The TR (1) provides acceptable methods for operability determinations to predict the volumetric flux of a non-condensable gas (β) at a pump inlet based on the gas volume at an upstream location and (2) provides justification for the location of a hydraulic jump in a lower horizontal pipe subject to the limitations and conditions provided in this SE.

1.0 REGULATORY CONSIDERATIONS

The regulations in 10 CFR Part 50, Appendix A, or similar plant-specific principal design criteria provide design requirements.[6] The regulations in 10 CFR Part 50, Appendix B, and 10 CFR 50.36 provide operating requirements.

10 CFR Part 50, Appendix A, requirements include the following:

- General Design Criterion (GDC) 1 requires that the subject systems be designed, fabricated, erected, and tested to quality standards.

- GDC 34 requires a residual heat removal (RHR) system designed to maintain specified acceptable fuel design limits and to meet design conditions that are not exceeded if a single failure occurs simultaneous with failure of specified electrical power systems.

- GDCs 35, 36, and 37 require an emergency core cooling system (ECCS) design that meets performance, inspection, and testing requirements.

- GDCs 38, 39, and 40 require a containment heat removal (CHR) system design that meets performance, inspection, and testing requirements.

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[6] The Atomic Energy Commission (AEC) published the rule that added 10 CFR Part 50, Appendix A, in the *Federal Register* (36 FR 3255) on February 20, 1971, with the rule becoming effective on May 21, 1971. Appendix A was not applied to plants with construction permits issued prior to May 21, 1971. Such plants were licensed in accord with principal design criteria that are generally similar to Appendix A requirements.

Applicable quality assurance criteria provided in Appendix B to 10 CFR Part 50 include:

- Criteria III and V require measures to ensure that applicable regulatory requirements and the DB, as defined in 10 CFR 50.2 and as specified in the license application, are correctly translated into controlled specifications, drawings, procedures, and instructions.

- Criterion XI requires a test program to ensure that the subject systems will perform satisfactorily in service and requires that test results shall be documented and evaluated to ensure that test requirements have been satisfied.

- Criterion XVI requires measures to ensure that conditions adverse to quality, such as failures, malfunctions, deficiencies, deviations, defective material and equipment, and non-conformances, are promptly identified and corrected, and that significant conditions adverse to quality are documented and reported to management.

- Criterion XVII requires maintenance of records of activities affecting quality.

Regulatory requirements covering TSs are provided in 10 CFR 50.36(c). The regulations in 10 CFR 50.36(c)(2) define limiting conditions of operability (LCO) as the lowest functional capability or performance levels of equipment required for safe operation of the facility. When an LCO of a nuclear reactor is not met, the licensee shall shut down the reactor or follow any remedial action permitted by the TSs until the condition can be met. Surveillance requirements (SRs), as stated in 10 CFR 50.36(c)(3), "are requirements relating to test, calibration, or inspection to assure that the necessary quality of systems and components is maintained, that facility operation will be within safety limits, and that the limiting conditions for operation will be met." A purpose of the correlations addressed here is to provide methodologies to predict gas accumulations in pump suction piping that do not jeopardize operability. This information may then be used to determine if SRs are satisfied.

The regulation in 10 CFR 50.46 provides specified ECCS performance criteria pertaining to peak cladding temperature, cladding oxidation, hydrogen generation, core cooling, long-term core temperature, and long-term decay heat removal.

There are additional systems that are important to safety that are not specified in the TR, such as the auxiliary feedwater system, that must be addressed when considering void accumulation in high point piping.

With respect to operability, 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 (NRC, January 31, 2014). This operability perspective is applicable to the TR and related documents since the intent of the reports is to provide a methodology for assessing operability.

2.0 TOPICAL REPORT PWROG-15060

The NRC staff SE that endorsed NEI 09-10 Revision 1a-A provided limitations regarding use of WCAP-17271 and WCAP-17276. In that review, the NRC staff stated that a scaling analysis provided general correlations for the dominant phenomena observed in the testing and that the empirical correlations that resulted from the scaling analyses were acceptable for pipe diameters ranging from 4 inches to 30 inches. The SE also reported that identified limitations had to be addressed.

The NRC staff inspections and audits have resulted in concerns that licensees may not have adequate guidance to apply the WCAP-17271 correlations. Members of NEI, the Pressurized Water Reactor Owners Group (PWROG), and the Boiling Water Reactor Owners Group (BWROG) met with the NRC staff on January 15, 2015 (Lyon, June 22, 2015) to examine these concerns. The NRC staff concurred with use of the WCAP-17271 empirical correlations and the WCAP-17276 simplified equation to model gas transport in pump suction piping systems for operability determinations. However, the NRC staff requested that additional guidance be provided to licensees to ensure the correlations are used within the SE limitations. PWROG-15060 addresses aspects of this request by providing proprietary correlations and addresses restrictions in the SE that are no longer needed.

3.1 Tests and Test Scaling

A key aspect of addressing transient void transport correlations is comparison to test data. It has been impractical to simulate entire systems and it has been necessary to use scaled test models. Therefore, it is generally necessary to apply methodologies that have been established to reasonably predict test behavior.

There are unique aspects of two component flow that require correctly scaled tests. In this respect, Odgaard (Odgaard, 1986) used a Weber number (W_e) > 720 and a Reynolds number (N_{Re}) > 1.1 X 10^5 or larger for concluding that surface tension and viscous effects were negligible. The NRC staff will accept $W_e \geq 720$ and $N_{Re} \geq 10^5$ as bounding values for test facility scaling and smaller values are acceptable when justified. Additional criteria are that minimum pipe diameter is four inches and the test scale can be no smaller than ¼ unless deviations are acceptably justified. Bubble size and therefore bubble rise velocity do not scale.

The PWROG funded programs included:

(1) An experimental investigation at Purdue University of two-phase (air / water) gas transport in piping systems with diameters from 4 to 12 inches is described in WCAP-17271, Volumes 1 through 3 (W, October 2010) (W, August 2010). Three types of void fraction meters were used. Characteristics are provided in the following table:

Type	Designation	Location	Characteristics
Parallel wire	PW	Top and bottom-header pipes.	Measurements are accurate for void fraction when flow is separated and for determining time interval over which gas was transported past the instrument for all flow regimes.
Arch impedance	AIMP or A,	Vertical DC.	Measures area averaged void fraction; not an accurate measure of void fraction if flow is separated near the meter.
Ring type impedance	RIMP or RW,	Top and bottom-header pipes.	Measures volume averaged void fraction over a length of pipe equal to one hydraulic diameter in separated and bubbly flow regimes.

(2) Investigation of a simplified equation to model gas transport (W, January 2011).

(3) Development of a methodology to address gas accumulation (W, October 2010).

(4) Investigation of two phase flow behavior at the Westinghouse (W) thermal hydraulic laboratory (W, December 31, 2015).

(5) Methods of applying the correlations for operability determinations to determine if systems, although degraded, will continue to perform the specified functions.

With the exception of offtakes, the TR does not address vortexing, localized level reduction, or air ingestion during flow from tanks, sumps, or large pipes such as during RHR operation when taking suction from a PWR hot leg during mid-loop operation. This is a concern if these conditions should occur.

Steady state gas / liquid flow regimes that are of potential interest for flow within horizontal pipes are illustrated in Figure 1.

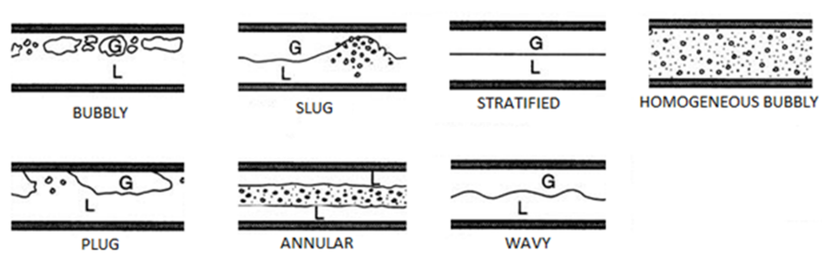

Figure 1 Gas / Liquid Flow Regimes

3.2 Topical Report Section 3, Acceptance Criteria

3.2.1 TR Section 3.1, Intended Use

Methods provided in the TR are stated to be of use in predicting the volumetric flux of a non-condensable gas at a pump inlet based on the gas volume at an upstream accumulation location for a given set of pump suction piping hydraulic conditions. These methods are intended for operability determinations to show that the system, although degraded, will continue to perform its specified function. These methods are not intended for use in establishing design criteria.

The intended use is acceptable subject to (1) applicability is limited to evaluation of gas movement in pump suction pipes and (2) limitations and conditions identified in this SE are met.

3.2.2 TR Section 3.2, Pump Gas Ingestion Acceptance Criteria

Much of the gas accumulation concern involves gas accumulation at a high point in suction piping. The purpose of analyzing pump suction piping is to establish that conditions at a pump entrance do not jeopardize operability. Typically, pumps require time to develop rated flow and during part of this time, pipe flow rates may be too low to transport gas into the pumps. However, should gas enter a pump under a low-flow condition, gas may form a pocket around the impeller eye. This could result in the impeller rotating in gas with no flow out of the pump. Once up to speed, the flow velocities during transients may be high enough to sweep small quantities of gas through the pump due to the system's flow inertia. Acceptable pump entrance criteria were discussed in SE Section 1.2. Operating procedures were addressed in SE Section 1.3.

3.2.3 TR Section 3.3, Terminology

Terms examined in this SE section include void fraction (α), volumetric flux ratio (β), time for gas to move past a location of interest (Δt), DC length required to achieve homogeneous bubbly flow (L_R), initial void fraction (Φ), (4) flow rate, (5) test scaling, and (6) Froude number (N_{FR}). These are discussed in the following SE subsections

3.2.3.1 Void Fraction, α, and Volumetric Flux Ratio, β

The pump gas ingestion acceptance criteria were presented in NEI 09-10 Revision 1a-A as the gas void fraction, α, a characteristic that was measured during tests conducted at Purdue University (W, October 2010). However, as discussed in SE Section 1.2, α is the void fraction that exists at a location. With the exception of homogeneous flow where there is no slip between phases, α is not a measure of what is flowing. This requires consideration of the slip that occurs between phases. The gas acceptance criteria must be based on criteria that include slip unless there is homogeneous flow.

For homogeneous flow conditions, at a distance from the top of a DC and at a time from transfer of all gas into the top of the DC, the void fraction, α, is defined by TR Eq. 3-1. The slip ratio is defined by TR Eq. 3-2. If there is slip between phases, the fraction of gas and liquid occupying a pipe is not meaningful for determining what is actually flowing and TR Eq. 3-1 cannot be used. In this case, α must be defined by TR Eq. 3-3 and, when slip occurs, TR Eq. 3-1 must be replaced by TR Eq. 3-4 that provides β, the volumetric flux ratio. TR Eq. 3-4 is representative of what is actually flowing in a pipe and describes what is entering a pump.

The TR provided Eq. 4-5 for β for the mixture passing a location in the pump suction piping where the location corresponds to the selection of Δt and 448.8 (gal/min) /(ft^3/sec) is a unit conversion factor, obtained from:

$$\frac{gal}{0.13368\, ft^3}\,\frac{60\, sec}{min} = 448.8 \qquad (4)$$

The source of Eq. 4-5 is readily understood by noting that the initial part of the equation is the definition of β and Q_g is the initial gas quantity divided by the time for all gas to pass through the location. The difficulty in calculating β from the Purdue test data is determining Δt since Δt was not measured. Calculation of Δt is described in SE Section 1.2.

It is important to remember that β is a calculated value when using the plotted points that are provided in the WCAPs that document the Purdue test results (W, August 2010). Also note that the correlations developed from the Purdue information are typically based on the assumption that time-averaged values can be used that cover the time before all gas has entered a pump.

3.2.3.2 Time for Gas to Move Past a Location of Interest, Δt

The TR provided an isometric diagram of the W dynamic vent facility in TR Figure A-1[7]. Tests were accomplished at this facility where air flow rates were measured, and this allowed the NRC staff to independently estimate Δt.

Water flow rate was measured at the magnetic flow meter (MFM) that is located upstream of the pump that is shown in TR Figure A-1.[8] This figure shows the high point location that includes Void Meter 7 (VM7) in a pipe that is 24.75 ft long. This is a 6-inch pipe with an inside diameter of 6.065 inches (0.506 ft) and a flow area of 28.89 in^2 (0.2006 ft^2). The high point volume is 24.75 X 0.2006 = 4.965 ft^3.

In the W tests, gas was placed in the top horizontal header where VM7 was located, and then pump flow was initiated at 500 gpm. (500 X 0.13368 / 60 / 0.2006 = 5.553 ft/sec, N_{FR} = 1.38[9]). The distance between VM7 and VM11 was 102.5 ft. Assuming homogeneous flow, the transport time from VM7 to VM11 was 102.5 / 5.553 = 18.458 sec. Gas holdup and slip between phases increases the time.

Figure 2 provides detail of the test configuration that is illustrated by the green line in TR Figure A-1 that shows piping immediately downstream of a high point.

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[7] The drawing is not to scale.
[8] The location of MFM was not included in the W figure.
[9] The NRC staff often includes more significant figures than is justified by the measurements to reduce calculation round-off error.

Figure 2 Six Inch Elbow Test Configuration

Three tests series were conducted at an assumed 14.7 psia and 70˚F with initial high point gas volumes of 0.1, 1.14, and 2.48 ft^3 (initial void fractions of 0.017, 0.23, and 0.50, respectively). System pressure was controlled by the tank level downstream of VM11, which was approximately 4 ft above the VM11 centerline. Consequently, hydrostatic pressure at VM11 was 14.7 + (4)(62.4)/144 = 16.4 psia. VM7 was located 13.5 ft above VM11 so its static pressure was 16.4 – (13.5)(62.4)/144 = 10.55 psia. Pressure drop due to frictional flow was assumed negligible so that the high point pressure was treated as constant throughout the test duration. This differed from the Purdue tests which involved valve manipulations that affected test pressures.

Most six-inch piping was clear PVC 6 inch Schedule 40 pipe with an inside diameter of 6.07 inches (flow area = 28.9 in^2, high point volume = 4.97 ft^3). Liquid flow rate was measured downstream of the pump. The tank was kept near atmospheric conditions (14.7 psia and 70˚F) to act as a gas separator, which maintained water solid conditions through the pump and liquid flow meter. The resulting void fractions from VM7 and VM11 are provided in TR Figures 9-1, 9-2, and 9-3. The initial spikes indicated by VM7 correspond to gas accumulation associated with a kinematic shock in the upper horizontal pipe where the void fraction upstream of the shock is zero; a water-solid condition. After this time, VM7 indicated that all gas had been swept downstream of that location and TR Figures 9-1 through 9-3 illustrate the expected kinematic shock behavior followed by all liquid flowing past VM7 for the remainder of the tests.

The distance between VM7 and VM11 was 102.5 ft. Assuming homogeneous flow, the transport time from VM7 to VM11 was 102.5 / 5.553 = 18.458 sec. But gas holdup and slip between phases will occur which will increase the 18.458 sec time. From TR Figures 9-1 through 9-3, the NRC staff estimated that the time it took for gas to reach VM11 was about 49 – 27 = 22 sec, 53 – 33 = 20 sec, and 63 – 46 = 17 sec, respectively, consistent with the 18.5 sec calculation of the homogeneous flow time.

From Figures 9-1 through 9-3 the NRC staff estimated that the times for all gas to have passed through VM11 starting at the time when flow was initiated through VM7 were about 90 – 24 = 66 sec, 101 – 31 = 70 sec, and 116 – 43 = 73 sec, respectively. (The TR estimated 66 sec, 69 sec, and 74 sec, in close agreement with the NRC staff estimates.) The NRC staff's estimate of the time it took for flow to pass through VM11 was 90 – 49 = 41 sec, 101 – 53 = 48 sec, and 116 – 64 = 52 sec, respectively. The W integral calculation process was estimated to yield 36 sec, 36 sec, and 49 sec. The Δt estimates are summarized in Table 2.

Table 2 Estimated Δt From W Hydraulic Laboratory Facility Data

Figure	NRC staff estimate of time to pass VM11 from figure, sec	NRC staff estimate of time to pass VM11 using W integral calculation process, sec
4 (9-1)	41	36
5 (9-2)	48	36
6 (9-3)	52	49

The method used to obtain Δt and β in the Purdue tests is confirmed by the W facility tests.

3.2.3.3 DC Length

The Purdue test void instruments showed that the DC was voided near the top at time zero. This is illustrated in Figure 3. Note that the data are parametric in Φ.

Figure 3 Times Upper-Most DC Instruments Show Complete Void for 8 Inch Purdue Tests

A completely voided condition sometimes extended into the next measured lower level in the DC, 6.7ft downstream of the elbow at the top of the DC, as illustrated for the 8 inch Purdue tests in Figure 4.

Figure 4 Times DAIMP1 Indicated Complete Void in 8 Inch Purdue Tests

This verifies that the model of occurrence of a void in the upper DC is acceptable.

The WCAP-17271 and -17276 correlations both require that a DC exist that is at least as long for the waterfall effect to no longer affect the gas flow behavior. Although this is addressed in TR Section 5 that is specific to WCAP-17276, the NRC staff has elected to provide an independent verification of the DC length since the DC requirement applies to both correlations.

A DC that is at least as long for the waterfall to no longer affect the gas flow behavior may be visualized as divided into three parts that were simulated by the Purdue tests (W, October 2010):

(1) An upper DC part that is initially completely voided for a length $L_{S,id}$ and is referred to as the ideal void length or the ideal shock length. Water from an upper horizontal pipe falls through this void and impacts on water at the top of the second DC part. The Purdue tests initiated with a measured void in the upper horizontal pipe and there was an immediate pressure decrease that caused the initial void to expand. This void was assumed to move to the top of a DC and this movement was considered to be complete at time zero in assessment of the Purdue test data. The resulting completely voided upper void length was described by TR Eq. 4-2.

