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Performance of Safety Injection Pumps With Air Ingestion

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1. SUMMARY

This report describes the result of an evaluation of the performance of safety injection pumps at Unit 1 of the South Texas Project Electric Generating Station. The evaluation was performed by Creare Inc. for Houston Lighting & Power Company. Walter Swift performed the evaluation at Creare with support from Victor Iannello. Albert McIntyre was the project manager for HL&P.

The evaluation consisted of an independant assessment of the behavior of the core spray (CS), high pressure safety injection (HPSI) and low pressure safety injection (LPSI) pumps during a postulated loss of coolant accident (LOCA – 1) assuming a double ended pump suction guillotine break with minimum safety injection (two of three pump trains in operation).

The evaluation included a review of assumptions and the calculation methodology performed by HL&P (MC–6126) with respect to pump operation. There are two major aspects to the operation of the pump system:

1) at the calculated flow rates for the safety system, what quantity of air (if any) is entrained in the sump pipe, and

2) if air entrainment occurs in the sump, how will this air affect pump performance?

Our evaluation does not address the first question. The methodology followed in the study calculation (MC–6126), which is based on guidelines set forth in NUREG – 0897, Rev. 1 [1], predicts an air ingestion rate in the sump of 8.94 % under the LOCA – 1 conditions. This prediction is based on a calculated Froude number of 0.759 at the sump, which depends on a sump pipe velocity U, which in turn depends on calculated flow rates and piping losses. We have reviewed the approach used to calculate the aggregate flow rate and thus arrive at the sump pipe velocity U. Our independent calculation would predict a marginally smaller value of U than that given in MC – 6126. However, the difference is small and well within the uncertainties of any similar calculation of system losses.

We then used the predicted sump air ingestion rate of 8.94 % and reviewed the calculations used to predict the air ingestion quantity at the pumps. We concur with the MC – 6126 result that the rate of air ingestion at the CS, LHSI and HHSI pumps predicted by the NUREG 0897 methodology is 7.86 % – 7.87 %. Furthermore, we have found that the calculations in MC – 6126 follow the NUREG 0897 methodology to predict an NPSHR penalty as a result of the predicted air ingestion rate. (However, NUREG 0897 is not to be applied to situations where the air ingestion rate at the pump exceeds 2 %).

Finally, we reviewed the statements about the safety significance of the pump performance given on page 13 of MC – 6126. An analysis is presented which relies on the results of tests on a single stage, low specific speed pump under various combinations of air ingestion rates and NPSH. The analysis concludes that at the NPSH available (30 ft.) and the 8 % air ingestion rate predicted by the NUREG analysis methodology, the pumps (CS, LHSI and HHSI) would be able to sustain at least 80 % of the normal (liquid) head. The analysis concludes that under the calculated conditions, there was no significant hazard to safety.

This conclusion depends on a prediction of the amount of head degradation for the CS, LHSI and HHSI pumps under air ingesting conditions from laboratory test data on other pumps. NUREG/ CR – 2792 [2] addresses this issue. Figure 3–2 from this reference (Figure 9 of this report) is a composite plot illustrating the variability in two – phase performance of pumps which have been documented in the literature. An important conclusion given in section 4.1 of the NUREG is that for ingestion rates above 2 %, pump behavior is highly variable, depending on the specific pump design, the flow rate, and other, unidentified variables. It is because of this variability that it is not possible to predict with absolute certainty how one pump will behave at some operating condition based on tests of another pump at similar conditions, or even from tests of the same pump at different conditions.

It is not appropriate to apply the data of Merry directly to predict the performance of the CS, LHSI and HHSI pumps. The pump used by Merry in the laboratory tests was a low specific speed (810 – U.S. units)[1], single stage machine, quite unlike the multi – stage safety pumps with mixed flow impellers (specific speed = 3110 per stage). Based on our review of the technical literature, there is no single set of data or a proven analytical method which can be directly applied to these pumps to exactly predict their behavior at an 8% level of air ingestion. However, one can make judgments about the likely behavior of the safety pumps based on the existing data base.

For example, it is known that the presence of an inducer substantially improves the cavitating and air ingesting performance of centrifugal pumps. It has also been demonstrated by test (as noted in MC – 6126 and NUREG/ CR –2792) that multistage pumps perform with less head degradation than single stage pumps under similar air ingestion rates. Arguments can also be made that based on existing data, mixed flow impellers will operate with less head degradation than low specific speed designs at similar air ingestion quantities. However, it is also known that operation with a sufficient amount of air ingestion over a period of time can result in the accumulation of air at pump impeller inlets, radically changing their ability to perform and occasionally causing mechanical problems. The combination of all these factors still cannot be used to quantify the amount of head degradation which would occur under the conditions studied in MC – 6126. One can only conclude that there is a reasonable probability that the head degradation under these conditions would be comparable to or less than the values given in the literature – which are comparable to values found in Merry's tests.

2. AIR ENTRAINMENT LEVELS IN THE PUMPS

The calculation methodology used in MC – 6126 was checked for the LOCA – 1 analysis. Our independent analysis predicted the same levels of air ingestion at the pump inlets as those identified in MC – 6126.

3. HEAD DEGRADATION/SAFETY SIGNIFICANCE

The analysis in MC – 6126 predicts an air ingestion rate of about 8 % at the pump inlets using the NUREG 0897 methodology for the LOCA – 1 set of assumptions. At air ingestion rates in excess of 2 %, NUREG – 0897 gives no guidance as to how to evaluate the behavior of centrifugal pumps. Section 3.2.2.2 of NUREG 0897 and Section 4.1 of NUREG/ CR – 2792 address the issue. Basically, there is so much variability in pump behavior (as indicated by tests) at ingestion rates above 2 % that the specification of generic technical guidelines for the prediction of behavior over a wide variety of pump types is not appropriate. However, there is also a reasonable amount of similarity in pump behavior at moderately low air rates

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1 The specific speed – rpm $(gpm)^{0.5}$ / $(ft)^{0.75}$ – of the Merry pump is incorrectly listed in Table 3 – 1 of NUREG/ CR – 2792 as 1,074.

from widely differing tests and types of pumps. A review of the more important literature on air effects in pumps allows one to draw some conclusions about the likely behavior of these safety pumps based on results from other tests. The following sections discuss important features of the safety pumps, review existing test data with respect to air ingestion performance at similar operating conditions and discuss these results with respect to the probable behavior of the safety pumps.

3.1 KEY FEATURES OF THE SAFETY PUMPS

Number of Stages

The CS and LHSI pumps are each five stage mixed flow machines. THe HHSI pumps are sixteen stage machines with mixed flow impellers. In general, multistage pumps show less head degradation than single stage pumps which use the same impeller.

Specific Speed

An important hydraulic feature of a centrifugal pump is its specific speed.

$$N_s = N(\text{rpm}) * (Q(\text{gpm}))^{0.5} / (H(\text{ft.}))^{0.75}$$

This parameter characterizes design dimensional and speed relationships for a pump. Pumps of comparable specific speed will generally have similar performance characteristics, although there is also variability because of individual design decisions for each pump. The CS and LHSI pumps are each five stage machines with a best efficiency flow rate of about 2700 gpm, and a corresponding best efficiency head of 460' (or 92' per stage) at a speed of 1780 rpm. This corresponds to a design specific speed of 3114 (per impeller stage). The impellers would be classified as mixed–flow designs.

Inducer

The CS and LHSI pumps are equipped with integral inducers at the inlet to the lowest stage impeller. In general these screw – like impellers provide improved performance with respect to cavitation and air or vapor entrainment.

3.2 EXISTING AIR/WATER TEST DATA

Test data from a number of pumps over various operating conditions are reviewed in this section. These data illustrate the variety in results of air water performance for pumps of different specific speed and number of stages for changing air/water flows and at various levels of NPSH.

Florjancic [3]

Tests were performed on a single stage pump and a three stage pump of comparable design to evaluate the behavior of the pump under mixed air/water and argon/water flow. The test results show two important trends:

1) the performance of a multistage pump under two phase flow situations is superior to a single stage pump of the same design, at the same flow conditions, and

2) the performance of a single stage pump under two phase flow conditions deteriorates as the upstream pressure is lowered.

