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88-201

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SUBJECT: Forwards response to NRC request for addl info re Safety Sys Functional Insp Unresolved Items 88-201-2A,2B & 2C.

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NIAGARA MOHAWK

NIAGARA MOHAWK POWER CORPORATION/301 PLAINFIELD ROAD, SYRACUSE, N.Y. 13212/TELEPHONE (315) 474-1511

July 6, 1989
NMP1L 0418

U.S. Nuclear Regulatory Commission
Attn: Document Control Desk
Washington, D.C. 20555

Re: Nine Mile Point Unit 1
Docket No. 50-220
DPR-63
TAC No. 73043

Gentlemen:

Enclosed is Niagara Mohawks response to the Staff's request for additional information for Safety System Functional Inspection Unresolved Items 88-201-2A, 2B and 2C.

Niagara Mohawk believes the evaluations submitted are sufficient to demonstrate the ability of the Core Spray System to perform its intended function with respect to the issues identified in unresolved items 88-201-2A, 2B and 2C. Therefore, Niagara Mohawk considers unresolved items 88-201-2A, 2B and 2C sufficiently addressed to allow core reload. Testing described in this submittal will be performed after core reload but prior to restart.

Very truly yours,

NIAGARA MOHAWK POWER CORPORATION

C. D. Terry
Vice President
Nuclear Engineering and Licensing

LW/mlf
7517G
xc: Regional Administrator, Region I
Mr. R. A. Capra, Director
Ms. M. M. Slosson, Project Manager
Mr. W. A. Cook, Resident Inspector
Mr. J. H. Doolin, Dresser Industries
Records Management

IE01
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ADDITIONAL INFORMATION

1. Unresolved Item 88-201-2A. The licensee should verify that the revised pump performance curves have been reviewed to ensure that design inputs are consistent with system testing results.

Response

The design inputs to the core spray system flow rate analysis are the head-flow curves for the core spray and topping pumps, and the calculated system resistance curve which is based on the core spray system isometric drawings. The pump head-flow curves were validated over a flow range of 1000 to 3000 gpm during core spray system tests performed in February and March of 1989. The results of these tests indicated that the total head developed by the core spray and topping pump combination, including allowances for uncertainties, exceeded the design curve over the flow range tested. Results of the pumps curve validation tests were given to NRC inspectors for review during the on-site inspection during the week of June 12, 1989.

The pump curve validation tests were performed by recirculating water from the discharge of the topping pumps back to the torus through the 6-inch test return line. In this lineup, the core spray system flow is limited to about 3000 gpm due to the resistance of the test return line. During the tests, the flow was throttled via the flow control valve in the test return line from about 3000 gpm down to 1000 gpm. The pressure at the discharge of the topping pumps was recorded at each flow rate tested.

During Operator Surveillance Test N1-ST-R9, Core Spray Operability Using Demineralized (C.S.T.) Water, the inside and outside isolation valves are opened, the core spray pumps (one pump set in each loop)

take suction from the condensate storage tanks, and pump demineralized water into the reactor vessel at 0 psig via the core spray spargers. It takes about 40 seconds for the reactor water level to increase from the Low Level Alarm (65 in) at the start of the test to the High Level Alarm (83 in), at which point the test is terminated. Demineralized water from the condensate storage tanks is used for this test rather than torus water to avoid the risk of introducing any containments into the reactor coolant system. The test is limited to the one pump set in each loop which is connected via piping to the condensate storage tanks.

Prior to startup, an augmented version of the N1-ST-R9 test will be performed. This augmented test is titled 88-7.12 Core Spray Injection Test. This augmented version will include temporary instrumentation installed to continuously record the pressure at the discharge of the topping pumps and the flow through the flow meter during the test. This data will be used to validate the pump head-flow curves at flows up to the runout flow of about 5000 gpm. From the measured pressures and flows resulting from the test and known elevations, the core spray system resistance curve can also be determined and compared with the calculated curve used as a design input to the core spray system flow rate analysis. This test is scheduled after core reload but prior to startup. The test will be performed after reload to utilize the fuel assemblies to protect incore instrumentation from the turbulence caused by the injection flows.

2. Unresolved Item 88-201-2B. The licensee's response states that NPSH calculations indicate that pump cavitation is expected to exist for 6 hours. The licensee should provide a verification from the pump manufacturer that the pumps will be able to perform their safety function during and following the 6 hours of cavitation. An analysis of expected vibration should be evaluated with respect to the other system components. In addition, expected operator actions during and

following the cavitation should be evaluated. In addition to the above, the licensee should discuss the capability of other plant systems to cool the core following a design basis accident and the loss of the core spray pumps.

Response

As stated in our letter dated March 28, 1989, during one pump set operation at a reactor pressure of 0 psig, the calculated flow through the core spray pumps (without regard to suction pressure) is about 5000 gpm. From the pump performance curves, the required $NPSH_r$ at this flow is 39 ft. At the maximum torus water temperature during a LOCA of 140°F and a torus air pressure of 0 psig (Reg. Guide 1.1 conditions), the available $NPSH_a$ is calculated to be 40 ft with a clean (unblocked) grate across the end of the suction pipe. However, with the grate 50 percent blocked, the available $NPSH_a$ is calculated to be 36 ft, i.e., 3 ft less than the required $NPSH_r$. In this case, the pumps would be required to operate with the available $NPSH_a$ less than the required $NPSH_r$ for about six hours. After six hours, the torus water temperature would be reduced to a lower value (118°F) such that the available $NPSH_a$ would be equal to or greater than the required $NPSH_r$.

