ATTACHMENT March 26, 2009

REVISION 2 TO NRC STAFF CRITERIA FOR GAS MOVEMENT IN SUCTION LINES AND PUMP RESPONSE TO GAS

I INTRODUCTION

This document provides acceptance criteria that the NRC staff may apply to assessment of gas movement in suction lines and pump response to gas in such documents as responses to GL 2008-01 and licensee functional and operability evaluations. This is not an all-inclusive document. Subjects not addressed below, such as gas in pump discharge piping, are important and should be addressed when they arise.

Revision 1 (Reference 1) addressed information received since the original criteria were provided in Reference 2 and it included editorial changes to better describe the subject. Revision 2 addresses information received since Revision 1 was issued and includes information obtained during the References 3 and 4 March 19, 2009 meeting with the Gas Accumulation Team (GAT)[1]. If the items being investigated are bounded by the Revision 2 criteria, then the items may be accepted by NRC staff members without further justification. Other criteria may also be used if acceptable justification is provided, consistent with the requirement that a reasonable expectation of operability is required, not an absolute expectation.[2] Industry is continuing to investigate GL issues pertaining to gas movement and pump response and future revisions to these criteria are anticipated as new information is obtained.

II REVISION CHANGES

A Changes Incorporated into Revision 1

1. Changed Item 1 in the Interim Gas Movement Criteria table from being applicable to a pipe diameter, D, from ≤ 3 inches to ≤ 8 inches on the basis of new understanding addressed in the Reference 5 tests. The remainder of the document was changed to be consistent.

2. Added qualifications to the tabulated criteria to address multi-dimensional flow configurations

3. Added qualifications to the tabulated criteria to exclude slug flow since available information indicates slug flow can cause immediate pump damage.

4. Corrected the transient times of void fractions of 100% and 50% in comparisons to the PWROG acceptable average value of 20%.

5. Incorporated Reference 5 discussion of behavior as a function of Froude number (N_{FR}).

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[1] The GAT consists of members of the Pressurized Water Reactor Owners Group (PWROG), the Boiling Water Reactor Owners Group (BWROG), the Nuclear Energy Institute (NEI), and several licensee representatives,

[2] Reasonable expectation does not mean absolute assurance. Operability may be based on analysis, a test or partial test, experience with operating events, engineering judgment, or a combination of these factors. This is addressed in References 6 and 7.

6. Included Flowserve information in discussion of pump response to gas.

B <u>Changes Incorporated into Revision 2</u>

1. Changed definition of steady state from > 20 seconds to no time limit in recognition than some plant transients may continue for a greater time and some may be less. The former appear to be represented by some unpublished plant operability assessments and the latter are consistent with recent test data illustrated in Reference 4.

2. Changed calculation of Φ for transients from a maximum or peak value to average values based on 0.5 second time spans in recognition of noise and rapid transient behavior in both calculations and test data that are not representative of actual behavior that would impact a pump. This eliminates the need for specifying that slug flow does not occur since anything approaching slug flow would be identified in the value of Φ and would not meet the acceptance criteria.

3. Expanded discussion of applicability of the void criteria from the emergency core cooling system (ECCS) to include the decay heat removal (DHR) system and the containment spray system, consistent with the subject systems addressed by GL 2008-01.

4. Updated the discussion to reflect these changes, to delete discussion that is no longer necessary, and to address other information and industry interactions that have occurred since Revision 1.

III NRC STAFF CRITERIA FOR GAS MOVEMENT IN SUCTION LINES AND PUMP RESPONSE TO GAS

Criteria the NRC staff will accept without further justification for transport of gas into a pump that is part of the subject systems are:

Table 1. Interim Gas Movement Criteria		N_{FR}
1.	Gas is not transported down a vertical pipe if Φ ≤ 20% at the top of the pipe and D ≤ 8 inches.	≤ 0.3
2.	Gas is not transported out of a nominally horizontal pipe into a downward-oriented vertical pipe under steady state conditions if the water is in the bottom of the horizontal pipe and Φ ≤ 50% at the horizontal pipe exit.	< 0.4

where: D = pipe diameter
Φ = average volumetric gas fraction measured in a plane perpendicular to the pipe centerline

$$N_{FR} = V \, [\, D \, g_c \, (\, \rho_L - \rho_g \,) \, / \, \rho_L \,]^{-1/2}$$

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

These criteria are not applicable to configurations where an equivalent diameter is used, such as in an annulus, because it may be necessary to consider both the liquid and the gas as separate components when calculating N_{FR}. Further, with the exception of pipes with a circular cross section and elbows that connect between horizontal and vertical pipes, the criteria only apply to geometries where the velocity is parallel to the pipe centerline because experimental data have not been provided to substantiate two phase / two component flows in other geometries.

