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TECHNICAL REPORT ON TASK #3 FINDINGS
(Draft No. 1)

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Office of Nuclear Reactor Regulation
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TASK #4 SCOPE:

To evaluate the technical justification for the current NRC guidance which allows operation with cavitation, if tests verify the capability of the pump to perform its safety function (flow rate and discharge pressure), when post-test inspection verifies no wear or damage. Further, to develop any additional or more detailed criteria if necessary, along with the basis for the recommendation.

HARDWARE SCOPE:

- Core Spray (CS) and Residual Heat Removal (RHR) centrifugal pumps, similar to Browns Ferry units

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 technical justification for the current NRC guidance which allows operation with cavitation, if tests verify the capability of the pump to perform its safety function (flow rate and discharge pressure), when post-test inspection verifies no wear or damage. Cavitation can and does exist in a centrifugal pump with NPSH Margin Ratios of from 2.0 to 20.0 (times the NPSHR), with the average being in the 4.0 to 5.0 range. Figures 2 and 3 of the Task #1 report show NPSH Margin Ratios of from 1.8 to 7.2 for the start of cavitation in the RHR and CS pumps. So some cavitation will exist during the vast majority of Nuclear pump operating conditions, especially those involved in a LOCA accident, but such cavitation will not necessarily be damaging to the pump, at least in the short term.

Current Acceptance Concept:

The writer generally agrees with the concept of using a short duration (2 to 6 hours) factory cavitation damage test (followed by zero damage observed during a post test internal inspection), for the acceptability of the Core Spray and/or Residual Heat Removal pumps. This cavitation damage test will include many key variables specific to the actual pump, which would not be included in any Sulzer "Recommended NPSHA/Life", or similar empirical predictions. However, to be acceptable, this cavitation damage test must:

1. Only apply if the accident application is of limited duration (from less than 10 minutes, to no more than 60 hours), as listed for the Sulzer Browns Ferry nuclear power plant report (see Tables 1 & 2), followed by 30 days of much higher (normal) NPSHA operation.

2. These short life tests are conducted on the actual pump with the same mechanical shaft seal (including the flush system), or at least on a pump of the same model, size, impeller diameter, materials of construction and mechanical seal / flush system.

3. The life tests are conducted at the *same (field application) speed*.

4. The tests are conducted at each of the accident scenario *NPSHA* conditions (see tables 2 and 3). This is critical, since a lower NPSHA (lower NPSH Margin) can actually reduce, not increase, the cavitation damage rate in some cases (see figure 1).

5. Obviously, the longer the test duration the better the damage prediction. For a 60 hour accident scenario, the test duration should be at least 6 hours (10% of the LOCA operating time).

Such a factory cavitation damage test should actually yield conservative results, meaning that the criteria of zero damage should yield a positive pump life margin, exceeding 30 days of normal life after a LOCA accident.

1. Even when cavitation erosion damage does occur, and has persisted for thousands of hours, it is often inconsequential to the safe running of the pump. With an impeller material that possesses some ductility (such as the chrome steel used for the RHR and CS pumps), if damage is to occur, the surface is first roughened by cavitation. 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 hydraulic performance (head and flow rate). The pump should still be able to operate for at least another 30 days, although at a slightly reduced head (if cavitation damage does occur), due to the increased surface roughness/friction within the impeller.

2. Factory cavitation erosion tests are typically conducted on cold ($50^{O}F$ to $104^{O}F$), clean water, even though in the case of an accident, the field water temperature will more likely be in the range of $210^{O}F$. Liquid temperature impacts pump cavitation damage, with the highest wear occurring at water temperatures of around 100 to 120 degrees F. At higher temperatures the damage is reduced due to the smaller size of the collapsing cavitation bubbles (which have less energy). This effect should provide a small positive margin on cavitation erosion life.

3. The air content of the factory test liquid (especially if a vacuum pump is used to lower the NPSHA) will typically be lower than the liquid air content during a LOCA field accident, due to the spraying and splashing actions within the reactor vessel during the accident scenario. Even though any increase in the amount of entrained and/or dissolved air will slightly increase the pump NPSHR, it will substantially reduce the erosive wear from the collapse of the cavitation bubbles, since it cushions the damage from the bubble collapse, as shown in figure 2

On the potential negative side, the field installation might slightly increase the amount of cavitation in the pump and, therefore, reduce the actual NPSH Margin, which could have a negative (or positive) impact on the erosion rate (figure 1), depending on the NPSH Margin level. The possible causes of these potential negative impacts are:

1. Operating at slightly higher than tested pump speed. Operation at less than the full rated motor power, and/or using a high efficiency motor will reduce motor slip, which could increase the motor speed by up to about ½%. This would slightly increase both the NPSHR (about 1%), and Suction energy (about ½%). The expected impact on cavitation erosion life should, however, be small.

