ENCLOSURE 1
TENNESSEE VALLEY AUTHORITY
BROWNS FERRY NUCLEAR PLANT (BFN)
UNITS 1, 2, AND 3

TECHNICAL SPECIFICATIONS (TS) CHANGES TS-431 AND TS-418 -
EXTENDED POWER UPRATE (EPU) -
NPSH REQUIREMENTS - PUMP VENDOR REPORT
(TAC NOS. MC3812, MC3743, AND MC3744)

NPSH TRANSIENT STUDY, REV. 1

SULZER

QUALITY LEVEL
- ☐ Direct
- ☐ Indirect

SULZER PUMPS (US) INC. DOCUMENT

DOC. NO: **E12.5.1296**
ORDER NO: **E-001-21417**

TITLE: **NPSH Transient Study**
RHR and Core Spray Pumps

ASME CODE SECTION	
CLASS NO.	
CODE EDITION (YEAR)	
SEASON YEAR	

CUSTOMER **TVA**

PROJECT **Browns Ferry NPS**

CUSTOMER P.O. NO. ____________ ____________ CONTRACT NUMBER

SPECIFICATION NO. ____________ ____________ ITEM / TAG NUMBER

CUSTOMER APPROVAL NUMBER:

SPACE FOR CUSTOMER APPROVAL STAMP
(when applicable/available)

CUSTOMER APPROVAL REQUIREMENT

☒ Yes ☐ No ☐ Information Only

CERTIFIED AS A VALID SULZER PUMPS (US) INC. DOCUMENT

☐ For Outside Vendor
☒ For Manufacture at Sulzer Pumps (US) Inc.
☐ Risk Release Inspection Report # ____________
☐ Other (specify) ____________

APPROVALS (SIGNATURE)		Date
Engineering	Don Spencer	9/13/06

CERTIFICATION (when applicable)

This Document is certified to be in compliance with THE APPLICABLE PURCHASE ORDER, SPECIFICATIONS, PROCEDURES, AND

ADDITIONAL REQUIREMENTS LISTED IN THE APPENDICES.

____
Professional Engineer

____________ ____________
State Registration No.

Date ____________

Originating Dept:	**Advance Engineering**
By:	Steven J Schoenbrun **Steven Schoenbrun**
Title:	**Project Engineer**
Initial Date:	**9/13/2006**

APPLICABLE S.O. NUMBERS:

DOCUMENT IDENTIFICATION	Rev.
E12.5.1296	1

PURPOSE: To review existing pumps to determine if they are capable of meeting new transient NPSHa conditions and estimate the expected pump life based on 8000 hours and limited NPSH values. Minimum flow evaluation is not a requirement of this study.

KNOWN: The existing pumps are RHR [Residual Heat Removal] and CS [Core Spray] SULZER serial numbers: SO270671/82 and SO280253/64. Pumps were originally supplied to General Electric Company.

RHR pumps [SO 270671/82] are SULZER model 18x24x28 CVIC:

- Pumps are single suction vertical inline type with welded inlet and outlet connections;
- Units are rated 10000 gpm @ 560 feet on ambient water;
- Electric motors are rated 2000 hp @ 1785 rpm on 4000/3/60 Hertz power;
- Estimated weight is 20000 lbs with a height of 150 inches from the foundation.

Construction Features are as follows:

- Cross Section D27358 with parts list;
- Pump case is carbon steel;
- Pump rotor is chrome steel and the impeller has integral wear rings;
- Pump shaft is connected to the electric motor via a rigid coupling;
- Pump thrust is taken in the driver.

Available information and test data:

- Certified performance tests 27872, 27935, 27811, 27936, 27801-04, 28267 and 28941-43;
- Internal SULZER tests for information and development, note these are not available for publication;
- Original test records have been lost or archived at a site unknown at present;
- Existing records limited to internal hardcopies and microfiche;
- One of the original test engineers is still with SULZER in a similar capacity.

Core Spray (CS) pumps [SO 280253/64] are SULZER model 12x16x14.5 CVDS:

- Pumps are double suction vertical inline type with welded inlet and outlet connections;
- Units are rated 3125 gpm @ 582 feet on 210 degree F water;
- Electric motors are rated 600 hp @ 3580 rpm on 4000/3/60 Hertz power;
- Estimated weight is 8730 lbs with a height of 112 inches from the foundation.

Construction Features are as follows:

- Cross Section Z6315 and parts list;
- Pump case is carbon steel;
- Pump rotor assembly is chrome steel and the impeller has integral wear rings;
- Pump shaft is connected to the electric motor via a rigid coupling;
- Pump thrust is taken in the driver;

Available information and test data;

- Certified performance tests 27376B-79B, 27970-73 and 28022-25;
- Internal SULZER tests for information and development, note these are not available for publication;
- Original test records have been lost or archived at a site unknown at present;
- Existing records limited to internal hardcopies and microfiche;
- One of the original test engineers is still with SULZER in a similar capacity.

Both RHR and CS pumps are being evaluated for their response to potential transient conditions that may occur due to various system scenarios. TVA Browns Ferry has provided system transient scenarios; data includes flows, times and available NPSHa data for both the RHR and Core Spray Pumps, as follows:

Event	Duration	RHR Pump Flow	RHR Min NPSHA	CS Pump Flow	CS Min NPSHA
ST-LOCA	<10 min	11500 gpm (broken loop)	26.4 ft	4125 gpm	26.5 ft
		10500 gpm (intact loop)	29.4 ft		
LT-LOCA	>10 min to 24 hrs	6500 gpm	38.5 ft	3125 gpm	35.1 ft
ATWS	8 hrs	6500 gpm	24.3 ft	none	none
APP R	60 hrs	9000 gpm	26.9 ft	none	none
SBO	24 hrs	6500 gpm	32.2 ft	none	none

Table 1: Potential Transient Events

Methodology (RHR & CS Pumps): This study utilizes empirical and theoretical NPSHA/R data and calculations to make NPSHr recommendations for transient responses.

For both RHR & CS pumps test and order related data/information was collected for evaluation:

- All certified tests were collected;
- Available development/model test results were located and copied;
- Product test records/notes were collected;
- Individual Bill of Materials were copied;
- Field records were assembled.

As a basis for evaluation, certified witness test performance curves, for both pump sets, were averaged to produce an "average performance" for each pump type. Development test data was used to create NPSHr curves, at 1% and 3% head loss, for both models.

Theoretical NPSHr calculations utilize Sulzer's current standard for recommended (40k hours at BEP) NPSHr and "cavitation free" NPSHr from "Centrifugal Pumps: Design & Application", 2nd Edition, Lobanoff & Ross, Gulf Publishing, 1992.

Minimum NPSHa vs. NPSHr evaluation is accomplished by plotting/comparison of calculated and empirical NPSH data to determine hydraulic/mechanical implications of transient events.

Technical Background for Analyzing NPSH test data: To evaluate the response of a pump to a transient event, and make a meaningful prediction for post event operating life, the behavior of the pump in the NPSH "knee" must be thoroughly understood.

NPSH performance assessments are related to the knees of the plotted NPSH data. Plots of NPSH vs. head (from NPSH test data) as the NPSH is reduced incrementally from ample suction pressure, will show that the head responds by staying constant, varying or dropping:

- o The "knee" is the area on an NPSH test curve where the head degrades more rapidly before falling off totally.

The shape of an NPSH knee is an important factor in recommending minimum NPSHr values. A knee may have a sharp or more rounded profile, each with its own implications:

- o When the knee is sharp, various head drop comparisons (1%, 3%, 6%, etc.) occur at about the same NPSH value.
  - o *Operation near a sharp knee is not recommended.*
- o In a well-rounded knee the various head drop comparisons occur over a wider range of NPSH values. The wider range of response allows operating recommendations with less margin.

NPSH data for both pump models is from development testing. Aspects of data collection include:

- o Several test points are required to define a knee.
- o Occasionally, test stand limitations do not allow suppression to a low enough NPSH to completely define the knee - i.e. the 3%, 6%, drop-off points may not be captured on test. Under some conditions these tests can still be used to evaluate acceptable operation in response to a transient event.
  - o If the head remains stable below the minimum proposed transient event NPSHA, the test is still a good validation tool - i.e. while the head may not have degraded enough to define the knee ,in response to a lowering of the NPSH (a true "knee" has not been established), the stable head response shows that the pump is suitable for operation.

Modeling from similar pumps is another long established pump industry method with a basis in ANSI/Hydraulic Institute, ASME and other standards. Size factored NPSHr values (from models of similar pumps) are commonly used to make NPSH recommendations.

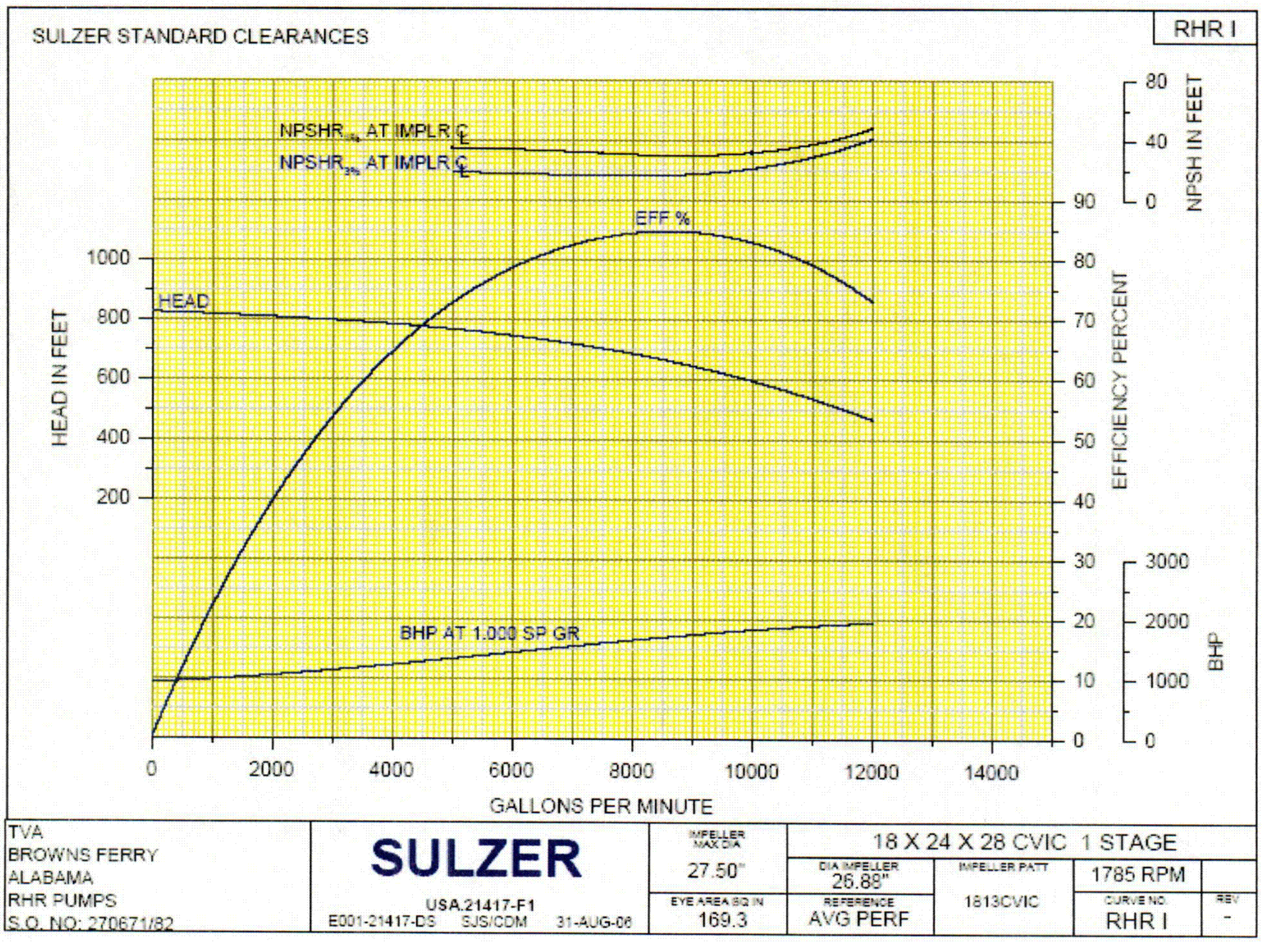
- o Modeling has not been used in this study.

RHR Pump NPSH Assessment and Analysis: Test and calculated NPSH values are analyzed and compared against the proposed transient events.

Performance curves 27935, 27811, 27936, 27801-04, 28267 and 28941-43 have been averaged relative to head and efficiency vs. flow and plotted as curve RHR I. For the basis of NPSH assessment, test points for NPSHR-3% and NPSHR-1% (4 capacities) have also been plotted on curve RHR I based on development testing (NPSH test data has been tabulated in Appendix A).

Specific speed (N_S) and Suction Specific Speed (N_{SS}) for both 3% and 1% head loss are as follows:

- $N_S = 1785*8600^{1/2}/656^{3/4} = 1277$
- $N_{SS-3\%} = 1785*8600^{1/2}/16^{3/4} = 20692$
- $N_{SS-1\%} = 1785*8600^{1/2}/29.5^{3/4} = 13077$



Curve 1: RHR Average Performance

Results of the "Cavitation Free" NPSHR calculation (based on Lobanoff and Ross) are as per the following table.

Flow	NPSH
5000 gpm	96.5 feet
7000 gpm	75.3 feet
9000 gpm	71.2 feet
10500 gpm	74.1 feet
12000 gpm	75.3 feet

Table 2: RHR "Cavitation Free" NPSH

The calculation set (5000, 7000, 9000, 10500 & 12000 gpm) is collected in Appendix A. A sample calculation follows:

"CAVITATION FREE" NPSHr CALCULATION

Q	=	5000	(GPM)	Flow.
N	=	1785	(rpm)	
A-B	=	368.2	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	169.3	(in^2)	Impeller eye area.
B_1	=	11	(deg.)	Blade inlet angle.
$(A-B)/A_E$	=	217.48	(%)	Area ratio (From Lobanoff and Ross).
K_1	=	1.58		From Lobanoff & Ross Figure 8-18.
D_t	=	15.25	(in.)	Impeller eye diameter
C_{M1}	=	9.4802	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	118.87	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
Tan(θ)	=	0.0798		Impeller inlet velocity ratio (C_{M1}/U_T).
θ	=	4.5598	(deg.)	Angle of flow approaching blade.
α	=	6.4402	(deg.)	Angle of incidence (B_1-theta).
K_2	=	0.46		From Lobanoff & Ross Figure 8-19.
C_B	=	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr	=	96.5	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application" 2nd Edition, Gulf Publishing, 1992

"NPSH-Recommended" calculation results are tabulated below. The calculation set (5000, 7000, 9000, 10500 & 12000 gpm) is collected in Appendix A.

