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**BACKGROUND:**

This analysis relates to a loss-of-coolant nuclear reactor accident (LOCA), where a reactor coolant system pipe is assumed to break, with the break being instantaneous and the two ends of the pipe break separate so that reactor coolant at critical flow discharges from both ends of the pipe into the atmosphere of the containment building. The peak containment pressure following a LOCA is predicted using conservative assumptions, and can approach 50-60 psig (which increases the NPSHA), with a peak predicted temperature of the suppression pool water in the range of 190-220 F (that increases the vapor pressure which reduces the NPSHA). In addition, during a LOCA accident the NPSHA is assumed to be further reduced by the partial blockage of the screens in the pump suction path from debris generated by the accident.

On a signal of high containment pressure or low reactor vessel water level the emergency pumps are started. The residual heat removal (RHR) pumps and the core spray (CS) pumps, being low head pumps, cannot discharge into the reactor vessel until the reactor vessel pressure is below approximately 300 psia (which should take less than 10 minutes). Prior to reaching this pressure and valve opening the pumps are recirculating a fraction of their full flow.

Based on the above scenario, the expected NPSH margin ratios (using the typical Available Static Mean NPSH during a LOCA accident), for the RHR and CS pumps are shown in Tables 1 and 2 and Figure 1 (an approximated scenario as provided by NRC). The question for this technical evaluation is then: how much of the containment accident pressure must be used in order to provide a sufficient NPSH margin ( $NPSHA - NPSHR$ ) that will allow the RHR and CS pumps to conservatively perform their safety function during a LOCA accident, plus operate an additional 30 days under normal conditions.

**TECHNICAL EVALUATION:**

Principal Consultant and Pump Specialist, Allan R. Budris, P.E., used his four decades plus experience on centrifugal pumps and their suction (and cavitation) condition, to evaluate the current NRC criteria of basing the use of the containment pressure on zero NPSH margin, or  $NPSHA - NPSHR = 0$ , for determining the adequate available NPSH.

The writer agrees with the basic concept of using the *actual site* 3% head drop NPSHR as the minimum NPSHA requirements ( $NPSHA - NPSHR = 0$ ) for a nuclear reactor accident scenario, provided that the following criteria are taken into consideration:

1. Operation is of limited duration (time), from less than 10 minutes, to no more than 100 hours.
2. The uncertainties in the available NPSH (NPSHA) during a reactor accident are *conservatively* taken into consideration. The writer has been informed by NRC personnel that this is the case. It would, however, also be good to know what the most likely (as vs. most conservative) NPSHA values would be to get a better idea of the most probable NPSH Margin Ratio that the pump will operate at.
3. The *actual site* NPSHR value can be expected to be higher (although in some rare cases it might even be lower) than the manufacturer's price book published, or factory NPSHR test values, with the average variations expected to be in the range of +/-10% to +/-20%, depending on the test method used (see Tables 3 & 4 from Task #2). A margin should, therefore, be provided, above the tested NPSHR value, to take into consideration this variance and to insure that the pump will produce the needed flow rate, at a NPSHA equal to the *actual site* NPSHR required value.
4. That when the  $NPSHA = NPSHR$ , the developed pump head will be only 97% of the non-cavitating NPSHA value, by definition. Failure to provide even this full NPSHR suction pressure can be expected to reduce the pump flow rate even further, as shown in figures 3 and 4.

5. That during operation at or near the actual pump NPSHR, a fair amount of the dissolved air in the pumpage will be liberated to become entrained air during the formation of the cavitation bubbles (see figure 5, from reference #1), which *without proper seal flushing* could cause failure of the mechanical shaft seal.
6. That if the pump Suction Energy puts it in the “*Very High Suction Energy*” region, that the pump not be allowed to operate in the low flow *Suction Recirculation* region for more than a very short period of time (not to exceed approximately 10 minutes). The Browns Ferry RHR and CS pumps have very high suction energy.

#### **CAVITATION DAMAGE TIME IMPACT:**

In all likelihood, the RHR and CS pumps will be operating with cavitation during a LOCA accident. Cavitation can exist in a centrifugal pumps up to NPSHA margin ratios of from 2.0 to 20.0, with an average limit of about 4.0. Whether or not this cavitation causes any or sufficient erosion damage to prevent a pump from performing its required function is dependent on: the pump suction energy level; NPSH margin; impeller material; if the pump is operating in the low flow suction recirculation region; the amount, size and hardness of any abrasives, the amount of entrained air, and finally the amount of time the pump spends under cavitating conditions.

Cavitation erosion damage takes time. The shortest cavitation damage failure period that the writer experienced over his over 40 years in the pump industry was three months (about 2,000 hours), *although severe cavitation damage has been reported to occur in a matter of hours in rare (extremely high suction energy) cases*. NPSH factory tests could not be conducted under cavitation operating conditions if it badly damaged the pump impeller during the time required to conduct the test, which has not been the case in the writer's experience. Sultzzer's factory 2-3 hour life tests on the RHR and CS pumps have not shown any cavitation damage under low NPSH margin ratio conditions. Based on the (experience based) erosion rate graph shown in figure 2 (which was also included in the Task #1 Technical Report), the wear rate from cavitation, at the 3% head drop point (NPSH Margin Ratio = 1.0), would generally not be expected to be greater than the damage potential at a NPSH Margin Ratio of about 2.0, due to the liberation of dissolved to entrained air under these severe cavitating conditions. Many fire pumps typically have high suction energy, but do not experience cavitation damage because they are only operated for short periods of time. Therefore, *limited operation (not to exceed 100 hours)* of the Very High Suction Energy RHR and/or CS type pumps in cavitation, even at a NPSH Margin ratio of 1.0, would not be expected to cause sufficient cavitation erosion damage to render the pump incapable of performing its LOCA safety function, plus another 30 days of normal operation.

Finally, since chrome steel was used for the RHR and CS pump impeller material, which possesses some ductility (and has 4 times the cavitation erosion resistance of carbon steel or cast iron), any damage that may occur will initially just roughen the surfaces in the impeller suction. This roughness will progressively increase *over time* until it begins to take on the appearance of very rough sandpaper. However, surface roughening produced by cavitation erosion, in itself, will normally have no significant effect on the hydraulic performance (head and flow rate).

#### **NPSHA VARIATIONS:**

The uncertainties in the available NPSH (NPSHA) during a reactor accident have been *conservatively* taken into consideration, according to Richard Lobel of NRC. These uncertainties include the peak containment pressure (which increases the NPSHA), peak temperature of the suppression pool water (which increases the vapor pressure, thus reducing the NPSHA), and partial blockage of the screens in the pump suction path from debris generated by the accident. However, this conservative approach could result in the NPSH Margin Ratio being at the maximum wear rate. Therefore, it would be an extremely good idea to also know the most likely values for the NPSHA.

Not included in the NPSHA uncertainties is the “Effective Vapor Pressure” (to account for liberated dissolved air) as proposed in references 3, 4 5 & 6, because the method used to determine the effective vapor pressure is overly conservative (see Impact of Dissolved and Entrained Air section below for more details on this issue). A small, more realistic, uncertainty to cover this (dissolved and Entrained Air) effect is included in the NPSHR variations

### **NPSHR VARIATIONS:**

Based on the findings of the Task #2 Technical Report, it definitely appears that some variation should be expected between the published or controlled factory pump suction performance NPSHR test, and the actual field pump NPSHR values. The estimated variations between the pump factory test vs. the actual field NPSHR(3%) values are summarized in Tables 3 (in feet) and 4 (in percent), along with totals for the individual average variations (NPSH Test, Field Speed, Suction Piping, Water Temperature and Air Content). The Total *Average* variations for the various test methods range from +/- 9% to +/-21%.

Average individual variations were used for the total, since the probability of all individual variations being at their extreme for any particular application is extremely slim. To be very conservative, however, the maximum individual variations could be used for the total, which would than range from +/-18 to +/-41%. However, since the cavitation erosion rate actually increases from low NPSH Margin ratios to a maximum of about 1.4 (see figure 2), an overly conservative NPSHR margin will actually reduce, not increase the pump reliability. A NPSH safety margin in the range of 10% to 20% would seem to be optimal.