2. Using insufficient lengths of pump suction piping (after a disturbing fitting), in the field, can cause more cavitation, which will increase the pump NPSHR (lower NPSH Margin). This could cause more or less erosion damage, depending on the where the pump is operating on the NPSH Margin vs. Erosion Rate curve (figure 1).

Other Cavitation Damage Prediction Methods:

There are two other more sensitive ways of predicting future cavitation damage during a short factory cavitation life test, if a larger safety margin is required.

1. The first is to paint the inlet impeller blade surfaces with an epoxy paint, prior to the test. Paint erosion tests provide the answer in many cases, especially where much longer life periods are required. The objective of paint erosion tests is to establish in a short period of time the propensity of cavitating flow to cause erosion to the more erosion resistant underling impeller material. A properly conducted paint erosion test can give a good indication of whether there is a risk from cavitation erosion attack.

2. The second is to measure the force of the collapsing cavitation bubble impact. A high-frequency accelerometer technique has been developed (ref. 1) for quantifying the amount of damage that occurs in a cavitating pump. The technique can be used to estimate the severity of the cavitation damage. It measures the high frequency, i.e. short time period, spikes in the vibration time signal, which result from the cavitation bubbles collapsing on the internal surfaces of the pump. This cavitation life prediction method is also normally used for longer life requirements.

Other Cavitation Damage Considerations:

Finally there are two other pump components which are susceptible to the damage caused by the forces and liberated air from pump cavitation. They are the mechanical shaft seal and pump bearings. Cavitation caused vibration will most likely not significantly shorten the life of the pump antifriction bearings to the extent that they will not be able to operate during the accident scenario, plus an additional 30 days under normal conditions.

However, if the pump is not provided with a shaft dual mechanical seal system with an external water flush (or some other method that will exclude air from getting between the seal faces and causing dry operation) the seal could fail in a short period of time. Excessive entrained air tends to be centrifuged inward to the shaft, where the mechanical seal is housed. As shown in figures 3 and 4, the amount of entrained air in a pump increases as the NPSH Margin Ratio is reduced towards the NPSHR (NPSH Margin Ratio = 1.0) condition. This additional entrained air comes from the dissolved air that comes out of solution as the cavitation vapor bubbles are formed. This means that, in order to protect the mechanical seal faces from any excess entrained air (during operation near or below the 3% NPSHR condition), that dual mechanical seals with an external water flush system (or equivalent) should be provided, for example as shown in figure 5. The mechanical shaft seal faces should be part of any post cavitation life test inspection.

Conclusion:

So based on the above, it can be concluded that relying on the results of actual factory cavitation life tests, when post-test inspection (including of the mechanical seal faces) verifies no wear or damage, and provided that the tests are conducted at the actual NPSHA conditions, is a sound acceptance criteria, for determining if the pump can perform its safety function (flow rate and discharge pressure) with some built in safety margin, during and following a LOCA accident scenerio. With zero damage under these test conditions, the pumps would almost certainly be able to operate for another 30 days after the accident, under normal (much higher) NPSHA values, if not for 8,000 hours or longer.

References:

1. "Cavitation Assessment of Large Double-Suction Pumps", William Marscher and Eric Olson, Mechanical Solutions, Inc., www.pump-zone.com, 10/9/09.

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APPENDIX – A

(Tables & Figures)

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

NAME	DURATION	FLOW (GPM)	NPSHA (FT)	NPSHR	NPSHA/ NPSHR
LT-LOCA	>10 min. to 24 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