Flow	NPSH
5000 gpm	45.6 feet
7000 gpm	31.9 feet
9000 gpm	33.5 feet
10500 gpm	42.9 feet
12000 gpm	99.8 feet

Table 3: RHR "Recommended NPSH"

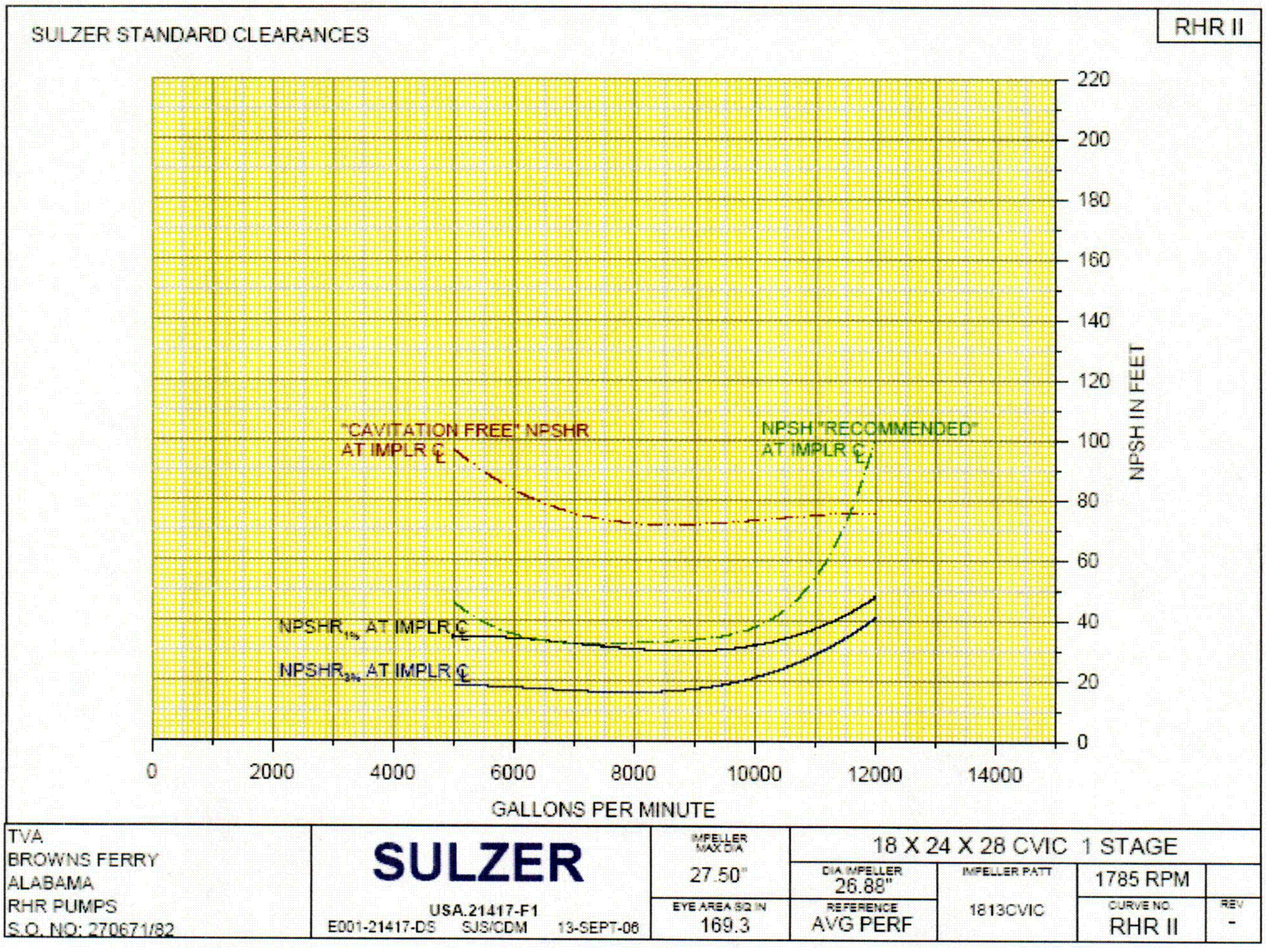
A sample "NPSH-Recommended calculation follows:

"NPSH RECOMMENDED" CALCULATION

Parameter		Value	Unit	Description
Q	=	5000	(GPM)	From performance curve
Q_{BEP}	=	8600	(GPM)	From performance curve
Q/Q_{BEP}	=	0.5814		
S_N	=	1.84		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN}	=	1.12		Function of pumpage and $NPSH_R$(3%)
S_T	=	0.97		Function of temperature and $NPSH_R$(3%)
S_M	=	1		Function of impeller material and pumpage
S_{LG}	=	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
N_{SS}(3%)	=	13390		Suction specific speed at 3%
N_{SS}(REF)	=	9300		Suction specific speed at reference
F_S	=	1.1999		{sqrt(N_{ss}(3%) / N_{ss}(REF))} for water if N_{ss}(3%) > 9300 = N_{ss}(REF)
$NPSH_R$(3%)	=	19	(ft)	From performance curve
F_{CT}	=	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by 1/F_{CT} to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$	=	45.6	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

Results of both the "NPSH-Recommended" and "Cavitation Free" calculations, as well as the test curves for 1% and 3% head and drop, are plotted on Curve RHR II:



Curve 2: RHR Test and Calculated NPSH

"Recommended" NPSH (as plotted) is Sulzer's theoretical recommendation for 40,000 hour life, based on limited cavitation damage to the impeller.

- Comparison to the "cavitation free" curve (Lobanoff & Ross) shows that some cavitation occurs at the "recommended" NPSHr. The slight erosion damage that occurs at this level is the basis for 40,000 hour criterion.

NPSHr curves based on 1% and 3% head loss are from development tests of these impellers, and represent the standard (Hydraulic Institute) method for determining NPSH;

- The same comparison as above demonstrates that slight cavitation will occur at these NPSH values.

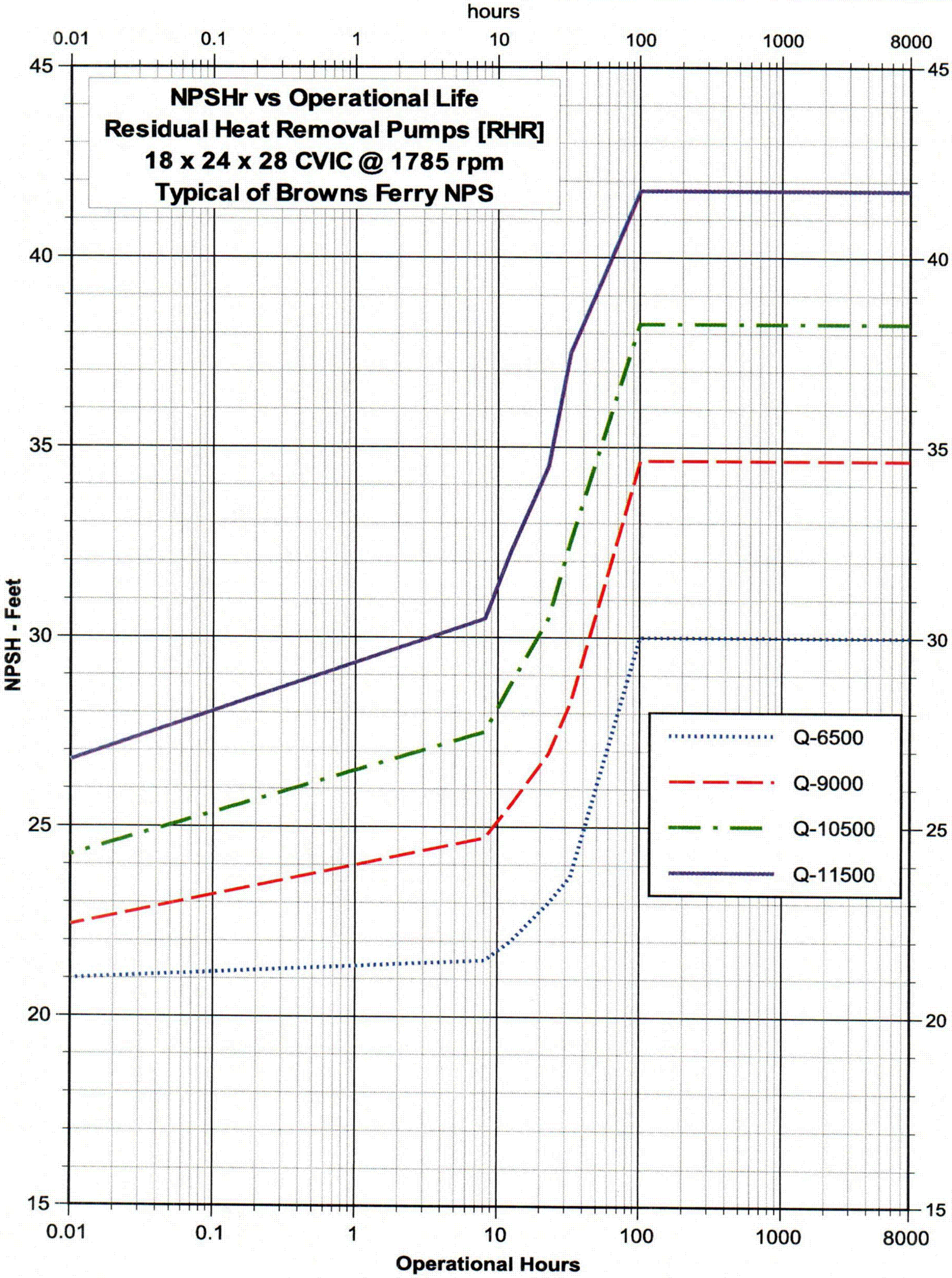
When the previously tabulated transient NPSHa cases are compared to the plots of RHR II, it is seen that the minimum NPSHa value from each event, except for the ST-LOCA-BL is equal, or greater, than the (standard) 3% curve at the same flow:

- LT-LOCA is above the "Recommended" NPSHr curve;
- APP R, ATWS and SBO are between the 1% and 3% head loss curves;
- ST-LOCA-IL (10500 gpm) is above the 3% head loss curve;
- ST-LOCA-BL (11500 gpm) is below the 3% head loss curve.

Since some cavitation exists at reduced NPSHa scenarios, a graph defining NPSHr vs. Operating Life (Curve 3 - as follows) based on mechanical damage (erosion) estimates has been developed in addition to the preceding NPSH analysis.

8000 hours (~1 year) has been selected as an adequate post transient event operational life. This is an estimate of the minimum life expectancy that will produce similar damage (during low NPSHa events) as that expected from an impeller operating with NPSHa above the "recommended" (40,000 hour) NPSHr curve:

- At the graphical NPSHr values for the origin (.01 hours) these are high suction energy pumps. The resulting lack of sufficient NPSH margin would result in life reduction (due to cavitation damage) if operated continually in the suppressed state;
    - Sulzer's graph provides a guideline for operating at the lowest possible NPSHa, while requiring an increase, over time, adequately removing enough energy from the pump to prevent catastrophic failure;
    - The recommended minimum NPSHr (time .01 hours), at all flows, range from slightly above 3% up to 6% head loss.
- Based on post-test inspection of the tested pumps the graph is conservative since the inspected impellers showed no damage;
    - Pumps were run for extended periods (2-3 hours) at 1% to 6% head loss without losing suction, despite surging, noise and increased vibration;
    - Several tests included NPSHa reduction to initiate loss of suction. Pumps recovered, with no visible damage, after NPSH was restored;
    - NPSHa increase over time, as dictated by the graph at a given flow, insures that recommended NPSH levels/duration will be less severe than that experienced during testing.



Curve 3: RHR NPSHr vs. Operating Life

RHR Results and Conclusions:

The subject pumps have been analyzed and found to be suitable for reduced NPSHa operation, as described above, with equipment in "as new" condition, with exceptions as noted.

Curve 3 provides a guideline for operational life vs. NPSHa as a general recommendation for operation when the pumps may be subject to transient events outside of their original scope.

Recommendations are also provided specifically to address the potential transient events provided by TVA Browns Ferry:

- Transient events identified as LT-LOCA, ATWS, SBO, APPR, ST-LOCA-IP all provide NPSHA values above the minimum established NPSHr, as established in the operating life graph (curve 3). They meet the criteria for determining operational life vs. NPSHa from the graph.
- The ST-LOCA-BL event provides NPSHA values below the required NPSH shown on the graph.

Analysis methodology compared test derived NPSHr values with those predicted theoretically. The pumps were evaluated against this comparative basis in order to predict the remaining operational life of a pump in the aftermath of a transient event;

- An 8000 hour post-transient operational lifetime was developed, based on similar cavitation damage to the 40,000 hour "recommended" NPSHr curve; the curve is well supported by the NPSH analysis and mechanical response on the test stand;
  - Graphical NPSHa levels and duration are less severe than that actually experienced on the test stand;
  - Empirical test information has been verified by one of the original test Engineers;
  - Despite NPSH testing that was more severe than the "recommended" curve, post-test inspection revealed no damage.

When pumps are in an "undamaged" condition they can be operated in accordance within the NPSHA guidelines provided with the expectation of the 8000 hour life described.

LT-LOCA, ATWS, SBO, APPR and ST-LOCA-IP transient scenarios are within the operating recommendations established in curve 3:

- Although vibration and noise may increase as a result of the transient events the units should continue pumping;
- Any non-detrimental impeller wear will be in accordance with the operational life graph.

The ST-LOCA-BL scenario falls outside of the established operating recommendations:

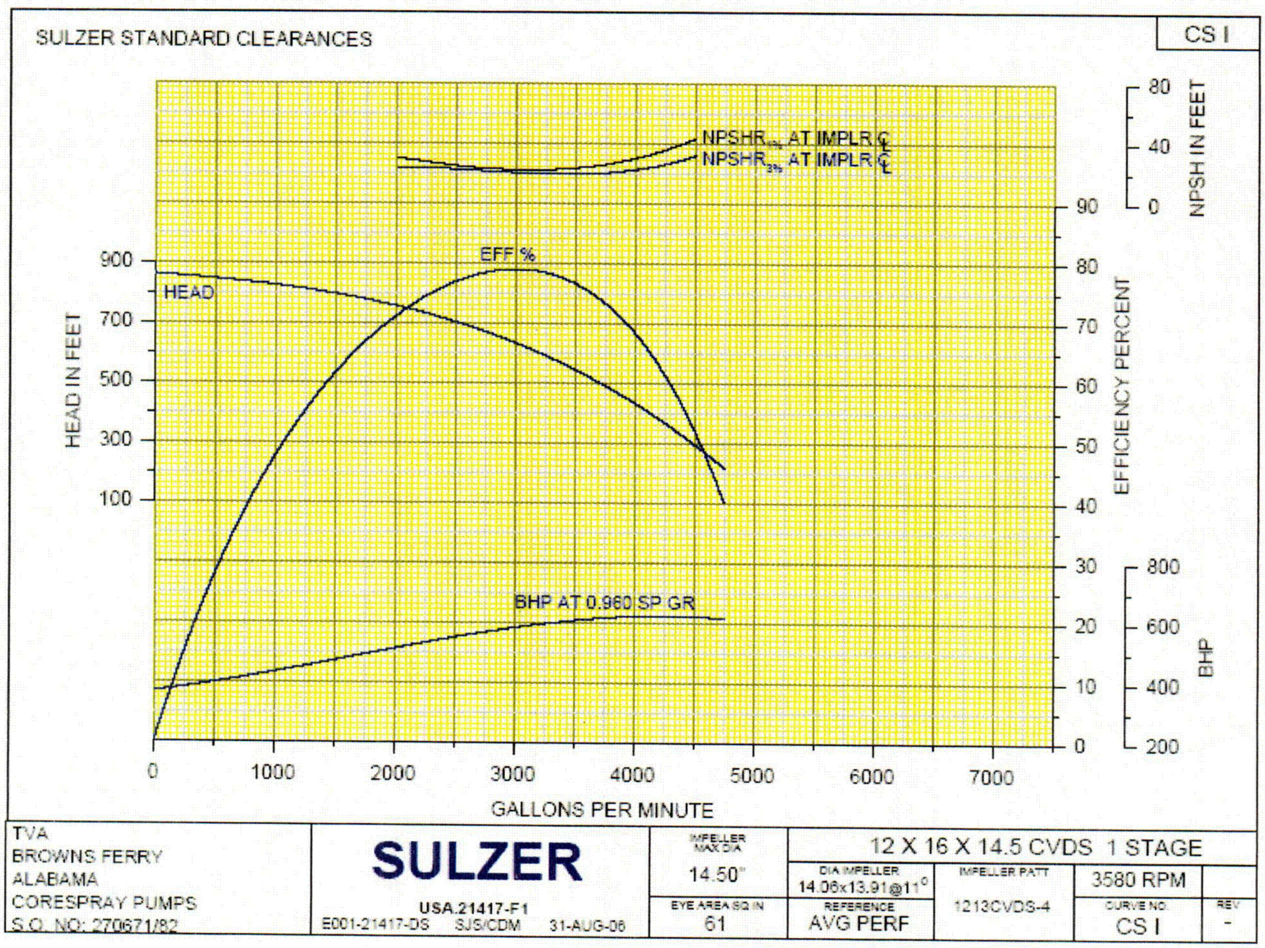
- o Although vibration and noise should increase due to surging and cavitation from the transient event, the units should continue operation;
- o Some detrimental damage is likely, due to the transient event, but should not be catastrophic. After 10 minutes, if the operational life graph is followed the pumps will continue to function.

