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BWR Owners' Group Technical Report
ECCS Pumps Suction Void Fraction Study

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Abstract

This report was prepared for the BWROG Gas Intrusion Committee. It reviews current and past industry information relative to the effects of gas intrusion on the performance of centrifugal pumps. This review was prompted by the issuance of NRC Generic Letter 2008-01, *Managing Gas Accumulation in Emergency Core Cooling, Decay Heat Removal, and Containment Spray Systems*. Westinghouse performed a similar review of Industry data and Operating Experience per PA-SEE-450 Task 2 to ensure that as much industry data as possible is included in the reviews. The conclusions of these reports were compared to ensure consistency.

By review and evaluation of available data, an acceptable gas void fraction is proposed that will not adversely affect safety system performance and is acceptable for use until future pump testing is performed. This report only addresses gas intrusion effects on ECCS pump and system performance. Effects of gas intrusion in the discharge piping are outside the scope of this report and are being addressed separately. Additionally, this report is not intended to address NRC Generic Safety Issue, GSI-193, *BWR Emergency Core Cooling System (ECCS) Suction Concerns*, which addresses the possible failure of ECCS pumps due to large quantities of entrained gas in the suction piping from BWR suppression pools due to blow down during various accident scenarios.

Based on evaluation of the gas intrusion data that was reviewed, a bounding 2% by volume continuous suction gas void fraction is acceptable for continuous pump operation. A 2% void could cause increased wear of the pump, but will not cause pump operability problems. Due to the lack of test data or operating experience of pump operation above 120% of the Best Efficiency Point (BEP), it is recommended that pumps that operate above this point be limited to a 1% allowable continuous void fraction. System operability would still need to be assessed for either limit above, including such factors as required NPSH versus available NPSH, duration of gas flow, and transients for which the system is credited.

Gas accumulation in the suction lines of BWR ECCS systems is not expected to occur. If a gas void is found in a suction line it will be a fixed volume and will not cause a continuous gas void flowing through the pump. As such it is overly conservative to apply the above void criteria to these types of voids. To evaluate pump and system effects of a void of a known volume, it is appropriate to use the guidance that an average void fraction less than 10% can be tolerated by the pump and system for a period of no greater than 5 seconds. This is assuming that the void is not initially located in the pump during pump start. The actual gas volume this constitutes will depend on pump suction line diameter, flow rate, and pressure.

Guidance in this report is generic and conservative and intended for evaluating short-term operability. Plant specific evaluation of any voiding discovered in the suction piping is not precluded and may provide a larger acceptable void fraction.

This report was provided to key pump vendors (Sulzer and Flowserve) for review, however, no comments were received prior to issuance. If voiding near, or exceeding, the acceptance limit established in this report is identified in an ECCS suction line, it is recommended that the pump vendor also be consulted to ensure that the pump is not an outlier relative to any generic assumptions made in the report.

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Energy Northwest – Columbia	First Energy – Perry
Entergy - Fitzpatrick	NPPD – Cooper
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Exelon (Clinton)	Progress Energy – Brunswick
Exelon (OC)	SNC – Hatch
Exelon (D/Q/L)	TVA – Browns Ferry

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ACRONYMS AND ABBREVIATIONS

BEP	Best Efficiency Point
BWR	Boiling Water Reactor
BWROG	Boiling Water Reactor Owner's Group
CS	Core Spray
CST	Condensate Storage Tank
ECCS	Emergency Core Cooling System
Fr	Froude number
FT	Feet
GEH	General Electric-Hitachi Nuclear Energy
GL	Generic Letter
GPM	Gallons per minute
HPCI	High Pressure Coolant Injection
INPO	Institute of Nuclear Power Operations
LOCA	Loss of Coolant Accident
NEI	Nuclear Energy Institute
NPSH	Net Positive Suction Head
NPSHa	Net Positive Suction Head Available
NPSHr	Net Positive Suction Head Required
NRC	Nuclear Regulatory Commission
PWR	Pressurized Water Reactor
RCIC	Reactor Core Isolation Cooling
Ref.	Reference
RHR	Residual Heat Removal
SEC	Seconds
TR	Topical Report
TVO	Teollisuuden Voima Oy

1.0 Purpose

This report was prepared for the BWROG Gas Intrusion Committee. It reviews current and past industry information relative to the effects of gas intrusion on the performance of centrifugal pumps. This review was prompted by the issuance of NRC Generic Letter, GL 2008-01, *Managing Gas Accumulation in Emergency Core Cooling, Decay Heat Removal, and Containment Spray Systems*.