(2) A second, middle DC part where bubbles are generated by the waterfall and homogeneous bubbly flow occurs at the bottom of the part. The length of this part plus the length of the upper part is described by L_R since this is the DC length required to establish homogeneous bubbly flow. The TR identified that a DC volume that is four times as large as the initial gas volume would satisfy the DC length requirement when the DC diameter is equal to the upper pipe diameter, the TR described the voided length plus the length that is affected by water falling through the void by TR Eq. 5-6 (see SE Section 1.6),

TR Eq. 5-6 is compared to the factor of four requirement in Figure 5 where the data are from the Purdue 8 inch tests and TR Eq. 5-6, the solid line, is described by **[**
]. The comparison shows that that TR Eq. 5-6 is conservative.

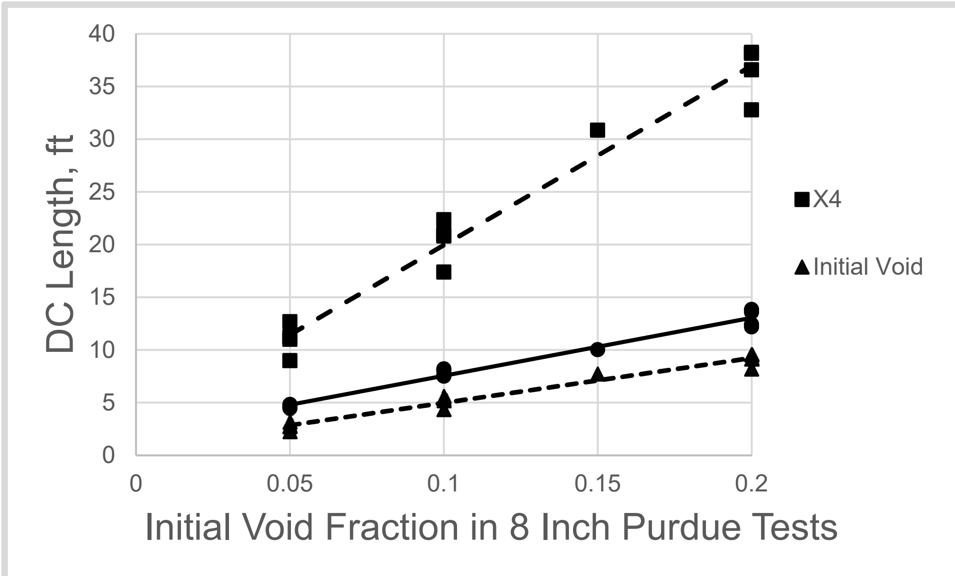

Figure 5 DC Length vs Purdue Data

(3) A third, lower part where homogeneous bubbly flow is assumed to exist although some larger bubbles may enter the DC from the DC exit elbow. These bubbles were observed to rapidly break up and to then exit the DC. The void fraction in this DC part is typically a weak function of elevation position as shown below.

The NRC staff estimated the DC location where homogeneous bubbly flow was established by estimating α as a function of Φ, instrumentation location, and N_{FR} from the graphs of W Purdue data provided in WCAP-17271-P Volume 2 (W, August 2010). A typical estimate using W Figures 3-741 through 3-854 for 8 inch pipe is provided in Figure 6 for a planned φ = 0.05 parametric in the planned N_{FR}.

Figure 6 Variation of α for Initial Φ = 0.05 in Eight Inch Upper Horizontal Pipe

The almost vertical upper line represents the DC length where the void fraction is changing due to the waterfall affecting the void fraction. The lower line is the DC length where the void fraction change is due to pressure variation and the voids are no longer within the region affected by the waterfall. This illustrates that α does not change significantly when level is greater than about 4.2 ft below the top of the DC for N_{FR} > ~1.0.

Figure 7 provides Φ = 0.10 estimated data taken from WCAP Figures 3-855 through 3-968 for 8 inch pipe. The value of α does not change significantly when level is greater than about 6.4ft below the top of the DC.

Figure 7 Variation of α for Initial Φ = 0.10 in Eight Inch Upper Horizontal Pipe

The DC length information is summarized in the following table:

Φ	Approximate length from TR Eq. 5-6, ft	Estimated Length from Figures 6 or 7, ft	Factor of four length with N_{FR} = 1.27, ft
0.05	4.5 – 5.5	**[ ]**	11.8
0.10	8 – 9.6	**[ ]**	23.5

TR Eq. 5-6 predicts that a greater DC length is required to bound the kinematic shock than is required by the data. It is significant that both approaches require less DC length than the factor of four method.

Next examine the DC characteristics by noting that the ideal void length is defined by the initial void volume that exists if all of the initial gas has been moved into the upper DC and assume the total DC length that will provide homogeneous bubbly flow from the upper DC kinematic shock is given by TR Eq. 5-6. For the 8-inch pipe in the Purdue tests, the NRC staff applied TR Eq. 5-6 to obtain Figure 8 where the lengths are provided parametrically in the planned Φ as identified in the right-hand part of Figure 8.

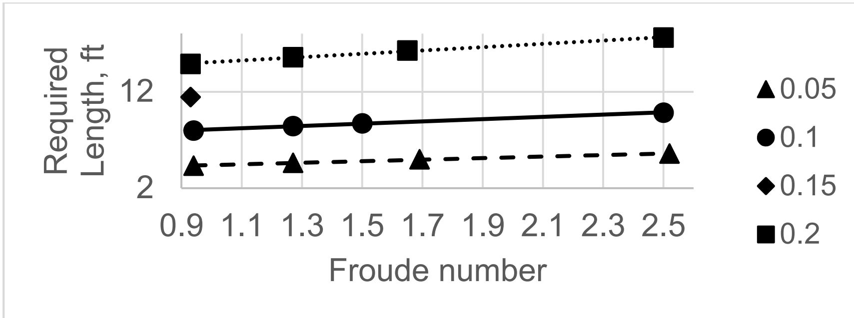

Figure 8 Required DC Length to Achieve Homogeneous Bubbly Flow

The shock lengths from TR Eq. 5-6, the solid lines, are compared to the Purdue 8-inch void meter data in TR Figures 6-1 through 6-4. These figures provide a prospective of the information scatter that is expected to occur during correlation application. The following observations apply:

(1) The shock length data points are from the Purdue data corresponding to V_g, Q_ℓ, and u_ℓ.

(2) The abscissa is the ideal shock length, $L_{S,id}$, that is described by TR Eq. 4-2. The transition length between the bottom of the void and establishment of homogeneous bubbly flow occurs below the bottom of this void.

(3) The ordinate is the ratio of the predicted depth to achieve bubbly flow, L_R, to the ideal shock length. The line represents the predicted depth to the DC where homogeneous bubbly flow is achieved as calculated by TR Eq. 5-6 (labeled FAI-09/130).

(4) The multiple data points at a similar ideal shock length are due to the variation in initial void fraction, Φ, which caused the calculated shock lengths to vary.

(5) TR Figures 6-1 through 6-4 “data” show shock length divided by ideal shock length values that are less than one for the smaller N_{FR}. This illustrates that some of the gas has remained in the upper horizontal pipe at low N_{FR}. Larger Φ (larger ideal shock length) and larger N_{FR} correspond to a larger proportion of initial gas being moved out of the upper horizontal pipe. Failure of the correlation to predict this behavior is not an operability concern related to this methodology since the correlation predicts a longer DC than required by the data. The data bracket the correlation for larger N_{FR}.

As identified in SE Sections 1.6 and 1.7 and established in Figure 8, the observations provide additional confirmation that TR Eq. 5-6 is acceptable for prediction of the DC length required to achieve homogeneous bubbly flow as required by the factor of four criterion discussed in the NRC NEI 09-10 SE. Consequently, the NEI 09-10 volume requirement is no longer a limitation. However, DC length must be sufficient to reasonably ensure homogeneous bubbly flow at the DC exit. It is possible that a short DC that satisfies TR Eq. 5-6 may not have a sufficient length.

3.2.3.4 Void Fraction Φ, Froude number, N_{FR}, and Flow Rate

TR Eq. 3-1 effectively contains Q_{mix}. In the W facility tests, the flow rate was **[**
]. From the time flow was started, the amount of water that entered the upper horizontal pipe that contained VM7 was **[**

] for the three flow rates, respectively. The initial gas volumes were **[ ]** of gas, respectively. These gas volumes would be smaller in the lower elevation parts of the system due to increased pressure. Assuming the liquid flow rate in these tests to be equal to the total flow rate as opposed to including the gas volume is an acceptable assumption when analyzing behavior since the error would be less than about three percent. The same conclusion applies to the Purdue tests since the applicable geometries are similar.

There was a ramp-up transient at the beginning of each Purdue test to simulate pump start-up that is not addressed in the TR. An initial flow transient that had a significant impact is shown in Figure 9 for an initial void fraction, Φ, of 0.20 and the maximum flow rate that corresponds to a planned Froude number, N_{FR}, of 2.5 (WCAP-17271-P Volume 2 Figure 3-1130).

Figure 9 D8A20F250R1R2R3-GPM2 Flow Rate

This shows that reaching the planned flow rate took about 10 seconds from the time flow was initiated. The NRC staff used this figure information to obtain the N_{FR} illustrated in Figure 10.

Figure 10 NRC Staff Estimate of N_{FR}

The void fraction in the lower horizontal pipe that is furthest from the DC exit for these tests is provided by Figure 11 that is reproduced from WCAP-17271-P Volume 2 Figure 3-1137.

Figure 11 D8A20F250R1R2R3 Void Fraction at PW4

This shows that all of the gas has passed through the test facility by 16 sec. Figure 10 shows that this is about the time when the actual N_{FR} reached the planned value. The actual average N_{FR} was less than the planned steady state value used in the correlations.

The flow rate transient was similar at other N_{FR} and Φ but the behavior at the exit from the test facility was different. For example, Figure 3-814 showed a negligible exit void fraction at about **[ ]** and Figure 3-795 showed that the exit void fraction never reached a negligible value at **[ ]**. Thus, the actual flow rate (and actual N_{FR}) was less than used in the correlations for larger Φ and larger actual N_{FR} but approached the correct values at smaller Φ and smaller actual N_{FR}.

This ramp-up was neglected in the correlations which meant that the N_{FR} used to correlate the results did not correspond to the actual average N_{FR} obtained during the tests. This inconsistency is acceptable since a plant pump startup transient was simulated by the Purdue tests and the correlations were acceptably correlated with the data.

The planned upper horizontal pipe void fraction, Φ, and planned long-term Froude number, N_{FR}, differed from the values obtained during the Purdue tests due to deviation from the planned flow rate although the planned values were often used when describing the data. These differences are illustrated in Figure 12. The maximum error is in Φ and is less than 30%. This error is not significant and is acceptable.

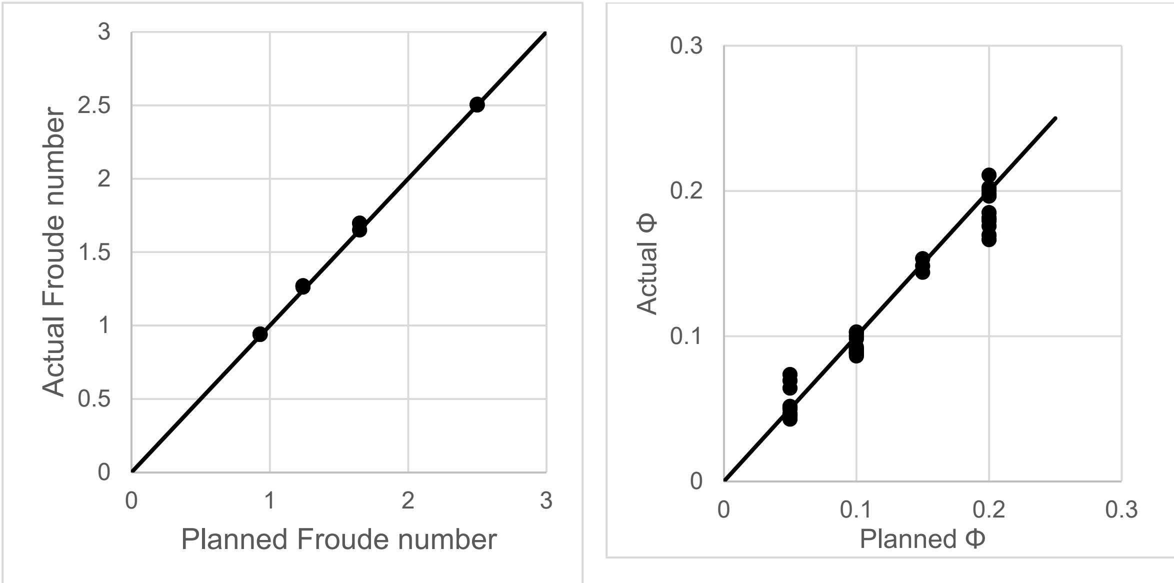

Figure 12 Planned Froude number and Planned Initial Void Fraction

The general suction pipe configuration addressed by the WCAP-17271 methodology was provided by the illustration of generic suction piping typical of PWRs that was provided in SE Section 1.8. As discussed in SE Section 1.8, the WCAP-17271 correlations provide an estimate of gas holdup at elbows in reducing the void fraction at the pump inlet. However, WCAP-17271 does not provide detailed guidance for addressing features of complex piping systems such as tees, offtakes, multiple header connections, and specific pump inlet geometries as identified in the NRC NEI 09-10 SE.

The WCAP-17271 correlations are discussed further in SE Section 3.3.

3.2.4 TR Section 3.4, Gas Transport Methodologies

The gas transport methods were developed to predict β at a pump inlet based on the gas volume at an upstream accumulation location. These are documented in WCAP-17276 (W, January 2011) and WCAP-17271 (W, October 2010) and are described in SE Section 1.4.

WCAP-17276 presents a simplistic modeling approach that is relatively easy to use. It does not account for gas hold-up at piping components nor does it address the limitations and conditions identified in the NRC SE on NEI 09-10 that are identified in SE Section 1.7. WCAP-17276 is discussed further in SE Section 3.4.

The WCAP-17271 methodology is based on testing at Purdue University for $N_{FR} \geq 0.93$. The modeling approach is to average parameters over the time it takes for the gas to move past an observation location and into a pump. This effectively starts with the pump void acceptance criteria and is followed by correlations that utilize averaged parameter values.

A key parameter is the change in volumetric flux ratio, Δβ, that occurs with flow through the elbow at the bottom of a DC. This is addressed in the Purdue tests by the difference in β between AIMP4 and PW4. The value at the bottom of the DC and hence at the entrance to the lower elbow is obtained by a linear extrapolation of DC values based on the assumption that DC pressure variation is linear. The value at PW4 is assumed to be equal to the elbow exit value to be representative of the region downstream of the kinematic shock in the lower horizontal pipe. This assumes the flow entering a pump is located far enough away from the elbow so that a kinematic shock, if it occurs, will be located upstream of the pump and it neglects the small pressure drop that occurs between the elbow exit and PW4. The TR description of flow behavior downstream of the elbow is acceptable.

3.3 TR Section 4, WCAP-17271 Application

The TR states that correlation equations were obtained from WCAP-17271 (W, October 2010) and it reproduced the equations with some nomenclature changes. The WCAP-17271 correlations were developed from Purdue test facility data and addressed two phenomena:

(1) An initially stagnant gas volume upstream of a vertical DC is entrained into the fluid stream through the formation of a kinematic shock in the top part of the DC. This is modeled by the flow initialization correlation. The purpose of the flow initiation correlation is to determine the average gas volumetric flux at the kinematic shock interface and the time it takes for the liquid flow to completely entrain the gas volume.

(2) Gas is held-up by the DC vertical-to-lower horizontal elbow so that it takes longer for gas to exit the elbow than it takes for gas to enter the elbow. This is modeled by the elbow hold-up correlation.

The TR states that the models are only applicable if a vertical DC exists between a gas accumulation location and a pump inlet and the DC must be large enough so that homogeneous bubbly flow is achieved within the DC. A minimum DC length that is consistent with this statement is provided by L_R as determined by TR Eq. 5-6.

The first step in assessing the effect of gas accumulation at a high point is to address if the flow rate will cause the gas to move. This is accomplished by calculating N_{FR} in Eq.1 and referencing Table 1. This is not addressed in the TR, but the TR assumes the gas will move which is conservative.

TR Section 4 is acceptable as an introduction to the WCAP-17271 and the TR correlations.

3.3.1 TR Section 4.1, Flow Initialization Correlation

The purpose of the flow initialization correlation is to determine the average gas volumetric flux at the exit of the kinematic shock interface at L_R and the time it takes for the liquid flow to completely entrain the gas volume, Δt_{init}. The model requires that a DC exists between the gas accumulation location and the pump. The model is provided in two forms:

(1) the average gas volumetric flux at the exit of the kinematic shock is provided as a function of the initial gas volume, mixture velocity, pipe area, and fluid properties, and

(2) the flow initialization time, the time to remove the initial gas volume, is provided as a function of the initial gas volume, mixture velocity, pipe area, and fluid properties.

The first correlation assumes the top horizontal header initial gas volume has instantaneously moved into the top of the vertical DC at 100% void fraction, an assumption found to be acceptable. The DC length that is initially completely voided is given by TR Eq. 4-2. V_i is based on the pressure that exists at the top of the vertical DC when the transport process is initiated. If the static pressure changes in the suction piping at initiation of the transport process due to a change in the suction source, as shown in TR Eq. 4-2, the gas volume must be adjusted using the ideal gas law to the pressure that exists once flow has started. This is acceptable provided the pipe diameter is constant since the volume is simply the length expressed as the initial volume divided by the pipe area.

