Industry Guidance for Evaluation of Unexpected Voids or Gas Identified in Plant ECCS and Other Systems

PURPOSE

The purpose of this attachment is to provide guidance for licensees in the evaluation of unexpected void or gas in ECCS and other systems. Specifically, the determination of Prompt Operability for these systems will be addressed, in the context of products provided by the Pressurized Water Reactor Owners' Group (PWROG) and Boiling Water Reactor Owners' Group (BWROG). These Owners Groups have spent significant effort in developing these products with the express intent of supporting system Operability. The guidance provided has been conservatively established to cover a broad spectrum of equipment and operation, and is not intended to displace more specific guidance from NSSS vendors, pump vendors, or engineering evaluation which a licensee has determined is more applicable to their configuration.

BACKGROUND

On January 11, 2008, the Nuclear Regulatory Commission (NRC) issued Generic Letter 2008-01 (Reference 1), requiring licensees to address the issue of gas[1] accumulation in the emergency core cooling, decay heat removal (DHR), and containment spray systems. A significant number of operating events have occurred, and continued to occur, suggesting that the licensees had not been sufficiently critical in their past operating experience reviews and application of lessons learned. Both the PWROG and BWROG formed committees to directly address the concerns raised by the Generic Letter and to support their members in responding to the Generic Letter and conditions discovered during the course of their evaluations. Both groups collaborated on funding of selected projects to characterize and better understand the phenomena. Other projects were funded individually by each owners group. These products were developed to more directly address the operability of these systems.

The projects addressed the transport of gas in piping systems on the suction side of pumps, as well as the ability of typical pumps to ingest gas and continue operating with no discernable mechanical damage or long-term loss of safety function. In order to provide a comprehensive package, pressure pulsations caused by initial gas or voids in piping systems on the discharge of pumps, and their potential downstream effects on the reactor pressure vessel were also addressed. Although some provided quantitative results, and others were qualitative, each of these projects produced documents approved under the contractors' 10 CFR 50 Appendix B Quality Assurance programs.

[1] "Gas" or "void", are terms intended to refer to the condition in a piping system where there is the undesired presence of air, nitrogen, hydrogen, water vapor, or any other space that is not filled with liquid water.

REASONABLE EXPECTATION OF OPERABILITY

Operability of Systems, Structures, and Components (SSCs) has been the subject of many publications. While each plant defines Operability in its plant specific Technical Specifications, and the system specific Limiting Conditions for Operation contained therein, much of the available literature on Operability is intended to guide the licensee and/or inspector.

When determining the Operability of an SSC, it is important to ensure a "reasonable expectation" of Operability. An absolute expectation is not required. From NRC IM Part 9900 (Reference 4):

> *"The discovery of a degraded or nonconforming condition may call the operability of one or more SSCs into question. A subsequent determination of operability should be based on the licensee's "reasonable expectation," from the evidence collected, that the SSCs are operable and that the operability determination will support that expectation. Reasonable expectation does not mean absolute assurance that the SSCs are operable. The SSCs may be considered operable when there is evidence that the possibility of failure of an SSC has increased, but not to the point of eroding confidence in the reasonable expectation that the SSC remains operable. The supporting basis for the reasonable expectation of SSC operability should provide a high degree of confidence that the SSCs remain operable. It should be noted that the standard of "reasonable expectation" is a high standard, and that there is no such thing as an indeterminate state of operability; an SSC is either operable or inoperable."*

When detailed performance for the SSC under the conditions being evaluated is not readily available, or the data is not as complete or detailed as one would prefer, alternative approaches are still accepted by the NRC:

> *"The scope of an operability determination must be sufficient to address the capability of SSCs to perform their specified safety functions. The operability decision may be based on analysis, a test or partial test, experience with operating events, engineering judgment, or a combination of these factors, considering SSC functional requirements."*

Often, a first principles understanding of the functioning of the system under degraded conditions must be supplemented with additional tools:

> *"When performing operability determinations, licensees sometimes use analytical methods or computer codes different from those originally used in the calculations supporting the plant design. This practice involves applying "engineering judgment" to determine if an SSC remains capable of performing its specified safety function during the corrective action period. …Although the use of alternative and normally more recent methods or computer codes may raise complex plant-specific issues, their use may be useful and acceptable in operability determinations."*

These citations support and affirm the PWROG and BWROG Operability positions quite well, considering that limited data is available in some areas, and engineering judgment has been applied in others. However, consistent with the NRC guidance, a "reasonable expectation" of Operability is assured by the appropriate application of these products.