CS Pump NPSH Assessment and Analysis: Test and calculated NPSH values are analyzed and compared against the proposed transient events.

Performance curves 27376B-79B, 27970-73 and 28022-25 have been averaged relative to head and efficiency vs. flow and plotted as curve CS I. For the basis of NPSH assessment, test points for NPSHR-3% and NPSHR-1% (3 capacities) have also been plotted on curve CS I based on development testing (NPSH test data has been tabulated in Appendix A).

Specific speed (N_S) and Suction Specific Speed (N_{SS}) for both 3% and 1% head loss are as follows:

- $N_S = 3580*3025^{1/2}/627^{3/4} = 1571$
- $N_{SS\text{-}3\%} = 3580*((3025/2)^{1/2})/21^{3/4} = 14193$
- $N_{SS\text{-}1\%} = 3580*((3025/2)^{1/2})/22^{3/4} = 13706$



Curve 4: CS Pump Average Performance

Results of the "Cavitation Free" NPSHR calculation (based on Lobanoff and Ross) are as per the following table.

Flow	NPSH
2000 gpm	159 feet
3000 gpm	126.3 feet
3750 gpm	87.6 feet
4500 gpm	76.7 feet

Table 4: CS "Cavitation Free" NPSH

The calculation set (2000, 3000, 3750 & 4500 gpm) is collected in Appendix A. A sample calculation follows:

"CAVITATION FREE" NPSHr CALCULATION

Q	=	*2000*	(GPM)	Flow.
N	=	*3580*	(rpm)	
A-B	=	*122.4*	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	*61.04*	(in^2)	Impeller eye area.
B_1	=	*16*	(deg.)	Blade inlet angle.
$(A-B)/A_E$	=	200.52	(%)	Area ratio (From Lobanoff and Ross).
K_1	=	*1.48*		From Lobanoff & Ross Figure 8-18.
D_t	=	*6.875*	(in.)	Impeller eye diameter
C_{M1}	=	10.518	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	107.48	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
Tan(θ)	=	0.0979		Impeller inlet velocity ratio (C_{M1}/U_T).
θ	=	5.5891	(deg.)	Angle of flow approaching blade.
α	=	10.411	(deg.)	Angle of incidence (B_1-theta).
K_2	=	*0.93*		From Lobanoff & Ross Figure 8-19.
C_B	=	*0.93*		From Lobanoff & Ross Figure 8-20.
NPSHr	=	**159.0**	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application" 2nd Edition, Gulf Publishing, 1992

"NPSH-Recommended" calculation results are tabulated below. The calculation set (2000, 3000, 3750 & 4500 gpm) is collected in Appendix A.

Flow	NPSH
2000 gpm	64.1 feet
3000 gpm	41.9 feet
3750 gpm	43.4 feet
4500 gpm	85.9 feet

Table 3: "Recommended NPSH"

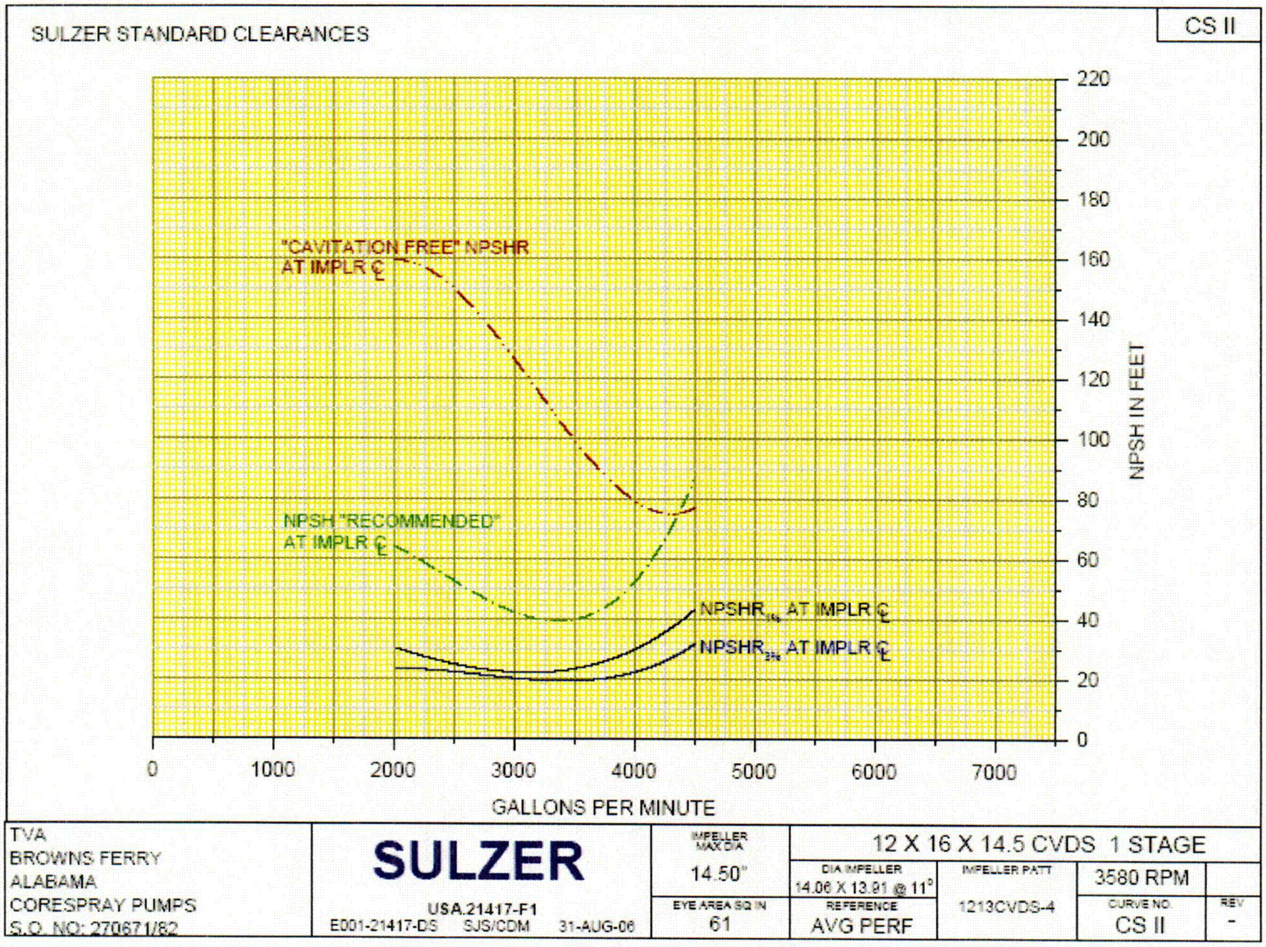
A sample "NPSH-Recommended calculation follows:

"NPSH RECOMMENDED" CALCULATION

Q	=	2000	(GPM)	From performance curve
Q_{BEP}	=	3000	(GPM)	From performance curve
Q/Q_{BEP}	=	0.6667		
S_N	=	1.62		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN}	=	1.16		Function of pumpage and $NPSH_R$(3%)
S_T	=	0.98		Function of temperature and $NPSH_R$(3%)
S_M	=	1		Function of impeller material and pumpage
S_{LG}	=	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
N_{SS}(3%)	=	13890		Suction specific speed at 3%
N_{SS}(REF)	=	9300		Suction specific speed at reference
F_S	=	1.2221		{sqrt(N_{ss}(3%) / N_{ss}(REF))} for water if N_{ss}(3%) > 9300 = N_{ss}(REF)
$NPSH_R$(3%)	=	28.5	(ft)	From performance curve
F_{CT}	=	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by $1/F_{CT}$ to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$	=	64.1	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

Results of both the "NPSH-Recommended" and "Cavitation Free" calculations, as well as the test curves for 1% and 3% head and drop, are plotted on Curve CS II:



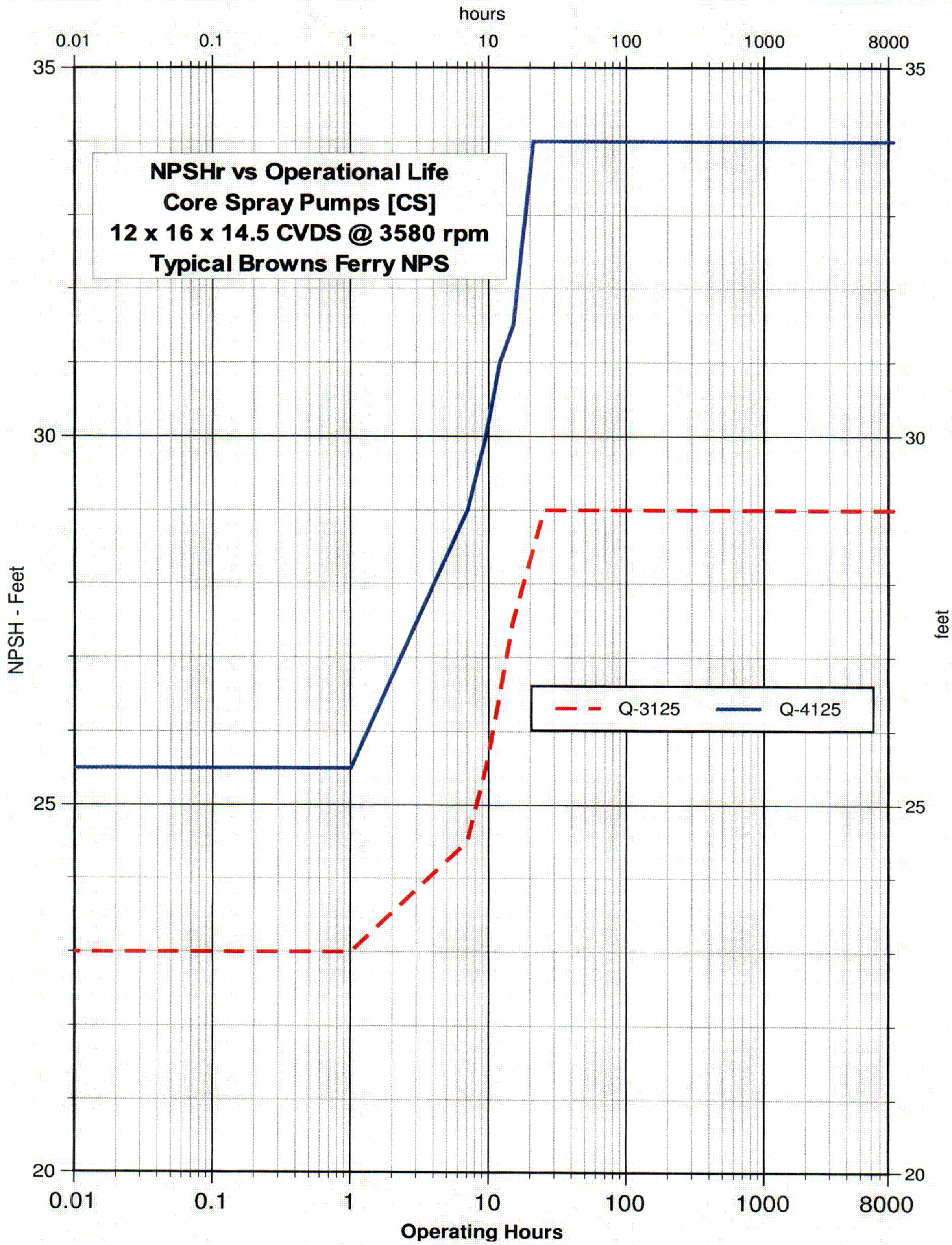
Curve 5: CS Test and Calculated NPSH

"Recommended" NPSH (as plotted) is Sulzer's theoretical recommendation for 40,000 hour life, based on limited cavitation damage to the impeller.

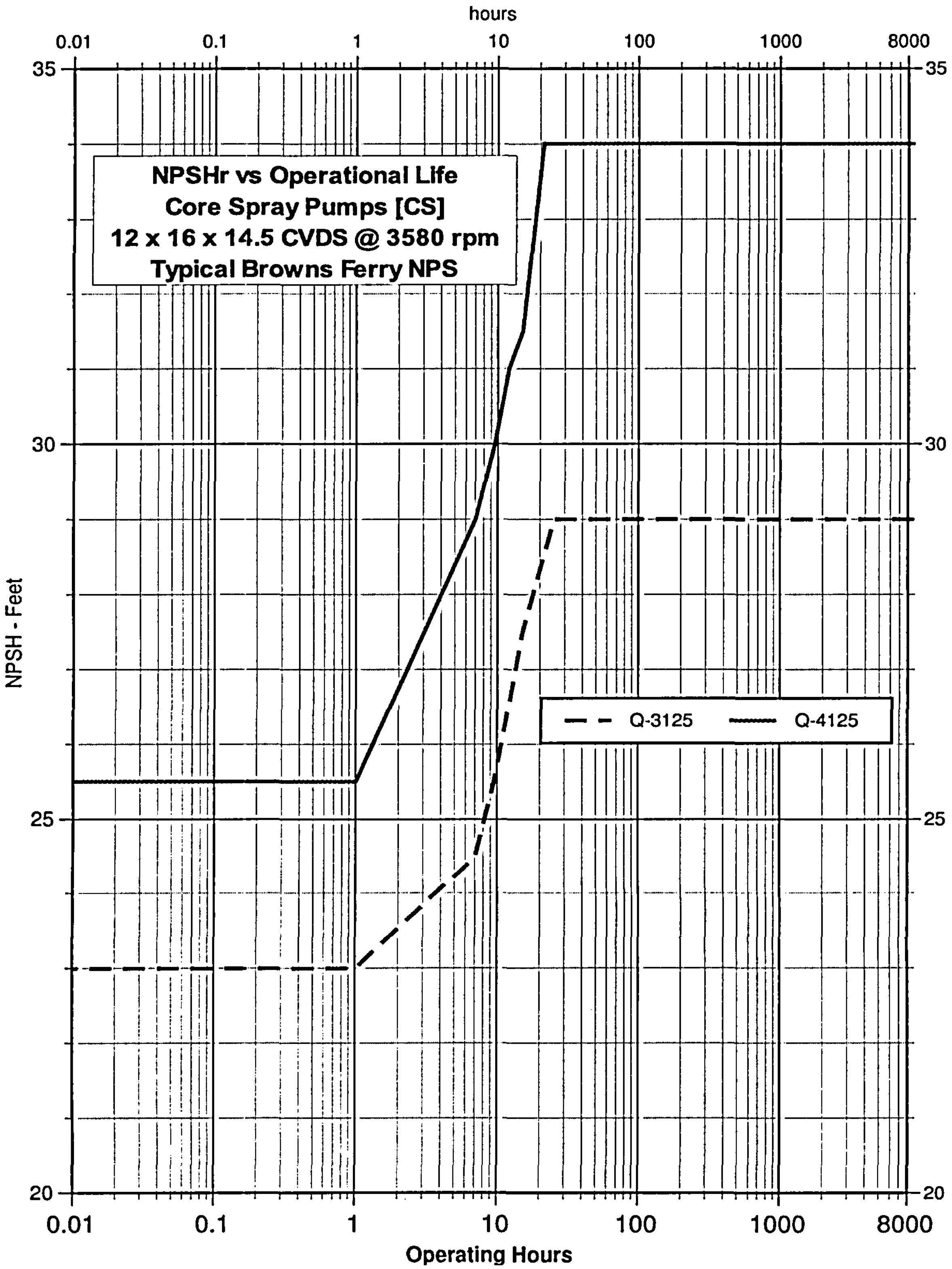
- Comparison to the "cavitation free" curve (Lobanoff & Ross) shows that some cavitation occurs at the "recommended" NPSHr. The slight erosion damage that occurs at this level is the basis for 40,000 hour criterion.