The NMP-1 core spray pumps are six stage vertical turbine pumps manufactured by Worthington Corporation (Model No. 15HH-41D-6). Worthington has since been acquired by Dresser Industries, Inc. On May 31, 1989, Niagara Mohawk met with representatives of the Dresser Pump Division to discuss the effects of operating the core spray pumps for a short period of time with the available $NPSH_a$ less than the required $NPSH_r$. Dresser confirmed that at the flow conditions calculated by Niagara Mohawk, the core spray pumps would operate satisfactorily during and following the six hours of operation with available $NPSH_a$ less than the required $NPSH_r$. The Dresser evaluation is provided in Attachment 1. In summary, the effects of operating the

NMP-1 core spray pumps for six hours at an available $NPSH_a$ of 36 ft compared to the required $NPSH_r$ of 39 ft would be as follows.

Flow Rate. The effect of operating a pump at an available $NPSH_a$ less than the required $NPSH_r$ would be to reduce the flow through the pump. However, the flow will be at least as high as the flow from the pump performance curves where the available $NPSH_a$ is equal to the required $NPSH_r$. This conclusion is supported by experimental test data from Minami, et. al, (1) and illustrated in Figure 1. If the available $NPSH_a$ is greater than or equal to the required $NPSH_r$, then the flow will be Q_A which is the intersection of the pump head-flow curve and the resistance curve. However, if the available $NPSH_a$ is less than the required $NPSH_r$, the flow will be Q_B which is the intersection of the resistance curve and the flow at which the available $NPSH_a$ is equal to the required $NPSH_r$.

For the NMP-1 core spray pumps, the values are:

Flow (gpm)	$NPSH_a$ (ft)	$NPSH_r$ (ft)
5000	36	39
4800	36	36

Therefore, at an available $NPSH_a$ of 36 ft, the flow through the core spray pumps will be at least 4800 gpm, which is consistent with calculations previously submitted to the NRC.

Impeller Erosion. A formula for predicting the erosion rate of an impeller due to cavitation has been developed by Guelich and Pace (2). The formula is based on research on boiler feed pumps funded by the Electric Power Research Institute. The formula indicates that the erosion rate:

o Increases with the cavitation bubble length raised to a power of 2.6 to 2.8 depending on whether the cavitation occurs on the pressure side or suction side of the impeller, respectively, and

o Decreases as the available $NPSH_a$ is reduced. The explanation for this is that as the available $NPSH_a$ is reduced, the cavitation bubbles tend to become detached from the surface of the impeller vane, reducing the erosion.

For the NMP-1 core spray pumps, cavitation would occur on the pressure side of the impeller since the calculated flow (4800-5000 gpm) is greater than the shockless capacity (3700 gpm) of the pump. The shockless capacity is the flow at which the relative flow angle of the inlet velocity triangle equals the inlet blade angle. It is not possible to quantify the relative erosion rate of the impeller when operating the pump at an available $NPSH_a$ of 36 ft relative to that when operating the pump at the required $NPSH_r$ of 39 ft since the relative cavitation bubble lengths are not known. Assuming the cavitation bubble length were to increase by 50 percent (considered a conservative assumption) and not considering the decrease in the erosion rate due to the pressure term, then the formula would predict the relative erosion rate would increase by a factor 2.87. However, the additional erosion that would occur during operation of the pump at an available $NPSH_a$ less than the required $NPSH_r$ would be insignificant due to the short period of time (six hours) that the pump would be operating in this condition. For example, if the erosion rate when operating for six hours at an available $NPSH_a$ of 36 ft were three times higher than when operating at the required $NPSH_r$ of 39 ft, then the total erosion of the impeller assuming 1000 hours of operation of the pump would increase by only 1.2 percent.

Pump Vibration. The vibration of the pump when operating at an available $NPSH_a$ of 36 ft would not be expected to be any higher than when operating at the required $NPSH_r$ of 39 ft. The pump vibration would be expected to vary as the pressure pulsations and acoustic noise level change. Studies by Nagengast (3) and McNulty and Pearsall (4) indicate that the pressure pulsations and the acoustic noise are highest at values of available $NPSH_a$ several times greater then the required $NPSH_r$, and that the acoustic noise and pressure pulsations

decrease as available $NPSH_a$ is reduced. Therefore, vibration of the pump and the effect of pump vibration on other system components would be negligible.

As indicated above, with a clean grate at the end of the suction pipe, the available $NPSH_a$ at the core spray pump suction is calculated to be greater than the required $NPSH_r$. The available $NPSH_a$ would not be expected to fall below the required $NPSH_r$ unless the grate across the end of the suction pipe becomes partially blocked. This condition would be indicated by the low suction pressure alarm. Operator response would be in accordance with the alarm responses in Operating Procedure N1-OP-2.

For extended operation of the core spray system, the topping pumps could be shut off. At 0 psig reactor pressure, the flow rate through the core spray pumps would be about 4000 gpm. With the grate across the end of the suction pipe 50 percent blocked, the available $NPSH_a$ at 4000 gpm is calculated to be 40 ft compared to the required $NPSH_r$ of 30 ft at this flow. Therefore, for extended operation of the core spray pumps, the available $NPSH_a$ is substantially greater than the required $NPSH_r$.

In addition to the core spray system, the following systems are also available to provide core cooling following a LOCA.

a. <u>Control Rod Drive System</u> taking suction from the condensate storage tanks (105,000 gallons available). Water would enter the reactor vessel through the CRD nozzle (Elevation 295'-11").

b. <u>HPCI System</u> taking suction from the condenser hotwell with makeup from the condensate storage tanks (180,000 gallons available). Water would enter the reactor vessel through the feedwater spargers (Elevation 295'-11").

c. Raw Water System via an intertie between the Raw Water System and the Core Spray System. Lake water would enter the reactor vessel through the core spray spargers (Elevation 294"-9"). This system is capable of providing water indefinitely in the event of a loss of the core spray pumps.

d. Fire Water System via an intertie between the Fire Water System and the Feedwater System. Lake water would enter the reactor vessel through the feedwater spargers.