The test pump is listed as an N_s = 95 (Mks system) design. However, no definition for N_s is given in the paper. The U.S. equivalent value is ambiguous because Sulzer (the company at which the tests were performed) has used differing equations from time to time to define N_s. The value lies between 5163 and 1397 in the comparable U.S. units, depending which of two definitions of N_s is selected.

The tests were limited to volumetric air fractions below about 6%. Figures 1, 2, 3, and 4 (Figures 3–7, 3–8 and 3–9 from NUREG/ CR – 2792, and an additional figure from the original paper) illustrate features of the effects of air on performance.

Figure 1 shows head, efficiency and power variations with flow for various air flows on a single stage pump. For air fractions of 2% or less, there is no serious degradation in head – even over a wide range of liquid flows This characteristic is typical of the behavior of all centrifugal pumps which were evaluated during the writing of Rev. 1 of NUREG 0897. As the air fraction increases to 6.4 %, head degradation becomes significant, and at high flow rates – severe. Figure 2 shows similar performance relationships for three stages af the same pump of Figure 1. It is clear that there is a significant reduction in head degradation in the multistage machine, particularly at flows lower than best efficiency point. This effect is summarized for rated flow in Figure 4. Figure 3 shows another important characteristic for centrifugal pumps when air is entrained. As the suction pressure is reduced, the effects of air tend to increase head degradation. This is generally coupled in some way with the NPSH requirements of the pump. But, there is insufficient information given in this reference about the cavitation characteristics of the pumps tested to arrive at any quantitative conclusions.

Creare Air/Water and B&W Air/Water [4]

Tests were performed at Creare on a single stage, mixed flow pump (N_s = 4200) with a 1.94" diameter impeller in air water mixtures. Comparable testing with a similar pump (N_s = 4317 – nondimensional, single phase performance curves of the two pumps agreed within 5 %) having an impeller diameter of 12.3" was carried out by Babcock and Wilcox. Single phase and two phase performance were documented for all four quadrants of operation. Figure 5 characterizes the two phase test results near design flow coefficient for each pump. The Figure (from reference 4) shows how head degradation varies with void fraction α_F.

The test results are presented in terms of homologous parameters h/α_N^2 and v/α_N, and void fraction α_F. h is the ratio of test head to single phase head, α_N is the ratio of test speed to rated speed, v is the ratio of volumetric flow to rated flow, and α_F is the ratio of volumetric air flow to total volumetric flow.

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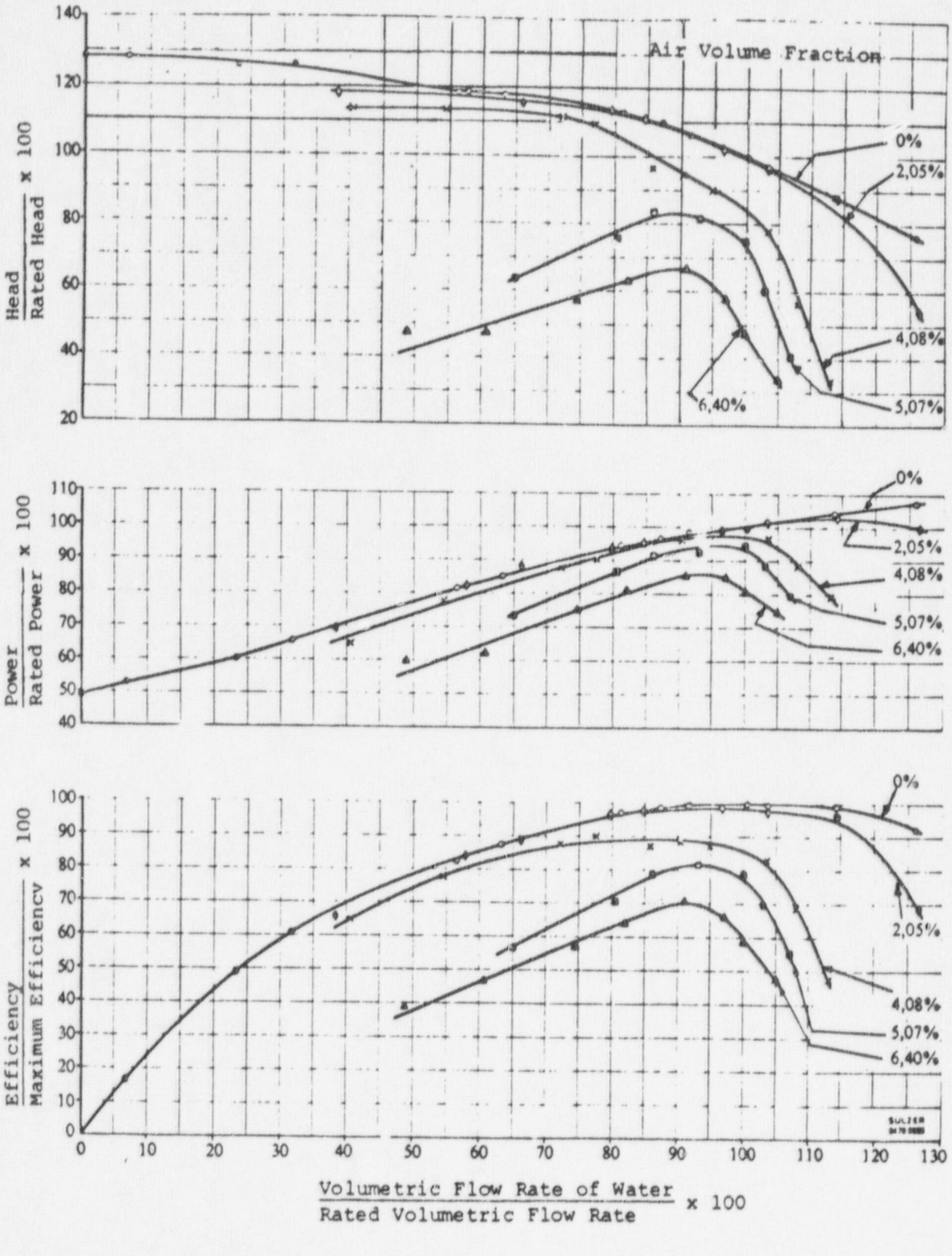