NPSHr curves based on 1% and 3% head loss are from development tests of these impellers, and represent the standard (Hydraulic Institute) method for determining NPSH;

- The same comparison as above demonstrates that slight cavitation will occur at these NPSH values.



Curve 6: CS NPSHr vs. Operating Life



Curve 6: CS NPSHr vs. Operating Life

CS Results and Conclusions:

The subject pumps have been analyzed and found to be suitable for reduced NPSHa operation, as described above, with equipment in "as new" condition.

Curve 6 provides a guideline for operational life vs. NPSHa as a general recommendation for operation when the pumps may be subject to transient events outside of their original scope.

Recommendations are also provided specifically to address the potential transient events provided by TVA Browns Ferry:

- Both potential LOCA events (as tabulated) provide NPSHA values above the minimum established NPSHr (as established in the operating life graph) and are acceptable - i.e. they meet the criteria for determining operational life vs. NPSHa from the graph (curve 6).

Analysis methodology compared test derived NPSHr values with those predicted theoretically. The pumps were evaluated against this comparative basis in order to predict the remaining operational life of a pump in the aftermath of a transient event;

- An 8000 hour post-transient operational lifetime was developed, based on similar cavitation damage to the 40,000 hour "recommended" NPSHr curve; the curve is well supported by the NPSH analysis and mechanical response on the test stand;
  - Graphical NPSHa levels and duration are less severe than that actually experienced on the test stand;
  - Empirical test information has been verified by one of the original test Engineers;
  - Despite NPSH testing that was more severe than the "recommended" curve, post-test inspection revealed no damage.

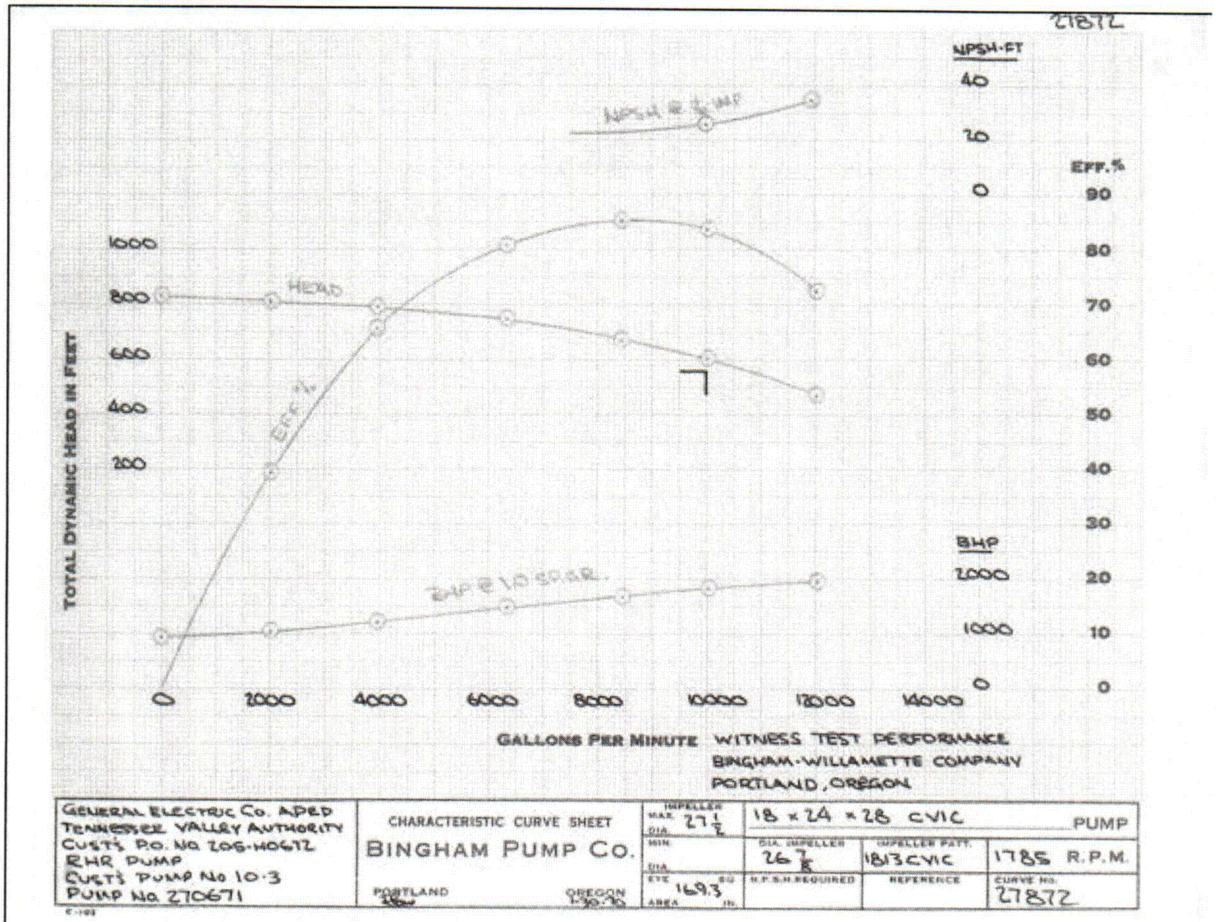
When pumps are in an "undamaged" condition they can be operated in accordance within the NPSHA guidelines provided with the expectation of the 8000 hour life described.

The tabulated transients are acceptable scenarios within the operating recommendations established in curve 6:

- Although vibration and noise may increase as a result of the transients, the units should continue pumping;
- Any non-detrimental impeller wear will be in accordance with the operational life graph.

APPENDIX A - TEST DATA AND CALCULATIONS

RHR Performance Curve:



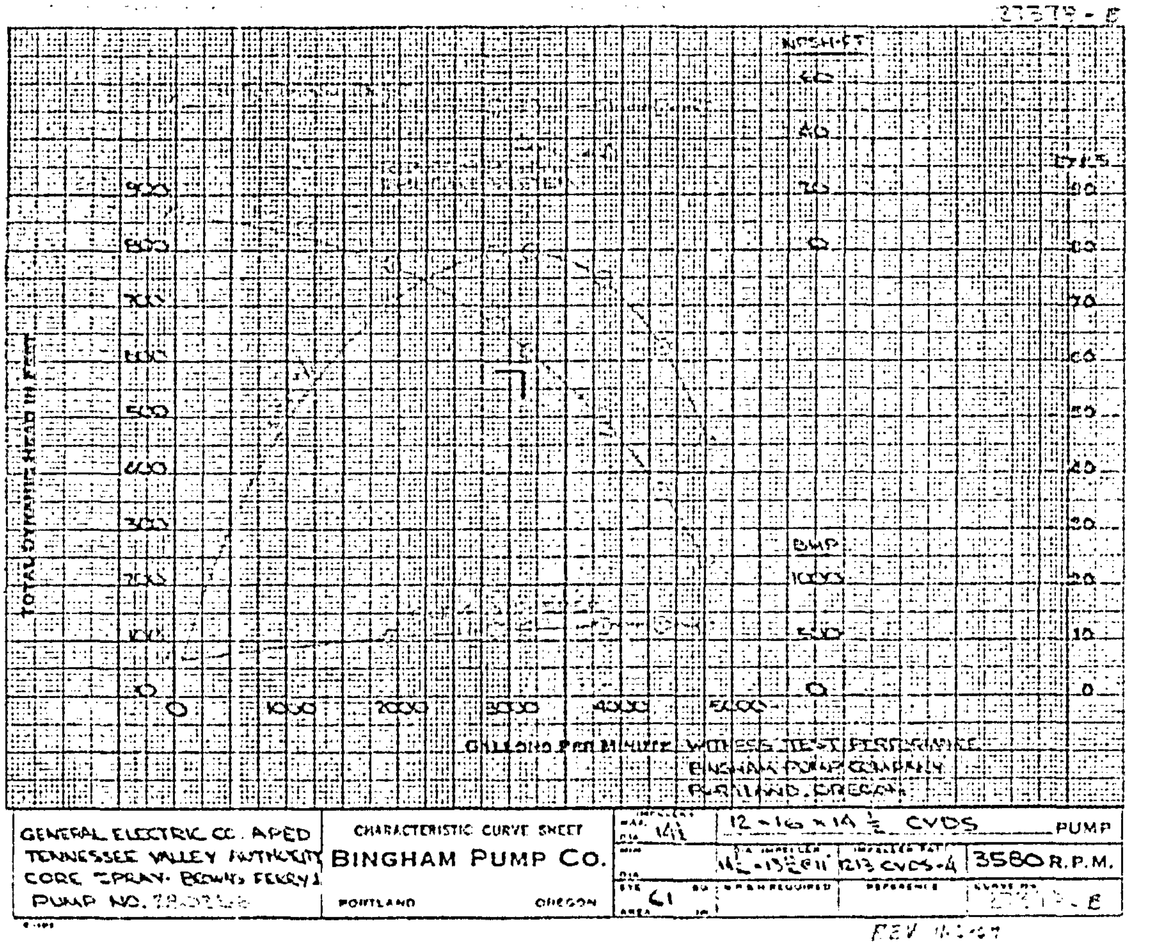
Customer Curve 27872: Typical RHR Witness Test Performance Curve

RHR NPSH TEST Data:

RHR NPSH test data is tabulated as follows:

Test	Flow	NPSH For Various Head Losses			Comments
		1% Loss	3% Loss	6% Loss	
270685-A	7,512	30.0 ft.	15.6 ft.	Untested	Test stopped at 15.6 feet NPSH-
	10,015	30.3 ft.	23.4 ft.	23.2 ft.	7512 gpm drop still only 2.3%.
270685-B	5,004	34.0 ft.	19 ft.	Untested	Test stopped at 19 feet NPSH -
	10,009	37.0 ft.	28.5 ft.	20.8 ft.	5004 gpm drop still only at 2.7%.
270685	5,000	34.2 ft.	19.5	Untested	5000 - 2.5% drop at 19.5 feet.
	7,505	31.0 ft.	15.9 ft.	Untested	
	10,000	31.5 ft.	20.8 ft.	20 ft.	
	12,000	47.5 ft.	40.7 ft.	36.2 ft.	

CS Performance Curve:



Customer Curve 27379-B: Typical CS Witness Test Performance Curve

CS NPSH TEST Data:

CS NPSH test data is tabulated as follows:

Test	Flow	NPSH For Various Head Losses 1% Loss	3% Loss	6% Loss	Comments
270427	3,110	21.3 ft.	21.2 ft.	21.0 ft.	Sharp knee @ 3110. NPSHr must
	4,510	43.0 ft.	31.5 ft.	26.0 ft.	be above knee.
270427	2,013	30.0 ft.	23.0 ft.	Untested	Test stopped - 1.6% @ 23 feet.

RHR Cavitation Free NPSH Calculations:

"CAVITATION FREE" NPSHr CALCULATION				
Q	=	5000	(GPM)	Flow.
N	=	1785	(rpm)	
A-B	=	368.2	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	169.3	(in^2)	Impeller eye area.
B_1	=	11	(deg.)	Blade inlet angle.
$(A-B)/A_E$	=	217.48	(%)	Area ratio (From Lobanoff and Ross).
K_1	=	1.58		From Lobanoff & Ross Figure 8-18.
D_t	=	15.25	(in.)	Impeller eye diameter
C_{M1}	=	9.4802	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	118.87	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
Tan(θ)	=	0.0798		Impeller inlet velocity ratio (C_{M1}/U_T).
θ	=	4.5598	(deg.)	Angle of flow approaching blade.
α	=	6.4402	(deg.)	Angle of incidence (B_1-theta).
K_2	=	0.46		From Lobanoff & Ross Figure 8-19.
C_B	=	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr	=	96.5	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application"
2nd Edition, Gulf Publishing, 1992

RHR PUMP @5000 GPM

"CAVITATION FREE" NPSHr CALCULATION				
Q	=	7000	(GPM)	Flow.
N	=	1785	(rpm)	
A-B	=	368.2	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	169.3	(in^2)	Impeller eye area.
B_1	=	11	(deg.)	Blade inlet angle.
$(A-B)/A_E$	=	217.48	(%)	Area ratio (From Lobanoff and Ross).
K_1	=	1.58		From Lobanoff & Ross Figure 8-18.
D_t	=	15.25	(in.)	Impeller eye diameter
C_{M1}	=	13.272	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	118.87	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
Tan(θ)	=	0.1117		Impeller inlet velocity ratio (C_{M1}/U_T).
θ	=	6.3709	(deg.)	Angle of flow approaching blade.
α	=	4.6291	(deg.)	Angle of incidence (B_1-theta).
K_2	=	0.345		From Lobanoff & Ross Figure 8-19.
C_B	=	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr	=	75.3	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application"
2nd Edition, Gulf Publishing, 1992

RHR PUMP @ 7000 GPM

"CAVITATION FREE" NPSHr CALCULATION

Q	=	9000	(GPM)	Flow.
N	=	1785	(rpm)	
A-B	=	368.2	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	169.3	(in^2)	Impeller eye area.
B_1	=	11	(deg.)	Blade inlet angle.
$(A\text{-}B)/A_E$	=	217.48	(%)	Area ratio (From Lobanoff and Ross).
K_1	=	1.58		From Lobanoff & Ross Figure 8-18.
D_t	=	15.25	(in.)	Impeller eye diameter
C_{M1}	=	17.064	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	118.87	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
$Tan(\theta)$	=	0.1436		Impeller inlet velocity ratio (C_{M1}/U_T).
θ	=	8.1693	(deg.)	Angle of flow approaching blade.
α	=	2.8307	(deg.)	Angle of incidence (B_1-theta).
K_2	=	0.31		From Lobanoff & Ross Figure 8-19.
C_B	=	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr	=	71.2	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application"
2nd Edition, Gulf Publishing, 1992

RHR PUMP @ 9000 GPM

"CAVITATION FREE" NPSHr CALCULATION

Q	=	10500	(GPM)	Flow.
N	=	1785	(rpm)	
A-B	=	368.2	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	169.3	(in^2)	Impeller eye area.
B_1	=	11	(deg.)	Blade inlet angle.
$(A\text{-}B)/A_E$	=	217.48	(%)	Area ratio (From Lobanoff and Ross).
K_1	=	1.58		From Lobanoff & Ross Figure 8-18.
D_t	=	15.25	(in.)	Impeller eye diameter
C_{M1}	=	19.908	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	118.87	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
$Tan(\theta)$	=	0.1675		Impeller inlet velocity ratio (C_{M1}/U_T).
θ	=	9.5077	(deg.)	Angle of flow approaching blade.
α	=	1.4923	(deg.)	Angle of incidence (B_1-theta).
K_2	=	0.31		From Lobanoff & Ross Figure 8-19.
C_B	=	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr	=	74.1	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application"
2nd Edition, Gulf Publishing, 1992

RHR PUMP @ 10500 GPM

"CAVITATION FREE" NPSHr CALCULATION

Q	=	12000	(GPM)	Flow.
N	=	1785	(rpm)	
A-B	=	368.2	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	169.3	(in^2)	Impeller eye area.
B_1	=	11	(deg.)	Blade inlet angle.
$(A\text{-}B)/A_E$	=	217.48	(%)	Area ratio (From Lobanoff and Ross).
K_1	=	1.58		From Lobanoff & Ross Figure 8-18.
D_1	=	15.25	(in.)	Impeller eye diameter
C_{M1}	=	22.753	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	118.87	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
$\tan(\theta)$	=	0.1914		Impeller inlet velocity ratio (C_{M1}/U_T).
θ	=	10.836	(deg.)	Angle of flow approaching blade.
α	=	0.1643	(deg.)	Angle of incidence (B_1-theta).
K_2	=	0.3		From Lobanoff & Ross Figure 8-19.
C_B	=	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr	=	75.3	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application"
2nd Edition, Gulf Publishing, 1992