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

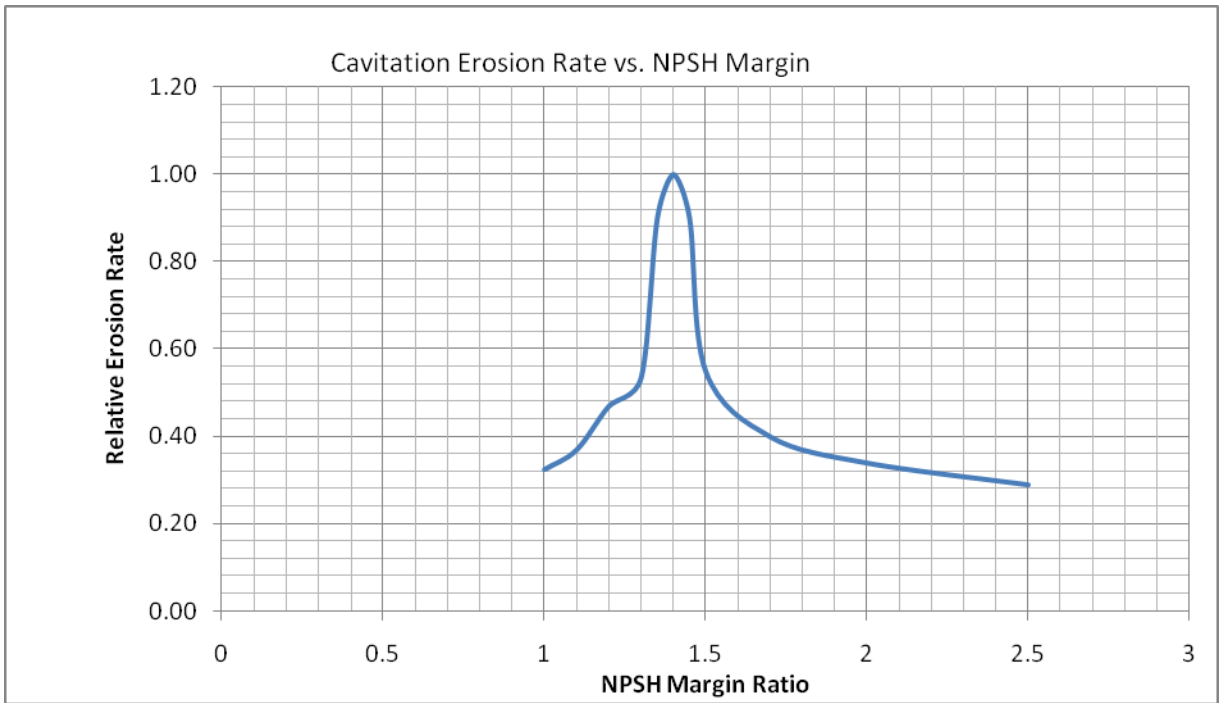

Figure 1: Typical Relative Erosion Rate vs. NPSH Margin near BEP Flow Rate

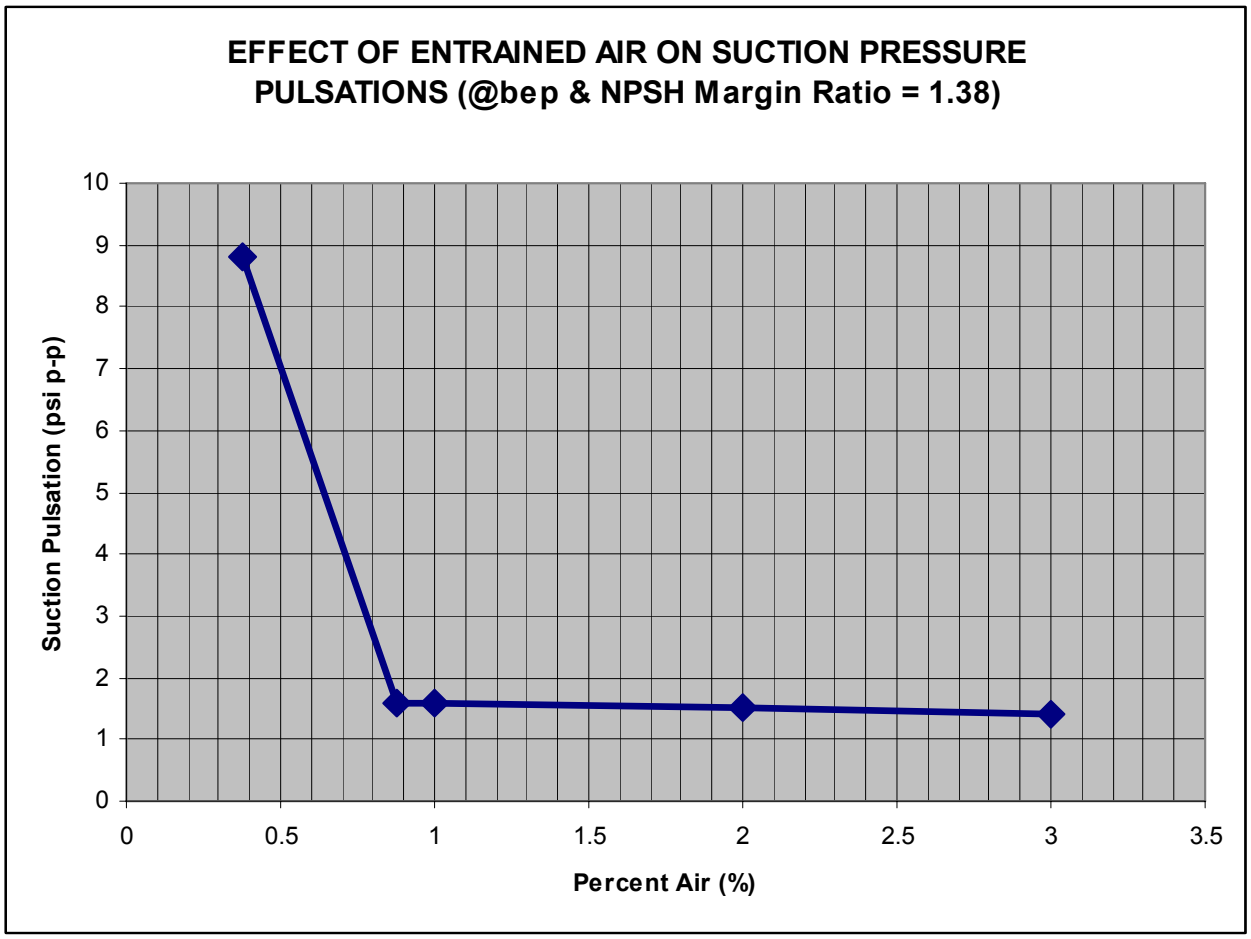

Figure 2: Effect of Entrained Air on Suction Pressure Pulsations and Operating Life