Figure 1. NORMALIZED HEAD, POWER AND EFFICIENCY IN AIR/WATER FLOW FROM FLORJANCIC [3] – SINGLE STAGE PUMP

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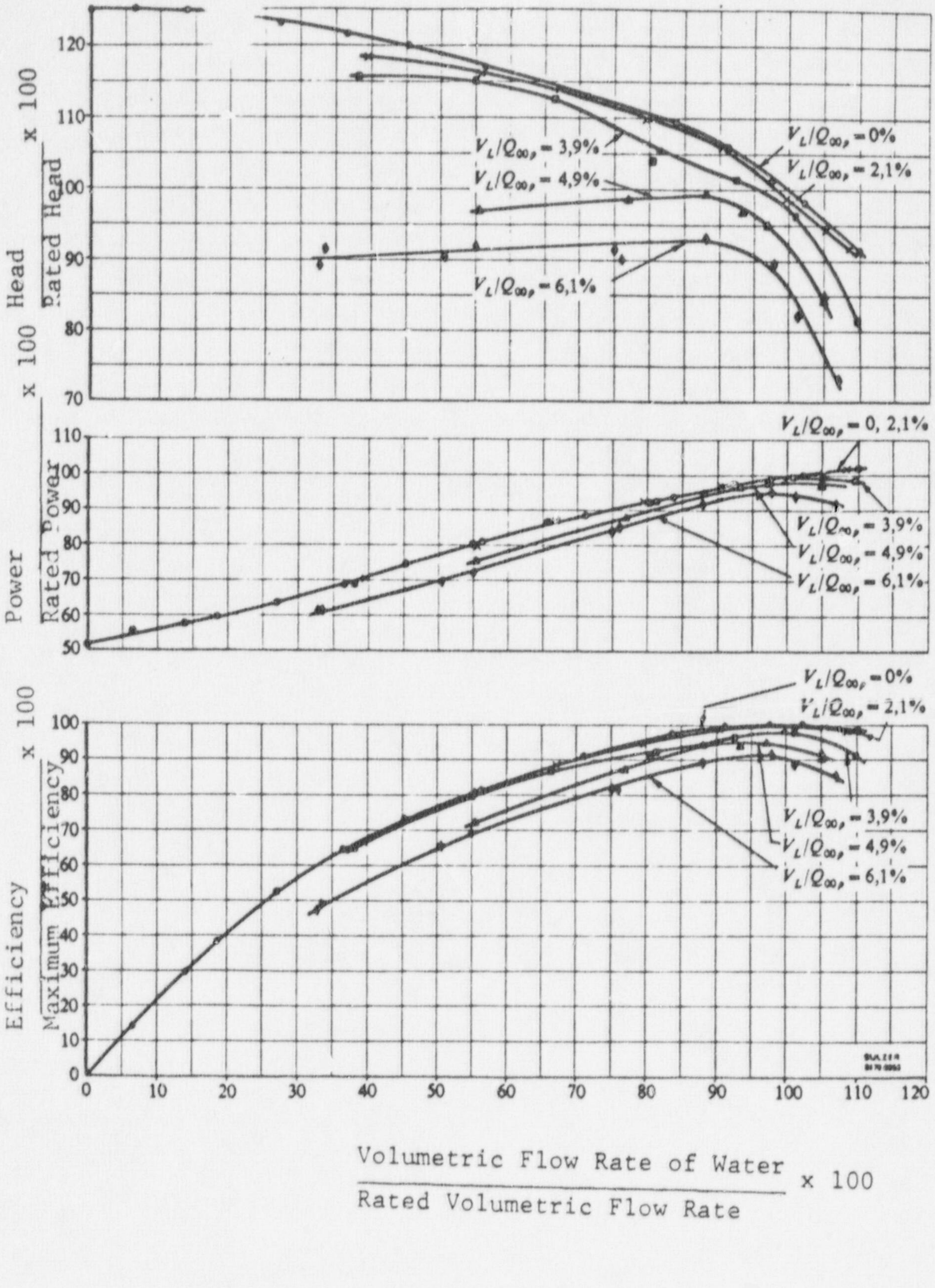

Figure 2. NORMALIZED HEAD, POWER AND EFFICIENCY IN AIR/WATER FLOW FROM FLORJANCIC [3] – THREE STAGE PUMP

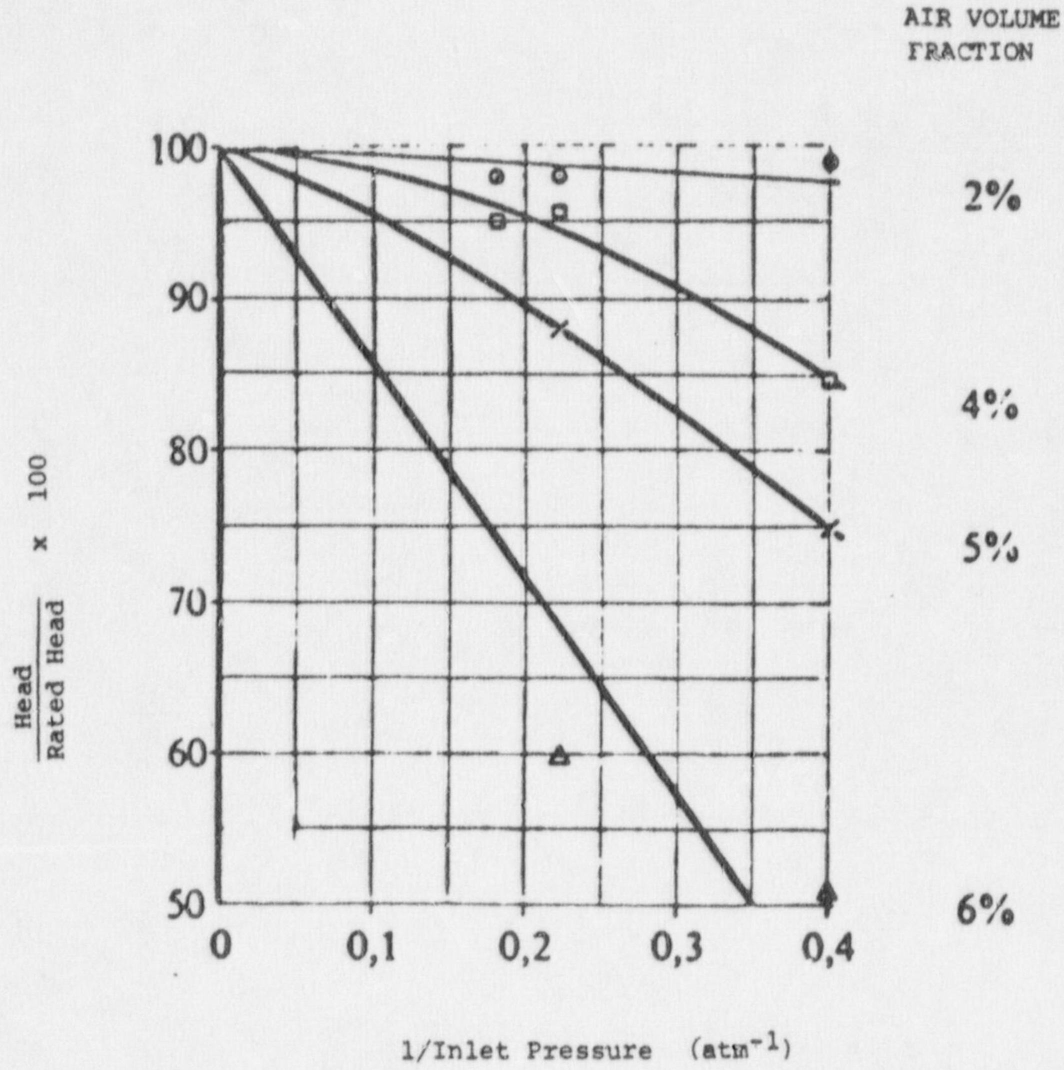

Figure 3. EFFECT OF INLET PRESSURE ON AIR/WATER PERFORMANCE FROM FLORJANCIC [3]