RHR PUMP @ 12000 GPM

CS Cavitation Free NPSH Calculations:

"CAVITATION FREE" NPSHr CALCULATION

Q	=	2000	(GPM)	Flow.
N	=	3580	(rpm)	
A-B	=	122.4	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	61.04	(in^2)	Impeller eye area.
B_1	=	16	(deg.)	Blade inlet angle.
$(A-B)/A_E$	=	200.52	(%)	Area ratio (From Lobanoff and Ross).
K_1	=	1.48		From Lobanoff & Ross Figure 8-18.
D_t	=	6.875	(in.)	Impeller eye diameter
C_{M1}	=	10.518	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	107.48	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
$Tan(\theta)$	=	0.0979		Impeller inlet velocity ratio (C_{M1}/U_T).
θ	=	5.5891	(deg.)	Angle of flow approaching blade.
α	=	10.411	(deg.)	Angle of incidence (B_1-theta).
K_2	=	0.93		From Lobanoff & Ross Figure 8-19.
C_B	=	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr	=	159.0	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application" 2nd Edition, Gulf Publishing, 1992

CS PUMP @ 2000 GPM

"CAVITATION FREE" NPSHr CALCULATION

Q	=	3000	(GPM)	Flow.
N	=	3580	(rpm)	
A-B	=	122.4	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	61.04	(in^2)	Impeller eye area.
B_1	=	16	(deg.)	Blade inlet angle.
$(A-B)/A_E$	=	200.52	(%)	Area ratio (From Lobanoff and Ross).
K_1	=	1.48		From Lobanoff & Ross Figure 8-18.
D_t	=	6.875	(in.)	Impeller eye diameter
C_{M1}	=	15.777	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	107.48	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
$Tan(\theta)$	=	0.1468		Impeller inlet velocity ratio (C_{M1}/U_T).
θ	=	8.3507	(deg.)	Angle of flow approaching blade.
α	=	7.6493	(deg.)	Angle of incidence (B_1-theta).
K_2	=	0.71		From Lobanoff & Ross Figure 8-19.
C_B	=	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr	=	126.3	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application" 2nd Edition, Gulf Publishing, 1992

CS PUMP @ 3000 GPM

"CAVITATION FREE" NPSHr CALCULATION

Symbol	=	Value	Unit	Description
Q	=	3750	(GPM)	Flow.
N	=	3580	(rpm)	
A-B	=	122.4	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	61.04	(in^2)	Impeller eye area.
B_1	=	16	(deg.)	Blade inlet angle.
$(A\text{-}B)/A_E$	=	200.52	(%)	Area ratio (From Lobanoff and Ross).
K_1	=	1.48		From Lobanoff & Ross Figure 8-18.
D_t	=	6.875	(in.)	Impeller eye diameter
C_{M1}	=	19.721	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	107.48	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
$Tan(\theta)$	=	0.1835		Impeller inlet velocity ratio (C_{M1}/U_T).
θ	=	10.397	(deg.)	Angle of flow approaching blade.
α	=	5.6027	(deg.)	Angle of incidence (B_1-theta).
K_2	=	0.46		From Lobanoff & Ross Figure 8-19.
C_B	=	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr	=	87.6	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application"
2nd Edition, Gulf Publishing, 1992

CS PUMP @ 3750 GPM

"CAVITATION FREE" NPSHr CALCULATION

Symbol	=	Value	Unit	Description
Q	=	4500	(GPM)	Flow.
N	=	3580	(rpm)	
A-B	=	122.4	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	61.04	(in^2)	Impeller eye area.
B_1	=	16	(deg.)	Blade inlet angle.
$(A\text{-}B)/A_E$	=	200.52	(%)	Area ratio (From Lobanoff and Ross).
K_1	=	1.48		From Lobanoff & Ross Figure 8-18.
D_t	=	6.875	(in.)	Impeller eye diameter
C_{M1}	=	23.665	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	107.48	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
$Tan(\theta)$	=	0.2202		Impeller inlet velocity ratio (C_{M1}/U_T).
θ	=	12.417	(deg.)	Angle of flow approaching blade.
α	=	3.5826	(deg.)	Angle of incidence (B_1-theta).
K_2	=	0.37		From Lobanoff & Ross Figure 8-19.
C_B	=	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr	=	76.7	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application"
2nd Edition, Gulf Publishing, 1992

CS PUMP @ 4500 GPM

RHR Recommended NPSH Calculations:

"NPSH RECOMMENDED" CALCULATION

Q =	5000	(GPM)	From performance curve
Q_{BEP} =	8600	(GPM)	From performance curve
Q/Q_{BEP} =	0.5814		
S_N =	1.84		{NPSH$_R$ - 0% / NPSH$_R$-3%} = Function of Q/Q_{BEP}
S_{EN} =	1.12		Function of pumpage and NPSH$_R$(3%)
S_T =	0.97		Function of temperature and NPSH$_R$(3%)
S_M =	1		Function of impeller material and pumpage
S_{LG} =	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
N_{SS}(3%) =	13390		Suction specific speed at 3%
N_{SS}(REF) =	9300		Suction specific speed at reference
F_S =	1.1999		{sqrt(N_{ss}(3%) / N_{ss}(REF))} for water if N_{ss}(3%) > 9300 = N_{ss}(REF)
NPSH$_R$(3%) =	19	(ft)	From performance curve
F_{CT} =	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by 1/F_{CT} to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
NPSH$_{REC}$ =	45.6	(ft)	NPSH$_{REC}$ = S_N x S_{EN} x S_T x S_m x S_{LG} x F_s x NPSH$_R$(3%) x F_{CT}

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

RHR PUMP @5000 GPM

"NPSH RECOMMENDED" CALCULATION

Q =	7000	(GPM)	From performance curve
Q_{BEP} =	8600	(GPM)	From performance curve
Q/Q_{BEP} =	0.814		
S_N =	1.35		{NPSH$_R$ - 0% / NPSH$_R$-3%} = Function of Q/Q_{BEP}
S_{EN} =	1.11		Function of pumpage and NPSH$_R$(3%)
S_T =	0.97		Function of temperature and NPSH$_R$(3%)
S_M =	1		Function of impeller material and pumpage
S_{LG} =	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
N_{SS}(3%) =	13390		Suction specific speed at 3%
N_{SS}(REF) =	9300		Suction specific speed at reference
F_S =	1.1999		{sqrt(N_{ss}(3%) / N_{ss}(REF))} for water if N_{ss}(3%) > 9300 = N_{ss}(REF)
NPSH$_R$(3%) =	18.3	(ft)	From performance curve
F_{CT} =	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by 1/F_{CT} to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
NPSH$_{REC}$ =	31.9	(ft)	NPSH$_{REC}$ = S_N x S_{EN} x S_T x S_m x S_{LG} x F_s x NPSH$_R$(3%) x F_{CT}

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

RHR PUMP @ 7000 GPM

"NPSH RECOMMENDED" CALCULATION

Q =	9000	(GPM)	From performance curve
Q_{BEP} =	8600	(GPM)	From performance curve
Q/Q_{BEP} =	1.0465		
S_N =	1.2		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN} =	1.11		Function of pumpage and $NPSH_R$(3%)
S_T =	0.97		Function of temperature and $NPSH_R$(3%)
S_M =	1		Function of impeller material and pumpage
S_{LG} =	1.2	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
N_{SS}(3%) =	13390		Suction specific speed at 3%
N_{SS}(REF) =	9300		Suction specific speed at reference
F_S =	1.1999		{sqrt(N_{ss}(3%) / N_{ss}(REF))} for water if N_{ss}(3%) > 9300 = N_{ss}(REF)
$NPSH_R$(3%) =	18	(ft)	From performance curve
F_{CT} =	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by 1/F_{CT} to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$ =	33.5	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

RHR PUMP @ 9000 GPM

"NPSH RECOMMENDED" CALCULATION

Q =	10500	(GPM)	From performance curve
Q_{BEP} =	8600	(GPM)	From performance curve
Q/Q_{BEP} =	1.2209		
S_N =	1.35		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN} =	1.13		Function of pumpage and $NPSH_R$(3%)
S_T =	0.98		Function of temperature and $NPSH_R$(3%)
S_M =	1		Function of impeller material and pumpage
S_{LG} =	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
N_{SS}(3%) =	13390		Suction specific speed at 3%
N_{SS}(REF) =	9300		Suction specific speed at reference
F_S =	1.1999		{sqrt(N_{ss}(3%) / N_{ss}(REF))} for water if N_{ss}(3%) > 9300 = N_{ss}(REF)
$NPSH_R$(3%) =	23.9	(ft)	From performance curve
F_{CT} =	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by 1/F_{CT} to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$ =	42.9	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

RHR PUMP @ 10500 GPM

"NPSH RECOMMENDED" CALCULATION

Q	=	12000	(GPM)	From performance curve
Q_{BEP}	=	8600	(GPM)	From performance curve
Q/Q_{BEP}	=	1.3953		
S_N	=	1.74		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN}	=	1.22		Function of pumpage and $NPSH_R$(3%)
S_T	=	0.98		Function of temperature and $NPSH_R$(3%)
S_M	=	1		Function of impeller material and pumpage
S_{LG}	=	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
N_{SS}(3%)	=	13390		Suction specific speed at 3%
N_{SS}(REF)	=	9300		Suction specific speed at reference
F_S	=	1.1999		{sqrt(N_{ss}(3%) / N_{ss}(REF))} for water if N_{ss}(3%) > 9300 = N_{ss}(REF)
$NPSH_R$(3%)	=	40	(ft)	From performance curve
F_{CT}	=	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by 1/F_{CT} to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$	=	99.8	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

RHR PUMP @ 11500 GPM

CS Recommended NPSH Calculations:

"NPSH RECOMMENDED" CALCULATION

Q =	2000	(GPM)	From performance curve
Q_{BEP} =	3000	(GPM)	From performance curve
Q/Q_{BEP} =	0.6667		
S_N =	1.62		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN} =	1.16		Function of pumpage and $NPSH_R(3\%)$
S_T =	0.98		Function of temperature and $NPSH_R(3\%)$
S_M =	1		Function of impeller material and pumpage
S_{LG} =	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
$N_{SS}(3\%)$ =	13890		Suction specific speed at 3%
$N_{SS}(REF)$ =	9300		Suction specific speed at reference
F_S =	1.2221		{sqrt($N_{ss}(3\%)$ / $N_{ss}(REF)$)} for water if $N_{ss}(3\%)$ > 9300 = $N_{ss}(REF)$
$NPSH_R(3\%)$ =	28.5	(ft)	From performance curve
F_{CT} =	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by $1/F_{CT}$ to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$ =	64.1	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

CS PUMP @ 2000 GPM

"NPSH RECOMMENDED" CALCULATION

Q =	3000	(GPM)	From performance curve
Q_{BEP} =	3000	(GPM)	From performance curve
Q/Q_{BEP} =	1		
S_N =	1.2		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN} =	1.13		Function of pumpage and $NPSH_R(3\%)$
S_T =	0.98		Function of temperature and $NPSH_R(3\%)$
S_M =	1		Function of impeller material and pumpage
S_{LG} =	1.2	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
$N_{SS}(3\%)$ =	13890		Suction specific speed at 3%
$N_{SS}(REF)$ =	9300		Suction specific speed at reference
F_S =	1.2221		{sqrt($N_{ss}(3\%)$ / $N_{ss}(REF)$)} for water if $N_{ss}(3\%)$ > 9300 = $N_{ss}(REF)$
$NPSH_R(3\%)$ =	21.5	(ft)	From performance curve
F_{CT} =	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by $1/F_{CT}$ to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$ =	41.9	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

CS PUMP @ 3000 GPM

"NPSH RECOMMENDED" CALCULATION

Q	=	3750	(GPM)	From performance curve
Q_{BEP}	=	3000	(GPM)	From performance curve
Q/Q_{BEP}	=	1.25		
S_N	=	1.4		$\{NPSH_R - 0\% / NPSH_R\text{-}3\%\}$ = Function of Q/Q_{BEP}
S_{EN}	=	1.13		Function of pumpage and $NPSH_R(3\%)$
S_T	=	0.975		Function of temperature and $NPSH_R(3\%)$
S_M	=	1		Function of impeller material and pumpage
S_{LG}	=	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
$N_{SS}(3\%)$	=	13890		Suction specific speed at 3%
$N_{SS}(REF)$	=	9300		Suction specific speed at reference
F_S	=	1.2221		$\{sqrt(N_{ss}(3\%) / N_{ss}(REF))\}$ for water if $N_{ss}(3\%) > 9300 = N_{ss}(REF)$
$NPSH_R(3\%)$	=	23	(ft)	From performance curve
F_{CT}	=	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by $1/F_{CT}$ to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$	=	43.4	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

CS PUMP @ 3750 GPM

"NPSH RECOMMENDED" CALCULATION

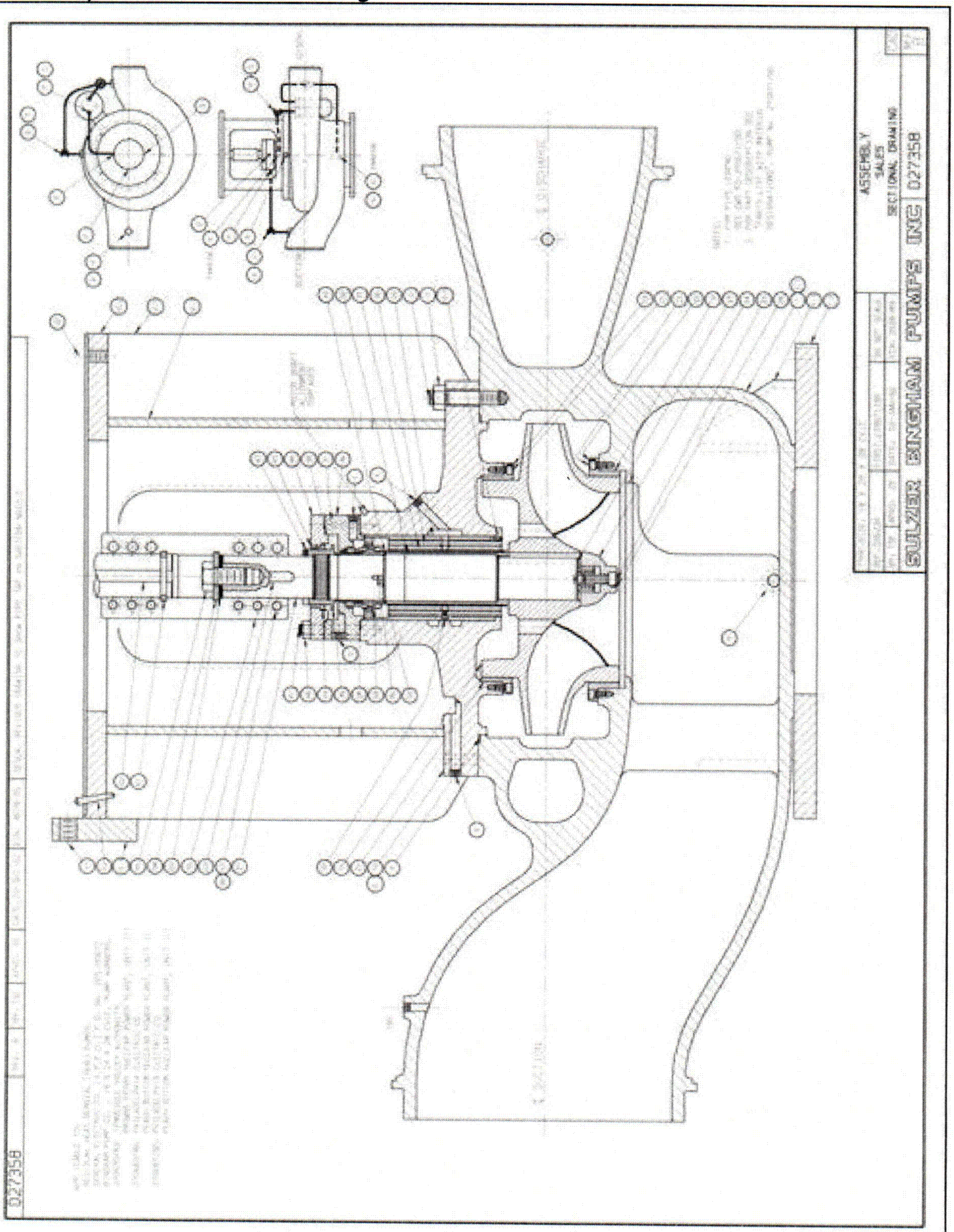
Q	=	4500	(GPM)	From performance curve
Q_{BEP}	=	3000	(GPM)	From performance curve
Q/Q_{BEP}	=	1.5		
S_N	=	1.93		$\{NPSH_R - 0\% / NPSH_R\text{-}3\%\}$ = Function of Q/Q_{BEP}
S_{EN}	=	1.18		Function of pumpage and $NPSH_R(3\%)$
S_T	=	0.98		Function of temperature and $NPSH_R(3\%)$
S_M	=	1		Function of impeller material and pumpage
S_{LG}	=	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
$N_{SS}(3\%)$	=	13890		Suction specific speed at 3%
$N_{SS}(REF)$	=	9300		Suction specific speed at reference
F_S	=	1.2221		$\{sqrt(N_{ss}(3\%) / N_{ss}(REF))\}$ for water if $N_{ss}(3\%) > 9300 = N_{ss}(REF)$
$NPSH_R(3\%)$	=	31.5	(ft)	From performance curve
F_{CT}	=	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by $1/F_{CT}$ to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$	=	85.9	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