3. Unresolved Item 88-201-2C. The licensee should evaluate the waterhammer analysis and verify that it is a bounding analysis. Specifically the licensee should discuss the initiation and transit of the air volume through a partially open isolation valve and the core spray spargers. In addition, the licensee should discuss how a waterhammer would be identified and what operator actions would be expected should a waterhammer occur in this system. The licensee should also discuss whether any spurious initiations of this system have occurred and whether any waterhammer was evident.

Response

Niagara Mohawk's analysis of the potential for waterhammer during startup of the core spray system during a LOCA is described in our letter dated March 28, 1989. Based on this analysis and the results of previous surveillance tests, it was concluded that the dynamic loads on the core spray piping, pipe supports, and sparger during startup of the core spray system during a LOCA would be acceptable. This analysis did consider the transit of the air volume through the sparger. The transit of the air volume through a partially open isolation valve was not considered significant, and therefore, not specifically considered. However, during the Core Spray Injection Test 88-7.12 described in Item 1, above, the sequence for starting the core spray and topping pumps, and opening the isolation valves inside

the drywell will be similar to the sequence of events during a LOCA, e.g., as follows:

Event	Small Break LOCA	Large Break LOCA
Start Core Spray Pump	t = 0 sec	t = 0 sec
Start Topping Pump	t = 7 sec	t = 7 sec
Open Isolation Valve	t = 30 sec	t = 0 sec

As noted previously, this test is scheduled after reload to protect incore instrumentation.

For the small break LOCA sequence, the pumps are allowed to reach rated speed prior to opening of the isolation valves inside the drywell. For the large break LOCA sequence, the isolation valves inside the drywell are assumed to open at approximately the same time that the core spray pumps start due to the rapid depressurization of the reactor vessel. These two sequences should bound the timing of the starting of the core spray pumps with respect to the opening of the isolation valves. Both loops will be tested using the small break LOCA sequence and the large break LOCA sequence.

Note that during these tests, when the valve from the condensate storage tanks to the core spray pump suction is opened, the water level in the core spray piping will rise about 28 ft. This partially compresses the initial air volume in the pipe since the condensate storage tanks are at a higher elevation (261'-0") than the normal torus water level. However, this is not expected to affect the dynamic loading on the core spray piping system components during startup of the system since the total air mass trapped in the pipe is the same.

Walkdowns of the core spray system will be performed before and after the tests to verify that dynamic loads during startup of the core spray system did not cause damage to the system.

Should a waterhammer occur during startup of the core spray system during a LOCA, it would most likely go undetected unless the loads were sufficient to cause functional damage to the core spray piping outside the reactor or the sparger. Functional damage would be damage which results in a reduction in the core spray flow (e.g., due to excessive deformation or a kink in the pipe) or rupture of the pipe. Operator actions would be in accordance with symptom based Emergency Operating Procedures and alarm responses in the Operating Procedures. That is, operators would respond to a waterhammer event based on the symptoms produced by the event, rather than the event itself.

A reduction in flow due to a kink in the pipe would be indicated by a lower than expected core spray flow rate. Other possible causes of a reduced core spray flow such as a partially blocked strainer or inlet grate, or pump degradation would have to be evaluated. In general, a core spray loop would not be shut down due to a low flow condition since a reduced flow rate is better than no flow at all. The Emergency Operating Procedures direct the operators to establish alternative sources of core cooling (see response to Item 2, above) if the core spray system becomes inoperable.

A rupture of the core spray pipe outside the reactor would be indicated by the low discharge pressure alarm and/or a higher than expected flow to the affected sump, if the break is outside the drywell. Operator actions would be in accordance with alarm responses in Operating Procedure N1-OP-2.

To date, there have been no spurious initiations of the core spray system which resulted in flow to the reactor vessel.