By review and evaluation of available data, an acceptable gas void fraction is proposed that will not adversely affect safety system performance and is acceptable for use until future pump testing is performed. This report only addresses gas intrusion effects on Emergency Core Cooling System (ECCS) pump and system performance. Effects of gas intrusion in the discharge piping are outside the scope of this report and are being addressed separately. Additionally, this report is not intended to address NRC Generic Safety Issue, GSI-193, *BWR Emergency Core Cooling System (ECCS) Suction Concerns*, which addresses the possible failure of ECCS pumps due to large quantities of entrained gas in the suction piping from BWR suppression pools due to blow down during various accident scenarios.

2.0 Summary

Based on evaluation of the gas intrusion data that was reviewed, a bounding 2% by volume continuous suction gas void fraction is acceptable for continuous pump operation. It could cause increased wear of the pump, but will not cause pump operability problems. However, due to the lack of test data or operating experience of pump operation above 120% of the Best Efficiency Point (BEP), it is recommended that pumps which are operated above this point be limited to a 1% allowable continuous void fraction. System operability would still need to be assessed for either limit above, including such factors as required Net Positive Suction Head (NPSHr) versus available Net Positive Suction Head (NPSHa), duration of gas flow, and transients for which the system is credited.

Gas accumulation in the suction lines of BWR ECCS systems is not expected to occur. If a gas void is found in a suction line it will be a fixed volume and will not cause a continuous gas void flowing through the pump. As such it is overly conservative to apply the above void criteria to these types of voids. To evaluate pump and system effects of a void of a known volume, it is appropriate to use the guidance that an average void fraction less than 10% can be tolerated by the pump and system for a period of no greater than 5 seconds. This assumes that the void is not initially located in the pump during a pump start. The actual gas volume this constitutes will depend on pump suction line diameter, flow rate, and pressure. Attachment 1 provides a method to determine an acceptable void volume assuming total void transport.

Guidance in this report is generic and conservative. It is intended for evaluating short-term system operability due to a void found in the ECCS suction piping and not for long-term design basis. Plant specific evaluation of voiding discovered in the suction piping is not precluded and may provide a larger acceptable void fraction.

3.0 Historical Background

As discussed in GL 2008-01, instances of gas accumulation in ECCS systems have continued to occur since the beginning of commercial nuclear power plant operation (Ref.1). The number of identified gas accumulation problems and their significance at some facilities raise concerns about whether similar unrecognized design, configuration, and operability problems exist at other facilities. Many of the past notices and reports were only addressed to Pressurized Water Reactors (PWR), however, there have been enough gas intrusion events at BWRs that the generic letter was addressed to all licensees.

Gas intrusion can have potential safety implications for ECCS systems. Gas in the suction line can cause a reduction in pump flow, reduced Net Positive Suction Head (NPSH), air binding, or pump vibration. Excess gas in the discharge lines can result in a water hammer or a system pressure transient. Additionally, excessive gas accumulation could result in pumping non-condensable gas into the reactor that may affect core flow or cause a delay in water delivery to the reactor.

Per GL 2008-01, the term "gas" includes air, nitrogen, hydrogen, water vapor, or any other void that is not filled with liquid water. Due to BWR design, the most likely gas to be entrained in an ECCS suction line is air. There is no identified mechanism to cause a water vapor void to occur in the suction lines under normal system alignments.

The generic letter provides current examples of gas intrusion events and technical discussion relative to the effects of gas intrusion. Much of the background technical data referenced in the generic letter relative to gas intrusion effects on pump suction are from NUREG/CR-2792, *An Assessment of Residual Heat Removal and Containment Spray Pump Performance Under Air and Debris Ingesting Conditions* (Ref. 2).

4.0 Data Collection Methodology

NUREG/CR-2792 (published 1982) contains an extensive compilation of test data and research on the effect of gas intrusion on centrifugal pump performance and provides a basis for much of the technical discussion in GL 2008-01. Research for this GEH study included review of this NUREG and related NRC documents on gas intrusion.
Additional testing and research available on the topic prior to, and since, the issuance of the NUREG was reviewed. GEH archive files were also searched for pertinent reports on gas intrusion. An Internet search was performed for relevant information on gas intrusion effects on performance of centrifugal pumps.