Criteria the NRC staff will accept without further justification for not jeopardizing operability of a subject system pump are:

Table 2. Pump Operation Interim Criteria		Allowable Φ	Comparison with Reference 4 GAT Criteria
1.	Steady state, 40% ≤ Q/Q_{BEP} ≤ 120%	2%	Identical except NRC staff uses separate assessment of head reduction. See Item 5.
2.	Steady state, Q/Q_{BEP} < 40% or >120%	1%	Reference 4 does not provide criteria.
3.	Transient of ≤ 20 sec duration. 70% ≤ Q/Q_{BEP} ≤ 120%	10% for all 0.5 sec time spans	NRC staff determines Φ over each 0.5 sec time span whereas Reference 4 averages over a 5 or 20 sec time span. GAT uses 10% for typical BWR pumps and PWR multi-stage flexible shaft pumps to preclude pump damage; 5% for typical single stage and 20% for multi-stage stiff shaft PWR pumps. Note the NRC staff criteria do not address the potential impact of reduced pump head on flow rate and the potential of suction pipe voids affecting NPSH.
4.	Transient with Q/Q_{BEP} < 70% or >120%	5% for all 0.5 sec time spans	Reference 4 uses 5% for typical single stage and multi-stage stiff shaft PWR pumps. The above Item 3 NRC staff criteria comments also apply.
5.	Head reduction is negligible if steady state and 80% ≤ Q/Q_{BEP} ≤ 110%. See Page 5, below, for NPSH.	2%	NEI uses 2% for 40% ≤ Q/Q_{BEP} ≤ 120%. NRC accepts 1 % for negligible head reduction and states that head reduction should be assessed if not within 80% ≤ Q/Q_{BEP} ≤ 110% with 1% < Φ < 2%.

where: Q = water volumetric flow rate
BEP = best efficiency point.

The acceptance criteria are based on available information with recognition that the available data are limited and, in some cases, non-existent. This is particularly true of transient conditions that often will present the most challenge to pump operation. In some cases, meeting the criteria will be straightforward. For example:

- One criterion addresses flow rates that are small enough that a significant gas quantity will not be swept downward in a pipe leading to the pump suction. When the pump is initially full of water,[3] meeting this criterion leads to the conclusion that there is no concern. A pump flow rate corresponding to flow in the miniflow line will often satisfy this criterion. If pump flow rate then increases slowly, the gas at the pump inlet may consist of small bubbles and the rate of gas movement into the pump may be small enough for the suction line gas to be cleared without significantly affecting the pump.

- Another criterion applies to a pump that develops a flow rate sufficient to sweep gas into the pump when Φ exceeds acceptance criteria. In this case, the pump must be assumed lost due to loss of operability unless the licensee can substantiate that the criterion is overly conservative for the existing conditions.

In other cases, the assessment will present more challenges. For example, consider an ECCS pump that is initially full of water that is injecting into the reactor coolant system (RCS) at a known pressure. An initial prediction of flow rate can be determined from a flow rate versus developed head curve[4] that applies to a $\Phi = 0$ condition by calculating discharge pressure at the pump as the sum of RCS pressure and downstream differential pressure where the latter is a function of flow rate. But if this predicted flow rate will cause gas to enter the pump from an upstream gas volume, the flow rate versus developed head curve will be affected and the developed head will be less than previously determined. Using the new developed head value will result in a reduction in predicted flow rate. An iterative process results to obtain convergence of Φ and flow rate. Simultaneously, pump net positive suction head (NPSH) criteria are affected by gas entering the pump and by gas in the suction line. NPSH criteria must continue to be met for the pump to be considered operable.

There is significant scatter in information used to correlate gas transport; available data do not adequately represent pipe orientation, flow rate, and pipe size; and a number of different flow regimes can occur in suction piping depending upon Φ, pipe orientation, flow rate, and pipe size. Further, licensees typically determine gas volumes without considering measurement uncertainties. These volumes are then used in determining the influence of Φ and gas location on pump operability. The NRC staff has considered this background in conjunction with the requirement that there be a reasonable expectation of operability in selecting its acceptance criteria as discussed below.