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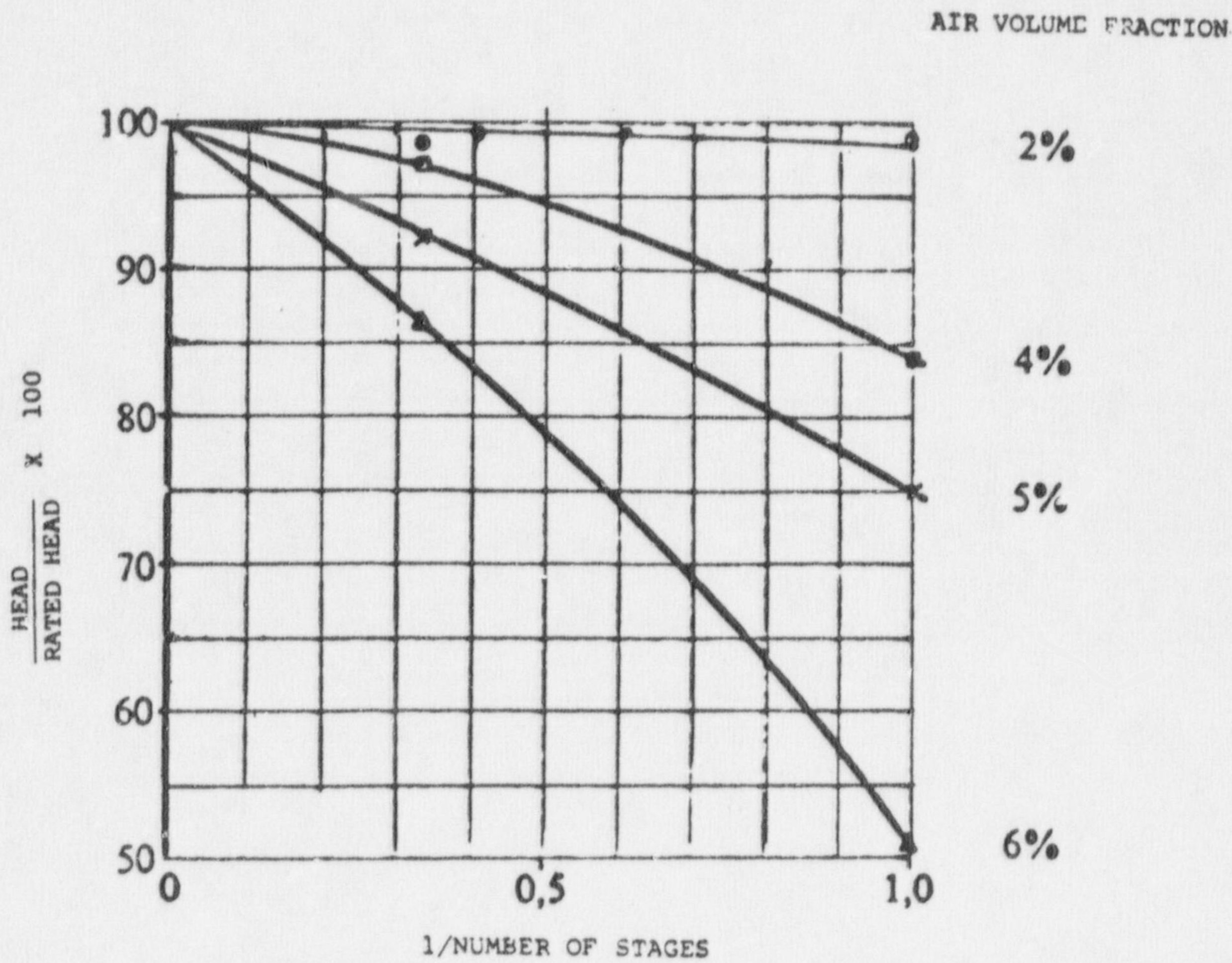

Figure 4. EFFECT OF NUMBER OF STAGES ON AIR/WATER PERFORMANCE FROM FLORJANCIC [3]

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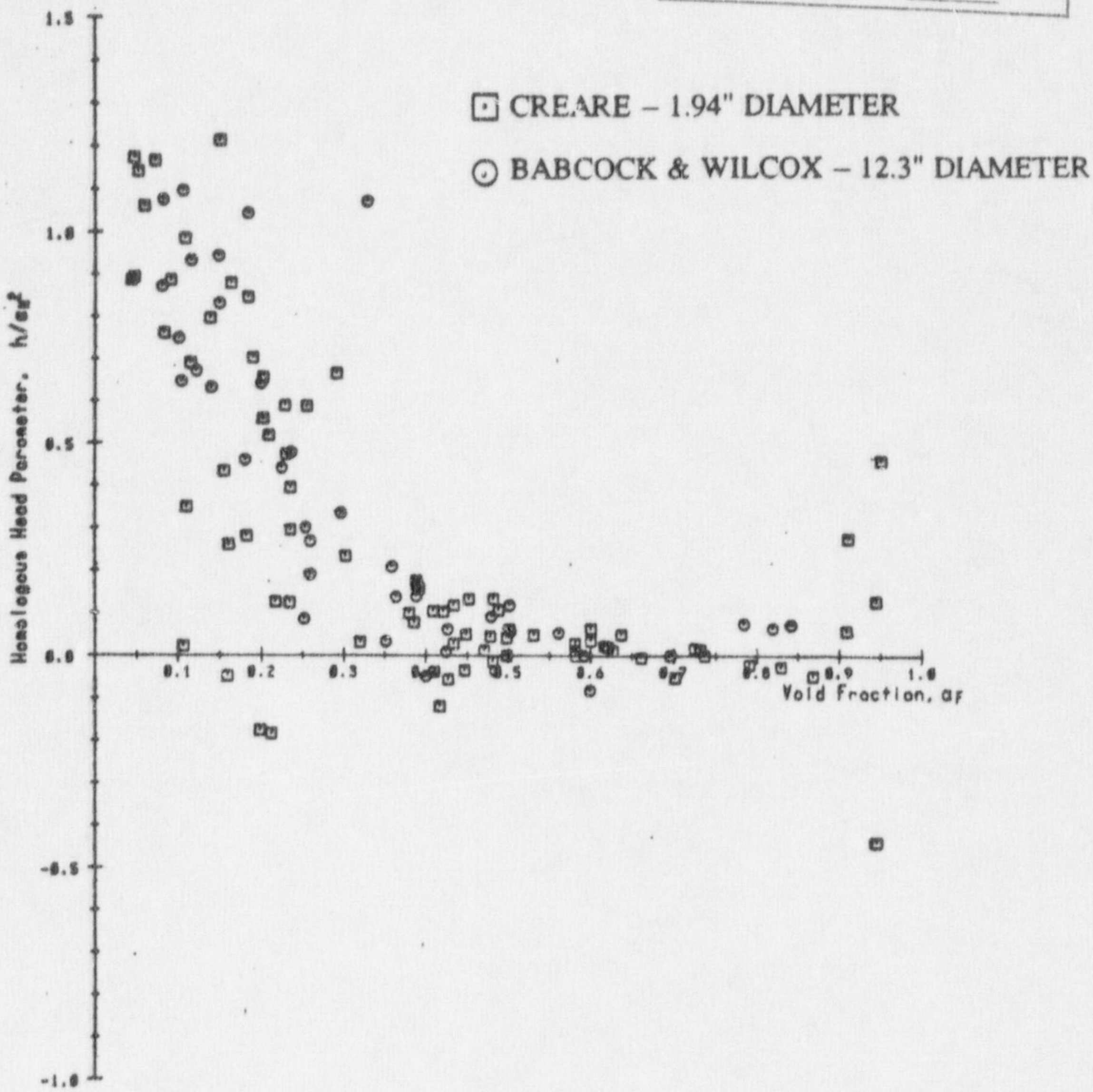

Figure 5. COMPARISON OF CREARE AIR/WATER AND B&W DATA — TWO PHASE FOR ν/α_N BETWEEN 0.80 AND 1.20 [4]

Three important conclusions can be drawn from these test results:

1) there is a fair amount of scatter in the results showing the variability in behavior (which includes uncertainties in measurements) between two nearly identical hydraulic designs at comparable operating conditions,

2) below 10 % air fraction the head remains above 60 % of the single phase value ($h/\alpha_N^2 = 1$), and

3) there is a fair amount of agreement between the two pumps in the trend of degradation with increased void fraction.

Unfortunately, there is no information provided in the reference (or other references relating to these tests) regarding variable suction pressures or the interaction between cavitation performance and air/water behavior.

Murakami et al. [5], [6], [7]

This group of Japanese researchers have tested several series of pumps – axial and centrifugal – with variations in speed, air volume, numbers of blades, etc. Among the tests are data on the combined effects of air and NPSH. Some of the results of their tests are summarized in Figure 6.

In tests on a low specific speed pump to evaluate air entrainment effects, they found virtually no change in performance below air fractions of about 4 % by volume [5]. Between 5 % and 10 % volumetric air fraction, they noted "discontinuities" in pump performance characteristics as a result of the introduction of air. The test pump was a radial flow centrifugal design with an 8.8" diameter impeller having 5 blades. There is evidence from their flow visualization during the tests that the discontinuities in the performance characteristics result from abrupt changes in the flow of air bubbles through the pump. Basically, because the machine is highly radial flow, the blade to blade pressure gradients are large. They tend to promote the accumulation of air bubbles in low pressure areas through the blade passages which severely distorts the liquid flow patterns. The attached bubbles grow in volume, then are swept out of the impeller – accompanied by flow and pressure fluctuations.

Comparative tests [6] were performed on three similar radial flow impellers of approximately the same design discussed in [5]. The effect of number of impeller blades was evaluated. A minor shift in peak efficiency occurred as the blade number varied (3, 5 and 7 blade impellers were tested). But the performance curves were comparable – specific speed at peak efficiency was within +/– 10 % for the three machines. The tests showed that for the three blade impeller, the flow discontinuities occurred at lower air fractions (about 3 %) – probably because of the stronger blade to blade pressure gradients associated with the fewer number of blades. In general, as the number of blades was increased, the quantity of air which the pump tolerated before evidence of "discontinuities" in flow also increased.