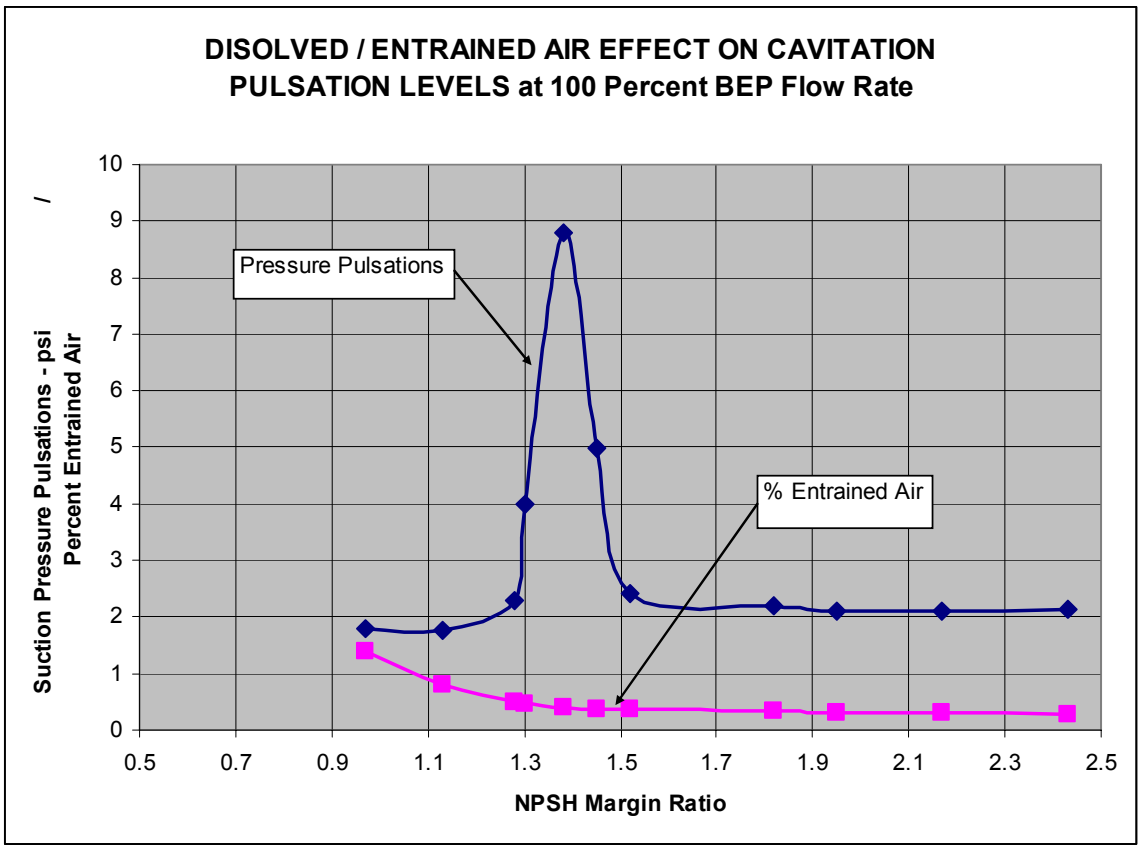

Figure 3: Dissolved air coming out of solution during formation of cavitation vapor bubbles, which increases entrained air, and reduces cavitation pressure pulsation below about NPSH Margin Ratio of about 1.3.