The Table 1 $N_{FR} \leq 0.3$ criterion is almost a factor of 3 less than the value sometimes used by licensees although it is close to the < 0.35 provided by References 4 and 5 for gas in a vertical pipe. 0.3, rounded from 0.31, was taken from Simpson's publication in Chemical Engineering (June 17, 1968) that is referenced in numerous other publications as a value to reasonably ensure that significant quantities of gas will not be transported downward in a vertical pipe. 0.3 is retained in Revision 2 because the NRC staff does not have sufficient data to justify a larger

[3] The NRC staff will consider that a pump is full of water if the gas volume within the pump is less than 5% before it is started. A pump that initially contains a larger gas volume will be considered to be inoperable unless operability is justified for the gas volume that exists.
[4] Pump characteristic curves may be based on conservative assumptions to bound 10 CFR 50.46 requirements. Such curves may not be applicable here. For example, a conservative curve may provide a smaller flow rate than actual which may, in turn, cause predicted Φ at the pump inlet to be too small. Conversely, use of a flow rate that is too great may cause the gas to move through the system more rapidly and may move the applicable acceptance criterion from the steady state to a transient condition where Φ may be found acceptable as opposed to a smaller allowable Φ in the steady state. It is also necessary to consider cases where all pumps are operating in contrast to design basis analyses where one train is assumed to be failed.

value. The $D \leq 8$ inches criterion is retained because additional test results for larger diameter pipes have not been provided to the NRC staff. This diameter criterion is likely to change when new information becomes available. The $\Phi \leq 20\%$ criterion is to ensure that water does not drop in a waterfall configuration into a vertical pipe where momentum might carry gas to the bottom of the vertical pipe.

The $N_{FR} < 0.4$ criterion is roughly 25% smaller than typically used to assess horizontal flow to account for gas volume determination and data uncertainty in addition to having transient conditions whereas most data are for a steady state. The NRC staff notes that Reference 5 states that $N_{FR} > 0.55$ will cause a pipe to run full if discharge is to an empty plenum and that $N_{FR} = 0.55$ may not be sufficient to purge all gas out of a local high point. The $\Phi \leq 50\%$ criterion at the pipe exit is to ensure that there is a layer of water in the bottom of a horizontal pipe where it meets a vertical pipe that includes consideration of a decrease in level as water flows along the horizontal pipe and to account for transient variation in flow along the pipe during startup or changing conditions.

Additional data and analysis will be necessary to assess gas movement for $\Phi > 20\%$, $D > 8$ inches, or larger N_{FR}, although the NRC staff believes larger Φ's in pipe diameters larger than a few inches may be reasonable if the vertical pipe is long enough to justify that local effects at the top of the pipe no longer affect the behavior. The NRC staff criteria that bound Φ at 20% or 50% are provided to address most of the concern associated with local gas behavior such as eliminating allowing a waterfall within acceptable criteria when water from a horizontal pipe enters a vertical pipe.

The 2% steady state value in Item 1 of Table 2 is consistent with the GAT Reference 4 values. The NRC staff expects consideration of the effect of voids on developed head when outside the $80\% \leq Q/Q_{BEP} \leq 110\%$ with $1\% < \Phi < 2\%$ as identified in Item 5. NUREG/CR-2792 discusses the increasing impact of Φ when Q is not close to Q_{BEP} that in some cases results in greater than a factor of two reduction in developed head. Other industry information states that $\Phi = 2\%$ is inappropriate for some conditions. The 1% in Item 2 is generally consistent with that information, although there is some information that identifies a concern that gas can accumulate in some pumps over time with $\Phi < 1\%$.

For transients, the PWROG and BWROG previously used an average Φ based on a time span of either 5 or 20 seconds (Reference 8). Reference 4 illustrates a Φ based on a 5 second time span that brackets the maximum Φ, but the time span that will actually be used is not defined and post-meeting discussion established that the time span to be used to calculate Φ is being evaluated. The NRC staff believes 5 seconds is too large since it could still allow slug flow to occur, although the NRC staff also recognizes that slug flow will not be allowed as stated in Reference 4. For purposes of this revision to the NRC staff criteria, an average Φ based on a time span of 0.5 seconds has been selected[5] to account for noise and rapid transient behavior in both calculations and test data that are not representative of actual behavior that would impact a pump. This also eliminates the need for specifying that slug flow does not occur since anything approaching slug flow would be identified in the value of Φ and would not meet the stated acceptance criteria. The GAT is considering an approach that considers such items as pump volume and flow rate in conjunction with Φ to better characterize the time span and, if acceptably developed with consideration of such characteristics as active pump volume and impeller response to void, then the NRC staff may change the 0.5 second criterion.