Later tests were also conducted on the three pumps to evaluate the combined effects of cavitation and air entrainment on performance [7]. The liquid cavitation performance of the 5 and 7 blade pumps were quite similar, that of the 3 blade impeller differed significantly from the other two. Figure 6 shows the combined effects of air and varying cavitation on the pump

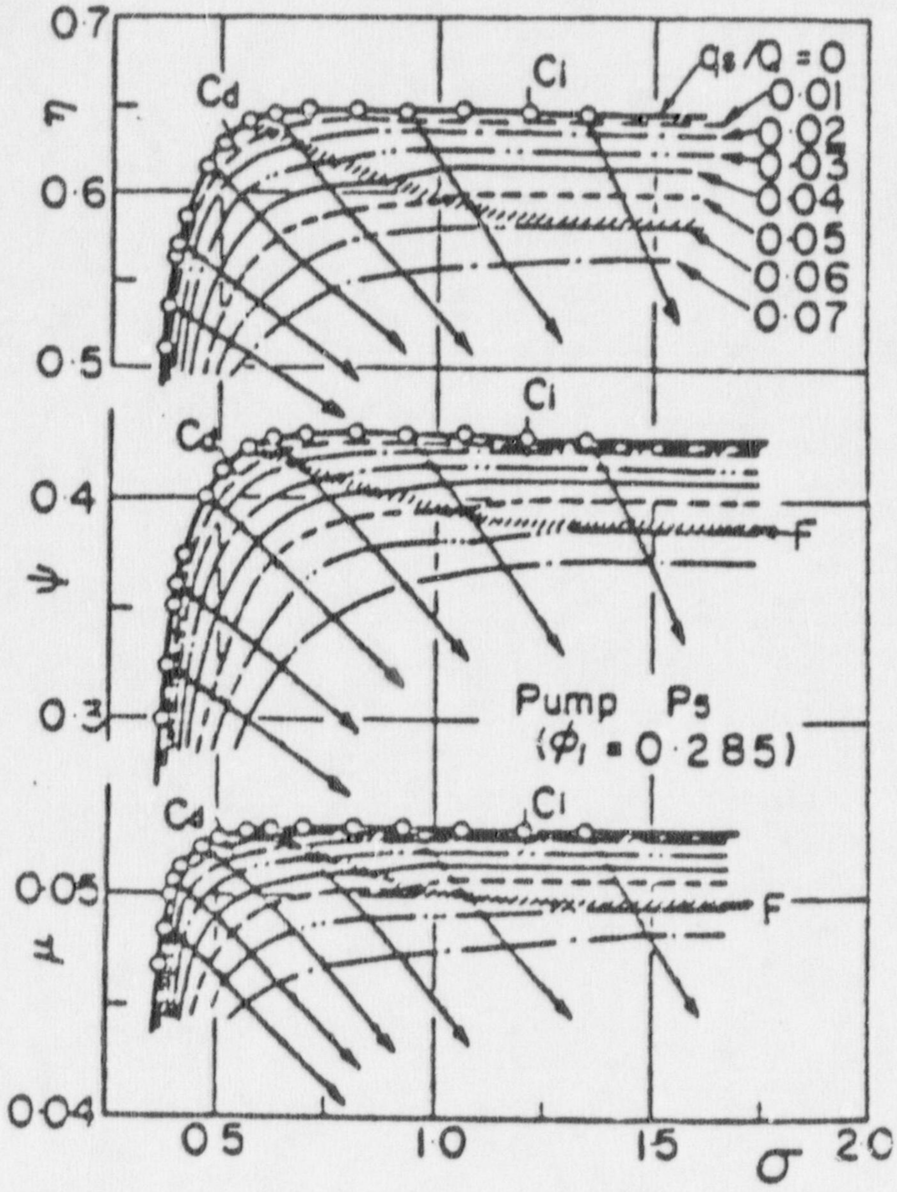

Figure 6. PERFORMANCE OF PUMP P_5 UNDER AIR ADMITTING CONDITIONS [7]

performance. The abscissa in the figure is σ = NPSH / ($u_1^2/2g$). The shading in the figure shows the band of "discontinuous" behavior. As airflow is increased or as NPSH is decreased, the flow in the impeller becomes unstable once the discontinuity band is reached.

Neumann & Lualdi [8]

Tests were performed on a mixed flow impeller in highly aerated conditions to determine the air handling behavior under differing blade settings and under differing means of air induction. Details of the pump design are not given in the paper – except that a Worthington model 16 MS 5 diffuser pump was used, with an equivalent specific speed of about 5100 (U.S. units). The pump produced a head rise of about 29 ft. at 7000 gpm, 740 rpm.

Figure 7 illustrates some of the results of these tests. In the region of best efficiency, two different methods were used to inject air. The dashed curves show behavior using the first device which did not control uniformity of the air entering the loop upstream of the pump. The authors describe flow conditions with a large degree of scatter in the data. The second device assured uniform bubble distribution of air. It is evident from the figure that upstream air flow distribution uniformity will strongly affect head degradation of the pump. It is also obvious that for relatively low levels of air (6 %) the effect is less pronounced.

Merry [9]

Tests by Merry were performed on a radial flow centrifugal pump to demonstrate the behavior of the pump under combined conditions of air ingestion and cavitation. These test results were used in NUREG/ CR – 2792 to illustrate these effects. While these results are useful for characterizing generic behavior of centrifugal pumps under these conditions, the curves cannot be arbitrarily applied to other machines. Figure 8 shows how the requirements for NPSH are increased as air quantities increase. The specific speed of the pump at best efficiency is 812 in U.S. units.

3.3 DISCUSSION

Figure 9 from [2] presents a large array of two phase pump test results which includes most of the data discussed in the previous section. The figure shows that for air fractions less than about 5 %, most of the existing two phase pump data shows head degradation less than 20 %. I.e., the collective set of data, which includes a large amount of variability in pumps, test conditions, etc., tends to indicate that for operation near design conditions, head degradation will be less than 20 % for an inlet air fraction of 5 % or less. The specific data of Florjancic indicates that multistage pumps will perform with even less degradation than a comparable single stage unit for the same air ingestion rate.

Figures 10 and 11 show the data of [6] and [9] in a reduced format to provide some guidance on the relative effect of NPSH on two phase head degradation. The vertical axis in each figure is test head divided by single phase rated head at the test flow and speed. The horizontal axis for each figure is σ/σ_{cr}. σ is defined here as the ratio of NPSH to rated head. σ_{cr} is the value of σ at the 3% head degradation point for single phase flow. By replotting the data in this format, one can evaluate differences between radically different machines on the same relative basis. On each figure, a dashed line shows the approximate locus of 3% head degradation for different air ingestion rates.