The DC length must be at least as long as $L_{S,id}$ or the correlation cannot be used since the model depends on a DC where the waterfall impacts on water at the lowest completely voided level.

During the Purdue tests, the water flow rate was measured in the water supply to the top header before air was entrained into the mixture and it was assumed that this was the mixture flow rate since the gas flow rate is small downstream of the upper horizontal pipe. This is consistent with assuming that the mixture flow rate is not a function of position in the test section and u_{mix} represents the average mixture velocity over the pipe cross-sectional flow area throughout the test section. This assumption is valid only if the gas is not undergoing significant pressure changes during the transport process. The TR acknowledged that during the flow initialization process the actual process deviated from the assumed process due to gas expansion as the test was initiated. This was acceptably addressed by taking the initial volume in the upper DC as the volume that resulted after the expansion.

WCAP-17271 Section 9.5 addressed differences between the 8 inch and other Purdue test results. Purdue and W believe the Purdue six-inch horizontal piping may have been tilted so that the elevation at one end of the upper horizontal pipe differed from the elevation of the other end. The effect on the actual φ is less for larger φ. Consequently, the 0.05 initial void fraction cases were not used in a scaling analysis. In light of this observation, care must be taken in using the Purdue six-inch test results since the effect may have resulted in an initial void fraction that was less than believed.

During the Purdue tests, the liquid volumetric flow rate was measured in the water supply to the top horizontal header before air was entrained into the mixture. No volumetric flow rates were measured in the test sections that contained both gas and liquid. After the initial transient startup of a test to simulate pump start-up, the liquid flow rate was maintained constant. Mixture volumetric flow rate, Q_{mix}, was considered the same as the liquid volumetric flow rate at the entrance to the upper horizontal pipe and was considered constant throughout the test sections. Therefore, the liquid N_{FR} is assumed to be identical to the mixture-based N_{FR} and the mixture velocity, u_{mix}, is assumed to be equal to the liquid velocity, u_ℓ.

u_{mix} is the average mixture velocity over the pipe cross-sectional flow area throughout the test section and was assumed to be constant during a test. Therefore, the mixture volumetric flow rate, Q_{mix}, was also assumed to be constant. These assumptions are valid if the gas pressure and liquid flow rate into the test section are constant. However, a sudden pressure decrease occurred in the Purdue tests when tests were initiated, and the corresponding increased void volume was used when developing the correlations. Examination of the test data established that this modeling approach is acceptable when the initial conditions are taken as those that exist after the initial pressure decrease.

The flow initialization time, the time to completely remove the initial gas volume from the bottom of the shock in the DC, is provided by TR Eq. 4-1.

The TR (W, December 31, 2015) and WCAP-17271-P (W, October 2010) are inconsistent in using L_S, the DC length where homogeneous bubbly flow is established, and $L_{S,id}$, the DC length that corresponds to the length required to hold the initial gas volume that W refers to as the ideal DC length. TR Eq. 4-1 and WCAP-17271-P Eq. 8-5, among others, incorrectly include L_S for the ideal DC length. Such use of L_S is inconsistent with its definition in TR Eq. 5-6, which provides the DC length that will result in homogeneous bubbly flow. The NRC staff has rewritten TR Eq. 4-1 to use $L_{S,id}$, consistent with the actual use in, for example, TR Section 11.1.9.2. The NRC staff uses L_R for the DC length required to realize homogeneous bubbly flow.

The TR expressed the Weber number, W_e, by TR Eq. 4-4. WCAP-17271-P used L_S in place of $L_{S,id}$ but the meaning of L_S in that usage was $L_{S,id}$. The use of L_S in place of $L_{S,id}$ in TR Eq. 4-4 is inconsistent with the definition of W_e but this use was established to acceptably describe the phenomena and it is therefore acceptable.

TR Eq. 4-3, the second form of the flow initialization model, provides the average gas volumetric flux ratio[10], $\beta_{R,out}$, over the initialization process. $\beta_{R,out}$ is the average gas volumetric flux at the kinematic shock exit at the bottom of the void in the DC where homogeneous bubbly flow is obtained. Hence, the flow initialization model covers: (1) the DC length to the bottom of the region affected by the waterfall and (2) the time for the void to be eliminated from the DC. The model is acceptable.

3.3.2 TR Section 4.2, Elbow Hold-Up Correlation

The TR assumed the DC static pressure would vary linearly from the average pressure in the top header over the transport interval to the average pressure in the bottom header over the transport interval. The linear pressure assumption was used in WCAP-17271-P Volume 1 Table 9. Comparison of the WCAP-17271-P Table 9 values to the Purdue eight inch test information showed the maximum error was 17%. This error is small in comparison to errors that often apply to application of the Purdue test results. The linear pressure assumption is acceptable.

Therefore, the gas volumetric flux at the entrance to an elbow below a DC can be acceptably described by TR Eq. 4-8.

TR Eq. 5-6 requires iteration to obtain the totally voided length plus the length that is affected by water falling through the void, L_R. Once L_R is calculated, $P_{R,out}$ can be calculated using the assumption that pressure varies linearly from the DC top to the bottom.

It is often desirable to determine V_g for an existing piping configuration. In this case, the rewrite of TR Eq. 5-6 to obtain TR Eq. 6-1 is convenient. Note that L_R is the length of a DC that determines the maximum allowable gas volume that would result in homogeneous bubbly flow at the DC exit and V_g is the volume at L_R. To obtain the high point gas volume, V_g must be multiplied by the pressure ratio at the L_R position in the DC to the gas accumulation location to account for the pressure change.

With $\beta_{el,in}$ at the elbow inlet determined by TR Eq. 4-8, $\beta_{el,out}$ at the elbow outlet can be determined by TR Eq. 4-6 where $\Delta t_{el,in}$ is the time fluid is entering the elbow from TR Eq. 4-1 and the nomenclature has been changed from Δt_{init}.

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[10] The TR incorrectly uses “flow ratio” in place of “flux ratio.”

This is the lower elbow holdup correlation. It allows the user to calculate the gas volumetric flux in a horizontal pipe downstream of an elbow based on the gas volumetric flux at the elbow inlet, the time over which gas enters the elbow, and N_{FR}. The correlation best fits the Purdue information if a sufficient length of lower horizontal pipe is provided to include a shock that returns flow to close to a water-solid condition. The correlation is not a good representation of behavior close to the elbow exit, a weakness in the methodology since, if the shock actually occurs near the elbow, the actual $\beta_{el,out}$ will be larger than predicted by TR Eq. 4-6. Since the gas holds up at the elbow, the gas transport time will increase at the elbow as provided by TR Eq.4-9.

The Purdue test configurations do not provide information at the entrance to and exit from the elbow. The NRC staff has used the AIMP4 and PW4 test information to represent the elbow holdup test change in β. AIMP4 is located near the bottom of the DC and PW4 is the measurement location that is downstream of the shock that returns flow to close to a water-solid condition in the lower horizontal pipe. The $\Delta\beta$ obtained from this test information is compared to the TR Eq. 4-6 correlation in Figure 13 where the solid line represents agreement between the test information and the correlation.

Figure 13 Approximate Elbow Holdup $\Delta\beta$ from Purdue Tests

Most of the correlation points are smaller than the “data,” supporting a conclusion that the elbow correlation generally bounds the Purdue “data” downstream of the shock.

If there are multiple DCs, the gas volume should be assumed to be located immediately upstream of the first DC between the actual accumulation location and the pump inlet which meets the TR Eq. 5-6 length requirement. If multiple vertical to horizontal elbows exist between the accumulation location and the pump inlet the elbow hold-up correlation can be applied at each vertical to horizontal elbow starting at the first DC that meets the TR Eq. 5-6 length requirement and including the downstream DCs provided the intervening piping does not cause a significant deviation from homogeneous bubbly flow. The W test facility provides data that illustrate this condition for three elbows as shown in Figure 14 where the line represents a straight line fit to the points.

Figure 14 Comparison of Calculated and Experimental Δt's

The calculated values are conservative since they are smaller than the experimental values. (A smaller Δt results in a larger β since the same amount of gas must pass in less time.)

The elbows used in the test are long sweep elbows with a radius to diameter ratio of 2.5. The TR typically does not identify the elbow radius to diameter ratio yet the NRC staff expects this will have an effect on the flow profile. The conservatism illustrated in Figure 14 will tend to compensate for this omission.

The TR states that successive application of the elbow hold-up model does not require that the gas remain in the dispersed bubbly flow regime during the entire transport process from the outlet of the first vertical-to-horizontal elbow to the pump suction. Even if the gas flow were to separate from the liquid flow and stratify in a horizontal pipe, the gas volumetric flux ratio will continuously decrease during the transport process to the pump unless a mechanism exists for gas to accumulate over time at a piping component and subsequently surge downstream. This statement is acceptable because minor changes in the flow profile are not judged to significantly affect elbow gas holdup.

The outlet transport time from the upstream elbow is assumed to be the inlet transport time to the downstream elbow. The inlet gas volumetric flux at the downstream elbow is assumed to be the outlet gas volumetric flux at the upstream elbow corrected by the ratio of static pressures.

The test information supports a conclusion that the elbow holdup correlation is acceptable for operability evaluations.

3.3.3 TR Section 4.3 WCAP-17271 Correlation Application Method

The flow initialization and elbow hold-up correlations are applied as discussed above subject to the identified limitations where the TR clarifies use of TR Eqs. 4-6 and 4-9 to predict $\beta_{e\ell,out}$ and $\Delta t_{e\ell,out}$ by stating that "additional limitations on the usage of this methodology are needed." TR

Sections 6.1 through 6.3 are referenced regarding usage limitations. The NRC staff assessments are provided in the discussion of those sections.

The TR identifies that the final outlet transport time must be compared to the TR Table 3-1 or Table 3-2 acceptance criteria to determine if the transient criteria or the steady-state criteria are applicable to pump operation. This is acceptable.

3.3.4 TR Section 4.4, WCAP-17271 Correlation Uncertainty Considerations

The TR identifies model prediction errors that were not identified in WCAP-17271, such as the initial transient flow rate, the experimental transit time associated with the Purdue tests, the linear DC pressure distribution, and the initial Φ and N_{FR} used to describe the Purdue test results. The NRC staff relies upon judgement and including safety factors when applying the correlations. It does not rely upon uncertainty calculations since they do not cover several of the variables that affect the methodologies.

The TR refers to TR Section 8 for recommendations for the treatment of uncertainty for an operability assessment. This is addressed in SE Section 3.6.

3.4 TR Section 5, Application of WCAP-17276 Simplified Equation

The TR gives the simplified equation as TR Eq. 5-1. The transition from vertically separated flow to bubbly flow is treated as a kinematic shock with the distance between the top of the DC and the bottom of the kinematic shock (including the length that is affected by the waterfall before homogeneous bubbly flow is obtained) determined by TR Eq. 5-6. The best fit for the transport time with respect to the Purdue data is stated to be provided by TR Eq. 5-7.

In practice, the first step in applying the simplified equation is to obtain pump-specific allowable β_p and Δt_p from TR Table 3-1. This provides the maximum allowable V_g. Then a new Δt is obtained using TR Eq. 5-7. If the transport time predicted by TR Eq. 5-7 is less that the allowable transport time in the TR Table 3-1 pump acceptance criteria, then TR Eq. 5-7 is used for Δt_p in TR Eq. 5-1.

The transport time was not measured during the Purdue tests but was calculated by a process that the NRC staff found acceptable. Therefore, Δt from the Purdue tests, and any Purdue test variables such as β that are calculated from Δt, cannot be assumed to be experimentally determined data as implied in many of the graphs in WCAP-17271 Volume 2 that provide β "data."

The simplified equation assumes (1) the waterfall model and (2) homogenous flow with corrections for system static pressure variations.

The TR listed four limitations that were specified in WCAP-17276 Section 3.6 on use of the simplified equation that are listed and addressed in SE Section 1.7.

The NRC's NEI 09-10 SE stated that the simplified equation is acceptable subject to seven identified limitations. These limitations and the present NRC staff assessment are discussed in SE Section 1.7.

3.5 TR Section 6, Gas Transport Analysis Methodology Limitations

The TR stated that WCAP-17271 does not consider piping system features such as elbows and offtakes. Further, no consideration for the pump inlet flow regime is stated to be provided. WCAP-17276 is stated to account for some complex piping features and the pump inlet flow regime but the NEI-09-10 SE is stated to have provided limitations and conditions.

The WCAP-17271 and WCAP-17276 methodologies that are referenced in the TR are based on Purdue tests that used water without additives. There is no mention of use of additives in plant piping. Licensees using the methodologies should clarify what additives are used in their piping and the potential impact on the methodologies.

Existing plant configurations differ from the Purdue test configurations due to presence of such items as thermowells, valves, orifices, and tees. Methodology limitations are discussed in more detail in SE Sections 3.5.1 through 3.6.

3.5.1 TR Section 6.1, NEI-09-10 Safety Evaluation Limitations

The TR listed six items that the NEI-09-10 SE identified were acceptable with qualifications regarding individual licensee responsibilities to assure homogeneous bubbly flow at the pump entrance and that the average void fraction meets acceptance criteria defined in NEI-09-10:

(1) If a vertical DC exists, verify that it is large enough to assure homogeneous bubbly flow at the exit if it is to be credited for providing a homogeneous exit flow.

(2) Identify if a piping configuration can exist that may result in a transition from a dispersed bubbly flow regime to a separated flow at a pump.

(3) If $N_{FR} > 2.5$, then address the potential of gas to be transported as a slug.

(4) If $N_{FR} \leq 2.5$ and flow from a vertical DC is directly to the top of a pump, then licensees may assume that bubbly flow will exist at the pump if the DC volume is at least four times as large as the gas volume that existed above the DC.

(5) If a horizontal pipe connects between the bottom of a DC and a pump entrance, a methodology should be applied that has a multi-dimensional two-phase capability that has been verified by comparison to experimental data. A suitable safety factor should be added.

(6) Flow stratification in horizontal pipes can lead to an accumulation of gas, such as in an off-take or tee, and a subsequent instability can lead to a large surge in downstream gas.

The TR closed TR Section 6.1 by stating that the remainder of the TR would provide guidance for assuring that the bubbly flow limitation is met when applying the WCAP-17271 correlations to determine gas void acceptance criteria considering the listed Items 1 - 6.

The NEI-09-10 SE also stated that:

(1) Pump miniflow requirements should be met so that pump cooling is ensured, and

(2) Head degradation should be addressed if the pump head, H, does not satisfy:

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

The NEI-09-10 SE stated that satisfying the above equation would reasonably ensure that operability requirements will be met if the steady state pump entrance criteria in TR Table 3-1 are met.

The NEI-09-10 SE added that the above criteria may be applied without additional conservatism when the TR Table 3-1 criteria are met but, when using analysis methodologies, an acceptable safety factor is likely necessary when predicting the pump entrance void fraction.

Finally, the NEI-09-10 SE stated that it is the licensee's responsibility to reasonably and acceptably address the relevant gas transport phenomena. This includes any configurations that may result in a transition from bubbly flow to either stratified or slug flow including:

- Kinematic shock at vertical plane elbows.
- Vortexing at off-takes.
- Phase separation at tees.
- Flow stratification in horizontal pipes.
- Pump entrance phenomena / piping entrance configuration.

3.5.2 TR Section 6.2, NEI 09-10 Guidance Regarding Limitations

The TR provided a list from the NEI 09-10 SE Section titled "Gas voids and transport in the pump suction piping**"** that identified possible approaches for addressing configuration limitations. The TR list of the NEI 09-10 SE **items are bolded**, and the NRC staff findings are as follows:

- **Appropriately scaled tests could be used to demonstrate operability.** The NRC staff finds this acceptable as discussed in SE Section 3.1.

- **Configurations that involve 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 can be treated by:**

    - **Limiting the gas volume to an appropriate fraction of the horizontal pipe volume between elbow and reducer, or**

    - **Verifying that in all situations of interest the liquid flow rate is sufficient to maintain the gas in a dispersed flow regime.**

  The NRC staff will accept existing methodologies as discussed in this SE and reasonable judgment in addressing this configuration.

- **Configurations which include pump suction headers with off-takes / tees can be treated by basing the allowable gas volume in the header on the limiting gas volume allowed by each off-take.** This is consistent and is acceptable to the staff.

- **The case of a vertical upward intake RHR pump where flow from a horizontal pipe passes through an elbow and short vertical pipe before entering the pump can be**

treated by ensuring the liquid flow rate is sufficient to maintain the gas in a dispersed flow regime. This is acceptable.

- **For the case of HPI pumps which take suction direct from a vertical pipe, the factor of four criterion must be applied.** TR Eq. 5-6 is acceptable for predicting DC length. The factor of four criterion for DC size is also acceptable.

3.5.3 TR Section 6.3, Technical Guidance for Addressing Limitations

TR Section 6.3 addresses limitations and conditions associated with WCAP-17271 and WCAP-17276. If the listed mechanisms do not exist, the TR states that the pump inlet gas flux will continually decrease as gas is moved from the accumulation location to the pump inlet.

The NRC staff finds this acceptable as the listed mechanisms all affect gas flow toward a pump. If they do not exist, the remaining mechanism is homogeneous bubbly flow from the bottom of the DC. This will decrease as gas is removed from the DC since the rate that gas falls from the void at the top of the DC will decrease with time.

3.5.3.1 TR Section 6.3.1, Vertical Down-Comer

The TR repeats that a vertical DC is a requirement to apply the methodology of WCAP-17271 and WCAP-17276. As discussed in SE Section 3.2.3.3, the DC length required to obtain the length that is affected by water falling through the void is acceptably described by TR Eq. 5-6. Homogeneous bubbly downward flow is achieved at this distance from the top of the DC. The TR also states that TR Section 7 is applicable if a DC is not present.

