March 31, 2005

MEMORANDUM TO: Jose G. Ibarra, GIOES Section Chief
Advanced Reactors and Regulatory Effectiveness Branch
Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research

FROM: Paulette A. Torres, Reactor Engineer ***/RA/***
Advanced Reactors and Regulatory Effectiveness Branch
Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research

SUBJECT: GI-193: "BWR ECCS SUCTION CONCERNS," ECCS PUMP PERFORMANCE LITERATURE REPORT

This memo is to inform you that item 1DAJ, Milestone: ECCS Pump Performance Literature Report, in the Operating Plan is completed.

Attachment: As stated

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GI-193: "BWR ECCS Suction Concerns", ECCS Pump Performance Literature Report

I. Introduction

A. Background

Emergency core cooling system (ECCS) require a clean, reliable water source to maintain long term recirculation following a loss of coolant accident (LOCA). Boiling Water Reactors (BWR) rely on pump suction intakes in the suppression pool or wet well to provide water to residual heat removal and core spray systems.

NRC Generic Safety Issue - 193 "BWR ECCS Suction Concerns" address the possible failure of the emergency core cooling system pumps due to unanticipated, large quantities of entrained gas in the suction piping from boiling water reactor suppression pools. The issue applies to MARK I, II, and III containments during large and medium break LOCAs, and could potentially cause pump failure or degraded performance due to gas binding, vapor locking, or cavitation.

B. Purpose

The purpose of this report is to research the available engineering literature on the ability of pumps to withstand entrained gas, particularly for short periods of time, thus to determine if any existing information is directly applicable to Generic Safety Issue - 193. The availability of specific data and literature on the operation of ECCS pumps in BWR is very limited. Nevertheless the understanding of the failure of ECCS pumps due to entrained gas in the suction piping from BWR suction pools is intended.

II. Discussion

The possible degradation of the hydraulic performance of the pump, that is, the inability of the pump to maintain sufficient recirculation flow as a result of entrained gas is of concern. Extensive two-phase pump tests to determine the effects of entrained gas (entrained gas relates to the mechanical mixture of gas bubbles having a tendency to separate from the liquid phase) on the performance of pumps have been conducted. Experimental results such as: (1) different size of pumps (from small bench-top model to full size reactor coolant circulation pumps); (2) pump types (mixed, radial or axial) that were not the same; (3) specific speed and flow rates that were very different and (4) two-phase test conditions that varied from low pressure air water flow to high pressure steam-water flow, makes this determination one that is very diverse [1]. The technical considerations relative to hydraulic performance (i.e., cavitation, air ingestion) in BWRs, are the same for single-stage or multi-stage designs. However, because of the differences in construction details between the two types of pumps, the effects of cavitation, air ingestion, etc. may be significantly different for each design [12].

Attachment

Two-phase flow pumping applications include situations where undissolved vapors or gases are being carried by the pump [2]. Air or other gases may enter the impeller inlet from several sources. The immediate effect usually will be a drop in pump pressure rise, flow rate, and power. Even small amounts of air can cause problems because the air expands substantially under low pressure to increase its volume, particularly at the inlet of the pump impeller [2]. Gas-liquid component flow results in significant pump performance degradation which is a function of the void fraction (percent volume of air in the mixture) at the pump inlet.

In an effort to understand the issue, we need to answer how much air can a centrifugal pump handle, and what can be done to prevent air binding. Literature available explain that a centrifugal pump can usually handle up to about 5% by volume of air. Above that, pumps will easily become airbound (air pressure or air pockets that prevents the liquid in a pipe from flowing smoothly [20]), especially at flow rates below the best efficiency point (BEP, is the highest efficiency point for a centrifugal pump). When pumping 5% air, the pressure developed will be reduced due to the reduced specific gravity of the fluid mixture [3].