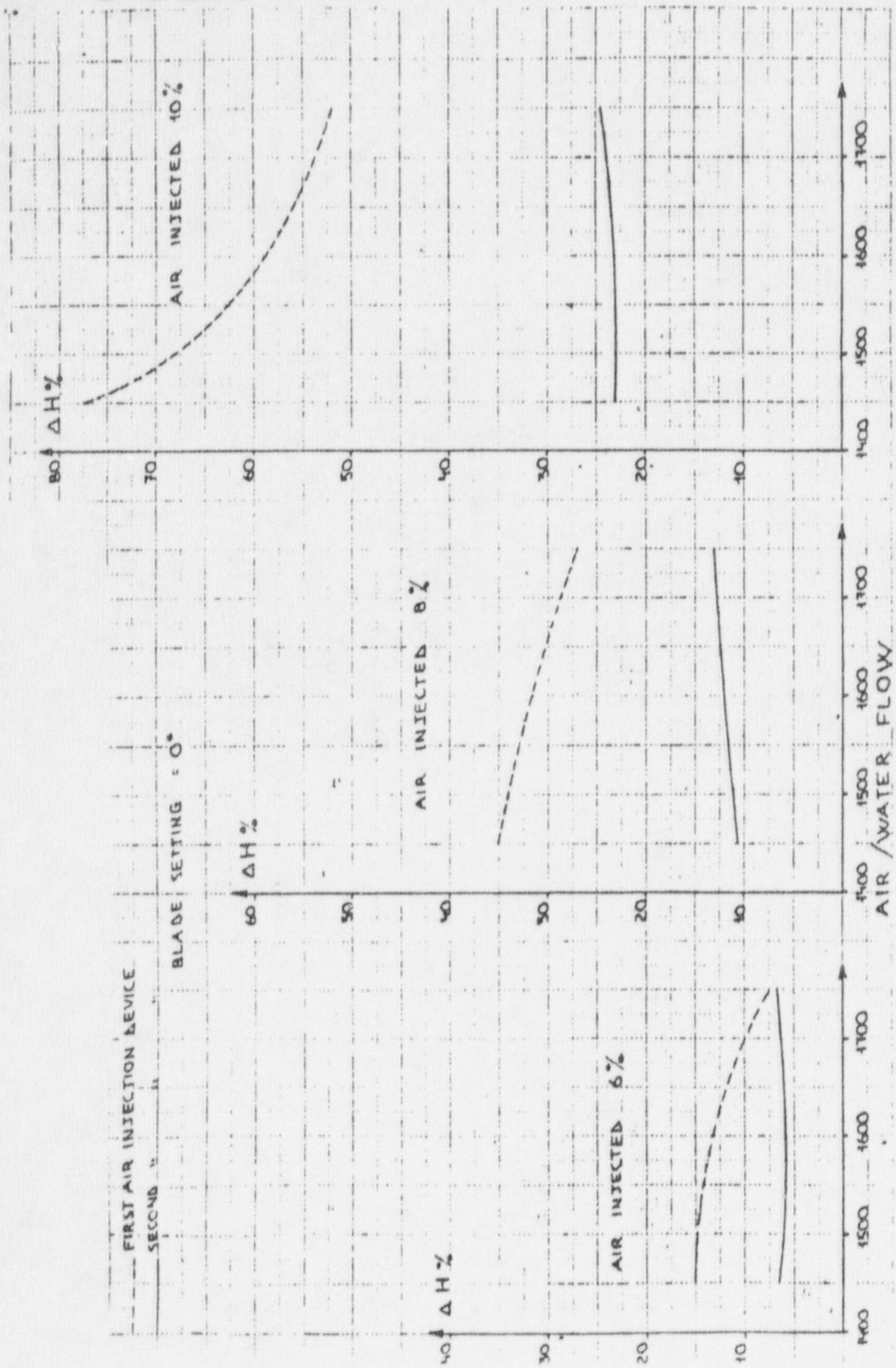

Figure 7. PERCENTAGE OF HEAD LOSS WITH DIFFERENT AIR INJECTION DEVICES [8]

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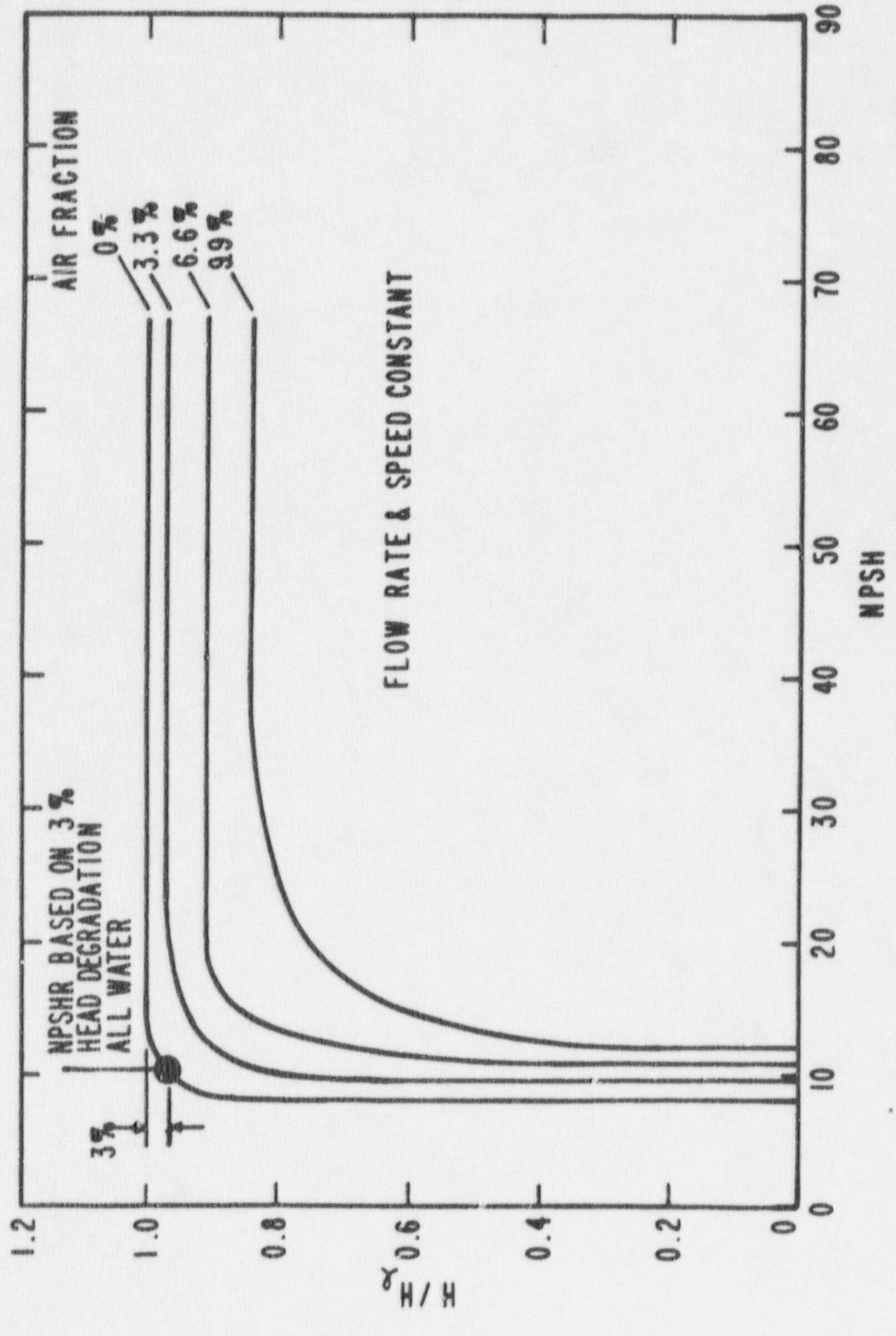

Figure 8. NORMALIZED HEAD VS. NPSH AT DIFFERENT VOID FRACTIONS FROM MERRY [9]