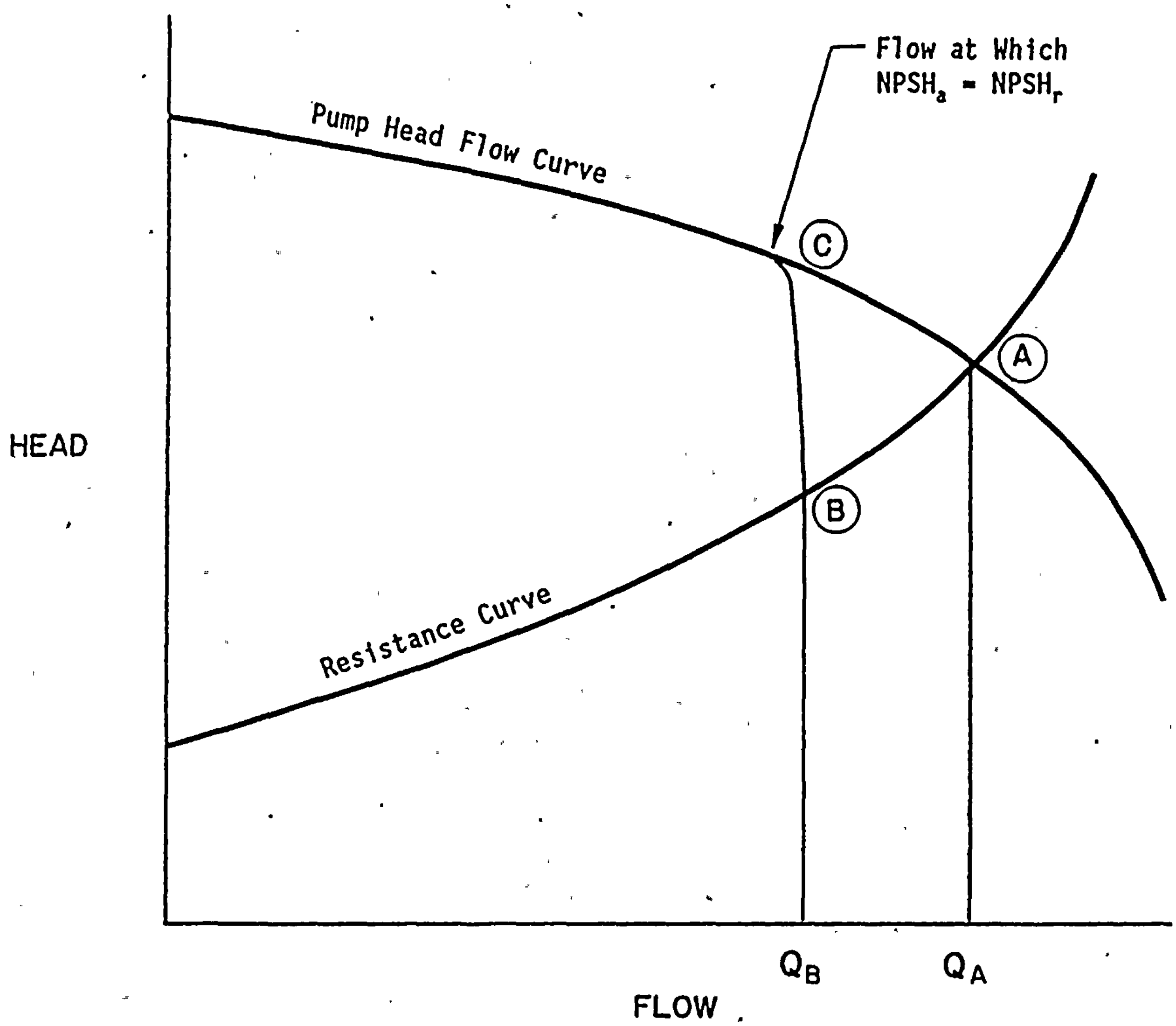
REFERENCES

1. S. Minami, K. Kawaguchi, and T. Homma - "Experimental Study on Cavitation in Centrifugal Pump Impellers." Japanese Society of Mechanical Engineers, Vol. 3, No. 9.

2. J. Guelich and S. Pace - "Quantitative Prediction of Cavitation lErosion in Centrifugal Pumps." AIHR Symposium, September 2-5, 1986.

3. P. Nagengast - "Cavitation Patterns and System Instabilities of a Shrouded Inducer." ASME Cavitation Forum, 1967.

4. P. J. McNulty and I. S. Pearsall - "Cavitation Inception in Pumps." Journal of Fluids Engineering, March 1982.



TYPICAL PUMP HEAD–FLOW CURVE SHOWING
HOW FLOW WOULD BE LIMITED BY NPSHa

FIGURE 1

DRESSER PUMP DIVISION DRESSER

Dresser Pump Division, Dresser Industries, Inc.
270 Sheffield Street • Mountainside, NJ 07092-2399 • 201/654-3300

JUN 2 6 ..

June 19, 1989

Mr. Lee A. Klosowski
Niagara Mohawk Power Corporation
301 Plainfield Road
Syracuse, NY 13212

Subject: Niagara Mohawk Power Corp. - Core Spray Pumps
Nine Mile Point Unit 1

Dear Mr. Klosowski:

This letter is to report on our review of the operating conditions determined by Niagara Mohawk for the Worthington 15HH-410 Core Sprays Pumps at Niagara Mohawk Power Corp., Nine Mile Point Unit 1.

The primary concern presented to us is the possibility of operation of the pumps for about six hours at a run out condition with 36 feet NPSHA (available) where the pump requires 39 feet NPSHR (required). This will cause the pump to operate at a capacity of about 4800 GPM but with sufficient cavitation to cause more than the 3 percent total head loss which is normal at the NPSHR condition.

In order to explore this situation in considerable detail, we met in our Harrison, NJ operation with the following people in attendance:

J. R. Leenhouts	-	Niagara Mohawk Power Corp.
W. S. Grant	-	MPR Associates, Inc.
J. W. Johnson	-	MPR Associates, Inc.
B. Schiavello	-	Dresser Pump Division
J. H. Doolin	-	Dresser Pump Division

Mr. Johnson began the meeting with a detailed review of the operating conditions for the NMP-1 core spray pumps. In addition, Dresser was provided with a copy of a Niagara Mohawk report to NRC on the issue titled, "Response to SSFI Issue 1.b" dated February 24, 1989.

Following this, Mr. Bruno Schiavello, our Engineering Manager Fluid Dynamics, presented an extensive discussion on the subject of cavitation and supported this discussion with technical publications listed on the attached bibliography. Copies of these papers were given to all attendees at the meeting. In brief summary, Mr. Schiavello provided detail discussion on the following:

- Shockless Capacity - Attachment 1
- Cavitation Erosion - Attachment 2
- Cavitation Domains - Attachment 3
- Erosion Prediction - Attachment 4

Prior to the meeting, a detailed analysis was made of the subject pump impeller to determine the shockless capacity which was determined to be 3700 GPM. Detail calculations are also attached to substantiate this fact.

A brief summary of the discussion is best explained by reference to attachment 3, Cavitation Domains. The upper family of curves identified as NPSHi (incipient) identifies the NPSHA value at which cavitation bubbles first appear. At this level, cavitation bubbles are less than 2 millimeters in length on the leading edge of the impeller vane, and no damage will occur.