Engineering Managers for key BWR ECCS pump vendors were contacted for available data or test information on gas intrusion. BWR counterparts in Japan and Spain were also contacted, but had no additional information on this topic.

A complete listing of references reviewed for this report is included in the References section of this report, although not all are specifically referenced in the body of the report.

5.0 BWR ECCS Pump Suction Voiding

The recent gas intrusion events cited in GL 2008-01 were reviewed. The BWR events cited were related to problems encountered in the discharge piping and were not related to suction voiding problems.

INPO SER 2-05 Rev. 1, *Gas Intrusion in Safety Systems*, was issued January 9, 2008 due to continuing gas intrusion problems in the industry and BWR events were included in the report. A review of the events cited in the report only identified one event where air in the suction of an ECCS pump caused failure of the system (Ref. 4). A RCIC pump trip in a Japanese BWR was caused by air trapped in the suction of the pump due to inadequate filling and venting.

INPO Topical Report TR 3-25, *Gas Voids Affecting BWR Injection Systems Important to Safety*, was issued in July 2003 (Ref. 5). A total of 15 events were reviewed by this topical report. For all but one event, air ingestion was attributed to improper venting of the affected system. Further review of the individual events for ECCS suction line voiding identified only 2 suction related events: 1) Air in a common RCIC/HPCI suction line due to inadequate filling after maintenance and 2) Condensate Storage Tank (CST) low level trip setpoint deficiency resulting in the potential for vortexing (actual vortexing/voiding did not occur).

Due to differing operational designs, the main contributor to suction line voiding differs between BWRs and PWRs. As noted in the above discussion, most BWR suction air intrusion issues are due to inadequate venting following system maintenance. BWR containment sumps (suppression pools) are maintained near atmospheric pressure and the only pressure at the pump is due to the head pressure from the fluid elevation. Other possible methods of gas intrusion into the suction lines are due to vortexing and outgassing of dissolved gas (gas coming out of solution). No BWR issues of ECCS suction line outgassing voids were identified in the reviewed documents. With proper level setpoints, vortexing from either the CST or the suppression pool should not be a concern.

Test data evaluated in the following sections of this report were from testing with a constant stream of a known volume of air to provide a known void fraction. The most probable event in a BWR will involve a shorter duration flow of gas after pump start due to gas trapped in the suction line following maintenance and/or inadequate venting. For that reason, testing data is not particularly representative of the expected pump suction voiding conditions expected in a BWR.

Void fraction, as used in this report, is defined as the volumetric ratio of gas to total flow rate assuming no slip between phases. It is generally specified as the percent by cross-sectional area entering the pump suction at a given inlet temperature and pressure. A 2% continuous suction gas void fraction means that at any point during injection the fluid entering the pump suction contains 2% voids in a cross-sectional area.

Degraded pump performance, as used in this report, includes unacceptable increases in required NPSH (NPSHr) or a decrease in pump flow rate that adversely affect system performance.

6.0 Discussion of Review Findings

There are several factors to consider when assessing pump performance with gas introduced into the pump suction line. The key factors are listed below and are discussed individually in the following sections.

- Percent gas intrusion (void fraction)
- Single or multi-stage pumps
- Number of impeller blades
- Pump flow rate
- Suction line configuration
- Net Positive Suction Head
- Pump Mechanical Condition
- Operating Experience and Event Review

6.1 Percent Gas Intrusion

As noted previously, NUREG/CR-2792 contains an extensive compilation of test data and research on the effect of gas intrusion on centrifugal pump performance. As such, it is referenced extensively in this report. Other sources of information, including test data and expert opinions suggest a void fraction value that should cause little or no degradation in pump performance. A summary of values recommended by the various referenced sources is provided below. The table includes the reference number that corresponds to the source listed in the reference section, and the recommended maximum acceptable void fraction suggested by the reference source. Void fraction testing and reference information applicable to the other listed variables are discussed in the following sections.

Table 1

Ref. No.	2	9	10	11	12	13	14	15	16	17	19	20
% Void	1% to 3%	4%	1% to 5%	2%	<2%	<2%	4%	0.5%	1% to 2%	<5%	4%	3% to 5%

As suggested in Table 1, the void fraction that is deemed to cause little to no degradation in pump performance (either by testing, analysis, or expert opinion) ranges from 0.5% to 5%, with the most recurring value being 2% or less.