In general, conventional centrifugal pumps aren’t designed to handle mixtures of liquid and gas. Pumping liquids containing significant amounts of entrained gas can lead to serious mechanical and hydraulic problems. Reference [4] states that a mixture of only 2% gas by volume will cause approximately a 10% reduction in capacity of the pump and 4% gas by volume will cause a reduction in capacity of the pump of over 43%. In addition to the loss of efficiency and wasted power, the pump will probably be noisy and may vibrate excessively. The research also states that entrained gases can cause shaft breakage, seal failures and, in some cases, accelerate corrosion.

A. **Gas Binding Effects**

Gas binding relates to the trapping or accumulation of gas in the pump. Gas binding occurs when a pocket of gas is trapped in the pump internals [5]. Gas is not condensable, that is, it must enter the pump with liquid or from an external source, and it must leave the pump, with the liquid, as a separate entity [6].

The American National Standard for Centrifugal Pumps state that the most dramatic effect of gas or vapor on centrifugal pump performance is the complete blocking of the impeller inlet as the pump becomes airbound. When this happens, the impeller acts as a centrifuge, and tends to separate the heavier liquid from the gas that builds up at the impeller inlet. At low rates of flow, the liquid flow cannot even carry the air through the impeller, and the gas bubble grows until it completely fills the impeller inlet (suction side). The result is complete cessation of liquid flow [2].

Figure 1 (reference 2) shows a typical system of curves, the top curve representing a liquid that is free of gas. When as little as 1% gas by volume is entrained and goes through the pump, the head and capacity are noticeably reduced. When small amounts of gas are carried through the impeller, the liquid capacity and pump discharge pressure are reduced [2]. This reduction is the result of the blockage of the flow by the gas, and a reduction in developed head due to the reduced specific gravity of the pumped mixture. When the specific gravity of liquid alone is used to convert pressure to head, a lower head measurement is indicated [2]. In addition, the curve can no longer be carried to shut-off (head value at zero flow) because at low capacity the pump becomes gas bound. Even with small percentages of air, the unit stops pumping liquid due to accumulated air in the impeller when operating near the shut-off condition of the pump. High velocities at higher rates of flow can carry with it higher percentages of gas. Therefore, when gas entrainment is a potential problem, pump should be operated at or beyond the BEP rate of flow specified by the manufacturer [2]. As the percent of gas is increased, the head and capacity are reduced further, and the minimum capacity gets to be a larger and larger value. Finally, a percentage of gas is reached beyond which the pump will not operate at all, not even at the higher capacities [6].

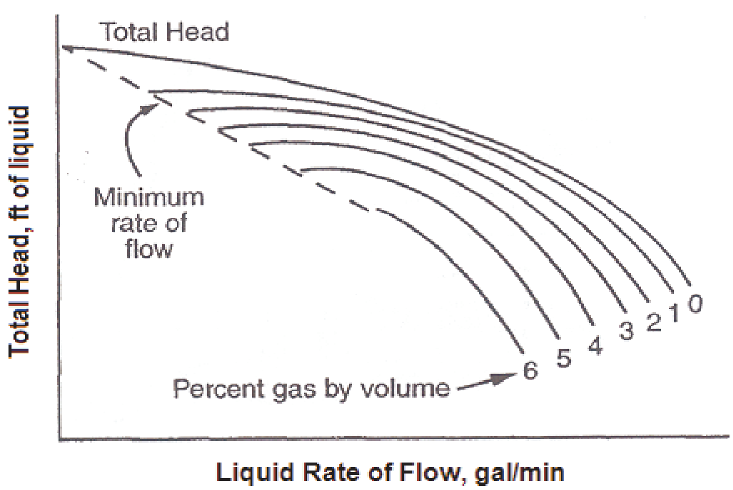


Figure. 1:
Effects of Gas on Pump Performance

Reference 7 presents the results of two independent investigations on the effect of free gas on centrifugal submersible pump performance. The results of the two investigations agreed in general at low pressures, where gas volumes exceeding 10% by total volume began to cause serious reduction in pump performance curves [7]. The effects of the free gas show up as a deterioration of head-capacity curve, such as areas of unstable head production, and effects similar to cavitation at higher flow rates [7].