With respect to correcting the degraded or non-conforming condition discovered in our systems, once Operability has been established, and continued Operability is expected, there are three generally recognized avenues for the resolution of the degraded or non-conforming condition. From RIS2005-20 (Reference 3):

> *"A licensee's range of corrective action may involve (1) full restoration to the UFSAR described condition, (2) a change to the licensing basis to accept the as-found condition as is, or (3) some modification of the facility or CLB other than restoration to the condition as described in the UFSAR.*
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> *If corrective action is taken to restore the degraded or nonconforming SSC to the UFSAR described condition, no 10 CFR 50.59 screening and/or evaluation is required. The 10 CFR 50.59 process applies when the final resolution of the degraded or nonconforming condition differs from the established UFSAR description or analysis. At this point, the licensee plans to make a change to the facility or procedures as described in the UFSAR. The proposed change is now subject to the review process established by 10 CFR 50.59. A change can be safe but still require NRC approval under the rule. The proposed final resolution may require staff review and approval (via amendment) without affecting the continued operation of the plant because interim operation is governed by the processes for determining operability and taking corrective action (10 CFR Part 50, Appendix B).*
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> *In two situations, the identification of a final resolution or final corrective action requires a 10 CFR 50.59 review, unless another regulation applies (e.g.,*

10 CFR 50.55a): (1) when a licensee decides the final corrective action is to change its facility or procedures to something other than full restoration to the UFSAR-described condition and (2) when a licensee decides to change its licensing basis, as described in the UFSAR, to accept the degraded or nonconforming condition as its revised licensing basis."

As long as continued Operability is expected, "*the licensee should establish a schedule for completing a corrective action…in a time frame commensurate with the safety significance of the condition.*" This is intended to allow correction of the identified condition "*at the first available opportunity*".

Given the mixture of quantitative and qualitative data available to the respective Owners Groups to address Operability, and the judgments required to consider a broad spectrum of operating conditions, **the PWROG and BWROG products were not developed to support permanent design changes at this time.**

As provided earlier by the NRC, an absolute expectation of Operability is not required, and therefore the appropriate application of the PWROG and BWROG products, without further conservatism being added, are sufficient to provide the tools to determine a reasonable expectation that a degraded SSC is Operable. Given situations where the PWROG and BWROG products do not provide sufficient, specific guidance, the NRC has also recognized the application of engineering judgment in the use of extending the available data. The licensees Criterion XVI Corrective Action Program are expected to direct the timely resolution of degraded or non-conforming conditions.

DISCUSSION

In general, a void in the pump suction piping presents a more significant challenge to the SSC function than a void in the pump discharge piping. A gas void in the pump suction could result in the momentary degradation of pump performance[2] or potentially gas binding of the pump if the void size is large enough and of sufficient duration. A gas void in the pump discharge typically would result in a pressure pulsation in the pipe and perhaps a short delay in the injection flow. Unbalanced forces potentially stress piping supports beyond their design, but rarely lead to severe damage that would challenge the successful fulfillment of the intended safety function. A pressure increase of sufficient duration may challenge a system relief valve, and the licensee should consider the potential impact due to an unexpected lift. Clearly, the consequence of gas binding a pump is more severe than momentary pump performance degradation.

Gas voids in the pump suction piping

A small amount of accumulated gas in pump suction piping could result in the momentary degradation of pump performance as the gas passes through the pump. In the event that a large accumulation of gas were to occur and if the flow rate is high enough to result in a high void fraction being transported to the pump suction piping, the pump may become gas bound, potentially leading to loss of function altogether. In order to address this potential, each licensee will assess the potential for gas accumulation to degrade ECCS functions.