As the NPSHA value is reduced, we reach the range identified as NPSHd (damage) where cavitation bubbles exceed about 10 millimeters in length and as they collapse on the impeller vane surface, pitting damage may take place.

Further reduction in NPSHA values will result in an increase in length of the cavitation bubbles with an increase in damage to the impeller. However, although cavitation bubble length continues to increase as NPSHA decreases below NPSHd, noise and damage to the impeller reaches a peak and then begins to decrease as the NPSHA is further lowered. This is due to the fact that the cavitation bubble is becoming more detached from the vane surface and implosion of the vapor bubble is not fully impinging on the surface and causing pitting.

When operating with NPSHA equal to the NPSHR value, there are substantial cavitation bubbles being formed on the impeller vanes and they reach a degree where they begin to block some of the flow area between vanes. This results in a reduction of flow and total head output. The Hydraulic Institute defines the NPSHR value as that which causes a reduction in pump total head of three percent.

Further reduction in NPSHA to values lower than NPSHR will increase the length and volume of cavitation bubbles and also reduce the impeller output in flow and total head. However, since much of this increase in cavitation bubbles is detached from the vane surface, increase in damage to the impeller is expected to be minimal.

Another approach to this subject is the Erosion Prediction formula presented on attachment 4. This is the result of extensive research on boiler feed pumps which was funded by the Electric Power Research Institute and published in a paper by Guelich and Pace (1). The formula shows that erosion rate is proportional to bubble length to 2.6 power since at capacities above the shockless one, cavitation is occurring on the pressure side (or hidden side) of the vane. Direct experimental data of the bubble length are not available for this type of pump at such operating conditions (high capacity and NPSHA close to NPSHR). If we assume that a marginal reduction in NPSHA below the NPSHR might increase the bubble length by about 50%, then the formula would indicate a damage increase by a factor 2.86.

While Dresser has no test data of pump vibration versus NPSHA, we would expect the pump vibration to vary as the acoustic noise and pressure pulsations. Papers by Nagengast (2) and McNulty (3) indicate that the acoustic noise and pressure pulsations are highest at values of NPSHA several times greater than the NPSHR, and that the acoustic noise and pressure pulsations decrease as NPSHA is reduced. Based on this, the vibration of the pump when operating at an NPSHA of 36 ft. would not be expected to be significantly different than when operating at the NPSHR 39 ft.

Based on the facts and discussion presented during this meeting, we would like to make the following observations on the operation of the subject core spray pumps.

1. Under circumstances where one pump alone will be supplying water to the spray header, it will tend to operate at 5000 GPM which is the flow at which the combined total head of the core spray pump and topping pump intersects with the system head curve. The NPSHR at this condition is 39 ft.

2. If the NPSHA to the pump is 36 feet, the pump flow will be reduced to about 4800 GPM, or possibly greater, which is the flow at which the NPSHR of the pump is also 36 feet.

3. When operating as described in item 2, the erosion rate of the impeller may be greater than operation at 5000 GPM with 39 feet NPSHA. A precise prediction is not possible, but based on the Guelich-Pace formula the erosion rate may be 2 or 3 times the rate with 39 feet available. However, the additional erosion that would occur during operation at NPSHA slightly less than NPSHR would be insignificant due to the short period of time (six hours) that the pumps would be operating in this condition.

4. When operating as described in item 2, the lower NPSHA value should have negligible effect on the vibration level of the impeller.

It is expected that the technical material distributed at the meeting and the above remarks will answer your questions about off peak operation of the subject pumps. If more refined information is required about variation of bubble length with NPSHA at capacities well above the shockless capacity, a special test can be performed using a soft paint technique to measure the cavitation damage length.

Very truly yours,

J. H. Doolin
Director, Technology

JHD:grs
Attachment

cc: J. Leenhouts (Niagara Mohawk)
W. Grant (MPR Associates)
J. Johnson (MPR Associates)
B. Schiavello (Dresser Pump Div.)

JD2 176

BIBLIOGRAPHY

Pump Cavitation Papers

(1) J. Guelich, S. Pace - "Quantitative Prediction of Cavitation Erosion in Centrifugal Pumps." IAHR 13e Symposium, September 2-5, 1986.

(2) P. Nagengast - "Cavitation Patterns and System Instabilities of a Shrouded Inducer." ASME Cavitation Forum, 1967.

(3) P. J. McNulty, I. S. Pearsall - "Cavitation Inception in Pumps." Journal of Fluids Engineering, March 1982

(4) S. Minami, K. Kawaguchi, T. Homma - "Experimental Study on Cavitation in Centrifugal Pump Impellers." Japanese Society of Mechanical Engineers, Vol. 3, No. 9.

(5) G. Wood, J. Murphy, J. Farquhar - "An Experimental Study of Caviation in a Mixed Flow Pump Impeller." Journal of Basic Engineering, Dec. 1960

(6) J. Kirejczyk - "On the Cavitation Intensity Estimation in Hydraulic Machines."

(7) J. Guelich - "Influence of Interaction at Different Components on Hydraulic Pump Performance and Cavitation." EPRI Power Plant Pumps Symposium, March 1987.