3.5.3.2 TR Section 6.3.2, Pipe Diameter

The TR states that the WCAP-17271 correlations should not be used for pipe diameters smaller than four inches. This is generally acceptable and deviations are acceptable when justified. The TR states that TR Section 7 guidance is applicable for smaller pipe diameters. This is addressed in SE Section 3.6.

The NRC staff stated in the NEI 09-10 SE that the correlations from the scaling analysis are acceptable for pipe diameters ranging from 4 inches to 30 inches. The TR states that 30 inches is not an upper limit. A larger upper limit is acceptable when justified. Further, the upper limit is applicable to use of the correlations and is not limited to scaling.

3.5.3.3 TR Section 6.3.3, Initial Gas Volume and Void Fraction

The TR states that the flow initialization correlation is applicable as long as the DC is large enough to accommodate the kinematic shock. This is acceptable when the kinematic shock is considered to include the DC section that is affected by the waterfall. This is achieved when the DC length is at least as long as predicted by TR Eq. 5-6.

3.5.3.4 TR Section 6.3.4, Down-Comer Volume

The TR recommends that TR Eq. 5-6 be used to predict the required length of the kinematic shock and hence the minimum DC length and provides information to support that recommendation. This is acceptable provided the DC length is sufficient for TR Eq. 5-6 to reasonably represent the behavior.

The TR also supports the rewrite of TR Eq. 5-6 to obtain TR Eq. 6-1 that provides the allowable high point gas volume for a known DC length. This is acceptable provided the DC length is sufficient for TR Eq. 5-6 to reasonably represent the behavior.

3.5.3.5 TR Section 6.3.5, Horizontal Pump Inlet

The NEI 09-10 SE (NEI/NRC, April 2013) stated that phenomena in the region from the lower end of a DC to immediately downstream of the vertical to horizontal elbow was not well understood. The purpose of TR Section 6.3.5 is to address this lack of understanding.

The Purdue tests showed that gas could accumulate downstream of a DC exit and that a kinematic shock may occur downstream of the vertical to horizontal elbow that is connected to the DC exit with a small void fraction or homogeneous bubbly flow downstream of the shock. This condition is illustrated by the Purdue tests where kinematic shocks were observed at the outlet of the vertical-to-horizontal elbow during the following test conditions (W, December 31, 2015):

[

]

Location of the shock could not be determined from the Purdue data since the void fraction at the first measurement downstream of the lower elbow was often large and further downstream of the elbow it was small. This is shown, for example, in WCAP-17271 Volume 1, reproduced as Figure 15.

Figure 15 Void Fractions near Bottom Horizontal Kinematic Shock

The top line is PW3, the closest void fraction measurement to the DC in the lower horizontal pipe, located 2.58 ft downstream of the DC bottom. The lower line is PW4 where the measurement is 13.08 ft downstream from the DC.

The only conclusion that could be reached was that a shock occurred between the two, measurement locations in the lower horizontal pipe. The concern was that pump operability could be jeopardized if the pump was located upstream of the shock in the lower horizontal pipe. The behavior was stated to be characterized by a large void fraction upstream of the shock and a low void fraction with dispersed bubbly flow downstream of the shock (W, October 2010).

3.5.3.5.1 TR Section 6.3.5.1, Flow Separation

At pump and flow initiation the DC region below the voided elevation, the elbow between the lower end of the DC and the lower horizontal pipe, and the lower horizontal pipe, will be water solid. Gas must accumulate near the entrance to the lower horizontal pipe for a kinematic shock to occur downstream of the gas accumulation location.

Tests were conducted at the W thermal hydraulic laboratory to develop a better understanding of the separation phenomena. Gas was injected through air flow meter (AFM) Location 1 in TR Figure A-1 or SE Figure 2. The initial air volumetric flow rate was about 5% of the water flow rate. Water flow rate was then held constant and air flow rate was increased until gas was observed to accumulate at the exit from the downstream elbow that was connected to the DC. This was assumed to correspond to initiation of a kinematic shock. This was also assumed to indicate that the DC and elbow could accumulate no additional air and air entering the DC would accumulate in the lower horizontal pipe. Flow rates were then held constant until the separated region extended to the horizontal downstream elbow located at the left end of the pipe illustrated in SE Figure 2. Then air injection was stopped and the hydraulic jump entrained the air away. Data were collected from the time air injection was stopped until all air was removed from the lower horizontal pipe. The test was completed once all air had been entrained away from the lower horizontal pipe and the average air entrainment rate was then determined. The average water flow rates for the W six-inch pipe diameter tests are provided in Table 3.

Table 3 Average W Test Data

Water Flow Rate, gpm	°F
309.5333	65.5
355.86	65.38
406.6333	64.83333
453.4333	63.73333
504.8333	63.93333
556.4667	63.66667
607.8667	63.66667
655.8667	64.3
719.0333	66.13333

Now assume there is a gas void at the top of a DC. The void will grow if the gas entry rate at the top of the DC exceeds the removal rate due to water falling through the void and impacting on water below the void. Consequently, if gas is entering the top of the DC at a rate less than the removal rate at the bottom of the DC, gas will not accumulate. (The smallest flow rate from Table 5 is 309.5 gpm which results is N_{FR} = 0.85, large enough to carry bubbles from the bottom of the DC.) In the W test, as the gas injection rate was increased, conditions in the upper DC reached a point where no additional gas could accumulate in the DC or the lower elbow and an increased gas flow rate would occur downstream. This is the time when gas injection was turned off in the W tests, resulting in the void volume decreasing since accumulated gas would continue to be removed until the voids were eliminated.

TR Figure 6-10 provides a comparison of the Purdue 8 inch test and the W β_{ave} values. $\beta_{ave} \approx$ **[ ]** represents the Purdue test information that covers whether or not a kinematic shock will occur in the lower horizontal pipe. (A smaller value indicates that there is insufficient gas for a shock to exist.) There is little agreement between the W dynamic venting values and the Purdue kinematic shock values. The TR stated that this is due to the Purdue tests being transient tests and the gas transport is non-linear. The peak gas transport flux at the exit from the region affected by the waterfall occurs at the start of the test and the flux decays with time. Therefore, the peak flux at the start of the test is what initiates formation of the kinematic shock and as long as the gas influx is greater than the entrainment rate at the shock exit and the gas transport through the elbow, the shock will continue to grow.

The same information is provided in TR Figure 6-11 for β_{max}.

TR Figures 6-10 and 6-11 illustrate that β_{max} provides better agreement between the W and Purdue results than β_{ave}. However, the Purdue tests appear to provide a β_{max} that is independent of N_{FR} in contrast to the W values that show an increase in β_{max} with increasing $N_{FR.}$

The β's have different meanings. β_{max} is the parameter that initiates a shock in the lower horizontal pipe. β_{ave} is the term computed by the WCAP-17271 methodology. The TR described how the W β_{ave} was determined using the measured air flow rate required to form the shock and the measured water flow rate. This was correlated as illustrated in TR Figure 6-9 that shows the required average β to form a kinematic shock in the lower horizontal pipe as a function of N_{FR}. The information was stated to be correlated by TR Eq. 6-6 for $1 \le N_{FR} \le 1.9$ with an R-squared value of 0.99. This correlation was assumed to hold in the TR for $1 \le N_{FR} \le 2.25$ with $\beta_{min\ reqd} = 0.188$ for $N_{FR} > 2.25$. (According to TR Eq. 6-6, a β equal to or larger than indicated will result in a kinematic shock.) The NRC staff estimated β_{ave} from TR Figure 6-9 and used Excel to develop Figure 16.

Figure 16 Conditions for Kinematic Shock in W 6 Inch Elbow Tests

The solid line is the NRC staff straight line fit to all of the β_{ave}. The dot line is TR Eq. 6-6 which is equal to the NRC staff's straight line fit to the β when the $N_{FR} = 1$ and $N_{FR} = 1.9$ points are omitted.

Figure 17 Conditions for Kinematic Shock in 6 Inch Elbow Tests

The cubic equation in Figure 17 is given by:

$$\beta_{avg} = 0.5929 – 1.2802\ N_{FR} + 0.9518\ N_{FR}^2 – 0.2132\ N_{FR}^3 \qquad (5)$$

The data obtained during the 2018 tests conducted by WEC and the associated calculation results are provided in Table 2 of LTR-SEE-18-202. The tests determined that the minimum required air volumetric flow ratio required to form a kinematic shock in the lower horizontal pipe at NFR = 2.25 is [$0.28 \leq \beta \leq 0.32$]. These calculated values are much greater than the value of β = [0.188] that was determined using PWROG-15060-P Equation 6-6 with an NFR = 2.25. Based on the 2018 WEWC test data the staff can have reasonable confidence that the assumption of a linear increase in the minimum required air volumetric flow ratio with a Froude number is a conservative assumption. The 2018 WEC tests confirm that the approach that was used in PWROG-15060-P was reasonable: the minimum required gas volumetric flow ratio varies linearly with Froude number between $1.0 \leq NFR \leq 2.25$, and remains constant for NFR > 2.25.

TR Eq. 6-9 provided a comparison of β_{avg} and β_{max}. TR Figure 6-11 provided a curve fit to the W data for β_{max} = **[ ]**. Using TR Eq. 6-9 yields β_{avg} = **[ ]**. Assuming this describes the W β_{avg} behavior, this is added to TR Figure 6-10 to obtain the dash line in Figure 18.

Figure 18 Comparison of TR Eq. 6-9 Application to W Data

TR Section 6.3.5.1.2 presents the TR Eq. 6-7 correlation of the maximum gas volumetric flux at the kinematic shock outlet where L_R is determined from TR Eq. 5-6 and d is the pipe diameter in inches.

TR Eq. 6-7 is compared to the Purdue information in TR Figure 6-12 where L_R was calculated by TR Eq. 5-6, β information was excluded for $L_R / D > 16.7$ which is stated to correspond to **[ ]**, and information for $N_{FR} < 0.93$ was excluded. Note D is in feet, not inches.

The β_{max} information is scattered and the TR stated that $R^2 = 0.6321$ which indicates that TR Eq. 6-7 has a relatively large uncertainty for predicting β_{max}. However, the comparison indicates that TR Eq. 6-7 is generally representative of the average of the information. TR Eq. 6-7 is acceptable.

If a pump entrance is located in the gas accumulation region immediately downstream of a DC vertical to horizontal exit elbow and is removing gas as it accumulates downstream of the elbow due to gas exiting the elbow, it is questionable if a void or kinematic shock will form downstream of the elbow exit. If a pump is not removing gas and the DC length meets the TR Eq. 5-6 requirement, the average mixture flow rate can be determined at the DC exit. This does not, however, ensure that the mixture will be homogeneous when it leaves the elbow since centrifugal force will concentrate the gas on the inside of the elbow. For example, if a pump suction is on the bottom of the horizontal pipe the pump will experience a smaller void fraction than if located at the top and the void may continue to increase as a result. The TR is focused on average flow characteristics and does not identify this behavior.

It is acceptable to not address the case where a pump is removing gas as it leaves the elbow at the DC exit because neglecting the effect will result in over-predicting gas movement toward the affected pump. However, when a pump is located close to the elbow exit and is removing gas at the rate that gas is leaving the elbow, the NRC staff will accept an assumption that a kinematic jump will not occur in the lower horizontal pipe provided the rate at which gas enters the pump meets the TR Tables 3-1 or 3-2 criteria.

In discussing TR Figure 6-12, the TR statement that β_{max} is less than **[ ]** is incorrect. This is shown by observing that many of the TR Figure 6-12 points and the TR Eq. 6-7 predictions are above **[ ]**.

The TR states that:

(1) The WCAP-17271 or WCAP-17276 methodology can be used to predict β_{avg} at the pump inlet.

(2) TR Eq. 6-9 can be used to predict β_{max} at the pump inlet for comparison to the allowable limit that is provided by TR Eq. 6-6.

(3) If the gas accumulation location is immediately upstream of the DC supplying the pump inlet then TR Eq. 5-6 should be used to predict the kinematic shock length and TR Eq. 6-7 should be used to predict β_{max} for comparison with the TR Eq. 6-6 limit.

The NRC staff TR Section 6.3.5 conclusions are provided in SE Section 3.5.3.5.3, below.

3.5.3.5.2 TR Section 6.3.5.2 Piping Length with Flow Separation at Elbow

The TR states that it is necessary to demonstrate that either a kinematic shock does not form or that the length of the lower horizontal pipe is long enough to contain the kinematic shock without allowing it reach the pump inlet. If a kinematic shock should form in the lower horizontal pipe, TR Section 6.3.5.2 is stated to provide information to estimate the length of the shock.

TR Figure 6-16 shows the maximum void fraction in the kinematic shock region where a kinematic shock occurred in the Purdue tests. The W test α_{max} are consistently smaller than the Purdue data and provide an acceptable lower bound.

From TR Figure A-1 and SE Figure 2, RIMP8 is located 1.0 ft from the downstream end of the elbow at the discharge end of the DC and RIMP9 is 6.6875 ft downstream of RIMP8. (RIMP has the same meaning as VM.) From SE Figure 2, the elbow will add 1.667 ft to the RIMP 8 separation distance from the elbow so that the effective separation distance is 2.667 ft. RIMP9 is located 6.6875 + 2.667 = 9.355 ft from the elbow.

The TR stated that the measured α_{max} at RIMP9 will be used as the basis for the kinematic shock depth for determining the required pump inlet piping length. The straight line fit to the RIMP9 data, as shown in TR Figure 6-16, is given by TR Eq. 6-20. The maximum allowable gas volume follows from TR Eq. 6-21 where V is the volume of the horizontal pump inlet pipe. When $V_{gas,\,max}$ is corrected for the pressure difference between the upper and lower horizontal pipes, it provides the $V_{gas,\,max}$ that must originally exist in the upper horizontal pipe for a shock to occur in the lower horizontal pipe. This use of RIMP9 as the basis for determining the required pump inlet piping length was stated to be conservative since a lower gas volume fraction requires a longer pipe length to accommodate the same gas volume.

In the Purdue eight inch tests, PW3 provided a void fraction measurement that was 2.75 ft from the DC centerline, PW4 was 13.25 ft from the DC centerline and, when a kinematic shock occurred, it occurred between the two measurement locations.

Since V = A L where A = pipe area and L = pipe length, the Purdue eight inch test volume is 0.3474 X 13.25 = 4.603 ft^3.

3.5.3.5.3 NRC Staff TR Section 6.3.5 Conclusions

The NRC staff concludes (1) TR Eq. 6-6 is acceptable for use, (2) no shock will form in the lower horizontal pipe if β_{avg} < **[ ]**, (3) TR provides a conservative method for predicting maximum shock length, (4) TR Eq. 6-7 is an acceptable description of void behavior when a safety factor is used to account for the β_{max} scatter in TR Figure 6-12.

3.5.3.6 TR Section 6.3.6 Horizontal Off-Takes

The mass flow rate is defined as G = ρ q / A where ρ = density, q = volumetric flow rate, and A = pipe flow area. Defining liquid mass flow rate as G_L, and gas mass flow rate as G_G, TR Eq. 6-24 provides β. The TR Figure 6-23 (Figure 19) flow regime map provided the gas mass flow rate, G_G, as a function of liquid mass flow rate, G_L. Approximate slug flow aspects are summarized in Table 4.

Table 4 Selected aspects of TR Figure 6-23

G_L lbs/(hr ft^2)	G_g lbs/(hr ft^2)	Description
1.25 X 10^5	10^3 - 10^4	Lower bound of slug flow
10^6	10^3 - 10^4	Upper bound of slug flow

TR Figure 6-23 (Figure 19) was reproduced from a Weisman report (Weisman, 1979). Weisman's test facility provided three glass pipe test sections of ~0.47 inches, 0.98 inches, and 2.00 inches diameter, each 20 ft long and containing a tee of the same diameter as the horizontal pipe. Gas was injected at one end of the test section. Observations were taken at the end of each pipe, at the middle, and approximately eight inches downstream of a horizontal tee where gas was injected. (The smallest section appeared to have some variation in diameter. Hence the approximate diameter.) Weisman stated that differences between the middle and end positions of the larger pipes were small. This indicates that the lengths were sufficient to approach fully developed flow with mixing provided by the tee.[11] Flow regime differences between the middle and end positions in the one inch pipe were slight.

Weisman's data were for pipe diameters from 0.5 to two inches and tee off takes were the same diameter in contrast to plant header configurations where the tee offtakes are often a smaller diameter than the header. The smallest pipe diameter included in the WCAP-17271 tests was four inches. WCAP-17271 indicates the maximum stable bubble size can be approximated as three inches and Purdue test data imply that some bubble diameter impacts occurred in four

[11] The pipe length to develop a flow regime and the length required to develop the flow distribution as a function of radial and angular distribution differ. The latter length was found to be roughly a hundred pipe diameters (Wermiel, June 7, 2004).

inch pipes. A three to four-inch pipe diameter limit can be considered the cutoff between large diameter and small diameter pipe behavior. Below this limit, stable, full diameter slug flow could exist. This raises the question of applicability of TR Figure 6-23 (Figure 19) to the pipe sizes of concern here. Further, the Purdue tests show that several flow regimes may occur in a horizontal pipe within a short distance downstream of a DC exit elbow.

Weisman mentioned that comparisons of determinations for one inch and five-inch pipes from other investigators provided conclusions that[12]:

(1) Annular flow begins at higher gas flow rates in the five-inch pipe.

(2) Intermittent and dispersed flow regions shift to higher liquid flow rates at larger pipe diameters.

