NRC DRAFT GUIDANCE FOR

THE USE OF CONTAINMENT ACCIDENT PRESSURE

IN DETERMINING THE NPSH MARGIN OF ECCS AND

CONTAINMENT HEAT REMOVAL PUMPS

ENCLOSURE

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CONTENTS

Purpose:

The purpose of this draft paper is to propose guidance to ensure that emergency core cooling system (ECCS) and containment heat removal pumps will perform their safety functions during postulated design basis accidents (DBAs) and certain postulated non-design basis accidents. In particular, this paper addresses the use of containment accident pressure to ensure adequate suction conditions for these pumps.

The NRC staff anticipates industry input on the technical merits of the proposed guidance. Comments should be supported, to the extent possible, with data available to the industry.

1.0 Introduction and Background

1.1 Basic Definitions

Cavitation is the formation of vapor bubbles in a flowing fluid due to a decrease in the local static pressure below the vapor pressure of the pumped liquid. The formation of this vapor and its subsequent rapid condensation can produce damage to and adversely affect the operation of a centrifugal pump. This cavitation is nearly always accompanied by the release of gases previously dissolved in the liquid. The first appearance of cavitation is called cavitation inception.

Directly related to cavitation is the net positive suction head (NPSH). NPSH is the total (or stagnation) energy at the pump suction relative to the vapor pressure of the pumped liquid. The available NPSH (NPSHA) is a function of the flow rates, flow losses, and liquid elevation relative to the pump for the system in which the pump is located. It is the total head relative to the vapor pressure head at the pump suction. The required NPSH (NPSHR) is a function of the pump design. The required NPSH is the value of NPSH which allows a specified amount of cavitation (or no cavitation) within the pump. Required NPSH is defined by the Hydraulic Institute as the value of NPSH which results in cavitation sufficient to cause a reduction of the pump total dynamic head by 3%. This value will be denoted in this paper as $NPSHR_{3\%}$. The NPSH margin is defined as the difference between the available NPSH and the required NPSH (NPSHA-NPSHR). The NPSH margin should be greater than or equal to zero. Another useful parameter is the NPSH margin ratio which is defined as the ratio of the available to the required NPSH (NPSHA/NPSHR).

When the suction pressure or the available NPSH is decreased from the value corresponding to cavitation inception, the region of cavitation enlarges and, if the decrease in available NPSH is sufficient, noise, cavitation erosion of pump parts (mainly the impeller) and pump performance degradation will occur.

Suction conditions in a centrifugal pump can be characterized by the suction specific speed which is defined as:

$$N_{SS} = \frac{n\,Q^{1/2}}{(NPSHR_{3\%})^{3/4}}$$

where

n = the pump speed in revolutions per minute (rpm)

Q = the pump capacity (volumetric flow rate) in gallons per minute (gpm)

NPSHR = the required NPSH in feet (ft)

Both Q and NPSHR are taken at the best (maximum) efficiency point on the pump curves. Values of N_{ss} for BWR ECCS and core spray pumps can be in the range of 12000 or more.

The suction energy concept is also used to assess the suction capability of a pump. Suction energy is defined as:

Suction energy = D_{eye} n N_{ss} sg

where

D_{eye} = pump eye diameter (inches)

n = pump speed (rpm)

N_{ss} = suction specific speed defined above

sg = specific gravity

Based on the experience of hundreds of centrifugal pumps, specific gating values have been derived for the start of “Low Suction Energy,” “High Suction Energy,” and “Very High Suction Energy,” for various centrifugal pump types. Suction energy was proposed as an alternative to suction specific speed in specifying acceptable suction conditions since it was found that pump suction specific speed was not always a dependable parameter to differentiate acceptable from unacceptable regions of operation with respect to cavitation.[1]

Boiling water reactor (BWR) and pressurized water reactor (PWR) ECCS and containment spray pumps generally have a high suction specific speed and are very high suction energy pumps.

1.2 The Role of ECCS and Containment Heat Removal Pumps

1.2.1 BWR Pumps

The BWR pumps which use containment accident pressure in determining NPSH margin are the residual heat removal (RHR) and core spray pumps.

RHR pumps are typically single stage, high capacity, low discharge head pumps. They have several modes of operation. In a BWR these include but are not limited to:

- Emergency coolant injection into the reactor vessel following a loss-of-coolant accident (LOCA)
- Cooling of the reactor coolant system during normal reactor shutdown

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[1] Allan R. Budris, The Shortcomings of using Pump Suction Specific Speed to Avoid Suction Recirculation Problems

- Suppression pool cooling either during normal operation if heat is being added to the suppression pool or following a postulated accident (e.g., LOCA, Appendix R Fire, station blackout, anticipated transient without scram (ATWS))
- Containment spray (drywell spray and wetwell spray in a BWR)

During normal operation, the BWR RHR pumps are in standby, configured for safety injection. They may be run for suppression pool cooling during normal operation and for surveillance testing in accordance with the American Society of Mechanical Engineers (ASME)[2] code and the plant's technical specifications.

The BWR core spray pumps are typically single stage, low head, high flow rate pumps. Their function is to spray water from the suppression pool into the core following a LOCA. During normal operation they are in standby except for surveillance testing.

1.2.2 PWR Pumps

PWR RHR pumps are typically single stage, low head, high capacity pumps. In a PWR the RHR functions are:

- Emergency coolant injection following a LOCA
- Cooling of the reactor coolant system during normal reactor shutdown

PWR containment spray pumps are single stage, low head, high flow rate pumps. They also are in standby during normal operation.

1.3 Regulatory Requirements and Guidance

As part of reactor safety calculations, licensees must demonstrate that the ECCS pumps and containment heat removal pumps will perform their safety function of delivering "abundant flow," as required by Title 10 of the *Code of Federal* Regulations (10 CFR), Part 50, Appendix A, General Design Criterion (GDC) 35, Emergency core cooling,[3] and to rapidly reduce the containment pressure and temperature, as required by GDC 38, Containment heat removal.[4] The ECCS pumps must perform their safety function during a LOCA, in order to satisfy the requirements of 10 CFR 50.46.

Regulatory Guide 1.82 Revision 3[5] Position 1.3.1.1 (for PWRs) and Position 2.1.1.1 (for BWRs) state that ECCS and containment heat removal system should be designed so that there is adequate available NPSH provided to the system pumps "with no increase in containment pressure from that present prior to the postulated LOCAs."

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[2] For example: ASME OM Code-2004, Code for Operation and Maintenance of Nuclear Power Plants

[3] General Design Criterion 35, Emergency Core Cooling, 10 Code of Federal Regulations Part 50, Appendix A

[4] General Design Criterion 38, Containment Heat Removal, 10 Code of Federal Regulations Part 50, Appendix A

[5] Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant-Accident, US NRC, Regulatory Guide 1.82, Revision 3, November 2003

However, Regulatory Guide 1.82 Revision 3 Position 1.3.1.2 (for PWRs) and Position 2.1.1.2 (for BWRs) state that for operating reactors "for which the design cannot be practicably altered," it is acceptable to use containment accident pressure greater than the containment pressure prior to the accident in determining the available NPSH of ECCS and containment heat removal pumps. The use of this higher containment pressure in determining available NPSH has been questioned by the Advisory Committee on Reactor Safeguards (ACRS). The most recent ACRS document on this subject is a March 18, 2009, letter to the NRC Executive Director for Operations.[6] This letter also references previous correspondence from the ACRS on this subject.

As part of this demonstration that the pumps will perform their safety function, licensees should demonstrate that the ECCS and containment heat removal pumps have adequate NPSH margin following the occurrence of a postulated accident. The calculation of NPSH margin is currently performed in accordance with the positions of Regulatory Guide 1.82 Revision 3, which specify conservative input values and "worst case" assumptions, including the postulated accident scenario, intended to minimize the NPSH margin. This paper proposes guidance intended to supersede portions of the guidance of Regulatory Guide 1.82 Revision 3 after appropriate regulatory processes have been completed.

The current NRC staff practice has been to find this use of containment accident pressure acceptable if it is demonstrated that the accident pressure used in the calculation of NPSH margin is less than the calculated containment accident pressure available at that time in the postulated accident. For the postulated DBA the calculated accident pressure includes conservatisms and worst-case scenario assumptions intended to minimize the NPSH margin. For non-design basis accidents which a BWR licensee may need to consider, such as shutdown after an Appendix R Fire, station blackout or an ATWS, nominal inputs may be used.

During NRC staff discussions with ACRS, ACRS recommended quantifying the uncertainty in the calculations used for determining the acceptability of using containment accident pressure in determining NPSH margin.

This paper proposes guidance for use of containment accident pressure in determining the available NPSH of ECCS and containment heat removal pumps in reactor safety calculations, taking the ACRS recommendations into consideration. The guidance includes the treatment of uncertainties in determining NPSH margin.