There are a number of factors affecting the transport of gas voids in the suction piping which can impact the final void fraction at the inlet to the pump. The simplest and most straightforward is the effect of static pressure as the elevation of the gas void changes. Also, larger bubbles resist transportation down vertical pipe runs due to buoyancy while the turbulence of the flow tends to

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[2] "Performance", in the context of a pump, is intended to refer to the pump's ability to provide the required flow at the required discharge pressure.

strip smaller bubbles from the larger bubbles resulting in prolongation of the transport time. The actual flowrate in the suction piping is a dominant factor as well. In some cases, the flowrate may be so low as to be insufficient to transport the gas void; low enough that the gas void may be sheared by the flow, or high enough that the gas void may be transported more or less in a homogeneous, or bulk flow manner. All of these effects reduce the average void fraction in the downstream process fluid. The Froude number is used to represent the balance between the inertial and gravitational forces:

$$N_{FR} = v \, [\, D \, g \, (\rho_l - \rho_g) \, / \, \rho_l \,]^{-1/2}$$

where:

- v = fluid velocity
- D = piping diameter
- g = acceleration due to gravity
- ρ_l = liquid density
- ρ_g = gas density

The large variation in installed plant piping may dictate a combination of these approaches.

Test data suggests that gas voids less than 20% will not be transported in piping with Froude numbers less than 0.31. When evaluating the operation of a given pump across the spectrum of operating conditions, this criterion is useful in dismissing those low flow conditions, such as early operation on minimum flow, or a dead-headed pump, where the void will remain essentially stationary and not challenge pump operation. Although test data is available for several pipe diameters up to and including 12 inches, the dimensionless Froude number can be used to scale these data to all pump suction piping sizes currently in use in the nuclear industry.

For BWR piping systems drawing suction on the suppression pool, there are relatively short runs of piping with little elevation change, and fewer restrictions to the flow such as piping elbows or other fittings when compared to PWR suction piping. In other BWR cases, the piping is dominated by elevation drops, such as the normal lineup of the HPCI or HPCS systems to a condensate storage tank. In those cases, the size of a gas void in the suction piping will decrease as the static pressure in the piping system increases nearing the pump suction. The transport of any voids is conservatively assumed to be bulk flow, with little overall reduction in the average void fraction.

Piping systems in PWRs generally are slightly more complex, with elevation changes combined with many pipe fittings such as elbows and eccentric reducers. Each of these tends to decrease the average void fraction ultimately arriving at the suction of the pump. The PWR Owners Group has conducted full-scale "ECCS Void Migration" tests on 6" and 8" test loops in 2005, and testing on a 12" loop was recently completed in 2008. Testing on a 4" test loop will be completed later in 2009. These tests are designed to obtain empirical void fraction reduction correlations as gas bubbles travel to a pump. These test data show significant break-up of gas void pockets up to 20% into bubbly flow when transported at Froude numbers greater than 0.60. PWR owners can use these data to determine whether initial void fractions greater than the pump acceptance criteria can be reduced by the pump suction piping sufficient to be within those criteria by the time they reach the pump inlet.

Gas void ingestion by pumps

The PWROG and BWROG gas ingestion acceptance criteria supplied to their members reflect the various styles of pumps currently in service in the nuclear industry. These include single and multi-stage pumps, with flexible and stiff shafts. The available pump data in the available literature reviewed for this effort also reflects these various pump designs. As there is no need to provide overly conservative or bounding criteria to ensure a reasonable expectation of Operability, it is appropriate to have the supplied criteria reflect the relative strengths and weakness of those designs.

In general, the available test data suggest that pumps with stiff shafts are less sensitive to gas ingestion and capable of accommodating a larger spectrum of loading considerations. On the other hand, flexible shaft pumps are more susceptible to damage and should have more limiting criteria applied. For a given load, a flexible shaft will have more deflection than a stiff shaft, and greater deflection results in a greater propensity for mechanical contact or eccentric loads resulting in damage to the pump. The PWROG criteria recognize the differences between the pump types and use established industry guidance to support this classification.