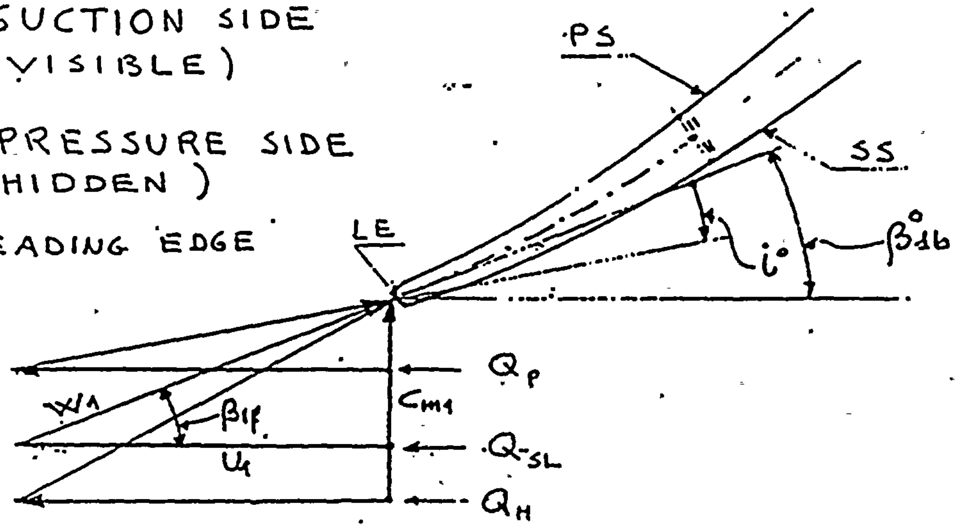
J. H. Doolin
6/19/89

INCIDENCE ANGLE - SHOCKLESS CAPACITY

SS : SUCTION SIDE (VISIBLE)

PS : PRESSURE SIDE (HIDDEN)

LE : LEADING EDGE



C_{m1} = MERIDIONAL ABSOLUTE VELOCITY ($\propto Q$ = CAPACITY)

U_1 = PERIPHERAL VELOCITY

W_1 = RELATIVE VELOCITY

β_{1f} = RELATIVE FLOW ANGLE

β_{1b} = BLADE ANGLE (ON CAMBER LINE)

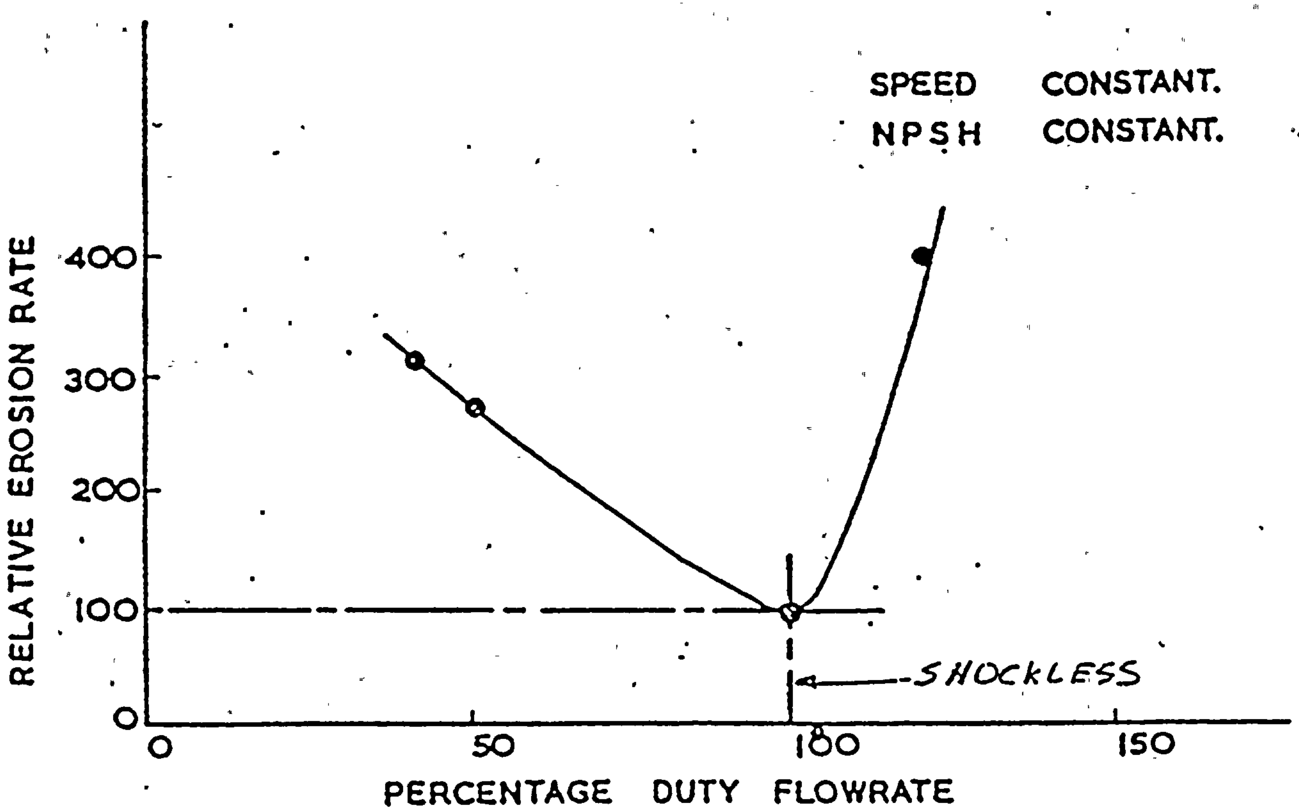
i = $\beta_{1b} - \beta_{1f}$ = INCIDENCE ANGLE

Q_{SL} = SHOCKLESS CAPACITY (ZERO INCIDENCE)

Q_P = PART CAPACITY ($< Q_{SL}$ i.e. POSITIVE INCIDENCE)

Q_H = HIGH CAPACITY ($> Q_{SL}$ i.e. NEGATIVE INCIDENCE)