1.4 Approach to Uncertainty

The current approach to calculating NPSH margin assigns bounding values to the parameters used in the calculation of NPSH margin. These bounding values and assumptions are typically based on historically high or low values or on technical specification limiting conditions for operation. The chosen accident scenario is also limiting. For example, the worst pipe break (giving the most limiting NPSH margin) is assumed for the LOCA and the worst single failure is assumed. It is also assumed that all these limiting conditions occur simultaneously.

[6] Letter from Mario V. Bonaca, Chairman, Advisory Committee on Reactor Safeguards, to R. W. Borchardt, Executive Director For Operations, U.S. Nuclear Regulatory Commission, Crediting Containment Accident Pressure in Meeting the Net Positive Suction Head Required to Demonstrate that the Safety Systems Can Mitigate the Accidents as Designed, March 18, 2009

For the DBA, the LOCA, the Boiling Water Reactor Owners' Group (BWROG) has proposed[7] an alternate method of calculating the NPSH margin in which the containment accident pressure is determined by a Monte Carlo calculation. This method is under NRC staff review. Input values for some parameters are sampled from statistical distributions and conservative (bounding) values are used for others. An acceptance criterion of a 95% probability at a 95% confidence level (95/95) is used for the Monte Carlo pressure calculation. However, since conservative values are used for other input to the available NPSH calculation, the tolerance limit on NPSHA is greater than the 95/95 value.

For the non-design basis events, NRC guidance is that more realistic input values may be used. Also, the assumption of a worst single failure is not necessary.

In accordance with this guidance, licensees should attempt to quantify uncertainty in the calculation of NPSH margin wherever this is possible. Where this is not possible, the use of bounding values is recommended.

1.5 Report Organization

The following sections discuss the NRC staff proposal for guidance to be used in assessing the acceptability of the use of containment accident pressure in determining NPSH margin.

The emphasis in this paper is on BWRs because many BWRs with Mark I containments use containment accident pressure in determining the available NPSH during postulated accidents. However, the criteria can also be applied to PWRs which use containment accident pressure to obtain adequate NPSH margin.

2.0 Use of Containment Accident Pressure in Determining the NPSH Margin of ECCS and Containment Heat Removal Pumps

2.1 Required NPSH and $NPSH_{eff}$

Required NPSH is a property of the pump itself. In addition to the pump design, required NPSH varies with the pump flow rate and the temperature of the pumped water.

The required NPSH corresponds to an acceptable level of pump cavitation, that is, the pump will accomplish its safety function with that level of cavitation for the time necessary. The necessary amount of time should include not only the duration of the accident when the NPSH margin may be limited, but any additional time needed for operation of the pump after recovery from the accident when the pump is needed to maintain the reactor and/or containment in a stable, cool condition but at a much greater NPSH margin. This additional time is usually taken as 30 days.

For practical application, the Hydraulic Institute has defined the required NPSH as corresponding to a decrease in pump total dynamic head of 3%.[8] This value of required NPSH

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[7] Containment Overpressure Credit for Net Positive Suction Head (NPSH), GE Hitachi Nuclear Energy (GEH) GEH Proprietary Information), NEDC-33347P, January 2008 (ADAMS Accession Number ML080520268)

[8] American National Standard for Centrifugal Pumps for Nomenclature, Definitions, Application and Operation, Hydraulic Institute, ANSI/HI 1.1-1.5-1994 Section 1.2.5.4

will be denoted $NPSH_{3\%}$. Although this definition is useful, it does not correspond to a physical process in the pump. At this value of required NPSH there is already significant pump cavitation. It can take from 1.05 to 2.5 times $NPSHR_{3\%}$ to achieve the 100 percent head point, and typically four to five times $NPSHR_{3\%}$ to totally eliminate cavitation.[9] This ratio can reach 20 for very high suction energy pumps.

Two values of NPSH do correspond to physical limits. The first is the value of NPSH corresponding to the inception of cavitation, $NPSH_i$. Determining cavitation inception (i.e., the first appearance of vapor) requires either visual observation or careful testing with sophisticated instrumentation. The second value of NPSH corresponds to a complete breakdown of the flow; that is, there is a total collapse of pump head. Since neither of these limits is of practical use, the Hydraulic Institute has chosen $NPSHR_{3\%}$ because it is relatively easy to determine.

The staff proposes that the NPSH margin be calculated from NPSHA - $NPSHR_{eff}$, where $NPSHR_{eff}$ is the $NPSHR_{3\%}$ value with uncertainties included. This calculated NPSH margin should be equal to or greater than zero.

NPSHR as a function of flow rate is typically obtained by testing the pump in question or a similar pump at the pump vendor's facility in accordance with the Hydraulic Institute Standard (ANSI/HI 1.6). Figure 1 shows the HI constant flow rate test for the determining $NPSHR_{3\%}$. The test begins with a large value of NPSHA in the test loop which is gradually reduced. The flow rate and the pump speed are held constant. As the test loop NPSHA is reduced, a value of NPSHA is reached at which the pump total dynamic head can no longer be maintained and decreases. The value of NPSHR is the value of the measured NPSHA for the test corresponding to a given measured decrease in the total dynamic head. The Hydraulic Institute defines NPSHR as corresponding to a total dynamic head 3% below the total dynamic head at higher values of NPSHA for which the total dynamic head is constant. This is $NPSHR_{3\%}$. Other values could also be obtained, e.g., $NPSHR_{1\%}$. These test methods are the most accurate for determining the $NPSHR_{3\%}$ of a pump. For best accuracy, the test should be conducted at the rated speed and impeller diameter, with the NPSHA controlled by a vacuum pump.

The resulting net NPSHR accuracy of this method would be expected to be in the range of ± 1 to 2 feet, or ± 2.5% to ± 5%, whichever is larger, depending on the accuracy of the instrumentation and air content of the test liquid.[10] However, it has been found from experience that the NPSHR of a pump when installed in the field is greater than the uncertainty obtained by testing at the pump vendor's facility. This is due to several effects:

(i) The NPSHR varies with changes in pump speed caused by motor slip.
(ii) NPSHR decreases with increasing water temperature.
(iii) Incorrectly designed field suction piping adversely affects the NPSHR.
(iv) The air content of the water used in the vendor's test may be lower than that of the pumped water in the field.

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9 American National Standard for Centrifugal and Vertical Pumps for NPSH Margin, Hydraulic Institute, ANSI/HI 9.6.1-1998

10 Technical Report on Task #2 Findings, Budris Consulting, October 8, 2009, ADAMS Accession Number ML093520009

(i) Pump speed.

The NPSHR varies as the square of the pump speed which changes with changes in the motor slip. Operation at less than full rated motor power and/or with high efficiency motors tends to reduce motor slip. Motor slip can cause the pump to operate at slightly higher speeds in the field compared to a factory test speed with the factory calibrated motor.

(ii) Water temperature

The NPSHR decreases with increasing water temperature. Pump vendor tests are run with cold water. As the water temperature increases, the specific volume of the vapor decreases, thus creating less void blockage. The enthalpy for creating vapor also decreases as the temperature increases. A Hydraulic Institute standard provides curves to adjust NPSHR for higher temperatures, lowering the value of the estimated NPSHR.

However, the effect of the uncertainty in the calculated water temperature should be taken into account. If the calculated water temperature is greater than the expected value, the magnitude of the reduction in NPSHR, which results in more apparent margin between NPSHA and NPSHR could be offset by a decrease in margin due to the effect of an increase in the vapor pressure on NPSHA which would reduce the apparent margin.

Therefore, this effect should not be included in determining the NPSHR at higher water temperatures.

(iii) Incorrectly designed suction piping

An approach flow as uniform as possible and free of swirl (pre-rotation of the water prior to entering the impeller) and vortices is important for acceptable pump operation. Suction piping should be short and straight. This is not always possible in field configurations. The pressure drop in the piping should be minimized to obtain the maximum available NPSH. High and very high suction energy pumps (such as the ECCS and containment spray pumps) are more susceptible to problems due to poor suction piping conditions.

(iv) Air content of pumped water

Another factor which affects the NPSH margin is the release of noncondensable gases (such as air or nitrogen) dissolved in the water as the minimum pressure in the pump approaches the water vapor pressure. The air has several effects: (1) air dampens the effect of cavitation by lessening the effect of the shock due to implosion of the condensing vapor bubbles which causes the cavitation erosion damage; (2) air in the pumped water also increases the required NPSH; and (3) air may interfere with the water cooling of pump seals.

Figure 2 shows an example of the effect of air on the required NPSH. The “knee” of the curve with high air occurs at a higher value of required NPSH.