Figures 2 through 8 presents the results (data points) obtained for reference 7 vs. published performance curves (smooth lines). Each figure shows a different value of percent by volume of gas at pump intake starting with pump performance with water only (figure 2) up to pump performance with 17% free gas at intake (figure 8). The results (data points) show the beginning of serious departure from head curves at about 7% free gas by total volume (figure 5) and intermittent gas locking at about 11% (figure 6). The band of calculated head shown in Figs. 6 and 7 indicate the head oscillated from high to low values with a frequency of a second or two. Although there is still the periodic head produced for still greater than 11 vol% of gas at pump intake, note that the pump is not performing at anywhere near published head values (smooth lines) once the percent by volume of gas exceeds some point between 7 and 11 vol% at intake. The tests all were made at 25 to 30 psig pump intake pressure. This series of test did not examine the effects of different fluids, high-annulus of net positive suction head (NPSH) pressure, or gas-bubble size [7].

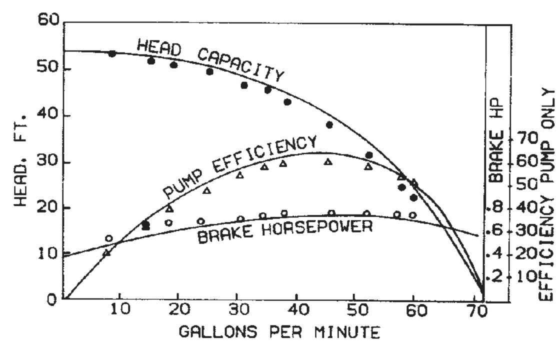


Fig. 2—Pump performance with water only.

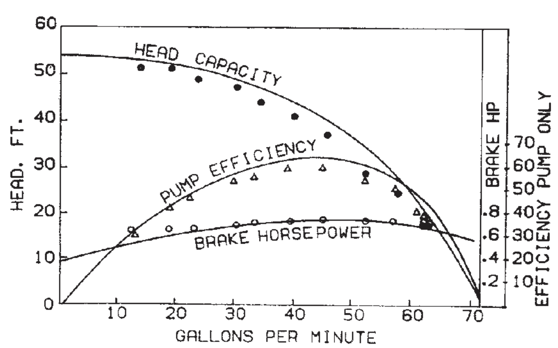


Fig. 3—Pump performance with 3.1% free gas at intake.

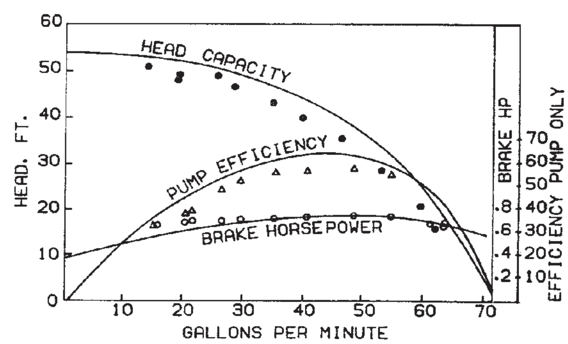


Fig. 4—Pump performance with 4.5% free gas at intake.

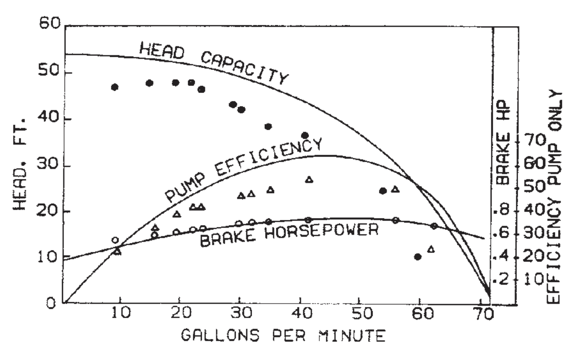


Fig. 5—Pump performance with 7.0% free gas at intake.