INDUSTRIAL PUMPS - CAVITATION EROSION TEST

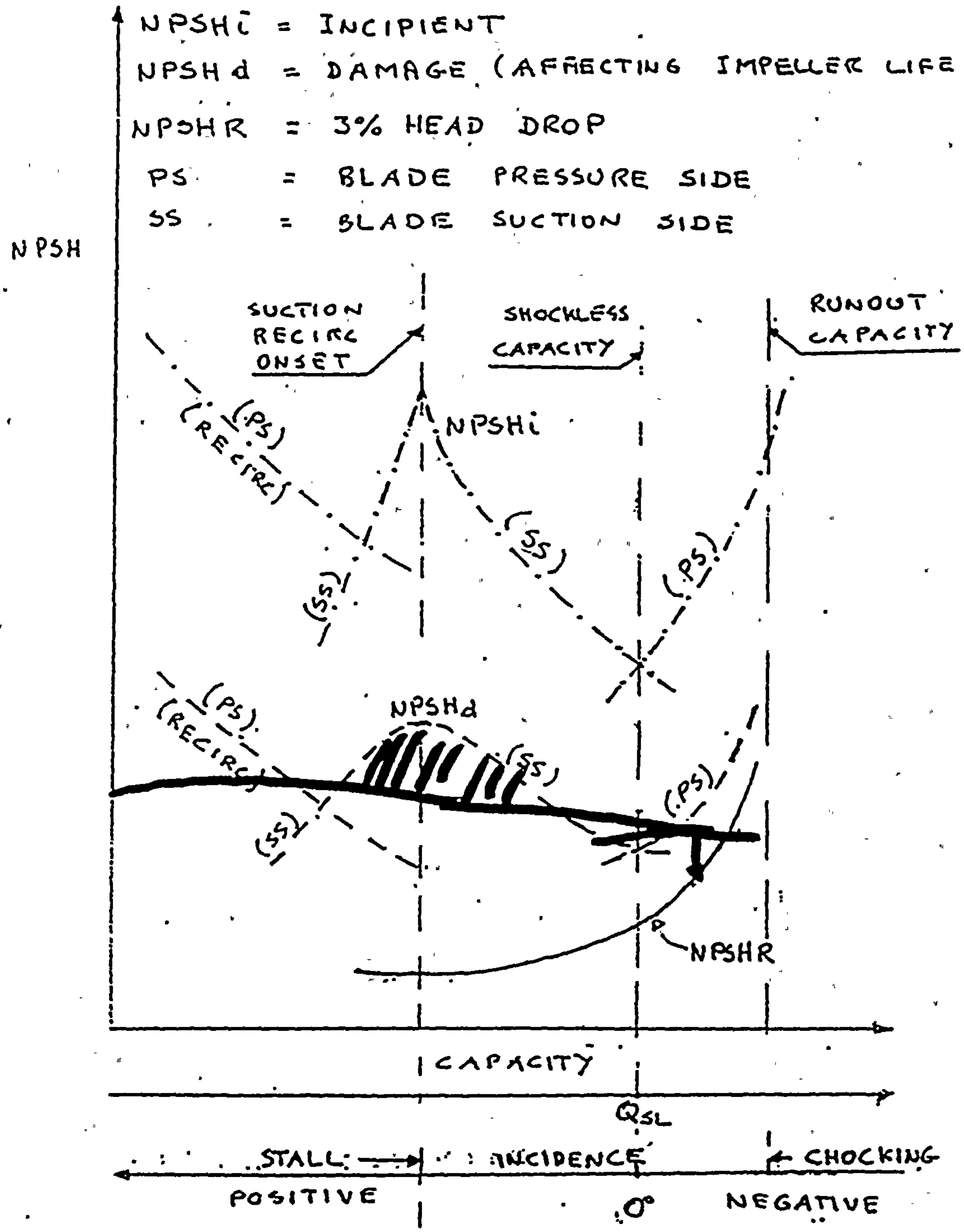


VARIATION OF EROSION RATE WITH FLOWRATE

ENDURANC TEST : TYPICAL RESULTS
(PUMP SPEED AT OR BELOW 3000 RPM)

(2)

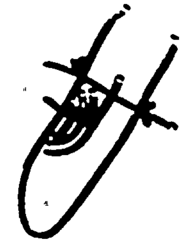
CAVITATION - TYPICAL CHARACTERISTICS / DOMAINS



CAVITATION EROSION PREDICTION ("ATTACHED" OR "SHEET CAVITATION")

$$ER = C_L \left(\frac{L_c}{L_{cref}}\right)^{X2} (P_o - P_{sat})^3 \; F_f \times F_m \times F_{cor} \qquad (1)$$

$$ER = MDP / T \qquad (mm/hr) \qquad (2)$$



ER = EROSION RATE

MDP = MEAN DEPTH PENETRATION (mm)

T = OPERATING TIME (hr)

$C_L \begin{cases} 1.1 \times 10^{-10} & \text{BLADE PRESSURE SIDE} \\ 2.2 \times 10^{-12} & \text{BLADE SUCTION SIDE} \end{cases}$

L_c = CAVITATION BUBBLE LENGTH

$X2 \begin{cases} 2.6 & \text{BL. PRESSURE SIDE} \\ 2.83 & \text{BL. SUCTION SIDE} \end{cases}$

$P_o - P_{sat}$ = SUPPRESSION PRESSURE (Kp/m^2)

F_f = FLUID PHYSICAL PROPERTIES

F_m = MATERIAL FUNCTION

F_{cor} = CORROSION FACTOR

$$P_o - P_{sat} = \gamma \left(NPSHA - \frac{C_{eye}^2}{2g}\right)$$

γ = SPECIFIC WEIGHT (Kp/m^3)