6.2 Single versus Multi-stage

Most BWR ECCS pumps are from 3 main pump suppliers: Byron Jackson (now Flowserve), Sulzer, and Ingersoll (now part of Flowserve). Pump type varies from single stage centrifugal to 15 stage centrifugal pumps. Little test data is available on the effects of gas intrusion on multi-stage pumps. Testing performed by Florjancic (Ref. 2), shows that at a given air volume fraction, degradation in performance is less pronounced at higher inlet pressures and in multistage pumps. This was attributed to the reduced volumetric expansion of air from the air ingestion point to the impeller inlet at higher suction pressures. In multistage pumps, air is raised to a higher pressure at each stage and has less effect on the performance of the next stage.

6.3 Number of Impeller Blades

Testing of gas intrusion with 3, 5, and 7 impeller blades was performed by Murakami and Minemura (Ref. 2, D-12). Head developed by the three-blade impeller actually increased slightly for less than 2.5% volume fraction of air (better performance than expected). This was attributed to an improvement in the flow patterns in the impeller.

Performance of the 5 and 7 blade impeller pumps was very comparable. Head decreased continuously with increasing air content until the pumps began to lose prime at volume fractions above 6%. For air fractions higher than 2.5%, the head-flow curve for all pumps were continuous but not smooth. Minor discontinuities in the head-flow curves were accompanied by changes in flow patterns in the impeller with air accumulation at various locations within the impeller. The data presented suggests a lower limit of air volume fraction of 2.5%, below which performance (developed head) is unaffected by air regardless of the number or impellers.

6.4 Pump Flow Rate

Most testing performed for gas intrusion effects was at the BEP for the pump. However, there are concerns on the effects of gas intrusion during lower and higher flow scenarios. During most BWR accident scenarios, High Pressure Coolant Injection (HPCI) and/or Reactor Core Isolation Cooling (RCIC) will start and inject immediately. Residual Heat Removal (RHR) and Core Spray (CS) may run on minimum flow for a period of time before low pressure permissives for injection are satisfied. Minimum flow is generally at approximately 10% of peak efficiency flow on the pump curve and is provided to ensure the pump does not overheat. Several utilities also report routine pump operation at points well above the BEP (for example 145% of BEP).

Testing by Merry (Ref. 2) indicates that there is less degradation in performance at the highest efficiency flow rate (BEP) than at lower or higher flow rates. Florjancic test results (Ref. 2) show a 10% head reduction at 120% of the BEP flow rate with 2% air ingestion. This head reduction will cause a drop in flow rate that will be dependent on the shape of the pump curve and what percent of BEP the pump is operating. During the same Florjancic tests, it was determined that for ingested air fraction of 2%, the head, power and efficiency at rated flow remained unchanged from the single-phase values at the pump best efficiency flow rate. Degradation occurred at higher air fractions. Based on this test data, a limit of acceptable air ingestion was established at 2% by volume. This applies to pumps near the BEP (Ref. 2). Due to the lack of test data or operating experience of pump operation above 120% of the BEP, it is recommended that pumps which operate above this point be limited to a 1% allowable continuous void fraction. However, as will be discussed in the Conclusion section of this report, it is overly conservative to apply a continuous void fraction to BWR suction line voiding. The most probable event in a BWR will involve a shorter duration flow of gas after pump start because of gas trapped in the suction line due to inadequate venting following maintenance activities.

For very low flows (less than 20% of best efficiency flow), air tends to accumulate at the center of the impeller due to strong recirculation. If the flow rate is sufficiently low, and if air ingestion occurs over an extended period of time, air can continue to accumulate and the pump can ultimately become air bound. This could occur at relatively low flow rates and at low air ingestion levels (less than 2% by volume). It should be noted that for flow rates at less than 50% of the rated flow (wording of this reference infers this is BEP flow), chances of air binding are substantial. However, at such low flow rates, pump suction pipe velocities would be proportionately less than the value at rated conditions and the likelihood of air ingestion decreases (Ref. 2, G-9). Reference 17 confirmed that gas can collect at the low pressure areas of the pump inlet or at high points in the suction piping. This gas collection can restrict flow into the impeller. The Reference concluded that centrifugal pumps can typically handle about 3% to 5% maximum gas entrainment before they cease to pump.