Item 1 indicates that the TR Figure 6-23 (Figure 19) slug flow regime may extend to larger G_G as pipe diameter is increased.

Weisman discussed a number of flow regime correlations. All were a function of pipe diameter and none were judged to be appropriate for use here.

The TR cited an article in the AIChE Journal (Taitel, January 1976) that provided TR Figure 6-26. This is based on theoretical modeling and does not include data that may be necessary to address the changing impact of bubble size when moving between two-inch and four inch pipe diameters.

The transition between stratified and intermittent and between intermittent and dispersed bubble flow in TR Figure 6-26 for two-inch pipe is consistent with TR Figure 6-23 (Figure 19). If TR Figure 6-26 is correct, it indicates that as the pipe diameter increases from 2 inches to 12 inches, the stratified-intermittent transition at low gas flow rates and the intermittent-dispersed bubble transition increase. The TR concludes that if $N_{FR} \geq 1$, it is ensured that G_L remains above the transition value for stratified–intermittent flow and near the transition from intermittent –dispersed bubble flow. Since the off-take criteria will be applied well upstream of the pump suction, it is not necessary to ensure that the flow regime is in the dispersed bubble regime as long as the flow is sufficient to ensure that gas bubbles will not coalesce into a stratified flow regime that could result in vortex formation at the off-take.

A scale model test program of the Palo Verde Nuclear Generating Stations ECCS system was conducted. TR Figure 6-22 illustrates some of the behavior. The behavior would be different if the offtake pipe diameter were equal to the header diameter. However, N_{FR} equaled 0.66 upstream of the offtake and, if $N_{FR} \geq 1$, stratified flow is stated in the TR to not have occurred upstream of the offtake. Nevertheless, the larger header diameter and correspondingly smaller N_{FR} may be typical of existing plant configurations. The WCAP-17271 correlations apply when $N_{FR} \geq 1$ and are not applicable to headers where N_{FR} is significantly less than one.

There are several differences between the above information and the issues to be addressed here, including:

- Weisman's tests were with offtake pipe diameters that were the same as the header diameter.

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[12] No data was provided.

- Weisman's pipe diameters were substantially smaller that the pipes of concern here and were smaller than needed to be used to be consistent with the TR statement that the WCAP-17271 correlations should not be used for pipe diameters smaller than 4 inches.

- Weisman's tests provided steady state information in contrast to the transient conditions of concern here.

TR Figure 6-23 (Figure 19) provides insights for purposes of assessing operability. In light of the flexibility identified in SE Section 2 for assessing operability and the general conservatism in the calculations, the NRC staff accepts TR Figure 6-23 (Figure 19) as part of the TR's objective of defining "a means of applying the correlations in a manner which meets the limitations imposed by the" NRC's SE that addressed NEI 09-10. (NEI/NRC, April 2013). The long-term solution to closing the issue, as described in the NEI 09-10 SE, included the following:

- If a horizontal pipe connects between the bottom of a DC and a pump entrance, a methodology should be applied that has a multi-dimensional two-phase capability that has been verified by comparison to experimental data. Since phenomena in this region are not well understood, judgment may be a significant factor and a suitable safety factor should be added to predicted behavior to reasonably ensure the prediction encompasses actual behavior. Further, operating experience may be used.

- Horizontal pipes may introduce other concerns. For example, flow stratification in horizontal pipes can lead to an accumulation of gas, such as in an off-take or tee geometry. Once gas is accumulated, a subsequent instability or flow path change can lead to a large surge in gas downstream.

In all cases, it is the licensee's responsibility to reasonably and acceptably address the relevant gas transport phenomena.

TR Section 6.3.6 concludes with a statement of the criteria that will be used to treat off-takes from horizontal headers that are upstream of pump inlets that are consistent with use of WCAP-17271:

(1) $N_{FR} \geq 1$ in header
(2) $\beta \leq 0.25$ in header
(3) gas is moving with the liquid in a bubbly or incipient plug flow regime
(4) gas will not accumulate or stratify at a tee
(5) gas is entirely transported though the off-take in the flow direction being considered.

Criteria 1, 2, 3, and 5 are acceptable. Criterion 4 is acceptable except when there is flow through a horizontal tee with a stagnant vertically upward offtake. TR Figure 12-8 implements this methodology for determining if a horizontal offtake limits the allowable gas volume.

3.5.3.7 TR Section 6.3.7 Co-Current Slug Flow

The 4, 6, and 8 inch Purdue tests covered $0.6 \leq N_{FR} \leq \sim 2.5$. The 12 inch tests were limited to $0.6 \leq N_{FR} \leq 1.0$ due to pump limitations. WCAP-17271 indicates that co-current slugging was observed in the DC during some cases with the 6 and 8 inch tests at $N_{FR} = 2.5$. These slugs tended to rapidly break up, were unstable, and did not result in an increase in downstream gas flux for the geometries tested. However, since it was not possible to define the formation and stability of co-current slugging based on the collected data, an upper limit of N_{FR} = 2.5 was placed on the correlations.

The TR stated that many systems have flow rates which correspond to $N_{FR} \geq 2.5$. For pipe diameters 6 inches and greater, N_{FR} = 2.5 corresponds to a mass velocity greater than $2x10^6$ lb /hr /ft^2. The report then cited TR Figure 6-23 (Figure 19) that indicates that the mass velocity corresponds to the dispersed flow regime for a horizontal header; and therefore, a slug would tend to quickly break up in the horizontal header if it made it to the bottom of the vertical DC.

If a horizontal pipe is connected to the DC exit, there will be a vertical to horizontal elbow between the DC exit and the horizontal pipe. This elbow will tend to collect gas, an effect addressed by WCAP-17271 that provides a correlation for β_{out} versus β_{in} (TR Eq. 4-6). In addition, WCAP-17271 notes that the tendency for a kinematic shock to form increases with gas flux. These phenomenon act to break up a co-current gas slug. Therefore, if a vertical DC is followed by an elbow and a horizontal run (that is, the vertical DC does not go directly into a pump), the TR concludes that a co-current slug may be assumed to be broken up quickly.

The NRC staff reported in Section 3.5.3.5.3 that TR Figure 6-23 (Figure 19) was acceptable for applicability to operability determinations. The long-term solution to closing the issue, as described in the NEI 09-10 SE (NEI/NRC, April 2013), may require obtaining new experimental data.

3.6 TR Section 7 Guidance If Limitations Cannot Be Met

If TR Section 6 cannot be met, the TR states that the NRC-approved method described in NRC's SE Section 3.15.2.5 can be used. The TR provided TR Eq. 7-1 that correctly describes the NRC method. If this results in a gas volume that is too small, then the TR states that appropriately scaled testing is the preferred approach. This is acceptable.

3.7 TR Section 8 Treatment of Uncertainties

The TR states that WCAP-17271 provides flow initialization correlation and elbow hold-up correlation uncertainties with a 90 percent confidence and it continues with examples that illustrate that the uncertainties are not precise. Further examples exist, such as that Δt and β are not measured, the test flow rate differed from the flow rate used in the methodologies, and the WCAP-17271 correlations are based on average behavior as opposed to more accurate multi-dimensional transient flow. The NRC staff agrees with the TR that a precise determination of the overall uncertainty is unnecessary and that conservatisms in the evaluation method may be used.

3.7.1 TR Section 8.1 Pump Criteria

The purpose of analyzing pump suction piping is to establish that conditions at a pump entrance do not jeopardize operability. Typically, pumps take a short time to develop rated flow and, during this time, pipe flow rates may be too low to transport gas into the pumps. However, should gas enter a pump under a low flow condition, gas may form a pocket around the impeller eye, resulting in the impeller rotating in gas with no flow out of the pump. Once up to speed, the flow velocities during transients may be high enough to sweep small quantities of gas through the pump due to the system flow inertia.

The transient operation criteria are based on the premise that homogeneous bubbly flow exists at the pump entrance, 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. The most likely condition that would result in pump damage would be 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 requirement that homogeneous bubbly flow exists at the pump entrance.

As discussed in SE Section 3.2.2 and in TR Table 3-1, conservative pump acceptance criteria were addressed in NEI 09-10 and found acceptable in the accompanying SE (NEI/NRC, April 2013). The EPRI pump roadmap report (EPRI, August 2012), TR Table 3-2, provides more realistic pump acceptance criteria than provided in TR Table 3-1. It represents best estimates of pump performance for the purpose of establishing pump operability. The TR states that the NEI 09-10 criteria are conservative by a factor of approximately two in most cases when compared to the EPRI pump roadmap criteria. The NRC staff agrees. Consequently, the NRC staff will accept the NEI 09-10 criteria as conservative and no further safety factors are usually necessary when those criteria are used.

3.7.2 TR Section 8.2 Treatment of Tees and Off-Takes

The TR does not provide detailed guidance for gas separation at offtakes and tees. Rather, the assumption is made that all of the gas will travel towards a pump along each potential path. However, some gas may accumulate in an inactive branch or in a larger diameter header and this could later move toward a downstream pump due to a subsequent instability as identified in NEI 09-10 Section 4. This approach is acceptable.

3.7.3 TR Section 8.3 Hold-Up at Components

Gas may be held up in components as gas moves through a system. The TR stated that such holdup is not typically accounted for in a gas transport evaluation. This is an acceptable approach unless holdup is acceptably justified such as has been accomplished for the elbow configurations in WCAP-17271.

3.8 TR Section 9 Comparison of WCAP-17271

SE Section 3.2.3 discussed the W system test information covered in TR Section 9. TR Section 9 also provided a comparison of WCAP-17271 correlation predictions of measured transportation times with W test data as summarized in TR Figure 9-4. The WCAP-17271 predicted times are smaller than the measured times but follow the trend of the measured data. They are conservative and acceptable since a smaller transport time corresponds to a larger predicted β.

3.9 TR Section 10 Implementation Process

3.9.1 TR Section 10.1 Background

The TR states that TR Section 10 outlines a general process and provides an example.

3.9.2 TR Section 10.2 Inputs Required

3.9.2.1 TR Section 10.2.1 Gas Accumulation Locations

The TR states that high points and potential gas accumulation locations in the pump suction piping should be identified in accordance with Section 8 of NEI 09-10. One-line pipe diagrams are recommended for this process. A list of locations that should be evaluated is provided. This is acceptable with one qualification: reducers should be clarified to include offsets in addition to concentric configurations.

3.9.2.2 TR Section 10.2.2 Flow Paths and Flow Rates

After identifying high point locations, the TR states that the flow path(s) and the location of potentially effected pumps should be determined and methods to accomplish this are identified. The intent is to use the WCAP-17271 and WCAP-17276 correlations in conjunction with the limitations established in the TR to demonstrate that β_{AVE} at the pump inlet is within the limits of TR Tables 3-1 or 3-2. The process is stated to use the maximum expected flow rates as these will result in the highest β and the lowest allowable gas volume.

The TR states that header flow rates should be identified assuming all pumps operate (no single failure) and assuming the limiting single failure. The larger flow rate should be used in the gas transport evaluation. The lower flow rate should be used to demonstrate that flow does not stratify in horizontal headers. Stratification may be a realistic condition, as illustrated in TR Figure 6-22.

This guidance is acceptable.

3.9.2.3 TR Section 10.2.3 Vertical Down-Comers

The TR states that flow path(s) from a high point location to a pump suction should be examined to identify any DCs. Each DC should be assessed to determine if it meets the TR Eq. 5-6 length requirement. The number of vertical-to-horizontal elbows between the gas accumulation location and the pump inlet should be identified if the WCAP-17271 methodology will be used. If credit is taken for an intermediate DC to meet the criteria, only the vertical-to-horizontal elbows downstream of the first DC that meets the TR Eq. 5-6 criterion can be credited in the WCAP-17271 methodology. The TR Section 10.2.3 guidance is acceptable.

3.9.2.4 TR Section 10.2.4 Off-Takes from Horizontal Pipes

The TR states that any off-takes between the high point and pump inlet must meet the TR Section 6.3.6 criteria. This is acceptable.

3.9.2.5 TR Section 10.2.5 Static Pressure Distribution During Gas Transport

This TR section acceptably addresses the static pressure with one exception. The friction and form losses should be estimated and either included in the pressure determination or shown to be negligible.

3.9.2.6 TR Section 10.2.6 Static Pressure Distribution During Surveillance Test

The static pressure distribution during surveillance test is acceptable since the NRC staff determined that a linear pressure distribution assumption was acceptable.

3.9.2.7 TR Section 10.2.7 Fluid Properties

TR Section 10.2.7 identifies that ρ_ℓ, ρ_g, and σ are necessary for certain calculations. The NRC staff agrees and finds this acceptable.

3.9.2.8 TR Section 10.2.8 Pump Inlet Piping Configuration

Two pump configurations are identified, a pump with a vertically downward inlet for which TR Section 6.3.7 criteria must be met and a pump with a horizontal inlet for which TR Section 6.3.5 criteria must be satisfied. It is necessary that TR Eq. 5-6 be satisfied for the path to each pump.

If the pump has a horizontal inlet, it is necessary to demonstrate that homogeneous bubbly flow occurs at the pump inlet or that any deviation from that condition does not jeopardize pump operability. If a kinematic shock occurs in the horizontal pipe leading to the pump, prediction of the shock location is poorly understood. Licensees should assess this condition using the available information. Further NRC staff findings are addressed in SE Section 4.

3.9.2.9 TR Section 10.2.9 Pump Data

The reference to TR Table 3-1 is modified to allow TR Tables 3-1 or 3-2. The TR discussion of pump data is acceptable.

3.9.3 TR Section 10.3 Method To Adjust Gas Flux Due To Change In Flow Rate

The TR states that the existing methodology does not incorporate a correlation to determine the gas flow distribution at an off-take and it is assumed that all of the gas goes through the off-take in the direction of the pump under evaluation. This is acceptable with the qualification that potential problems that could result in gas accumulation due to assuming a lower flow rate are addressed.

3.9.4 TR Section 10.4 Allowable Gas Volume Calculation Process

3.9.4.1 TR Section 10.4.1 Pump Gas Volumetric Flux Ratio & Transport Time

The TR states that the pump operating flow rate and pump best efficiency flow rate should be applied to determine the allowable gas volumetric flux ratio from TR Tables 3-1 or 3-2 based on the applicable pump type. The staff have determined that this is acceptable.

3.9.4.2 TR Section 10.4.2 Estimate Initial Gas Volume

3.9.4.2.1 TR Section 10.4.2.1 WCAP-17276 (Simplified Equation) Methodology

In general, TR Section 10.4.2.1 is consistent with the description of the Simplified Equation provided in SE Section 3.4. Therefore, TR Section 10.4.2.1 is acceptable.

3.9.4.2.2 TR Section 10.4.2.2 WCAP-17271 Methodology

TR Section 10.4.2.2, with minor changes, is consistent with SE Sections 3.3.1, 3.3.2, and 3.3.3. Additional TR guidance is provided in Steps 9 through 12. TR Section 10.4.2.2 is acceptable.

3.9.4.3 TR Section 10.4.3, Verify Vertical Down-Comer Limitation

TR Section 10.4.3 leads to the following:

(1) Gas volumes must be consistent with meeting the pump criteria provided in TR Tables 3-1 or 3-2 and TR Eq. 5-6 can be used to show that the DC ensures that homogeneous bubbly flow exists immediately below the DC region affected by the waterfall[13]. Alternatively, TR Figures 6-5 through 6-8 are identified as possible references that can be used to estimate the required DC length and the allowable gas volume.[14]

(2) If credit is taken for an intermediate DC volume to meet the TR Section 6.3.4 criteria, then the gas volume must be adjusted for the static pressure which exists at the intermediate DC.

(3) If credit is taken of an intermediate DC volume to meet the TR Section 6.3.4 criteria, only the vertical-to-horizontal elbows downstream of the intermediate DC can be credited in the WCAP-17271 methodology.

If TR Figures 6-5 through 6-8 are used, TR Eq. 5-6 should be applied for verification. With this qualification, TR Section 10.4.3 is acceptable.

3.9.4.4 TR Section 10.4.4, Verify Horizontal Off-Take Limitation

TR Section 10.4.4 provides the following:

(1) Gas volumes calculated in TR Section 10.4.2 must be consistent with meeting the pump criteria provided in TR Tables 3-1 or 3-2.

(2) If an off-take is located in a horizontal run of pipe, the criteria in TR Section 6.3.6 are met if $N_{FR} \geq 1$ and $\beta < 25\%$ where the criteria apply to the off-take.

(3) If $N_{FR} < 1$, the Taitel-Dukler methodology (Taitel, January 1976) may be used to demonstrate that the flow is in the intermittent flow regime.

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[13] The TR states that bubbly flow exits the bottom of the DC. This fails to recognize that bubbles may re-enter the DC where they are broken up and then leave the DC.

[14] The NRC staff did not review these figures for accuracy.

Items 1 - 3 are acceptable. Further, the NRC staff often uses $N_{FR} \geq 0.93$ in calculations that involve the Purdue test results provided most gas is removed from the upper horizontal pipe, a condition necessary to meet the modeling assumptions.

3.9.4.5 TR Section 10.4.5, Verify Pump Inlet Limitation

TR Section 10.4.5.1 provides the following followed by **the NRC staff assessment**:

(1) If the pump has a horizontal inlet preceded by a vertical DC, it should be verified that either a kinematic shock does not form in the horizontal pipe downstream of the elbow, or that the length of horizontal pipe is sufficient to prevent the kinematic shock from directly entering the pump. **Acceptable but see Item 3, below.**

(2) TR Eqs. 6-6 and 6-7 provide kinematic shock localization information. **TR Eqs. 6-6 and 6-7 provide β_{max}, not a location. TR Eq. 6-6 is acceptable for $1.25 \leq N_{FR} \leq 1.75$; TR Eq. 6-7 js acceptable when appropriate conservatisms are provided.**

(3) If a kinematic shock does form, Eq. 6-21 provides the pipe volume to prevent the kinematic shock from directly entering the pump. **Acceptable for $0.93 \leq N_{FR} \leq 2$. Eq. 6-21 follows from Eq. 6-20 that was generated from TR Figure 6-16. TR Figure 6-16 information covers $0.93 \leq N_{FR} \leq 2$.**

The TR does not clearly establish the kinematic shock behavior. The Purdue test data establish that a shock exists before the last downstream void measurement location in the test facility. With respect to pump inlet characteristics, lacking other information, justified judgements may be used.