The solubility of air and nitrogen in water decreases with increasing temperature. This would tend to decrease the gas entrained in the pump flow. The effect of air coming out of solution on the erosion rate is shown in Figure 3. Figure 3 is a plot of cavitation noise (due to bubble collapse and measured with acoustic instrumentation) as a function of the NPSH margin ratio. The cavitation noise is a measure of the intensity of cavitation occurring in the pump and correlates with the extent of cavitation erosion. The cavitation noise reaches a maximum value at an NPSH margin ratio greater than 1.0 (NPSHA = NPSHR) and decreases. The decrease is due to the effect of air coming out of solution with the vapor formation and cushioning the effect of the vapor bubble collapse. The cavitation acoustic noise (an indication of the cavitation erosion rate) is greatly reduced as the amount of air coming out of solution is increased. The amount of dissolved air varies with the temperature of the water. Budris and Mayleben[11] describe tests which demonstrate this effect.

The second effect of noncondensable gas coming out of solution at the low pressure region within the pump is to increase the required NPSH by creating additional blockage. Sufficient gas can interrupt pumping altogether by “gas locking” or “gas binding.” Both entrained and dissolved air/gas will increase the NPSHR of a pump due to the added blockage of entrained and dissolved air at the low local internal pressures within the pump. (See Figure 2 and Figure 4-2 of NUREG/CR 2792[12]).

NUREG/CR-2792 discusses the effects of air and proposes an “arbitrary” relationship between NPSHR and the fraction of air at the pump suction. This relationship is

$$NPSHR_{air/water} = NPSHR_{water}\ (1 + 0.5\ AF)$$

where AF is the air volume fraction in percent. As shown in Figure 4-3 of NUREG/CR-2792, this relation significantly overpredicts the effect of air on NPSHR for the one set of data presented.

Penney[13] proposed a method of determining the effect of noncondensable gas coming out of solution on the NPSH margin. This method was expanded upon by Tsai[14] and Chen.[15] Penney’s method calculates the pressure at the pump eye necessary to ensure that no more than the acceptable void fraction of noncondensable gas comes out of solution. A paper by Wood, et al.[16] gives an example of a successful application of this method.

The Penney method assumes that cavitation starts in a centrifugal pump at the required NPSH. As stated earlier, cavitation actually starts at from 2 to 20 times the NPSHR value. The method also assumes that the pressure at the inlet to the pump impeller is uniform and the entire suction area of the pump reaches the vapor pressure at the same time. The flow through the impeller is actually very complex, with local pressure depressions due to locally high velocities. Therefore, not all the inlet flow cavitation liberates dissolved gas at the same time. In addition, there is a time delay to the release of dissolved gas in a liquid. Not all the dissolved gas comes out of solution at the same time.

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[11] Allen R. Budris and Pillip A. Mayleben, Effects of Entrained Air, NPSH Margin, and Suction Piping on Cavitation in Centrifugal Pumps Proceedings of the 15th International Pump Users Symposium, 1998,

[12] An Assessment of Residual heat Removal and Containment Spray Pump Performance Under Air and Debris Ingesting Conditions, NUREG/CR-2792, Creare, Inc for the US NRC, September 1982

[13] W. Roy Penney, Inert Gas in liquid Mars Pump Performance, Chemical Engineering, July 3, 1978

[14] Mao J Tsai, Accounting for Dissolved Gases in Pump Design, Chemical Engineering, July 26, 1982

[15] C. C. Chen, Cope With Dissolved Gases in Pump Calculations, Chemical Engineering, October 1993

[16] Daniel; W. Wood, Robert J. Hart and Ernesto Marra, Pumping Liquids Loaded with Dissolved Gas, Chemical Engineering, July 1998

Therefore, the staff concludes that the Penney method is overly conservative. The effect of air on required NPSH can be included as an uncertainty component of $NPSHR_{eff}$.

The mechanical effects of air on pump operation are discussed in Section 2.4.

Licensees should determine a value of $NPSHR_{eff}$ applicable to their pumps, taking into consideration the effect of suction piping, air content of the water and motor slip.

For nondesign basis events such as the BWR events that result in raising the temperature of the suppression pool, e.g., shutdown after an Appendix R Fire, an anticipated transient without scram (ATWS) or station blackout, no uncertainty on $NPSHR_{3\%}$ is required. NPSHA may also be calculated using realistic (rather than conservative) assumptions.

It is possible that the available NPSH may be less than $NPSHR_{eff}$. In this case, allowing operation in this mode is acceptable if based on the results of tests in which the pump is run in cavitation and inspected after the test and found to show acceptable wear and no damage. The following conditions should apply:[17]

- Predicted operation during the postulated accident below $NPSHR_{eff}$ (LOCA) or $NPSHR_{3\%}$ (nondesign basis event) is of limited duration (less than 100 hours).
- The tests are conducted on the actual pump with the same mechanical shaft seal (including flush system) or at least a pump of the same model, size, impeller diameter, materials of construction and pump seal/flush system.
- The test is conducted at the same (field application) speed.
- The test is conducted at the actual predicted available NPSH since testing at a lower NPSHA can actually reduce, rather than increase, the cavitation erosion rate in some cases.
- The test duration should be for the time NPSHA is predicted to be less than $NPSHR_{eff}$ (LOCA) or $NPSHR_{3\%}$ (nondesign basis event).
- The flow rate and discharge head must remain above the values necessary to provide adequate core and containment cooling.

2.2 Cavitation Erosion and the Use of Containment Accident Pressure

One of the adverse effects of insufficient NPSH margin is cavitation which results in erosion (pitting) of the surface of the impeller blades and possibly other parts of the pump due to the condensation (implosion) of vapor bubbles near a solid surface.

Visual studies, acoustical measurements and field experience show that the region of maximum cavitation erosion rate occurs at an available NPSH value between the $NPSHR_{3\%}$ value (NPSH margin ratio = 1.0) and the point of cavitation inception (NPSH margin ratio of 4.0 or higher). The exact value will vary depending on the pump, the amount of air dissolved in the water and the point of operation on the pump curve with respect the best efficiency point.

Figure 4 is a qualitative representation of the various operating regions with respect to cavitation erosion. Figure 4 is a plot of NPSH vs. pump flow rate. Three curves are shown. The top

[17] Technical Report on Task #3 Findings, Draft No. 1, Allan R. Budris, P.E. – Consulting, October 14, 2009 (ADAMS Accession Number ML093510152)

curve is the NPSH corresponding to incipient cavitation ($NPSH_i$). The middle curve is the NPSH at which the maximum erosion rate occurs ($NPSH_d$). The bottom curve is required NPSH, which gives a reduction in head of 3%. Note that the maximum erosion curve is above the $NPSH_{3\%}$ curve. The available NPSH at which the maximum erosion rate occurs can be two to four times $NPSHR_{3\%}$.

The NPSH curve of incipient cavitation and the NPSH curve of maximum cavitation erosion have the same shape. Both curves peak at the run out capacity. Both curves then decrease to the point of "shockless entry." At this point the impeller pressure distribution is most favorable and incipient cavitation and cavitation erosion are both minimized. As the flow rate further decreases and incipient pump cavitation occurs at higher values of NPSH, the NPSH corresponding to maximum erosion rate also increases. Hydraulic instabilities may occur in this region.

Since the available NPSH depends on the containment pressure, which the operator cannot control (except to limit it through the use of containment sprays and/or fan coolers), the available NPSH will vary during a postulated accident and could spend some time in the region of the maximum erosion rate.

Pump tests indicate that the zone of maximum erosion rate lies between NPSH margin ratios of 1.1 to 1.6 for pumps operating outside of the zone of suction recirculation.[18,19] While very high suction energy pumps, such as BWR RHR and core spray pumps, are subject to cavitation erosion, the time operating in the maximum erosion zone has not been correlated with the degree of damage. Therefore, an open issue is how long a pump may operate in the maximum cavitation zone without failing and how this cumulative time to failure relates to the pump mission time. The staff is soliciting additional information and data to better define the need for and length of a time limit. For this paper a time limit of 100 hours was selected for the time permitted in the maximum erosion zone.

Figure 5 is a sample plot of the NPSH margin ratio (NPSHA/NPSHR) vs. time for a BWR/4 with a Mark I containment. Three NPSHA values are calculated. These are a conservative value, a “realistic” value which uses mostly nominal input values, and a value which is the mean of a Monte Carlo calculation. The value of $NPSHR_{eff}$ shown in Figure 5 is based on engineering judgment of typical numbers and is not applicable to any specific pumping system. Figure 5 is only shown as an illustration of the application of the maximum erosion criterion. Note that the Monte Carlo mean value and the “realistic” curve show good agreement in this example. This figure shows the application of the 100 hour limit between the NPSH margin ratios of 1.1 and 1.6. The NPSH margin ratio is plotted vs. time to approximately 100 hours. At the end of this time, for this example, the NPSH margin ratio based on a realistic calculation is above the maximum cavitation erosion band while the conservative calculation is still within the band of 1.1 to 1.6 at 100 hours.