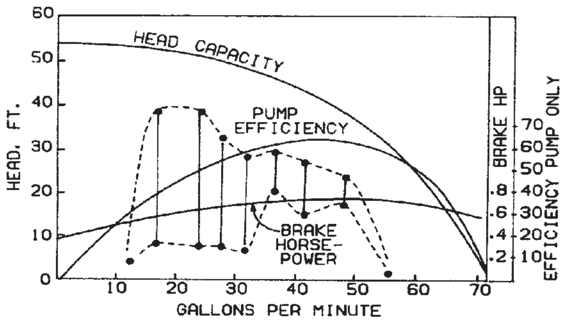


Fig. 6—Pump performance with 11% free gas at intake.

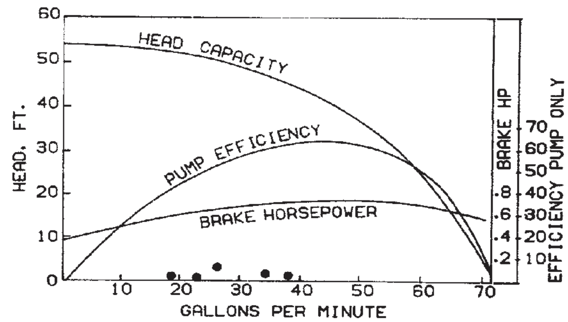


Fig. 8—Pump performance with 17% free gas at intake.

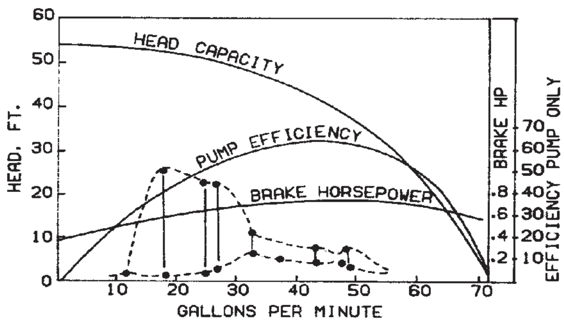


Fig. 7—Pump performance with 14% free gas at intake.

LEGEND

● HEAD
△ EFFICIENCY
○ HORSEPOWER
CURVES ARE PUBLISHED VALUES

B. **Cavitation Effects**

Cavitation is the formation of vapor bubbles in a liquid and it occur when the local static pressure in a fluid falls below the local vapor pressure of the liquid at the actual temperature [8]. In pumps, cavitation is most likely to occur at the inlet to the blades of the impeller where the static pressure is the lowest. Cavitation in the pump is undesirable not only because it can alter the flow pattern and thus degrade the pump performance, but also because collapsing cavities cause noise, vibration and mechanical damage to the impeller [9]. Cavitation is associated with the appearance of the vapor phase of the liquid being pumped. This vapor phase is condensable, and can appear and disappear in the pump and not be externally visible [6].

Cavitation damage is the loss of material produced by the collapse of the vapor bubbles against the surfaces of the impeller or casing. The vaporization itself does not cause the damage, the damage happens when the vapor almost immediately collapses after evaporation when the velocity is decreased and pressure increased [10]. To avoid cavitation in the pumps, the NPSH available (the absolute pressure in feet of liquid at pumping temperature available at the pump suction flange, above vapor pressure) at the pump inlet should be at least as large as the NPSH required (the reduction in total head as the liquid enters the pump) [9]. When these cavities form at the suction of the pump several things happen all at once: (1) there is a loss in capacity; (2) the pump can no longer build the same head (pressure); (3) the efficiency drops; (4) the cavities or bubbles will collapse when they pass into the higher regions of pressure causing noise, vibration, and damage to many of the components [11].

Air ingestion has an affect on the pump. Reference 11 states that a centrifugal pump can handle 0.5% air by volume and that at 6% air the results can be disastrous. The bubbles collapse as they pass from the eye of the pump to the higher pressure side of the impeller. Air ingestion seldom causes damage to the impeller or casing. The main effect of air ingestion is loss of capacity [11]. Air ingestion has a noticeable effect on performance when NPSH values are close to those required by the pump [9]. At low NPSH values, close to the NPSH required, air ingestion will increase the degradation in performance in comparison to operation in the absence of air. The amount of degradation depends on the quantity of air and on the difference between the available NPSH and NPSH required [9].