CS PUMP @ 4500 GPM

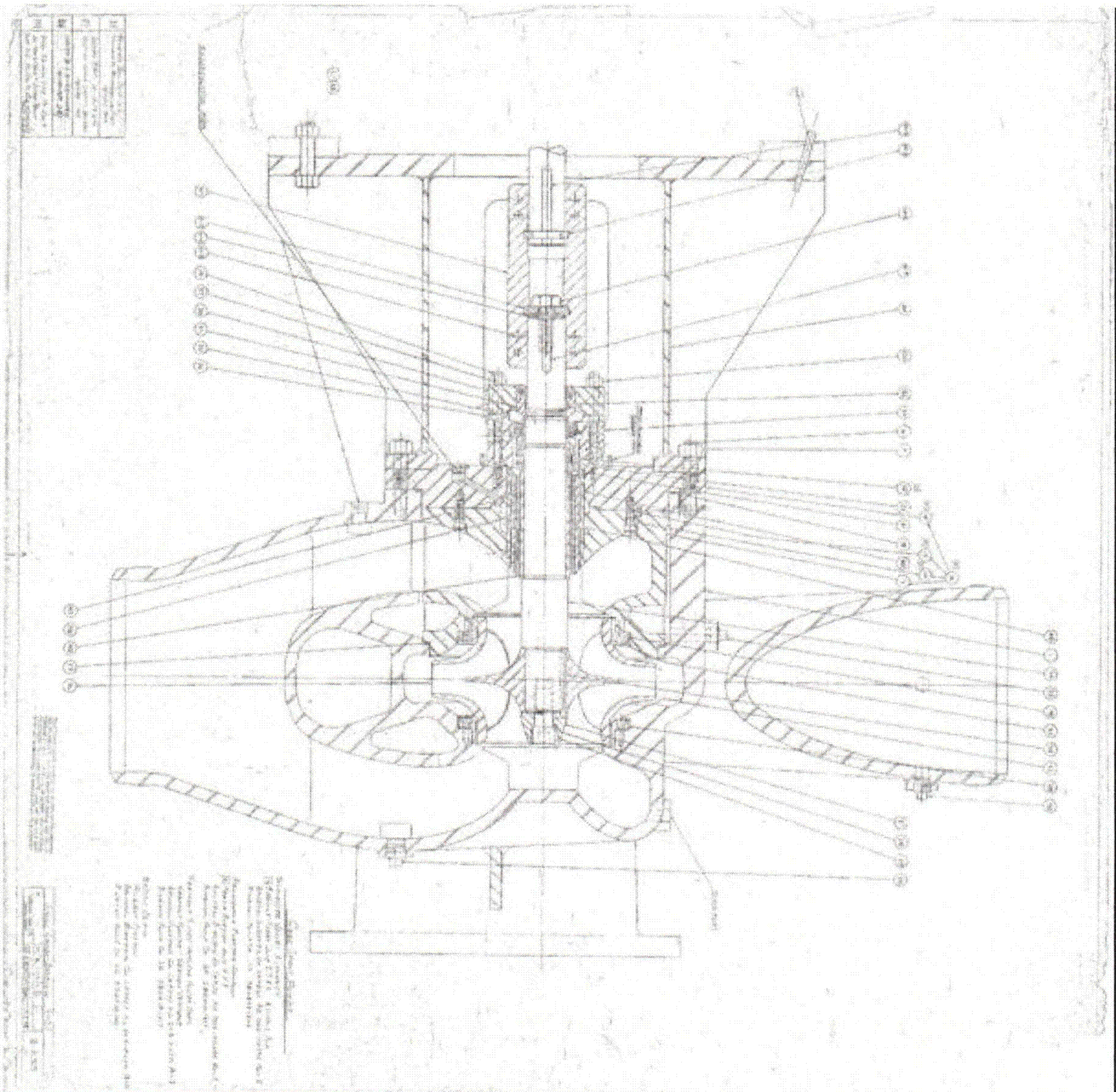
APPENDIX B - PUMP CROSS SECTIONS

RHR Pump Cross Sectional Drawing:



Sulzer Drawing D27358: RHR Pump Cross Sectional Drawing

CS Pump Cross Sectional Drawing:



Sulzer Drawing Z6315: CS Pump Cross Sectional Drawing

SULZER

DOCUMENT REVISION RECORD

Pump Serial Number: Report no. E12.5.1296

Rev. No.	Issue Date	ECR No.	Location	Description (Field Engineering Assistance Request No.) (Parts / Repair Order No.) By/Appr.
1	10/05/2006	140535	pp. 11/12	RHR Conclusion: Distinguished between "non-detrimental impeller wear" and "detrimental damage". SJS/DS
1	10/05/2006	140535	Page 19	CS Conclusion: changed "damage" to "non-detrimental impeller wear". SJS/DS

Page 1 of 1

DOC REV.DOC

ENCLOSURE 2
TENNESSEE VALLEY AUTHORITY
BROWNS FERRY NUCLEAR PLANT (BFN)
UNITS 1, 2, AND 3

TECHNICAL SPECIFICATIONS (TS) CHANGES TS-431 AND TS-418 -
EXTENDED POWER UPRATE (EPU) -
NPSH REQUIREMENTS - PUMP VENDOR REPORT
(TAC NOS. MC3812, MC3743, AND MC3744)

NPSH TRANSIENT STUDY, REV. 0 (Draft)

SULZER

QUALITY LEVEL
☐ Direct
☐ Indirect

SULZER PUMPS (US) INC. DOCUMENT

DOC. NO: **E12.5.1296**
ORDER NO: **E-001-21417**

TITLE: **NPSH Transient Study**
RHR and Core Spray Pumps

ASME CODE SECTION
CLASS NO.
CODE EDITION (YEAR)
SEASON YEAR

CUSTOMER **TVA**

PROJECT **Browns Ferry NPS**

CUSTOMER P.O. NO. ______ CONTRACT NUMBER

SPECIFICATION NO. ______ ITEM / TAG NUMBER

Draft - Superceded

CUSTOMER APPROVAL NUMBER:

SPACE FOR CUSTOMER APPROVAL STAMP
(when applicable/available)

CUSTOMER APPROVAL REQUIREMENT

☒ Yes ☐ No ☐ Information Only

CERTIFIED AS A VALID SULZER PUMPS (US) INC. DOCUMENT

☐ For Outside Vendor
☒ For Manufacture at Sulzer Pumps (US) Inc.
☐ Risk Release Inspection Report # ______
☐ Other (specify) ______

APPROVALS (SIGNATURE)		Date
Engineering	Don Spencer	9/13/06

CERTIFICATION (when applicable)

This Document is certified to be in compliance with THE APPLICABLE PURCHASE ORDER, SPECIFICATIONS, PROCEDURES, AND ADDITIONAL REQUIREMENTS LISTED IN THE APPENDICES.

______
Professional Engineer

______ ______
State Registration No.

Date ______

Originating Dept: **Advance Engineering**

By: Steven Schoenbrun
Steven Schoenbrun

Title: **Project Engineer**

Initial Date: **9/13/2006**

APPLICABLE S.O. NUMBERS:

DOCUMENT IDENTIFICATION	Rev.
E12.5.1296	**0**

PURPOSE: To review existing pumps to determine if they are capable of meeting new transient NPSHa conditions and estimate the expected pump life based on 8000 hours and limited NPSH values. Minimum flow evaluation is not a requirement of this study.

KNOWN: The existing pumps are RHR [Residual Heat Removal] and CS [Core Spray] SULZER serial numbers: SO270671/82 and SO280253/64. Pumps were originally supplied to General Electric Company.

RHR pumps [SO 270671/82] are SULZER model 18x24x28 CVIC:

- Pumps are single suction vertical inline type with welded inlet and outlet connections;
- Units are rated 10000 gpm @ 560 feet on ambient water;
- Electric motors are rated 2000 hp @ 1785 rpm on 4000/3/60 Hertz power;
- Estimated weight is 20000 lbs with a height of 150 inches from the foundation.

Construction Features are as follows:

- Cross Section D27358 with parts list;
- Pump case is carbon steel;
- Pump rotor is chrome steel and the impeller has integral wear rings;
- Pump shaft is connected to the electric motor via a rigid coupling;
- Pump thrust is taken in the driver;

Available information and test data:

- Certified performance tests 27872, 27935, 27811, 27936, 27801-04, 28267 and 28941-43;
- Internal SULZER tests for information and development, note these are not available for publication;
- Original test records have been lost or archived at a site unknown at present;
- Existing records limited to internal hardcopies and microfiche;
- One of the original test engineers is still with SULZER in a similar capacity.

Core Spray (CS) pumps [SO 280253/64] are SULZER model 12x16x14.5 CVDS:

- Pumps are double suction vertical inline type with welded inlet and outlet connections;
- Units are rated 3125 gpm @ 582 feet on 210 degree F water;
- Electric motors are rated 600 hp @ 3580 rpm on 4000/3/60 Hertz power;
- Estimated weight is 8730 lbs with a height of 112 inches from the foundation.

Construction Features are as follows:

- Cross Section Z6315 and parts list;
- Pump case is carbon steel;
- Pump rotor assembly is chrome steel and the impeller has integral wear rings;
- Pump shaft is connected to the electric motor via a rigid coupling;
- Pump thrust is taken in the driver;

Available information and test data;

- Certified performance tests 27376B-79B, 27970-73 and 28022-25;
- Internal SULZER tests for information and development, note these are not available for publication;
- Original test records have been lost or archived at a site unknown at present;
- Existing records limited to internal hardcopies and microfiche;
- One of the original test engineers is still with SULZER in a similar capacity.

Both RHR and CS pumps are being evaluated for their response to potential transient conditions that may occur due to various system scenarios. TVA Browns Ferry has provided system transient scenarios; data includes flows, times and available NPSHa data for both the RHR and Core Spray Pumps, as follows:

Event	Duration	RHR Pump Flow	RHR Min NPSHA	CS Pump Flow	CS Min NPSHA
ST-LOCA	<10 min	11500 gpm (broken loop)	26.4 ft	4125 gpm	26.5 ft
		10500 gpm (intact loop)	29.4 ft		
LT-LOCA	>10 min to 24 hrs	6500 gpm	38.5 ft	3125 gpm	35.1 ft
ATWS	8 hrs	6500 gpm	24.3 ft	none	none
APP R	60 hrs	9000 gpm	26.9 ft	none	none
SBO	24 hrs	6500 gpm	32.2 ft	none	none

Table 1: Potential Transient Events

Methodology (RHR & CS Pumps): This study utilizes empirical and theoretical NPSHA/R data and calculations to make NPSHr recommendations for transient responses.

For both RHR & CS pumps, test and order related data/information was collected for evaluation:

- All certified tests were collected;
- Available development/model test results were located and copied;
- Product test records/notes were collected;
- Individual Bill of Materials were copied;
- Field records were assembled.

As a basis for evaluation, certified witness test performance curves, for both pump sets, were averaged to produce an "average performance" for each pump type. Development test data was used to create NPSHr curves, at 1% and 3% head loss, for both models.

Theoretical NPSHr calculations utilize Sulzer's current standard for recommended (40k hours at BEP) NPSHr and "cavitation free" NPSHr from "Centrifugal Pumps: Design & Application", 2nd Edition, Lobanoff & Ross, Gulf Publishing, 1992.

Minimum NPSHa vs. NPSHr evaluation is accomplished by plotting/comparison of calculated and empirical NPSH data to determine hydraulic/mechanical implications of transient events.

Technical Background for Analyzing NPSH test data: To evaluate the response of a pump to a transient event, and make a meaningful prediction for post event operating life, the behavior of the pump in the NPSH "knee" must be thoroughly understood.

NPSH performance assessments are related to the knees of the plotted NPSH data. Plots of NPSH vs. head (from NPSH test data) as the NPSH is reduced incrementally from ample suction pressure, will show that the head responds by staying constant, varying or dropping:

- The "knee" is the area on an NPSH test curve where the head degrades more rapidly before falling off totally.

The shape of an NPSH knee is an important factor in recommending minimum NPSHr values. A knee may have a sharp or more rounded profile, each with its own implications:

- When the knee is sharp, various head drop comparisons (1%, 3%, 6%, etc.) occur at about the same NPSH value.
  - *Operation near a sharp knee is not recommended.*
- In a well-rounded knee the various head drop comparisons occur over a wider range of NPSH values. The wider range of response allows operating recommendations with less margin.

NPSH data for both pump models is from development testing. Aspects of data collection include:

- Several test points are required to define a knee.
- Occasionally test stand limitations do not allow suppression to a low enough NPSH to completely define the knee - i.e. the 3%, 6%, drop-off points may not be captured on test. Under some conditions these tests can still be used to evaluate acceptable operation in response to a transient event.
  - If the head remains stable below the minimum proposed transient event NPSHA, the test is still a good validation tool - i.e. while the head may not have degraded enough to define the knee ,in response to a lowering of the NPSH (a true "knee" has not been established), the stable head response shows that the pump is suitable for operation.

Modeling from similar pumps is another long established pump industry method with a basis in ANSI/Hydraulic Institute, ASME and other standards. Size factored NPSHr values (from models of similar pumps) are commonly used to make NPSH recommendations.