A Diablo Canyon Void Evaluation (Ref. 20) concluded that if the Froude number is < 0.9 the void fraction will be less than 5% if a creditable vertical descending run exists. In other words, since the Froude number is directly proportional to flow rate, only a fraction of a gas void accumulated at a high point of the suction piping will be transported down through the pump during low flow conditions. Full-scale experiments have shown that no air ingestion occurs for BWR suction inlet designs up to a Froude number of Fr 0.8 (Ref.16). Per reference 7, Page 45, a study performed by G. Corcos published in 2003, found that a Froude number above 0.484 was necessary to move air pockets in a horizontal pipe, and that a Froude number above 0.638 is required to move stationary air pockets downstream past a downward sloping section of pipe. For typical flow rates and suction pipe diameters, Fr numbers for RHR and CS are approximately 0.1 to 0.2 when operating on minimum flow. Therefore, air ingestion by the RHR and CS pumps is unlikely at low flow rates. Although there is no time limit for operation of ECCS pumps on minimum flow, extended operation of ECCS pumps on minimum flow is discouraged and should not occur over an extended period of time.

Gas Intrusion testing performed in Finland, and published in 2002, is documented by References 18 and 19. The behavior of non-condensable gas in the condensation pools of the Olkioluoto Nuclear Power Plant in a possible loss of coolant accident (LOCA) was studied experimentally with a scaled down test facility. During the test, air bubbles were detected inside the strainer. The volume of bubbles was, however, negligible after about 30 seconds. The ECCS pump head and water flow rate didn't decline due to the air bubbles drifting inside the pump in any test.

In low velocity (minimum flow) test cases performed per Reference 18, a negligible void volume (bubble volume) was detected inside the strainer or intake to the pump.

In another test, air was blown directly into the intake pipe with four different pump flow rates between 12.5 and 75 Liters/sec (200 gpm to 1200 gpm) (single-stage pump, type KSB CPKE 100-315, 2970 rpm, impeller diameter 10.4", suction pipe 5.5"). With volumetric flow rates of 900 to 1200 gpm, air was injected at 3% to 4% before the head and flow declined considerably. Air ingestion was closer to 4% before a decline in performance was noted during the 900 gpm test. It was noted that this was due to the fact that the pump was operating closer to its peak efficiency point so it was possible to inject more air during this test. With lower flows of 200 to 400 gpm, the head and flow started to decline after injection was started and collapsed totally when air was more than 7% in the intake pipe. After the air injection was switched off, the head and flow normalized in a few seconds back to the original values. One exception was noted. With the smallest flow rate (200 gpm), it took about 30 seconds for the pump head to normalize (Ref. 19).

6.5 Suction Line Configuration

Suction line configuration can affect the amount of gas transported to the pump and the "consistency" of the flow (bubbly, slug, etc). Sections with inverted "U" shaped piping configurations can also trap air if not properly vented. BWR ECCS suction sources are at a higher elevation than the pumps to ensure adequate available NPSHa and would maintain the suction pipe continuously filled under a positive static head pressure. Any gas in this pipe would most likely be from the system not being properly restored from maintenance or minor voids trapped in high points.

This suction line configuration is consistent with good engineering design for the placement of a pump in a pipe network. Nuclear and non-nuclear operating experience has shown this configuration to be one that prevents a pump from becoming air bound or losing its prime. When a pump's suction source is at a higher elevation than the pump, there is no operating experience which supports the conjecture that voids due to unfavorable pipe slope or pipe bow in an otherwise full, nominally horizontal pipe cause a pump to lose its prime.

In addition, BWR ECCS pumps start with their minimum flow lines open or they are opened upon pump start. These lines are from the pump discharge to a low pressure tank or the suppression pool. This configuration ensures that flow through the ECCS pumps does not stop (due to head degradation) as voids pass through the pump suction. That is, the minimum flow line pipe configuration ensures that gas in the suction pipe does not accumulate at the pump and cause it to lose its prime.

Buoyancy causes bubbles to transport down the pipe at a slower rate. With a fixed, unchanging amount of gas in the ECCS piping, the extended bubble transport time results in a lower void fraction in the downstream process fluid. Bigger bubbles tend to break into smaller bubbles with flow down a vertical pipe thus promoting bubbly flow (Ref. 20). In the bubble flow regime, the bubbles can move at approximately the same speed, or slightly faster (up a pipe), than the liquid (Ref. 7, Page 25).