NUREG-0897 (reference 12) reports that air ingestion affects NPSH required for pumps. Test data on the combined effects of cavitation and air ingestion are limited, but the combined effects of both increase the NPSH required. Figure 9 shows that as the air ingestion rate increases, the NPSH requirement for a pump also increases. The curves for this particular pump show that air ingestion levels of about 2% result in a 60% increase in the NPSH required (zero % air) (allowed head degradation based upon 3% degradation from the liquid head performance). A value of 3% degradation in pump output pressure for the combined effects of air ingestion and cavitatio
performance.

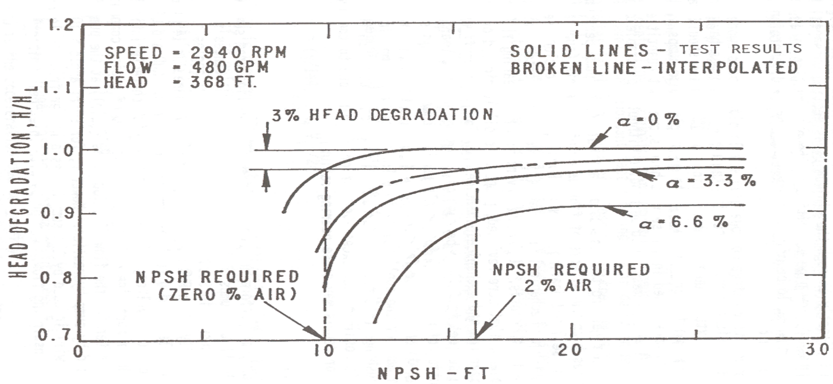
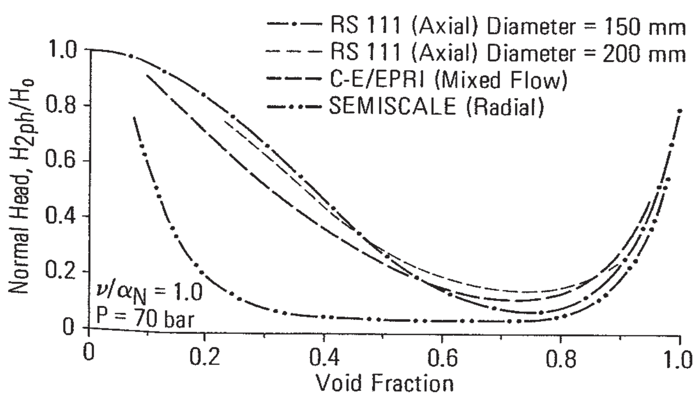


Figure. 9:
Effect of Air Ingestion on NPSH Requirements for a Centrifugal Pump

Reference 13 developed basic equations to express the volume fraction of flashed gas as a function of solubility, vapor and liquid densities, liquid vapor pressure and total pressure. This research used these equations to analyze some pump performance problems created by dissolved gas, specifically, the effects of entrained gas on centrifugal pump. This research reported that the maximum amount of inert gas should be 3% by volume. "Dissolved gases do no flash from solution instantaneously, and their volume fraction is not uniform throughout the pump. The recommended 3% by volume is for constant fraction of inert gas entering and leaving the pump. Thus, the 3% by volume as a maximum for "flashed" dissolved gas should be more conservative than 3% by volume for entrained gas".

Reference 14 presents test results at steady-state operating conditions using various pump models and two-phase pump data. The results demonstrated that there is a significant change in the delivery performance of a centrifugal pump when supplied with steam/water flow mixture. As soon as steam bubbles appears in the pump, or as soon as a mixture of steam and water or air and water flow through the pump, the head degrades. Consequently, the pump is incapable of lifting the fluid to the same height; i.e., for the same head, it is only possible to lift a significantly smaller volumetric flow [14]. This phenomenon is illustrated by figure 10, where the two-phase head normalized to the rated value of the pump is plotted as a function of the void fraction of the flow at the pump inlet. With a void fraction of zero, i.e., with a pure water flow, we obtain the design value given in this example as 1.0. As soon as steam bubbles appear and the void fraction rises as a result, the head degrades rather severely [14]. Also note from figure 10, that with a 100% void fraction, the head also recovers to 100% as a result of the pure single-phase steam flow. It is important to mention that the values for head degradation as a function of the void fraction are valid only for a specified flow rate, a definite speed, and a constant pressure. With varying system pressures, we also obtain differing head characteristics, which is illustrated in figure 11. This research concluded that different pump types exhibit different performance behavior with two-phase flow and that pump behavior is influenced by the void fraction as well as by system pressure, speed, and volumetric flow rate [14].