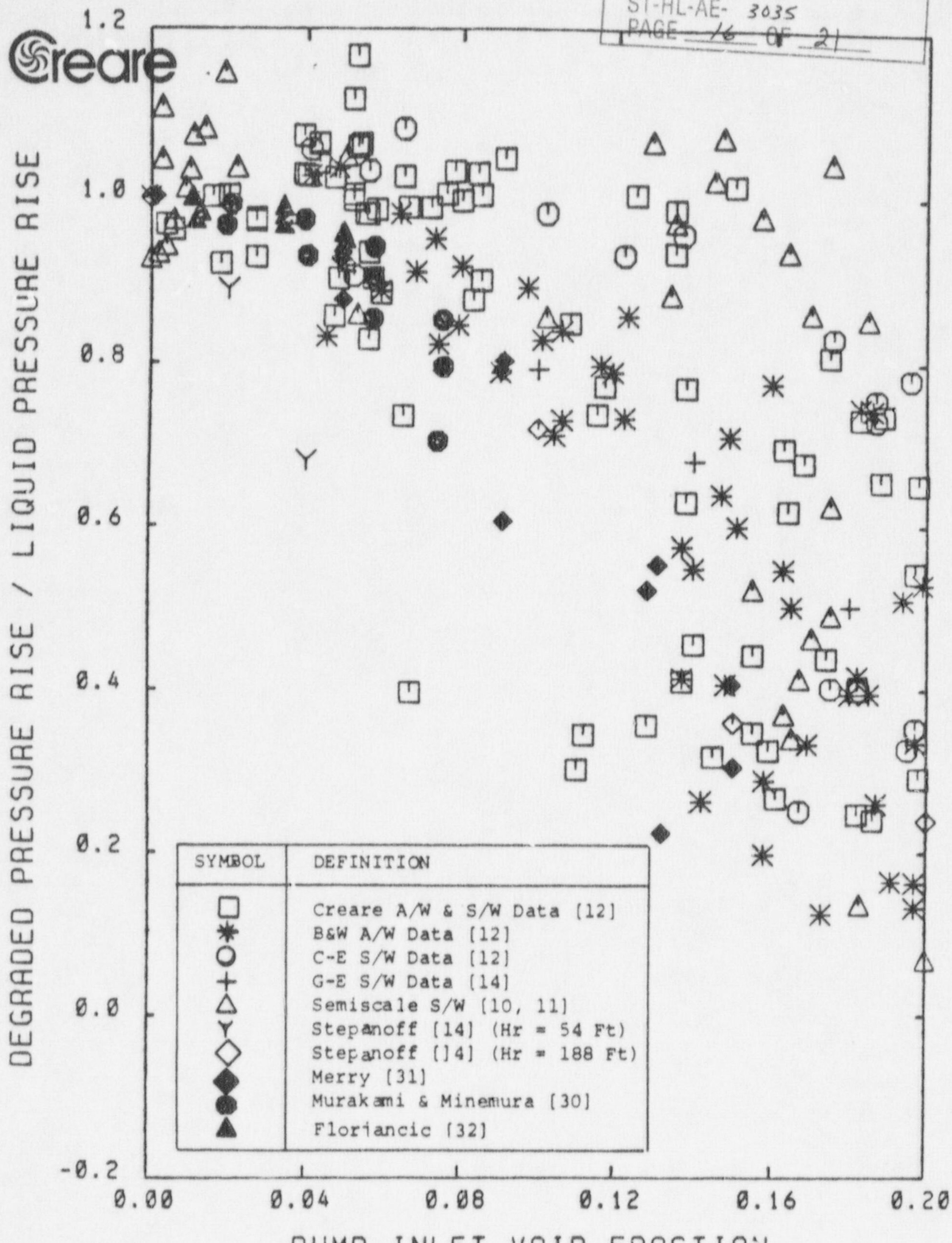

Figure 9. PUMP PRESSURE RISE IN AIR/WATER AND STEAM WATER FLOWS [2]

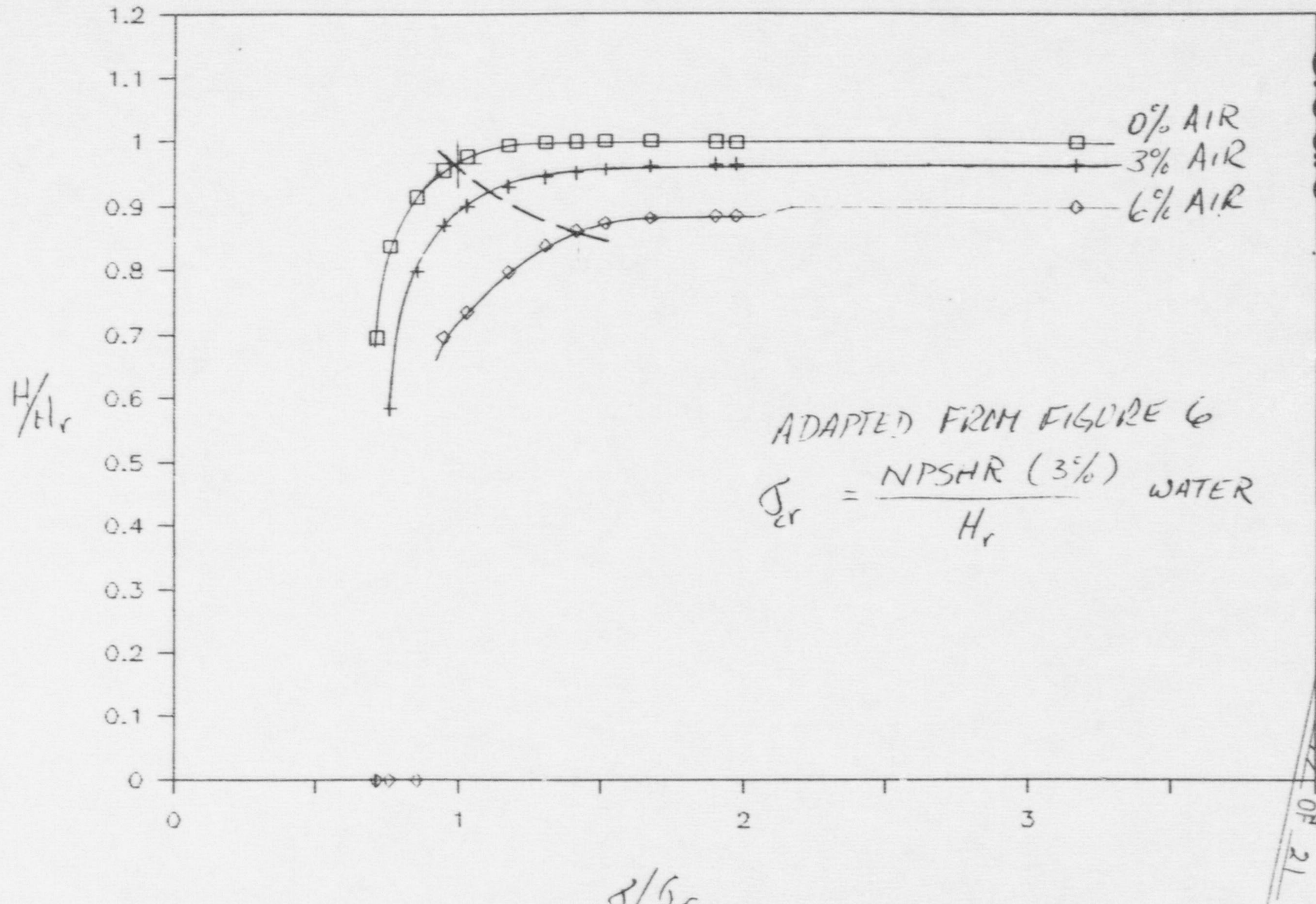

Figure 10. EFFECTS OF NPSH ON HEAD DEGRADATION WITH AIR [6]