6.6 Net Positive Suction Head

Per Arie and Fukusako tests (Ref. 2), as air fraction increases, the pump requires higher NPSH to operate satisfactorily. Also, Reference 10 indicates that entrained gas will cause the pump to develop slightly less head than normal. The amount of performance degradation depends on the amount of air and the difference between available and required NPSH (Ref. 2).

The exact amount of change in NPSHr is questionable due to limited testing in this area. Reference 16 refers to a publication that suggests a mixture of only 2% gas by volume will cause approximately a 10% reduction in the capacity of the pump. Several references discuss the use of a correction factor (discussed below) to determine the increase in NPSHr due to pump gas ingestion (Ref. 2, 3 and 16).

The pump industry historically has determined required NPSH for pumps on the basis of a percent degradation in pumping capacity. The percent has at times been arbitrary, but generally is in the range of 1 to 3%. A 2% limit on air ingestion is recommended since higher levels have been shown to initiate degraded pumping capacity. However, air ingestion levels less than 2% can also affect NPSH margin and should be independently evaluated. The formula recommended to determine NPSHr with air ingestion is: $NPSHr_{(\alpha p<2\%)} = NPSHr_{(liquid)} \times \beta$ where $\beta=1+0.5_{\alpha p}$ and αp is the air ingestion rate (in percent by volume, for example 1%) at the pump inlet flange (Ref. 16). However, this equation was developed based on limited data. The relationship is shown on Fig 4-3 of Reference 2 and it is indicated that the conservatism used in establishing the straight line is arbitrary.

If NPSHr increases above NPSHa, pump cavitation and a reduction in flow will occur. As discussed previously, if gas is present in an ECCS pump suction line, ingestion by the pump would be expected to occur early in an event. Early in an event, NPSHa is higher than would be expected later in an event due to increased water source temperature and/or decreased water level. Additionally, as discussed later in the report, flow of entrained gas through the pump is only expected to occur for a short duration (seconds). The amount of time is dependent on flow rate. A higher transport rate will flush the void through the pump more rapidly with more of the gas void being transported as the flow rate increases to full flow. During this time, the small reduction in flow has not resulted in degraded system performance. As such, recalculation of pump NPSHr should not be required.

Water temperature should not be a concern for BWR ECCS pump suction since any air passed thru the pump will be early in an event and before the suppression pool temperature increases significantly. Systems taking suction from the CST would also not see any temperature increase due to an accident requiring injection. Thus, the temperature effect upon NPSHa should not be a consideration for BWR pump configurations.

6.7 Pump Mechanical Condition

GL 08-01 indicates that >5% void fraction in the flow stream to a pump may result in pump damage or failure due to force imbalances on the pump impeller and that multistage pumps under low flow conditions are especially susceptible to damage due to low flow conditions caused by a slug of gas. These statements are not supported by operating experience. Without an analytic model of the pump or pump test data, it is not possible to prove or disprove these qualitative statements. As long as the flow to the pump remains in the bubbly flow regime, the pressure imbalances due to voids passing through the pump impeller vanes will be small. Bubbly flow is expected to occur if the gas void fraction is low (< 20% void fraction), flow is near BEP or rated, and downward slopes and bends exist to disperse the void. The resulting bending forces on the pump shaft will also be small. Because the shafts of BWR ECCS pumps are designed for large torsional loads, there will not be significant deformation of the shaft. Therefore, BWR ECCS pumps are not expected to experience damage or fail due to voiding in the flow stream as described in GL 08-01.

Air ingestion seldom causes damage to the impeller or casing. The main effect of air ingestion is a relatively short term loss of capacity (Ref. 15). Also, Reference 21 indicates that, in general, the presence of air for a few minutes should not result in impeller damage, although degraded performance may occur during the air entrainment period.

The test pump was inspected after low flow testing performed in Reference 19. Air was injected during low flow conditions until the pump worked as "a blower". For the 200 and 400 gpm flow tests, the report indicates that after the test the pump was undamaged. The test report did not indicate if an increase of wear of any components was noticed.