The differences in allowable average void fractions between BWR and PWR typical pumps, or between single and multi-stage pumps, are not a difference in the application of this conservatism. Instead, they are a reflection of the different performance aspects of the various designs of pumps currently in service in the nuclear industry.

Much of the testing discussed in open literature and documented in PWROG and BWROG documents was performed within the bubbly flow regime. As the information reviewed was an essential element in the development of the pump criteria, additional clarification in this regard is warranted. It is understood that flows containing large slugs of gas would present serious concerns to pump operation, and that pump operation in this regime should be avoided or that additional measures should be taken to dissipate these slugs of gas prior to reaching the pump. Similarly, there is insufficient data to determine that an initially voided pump will be able to develop adequate head. Therefore, the pump criteria supplied by the PWROG and BWROG are only applicable to non-slug flow conditions, and in pumps with an initial void fraction not exceeding 5%. Without further data, it is not a reasonable expectation that Operability could be assured.

The industry pump acceptance criteria have used averaged void fraction to establish the guidance. Based on gas transport testing, the temporal profile of void fraction indicates a peak followed by a rapid decay. This should not be misconstrued as a slug of gas. Rather, as the void is transported to the pump it is to be expected that the void fraction will vary with a tendency to decrease as the gas is forced through the pump. Figure 1 demonstrates this typical behavior.

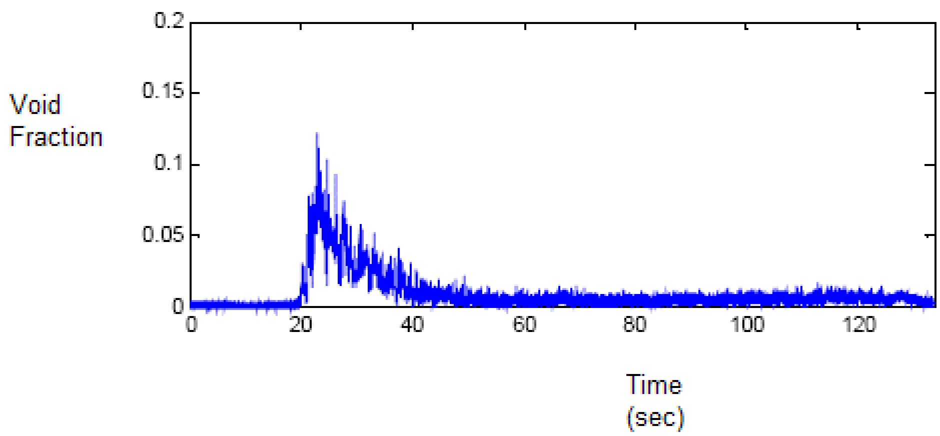

Figure 1: An Illustration of Typical Void Fraction Transport Time Dependency

It is agreed that the use of a peak vice an average void fraction is more conservative. However, it is the contention of the respective Owners Groups that this may result in overly conservative criteria. With the added restriction of a no slug flow regime, the concern relative to large, short duration peak void fractions is adequately addressed, and further conservatism is not required beyond that already reflected in the pump gas void ingestion criteria discussed below.

The criteria presented in the following tables are generic in nature and already include significant conservatism in the application of the available industry data on pump performance. Additionally, these data have taken into consideration the body of testing reported in NUREG/CR-2792 (Reference 8). Where data were not available for pump operation outside the range of normal operation, one-half the value of the criterion recommended for the applicable normal operating range was used as an additional conservatism. Table 1 presents criteria which provide reasonable expectation that pump mechanical damage will be prevented, while Table 2 presents conditions that provide a reasonable expectation that pump discharge head will not be significantly impacted. For those conditions where less than rated pump discharge head is assured, the licensee should ensure the impact of reduced system performance for the duration of the gas void passage has been considered relative to accident analyses assumptions.