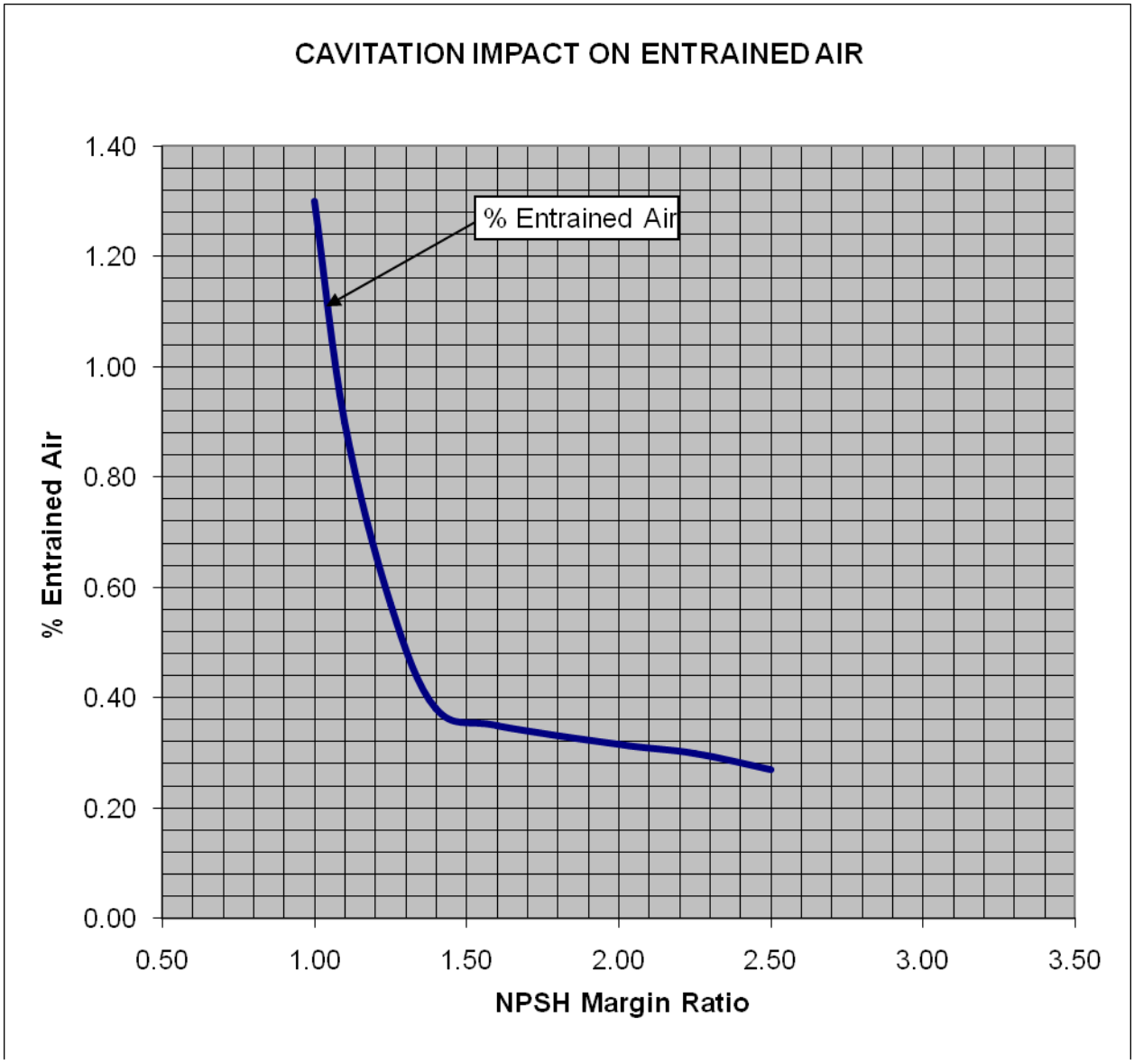

Figure 4: Entrained Air content increase with reducing NPSH Margin Ration (amount of cavitation).

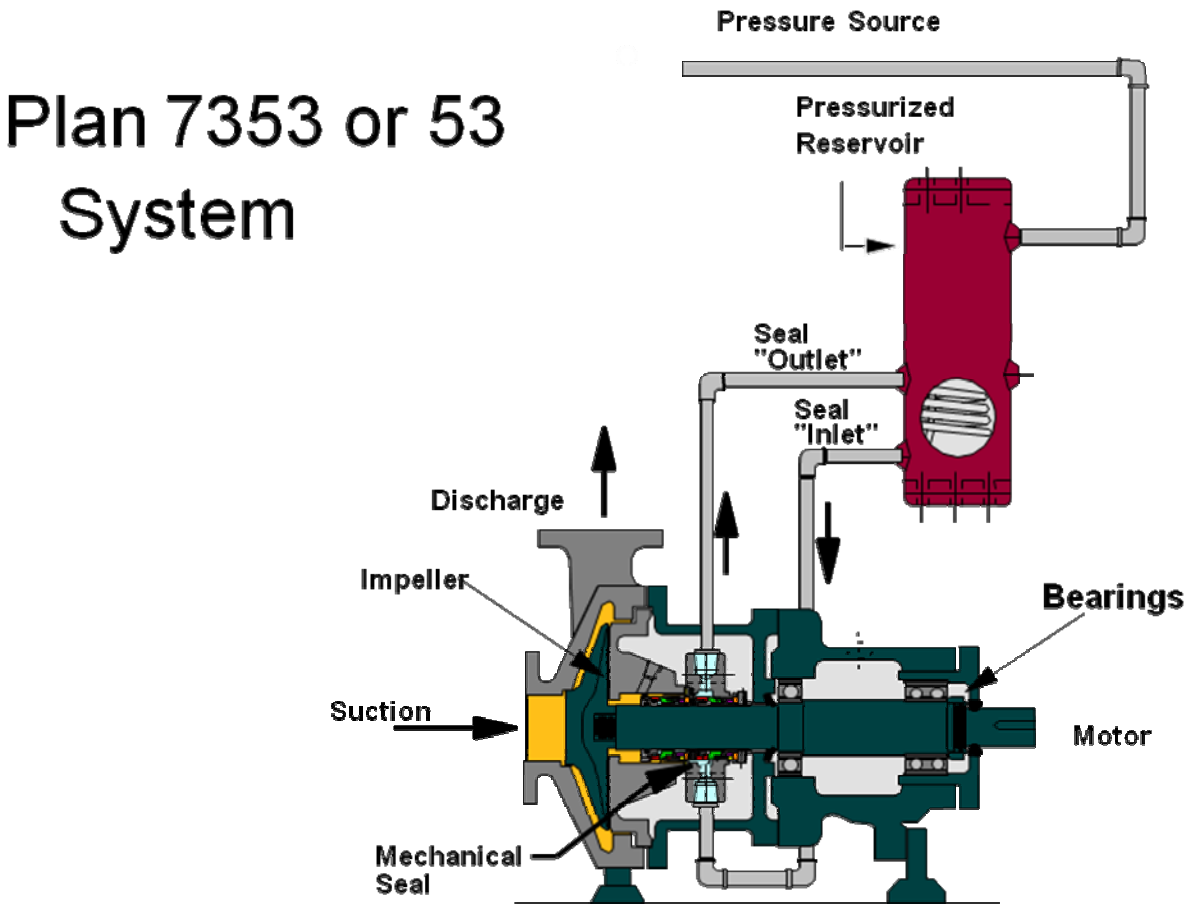

Figure 5: Typical Dual Seal Flush Support System