TR Section 10.4.5.2 states that, if the pump has a vertical downwards inlet, the methodology provided in TR Section 10.4.6 should be used to demonstrate that the liquid flow rate is not sufficient to transport a co-current gas slug directly to the pump inlet. This is addressed in SE Section 3.9.4.6.

3.9.4.6 TR Section 10.4.6 Verify Maximum Flow Limitation

This limitation is stated to ensure that the liquid flow will not transport a co-current gas slug directly to the pump inlet. WCAP-17271 stated that any slugs that entered the bottom of a vertical DC were unstable and broke up in the vertical pipe. For pipe diameters 6 inches and greater, $N_{FR} = 2.5$ corresponds to a mass velocity greater than $2x10^6$ lbm/hr-ft^2. TR Figure 6-23 (Figure 19) indicates that the mass velocity corresponds to the dispersed flow regime for a horizontal header; therefore, a slug would tend to quickly break up in the horizontal header if it made it to the bottom of the DC. In addition, WCAP-17271 notes that the vertical-to-horizontal elbow tends to hold-up gas at the elbow, and the tendency for a kinematic shock to form increases with gas flux. The TR states that these phenomenon act to break up a co-current gas slug. Therefore, if a DC is followed by an elbow and a horizontal run (that is, the vertical pipe does not go directly into the pump), it can be assumed a co-current slug would be broken up quickly, and the N_{FR} limit of 2.5 is not applicable. This limit remains applicable for pumps with vertically downward inlets when the gas accumulation location is immediately upstream of the pump inlet.

The general shape of the TR Figure 6-23 (Figure 19) transitions between flow regimes may be correct although the transition value of $2x10^6$ lbm/hr-ft^2 may be too small. Since $N_{FR} = 2.5$

corresponds to a mass velocity greater than $2x10^6$ lbm/hr-ft^2 and considering the observed Purdue test behavior, the maximum flow limitation of $N_{FR} > 2.5$ is not necessary to ensure that the liquid flow rate will not be high enough to transport a co-current slug of gas directly to a horizontal pump inlet provided the horizontal pipe is long enough so that a hydraulic jump results in a small void fraction at the pump entrance.

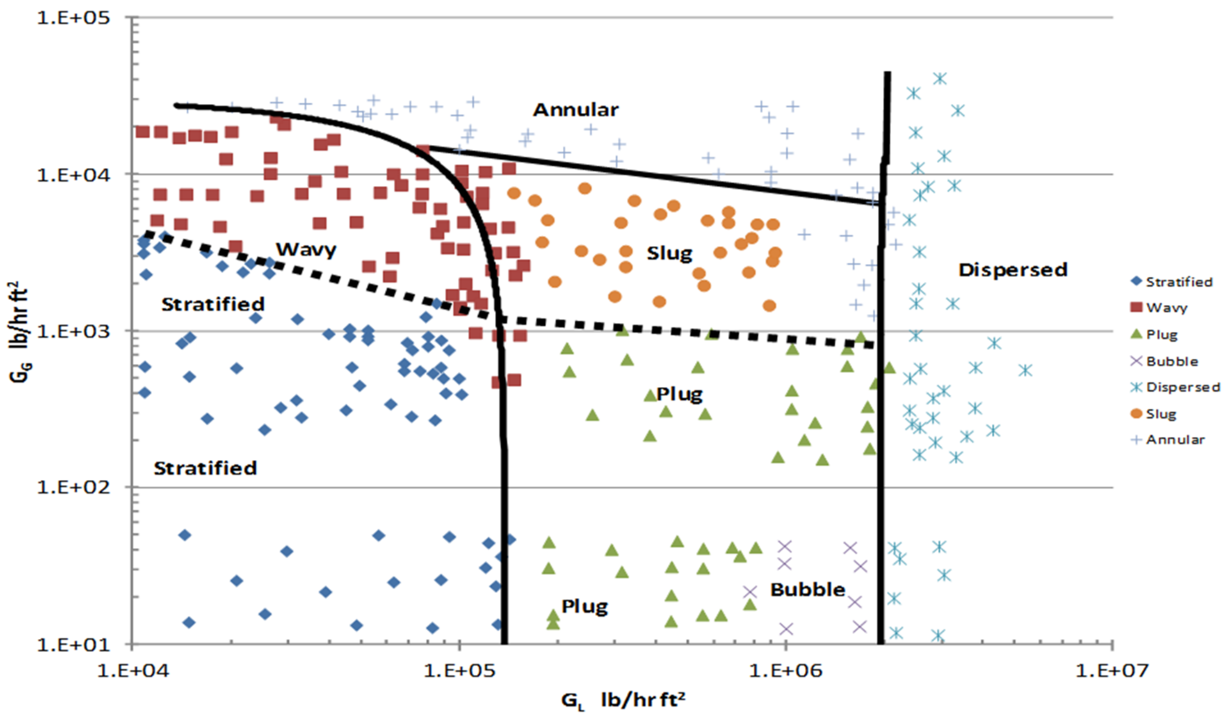

Figure 19 Flow Regime Map for a Horizontal Pipe

3.9.4.7 TR Section 10.5, Gas Volume Based On Surveillance Static Pressure

The TR states that the allowable gas volume calculated in TR Section 10.4 must be adjusted to the static pressure which will exist during surveillance testing using the ideal gas law. This is acceptable.

3.10 TR Section 11, Example Problem

3.10.1 TR Section 11.1, Inputs Required

3.10.1.1 TR Section 11.1.1, Gas Accumulation Locations

The one-line drawing is shown in TR Figure 11-1. This is applicable to the RWST supply to two SI pumps. There are two gas accumulation locations. The first is formed by the inverted U-tube caused by the down-turned elbow in the RWST. The second is formed by the eight inch check valve at the 170 ft elevation which does not allow the gas to vent back to the RWST.

3.10.1.2 TR Section 11.1.2, Flow Paths and Flow Rates

The TR identified flow rates to be used with TR Figure 11-1.

3.10.1.3 TR Section 11.1.3, Vertical Downcomers

The NRC staff calculated the Table 5 DC properties.

Table 5 Vertical Downcomers

Down-comer Location	L	D	A	V
	ft	inch	ft^2	ft^3
A-B	15	23.25	2.9483	44.23
B-C	30	23.25	2.9483	88.45
E-F	5	7.981	0.3474	1.74
G-H	12	6.065	0.2006	2.41
I-J	12	6.065	0.2006	2.41

3.10.1.4 TR Section 11.1.4, Off-Takes from Horizontal Pipes

The NRC staff compiled the Table 6 horizontal offtake values.

Table 6 Horizontal Offtakes

Horizontal Off-take	Description	Q_{in}	Q_{out}	Q_{in} / Q_{out}
	ft	gpm	gpm	
D	24"x24"x8" tee	18548	870	21.32
G	8"x8"x6" tee	870	660	1.32

3.10.1.5 TR Section 11.1.5, Static Pressure Distribution during Pump Operation

TR Table 11-4 provides the static pressure distribution during pump operation. The values were stated to have been obtained from the NPSHA calculation and adjusted by the difference in hydrostatic head due to the RWST elevation assumed during the $NPSH_A$ calculation and the RWST elevation during normal operation when surveillance testing is performed (270 ft). The NRC staff determined that there was not enough information to verify these values, but verification was not necessary for the example problem to be useful.

3.10.1.6 TR Section 11.1.6, Static Pressure Distribution during Surveillance Testing

TR Table 11-5 identifies the static pressure distribution during surveillance testing and was obtained by using an RWST water level static pressure of 14.7 psia and adding the hydrostatic head between the RWST level (270 ft) and the location elevation. Table 7 provides the TR Table 11-5 information and a comparison with NRC – calculated values that confirm the TR values.

Table 7 Static Pressure Distribution during Surveillance Testing

Location	Y	PADJ	NRC
	ft	psia	psia
A	215	38.50	38.50296
B	200	44.98	44.99467
C	170	57.96	57.9781
D	170	57.96	57.9781
E	170	57.96	57.9781
F	165	60.13	60.14201
G	165	60.13	60.14201
H	153	65.32	65.33538
I	165	60.13	60.14201
J	153	65.32	65.33538

3.10.1.7 TR Section 11.1.7, Fluid Properties

TR Table 11-6 provides acceptable fluid properties.

3.10.1.8 TR Section 11.1.8, Pump Inlet Piping Configuration

TR Table 11-7 identifies the pump inlet configurations and inlet volumes determined for use in TR Eq. 6-21. The NRC staff confirmed these values and finds them acceptable.

3.10.1.9 TR Section 11.1.9, Pump Data

The NEI/NRC SE 09-10 requires that if the steady-state criteria in TR Table 3-1 are used to develop the allowable gas volume, the pump head margin should be evaluated to verify that at least 3 percent margin exists between the pump developed operating head and the minimum head required to meet operability conditions.

TR Table 11-8 provides the required pump data for Flowserve Model JHF pumps. The TR states that both pumps have 12.5 percent margin between actual operating head and the required head for pump operability. (The TR states that the NEI 9-10 requirement is 4 percent, not 3 percent.) The NRC staff finds TR Table 11-8 values acceptable.

3.10.2 TR Section 11.1.9.1, WCAP-17276 (Simplified Equation) Methodology

The first step is to address the requirements of the SI pumps. These each have a 6.065-inch suction pipe preceded by a 12 ft DC. Flow rate is 660 gpm. The TR stated that the RWST top level was 270 ft. TR Figure 11-1 shows the first gas accumulation location is at Level 215 ft and TR Table 11-4 provides the gas accumulation pressure as 36.12 psia and pressure at the pump elevation as 39.04 psia. TR Table 11-8 provides $\beta_p = 0.05$ and $\Delta t_p = 5$ sec. The NRC staff verified the input values of TR Table 11-9.

The NRC staff provided a rewrite of TR Eq. 5-1 as TR Eq. 6-1. Substituting the identified input values, TR Eq. 6-1 yields $V_g = 0.397$ ft^3. The TR reported 0.40 ft^3. Therefore, the output value in TR Table 11-9 is verified.

The first DC consists of a 24-inch pipe that is 15 ft long. This is followed by a 30 ft DC. Flow rate is 18548 gpm, pipe diameter is 23.3250 in, flow area is 2.9483 ft^2, and velocity is 14.02 ft/sec, consistent with the TR Table 11-10 value of 14 ft/sec. TR Table 11-4 gives the pressure at Point A as 36.12 psia and Point B as 38.33 psia during pump operation. TR Eq. 5-6 yields a DC length of 0.6036 ft, well within the 15 ft length shown in TR Figure 11-1 and consistent with the TR Table 11-10 value of 0.6035 ft. TR Table 11-10 is verified. The NRC staff observes that TR Eq. 5-6 is based on the assumption that average fluid behavior exists with respect to radial position at the predicted distance. The short DC length prediction of 0.6036 ft would indicate a condition where the waterfall only affected part of the DC. However, this is not of concern since the 15 ft length provides sufficient distance to alleviate the failure to achieve a uniform condition at the DC exit.

The transport time is calculated using TR Eq. 5-7. The NRC staff calculated 1.47 sec and the TR reported 0.3 sec in TR Table 11-1, part of which is reproduced in Table 8:

Table 8 TR Eq. 5-7 Results

Item	TR Table 11-11	NRC Staff
Q (input)	18548 gpm	18548 gpm
D (input)	23.25 in (see following comment)	23.25 in
V_g (initial guess – input)	0.40 ft^3	0.397 ft^3
L_R (calc)	0.6035 ft	0.6036 ft
Δt (calc)	0.3 sec	1.466 sec
V_g (calc)	0.024 ft^3	0.116 ft^3

If d is incorrectly entered as 23.25 / 12 = 1.94 ft in the TR calculation using TR Eq. 5-7, the NRC staff obtains 0.3 sec. The TR calculation of Δt = 0.3 sec is incorrect due to entering the incorrect units for d.

TR Section 3.4 states that the NEI 09-10 value of Δtp cannot be larger than the transport time dictated by the gas volume and flow conditions. This is accomplished by using the lower value of Δt predicted by TR Eq. 5-7 and Δtp provided in the NEI 09-10 pump criteria. TR Table 11-8 stated that the allowable Δt was 5 sec. Table 8 shows that the gas will transport more quickly than the allowable transient transport time based on TR Table 3-1. As a result, the allowable gas volume must be adjusted. The TR used the incorrect 0.3 sec to predict an allowable high point volume of 0.024 ft^3 in contrast to the NRC staff's Δt = 1.466 sec and the correct allowable high point volume of 0.397 X 1.466 / 5 = 0.116 ft^3. TR Table 11-11 has incorrect values for the simplified equation methodology prediction

3.10.3 TR Section 11.1.9.2, WCAP-17271 Methodology

Review of the WCAP-17271 methodology is accomplished by following the steps provided in SE Section 3.3.

The first step is to assume a gas high point volume at TR Figure 11-1 Location A. If not previously calculated, the next step is to compute N_{FR} and to determine if the flow rate is sufficient to move gas from the high point at TR Figure 11-1 Location A by consulting TR Table 1. If the flow rate will not move the gas void <u>and</u> there is sufficient liquid flow area for water to move freely through the partially voided pipe, an analysis is not necessary.

The TR methodology to obtain the flow characteristics downstream of the first vertical to horizontal elbow (the TR Figure 11-1 elbow downstream of Elbow A) is described by the following equations:

(1) TR Eq. 4-2. The DC length that is initially voided is given by TR Eq. 4-2. This assumes the top horizontal header initial gas volume has instantaneously moved into the top of the vertical DC at a 100 percent void fraction.

(2) TR Eq. 4-1. The flow initialization time, the time to completely remove the initial gas volume from the bottom of the shock in the DC, is expressed in terms of the mixture velocity and the ideal shock length in TR Eq. 4-1.

(3) TR Eq. 4-4. WCAP-17271-P used L_S in place of $L_{S,id}$ to compute W_e but the meaning of L_S in that usage was $L_{S,id}$. The use of L_S in place of $L_{S,id}$ in Eq. 4-4 is inconsistent with the definition of W_e but this use was established to acceptably describe the phenomena and it is therefore acceptable.

(4) TR Eq. 4-3. This is the second form of the flow initialization model. It provides the average gas volumetric flux over the initialization process at the kinematic shock exit at the bottom of the void in the DC where homogeneous bubbly flow is obtained. Hence, the flow initialization model covers the DC length to the bottom of the kinematic shock and the time for the void to be effectively eliminated from the top of the DC.

(5) TR Eq. 4-8 provides the gas volumetric flux at the entrance to an elbow below a DC.

(6) TR Eq. 4-7 (the above Eq. 1) provides N_{FR}. Note the NRC staff calculated N_{FR} earlier to assess whether a calculation was necessary, a step not addressed in the TR.

(7) TR Eq. 4-6 provides the lower elbow holdup correlation $\beta_{el,out}$, the gas volumetric flux at the elbow outlet. It calculates the gas volumetric flux in a horizontal pipe downstream of an elbow based on the gas volumetric flux at the elbow inlet, the time over which gas enters the elbow, and N_{FR}. Note that TR Eq. 4-6 is based on the unstated assumption that $\beta_{el,out}$, occurs downstream of any shock that occurs in the lower horizontal pipe.

(8) TR Eq. 4-9 addresses the gas transport time increase at the DC exit elbow due to gas hold up at the elbow.

Calculation results as discussed above are summarized in Table 9.

Table 9 Comparison of TR and NRC staff Calculations

Eq.	Item	TR result from TR Tables 11-12 and 11-13	NRC staff calculation
4-2	$L_{S,id}$, ft	0.1458	0.1458468
4-1	Δt_{init}, sec	0.32	0.320747
4-4	W_e	11089	11061.53
4-3	$\beta_{R,out}$	0.0327	0.032651
4-8	$\beta_{el,in}$	0.0308	0.030769
4-7	N_{FR}	1.77	1.789231
4-6	$\beta_{el,out}$	0.0013	0.001314
4-9	$\Delta t_{el,out}$	7.73	7.508496

The TR calculations summarized in Table 9 are acceptable.

The NRC staff did not review the remainder of the Example Problem WCAP-17271 calculations since $\beta_{el,out}$ and $\Delta t_{el,out}$ are calculated by repeated application of the same steps.

3.10.4 TR Section 11.1.10, Verify Vertical Down-Comer Limitation

The DC length must be at least as long as the DC length from the top of the DC to the end of the region affected by the waterfall, L_R, or the WCAP-17271 correlation cannot be used. It must be demonstrated that the vertical DC limitation is met to ensure the separated flow region remains in the DC and bubbly flow exits the bottom of the region affected by the waterfall. This can be done by using TR Eq. 5-6 to calculate the required DC length, L_R. TR Eq. 5-6 requires iteration to obtain L_R. Since TR Eq. 5-6 is based on average properties, L_R must be at least equal to several pipe diameters.