Enclosure

Table 1 - Allowable Average Non-Condensable Gas Void Fractions (to preclude pump mechanical damage)

		$\% \frac{Q}{Q_{BEP}}$	**BWR Typical Pumps**	**PWR Typical Pumps**		
				Single Stage (WDF)	Multi-Stage Stiff Shaft (CA)	Multi-Stage Flexible Shaft (RLIJ, JHF)
A	Steady State Operation > 20 seconds	40%-120%	2%	2%	2%	2%
B	Steady State Operation > 20 seconds	< 40% or > 120%	1%	1%	1%	1%
C	Transient Operation ≤ 5 seconds	70%-120%	10%			10%
D	Transient Operation ≤ 5 seconds	< 70% or > 120%	5%			5%
E	Transient Operation ≤ 20 seconds	70%-120%		5%	20%	
F	Transient Operation ≤ 20 seconds	< 70% or > 120%		5%	5%	

Guidance provided has been conservatively established based on engineering judgment to cover a broad spectrum of equipment and operation, and is not intended to displace more specific recommendations from NSSS vendors, pump vendors, or engineering evaluation which a licensee has determined is more applicable to their configuration.

Further review by the respective Owners Groups may determine that criteria for pump operation below 70% BEP may not be required, as the conditions are bounded by the set of criteria for the 70%-120% BEP range. As additional data and methods become available in the future, they may be used to change, simplify, or eliminate some of these criteria.

Table 2 - Allowable Average Non-Condensable Gas Void Fractions (to preclude significant reduction in discharge head)

	$\% \frac{Q}{Q_{BEP}}$	**BWR Typical Pumps**	**PWR Typical Pumps**		
			Single Stage	Multi-Stage Stiff Shaft	Multi-Stage Flexible Shaft
Steady State Operation > 20 seconds	40%-120%	2%	2%	2%	2%

Note: Criteria in this table have been conservatively established based on engineering judgment to cover a broad spectrum of equipment and operation, and is not intended to displace more specific recommendations from NSSS vendors, pump vendors, or engineering evaluation which a licensee has determined is more applicable to their configuration. As additional data and methods become available in the future, they may be used to change, simplify, or eliminate some of these criteria.

Enclosure

<u>NPSHr for pumps</u>

The Net Positive Suction Head (NPSH) required is an industry standard criterion used in the design and operation of pumps. The Hydraulic Institute defines NPSHr as the total suction head in feet absolute, determined at the suction nozzle and corrected to datum, less the vapor pressure of the liquid in feet absolute. Simply stated, it is an analysis of energy conditions on the suction side of a pump to determine if the liquid will vaporize at the lowest pressure point in the pump. The pump manufacturers' performance curves normally supply this data.

Cavitation is a term used to describe the phenomenon, which occurs in a pump when there is insufficient NPSH available. When the pressure of the liquid is reduced to a value equal to or below its vapor pressure the liquid begins to boil and small vapor bubbles or pockets begin to form. As these vapor bubbles move along the impeller vanes to a higher-pressure area above the vapor pressure, they rapidly collapse. The collapse of the bubbles may cause serious pitting damage to the impeller.

NPSHr testing methods vary based on test loop arrangements, but each method requires stabilized conditions to assess pump performance. NPSHr is typically identified by 3% degradation in pump head. This 3% head degradation is usually an immediate precursor for a dramatic change in head due to head breakdown. With the addition of entrained air, the nature of the head degradation changes. Non-Condensable gas does not collapse under increased pressure. Typically, some amount of head degradation is present and tends to become more pronounced as the suction pressure is reduced. With small amounts of air, the head breakdown can typically be discerned, but with increased amounts of air, this phenomenon becomes less readily apparent as head degradation leading to this point becomes more dominant.

Industry's interest in avoiding cavitation is to ensure the long-term mechanical health of the pump (i.e., ensuring that the pump will meet its design lifecycle). As such, its focus is on pump/system compatibility. Short-term failures due to pump cavitation typically manifest themselves in large vibration levels, noise, and lower than expected head rise, prior to pump failure. Longer-term failures due to cavitation may not initially manifest themselves in terms of decreased head rise, but typically vibration and/or noise provide some insight into the conditions at the pump. Whether short or long term failure modes are under consideration, the duration of pump operation necessary for such damage is substantially longer than the time necessary for the void to be transported through the pump.