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[18] Cavitation and the Centrifugal Pump: A Guide for Pump Users, Edward Grist, Taylor and Francis, 1999

[19] Allan R Budris and Phillip A. Mayleben, Effects of Entrained Air, NPSH Margin, and Suction Piping on Cavitation in Centrifugal Pumps

2.3 Containment Accident Pressure and Available NPSH

In addition to consideration of the required NPSH and the adverse mechanical effects of cavitation, it is necessary to determine the available NPSH to determine the NPSH margin.

If the available NPSH assuming the containment pressure is at its pre-accident value is less than $NPSHR_{eff}$, the containment pressure is increased so that NPSHA equals $NPSHR_{eff}$. The amount of containment pressure necessary for NPSHA to equal $NPSHR_{eff}$ is the amount of containment accident pressure used. The necessary amount of containment accident pressure must be less than the total containment accident pressure at that time.

To determine the available NPSH, the temperature of the pumped water and the pressure above the water free surface must be known. The flow losses in the suction piping from the water source (suppression pool in a BWR or sump in a PWR) must also be known.

The containment accident pressure, water temperature and water elevation above the pump suction should be calculated with an NRC-approved method. Calculation of containment accident pressure and water temperature involves heat and mass transfer processes within the containment and the tracking of the water, gas and vapor inventory in the containment. The modeling of plant equipment is also necessary. The mass and energy flows into the containment caused by the postulated accident must also be determined.

The containment calculations for NPSH analyses are typically conservative. In this approach all parameters which have a significant effect on the containment pressure and water temperature are assumed to be simultaneously at bounding values; these values are typically either technical specification limits such as limiting conditions for operation or values known to bound the expected value of a parameter.

The BWROG has proposed[20] a Monte Carlo method for calculating the lower tolerance limit (e.g., the 95/95 value) of the variable H_{ww} which is defined in the BWROG topical report as:

$$H_{ww} = \frac{P_{ww} - P_v}{\rho g}$$

where

P_{ww} = the wetwell pressure above the pool surface

P_v = the water vapor pressure

ρ = the water density

g = gravity acceleration

H_{ww} consists of two of the terms in the equation for the available NPSH obtained from the containment analysis. The other two terms in the calculation of NPSHA are the elevation of the water level above the pump suction centerline and the flow losses. The elevation of the water

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[20] Containment Overpressure Credit for Net Positive Suction Head (NPSH) , GE Hitachi Nuclear Energy (GEH)GEH Proprietary Information), NEDC-33347P, January 2008 (ADAMS Accession Number ML080520268)

level above the pump centerline can also be determined in the containment calculation or a conservatively low value may be used. The flow loss term in the NPSH equation is calculated conservatively to bound the expected value. For the LOCA, the flow loss term includes the flow resistance due to the accumulation of debris on the suction strainers or screens upstream of the pump suction.

The NRC staff performed independent Monte Carlo, conservative and more realistic calculations for a LOCA in a typical BWR/4 with a Mark I containment. These calculations are documented in a staff memorandum.[21] Portions of the Phenomena Identification and Ranking Table (PIRT) method[22] were applied to the determination of NPSH margin to identify the important parameters to be considered. Sensitivity studies were performed for a BWR 4 with a Mark I containment using the GOTHIC computer code[23] for those parameters determined to be significant. The results of this sensitivity study are shown in Table 1. In addition to the values listed, the single failure criterion was assumed to apply in both the conservative and the Monte Carlo calculations. The containment (drywell and wetwell) sprays were assumed to be in operation for the duration of the event.

Variables which tend to increase the suppression pool (or sump) temperature have the greatest effect in minimizing the available NPSH. These variables include the reactor power, decay heat, initial suppression pool temperature, RHR heat exchanger effectiveness, and service water temperature. The other parameters in the table affect the containment pressure. They are chosen so as to minimize the drywell and wetwell pressures.

The results of the staff calculations are shown in Figure 6. Figure 6 shows both the Monte Carlo results and the conservative results in terms of NPSHA. The mean and minimum Monte Carlo results are shown. The minimum value corresponds to a 95/95 lower tolerance limit. Notice that the conservative calculation results and the Monte Carlo lower tolerance limit (95/95) give reasonably close agreement. This quantifies the level of conservatism in the conservative calculation.

Since sensitivity studies show that the conservative approach and the BWROG method at the 95/95 lower tolerance limit are in reasonably close agreement, either method may be used to calculate the containment conditions and the available NPSH.

Figure 6 also shows that the realistic calculation and the statistical mean of the Monte Carlo calculation also show close agreement.

Computer code modeling uncertainty was not included in the BWROG methods. This is acceptable to the staff since the BWROG method uses the General Electric Hitachi (GEH) computer code SHEX which is biased conservatively. The staff calculations using GOTHIC have verified this conservatism.

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[21] Memorandum from Ahsan Sallman, NRC, to Robert Dennig, NRC, GOTHIC Calculations for a Typical BWR/4 with a Mark I Containment to Study the Use of Containment Accident Pressure, ADAMS Accession Number ML100480097

[22] B. Boyack, et al., Quantifying Reactor Safety Margin: Application of Code Scaling, Applicability, and Uncertainty Evaluation Methodology to a Large Break Loss of Coolant Accident, Idaho national Engineering Laboratory, NUREG/CR-5249, December 1989

[23] GOTHIC Containment Analysis Package, Technical Manual, Version 7.2a, NAI 8907-06, Rev 16, January 2006

Staff calculations in this paper use the GOTHIC computer code. There is no publically available modeling uncertainty for the GOTHIC code. GOTHIC predictions of Marviken (a Swedish BWR with a vent system similar to a U.S. Mark II BWR containment) blowdown test data for wetwell pressure, drywell-to-wetwell differential pressure and wetwell liquid and vapor pressure temperatures show good agreement between the GOTHIC code and data. Therefore, GOTHIC modeling uncertainty is not expected to be a significant contributor to overall uncertainty in NPSHA.

Licensees proposing to use containment accident pressure in determining available NPSH should also perform a realistic calculation of available NPSH to compare with the conservative calculation or the Monte Carlo 95/95 calculation.

2.4 Effect of Noncondensable Gas on Pump Mechanical Performance

As shown in Figure 7, the amount of entrained air in a pump increases as the NPSH margin ratio is reduced towards an NPSH Margin Ratio of 1.0 and below. This additional entrained air comes from the dissolved air coming out of solution as local static pressure drops below the vapor pressure. Centrifugal pumps not specifically designed to transport gas-liquid mixtures can generally accommodate (at inlet pressures near one atmosphere) up to approximately 2% gas volume in the inlet nozzle without appreciable effect.[24] Operation in an air bound condition can cause overheating and failure (seizing of the impeller in the casing of the pump). This damage can occur in 10 minutes or less. Figure 8 shows the impact of air in the pump suction on the pump performance. This figure shows an example of the drop in total pump head as a percent of the best efficiency point (BEP) flow rate. Notice the large loss in performance at greater than 2% volume air fraction.

Larger quantities of entrained air can impact pump mechanical performance including complete loss of prime or air binding and mechanical damage. The entrained air may be from air entrained in the suction water source, transported by vortices or by dissolved air coming out of solution. The sump and suppression pool configurations should eliminate consideration of entrained air (for instance, due to air entrained by containment sprays) and vortices since any air bubbles will rise to the free surface of the pool and steps are taken in sump design to eliminate vortices. In addition, data developed as part of the resolution of Unresolved Safety Issue A-43, Containment Emergency Sump Performance, show that vortices decay to negligible levels within 14 pipe diameters so that vortices created in a pool would not travel completely through the pump intake piping to the pump suction.[24]

Another concern with operating a pump in the vicinity of the 3% NPSHR condition is the damage that the water vapor and/or entrained air could do within the pump to the mechanical shaft seal faces which could fail in a very short period of time if the seal faces run dry. Excessive entrained air tends to accumulate in the vicinity of the shaft, where the mechanical seal is housed.

This means that, to protect the mechanical seal faces from this excess entrained air in the vicinity of the 3% NPSHR condition, dual mechanical seals with an external cold water flush system (or equal) should be provided.

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[24] An Assessment of Residual heat Removal and Containment Spray Pump Performance Under Air and Debris Ingesting Conditions, NUREG/CR-2792, Creare, Inc for the US NRC, September 1982

2.5 Pump Flow Rate

The flow rate chosen for the available NPSH analysis should be greater than or equal to the flow rate assumed in the safety analyses that demonstrate adequate core and containment cooling. This ensures that the safety analysis and the NPSH analysis are consistent.