If credit is taken of an intermediate DC volume to meet the TR Section 6.3.4 criteria, the gas volume must be adjusted for the static pressure which exists at the intermediate DC. Once L_R is calculated, $P_{R,out}$ can be calculated using the assumption that pressure varies linearly from the DC top to the bottom. Once pressure is known, DC volume can be adjusted. In addition, if credit is taken for an intermediate DC volume to meet the TR Section 6.3.4 criteria, only the vertical-to-horizontal elbows downstream of the intermediate DC can be credited in the WCAP-17271 methodology.

TR Table 11-10 indicates that the length of the kinematic shock for a gas volume of 0.4 ft^3 is 0.6 ft of 24 inch pipe. The allowable gas volume of 0.43 ft^3 will therefore require a DC which is larger than 0.6 ft. The length of the first DC is 15 ft., which exceeds the required length and provides sufficient length for mixing below the water impact location. Therefore, the first DC length is acceptable.

3.10.5 TR Section 11.1.11, Verify Horizontal Off-Take Limitation

The gas volume calculated in TR Section 10.4.2 meets the pump criteria provided in Table 2. However, it must be demonstrated that if an off-take is located in a horizontal run of pipe, the criteria in TR Section 6.3.6 are met. The limitation is met If the horizontal header $N_{FR} \geq 1$ and $\beta \leq 0.25$. TR Table 11-14 indicates $N_{FR} = 1.77$ in the 24 inch pipe upstream of the first off-take. TR Table 11-15 indicates that $\beta = 0.0007$ at the offtake inlet and 0.0156 at the outlet. TR

Table 11-16 indicates N_{FR} = 1.20 at the outlet of the off-take. TR Table 11-16 indicates N_{FR} = 1.20 in the 8 inch pipe upstream of the second off-take and TR Table 11-17 indicates β = 0.0059 at the inlet and 0.0078 at the outlet. Therefore, assuming the TR table values are correct, both off-takes are within the limits to ensure the gas does not stratify.

3.10.6 TR Section, 11.1.12, Verify Pump Inlet Limitation

The TR states that, if there is a pump with a horizontal inlet preceded by a vertical DC, it should be verified that either a kinematic shock does not form in the horizontal pipe downstream of the elbow or that the horizontal pipe is long enough to prevent the kinematic shock from directly entering the pump. The NRC staff concluded SE Section 3.5.3.6 by stating that the following criteria were acceptable except for flow through a horizontal tee with a stagnant vertically upward offtake:

(1) $N_{FR} > 1$
(2) $\beta \leq 0.25$
(3) gas is moving with the liquid in a bubbly or incipient plug flow regime
(4) gas will not accumulate or stratify at a tee
(5) gas is entirely transported though the off-take in the flow direction being considered.

SE Section 3.5.3.5.3 stated that the NRC staff concludes (1) TR Eq. 6-6 provides the required allowable gas volumetric flow ratio to form a kinematic shock at the outlet of a vertical-to-horizontal elbow in terms of the Froude number. This is acceptable provided $1.25 \leq N_{FR} \leq 1.75$, (2) no shock will form in the lower horizontal pipe if β_{avg} < **[ ]**, (3) if a shock forms, there is little information to establish the shock formation location, (4) TR Eq. 6-7 provides a relation between the maximum gas volumetric flux at the DC outlet and the shock length y calculated by TR Eq. 5-6 divided by the DC diameter. TR Eq. 6-7 is an acceptable description of void behavior when a safety factor is used, and (5) if a pump is located near the end of the lower elbow, a methodology based on average fluid properties should be further justified.

If a kinematic shock does form, The TR states that TR Eq. 6-21 provides the necessary pipe volume to prevent the kinematic shock from directly entering the pump.

In TR Section 3.6, TR Eq. 7-1 was stated to be acceptable for prediction of the allowable gas volume that would not jeopardize operability. If this results in a gas volume that is too small, then the TR states that appropriately scaled testing is the preferred approach. The NRC staff agrees.

TR Table 11-7 indicates both pumps have a horizontal inlet and Pump 2 has a horizontal inlet pipe with a volume of 1.0 ft3. TR Eq. 6-21 is used to determine the allowable gas volume in the lower horizontal pipe if a kinematic shock forms.

TR Table 11-19 summarizes the results of these calculations. The allowable gas volume if a kinematic shock occurs is calculated to be 0.21 ft^3, which is less than the value of 0.43 ft^3 based on pump limits. The minimum required volumetric flux to create a kinematic shock in the horizontal pipe is 0.13. A 0.43 ft^3 gas volume in a 6-inch pipe with a flow rate of 660 gpm is calculated by TR Eq. 5-6 to provide a kinematic DC shock at 3.797 ft which results in a maximum volumetric flux of 0.1295 which is slightly less that the allowable value of 0.13. Therefore, a kinematic shock is predicted to not occur. In addition, the 3.797 ft shock length is less than the 12 ft vertical DC length at the pump inlet. Therefore, the pump inlet criteria are met.

3.10.7 TR Section 11.1.13, Verify Maximum Flow Limitation

The flow limitation is not applicable since the Froude number does not exceed 2.5 throughout the system and the pump does not have a vertical downwards inlet.

3.10.9 TR Section 11.2, Summary of Results

The WCAP-17276 methodology initially allowed a gas volume of 0.40 ft^3. However, this was limited to 0.024 ft^3 due to the 14 ft/sec gas velocity in the gas accumulation location that would entrain the gas at a faster rate (0.3 sec) than the pump transient limit (5 sec). Therefore, a reduction in void fraction was necessary to limit the average void fraction to 0.05 over the transport time period. Since the gas transport time predicted by the WCAP-17276 methodology is less than the minimum 0.5 second transport time limit, the gas volume could be increased to (0.5 sec/ 0.3 sec) (0.024 ft3) = 0.04 ft^3.

The WCAP-17271 methodology allowed a gas volume of 0.43 ft^3 during operating conditions if the void had not been reduced to the DB value. The flow initialization model for WCAP-17271 predicted a flow initialization time of 0.32 seconds for a 0.43 ft^3 gas volume. However, due to the presence of several elbows, the predicted transport time to the pump was 33 sec. This is above the transient time limit of 5 seconds. Since the pump operating flow rate was 47 percent beyond the best efficiency flow rate, TR Table 3-1 limits the steady state pump gas volumetric flux ratio to 0.01. The 0.43 ft^3 void meets this limit.

The TR methodologies were reported to be used to evaluate the effect of the TR Figure 11-1 configurations on allowable gas volume:

(1) TR Eq. 5-6 was used to determine that the kinematic shock length is 0.6 feet as compared to a DC length of 15 feet. A length of 0.6 ft may not be sufficient to ensure the water impact effects are homogenized but the length of 15 ft is sufficient.

(2) N_{FR} at the inlet to each of the two horizontal off-takes is greater than 1 and the corresponding gas volumetric flux is 0.01 which is less than the allowable limit of 0.25.

(3) Both pumps have horizontal inlets. TR Eq. 6-21 was used to demonstrate that if a kinematic shock were to occur, the pump inlet piping would limit the gas volume to 0.21 ft^3 to prevent the kinematic shock from entering the pump. TR Eq. 6-6, that is acceptable when $1.25 \leq N_{FR} \leq 1.75$[15], was used to determine that a gas flux ratio of 0.13 was required to form a kinematic shock at the vertical-to-horizontal elbow exit. TR Eq. 6-7 was used to determine that the gas volumetric flux at the entrance to the vertical-to-horizontal elbow was 0.1295 based on the shock length from TR Eq. 5-6. This is less than the allowable limit of 0.13 and is acceptable.

(4) There are no pumps with vertical downwards inlets and it was not necessary to demonstrate that the gas volume was limited to preclude a kinematic shock from entering a vertical pump inlet or demonstrating that N_{FR} at the pump inlet did not exceed 2.5.

[15] N_{FR} = 1.77 is considered close enough to the 1.75 bound to be acceptable.

The allowable gas volume of 0.43 ft^3 during operating conditions was acceptably adjusted to 0.40 ft^3 to account for the difference in static pressure between operating conditions and surveillance testing by applying TR Eq. 11-1.

3.11 TR Section 12, Road Map for Determining Operability Limits

The intent of this section is stated to provide a road map to the overall process of developing operability limits using flow charts to clarify the process. TR Figure 12-1 depicts the overall process which includes developing the inputs, choosing an evaluation tool, and determining if piping layout geometry limits the gas volume.

TR Figure 12-1 references TR Figures 12-2 through 12-8 and TR Eq. 11-1. TR Eq. 11-1, the adjustment of the gas accumulation volume for the surveillance test condition, was stated to be acceptable in TR Section 3.10.9. TR Figures 12-2 through 12-8 are addressed below.

TR Figure 12-2 describes input parameter development as consisting of (1) a One Line Drawing, (2) System Data, and (3) Pump Data. Each item and the NRC staff finding are addressed in Table 10:

Table 10 Assessment of TR Figure 12-2

Item	TR Section/SE Section	NRC staff assessment
One Line Drawing	10.2.1/3.9.2.1	Acceptable with one qualification: Reducers should be clarified to include offsets in contrast to concentric locations.
	10.2.2/3.9.2.2	Acceptable with a qualification that stratification may be acceptable when it is acceptably addressed.
	10.2.3/3.9.2.3	Acceptable.
	10.2.4/3.9.2.4	The TR states that any off-takes between the high point and pump inlet must meet the TR Section 6.3.6 criteria. The information is sufficient to evaluate offtakes.
	10.2.8/3.9.2.8	TR Eq. 5-6 must be satisfied for each pump if there is a DC upstream of the pump. The TR states that TR Section 6.3.7 criteria must be met if a pump has a vertically downward inlet. This is acceptable. The TR states that TR Section 6.3.5 criteria must be satisfied if a pump has a horizontal inlet and homogeneous bubbly flow must occur at the pump inlet or any deviation from that condition must be shown to not jeopardize pump operability. Further horizontal inlet conclusions include: (1) Eq. 6-6 is acceptable for use provided $1.25 \leq N_{FR} \leq 1.75$, (2) no shock will form in the lower horizontal pipe if β_{avg} < **[ ]**, (3) if a shock forms, there is limited information to establish the shock formation location, (4) TR Eq. 6-7 is an acceptable description of void behavior when a safety factor is used, and (5) if a pump is located near the end of the lower elbow, a methodology based on average fluid properties must be further justified.

System Data	10.2.7/3.9.2.7	TR Section 10.2.7 identifies that ρ_ℓ, ρ_g, and σ are necessary for certain calculations. Acceptable.
	10.2.5/3.9.2.5	This TR section acceptably addresses the static pressure with one exception. The friction and form losses should be estimated and either included in the pressure determination or shown to be negligible.
	10.2.6/3.9.2.6	Acceptable.
	10.2.2/3.9.2.2	Acceptable with a qualification that stratification may be acceptable when it is acceptably addressed.
Pump Data	10.2.9/3.9.2.9	Pump data are addressed in SE Section 1.2.
	10.2.9/3.9.2.9	Pump data are addressed in SE Section 1.2.
	10.2.9/3.9.2.9	Pump data are addressed in SE Section 1.2.
	10.4.1/3.9.2.1	The TR states that the pump operating flow rate and pump best efficiency flow rate should be applied to determine the allowable gas volumetric flux ratio from TR Table 3-1 or 3-2 based on the applicable pump type. A transport time of 20 seconds is applicable to the steady state criteria. This is acceptable. The TR Table 3-1 criteria may be applied with no allowance for uncertainty. An appropriate safety factor should be applied if the TR Table 3-2 criteria are used.
	10.4.1/3.9.2.1	The TR states that the pump operating flow rate and pump best efficiency flow rate should be applied to determine the allowable gas volumetric flux ratio from TR Table 3-1 or 3-2 based on the applicable pump type. A transport time of 20 seconds is applicable to the steady state criteria. This is acceptable. The TR Table 3-1 criteria may be applied with no allowance for uncertainty. An appropriate safety factor should be applied if the TR Table 3-2 criteria are used.

Sufficient information is provided in Table 10 to justify an acceptable approach.

TR Figure 12-3 is stated to determine if WCAP-17271 or WCAP-17276 can be used. There are two end blocks:

(1) Use WCAP-17271 or WCAP-17276.

(2) Use NRC conservative method (TR Section 7).

Item 1 is addressed in TR Figures 12-4 and 12-5.

Four of the paths in Item 2 provide a transfer to the approved NRC method discussed in TR Section 7. This method is often too conservative. In this case, TR Section 7 states that appropriately scaled testing is the preferred approach to demonstrate a larger allowable gas volume and that this does not preclude the use of other data sets that may be available to justify operability. The NRC staff agrees.

Next, consider the case of a gas accumulation location followed by a DC followed by a short horizontal pipe followed by a pump. If the DC is long enough to satisfy TR Eq. 5-6 and the need for sufficient length to reasonably ensure a homogeneous DC exit flow and $1 < N_{FR} < 2.5$, the

NRC staff accepts TR Figure 6-23 (Figure 19) as part of the TR's objective of defining "a means of applying the correlations in a manner which meets the limitations imposed by the" NRC's SE that addressed NEI 09-10 (NEI/NRC, April 2013).

There are four potential conditions that can preclude the use of the WCAP-17271 or WCAP-17276 methodologies:

(1) If a vertical DC does not exist between the gas accumulation location and the pump inlet, then neither the WCAP-17271 nor WCAP-17276 methodologies can be applied. Both the WCAP-17271 and WCAP-17276 methodologies rely upon the presence of a vertical DC to entrain the gas from an initially separated regime into dispersed bubbly flow.

(2) If flow conditions allow the gas to stratify in a horizontal pipe which contains an off-take (and the off-take is either horizontal or rotated downwards), this can result in a downstream surge of gas if a vortex were to occur. The conditions for stratification are addressed in TR Section 6.3.6. If the TR Section 6.3.6 methods indicate flow can stratify in the horizontal pipe, then the following options are stated to exist:

    (a) If there is a vertical DC in the flow path downstream of the off-take, the allowable gas volume can be calculated using WCAP-17271 or WCAP-17276 by assuming the accumulation location is downstream of the off-take.

    (b) If the off-take is vertically upwards then a vortex will not occur and WCAP-17271 or WCAP-17276 can be used

    (c) If Conditions a or b do not apply, then WCAP-17271 or WCAP-17276 cannot be used.

(3) If the pump has a vertical downwards inlet and the gas accumulation location is immediately upstream of that DC, WCAP-17271 or WCAP-17276 cannot be applied if $N_{FR} > 2.5$. This situation can result in co-current slug flow of gas directly into the pump inlet.

(4) If the pump has a horizontal inlet preceded by a vertical DC, and $N_{FR} < 1$, WCAP-17271 or WCAP-17276 cannot be applied since criteria are not available for determining if a kinematic shock or hydraulic jump would occur in the horizontal inlet piping. Note, however, that the NRC staff has used $N_{FR} = 0.93$ data when it contributed to verification of correlations.

TR Figure 12-4 outlines the WCAP-17276 methodology, commonly referred to as the Simplified Equation. This corresponds to TR Section 10.4.2.1 that was found to be acceptable.

TR Figure 12-5 outlines the WCAP-17271 methodology, also referred to as the Purdue method or Purdue correlations. The description is consistent with the NRC staff assessments and is acceptable.

TR Figure 12-6 shows the method used to determine if the allowable gas volume is limited by the DC volume. This starts with using TR Eq. 6-1 to determine the gas volume that can be accommodated by the DC consistent with containing the waterfall effect. The remainder of the figure is correct although the choice of words could be improved because the meaning of "gas volume" is not clear. As discussed previously, TR Eq. 6-1 is acceptable. Consequently, TR Figure 12-6 is acceptable.

TR Figure 12-7 provides a method for evaluating the horizontal pump inlet flow. If a pump has a horizontal inlet, then homogeneous bubbly flow must occur at the pump inlet or any deviation from that condition must be shown to not jeopardize pump operability. Additional horizontal pump inlet conclusions include (1) TR Eq. 6-6 is acceptable for use provided $1.25 \leq N_{FR} \leq 1.75$, (2) no shock will form in the lower horizontal pipe if β_{avg} < **[ ]**, (3) if a shock forms, there is limited information to establish the shock formation location, (4) TR Eq. 6-7 is an acceptable description of void behavior when a safety factor is used to account for the β_{max} scatter shown in TR Figure 6-12, (5) if a pump is located near the end of the lower elbow, a prediction based on average fluid properties should be justified, and (6) TR Figure 12-7 references TR Eq. 6-19 for calculating a gas volume but the TR provides a TR Eq. 6-19 that calculates head loss. Consequently, TR Figure 12-7 is not acceptable.

TR Figure 12-8 provides a method for determining if a horizontal off-take limits the allowable gas volume. This is an oversimplification and is not acceptable.

3.12 TR Section 13, Conclusions

The TR stated that Section 3.15.3 of the NEI-09-10 SE placed limitations on gas void ingestion by pumps to assure bubbly flow at the pump entrance and that the average void fraction meets acceptance criteria defined in NEI-09-10. The TR summarized addressing these limitations on the use of WCAP-17271 and WCAP-17276 in **bold** followed by the NRC staff assessment as follows:

- **Sufficient volume in the vertical down-comer downstream of the gas accumulation location is needed to assure bubbly flow at the down-comer exit if a vertical down-comer exists.** TR Eq. 5-6 was found acceptable to predict DC size in SE Section 3.2.3.3 subject to the limitation that DC length must be sufficient to reasonably ensure a homogeneous exit flow since a short DC that satisfies TR Eq. 5-6 may not satisfy the assumption that the model is based on the existence of uniform properties in the pipe cross sectional area.

- **If a horizontal pipe connects between the bottom of a down-comer and a pump entrance, a methodology should be applied that has a multi-dimensional two phase capability that has been verified by comparison to experimental data.** The TR states that the phenomena are not well understood, judgement may be a significant factor, and a suitable safety factor should be added. This applies to the region immediately downstream of the DC exit elbow that connects to the lower horizontal pipe. The NRC staff agrees.