The impact of cavitation from fluid vapor pockets forming and then collapsing as they condense is well documented in terms of erosion, wear, fatigue, etc. The temporal nature of these degradation mechanisms does not lend themselves to an immediate failure mode. Cavitation of the pump would need to be occurring for an extended period of time, much greater then the transient times under consideration above, in order for these failure modes to be realized. Even if a pump was subjected to these conditions multiple times, it is highly unlikely that any damage would occur. Detection and resolution of long-term degradation mechanisms such as these is the purpose of quarterly in-service testing performed for these safety-related pumps. Severe cavitation would be required in order to have prompt mechanical damage, which would have been already covered by the pump ingestion criteria discussed earlier.

The timeframe for a pump to experience a gas intrusion event is expected to be at the beginning of an event, when the pump is automatically started by the plant's ECCS actuation systems. This is the time of maximum NPSH available as well, since suction sources are at their highest elevations, and the fluids are at their coldest temperatures.

In summary, NPSHr criteria can only be assessed at steady state conditions, since the vendor NPSHr criteria are determined by head degradation testing at stabilized conditions and are not applicable during transients. These criteria are developed by the industry in order to ensure pump/system steady state compatibility. In addition, damage due to cavitation is highly unlikely for a condition that lasts on the order of seconds unless the cavitation were to be so severe as to already be bounded by the pump ingestion criteria presented above. It is also expected that any gas voids present would be transported through the pump at a time when margin in NPSH available is quite large. Finally, transient NPSHr test data is not available nor is a procedure for collecting such data currently defined by the industry. Reasonable expectation of Operability is assured without the application of NPSHr criteria.

Pump Discharge Pressure Pulsations and Downstream Effects

Both PWROG and BWROG have provided additional guidance documents to their members (References 11-15) to assist in the evaluation of discovered voids on the discharge side of the pump. The expected system impacts can be pressure pulsations and/or non-condesnable gas/water water hammers, which, despite having the potential for damage to piping supports and other piping attachments, are rarely severe enough to compromise the intended safety function of the SSC. As noted previously, the potential for lifting of relief valves is also evaluated as part of the pressure pulsation assessments. The licensee must still provide an evaluation of these effects, and ensure that they are bounded by the methods provided, and conclusions drawn, in those respective Owners Group documents. These Owners Group's methods may be supplemented by the licensees own applicable plant operating experience, as well as analytical models and/or computer codes.

CONCLUSIONS

This attachment has provided the criteria, which can to be applied to a gas void discovered condition in a typical ECCS piping system. These criteria have been conservatively determined from the best available open literature in the industry at this time, as well as recent PWROG test results before not yet documented. Further application of conservatism is not required, and engineering judgment in the application of these generic criteria to specific conditions within a plant are within NRC guidelines for determining a reasonable expectation of Operability for the SSCs.

The final void fraction of gas voids transported through the system suction piping to the pump suction is subject to changes in the fluid pressure due to the static elevation head, and the competing forces due to buoyancy of the bubbles and turbulence of the flow. Guidance has been provided in PWR Owners Group documents in order to determine a reduced average void fraction at the pump inlet.

Open literature on the behavior of gas voids ingested by pumps has been reviewed by the respective Owners Groups for pump designs typically in use in their plants. The criteria presented for these pumps reflect the void fraction dependency on pump operating point (flowrate), as well as the expected duration of the pump event. These criteria address mechanical damage to the pump, as well as the potential for reduced discharge head. Application of steady-state criteria such as NPSHr to preclude long-term performance degradation is not required, and short-term mechanical failure has been adequately addressed by the average void fraction limitations provided in Table 1.

Finally, guidance has been provided by the respective Owners Groups on the downstream effects in the ECCS piping systems. Although not expected to significantly impact the intended safety function of the SSC, a complete evaluation of Operability would include a discussion of these effects.

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