### **FLOW RATE IMPACT FROM OPERATION AT OR BELOW THE NPSHR(3%):**

The resulting typical RHR and CS “Available Static Mean NPSH” levels during a LOCA accident, have been provided by NRC (see Tables 1 and 2 from Browns Ferry report, and Figure 1 from Richard Lobel). As can be seen, there are periods during a LOCA accident when the NPSHA could be close to or less than the NPSHR, if the containment accident pressure were not considered. However, NRC’s objective is to not select a pump that would allow operation below the NPSHR.

If the system forced the pump to operate at a NPSH below the (3%) NPSHR value, cavitation vapor bubble blockage would limit the pump flow, until the pump head drops to the system head curve. This impact can be seen in figure 3 for the Browns Ferry RHR pump, where for system 3, the flow rate will drop from 11,500 gpm for a NPSHA of 38 ft to 10,200 gpm at an NPSHA of 24’ (as an example). Remember a pump will always operate at the intersection between the pump head-capacity and system head-capacity curves. Figure 3 shows the pump head-capacity curves for 100% head, 97% head (NPSHR-3%), NPSHA=24’, NPSHA=29’ and NPSHA=38’. Also shown in figure 3 are three separate approximated system head-capacity curves for system #1 (6,500 gpm), system #2 (9,000 gpm), and system #3 (11,500 gpm). Figure 4 displays similar head-capacity curves for the Browns Ferry CS pump system, during an accident.

Now let us examine the specific RHR operating conditions listed in Table 1. At the ST-LOCA, broken (<10 min.), 11,500 gpm, 26.4’ NPSHA (NPSH Margin Ratio=.75) scenario, the pump would not be able to produce more than about 10,500 gpm (see figure 3). Regarding the CS pump (Table 4), at the ST-LOCA, (<10 min.), 4,125 gpm, 26.8’ NPSHA (NPSH Margin Ratio = .95) scenario, the pump should just about be able to run out to the 4,125 gpm requirement (see System 2 in figure 4). This CS scenarios would be marginal at best and not leave any margin for error or variations with the actual NPSHR, especially with a sharp NPSH curve knee. Further, the Static Mean NPSH Margin ratio curves shown in figure 1 indicate that, without containment accident pressure, the NPSHA for the RHR and CS pumps would be less than the pump NPSHR for over 30 hours of operation, which would not be allowed.

**IMPACT OF DISSOLVED AND ENTRAINED AIR:**

In addition to the reduction in system flow rate from operation at NPSHA values below the pump NPSHR, such operation will liberate relatively large amounts of dissolved air, as shown in figure 5, which can have both positive and negative impacts on pump reliability. On the positive side, this increase in percent entrained air will cushion the cavitation bubble collapse, which will reduce the resulting pressure pulsations and therefore cavitation erosion damage (see figure 6).

The primary concern with operating a pump at or below the 3% NPSHR condition is the damage that the water vapor and/or entrained air could do inside 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 be centrifuged inward to the shaft, where the mechanical seal is housed. As shown in figures 5, the amount of entrained air in a pump increases as the NPSH Margin Ratio is reduced towards the NPSHR (NPSH Margin Ratio = 1.0) and below. This additional entrained air comes from the dissolved air that comes out of solution as local static pressure drops below the vapor pressure and the cavitation vapor bubbles are formed. This means that, in order to protect the mechanical seal faces from this excess entrained air (under operation at or below the 3% NPSHR condition), that dual mechanical seals with an external cold water flush system (or equal) should be provided, similar to that shown in figure 7.

It should be noted that the amount of dissolved air in the pumpage does impact the amount of air that is available to come out of solution and become entrained air during the formation of the cavitation bubbles. However, the solubility of air in water decreases with increasing temperature, from 2.0% at 68°F to only 1.2% at 212°F, both at atmospheric pressure, which is low regarding the expected impact on the pump performance (see figure 8). Both entrained and dissolved air/gas will increase the NPSHR of a pump, as shown in figure 9, due to the added blockage of entrained and dissolved air at the low local internal pressures within the pump inlet. Tables 3 and 4 do include a variance of 2 feet (or 5%) to account for this phenomena. However, the method proposed by references 3, 4, 5 & 6, (which has been under consideration by NRC) to calculate the specific impact of dissolved air on the pump NPSHR (or NPSHA), by calculating an "Effective Vapor Pressure", is overly conservative and therefore not recommended, because of the below overly simplified base assumptions:

1. "That cavitation starts in a centrifugal pump at the NPSHR". Cavitation starts at from 2 to 20 times the NPSHR value.
2. "That the pressure in the inlet to the pump impeller is uniform and all of it reaches the vapor pressure at the same time." The flow through the impeller is very complex, with local pressure depressions due to locally high velocities. So not all of the inlet flow cavitates or liberates dissolved gas at the same time, or suction pressure.
3. "That the liberation of dissolved air always causes damage to the pump", which as mentioned elsewhere in this report is not the case.
4. The amount of dissolved air being very low at the high LOCA operation temperatures should not make this (liberated dissolved air) much on an issue.

On the other hand, entrained air (if it is too high) can have a large impact on pump performance, up to the complete loss of prime/flow (air binding). Operation in an air bound condition for an extended period, over about 10 minutes, can cause overheating and failure (seizing of the impeller in the casing) of the pump. If a pump does become air bound, stopping the pump to let the suction air bubble escape, and then restarting the pump, can normally reestablish flow. Figure 8 gives an example of how larger amount of entrained air can affect the performance of a centrifugal pump. The performance corrections for a specific pump are affected by many variables, including pump specific speed, operating speed, impeller design and number of vanes, operating point on the curve, and suction pressure. Conventional pump designs can be used for low percentages by volume (up to 4%), while special modified impellers can be used effectively for up to 10% gas by volume. Performance corrections are required in all cases with gas content above approximately 2%. The writer reviewed the reference number 2 NRC

document for this report, which talks about GE Experimental Work (in the late 1970's) on the suppression pool throughout an actual LOCA event. It states that the highest level of entrained air was 3% (for 15 seconds following the accident), dropping to .2% to 25 seconds, and then leveling off at .4%. If correct, this is not high enough to have a marked effect on the performance of these emergency pumps. Except for the potential problem of extended operation in the air bound condition, the impact of entrained air on the mechanical shaft seal, and/or reduced performance, entrained air should not be disastrous to a centrifugal pump, especially below 4%.

There are devices, such as an "air release valve" (if such a release would not be radioactive) that can reduce the amount of entrained air in the suction line of a pump before the air reaches the pump.

### **SUCTION RECIRCULATION AND SUCTION ENERGY:**

Since a nuclear power plant operator may be inclined to throttle the flow of a RHR and/or CS pump during a LOCA accident (as a means of obtaining adequate NPSH margin) a minimum allowable flow rate restriction, based on *suction recirculation*, should be established for very high suction energy pumps. This minimum flow limit should also be included in any criteria on the use of containment accident pressure in the NPSHA calculation, in order to insure the survival of these pumps to perform their required safety function.

All centrifugal pumps experience suction recirculation at some reduced flow rate, when the impeller eye becomes too large for the through flow, and this causes reverse flow at the outer periphery of the impeller eye. Suction recirculation causes high velocity vortices between impeller vanes. These high velocities greatly increase the intensity of the cavitation within the pump, requiring much higher NPSH margins to subdue this cavitation. Figure 10, compares the cavitation caused suction pressure pulsations levels of a high suction energy pump, at the best efficiency and suction recirculation flow rates. As can be seen, the peak pressure pulsation level is 50% higher in suction recirculation, plus it takes twice the NPSH margin ratio (1.5 vs. 3.0) to suppress the cavitation caused pressure pulsations, when the pump is operating in suction recirculation region as compared to operation at the best efficiency flow rate. Also, as shown in figure 11, this high suction energy pump was much more sensitive to questionable suction piping when operating in suction recirculation as compared to operation above the start of suction recirculation.

*Very High Suction Energy RHR and CS type pumps should not be allowed to operate in their low flow suction recirculation regions.*

#### **Suction Energy:**

As mentioned earlier in this report, very high NPSH margins are required to completely suppress cavitation. It can take from 1.05 to 2.5 times the NPSHR just to achieve the 100 percent head point, and typically 4 to 5 times the 3% NPSHR of the pump to totally eliminate cavitation, within the allowable operating range (above the start of suction recirculation). We therefore know that cavitation is sure to exist in a high percentage of pump applications. However, we also know that acceptable life is achieved in most installations, despite this cavitation. So how can we predict when cavitation, within or outside the suction recirculation region, is likely to cause problems, and/or erosion damage? One such method is to determine the amount of *suction energy* in the pumped fluid which flashes into vapor and then collapses back to a liquid in the high pressure areas of the impeller, in order to determine the extent of any noise and/or damage from cavitation.