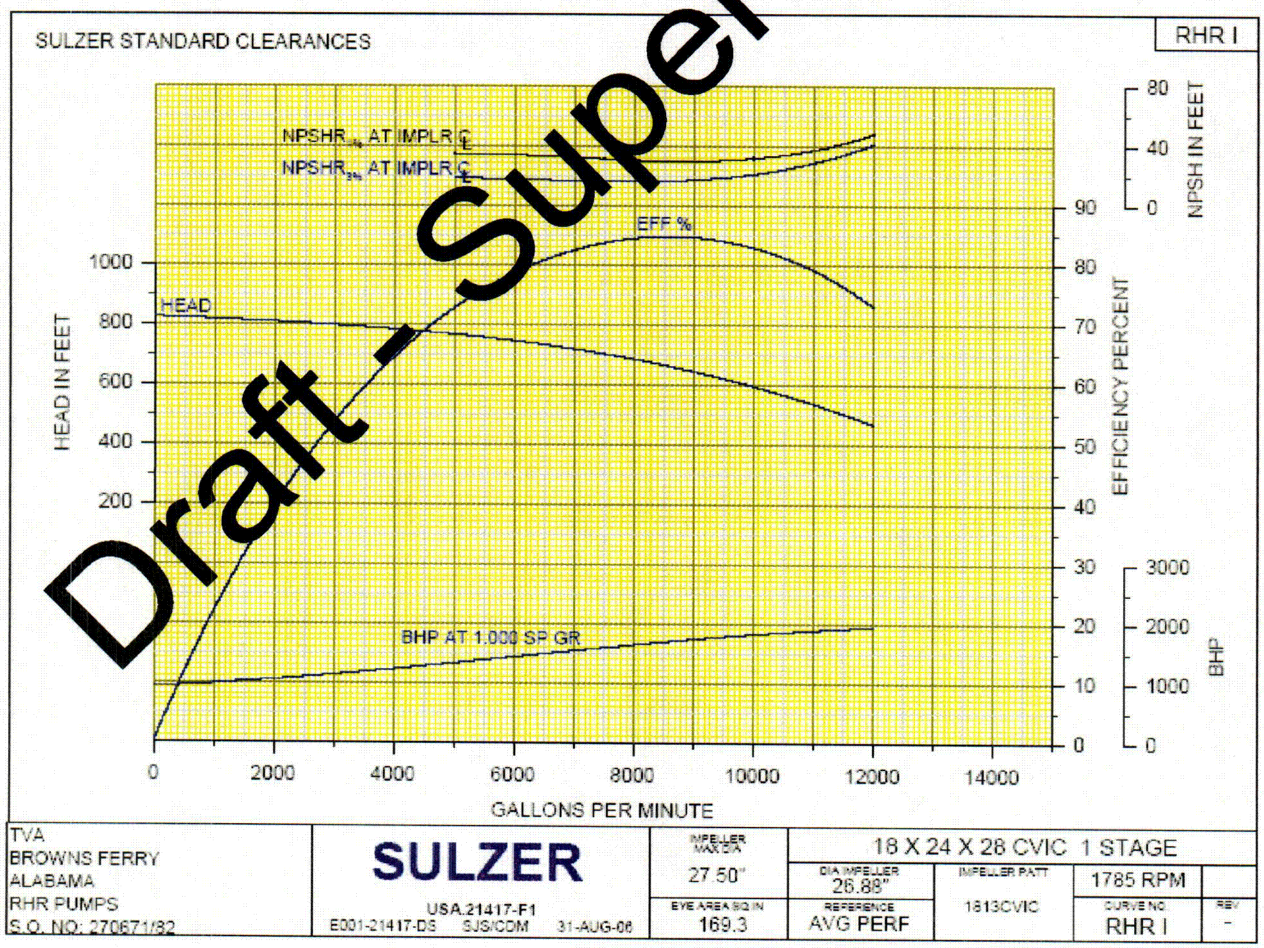
- Modeling has not been used in this study.

RHR Pump NPSH Assessment and Analysis: Test and calculated NPSH values are analyzed and compared against the proposed transient events.

Performance curves 27935, 27811, 27936, 27801-04, 28267 and 28941-43 have been averaged relative to head and efficiency vs. flow and plotted as curve RHR I. For the basis of NPSH assessment, test points for NPSHR-3% and NPSHR-1% (4 capacities) have also been plotted on curve RHR I based on development testing (NPSH test data has been tabulated in Appendix A).

Specific speed (N_S) and Suction Specific Speed (N_{SS}) for both 3% and 1% head loss are as follows:

- $N_S = 1785*8600^{1/2}/656^{3/4} = 1277$
- $N_{SS\text{-}3\%} = 1785*8600^{1/2}/16^{3/4} = 20692$
- $N_{SS\text{-}1\%} = 1785*8600^{1/2}/29.5^{3/4} = 13077$



Curve 1: RHR Average Performance

Results of the "Cavitation Free" NPSHR calculation (based on Lobanoff and Ross) are as per the following table.

Flow	NPSH
5000 gpm	96.5 feet
7000 gpm	75.3 feet
9000 gpm	71.2 feet
10500 gpm	74.1 feet
12000 gpm	75.3 feet

Table 2: RHR "Cavitation Free" NPSH

The calculation set (5000, 7000, 9000, 10500 & 12000 gpm) is collected in Appendix A. A sample calculation follows:

"CAVITATION FREE" NPSHr CALCULATION

Q	=	5000	(GPM)	Flow.
N	=	1785	(rpm)	
A-B	=	368.2	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	169.3	(in^2)	Impeller eye area.
B_1	=	11	(deg.)	Blade inlet angle.
$(A-B)/A_E$	=	217.48	(%)	Area ratio (from Lobanoff and Ross).
K_1	=	1.58		From Lobanoff & Ross Figure 8-18.
D_t	=	15.25	(in.)	Impeller eye diameter
C_{M1}	=	9.4802	(ft/sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	118.[illegible]	(ft/sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
$Tan(\theta)$	=	0.[illegible]798		Impeller inlet velocity ratio (C_{M1}/U_T).
θ	=	[illegible]5598	(deg.)	Angle of flow approaching blade.
α	=	6.4402	(deg.)	Angle of incidence (B_1-theta).
K_2	=	0.46		From Lobanoff & Ross Figure 8-19.
C_B	=	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr	=	96.5	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application"
2nd Edition, Gulf Publishing, 1992

"NPSH-Recommended" calculation results are tabulated below. The calculation set (5000, 7000, 9000, 10500 & 12000 gpm) is collected in Appendix A.

Flow	NPSH
5000 gpm	45.6 feet
7000 gpm	31.9 feet
9000 gpm	33.5 feet
10500 gpm	42.9 feet
12000 gpm	99.8 feet

Table 3: RHR "Recommended NPSH"

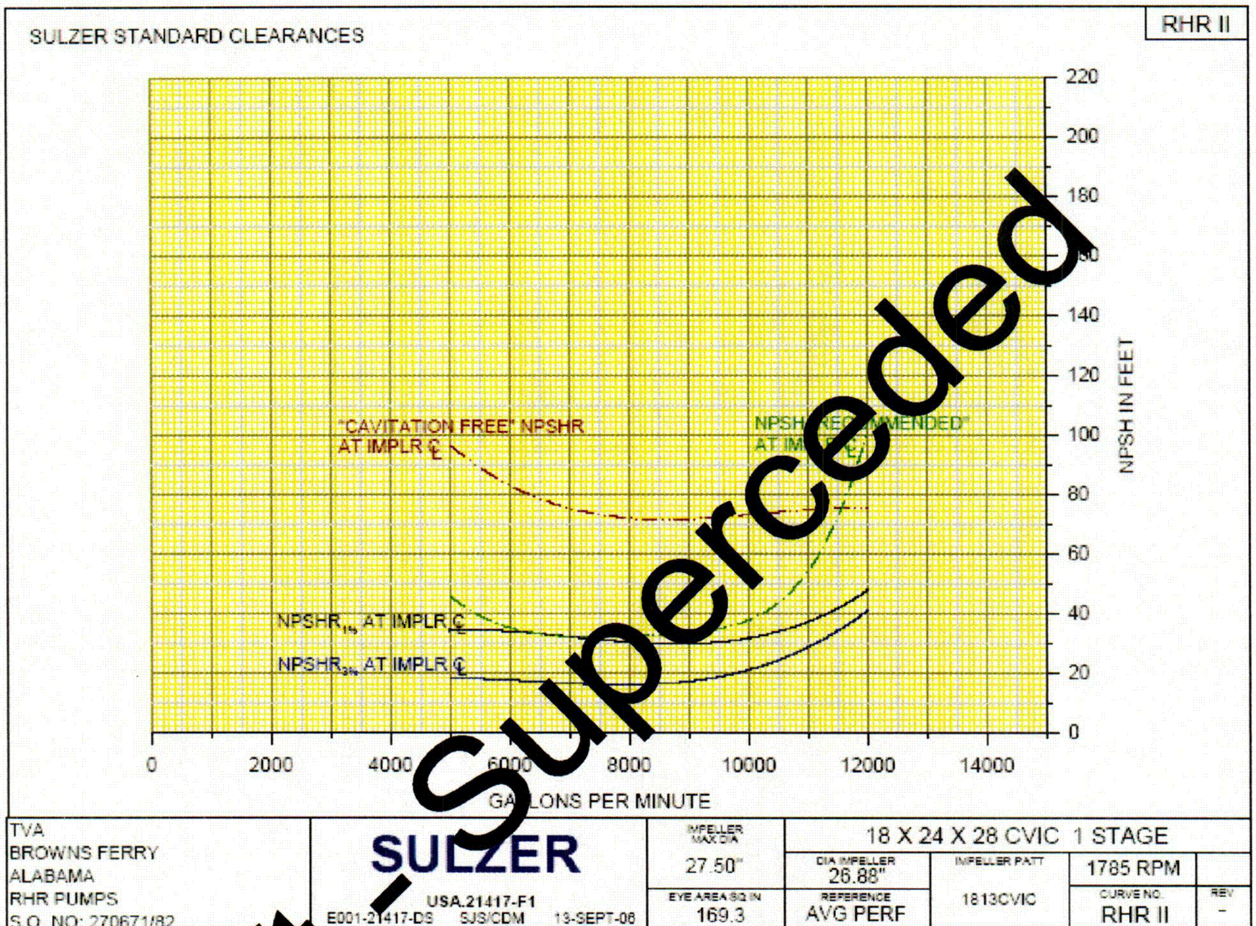
A sample "NPSH-Recommended calculation follows:

"NPSH RECOMMENDED" CALCULATION

Q =	5000	(GPM)	From performance curve
Q_{BEP} =	8600	(GPM)	From performance curve
Q/Q_{BEP} =	0.5814		
S_N =	1.84		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN} =	1.12		Function of pumpage and $NPSH_R(3\%)$
S_T =	0.97		Function of temperature and $NPSH_R(3\%)$
S_M =	1		Function of impeller material and pumpage
S_{LG} =	1		S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
$N_{SS}(3\%)$ =	13390		Suction specific speed at 3%
$N_{SS}(REF)$ =	9300		Suction specific speed at reference
F_S =	1.1999		{sqrt($N_{ss}(3\%)$ / $N_{ss}(REF)$)} for water if $N_{ss}(3\%)$ > 9300 = $N_{ss}(REF)$
$NPSH_R(3\%)$ =	19	(ft)	From performance curve
F_{CT} =	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by $1/F_{CT}$ to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$ =	45.6	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

Results of both the "NPSH-Recommended" and "Cavitation Free" calculations, as well as the test curves for 1% and 3% head and drop, are plotted on Curve RHR II:



Curve 2: RHR Test and Calculated NPSH

"Recommended" NPSH (as plotted) is Sulzer's theoretical recommendation for 40,000 hour life, based on limited cavitation damage to the impeller.

- Comparison to the "cavitation free" curve (Lobanoff & Ross) shows that some cavitation occurs at the "recommended" NPSHr. The slight erosion damage that occurs at this level is the basis for 40,000 hour criterion.

NPSHr curves based on 1% and 3% head loss are from development tests of these impellers, and represent the standard (Hydraulic Institute) method for determining NPSH;

- The same comparison as above demonstrates that slight cavitation will occur at these NPSH values.

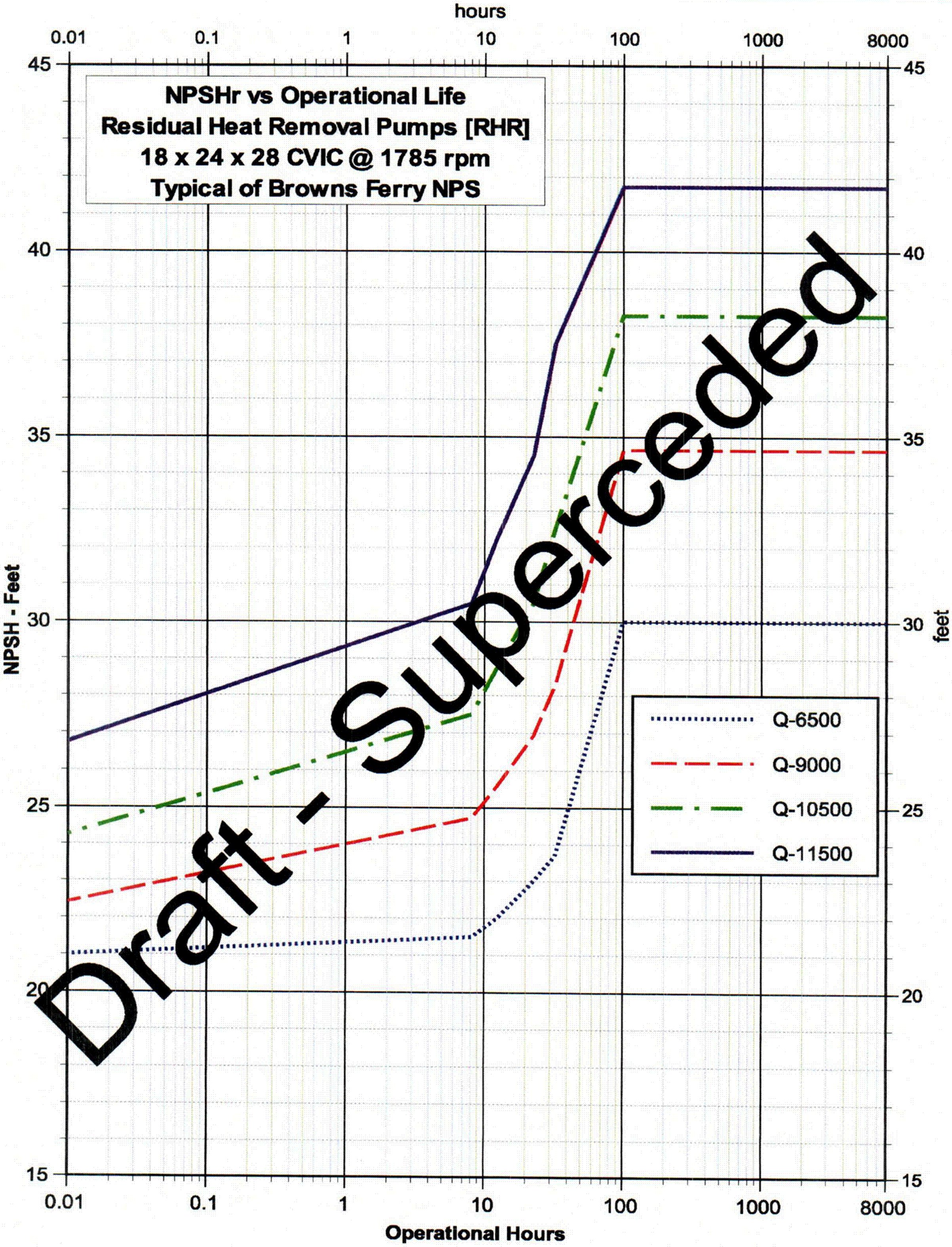
When the previously tabulated transient NPSHa cases are compared to the plots of RHR II, it is seen that the minimum NPSHa value from each event, except for the ST-LOCA-BL is equal, or greater, than the (standard) 3% curve at the same flow:

- LT-LOCA is above the "Recommended" NPSHr curve;
- APP R, ATWS and SBO are between the 1% and 3% head loss curves;
- ST-LOCA-IL (10500 gpm) is above the 3% head loss curve;
- ST-LOCA-BL (11500 gpm) is below the 3% head loss curve.

Since some cavitation exists at reduced NPSHa scenarios, a graph defining NPSHr vs. Operating Life (Curve 3 - as follows) based on mechanical damage (erosion) estimates has been developed in addition to the preceding NPSH analysis.