Legend

< = normalized flow rate
α_N = normalized pump speed
H = pump head (m)
2 ph = value for two-phase flow

Figure. 10: Head Degradation for Model Pumps of Different Construction Types

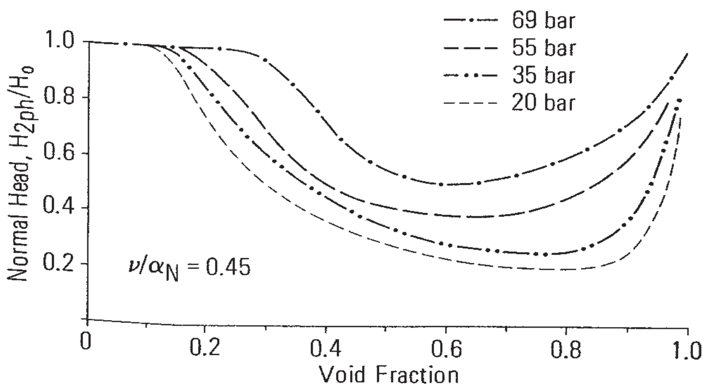


Figure. 11: Head Degradation at Various Pressures

Reference 19 investigated the performance of a full-size nuclear reactor primary heat transport pump under high pressure, steam-water two-phase flow conditions. Two-phase pump performance test data was obtained with local void fraction and mass flux measurements at the pump suction. It was found that all major pump parameters (i.e. pump head, shaft torque and pump flow) showed similar degradation characteristics under two-phase flow conditions. The two-phase pump performance was found to be very sensitive to the operating temperature and pressure. At high temperatures (260*C and above), the pump maintained its head much longer when compared to lower temperature test as suction void increased [19].

IV. NRC Research Work on Gas Entrainment

NUREG/CR-2772 (reference 15) reports on the hydraulic performance of representative BWR residual heat removal (RHR) suction inlet configurations; Mark I, Mark II and Mark III designs. Parameters of interest were air ingestion levels, vortex types, suction pipe swirl, and the RHR inlet pressure loss coefficient. The results for air ingestion are as follow: (1) zero air ingestion was measured for Froude numbers ($Fr = u\sqrt{gs}$), where u is the velocity of flow in the suction pipe, g is the acceleration due to gravity and s is the submergence of the pipe centerline from the water surface) equal to or less than 0.8 even under non-uniform approach flows; (2) at a Froude number above 1.0 and with non-uniform approach flow, air ingestion up to 4% by volume was observed in the Mark I design and air ingestion up to 0.5% by volume were observed in the Mark II and Mark III designs. This report states that the effect of the strainer in reducing air entrainment is not significant considering the accuracy of void fraction measurements, about ±1%.