Suction energy is another term for the liquid momentum in the suction eye of a pump impeller, which means that it is a function of the mass and velocity of the liquid in the inlet. Suction energy is defined as:

$$\text{Suction Energy (S.E.)} = D_e \times N \times S \times \text{S.G.}$$

Where:

$D_e$  = Impeller eye diameter (inches)

$N$  = Pump speed (rpm)

$S$  = Suction specific speed (rpm x (gpm)<sup>0.5</sup>) / (NPSHR)<sup>0.75</sup>

S.G. = Specific gravity of liquid pumped

Based on the experience of hundreds of centrifugal pumps, the writer was able to establish the specific gating values listed in Table 5, for the start of "High Suction Energy" and "Very High Suction Energy", for various pump types. Dividing the actual pump suction energy by these High Suction Energy gating values yields the more meaningful "Suction Energy Ratio". Suction Energy Ratio values can then be broken down into three categories:

Low Suction Energy (Actual Suction Energy/High Suction Energy Gating Value < 1):

Pumps with levels of suction energy below these values are considered to have low suction energy. Generally speaking, low suction energy pumps are not prone to noise, vibration or damage from cavitation or recirculation. However, there could be detrimental effects on mechanical seals from the air or vapors which may be liberated from the liquid during the formation of the cavitation bubbles, under low NPSH margin conditions (below 1.1 – 1.3 NPSH margin ratio).

High Suction Energy (Actual Suction Energy/High Suction Energy Gating Value = 1.0 to 1.5):

Pumps with high suction energy and low NPSH margins, especially when operated in the suction recirculation flow range, may experience noise, vibration and/or minor cavitation erosion damage with impeller materials that have low cavitation resistance, such as cast iron. For suction specific speed values of 8,000 to 10,000, high suction energy starts at about 3,560 rpm in end suction pumps with 6" and larger suction nozzle sizes, and split case pumps with 8" and larger suction nozzles. At 1,780 rpm, high suction energy starts with 10" suction nozzle size end suction pumps, and 12" suction split case pumps.

Very High Suction Energy (Actual Suction Energy/High Suction Energy Gating Value > 1.5):

Pumps with very high suction energy and low NPSH margins, especially when operated in the suction recirculation flow range, may experience erosion damage, even with cavitation resistant materials, such as stainless steel.

RHR Suction Energy:

The actual suction energy value for the Browns Ferry RHR pump is in question, since several suction specific speed and impeller eye diameters were listed in the Sulzer report:

$D_e$  = Impeller eye diameter = 14.68" or 15.25"

$N$  = Pump speed = 1,785 rpm

$S$  = Suction specific speed (rpm x (gpm)<sup>0.5</sup>) / (NPSHR)<sup>0.75</sup> = 13,390 to 20,692

S.G. = Specific gravity of liquid pumped = .96

This data gives suction energy values of from  $340 \times 10^6$  to  $546 \times 10^6$ , which is a wide range. Based on the "End Suction" pump gating value of  $160 \times 10^6$ , the Suction Energy Ratios would then range from 2.13 to 3.41, which in any case classifies this pump as having "Very High Suction Energy". The end suction gating value can be used for side suction pumps which have good inlet flow control. It should be noted that the Sulzer Browns Ferry Report based their life predictions on the lower suction specific speed (and therefore suction energy ratio) number.

### CS Suction Energy:

The suction energy value for the Browns Ferry CS pump can be calculated based on the following:

$D_e$  = Impeller eye diameter = 6.875"

$N$  = Pump speed = 3,580 rpm

$S$  = Suction specific speed ( $\text{rpm} \times (\text{gpm})^{0.5} / (\text{NPSHR})^{0.75} = 14,193$

S.G. = Specific gravity of liquid pumped = .96

This data gives a suction energy value of  $335 \times 10^6$ . Now based on the "End Suction" pump gating value of  $160 \times 10^6$ , the Suction Energy Ratio comes out to 2.10, which also puts this pump in the "Very High Suction Energy" range. The end suction gating value can be used for side suction pump which have good inlet flow control.

### Start of Suction Recirculation:

Since both the RHR and CS pumps have Very High Suction Energy, it becomes critical to identify where suction recirculation starts in these pumps, in order to set the minimum allowable flow rates. Factory performance tests can establish the start of reverse flow / suction recirculation in a centrifugal pump, and should be the primary method for this determination. Figure 10 shows the typical minimum stable continuous percent best efficiency flow rate, based on the specific speed and suction specific speed of a pump.

RHR and CS type pumps, that need very low NPSR values are more likely to have high suction specific speed, and therefore high suction energy values, which as shown in figure 12, tends to increase the percent best efficiency flow rate where suction recirculation starts. This is another reason why knowing the true suction specific speed value is important.

At a RHR suction specific speed value of 18,942 (and specific speed of 1,277) the suction recirculation would start at 90% of the pump best efficiency flow point ( $.90 \times 8,600 \text{ gpm} = 7,740 \text{ gpm}$ ). This would mean that under the 6,500 gpm LOCA scenario, the pump could be operating in the suction recirculation region. On the other hand, if the RHR suction specific speed is 13,390, suction recirculation would more likely start at a flow rate of 4,644 gpm ( $.54 \times 8,600 \text{ gpm}$ ), which would put the 6,500 gpm scenario above the start of suction recirculation. Only an actual pump test (or possibly a CFD analysis) can identify the flow rate at which suction recirculation starts in a pump.

At the CS suction specific speed value of 14,143 (and specific speed of 1,571) the suction recirculation would start at 56% of the best efficiency flow point ( $.56 \times 3,025 \text{ gpm} = 1,694 \text{ gpm}$ ) for this pump. This would mean that under the 3,125 gpm LOCA scenario, the pump would be operating well above the suction recirculation region. However, only an actual pump test (or possibly a CFD analysis) can identify the flow rate at which suction recirculation starts in a pump.

### RECOMMENDED NPSHA LOCA CRITERIA:

Based on the above analysis, a minimum NPSH Margin Ratio of **1.15** (or 5 feet, whichever is greater) should be applied to the factory test established NPSHR(3%,) for the NRC criteria for the containment pressure NPSHA. This should cover the accuracy of NPSHR testing on the specific pump (in accordance with the Hydraulic Institute standard), plus any field installation NPSHR uncertainties, in a reasonably conservative manner. This minimum NPSH margin should be coupled with following additional criteria for best reliability:

1. Dual mechanical shaft seals should be used with external cold water flush, to insure that the seal faces do not run dry.
2. The suction energy level should be determined, and this value should be compared with the pump type gating values listed in Table 5, to determine if the pump has very high suction energy.

3. If the pump has very high suction energy, the flow rate at which suction recirculation starts should be determined, preferably based on a factory performance test, or CFD calculation.
4. If the pump has very high suction energy, operation should not be allow at or below the start of suction recirculation. An exception to this would be for intermittent operation that does not exceed 10 minutes.
5. The impeller material should be chrome steel, or another material which has equivalent cavitation erosion resistant.