If the assumption that NPSHA equals $NPSHR_{eff}$ is used to determine the containment accident pressure used, then the pump flow rate used in the core and containment cooling calculations should be equal to or less than the flow rate resulting from a 3% decrease in pump total dynamic head. This is illustrated in Figure 9.

2.6 Duration of the Need for Containment Accident Pressure

As stated above, based on pump performance considerations, the time for operation in the region of maximum cavitation erosion should be limited.

In addition, in considering containment integrity, the duration of the need for containment accident pressure to maintain acceptable available NPSH is, in general, not risk significant. Therefore no time limit based on containment integrity is necessary since such factors as preexisting leaks or failure to isolate the containment upon receipt of a containment isolation signal dominate risk and are independent of the time interval during which containment accident pressure is used.

2.7 Loss of Containment Isolation and Containment Leakage

A loss of containment isolation that could compromise containment integrity should be considered. Possible losses of containment integrity include containment venting required by procedures or loss of containment isolation due to a postulated Appendix R fire. It should be demonstrated conservatively that, for the plant examined, loss of containment integrity from these causes cannot occur or that they would occur only after use of containment accident pressure is no longer needed.

To reduce the likelihood of a preexisting leak, licensees proposing to use containment accident pressure in determining NPSH margin should:

(i) Determine the minimum containment leakage rate sufficient to lose the containment accident pressure needed for adequate NPSH margin.

(ii) Propose a method to determine if the actual containment leakage rate exceeds the leakage rate determined in (i) above. For inerted containments, this method could consist of a periodic quantitative measurement of the nitrogen makeup performed at an appropriate frequency to ensure that no unusually large makeup of nitrogen occurs. Monitoring oxygen content is another method. For subatmospheric containments, a similar procedure might be used.

(iii) Propose a limit on the time interval that the plant operates when the actual containment leakage rate exceeds the leakage rate determined in (i) above.

2.8 Overcooling the Containment During an Event in Which Containment Accident Pressure is Used.

It should be demonstrated that operation of sprays and fan coolers will not cause the containment accident pressure to be less than that needed to maintain adequate available NPSH. Operator action to control the containment pressure by means of containment sprays or fan coolers is acceptable, if justified. Adequate guidance should be included in the appropriate procedures (emergency, abnormal, etc.).

2.9 Alternatives to the Use of Containment Accident Pressure

Regulatory Guide 1.82 Revision 3, Position 1.3.1.2 (for PWRs) and Position 2.1.2 (for BWRs) state that for certain operating PWRs or BWRs for which the design cannot be practicably altered, it may not be possible to assume no increase in containment pressure from that present prior to the postulated LOCA. Licensees requesting use of containment accident pressure should demonstrate that it is impractical to avoid use of containment accident pressure.

3.0 Quantifying NPSH Margin

One of the goals of this work is to quantify the margin between the expected (realistic, best estimate, nominal) value of NPSH margin and the NPSH margin obtained from licensing calculations. This has been done in several ways.

For non-design basis accidents, termed “special events” for BWRs, realistic containment calculations are acceptable. This is consistent with NRC staff guidance for these events. Realistic calculations imply that no conservative bias is built into the calculations. Conservative assumptions such as the single failure assumption are not necessary. Input values may be those associated with normal operation and not values based on technical specification limiting conditions for operation or bounding assumptions (e.g., 100% drywell relative humidity). Where a realistic value is not available or cannot be easily defined, a more conservative value should be used. For example, the service water temperature may vary over a wide range (depending on the season) and therefore the service water temperature giving the more limiting NPSH margin should be used.

For the non-design basis calculations, the required NPSH may be used without considering its uncertainty.

For design basis accidents, a conservative (bounding) NPSH margin analysis should be used. Input values should be based on bounding values for significant parameters and technical specification limiting conditions for operation should be used where applicable. NRC staff BWR/4 Mark I containment calculations have shown that conservative calculations of NPSH margin fall close to the 95/95 lower tolerance limit of a Monte Carlo calculation of the same problem. This serves as a quantification of the margin in the conservative calculation. In addition, the NRC staff proposes that a realistic calculation should be performed to compare with the conservative calculation. This will also provide a measure of the margin in the conservative calculation.

It is also acceptable to perform a Monte Carlo calculation, using the 95/95 lower tolerance limit of available NPSH for the conservative case.

For the design basis calculations, the required NPSH used should include its uncertainty.

4.0 Guidance Summary

Based on the discussion in Section 3 the NRC staff proposes the following guidance for the use of containment accident pressure in determining available NPSH of safety related pumps.

4.1 For design basis accidents, a value of $NPSHR_{eff}$ should be used in analyses concerning the use of containment accident pressure that includes the uncertainty in the value of $NPSHR_{3\%}$ based on vendor testing and installed operation. The effects of motor slip, suction piping configuration and air content should be included.

$$NPSHR_{eff} = (1 + \text{uncertainty})\ NPSHR_{3\%}$$

For non-design basis accidents, $NPSHR_{3\%}$ may be used.

4.2 The maximum flow rate chosen for the available NPSH analysis should be greater than or equal to the flow rate assumed in the safety analyses that demonstrate adequate core and containment cooling. This ensures that the safety analysis and the NPSH analysis are consistent. If the available NPSH is assumed equal to the $NPSHR_{3\%}$, the usual assumption for determining the amount of containment accident pressure used, then the flow rate used in the core and containment cooling analyses should also be equal to or greater than the flow rate resulting from a 3% decrease in pump total dynamic head.

4.3 Either a conservative approach or a 95/95 lower tolerance limit may be used to calculate the containment accident pressure used to determine the available NPSH.

4.4 It should be demonstrated conservatively that, for the plant examined, loss of containment integrity from containment venting, Appendix R Fire associated circuit issues or other causes cannot occur or that they would occur only after use of containment accident pressure is no longer needed.

4.5 Operator action to control containment accident pressure is acceptable. Any operator actions should be approved by the NRC staff and included in the appropriate procedures (emergency, abnormal, etc.)

4.6 It is possible that the available NPSH may be less than $NPSHR_{eff}$ (LOCA) or $NPSHR_{3\%}$ (non design basis accident). In this case, operation in this mode is acceptable if appropriate tests are done to demonstrate that the pump will continue to perform its safety function(s). The following conditions should apply:

- Predicted operation during the postulated accident below $NPSHR_{eff}$ (LOCA) or $NPSHR_{3\%}$ (non design basis event) is of limited duration (less than 100 hours).
- The tests are conducted on the actual pump with the same mechanical shaft seal (including flush system) or at least a pump of the same model, size, impeller diameter, materials of construction and pump seal/flush system.
- The test is conducted at the same (field application) speed.
- The test is conducted at the actual predicted available NPSH since testing at a lower available NPSH can actually reduce, rather than increase, the cavitation erosion rate in some cases.
- The test duration should be for the time NPSHA is predicted to be less than $NPSHR_{eff}$ (LOCA) or $NPSHR_{3\%}$ (non design basis event).

- The flow rate and discharge head must remain above the values necessary to provide adequate core and containment cooling.

4.7 In order to reduce the likelihood of a pre-existing leak, licensees proposing to use containment accident pressure in determining NPSH margin should:

(i) Determine the minimum containment leakage rate sufficient to lose the containment accident pressure needed for adequate NPSH margin.

(ii) Propose a method to determine if the actual containment leakage rate exceeds the leakage rate determined in (i) above. For inerted containments, this method could consist of a periodic quantitative measurement of the nitrogen makeup performed at an appropriate frequency. For subatmospheric containments, a similar procedure might be used.

(iii) Propose a limit on the time interval that the plant operates when the actual containment leakage rate exceeds the leakage rate determined in (i) above.

4.8 Regulatory Guide 1.82 Revision 3, Position 1.3.1.2 (for PWRs) and Position 2.1.2 (for BWRs) states that for certain operating PWRs or BWRs for which the design cannot be practicably altered, it may not be possible to assume no increase in containment pressure from that present prior to the postulated LOCA. Licensees requesting use of containment accident pressure should demonstrate that it is impractical to avoid use of containment accident pressure in determining the available NPSH of ECCS and containment heat removal pumps.

4.9 The zone of maximum erosion rate should be considered to lie between NPSH margin ratios of 1.1 to 1.6. The permissible time in this range, for very high suction energy pumps, should be limited unless operating experience, test or analysis justifies a longer time. Realistic calculations should be used to determine the time within this band of NPSH ratio values.

4.10 A realistic calculation of available NPSH should be performed to compare with the NPSHA determined from a conservative calculation or the Monte Carlo 95/95 calculation.

4.11 The necessary mission time for a pump using containment accident pressure should include not only the duration of the accident when the NPSH margin may be limited, but any additional time needed for operation of the pump after recovery from the accident when the pump is needed to maintain the reactor and/or containment in a stable, cool condition but at a much greater NPSH margin. This additional time is usually taken as 30 days.