NUREG/CR-2792 (reference 9) presents an assessment of the performance of RHR and containment spray (CS) pumps during the recirculation phase of reactor core and containment cooldown following a LOCA in a pressurized water reactor (PWR). NUREG/CR-2792 reports the following on air ingestion: (1) for a wide range of operating flow rates, RHR and CS pumps should handle volumetric air quantities up to 2% by volume with negligible degradation in performance; (2) for air quantities greater than 2% performance degradation of pumps varies substantially depending on design and operating conditions; (3) for very low flow rates (less than about 50% of BEP) the presence of air may cause air binding in the pump; (4) small quantities of ingested air will increase the NPSH requirements for a pump. A correction factor for NPSH requirements to account for ingested air has been proposed; (5) swirl at the pumps resulting from sump surface vortices will be negligible because of the long suction pipes between the sumps and pump inlets; (6) Industrial experience and the technical literature provide corroborative data to support these findings on the behavior of pumps in air/water mixtures. NUREG/CR-2792 also state, that the performance of centrifugal pumps is known to degrade with increasing vapor or gas content in the fluid. The amount of degradation is a function of various parameters; the important ones being pump design, specific speed, flow rate, inlet pressure, and fluid properties. A general guideline commonly adhered to by the pump industry is that for air ingestion levels less than about 2% by volume, degradation is not a concern at normal flow rates; for air ingestion between 2% and 15%, performance is dependent on pump design and for air ingestion greater than 15%, most centrifugal pumps are fully degraded. It is also generally recognized that for NPSH values close to those required by the pump, air ingestion has a noticeable effect on performance.

NUREG-0897 (reference 12) provide technical findings relevant to NPSH effects on pumps performing the functions of residual heat removal, emergency core cooling, and containment atmosphere cleanup. NUREG-0897 provide data on the performance and air ingestion characteristics of BWR suction strainer configurations. The report technical findings show (1) that air ingestion levels were correlated with the Froude number (Fr) that embodies suction submergence level and suction inlet flow velocity. Full scale experiments shown zero air ingestion for BWR suction inlet designs up to Fr # 0.8; (2) excessive air ingestion levels (i.e., > 2 to 4 volume %) can lead to degradation of pumping capacity; (3) low levels of air ingestion can be tolerated. However, pumping performance should be based on calculated pump inlet conditions for the postulated LOCA, including adjustment of the NPSH required for low levels of air ingestion.

AEOD/E218 (reference 8) reports the potential for air binding or degraded performance of BWR RHR system pumps during the recirculation phase of a LOCA. This potential, which is due to air bubble generation in the torus pool during the blowdown phase, has been studied, with the concerns being identified as (1) the degraded capability of the RHR system pumps due to air bubble entrainment, and (2) attendant pumping of a water-air mixture through the RHR torus-to-pump suction piping. Air binding of a pump due to bubble rise coalescence potentially could be an associated concern and has also been assessed.

Regulatory Guide 1.82, "Water Sources for Long-Term Recirculation Cooling Following a Loss-Of-Coolant Accident," Revision 3 (reference 16), describes methods acceptable to the NRC staff for implementing these requirements with respect to the sumps and suppression pools performing the functions of water sources for emergency core cooling, containment heat removal, or containment atmosphere clean up. The guide also provides guidance for evaluating the impact of debris on ECCS performance during long-term recirculation cooling following a LOCA. Regulatory Guide 1.82 estimate the affects of the air void on available NPSH for the high-pressure safety injection (HPSI) and CS pumps and describes methods acceptable to the staff for evaluating the NPSH margin. Regulatory Guide 1.82, appendix A, states that for BWRs, full-scale tests of suppression pool suction strainer screen outlet designs for recirculation pumps have shown that air ingestion is zero for Froude numbers less than 0.8 with a minimum submergence of 6 feet, and operation up to a Froude number 1.0 with the same minimum submergence may be possible before air ingestion levels of 2% may occur. Regulatory Guide 1.82, appendix A, Pump Performance under Adverse Conditions: The pump industry historically has determined required NPSH for pumps on the basis of a percentage degradation in pumping capacity. The percentage has at times been arbitrary, but generally is in the range of 1% to 3%. A 2% limit on allowed air ingestion is recommended since higher levels have been shown to initiate degradation of pumping capacity. The 2% by volume limit on sump air ingestion and the NPSH criteria are applied independently. However, air ingestion levels less than 2% can also affect NPSH margin. If air ingestion is indicated, correct the required NPSH from the pump curves by the relationship: $NPSH_{required(\alpha p<2\%)} = NPSH_{required(liquid)} \times \beta$, where $\beta = 1 + 0.50\alpha_p$ and α_p is the air ingestion rate (in percent by volume) at the pump inlet flange.