6.8 Operating Experience and Event Review

Hydraulic transients due to suspected air trapped in a HPCI suction line were analyzed for Limerick (Reference 22). This evaluation states: " An experience based criterion has been suggested, that a void fraction less than 20% can be tolerated by the pump for a period of 5 seconds without adversely affecting pump operation". A calculated void averaging 13% passing thru the pump (pumped from the suction to discharge) over 7.8 seconds (or 10.77 ft^3 at suppression pool pressure) was determined to be acceptable for pump operation, and from a suction hydraulic standpoint. Additionally, a calculated 100 percent void (10.77 ft^3) assumed to pass thru the pump in less than 1 second was determined to be acceptable, with only minor effects on pump operation. Water hammer was also evaluated for the change in velocity of the water column caused by a slug of air passing thru the pump in 1 second. No detrimental effects to the pump or system were expected due to an air slug. For each scenario, the trapped air was determined to be in the pump suction piping and not initially in the pump.

An evaluation of an air void between the containment sump suction supply valves by Kewaunee Nuclear Power Plant concluded that 3 to 5 % air entrainment by volume over a period of 20 seconds is not expected to cause any significant problems (Ref. 25).

Ingersoll-Dresser (now Flowserve), the original pump vendor, provided input to an operability evaluation for a recent Wolf Creek Nuclear Power Plant gas intrusion event that resulted in a gas void of approximately 2% by volume (Ref 26). The vendor input indicated that the subject pumps could handle up to 5% gas by volume without distress. The operability evaluation further stated that test results referenced in a Dominion Engineering report show that for gas volumes less than 20% of total volume, the two phase flow mode is expected to be bubbly flow which does not produce significant pressure pulses or surges in the piping.

A qualitative review of a Comanche Peak Nuclear Power Plant gas intrusion event's effect on containment spray pump performance was performed by Sulzer (Ref. 27). Void fraction for one event was postulated to average 15% over 5 seconds. The review indicated that pump head and capacity will probably decrease, and vibration increase, while air is passing through the pump, but the pump will continue to operate. After the air passes through the pump, the pump should return to its pre-transient performance level. General discussion stated that air entrainment produces a mechanical and hydraulic transient to the pump. However, the transient is usually short (on the order of seconds), so any damage should be minimal. The system flow inertia prior to air reaching the pump contributes to continued pump operation during the two-phase flow transient. The event review was qualified by stating that the percent entrained air, pre-transient parameters, and transient duration need to be considered together to determine pump operability.

Pressure transients that cause relief valve lifts and pump trips on low suction pressure are not expected due to minor amounts of gas in the suction line. Such events have been caused by water hammers in the discharge piping (vs. suction piping) due to gas voids causing pressure perturbations and a recoil of the pressure wave. Such an event noted in Reference 4 was a low suction pressure trip of RCIC at the Hope Creek Nuclear Power Plant caused by air trapped in the discharge piping.

7.0 Conclusion

Based on evaluation of the gas intrusion data that was reviewed, a bounding 2% by volume continuous suction gas void fraction is acceptable. It could cause increased wear of the pump, but will not cause pump operability problems. Although, test data is available for fractions up to 4% having minimal effects on pump performance, other test data shows performance degradation (although minor) under certain conditions, such as low flow and flow beyond the Best Efficiency Point (BEP), beginning at about 2%. Due to the large number of variables and pump types that can affect pump performance while ingesting gas, a bounding 2% void fraction is considered appropriate and conservative for continuous pump operation. However, due to the lack of test data or operating experience of pump operation above 120% of the BEP, it is recommended that pumps which operate above this point be limited to a 1% allowable continuous void fraction. System operability would still need to be assessed for either limit above, including such factors as required NPSH versus available NPSH, duration of gas flow, and transients for which the system is credited.

As noted in the previous sections, gas accumulation in the suction lines of BWR ECCS systems is not expected to occur. If a gas void is found in a suction line it will be a fixed volume and will not cause a continuous gas void flowing through the pump. The void will most likely be similar to those discussed in the Operating Experience and Event Review Section (Section 6.8). As such it is overly conservative to apply the 1% or 2% void criteria to these types of voids.

To evaluate pump and system effects of a void of a fixed known volume, it is appropriate to use the guidance contained in Section 6.8, that an average void fraction less than 20% can be tolerated by the pump for a period of 5 seconds. However, since this criteria is qualitative in nature, for the purpose of this report, a more conservative guideline of an average 10% void fraction for no greater than 5 seconds is recommended for use. This assumes that the void is not initially located in the pump during a pump start. Proposing an acceptance criteria of 10% void fraction over no greater than 5 seconds to evaluate pump and system operability acknowledges the qualitative nature by which the limit was developed. Additionally, this limit more closely aligns with similar limits that Westinghouse is developing (per discussion with Westinghouse Project Engineers). Also, bubble surges during transport will result in a varying void fraction that will likely peak over 10%, but should average less than 10%. The actual gas volume this constitutes will depend on pump suction line diameter, flow rate, and pressure. Attachment 1 provides a method to determine an acceptable void volume assuming total void transport. For smaller void fractions which may require more time to pass through the pump, the guidance of Westinghouse PA-SEE-450 Task 2 evaluation can be used for evaluation of the condition.