*Over the longer term, It should be noted that a centrifugal pump is more likely to fail from the impact of cavitation vibration on the mechanical shaft seals and bearings, then from erosion damage to the impeller, over an extended period of time. Further, the more a pump exceeds the start of "Very High Suction Energy", for a given NPSH Margin, the lower the reliability. Finally, it should be noted that any abrasives in the pumped liquid, such as debris from the accident, will accelerate the erosive damage from the collapse of the cavitation bubbles, and the higher and harder the abrasive concentration the greater the damage. This (abrasives) can also lead to cavitation damage with low suction energy pumps, over time.*

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# **APPENDIX – A**

**(Tables)**

**Table 1: Minimum NPSHA requirements for Browns Ferry nuclear reactor accident scenarios**

<u>NAME</u>	<u>DURATION</u>	<u>FLOW (GPM)</u>	<u>NPSHA (FT)</u>	<u>NPSHR</u>	<u>NPSHA/ NPSHR</u>
	>10 min. to 24				
LT-LOCA	hrs	6,500	38.5	16	2.41
SBO	24 hrs	6,500	32.2	16	2.01
ATWS	8 hrs	6,500	24.3	16	1.52
APP R	60 hrs	9,000	26.9	19	1.42
ST-LOCA (Intact)	< 10 min.	10500	29.4	27	1.09
ST-LOCA (Broken)	< 10 min.	11,500	26.4	35	0.75

**Table 2: Minimum NPSHA requirements for Browns Ferry nuclear reactor accident scenarios**

<u>NAME</u>	<u>DURATION</u>	<u>FLOW (GPM)</u>	<u>MIN. NPSHA (FT)</u>	<u>NPSHR</u>	<u>NPSHA/ NPSHR</u>
ST-LOCA	< 10 min.	4,125	26.5	28	0.95
	>10 min. to 24				
LT-LOCA	hrs	3,125	35.1	21.4	1.64

Table 3: NPSHR Variation Summary (feet)

TYPE VARIATION	NPSHR TEST METHOD (feet)				
	HI Factory	HI Similar	Model	ANSYS CFX	Field
NPSH Test	+/- 1 to 2	+/- 2 to 4	+/- 3 to 5	+/- 3 to 5	+/- 1 to 10
Field Speed	0 to +.5	0 to +.5	0 to +.5	0 to +.5	0 to +.5
Suction Piping	0 to +3	0 to +3	0 to +3	0 to +3	0 to +3
Water Temperature	-1	-1	-1	-1	-1
Water Air	0 to +2	0 to +2	0 to +2	0 to +2	0 to +2
TOTAL (AVG)	+3'	+5'	+6'	+6'	+7.5'

Table 4: NPSHR Variation Summary (Percent)

TYPE VARIATION	NPSHR TEST METHOD (Percent)				
	HI Factory	HI Similar	Model	ANSYS CFX	Field
NPSH Test	+/- 2.5 to 5	+/- 5 to 15	+/- to 18	+/- 7 to 18	+/- 2.5 to 30
Field Speed	0 to +1	0 to +1	0 to +1	0 to +1	0 to +1
Suction Piping	0 to +10	0 to +10	0 to +10	0 to +10	0 to +10
Water Temperature	- 3%	- 3%	- 3%	- 3%	- 3%
Water Air	0 to + 5%	0 to + 5%	0 to + 5%	0 to + 5%	0 to + 5%
TOTAL (AVG)	+9%	+15%	+17.5%	+17.5%	+21%

**Table 5: Suction Energy Gating values**

Pump Type	Start of "High Suction Energy"	Start of "Very High Suction Energy"
2-Vane Sewage Pumps*	100 x 10 <sup>6</sup>	150 x 10 <sup>6</sup>
Double Suction Pumps	120 x 10 <sup>6</sup>	180 x 10 <sup>6</sup>
End Suction Pumps	160 x 10 <sup>6</sup>	240 x 10 <sup>6</sup>
Vertical Turbine Pumps	200 x 10 <sup>6</sup>	300 x 10 <sup>6</sup>
Inducers	320 x 10 <sup>6</sup>	480 x 10 <sup>6</sup>