NRC Information Notice 88-23 alerts of the potential to gas bind high-pressure safety injection (HPSI) pumps in PWRs. The Information Notice states that the HPSI pumps are relative intolerant of gas ingestion. Starting an idle HPSI pump with gas in the suction line or the pump casing may result in gas binding or mechanical damage to the pump. The Information Notice reports on three (3) incident dealing gas binding HPSI pumps on Beaver Valley (1988), Diablo Canyon (1998), and Turkey Point (1999). (http://www.nrc.gov/reading-rm/doc-collections/gen-comm/info-notices/1988/in88023s5.html)

Draft IR 05000321/366, 2002-06, Hatch Nuclear Power Plant SSDI (reference 17) identified green finding for inadequate design control of the high pressure coolant injection (HPCI) system suction source from the condensate storage tank (CST). Vortexing in the CST was not accounted for when the licensee calculated the CST level setpoint specified in the Technical Specifications (TS) for automatic HPCI system suction switchover from the CST to the suppression pool. Vortexing could cause air ingestion into the HPCI system suction from the CST and the air could then damage the HPCI pump. This finding was of very low safety significance because licensee use of the non-safety CST as a HPCI pump suction source with the CST at low levels was unlikely since the reactor vessel or suppression pool would generally reach a high level first, where the HPCI pump would be automatically stopped or its suction would be automatically switched to the safety-related suppression pool. In addition, alternate core cooling methods would normally be available, including reactor core isolation cooling (RCIC) as well as automatic depressurization system (ADS) and low pressure coolant injection (LPCI).

IR 05000528/529/530, 2004-014, Palo Verde Nuclear Generating Station (PVNGS) Special Inspection Report (reference 18) identified green finding that involved the failure to maintain design control of the containment sump safety injection suction piping at all three PVNGS units. Specifically, a significant portion of this piping was not consistently maintained full of water since initial plant operations.

The International Incident Reporting System (IRS) captured an event on 08/18/1986, were air was detected in the part of the suction line from the containment sump to the low pressure coolant injection system pump. With air in the suction line of the pump, the ability of the LPCI pump to supply water from the containment sump after a LOCA was not guaranteed. (http://nrr10.nrc.gov/rorp/airs/00000931.html)

V. **Recommendations**

Reference 2 makes various recommendations and they are listed as follows:
(1) Provides inducers or inlet boosters. They are devices designed to benefit the functioning of the impeller in that they increase the fluid pressure before the mixture enters the pump. This increase in pressure reduces the volume of the air, thereby reducing its negative effect on the impeller performance. Since inducers generate low levels of pressure, they will have little benefit on high suction pressure applications.
(2) Install a high specific speed booster pump in series with a low specific speed pumping unit in order to minimize the effect of the gas. Laboratory test have shown that pumps with higher specific speed (high flow and low head) are affected less by the presence of gas than those with low specific speed (low flow and high head).
(3) Provides open impellers that may handle gas better than closed impellers, particularly with large clearances between the impeller and the casing. The large clearance generates turbulence which helps prevent the accumulation of large gas pockets.
(4) Provide a gas vent at the pump inlet. The suction pipe should be sized about twice as large as the flange at the pump inlet in order to keep inlet velocities low. A vent connection should be located at the top of the pipe, close to the pump so that gas can escape back to the source.
(5) When the pump takes suction from a closed tank (in our case the suppression pool), pressurize the inlet if possible, thereby reducing the volume of entrained gas, or turn some vapors back to liquid. Where vapor is the primary problem, subcooling of the inlet pipe may be helpful. This will also tent to turn vapor back to liquid, and thus reduce the volume of free vapor that must me handled by the pump.

Reference 6 recommends that if it appears that entrained air or gas is going to be a problem, it is better to go to a pump with an impeller of larger diameter rather than to a pump with a larger suction nozzle.

NUREG-0897 (reference 12) state that the use of vortex suppressors can effectively reduce air ingestion to zero. For BWR suction inlets, the inlet strainer appears to act as a vortex suppressor and retardant to air ingestion.

VII. **References**

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