Although no specific test data was located which empirically validates this guidance, it is considered bounding and appropriate for the following reasons:

- At the pump BEP or rated speed, a gas void present in a suction line would be swept through the pump due to system flow inertia as bubbly flow in a short amount of time (seconds).
- The flow of entrained gas through the pump would occur for a short duration (seconds), during which, a small reduction in flow may occur, but will not compromise system performance. As such, recalculation of pump NPSHr should not be required.
- As noted above, a small reduction in flow may occur for several seconds. Although it difficult to quantify the short duration reduction in flow, it is more than offset by conservative accident analysis assumptions, such as not crediting ECCS flow until the time the injection valve is assumed full open. In reality, significant flow occurs early in the opening stroke, before flow is actually credited.
- If gas was present in an ECCS pump suction line, ingestion by the pump would be expected to occur early in an event when NPSHa is higher, rather than later in an event.
- A pump vendor's review of an event with a similar amount of voiding, averaging 15% void fraction over 5 seconds, indicated that the pump will continue to operate, and the pump will return to its pre-transient flow as the voiding clears.
- Test documentation (Reference 19) found that after air injection was increased to the point that flow collapsed or totally ceased, air injection was switched off and the head and flow normalized in a few seconds back to the original values, with one exception. With the smallest flow rate (200 gpm or approximately 20% of rated flow), it took about 30 seconds for the pump head to normalize.
- Due to the short duration of time (generally minutes) that pumps are expected to run on minimum flow, accumulation of sufficient gas to cause pump binding is not expected. Additionally, flow velocities on minimum flow are not high enough to push minor

voiding into the pump suction. As such, time restrictions for minimum flow operation are not recommended.

- The criteria chosen assumes all of the void volume in the suction line is transported through the pump. Depending on the suction flow rate, a lower percent of this volume will be transported through the pump (lower flow yields a lower Froude number). More detail of gas transport is included in Westinghouse PA-SEE-450 Task 2.

Guidance in this report is generic and conservative. It is intended for evaluating short-term system operability due to a void found in the ECCS suction piping and not for long-term design basis. Plant specific evaluation of any voiding discovered in the suction piping is not precluded and may provide a larger acceptable void fraction. If voiding near, or exceeding, the acceptance limit established in this report is identified in an ECCS suction line, it is recommended that the pump vendor also be consulted to ensure that the pump is not an outlier relative to any generic assumptions made in the report.

8.0 References

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4) SER 2-05 Rev. 1, *Gas Intrusion in Safety Systems*
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6) NRC Inspection Report 5000482/2008007, Wolf Creek Generating Station- NRC Special Inspection
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22) GE-NE-0000-0040-2656-R0, *Limerick Generating Station Unit 1, HPCI Suction Pipe Void Fraction and Pump Operability*, September 2005
23) ANSI/HI 1.3-2000, *American National Standard for Centrifugal Pumps for Design and Application* (pages 19-20)
24) NUREG/CR-2772, *Hydraulic Performance of Pump Suction Inlets for Emergency Core Cooling Systems in Boiling Water Reactors*
25) Kewaunee Unresolved Item, ID 36672 Observation 4 (from NEI website posting)
26) Wolf Creek Operability Evaluation, PIR 2008-000008, dated 1/10/08
27) Sulzer Pump Memo, "Containment Spray Pump at CPSES Air Void Issue Rev 1", Dated 12/19/06

* Teollisuuden Voima Oy (TVO) is neither responsible for the content of the reports nor how GEH/BWROG is using the reports.

Attachment 1

Sample Void Evaluation

The following acceptance criteria is recommended for evaluation of gas voids in ECCS suction piping: [[

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Determining the velocity differences and gas transport behavior is an ongoing effort through Westinghouse. Additional gas transport information is in WCAP-16631 and is to be included in Westinghouse PA-SEE-450 Task 2.