\* - Applies to all pumps with less than 15° of impeller vane overlap

# **APPENDIX – B**

**(Figures)**

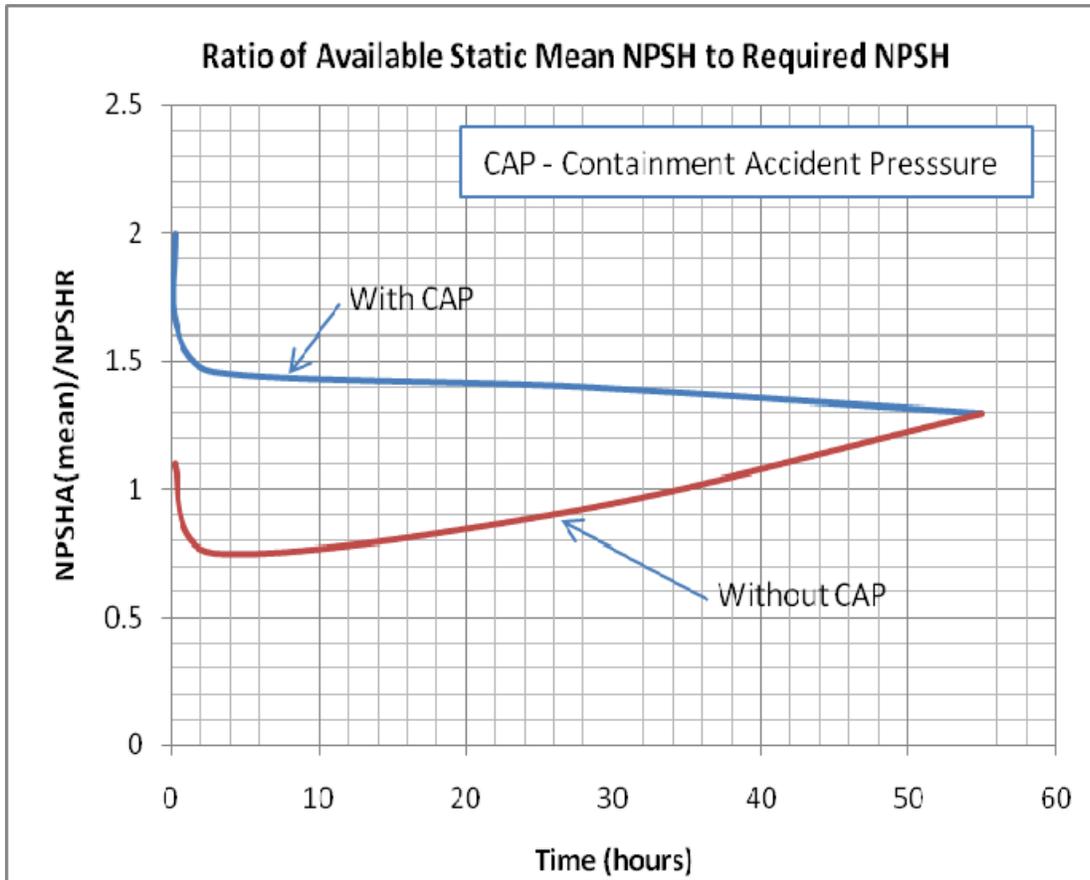


Figure 1: Potential Ratio of Available Static Mean NPSH to Typical Required NPSH

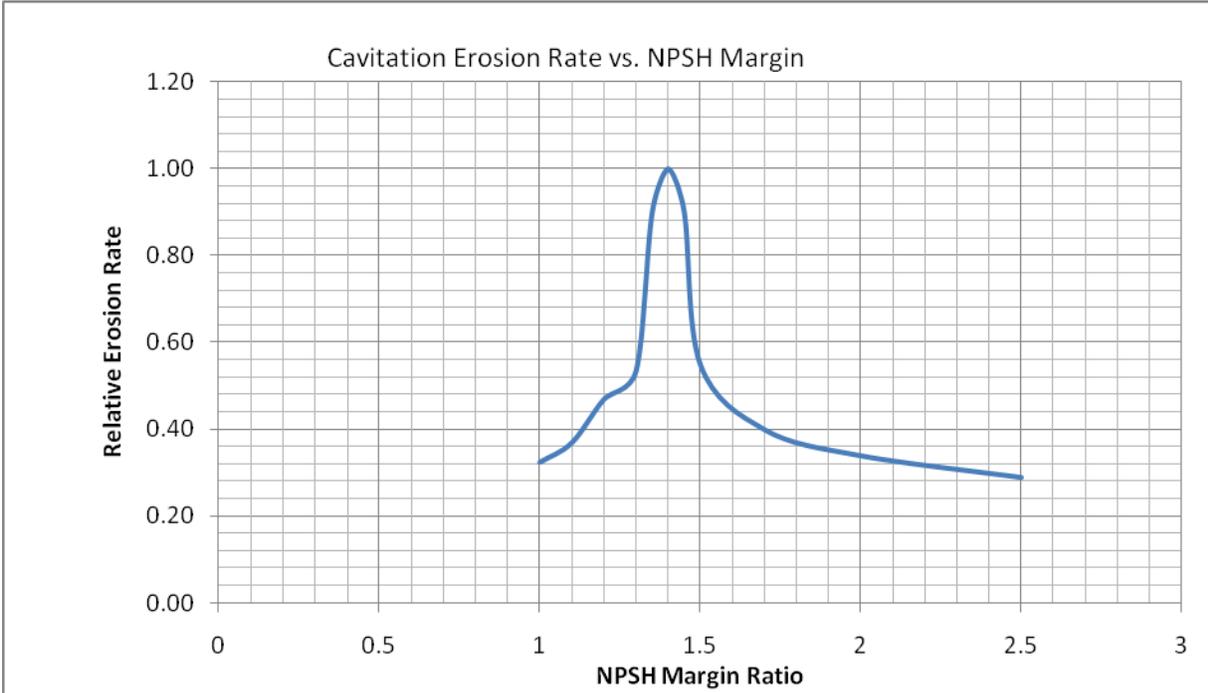


Figure 2: Typical Relative Erosion Rate vs. NPSH Margin near BEP Flow Rate

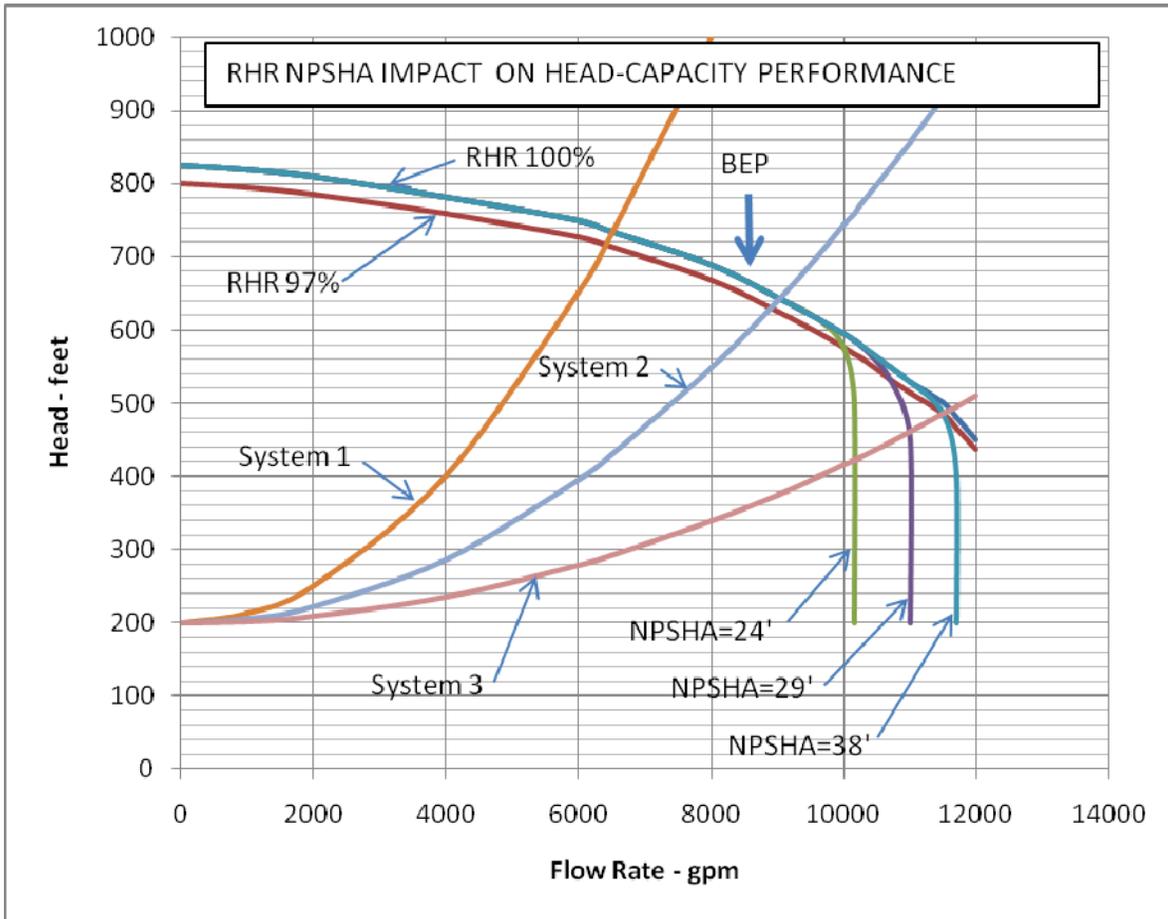
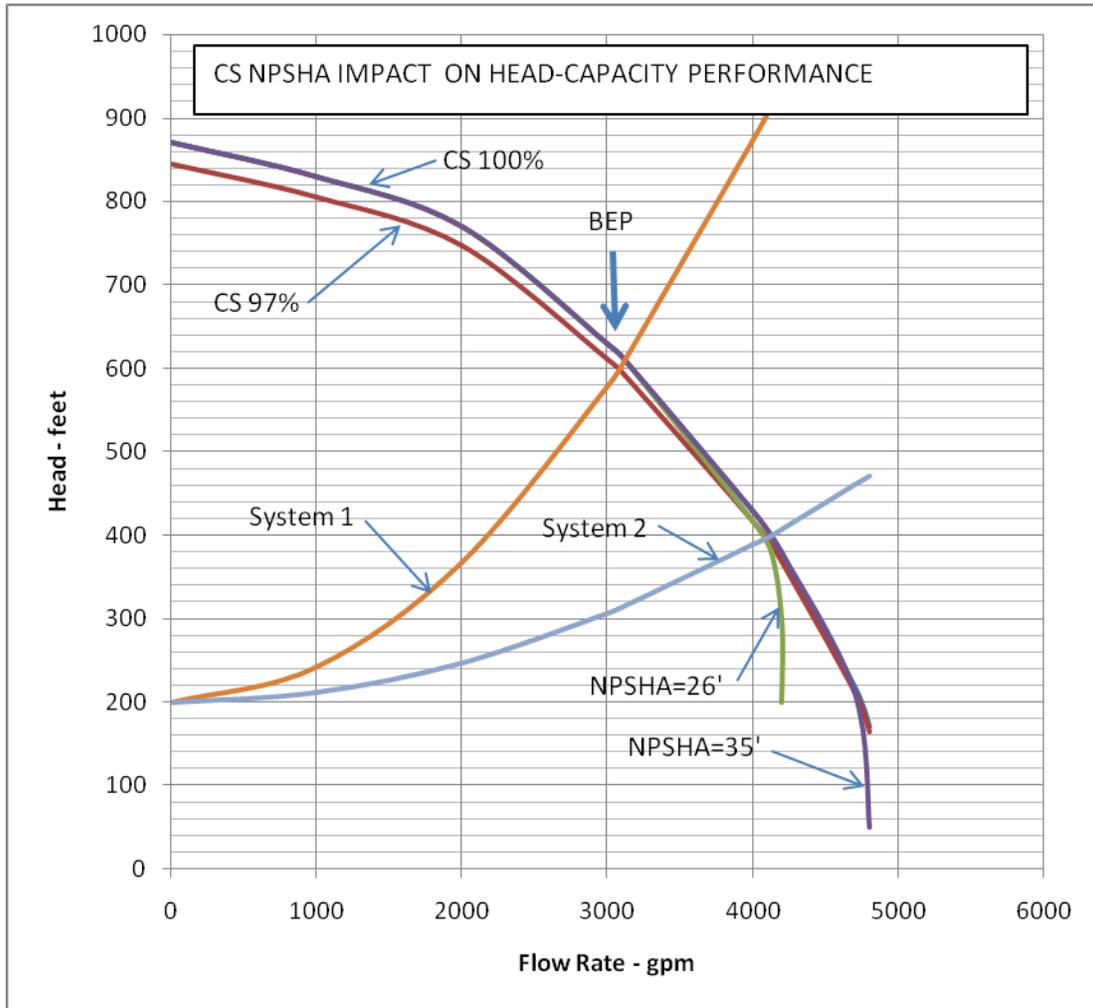
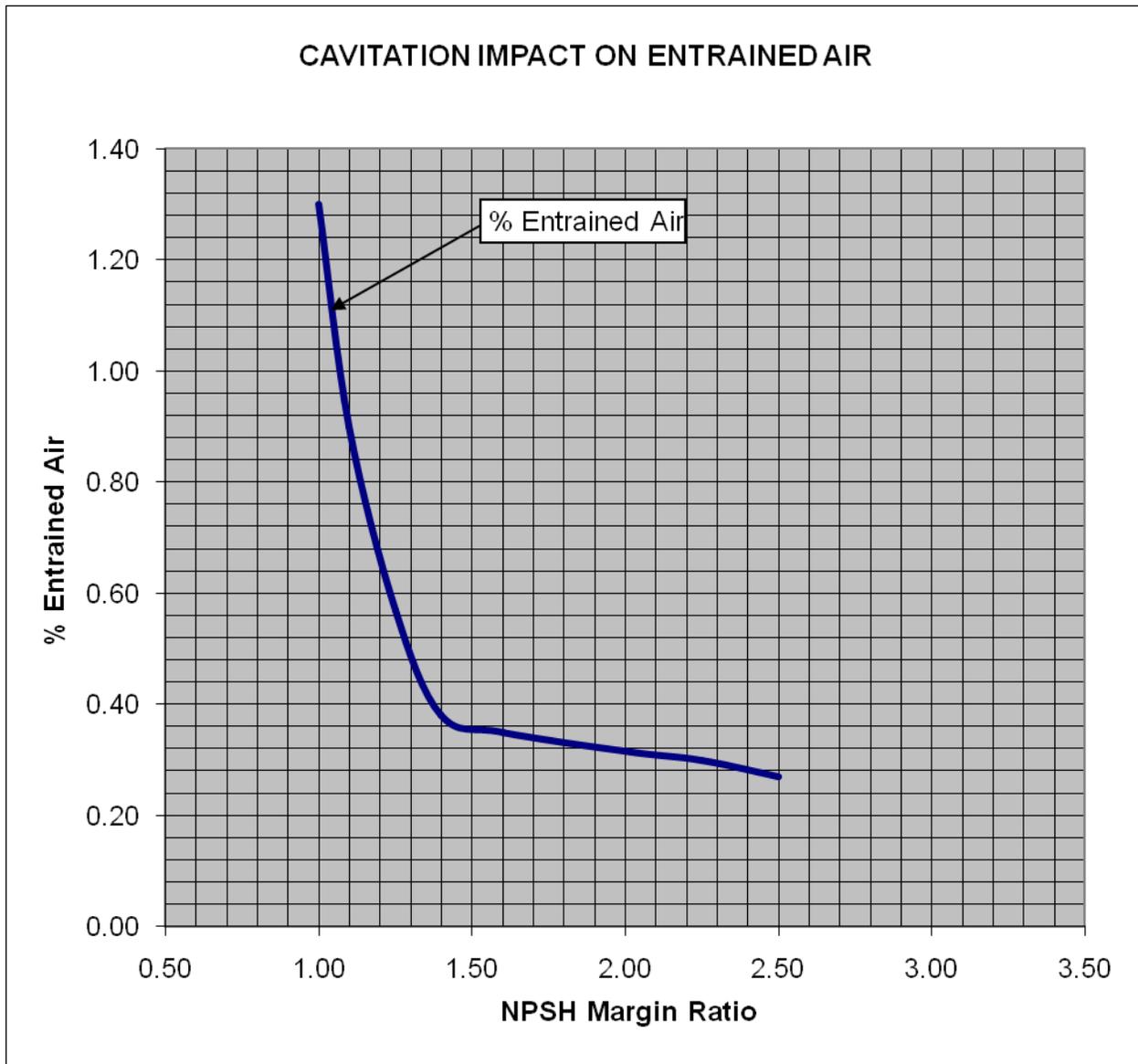