[5] The intent is that the transient will be divided into 0.5 second segments and Φ will be calculated for each segment.

The PWROG Reference 4 pump transient criteria applicable to pump damage for 70% ≤ Q/Q_{BEP} ≤ 120% are as follows:

Interim Criteria	Average Φ, %
Single stage for 20 sec	5
Multi-stage stiff shaft for 20 sec	20
Multi-stage flexible shaft for 5 sec	10

The NRC staff uses one criterion of Φ = 10% for all pumps and a 20 second transient span time where Φ is calculated for 0.5 second time spans over the duration of the transient. This is based on such considerations as air binding of the first impeller which would starve following impellers in multi-stage pumps and reduce the head, but not necessarily cause pump damage, and the 0.5 second time span used to obtain values of Φ over the transient which effectively increases the Reference 4 5% value that is determined over a 20 second time span.

Assessments are also necessary to establish pump operability. Head degradation and NPSH must be assessed to confirm that the Φ limits are acceptable because Φ > 0 may (1) reduce the developed head, (2) reduce the available NPSH, and (3) increase NPSH required by the pump. Either the smaller of the tabulated Φs or the value of Φ that does not reduce flow rate below an acceptable value is to be used for an acceptance determination.

The NPSH required for an air / water mixture can be calculated from the NUREG/CR-2792 equation that was selected by some in industry for this purpose:

$$NPSH_r = NPSH_{r\ for\ liquid}\ [\ 1 + 0.5\ \Phi\ ]$$

where Φ ≤ 2%. Although the correlation is based upon meager data, it includes a substantial conservatism.

REFERENCES

1. Beaulieu, David P., “Forthcoming Meeting With The Nuclear Energy Institute (NEI) To Discuss NRC Generic Letter 2008-01, ‘Managing Gas Accumulation In Emergency Core Cooling, Decay Heat Removal, And Containment Spray Systems,’” NRC Memorandum, ML090150637, January 15, 2009.

2. Beaulieu, David P., “Forthcoming Meeting With The Nuclear Energy Institute (NEI) To Discuss NRC Generic Letter 2008-01, ‘Managing Gas Accumulation In Emergency Core Cooling, Decay Heat Removal, And Containment Spray Systems,’” NRC Memorandum, ML083250536, November 21, 2008.

3. Lyon, Warren C., “03/19/2009 – Notice of Public Meeting with the Nuclear Energy Institute (NEI) to discuss NRC Generic Letter 2008-01, ‘Managing Gas Accumulation In Emergency Core Cooling, Decay Heat Removal, And Containment Spray Systems,’” NRC Memorandum, ML090560528, February 25, 2009.

4. “NRC – Industry Gas Accumulation Team Meeting,” Industry Gas Accumulation Management Team slides received by NRC during the Reference 5 meeting, ML??, March 19, 2009 . THIS NEEDS TO BE UPDATED TO THE DOCUMENT THAT DAVE WILL PUT INTO ADAMS.

5. Preliminary Assessment of "Testing And Evaluation of Gas Transport to the Suction of ECCS Pumps," Westinghouse Electric Company LLC, WCAP-16631-NP, Revision 0, October 2006. (This document has not been provided to NRC on the docket. Referenced information is based on notes from reading the reference.)

6. "Technical Guidance, Operability Determinations & Functionality Assessments for Resolution of degraded or Nonconforming Conditions Adverse to Quality or Safety," NRC Inspection Manual Part 9900, ML052060365, September 26, 2005.

7. "Functionality Assessments for Resolution of degraded or Nonconforming Conditions Adverse to Quality or Safety," NRC Regulatory Issue Summary (RIS) 2005-20 Rev. 1, ML073440103, April 16, 2008.

8. Beaulieu, David P., "Summary of the September 4, 2008, Category 2 Public Meeting with the Nuclear Energy Institute to Discuss NRC Generic Letter 2008-01, 'Managing Gas Accumulation In Emergency Core Cooling, Decay Heat Removal, And Containment Spray Systems,'" NRC Memorandum, ML082770088, October 6, 2008. See also "Industry / NRC Meeting on Generic Letter 2008-01, 'Managing Gas Accumulation In Emergency Core Cooling, Decay Heat Removal, And Containment Spray Systems," Nuclear Energy Institute presentation slides, ML082770090, September 4, 2008.