SHOCKLESS CAPACITY

Pump: 15HH-410-6
Impeller pattern drawing No.: 5287A (Worthington Corp., Denver, Colorado).
Number of blades: Z=6
Impeller eye diameter: Deye = 8.5625" = 0.2174 M
Pump rotational speed: N = 1760 RPM (ω = 184.3 rad/s)
Pump capacity at best efficiency point (b.e.p.): (Curve No: DEN 21274, 3/13/68) Qbep=3700 GPM = 0.2333 M3/S

Volumetric efficiency: η_v = 0.98 (assumed)
Impeller capacity at b.e.p.:
Qimp,bep = Qbep/η_v = 3700/0.98 = 3775.5 GPM = 0.2381 M3/S

A purely one-dimensional flow approach is followed for the incidence analysis of the relative flow at the impeller tip and hub, i.e., the influence of the curvature of the tip/hub meridional contour on the meridional velocity component is neglected.

1. Impeller Tip

1.1. Geometrical Data

Radius at the blade leading edge: R1 = 4.33" = 0.11 M

Inlet area (meridional channel): A1 = 53.9 sqi=0.0348 M2
Inlet blade angle on pressure side: $\beta_{1b,ps}$ = 21°
Inlet blade angle on suction side: $\beta_{1b,ss}$ = 20°
Inlet blade thickness: S1 = 5/32" = 0.004 M

1.2. Incidence angle calculation (at b.e.p.)

- Meridional component of the absolute velocity without blade blockage.

  Cm1' = Qimp, bep/A1 = 0.2381/0.0348=6.84M/s=22.5FT/s

- Inlet blade angle on camber line:

  β_{1b} = ($\beta_{1b,ps}$ + $\beta_{1b,ss}$)/2 = (21+20)/2 = 20.5°

- Inlet blade blockage:

$$\xi_1 = \frac{1}{1 - (Z*S1)/(2\pi R \sin\beta_{1b})} =$$

$$= \frac{1}{1 - (6 * 0.004)/(2\pi\, 0.11 \sin 20.5)} = 1.11$$

- Meridional component of the absolute velocity with

  $Cm1 = 1.11 * 6.84 = 7.59$ M/S = 24.9 FT/S

- Tangential component of the absolute velocity (assuming no prerotation)

  $Cm1 = 0.$ M/S = 0. FT/S

- Peripheral velocity

  $U1 = \omega R1 = 184.3 * 0.11 = 20.3$ M/S = 66.6 FT/S

- Flow Coefficient (at b.e.p.)

  $\varphi_{1bep} = Cm1/U1 = 7.59/20.3 = 0.374$

- Flow angle of the relative velocity (β_1) by definition

  $\tan \beta_1 = Wm1/Wu1$

Where: Wm1 = meridional component of the relative velocity.

Wu1 = tangential component of the relative velocity.

We have: $Wm1 = Cm1$

$Wu1 = U1 - Cu1 = U1$ (zero prerotation)

Therefore: $\beta_{1,bep} = \arctan \varphi_{1bep} = \arctan 0.374 = 20.5^\circ$

- Incidence angle at b.e.p.

  $ibep = \beta_{1b} - \beta_{1bep} = 20.5 - 20.5 = 0.0^\circ$

Therefore the shockless capacity, Qsl, which corresponds to zero incidence angle, occurs at pump b.e.p., i.e.,

$Qsl,tip = Qbep = 3700$ GPM

2. Impeller hub

2.1. Impeller geometrical data

$R1 = 2.05" \; 0.052 \; M$
$A1 = 5.94 \text{ sqi} = 0.0383 \; M2$
$\beta_{1b,PS} = 38^\circ$
$\beta_{1b,SS} = 35^\circ$
$S1 = 5/32" = 0.004 \; M$

2.2. Incidence angle calculation (at b.e.p.)

$Cm1 = 0.2381/0.0383 = 6.22 \; M/S = 20.4 \; FT/S$

$\beta_{1b} = (38 + 35)/2 = 36.5^\circ$

$$\xi_1 = \frac{1}{1-(6.0.004)/(2\pi \times 0.052 \sin 36.5)} = 1.14$$

$Cm1 = 1.14 * 6.22 = 7.09 \; M/S = 23.3 \; FT/S$

$Cu1 = 0$ (assumed)

$U1 = 184.3 * 0.052 = 9.58 \; M/S = 31.5 \; FT/S$

$\varphi_{1bep} = 7.09/9.58 = 0.740$

$\beta_{1bep} = \arctan 0.740 = 36.5$

$ibep = \beta_{1b} - \beta_{1b,bep} = 36.5 - 36.5 = 0.0^\circ$

The shockless capacity at the impeller hub is occurring at the b.e.p. capacity, i.e.,

Qsl,hub = Qbep = 3700 GPM

3. Pump Shockless Capacity (Qsl)

From cavitation behavior standpoint, the impeller tip section is usually the most critical one because the peripheral velocity and so the relative velocity dynamic head is higher than the one at the hub. Therefore the shockless capacity of the pump for which the tendency to cavitation is minimum usually corresponds to the impeller tip shockless capacity, i.e., in the case of the pump 15HH-410-6.

Qsl = Qsl,tip = 3700 GPM

The shockless capacity at the hub is in first approximation equal to the one at the tip, indicating that the full blade has been optimized for the same flowrate, which is also the b.e.p. capacity.

The cavitation will start and grow on the blade pressure side (hidden side) at capacity above Qsl.

A more refined two-dimensional flow approach should include the influence of the curvature of the tip/hub contour. It is expected that the shockless capacity at the tip end so the pump shockless capacity would be marginally lower than the above value.

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