Figure 3: The impact of NPSHA of RHR Pump Performance and how this interacts with varying system H-Q Curves



**Figure 4: The impact of NPSHA of CS Pump Performance and how this interacts with varying system H-Q Curves**



**Figure 5: Entrained Air content increase with reducing NPSH Margin Ratio (amount of cavitation).**

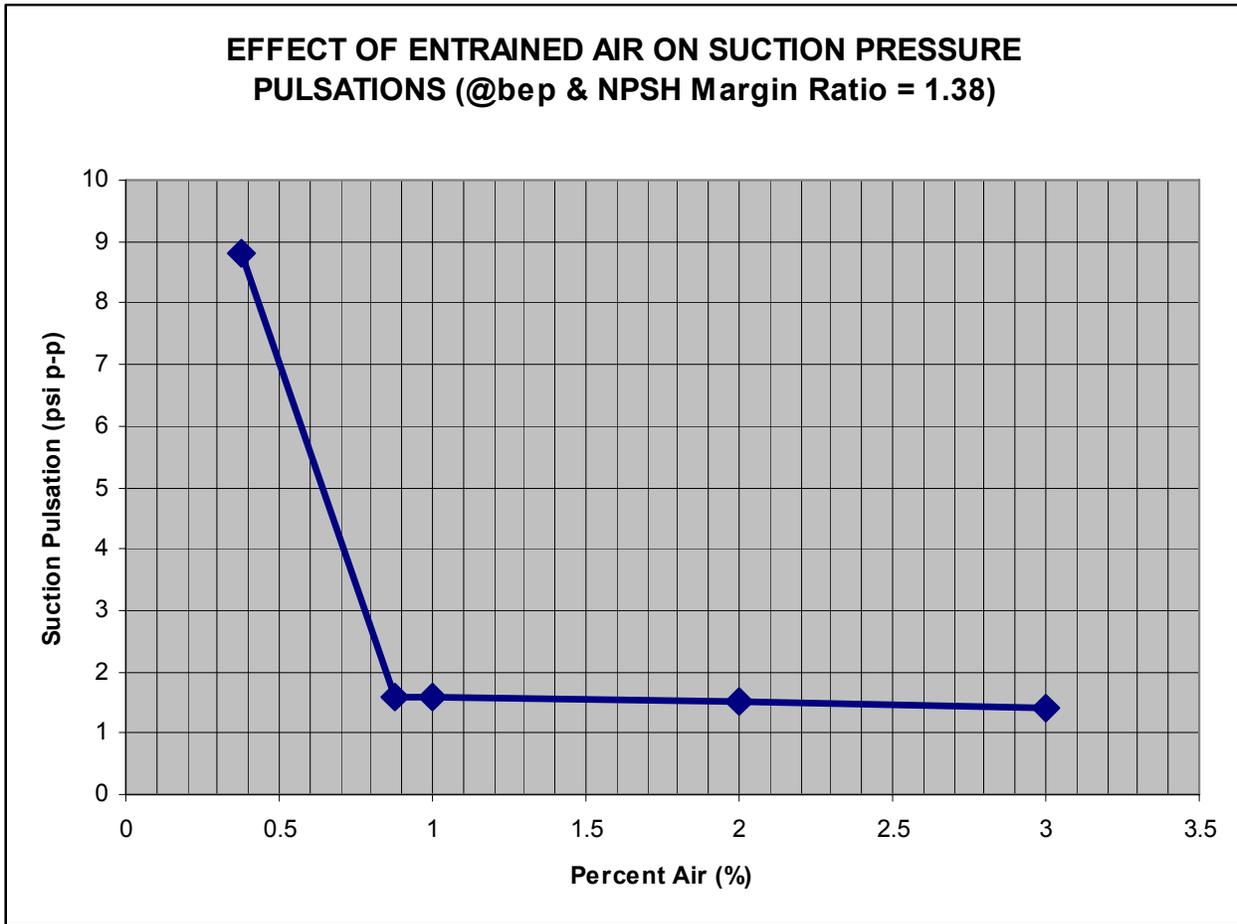


Figure 6: Effect of Entrained Air on Suction Pressure Pulsations and Operating Life