ACRONYM LIST

ACRS	Advisory Committee on Reactor Safeguards
ANSI	American national Standards Institute
ASME	American Society of Mechanical Engineers
BEP	Best Efficiency Point
BWR	boiling water reactor
BWROG	Boiling Water Reactor Owners' Group
CFD	computational fluid dynamics
CFR	Code of Federal Regulations
DBA	design basis accident
ECCS	emergency core cooling system
GEH	General Electric Hitachi
HI	Hydraulic Institute
LOCA	Loss-of-coolant accident
N_{SS}	suction specific speed
NPSH	net positive suction head
NPSHA	available net positive suction head
NPSH margin	net positive suction head margin
NPSHR	required net positive suction head
NPSH ratio	net positive suction head ratio (NPSHA/NPSHR)
NRC	US Nuclear Regulatory Commission
PIRT	phenomena identification and ranking table
PWR	pressurized water reactor

TABLE 1

Sensitivity Study of the Influence of Input Parameters on Available NPSH for a Postulated Recirculation Line Break LOCA in a BWR/4 with a Mark I Containment

Case No.	Parameter	Base Value (B)	Compared Value (C)	Change in Parameter Value (%) (Note 1)	Change in Supp Pool Temp (%) (Notes 2 & 5)	Change in Wetwell Pressure (%) (Notes 3 & 5)	Change in Maximum Available NPSH (%) (Notes 4, 5, & 6)
1	Power (percent)	100	95	-5	-2.34	-5.47	-4.24
2	Decay Heat (sigma)	2	0		-4.36	-8.14	-5.04
2a	Decay Heat (sigma)	2	1.9	-5	-0.12	-0.22	0.21, -0.45
3	Initial Supp Pool Temp (°F)	90	85.5	-5	-2.93	-3.89	-2.27
4	Service Water Temperature (°F)	90	85.5	-5	-2.63	-3.83	-2.26
5	RHR HX K-Value (Btu/sec °F)	147	139.65	-5	2.76	4.89	2.14
6	Initial Drywell Relative Humidity (%)	100	95	-5	-0.09	0.44, -0.72	0.67, -0.76
7	Initial Drywell Pressure (psia)	14.26	14.97	5	-0.1	2.02	2.53
8	Initial Wetwell Pressure (psia)	14.26	14.97	5	-0.2	2.16	2.32
9	Initial Drywell Temperature (°F)	135	128.25	-5	-0.12	1.58	2.02
10	Initial Torus Liquid/Volume Ratio	0.3858	0.4051	5	-1.82	-3.67	1.29, -0.96
11	Core Spray Flow Rate (gpm)	3027	2876	-5	-0.17	1.12	2.67
12	Drywell Spray Flow Rate (gpm)	3800	3610	-5	-0.08	0.77	0.88, -0.22

Case No.	Parameter	Base Value (B)	Compared Value (C)	Change in Parameter Value (%) (Note 1)	Change in Supp Pool Temp (%) (Notes 2 & 5)	Change in Wetwell Pressure (%) (Notes 3 & 5)	Change in Maximum Available NPSH (%) (Notes 4, 5, & 6)
13	Wetwell Spray Flow Rate (gpm)	200	190	-5	-0.01	0.34, -0.08	0.54, -0.09
14	Containment Leakage (Wt%/day)	1.2	6.0	500	-0.02	-2.31	-2.86
14a	Containment Leakage (Wt%/day)	1.2	1.26	5	0.01, -0.03	0.12, -0.14	0.16, -0.17
15	Passive Heat Sinks	Present	Absent	-	1.31	2.12, -0.15	1.52, -0.03
16	Strainer & Piping Loss (ft)	5.79	5.5	-5	0	0	0.78

Notes

1. Change in parameter is percentage change ("compared" minus "base" value)*100/"base" value

2. Change in suppression pool temperature, i.e., (TsC-TsB)*100/TsB, where:
TsB = Suppression pool temperature at base value of parameter, and
TsC = Suppression pool temperature at the compared value of parameter

3. Change in wetwell pressure i.e., (PwC-PwB)*100/PwB, where:
PwB = Wetwell pressure at the base value of parameter, and
PwC = Wetwell pressure at the compared value of parameter

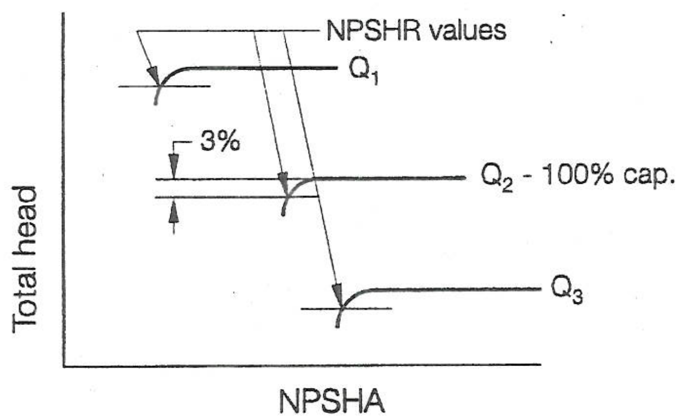
4. Change in maximum available NPSH during the transient, i.e., (NPSHC - NPSHB)*100 / NPSHB, where:
NPSHB = Available NPSH at the base value of parameter, and
NPSHC = Available NPSH at compared value of parameter