  Further, in response to the TR statements, (1) TR Eq. 6-6 is acceptable for predicting the minimum required β to develop a kinematic shock at the elbow outlet provided $1.25 \leq N_{FR} \leq 1.75$, (2) no shock will form in the lower horizontal pipe if β_{avg} < **[ ]**, (3) TR Eq. 6-7 is acceptable for prediction of β_{max} when a safety factor is used, and (4) TR Eq. 6-21 provides the pipe inlet volume to ensure the kinematic shock does not encroach on the pump inlet.

- **Horizontal pipes may introduce concerns such as flow stratification that can lead to an accumulation of gas, such as in off-take or tee geometry. Once gas is accumulated, a subsequent instability can lead to a large surge in gas downstream.** The TR states that the provided flow regime maps and analytical considerations demonstrate that flow stratification will not occur when $N_{FR} \geq 1$ and $\beta_{max} \leq 0.25$. The NRC staff finds this acceptable.

- **If Froude number is greater than 2.5, there is a potential that a void will be transported as a slug.** This limit was imposed because the Purdue tests did not significantly cover N_{FR} > 2.5. However, co-current slugs that broke up rapidly were observed in some of the Purdue tests at N_{FR} > 2.5, consistent with TR Figure 6-23 (Figure 19) that indicates a dispersed flow regime would exist in a horizontal header. This information, in addition to the vertical to horizontal elbow that holds up gas, led to a TR assumption that a co-current slug would be broken up quickly, and the Froude number limit of 2.5 is not applicable to a horizontal pipe entrance to a pump. This is acceptable.

The TR concludes that the TR information enables licensees to develop acceptance criteria to be used in operability evaluations for allowable gas volumes in safety related pump suction piping. The NRC staff agrees.

3.13 TR Appendix A, Description of Dynamic Venting Test Facility

Aspects of the W facility were described in TR Figures A-1 and A-2 and in Table 4. This facility and associated tests were first reported to the NRC in the TR. Both gas and liquid flow rates were measured. This provides a basis for improved guidance in tests associated with suction piping. The TR Figure A-1 double ring impedance meters are designated by VM.

Most 6-inch piping was clear PVC six-inch Schedule 40 pipe with an inside diameter of 6.065 inches and a flow area of 0.2006 ft^2. The high point volume that includes VM7 is (24.75)(0.2006) = 4.965 ft^3. The high point volume associated with Location 1 is (8)(0.2006) = 1.605 ft^3. Two AFMs were used in different tests. Air injection location 1 was used for tests involving the four-inch and six-inch 90° elbow. Air injection location 2 was used for tests involving orifices and a check valve. Liquid flow rate was measured downstream of the pump. The tank was kept near 14.7 psia and 70˚F to act as a gas separator, which maintained water solid conditions through the pump and liquid flow meter.

Figure 20 illustrates the test facility piping that was used for four-inch elbow testing.

Figure 20 Four Inch Elbow Test Configuration

Figure 21 illustrates the piping used for orifice tests.

Figure 21 Orifice Tests

A dynamic venting test program was conducted in which gas was injected through AFM Location 1 (see TR Figure A-1). The initial air volumetric flow rate was about 5 percent of the water flow rate. Water flow rate was then held constant and air flow rate was increased until gas was observed to accumulate (kinematic shock was initiated) at the exit from the downstream elbow that was connected to the DC. This was assumed to indicate that the DC and elbow could accumulate no additional air and air entering the DC would result in the same quantity being expelled into the lower horizontal pipe. Flow rates were then held constant until the separated region extended to the horizontal downstream elbow located at the left end of the pipe illustrated in Figure A-2. Then air injection was stopped, and the hydraulic jump entrained the air away. Data were collected from the time air injection was stopped until all air was removed from the lower horizontal pipe.

3.0 CONCLUSIONS

4.1 PWROG-15060

Topical report (TR) PWROG-15060 (W, December 31, 2015):

(1) provides acceptable methods for operability determinations to predict the volumetric flux (β) of a non-condensable gas at a pump inlet based on the gas volume at an upstream location. This enables licensees to develop acceptance criteria to be used in operability determinations and evaluations for allowable gas volumes in pump suction piping.

(2) is weak when addressing the location of a kinematic shock in a lower horizontal pipe that can affect a downstream pump; a condition that the NRC staff will accept as allowed for operability determinations in the NRC SE Section 2 but a condition that should be improved. The TR treatment of this condition was summarized as acceptable in SE Section 3.12.

4.2 Analysis Methods and Related Findings

The TR analysis methods apply to a configuration that consists of an upper horizontal pipe where gas is assumed to have accumulated, a vertical DC, and a lower horizontal pipe that leads to a pump. The modeled behavior assumes that (1) at time zero a pump has started, and all gas has moved into the upper DC and (2) the DC length is sufficient that TR Eq. 5-6 may be used to predict DC length. With the exception of offtakes, the TR does not address vortexing, localized level reduction, or air ingestion during flow from tanks, sumps, or large pipes.

The analysis methods are based on position and time-averaged properties. The correlating parameters are sometimes inconsistent. For example, pump ramp-up is sometimes not complete before the analysis that is based on completion of the ramp-up has finished and correlating parameters such as Froude number (N_{FR}) and the initial upper horizontal pipe void fraction (α) are inconsistent with the values used in the analyses. Despite this, the analysis methods have been shown to acceptably correlate experimental data for operability determinations.

The TR describes a Simplified Equation that is documented in WCAP-17276 (W, January 2011) that assumes homogeneous flow with no allowance for trapping gas in the suction piping and the TR describes a more comprehensive method documented in WCAP-17271 that considers gas accumulation in suction pipes as gas passes through the pipes (W, October 2010). The WCAP-17271 method includes an upper elbow holdup correlation and a lower elbow holdup correlation that reduces the amount of gas that reaches a pump.

The gas analysis methodologies require a sufficient volume in the vertical DC downstream of the gas accumulation location to assure bubbly flow at the DC exit if a vertical DC exists. TR Eq. 5-6 provides a minimum DC length to meet this requirement provided DC length is sufficient to meet modeling assumptions. A length of three pipe diameter is judged to meet this requirement.

4.3 Tests

WCAP-17271 (W, October 2010) summarizes the results of gas transport testing in pump suction piping conducted at Purdue University. These results were used to develop the acceptable TR Eq. 6-7 that describes the maximum β at the DC exit as a function of the vertical kinematic shock length as predicted by TR Eq. 5-6.

The TR did not address that RCS water contains chemicals that may change the water flow characteristics yet the analysis methods are based on tests that used clean water. The NRC staff concluded the potential flow differences could be neglected on the basis of published regulatory guidance (NRC, January 31, 2014).

TR Eq. 5-6 acceptably predicts the distance the separated flow region (kinematic shock) will extend from the top of the horizontal elbow at the entrance to a DC to ensure bubbly flow exists at the DC outlet provided the predicted length is sufficient to reasonably ensure that a homogeneous flow condition exists at the DC exit as assumed in the derivation of TR Eq. 5-6.

The testing measured the kinematic shock depth as a function of distance and flow rate. The data were used to establish TR Eq. 6-21, the pipe volume required to ensure the kinematic shock does not encroach upon the pump inlet.

The method used to obtain time span (Δt) and β in the Purdue tests is confirmed by the W facility tests where air flow rates were measured.

4.4 Lower Horizontal Pipe Issues

W summarized tests to establish dynamic venting requirements (W, September 2012). As part of this testing, the air flow rate necessary to develop gas flow separation (kinematic shock) at the outlet of a vertical-to-horizontal elbow was determined as a function of water flow rate. These data were used to develop TR Eq. 6-6 for the minimum required β to develop a kinematic shock at the elbow outlet as a function of N_{FR}. A limitation in use of TR Eq. 6-6 is that it is limited to $1.25 \leq N_{FR} \leq 1.75$ in contrast to the TR claim of a wider range. Although the TR approach to addressing the lower horizontal pipe phenomena is acceptable, it should be improved to provide the location of a shock in the lower horizontal pipe.

The lower elbow holdup correlation covers the distance between a vertical DC to a horizontal pipe to downstream of a kinematic shock in the horizontal pipe provided the horizontal pipe is long enough to contain the shock. It does not model the flux ratio change from the elbow entrance to the elbow exit. This is a weakness that should be addressed, perhaps by a new series of tests. Regardless, the existing methodology is acceptable in recognition of conservatisms incorporated into the calculations, the investigations described in the TR, and the flexibility permitted by the regulations as discussed in SE Section 2 for operability determinations.

Horizontal pipes could potentially introduce flow stratification that could lead to gas accumulation such as in an off-take or tee geometry. Once gas is accumulated, a subsequent instability or change in the flow path could lead to a large surge in gas downstream. The TR states that the provided flow regime maps and analytical considerations demonstrate that flow stratification will not occur when $N_{FR} \geq 1$ and $\beta_{max} \leq 0.25$. This is acceptable.

It is the licensee's responsibility to reasonably and acceptably address the relevant gas transport phenomena. This includes any configurations that may result in a transition from bubbly flow to either stratified or slug flow.

4.5 Offtakes and Tees

The WCAP correlations do not provide in-depth guidance for addressing features of complex piping systems such as tees, offtakes, multiple header connections, and specific pump inlet geometries. The broad generalizations are acceptable for addressing such configurations.

TR Section 6.3.6 concludes by stating that the following criteria that will be used to treat off-takes from horizontal headers that are upstream of pump inlets that are consistent with use of WCAP-17271:

[

]

Criteria 1, 2, 3, and 5 are acceptable. Criterion 4 is not acceptable for flow through a horizontal tee with a stagnant vertically upward offtake.

TR Section 6.3.6 utilizes flow regime maps for horizontal pipes developed from air-water test data (Weisman, 1979) and from analytical considerations (Taitel, January 1976) to demonstrate that as long as $N_{FR} \geq 1$ and $\beta \leq 0.25$ in an offtake header or a tee, gas cannot separate from the liquid into a stratified flow regime. The TR states that gas will be transported by the liquid in an flow regime which will preclude gas accumulation such as in off-take or tee geometry The Weisman tests were with small diameter pipes and geometries that are inconsistent with plant configurations. Never-the-less, the test results are useful in identifying trends.

4.6 Additional Guidance

If TR Section 6 cannot be met, TR Eq. 7-1 provides the NRC method for calculating a gas accumulation volume. This often predicts a volume that is too small and, when this occurs, the TR states that appropriately scaled testing is the preferred approach. This is acceptable.

TR Section 6.3.7 supports a conclusion that a co-current slug in a DC would be broken up quickly, and the N_{FR} limit of 2.5 is not applicable. Removal of this limit is acceptable except for pumps with vertically downward inlets.

4.7 Errors and Approximations

The TR examples and usage guidance contain errors that must be considered if the processes are followed. For example:

- The TR Section 11 simplified equation example contains a calculation error that results in prediction of a time, Δt, = 0.3 sec and an allowable high point volume of 0.024 ft^3. The correct values are 1.466 sec and 0.116 ft^3.

- TR Eq. 6-6 is claimed to apply to a wide N_{FR} range.

The TR states that the pump inlet gas flux will continually decrease as gas is moved from the accumulation location to the pump inlet. In general, this is acceptable but there are exceptions. For example, the TR 6.3.4 description incorrectly omits DC behavior below the gas volume due to the waterfall impact although this is addressed in TR Section 6.3.1.

5.0 LIMITATIONS AND CONDITIONS

In general, the WCAP-17271 correlations should not be used for pipe diameters smaller than 4 inches. However, smaller pipes are acceptable if no gas passes through those pipes.

The WCAP 17271 and 17276 methodologies are not applicable if there is a kinematic shock in a vertical DC which is too small to contain the separated gas.

All of the gas should be assumed to travel towards a pump along each potential path when assessing gas movement at offtakes and tees unless an acceptable alternate approach is provided. Some gas may accumulate in an inactive branch or in a larger diameter header and this could later move toward a downstream pump. Licensees should reasonably establish that potential gas accumulation will not lead to subsequent gas movement into a pump that could cause a loss of operability.

The TR states that header flow rates should be identified assuming all pumps operate (no single failure) and assuming the limiting single failure. The larger flow rate should be used in the gas transport evaluation. The lower flow rate should be used to demonstrate that flow does not stratify in horizontal headers.

Two pump configurations are identified in TR Section 10.2.8, a pump with a vertically downward inlet for which TR Section 6.3.7 criteria must be met and a pump with a horizontal inlet for which TR Section 6.3.5 criteria must be satisfied. It is necessary that TR Eq. 5-6 be satisfied for each pump. If the pump has a horizontal inlet, it is also necessary to demonstrate that homogeneous bubbly flow occurs at the pump inlet or that any deviation from that condition does not jeopardize pump operability.

The TR states that the existing methodology does not incorporate a correlation to determine the gas flow distribution at an off-take and it is assumed that all of the gas goes through the off-take in the direction of the pump under evaluation. This is acceptable with the qualification that potential problems due to assuming a lower flow rate are addressed.

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Appendix A PWROG Draft SE Comments and NRC Staff Responses					
Comment Number	**DSE Page No.**	**DSE Line No.**	**Comment Type**	**PWROG Comment**	**NRC Response**
1	15	6	Correct a typographical error	The OG-18-224 comment indicated that 10^2 should be changed to $10D^{2.5}$. This change was made in the title of the paragraph, but not in the last sentence of the paragraph. Therefore 10^2 should be changed to $10D^{2.5}$ in the revised DSE.	Agreed. Change was made.
2	18	9-10	Correct an inconsistency	PWROG Comment B.0 of OG-18-224 Attachment B addressed the DSE limitation of TR Equation 6-6 to $1.25 \leq N_{FR} \leq 1.75$. The revised DSE states "TR Eq. 6-6 was incorrectly correctly assumed to hold for $1 \leq N_{FR} \leq 2.25$ with βmin reqd = 0.188 for $N_{FR} > 2.25$." The word "incorrectly" should be replaced with "correctly" to address the PWROG comment B.0 of OG-18-224 and for consistency with page 47, lines 17 and 18 of the revised DSE.	Agreed. Change was made.
3	18	34-35	Correct an inconsistency	PWROG Comment B.0 of OG-18-224 Attachment B addressed the DSE limitation of TR Equation 6-6 to $1.25 \leq N_{FR} \leq 1.75$. The revised DSE states "Eq. 6-6 is not	Agreed. Change was made.

Appendix A PWROG Draft SE Comments and NRC Staff Responses					
Comment Number	**DSE Page No.**	**DSE Line No.**	**Comment Type**	**PWROG Comment**	**NRC Response**
				acceptable for use significantly outside of 1.25 ≤ N_{FR} ≤ 2.25." This should be replaced with "Eq. 6-6 is acceptable for use for 1.00 ≤ N_{FR} ≤ 2.25, and remains constant for N_{FR} > 2.25" to address the PWROG comment B.0 of OG-18-224 and for consistency with the revised DSE page 47, lines 17 and 18.	
4	42	14	Correct a typographical error	PWROG Comment B.1 of OG-18-225 Attachment B indicated that RCS Chemical Effects need not be addressed. This comment was incorporated, but the phrase "With one exception," should be deleted, since the exception relates to RCS Chemical Effects, which was deleted in the revised DSE.	Agreed. Change was made.
5	44 45	47 1-2	Correct the inconsistency	PWROG Comment B.2 of OG-18-225 Attachment B addressed kinematic shock formation and growth in the lower horizontal header. The revised DSE phrase "This was also assumed to indicate that the DC and elbow could accumulate no additional air and air entering the DC would result in *the same quantity being*	Agreed. Change was made.

Appendix A PWROG Draft SE Comments and NRC Staff Responses					
Comment Number	**DSE Page No.**	**DSE Line No.**	**Comment Type**	**PWROG Comment**	**NRC Response**
				expelled into the lower horizontal pipe" should be replaced with "This was also assumed to indicate that the DC and elbow could accumulate no additional air and air entering the DC would *accumulate in* the lower horizontal pipe." The shock grows by accumulating air. If the air was expelled then the shock would not grow. The additional air into the DC and elbow accumulates in the lower horizontal header once the DC and elbow cannot accumulate additional air.	
6	46	21-22	Correct an inconsistency	PWROG Comment B.0 of OG-18-224 Attachment B addressed the DSE limitation of TR Equation 6-6 to $1.25 \leq N_{FR} \leq 1.75$. The revised DSE phrase "This is inconsistent with the TR statement that TR Eq. 6-6 covers the NFR range from 1 to 1.9" should be deleted, since this refers to DSE Figure 16 which does not incorporate the 2018 PWROG data. This change is also necessary for consistency with the revised DSE statement on page 47, lines 17 and 18.	Agreed. Change was made.

Appendix A PWROG Draft SE Comments and NRC Staff Responses					
Comment Number	**DSE Page No.**	**DSE Line No.**	**Comment Type**	**PWROG Comment**	**NRC Response**
7	46 47	24-26 1-7	Correct an inconsistency	The revised DSE states "The TR assumed linear behavior (sic) could be assumed out to NFR = 2.25 and that β = 0.188 for NFR > 2.25. The staff found that a cubic equation was the best fit for TR Eq. 6-6 between NFR =1 and 1.9, which is shown by the dotted line in Figure 17." DSE Figure 17 does not incorporate the PWROG data obtained in 2018 for N_{FR} > 2.2. Incorporation of the 2018 data in Figure 17 would clearly demonstrate that the cubic polynomial does not represent a better fit than TR Eq 6-6. The revised DSE statement that a cubic equation was the best fit for TR Eq. 6-6 between NFR =1 and 1.9 is also inconsistent with the statement on page 47, lines 9-18 of the revised DSE.	Agreed. Change was made