# Plan 7353 or 53 System

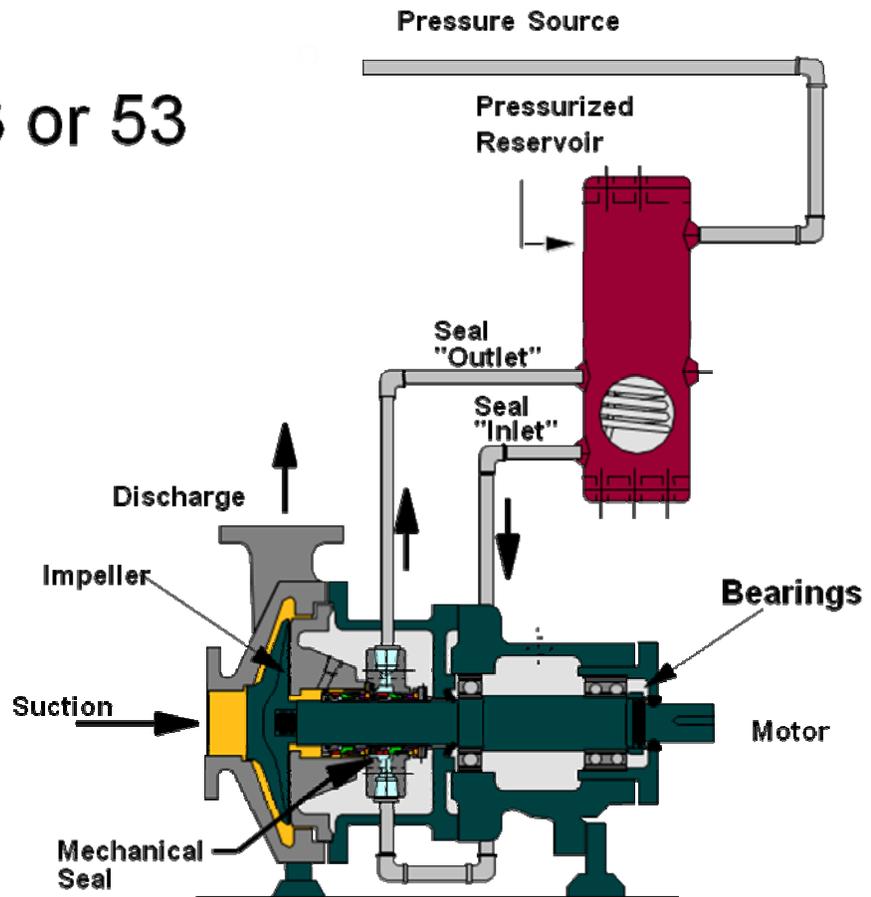


Figure 7: Typical Dual Seal Flush Support System

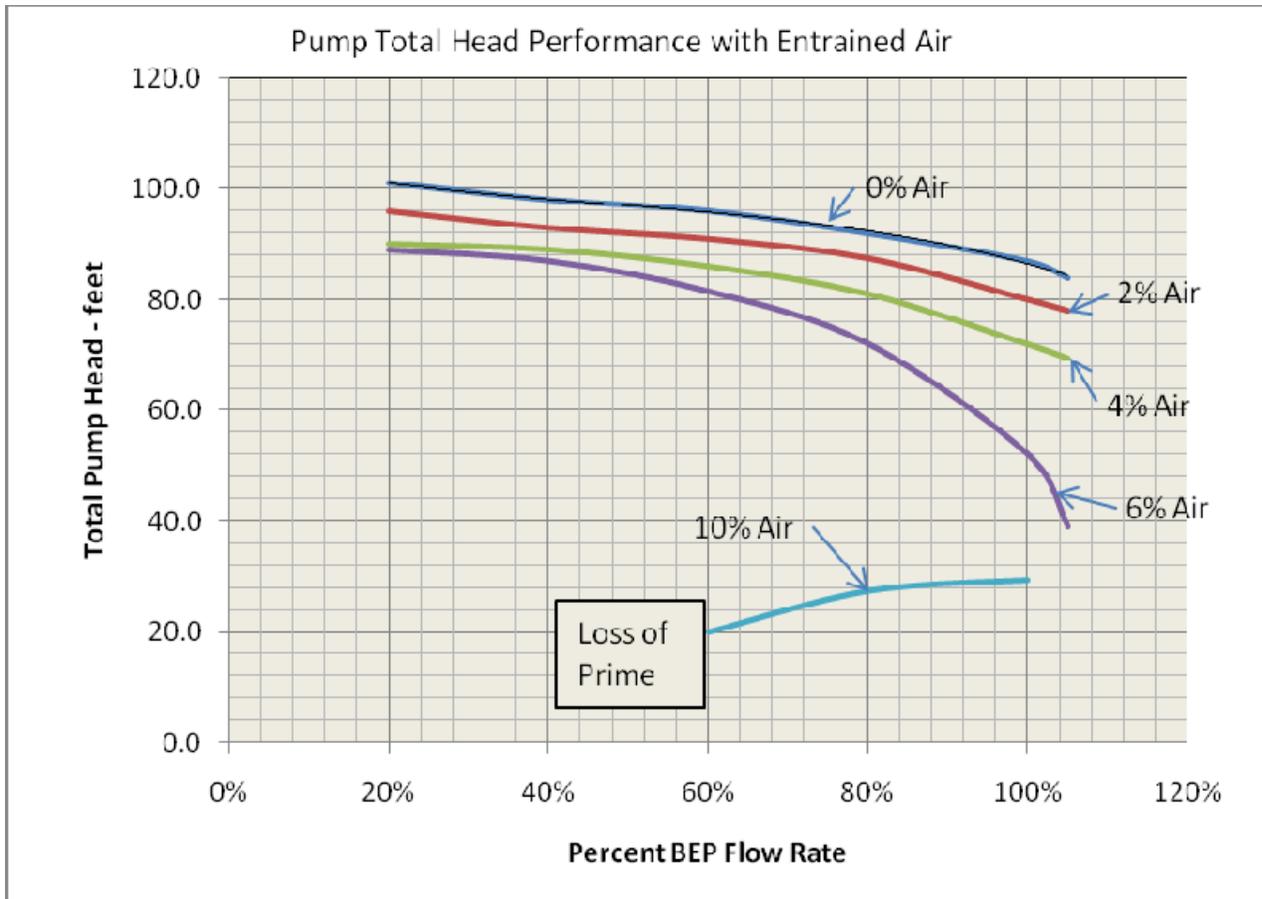


Figure 8: Example of Pump Total Head Performance with varying amounts of Entrained Air