5. Changes described in Notes 2, 3, and 4 above are at different times during the transient.

6. Where two values are given, one is the maximum and the other is the minimum calculated during the event.

FIGURES

FIGURE 1



NPSH test with rate of flow held constant

FIGURE 2

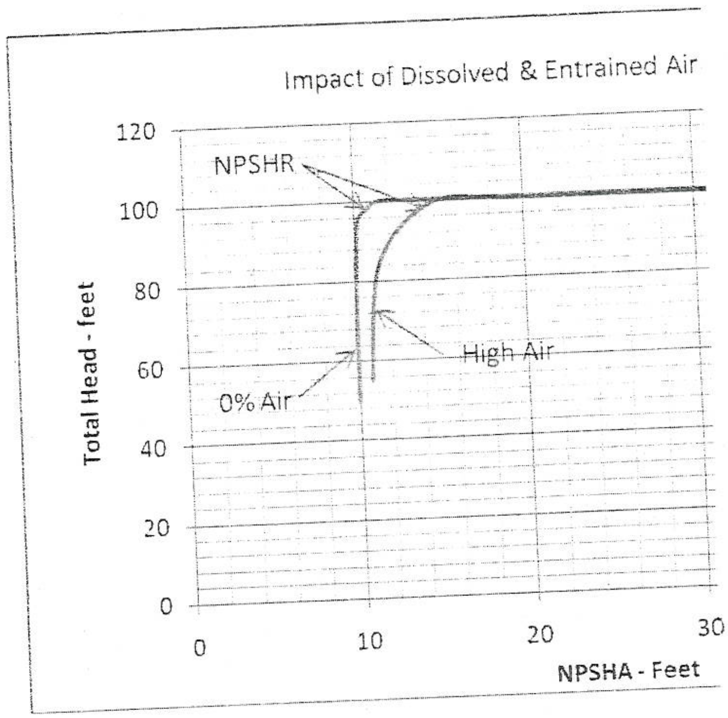
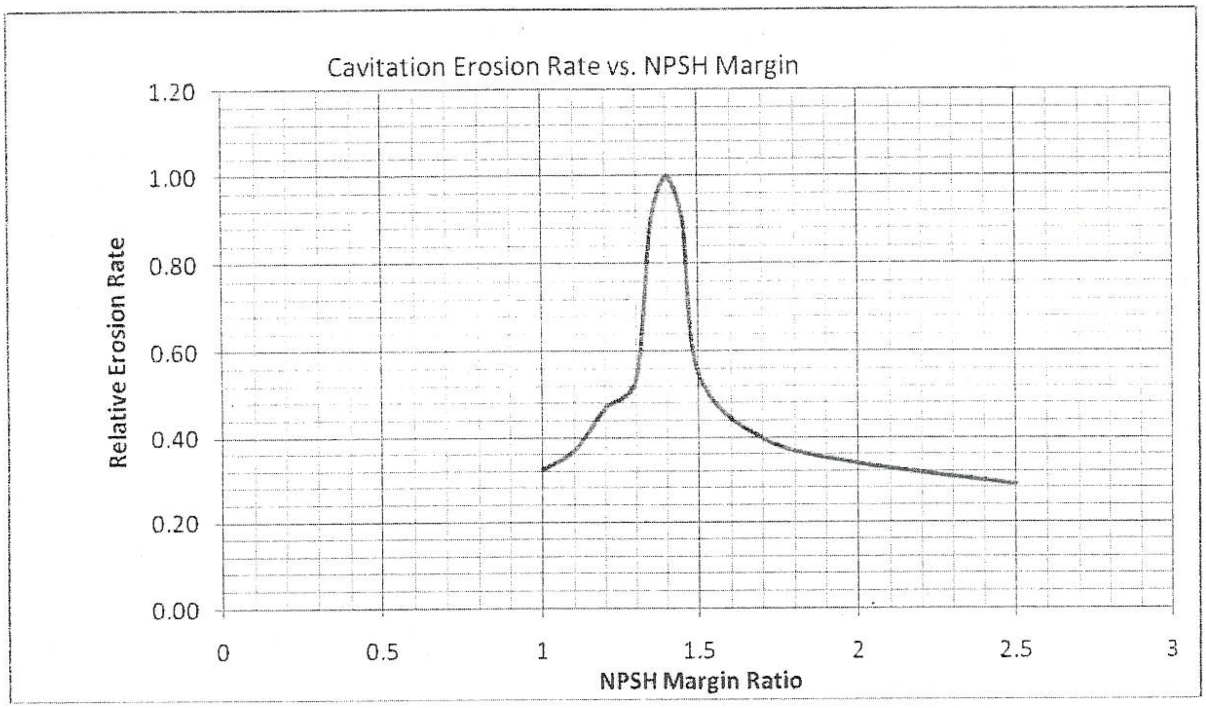
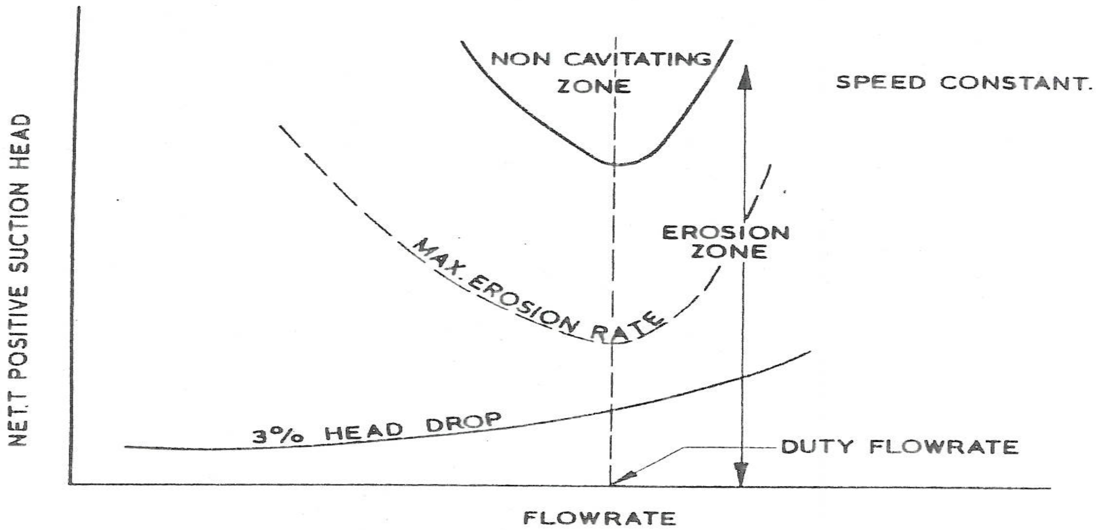

Impact of Dissolved & Entrained Air
NPSHR
High Air
0% Air
Total Head - feet
NPSHA - Feet
120
100
80
60
40
20
0
0
10
20
30

FIGURE 3



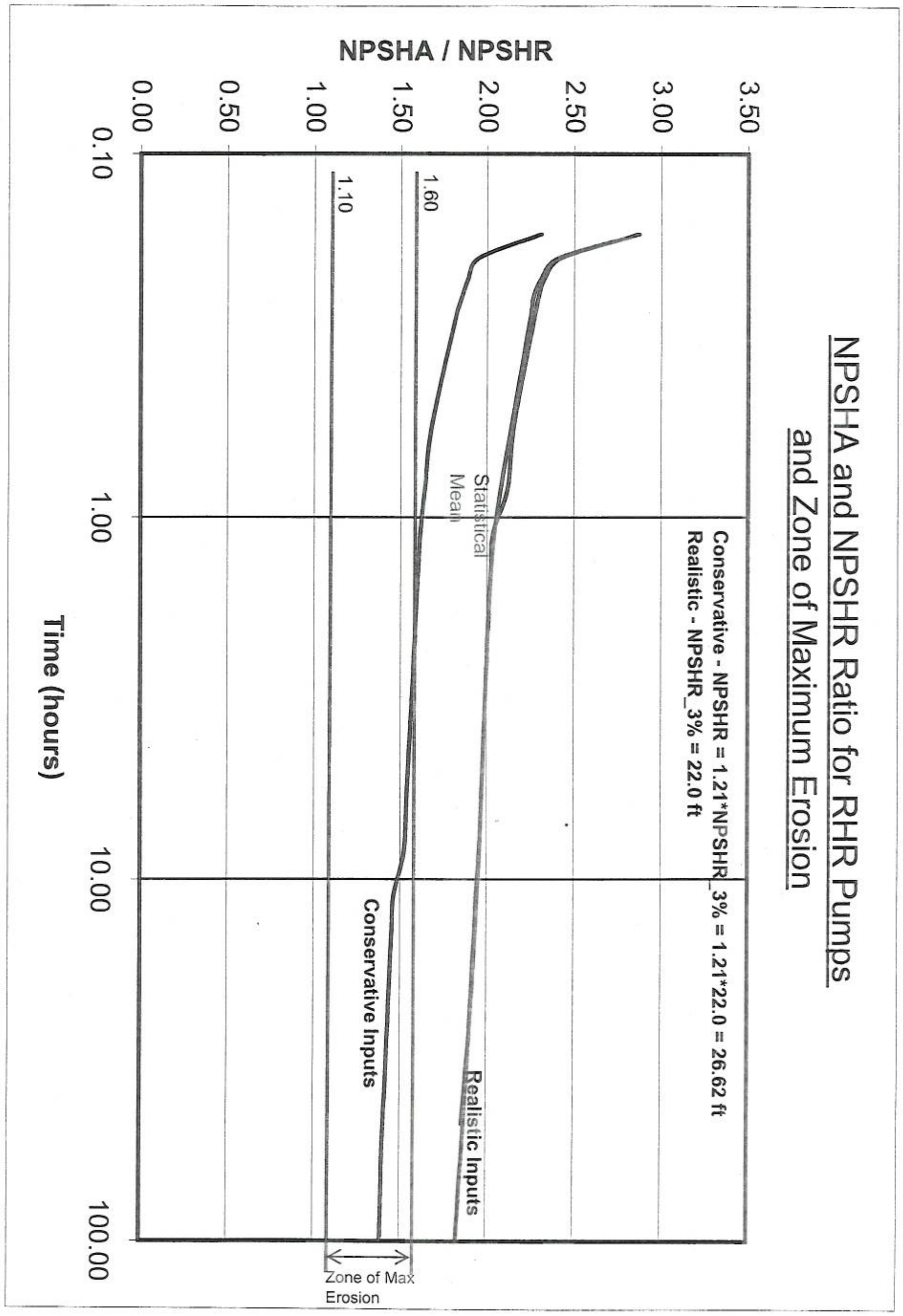
Typical Relative Erosion Rate vs. NPSH Margin near BEP Flow Rate

FIGURE 4



EROSION ZONE BOUNDARY

FIGURE 5



NPSHA and NPSHR Ratio for RHR Pumps and Zone of Maximum Erosion
Conservative - NPSHR = 1.21*NPSHR_3% = 1.21*22.0 = 26.62 ft
Realistic - NPSHR_3% = 22.0 ft
NPSHA / NPSHR
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
Time (hours)
0.10
1.00
10.00
100.00
1.10
1.60
Statistical Mean
Realistic Inputs
Conservative Inputs
Zone of Max Erosion