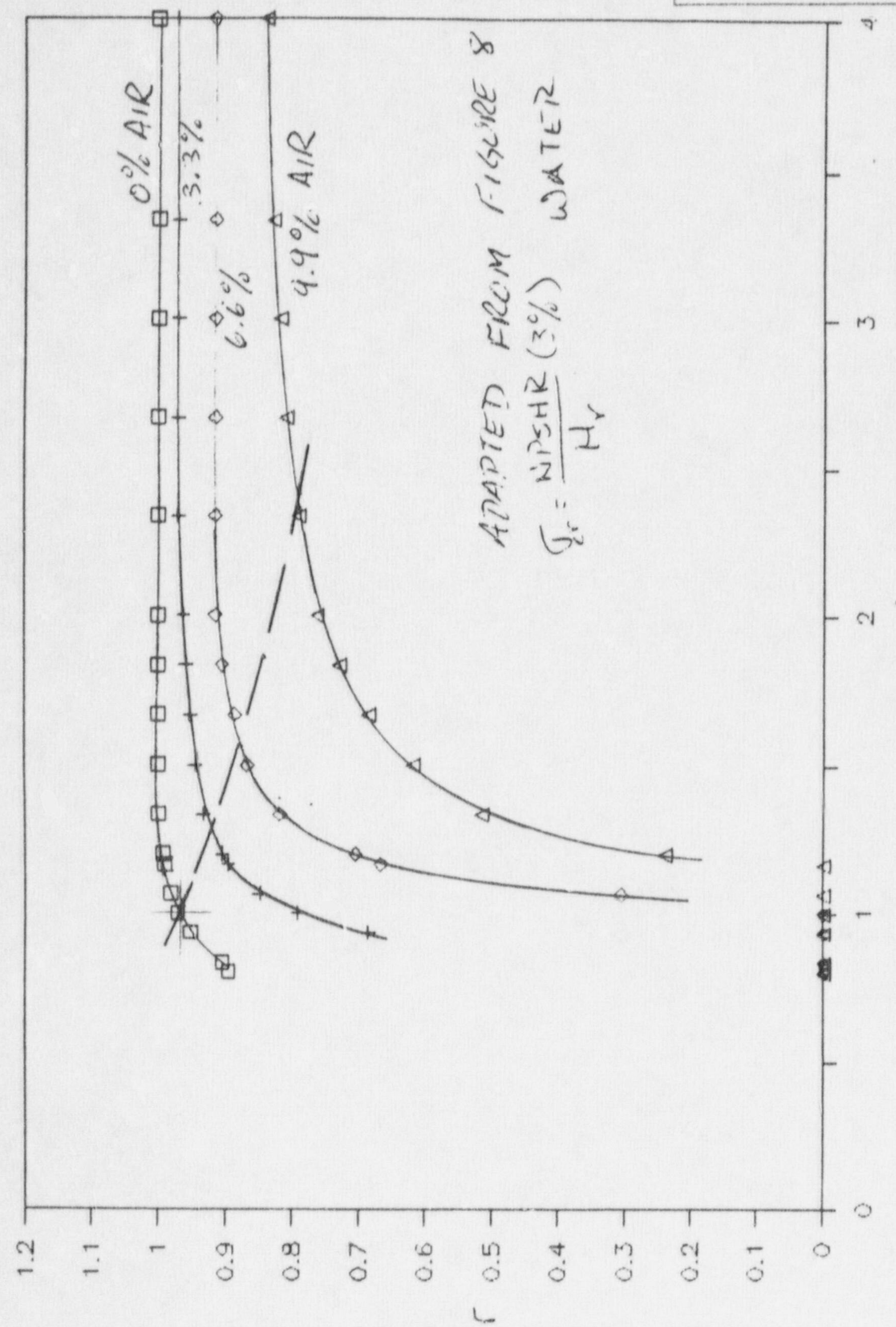

Figure 11. EFFECTS OF NPSH ON HEAD DEGRADATION WITH AIR [9]

Figure 12 then shows the combined set of data in terms of σ ratio at which there is a three per cent head drop for varying air ingestion rates. The result shows that for these two sets of pump data, the degradation in head (from NPSH effects) is expected to be less than 3% of the nominal two phase value for σ ratios above the dashed curve. One could conclude therefore, that for an expected air ingestion rate of 4%, a sigma ratio of more than 1.4 is required to assure no appreciable head degradation beyond that predicted by just air ingestion considerations alone. This is equivalent to a required increase in NPSH of 1.4 times the NPSH required for all liquid flow. At 8% air fraction, the NPSH requirement would be about twice the all liquid value.

The calculations in MC – 6126 indicate that for the LOCA – 1 analysis, the net positive suction head available at the pumps is about 30'. The pump performance curve shows an NPSH requirement of about 11' at a corresponding flow rate for operation with 100% liquid. This implies that the sigma ratio for the LOCA – 1 analysis is 30/11 = 2.7. Using the results of the Merry tests and the work of Murakami & Minemura, this would imply that the additional head degradation due to NPSH would be less than 3 % even up to 10 % air fraction.

The test results given in the previous section cannot be strictly applied to predict exactly how the safety pumps would behave under air ingesting conditions. As noted earlier, there is a great deal of variability in the pumps and test conditions. However, based on the collective results in the literature and the design features of the safety pumps (the fact that they are multistage and have inlet inducers), it seems highly probable that these machines would have been capable of sustaining at least 80 % of the nominal rated head for air fractions of up to 5 % at the pump inlet under the LOCA – 1 conditions and assumptions. It is also likely based on the data and margins of uncertainty that the pumps would have been able to sustain operation with less than 50% head degradation for air fractions up to 8% for at least short periods of time.

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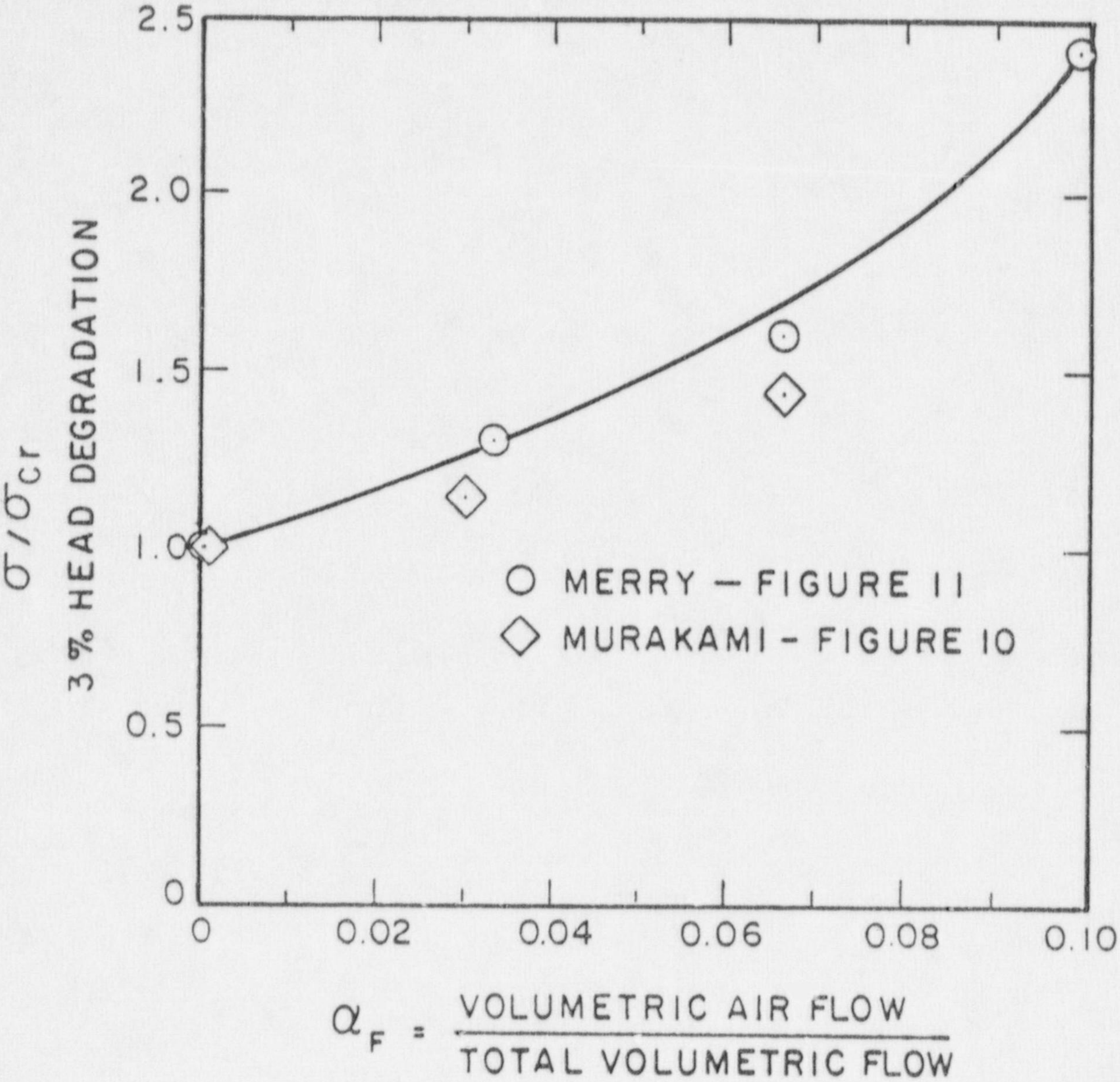

Figure 12. COMBINED DATA FROM [6] & [9] SHOWING LOCUS OF 3% HEAD DEGRADATION

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