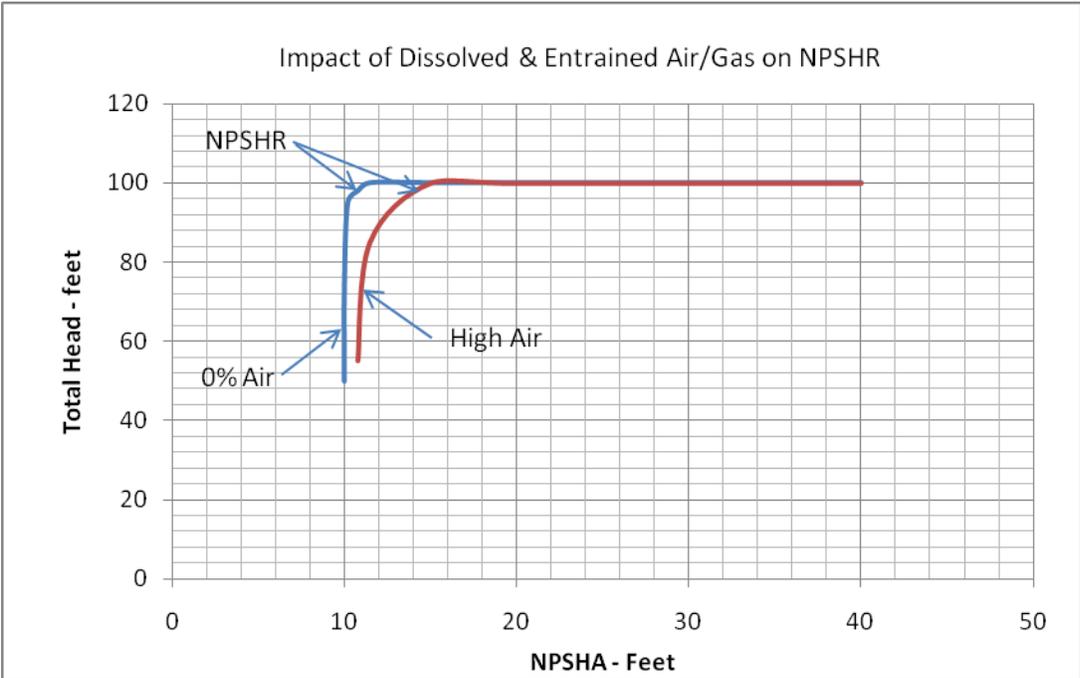


Figure 9: Impact of Dissolved & Entrained Air/Gas on NPSHR

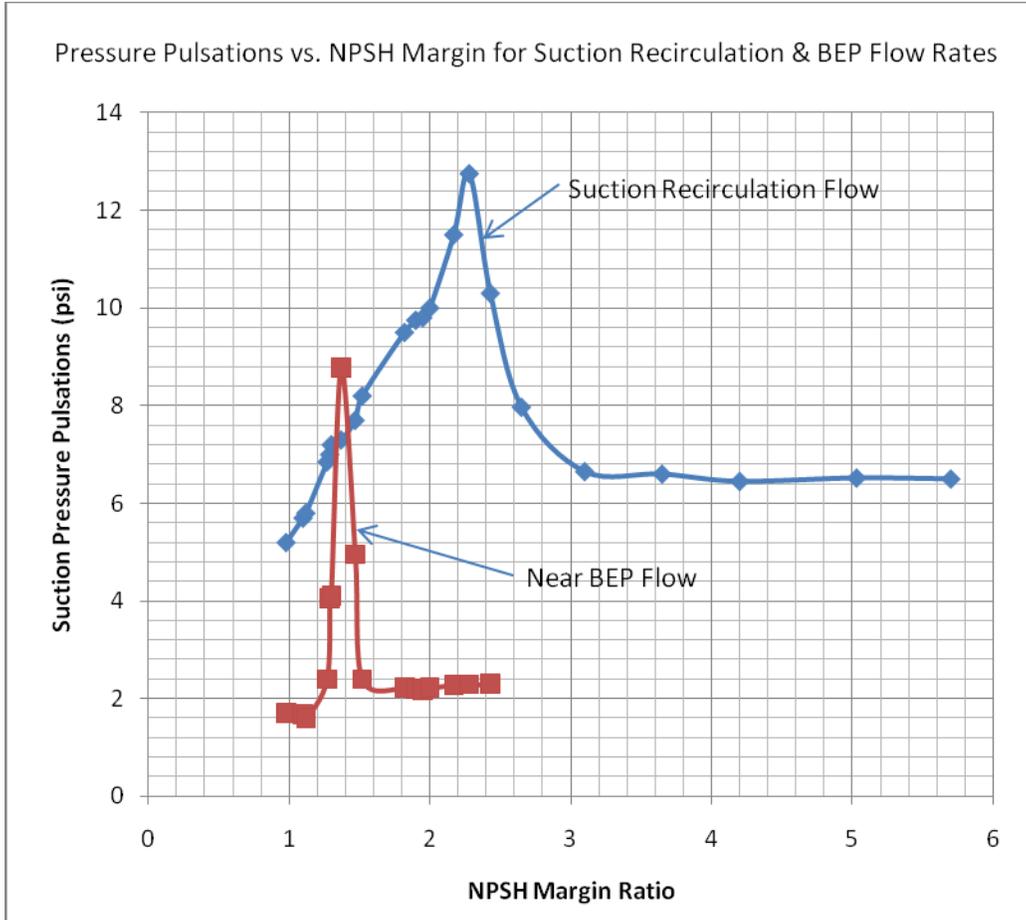
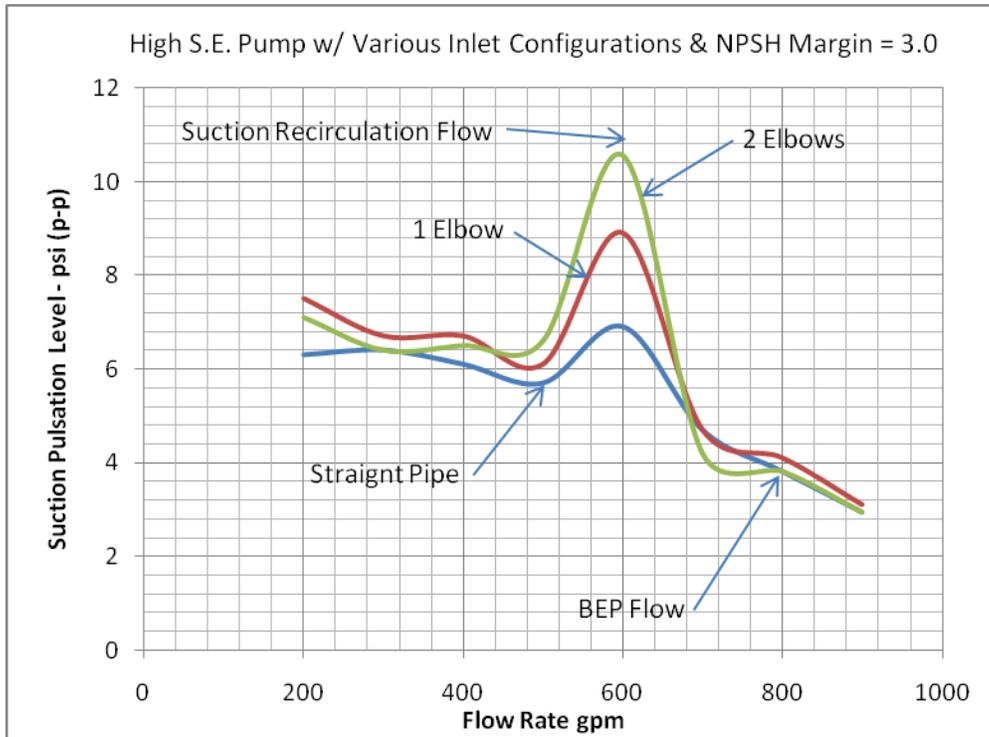


Figure 10: Pressure Pulsation level vs. NPSH Margin Ratio for Recirculation and BEP flow rates



**Figure 11: Pressure Pulsation level vs. Flow Rate for Good (straight pipe), Fair (1 short radius elbow), and Poor (2 short radius elbows at right angles) Suction Piping**

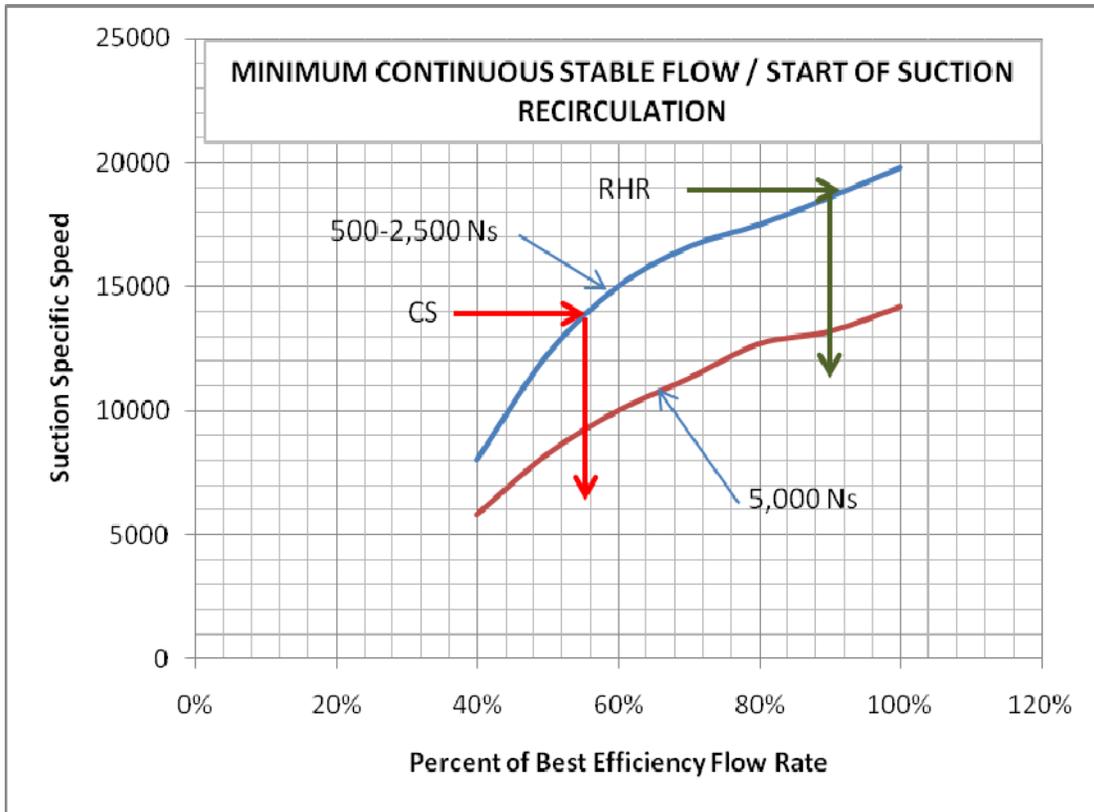


Figure 12: Minimum Continuous Stable Flow / Start of Suction Recirculation