FIGURE 6

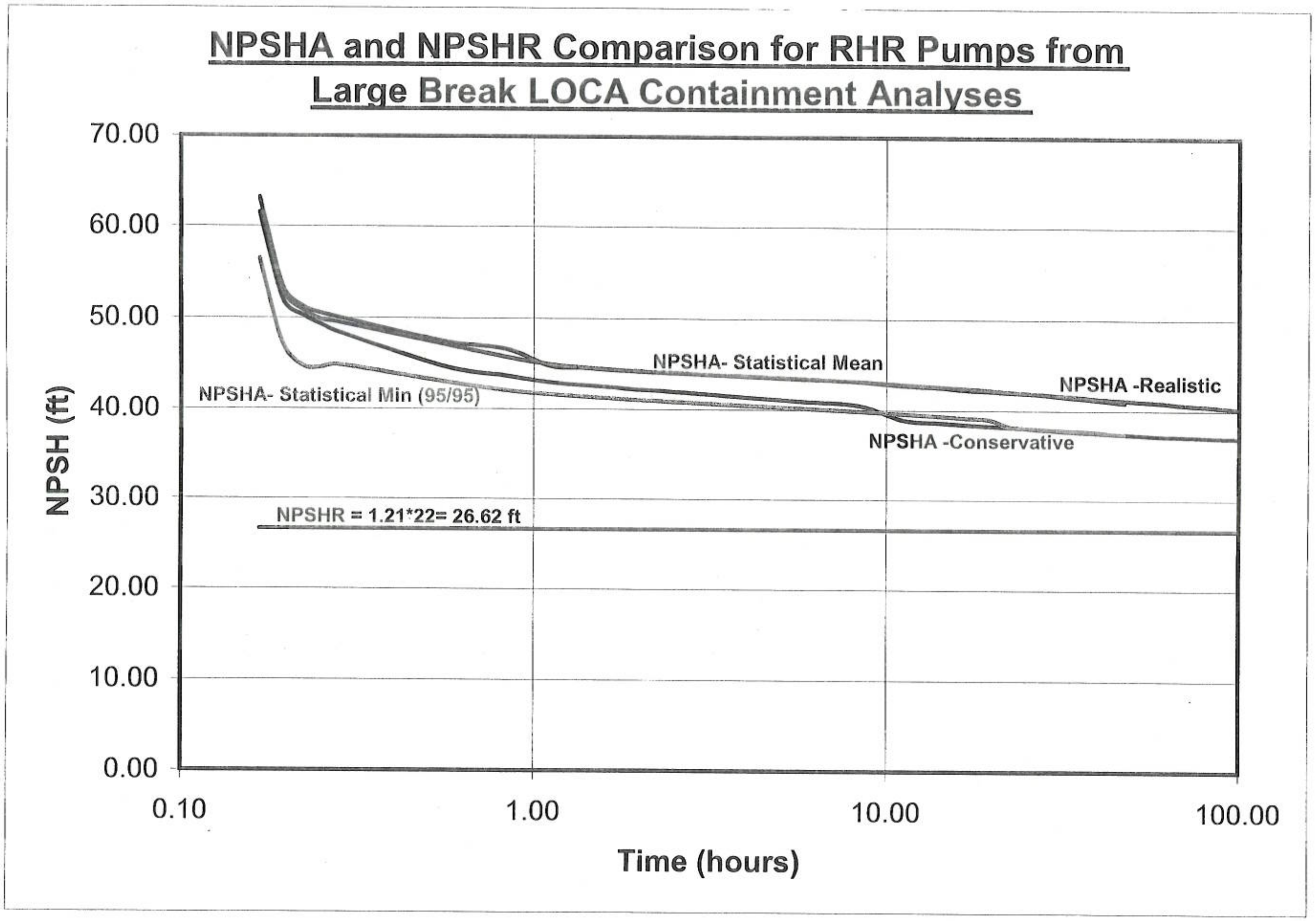
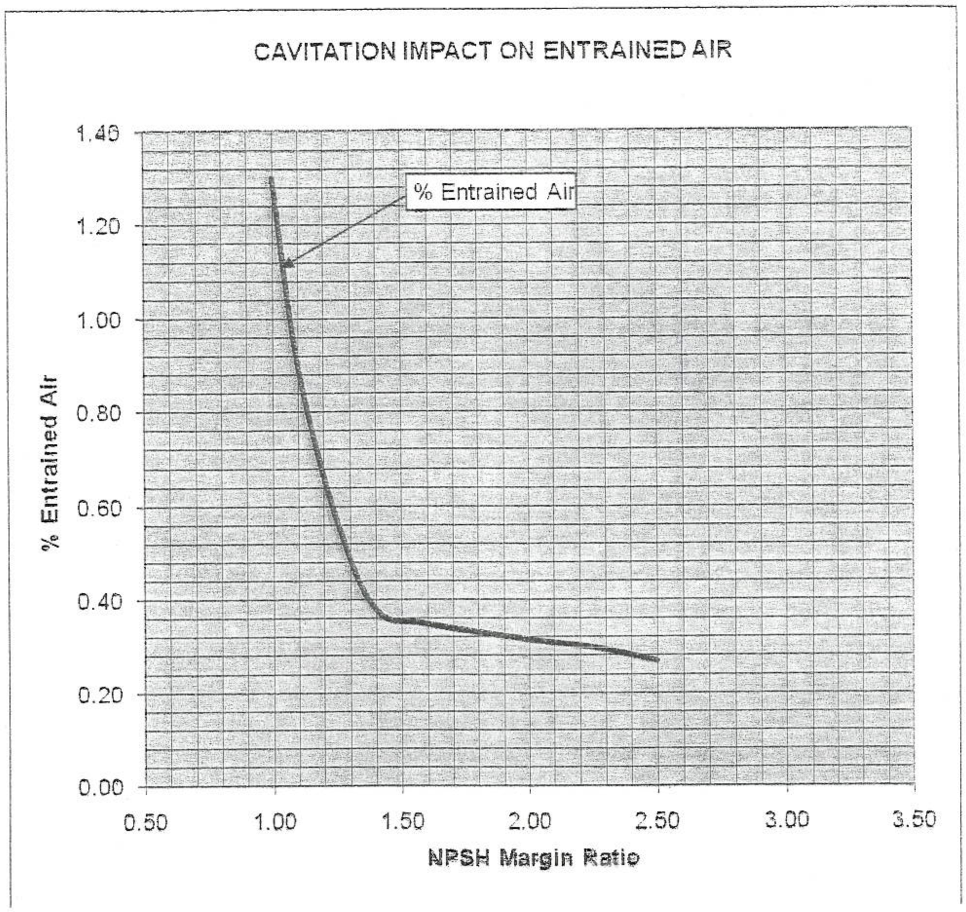
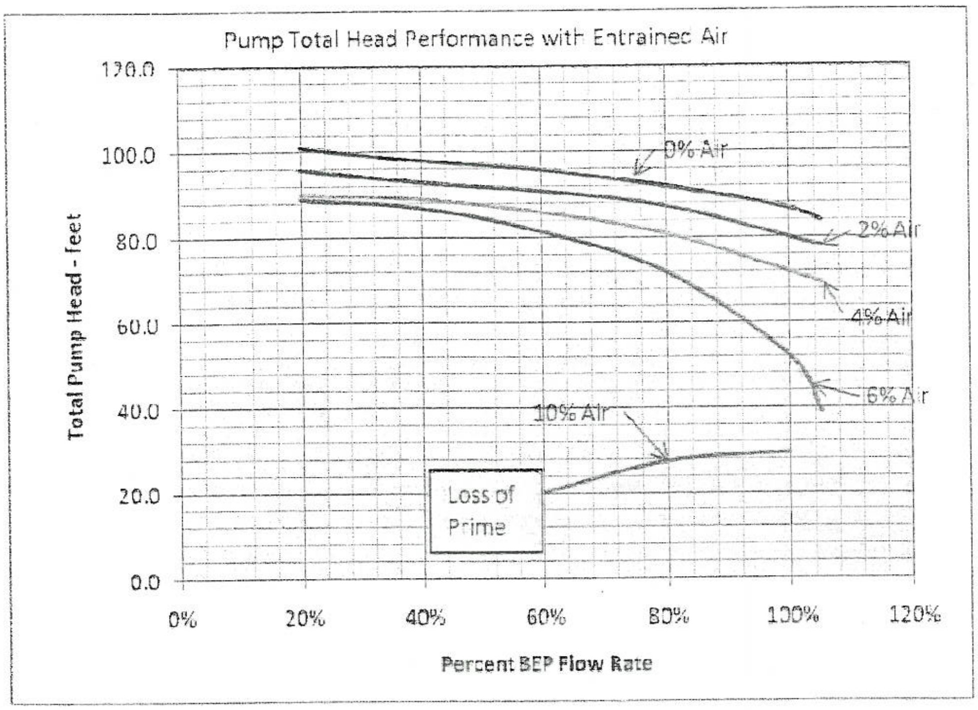

NPSHA and NPSHR Comparison for RHR Pumps from Large Break LOCA Containment Analyses
NPSH (ft)
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0.10
1.00
10.00
100.00
Time (hours)
NPSHA- Statistical Mean
NPSHA -Realistic
NPSHA- Statistical Min (95/95)
NPSHA -Conservative
NPSHR = 1.21*22= 26.62 ft

FIGURE 7



Entrained Air content increase with reducing NPSH Margin Ration (amount of cavitation).

FIGURE 8



Example of Pump Total Head Performance with varying amounts of Entrained Air

FIGURE 9