8000 hours (~1 year) has been selected as an adequate post transient event operational life. This is an estimate of the minimum life expectancy that will produce similar damage (during low NPSHa events) as that expected from an impeller operating with NPSHa above the "recommended" (40,000 hour) NPSHr curve:

- At the graphical NPSHr values for the origin (.01 hours) these are high suction energy pumps. The resulting lack of sufficient NPSH margin would result in life reduction (due to cavitation damage) if operated continually in the suppressed state;
    - Sulzer's graph provides a guideline for operating at the lowest possible NPSHa, while requiring an increase, over time, adequately removing enough energy from the pump to prevent catastrophic failure;
    - The recommended minimum NPSHr (time .01 hours), at all flows, range from slightly above 3% up to 6% head loss.
- Based on post-test inspection of the tested pumps the graph is conservative since the inspected impellers showed no damage;
    - Pumps were run for extended periods (2-3 hours) at 1% to 6% head loss without losing suction, despite surging, noise and increased vibration;
    - Several tests included NPSHa reduction to initiate loss of suction. Pumps recovered, with no visible damage, after NPSH was restored;
    - NPSHa increase over time, as dictated by the graph at a given flow, insures that recommended NPSH levels/duration will be less severe than that experienced during testing.



Curve 3: RHR NPSHr vs. Operating Life

RHR Results and Conclusions:

The subject pumps have been analyzed and found to be suitable for reduced NPSHa operation, as described above, with equipment in "as new" condition, with exceptions as noted.

Curve 3 provides a guideline for operational life vs. NPSHa as a general recommendation for operation when the pumps may be subject to transient events outside of their original scope.

Recommendations are also provided specifically to address the potential transient events provided by TVA Browns Ferry:

- Since the transient events identified as LT-LOCA, ATWS, SBO, APPR, ST-LOCA-IP all provide NPSHA values above the minimum established NPSHr, as established in the operating life graph (curve 3) they are acceptable - i.e. they meet the criteria for determining operational life vs NPSHa from the graph.
- ST-LOCA-BL provides NPSHA values below the required NPSH shown on the graph. *Sulzer cannot recommend running at this transient due to inadequate data.*
  - At the flows above 11000 gpm this pump was not NPSH tested to fully describe the knee. It is not known whether the knee is sharp or rounded (see previous NPSH technical background discussion).
    - There is no adequate similar pump to adequately model the high flow NPSH values.

Analysis methodology compared test derived NPSHr values with those predicted theoretically. The pumps were evaluated against this comparative basis in order to predict the remaining operational life of a pump in the aftermath of a transient event;

- An 8000 hour post-transient operational lifetime was developed, based on similar cavitation damage to the 40,000 hour "recommended" NPSHr curve; the curve is well supported by the NPSH analysis and mechanical response on the test stand;
    - Graphical NPSHa levels and duration are less severe than that actually experienced on the test stand;
    - Empirical test information has been verified by one of the original test Engineers;
    - Despite NPSH testing that was more severe than the "recommended" curve, post-test inspection revealed no damage.

When pumps are in an "undamaged" condition they can be operated in accordance within the NPSHA guidelines provided with the expectation of the 8000 hour life described.

Of the potential transient scenarios considered, only the ST-LOCA-BL event exceeds the limits established in this report:

- Operation with lower than required NPSHA will result in surging and cavitation;
- Impeller damage may occur, but should not be catastrophic from this ten minute event;
- There is insufficient data to predict the pumps' response.

Operation at the remainder of the transient scenarios is recommended:

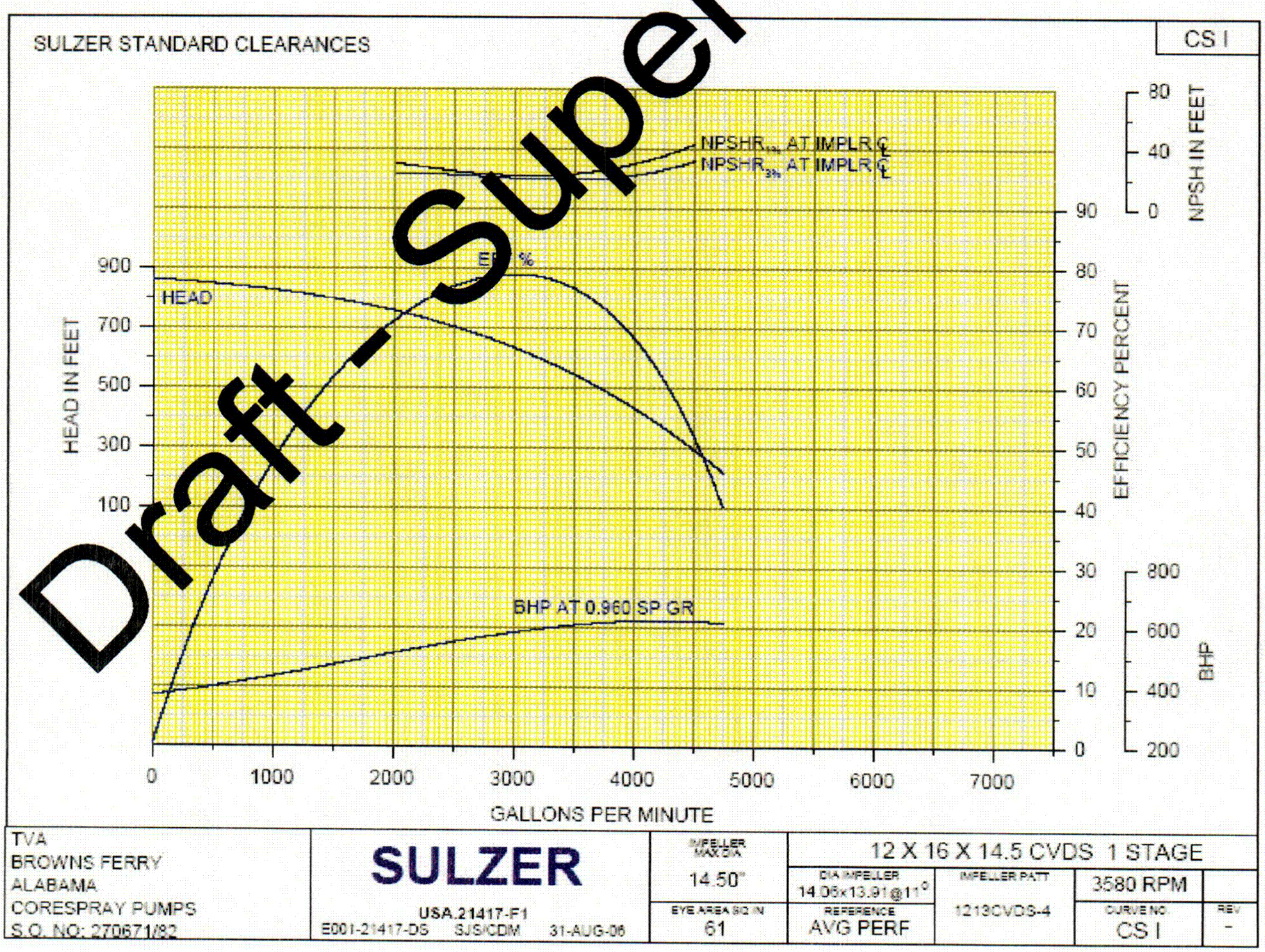
- Although vibration and noise may increase as a result of severe transients, the units should continue pumping;
- Damage is likely, due to a transient event, but will not be catastrophic. If the operational life graph is followed the pumps will continue to function.

CS Pump NPSH Assessment and Analysis: Test and calculated NPSH values are analyzed and compared against the proposed transient events.

Performance curves 27376B-79B, 27970-73 and 28022-25 have been averaged relative to head and efficiency vs. flow and plotted as curve CS I. For the basis of NPSH assessment, test points for NPSHR-3% and NPSHR-1% (3 capacities) have also been plotted on curve CS I based on development testing (NPSH test data has been tabulated in Appendix A).

Specific speed (N_S) and Suction Specific Speed (N_{SS}) for both 3% and 1% head loss are as follows:

- $N_S = 3580*3025^{1/2}/627^{3/4} = 1571$
- $N_{SS\text{-}3\%} = 3580*((3025/2)^{1/2})/21^{3/4} = 14193$
- $N_{SS\text{-}1\%} = 3580*((3025/2)^{1/2})/22^{3/4} = 13706$



Curve 4: CS Pump Average Performance

Results of the "Cavitation Free" NPSHR calculation (based on Lobanoff and Ross) are as per the following table.

Flow	NPSH
2000 gpm	159 feet
3000 gpm	126.3 feet
3750 gpm	87.6 feet
4500 gpm	76.7 feet

Table 4: CS "Cavitation Free" NPSH

The calculation set (2000, 3000, 3750 & 4500 gpm) is collected in Appendix [illegible]. A sample calculation follows:

"CAVITATION FREE" NPSHr CALCULATION

Q	=	2000	(GPM)	Flow.
N	=	3580	(rpm)	
A-B	=	122.4	(in^2)	Suction area. Lobanoff & Ross and Sulzer [illegible]awing Z06196.
A_E	=	61.04	(in^2)	Impeller eye area.
B_1	=	16	(deg.)	Blade inlet angle.
$(A-B)/A_E$	=	200.52	(%)	Area ratio (From Lo[illegible]noff a[illegible] Ro[illegible]).
K_1	=	1.48		From Loba[illegible]off [illegible] Figure 8-18.
D_t	=	6.875	(in.)	Impeller eye dia[illegible]er
C_{M1}	=	10.518	(ft./sec.)	Avera[illegible] meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	107.48	(ft.[illegible]c.)	[illegible]ripheral velocity of impeller blade ($D_TN/229$).
$\tan(\theta)$	=	0.097[illegible]		[illegible]mpeller inlet velocity ratio (C_{M1}/U_T)
θ	=	[illegible]5891	([illegible]eg.)	Angle of flow approaching blade.
α	=	[illegible].411	(deg.)	Angle of incidence (B_1-theta).
K_2	[illegible]	0.93		From Lobanoff & Ross Figure 8-19.
C_B	=	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr	=	159.0	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application"
2nd Edition, Gulf Publishing, 1992

"NPSH-Recommended" calculation results are tabulated below. The calculation set (2000, 3000, 3750 & 4500 gpm) is collected in Appendix A.

Flow	NPSH
2000 gpm	64.1 feet
3000 gpm	41.9 feet
3750 gpm	43.4 feet
4500 gpm	85.9 feet

Table 3: "Recommended NPSH"

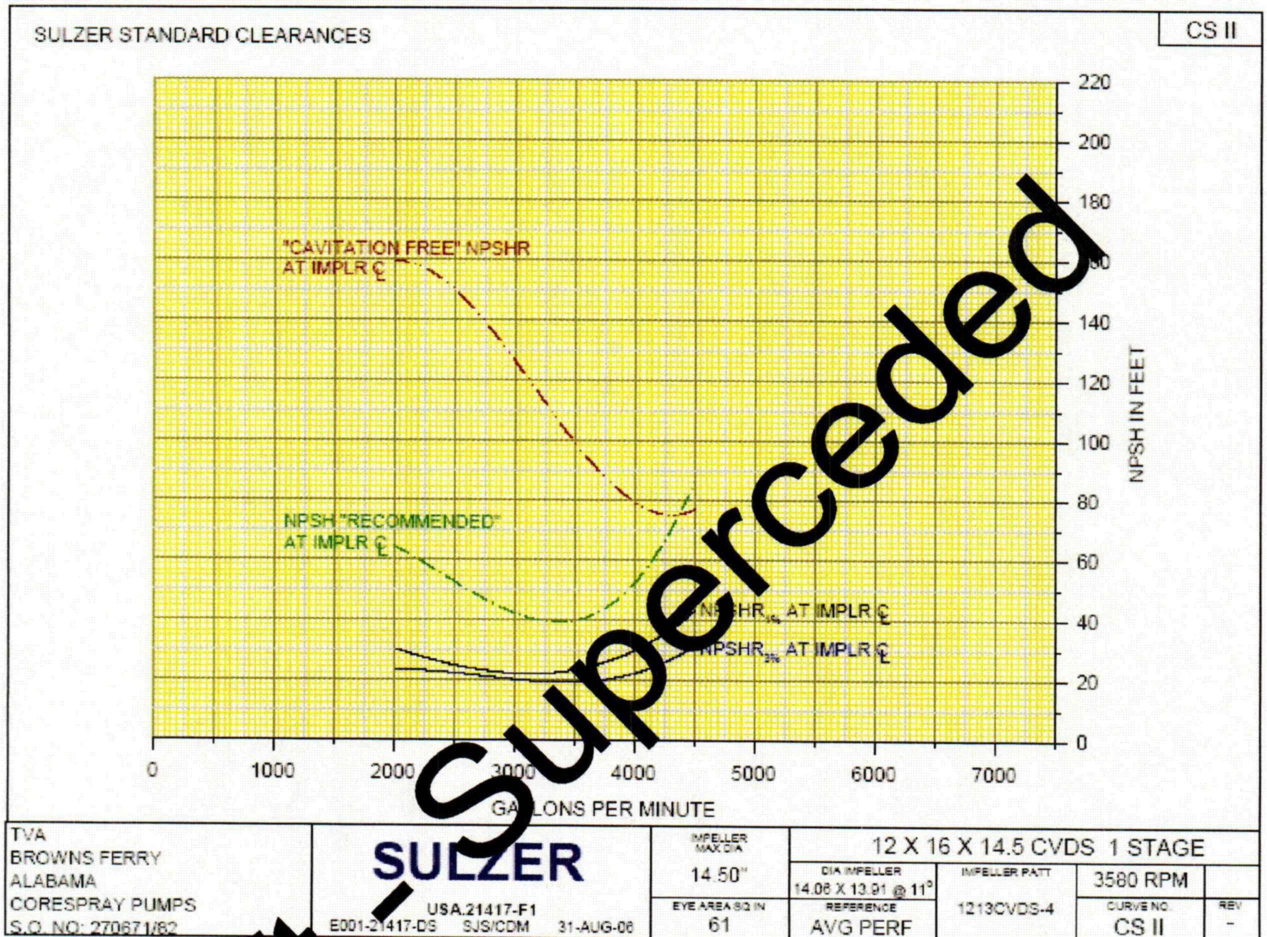
A sample "NPSH-Recommended calculation follows:

"NPSH RECOMMENDED" CALCULATION

Q =	2000	(GPM)	From performance curve
Q_{BEP} =	3000	(GPM)	From performance curve
Q/Q_{BEP} =	0.6667		
S_N =	1.62		{$NPSH_R$ - 0% / $NPSH_R$-3%} - Function of Q/Q_{BEP}
S_{EN} =	1.16		Function of pumpage and $NPSH_R$(3%)
S_T =	0.98		Function of temperature and $NPSH_R$(3%)
S_M =	1		Function of impeller material and pumpage
S_{LG} =	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
N_{SS}(3%) =	13890		Suction specific speed at 3%
N_{SS}(REF) =	9300		Suction specific speed at reference
F_S =	1.2221		{sqrt(N_{ss}(3%) / N_{ss}(REF))} for water if N_{ss}(3%) > 9300 = N_{ss}(REF)
$NPSH_R$(3%) =	28.5	(ft)	From performance curve
F_{CT} =	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by 1/F_{CT} to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$ =	64.1	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

Results of both the "NPSH-Recommended" and "Cavitation Free" calculations, as well as the test curves for 1% and 3% head and drop, are plotted on Curve CS II:



Curve 5: CS Test and Calculated NPSH

"Recommended" NPSH (as plotted) is Sulzer's theoretical recommendation for 40,000 hour life, based on limited cavitation damage to the impeller.

- Comparison to the "cavitation free" curve (Lobanoff & Ross) shows that some cavitation occurs at the "recommended" NPSHr. The slight erosion damage that occurs at this level is the basis for 40,000 hour criterion.

NPSHr curves based on 1% and 3% head loss are from development tests of these impellers, and represent the standard (Hydraulic Institute) method for determining NPSH;

- The same comparison as above demonstrates that slight cavitation will occur at these NPSH values.

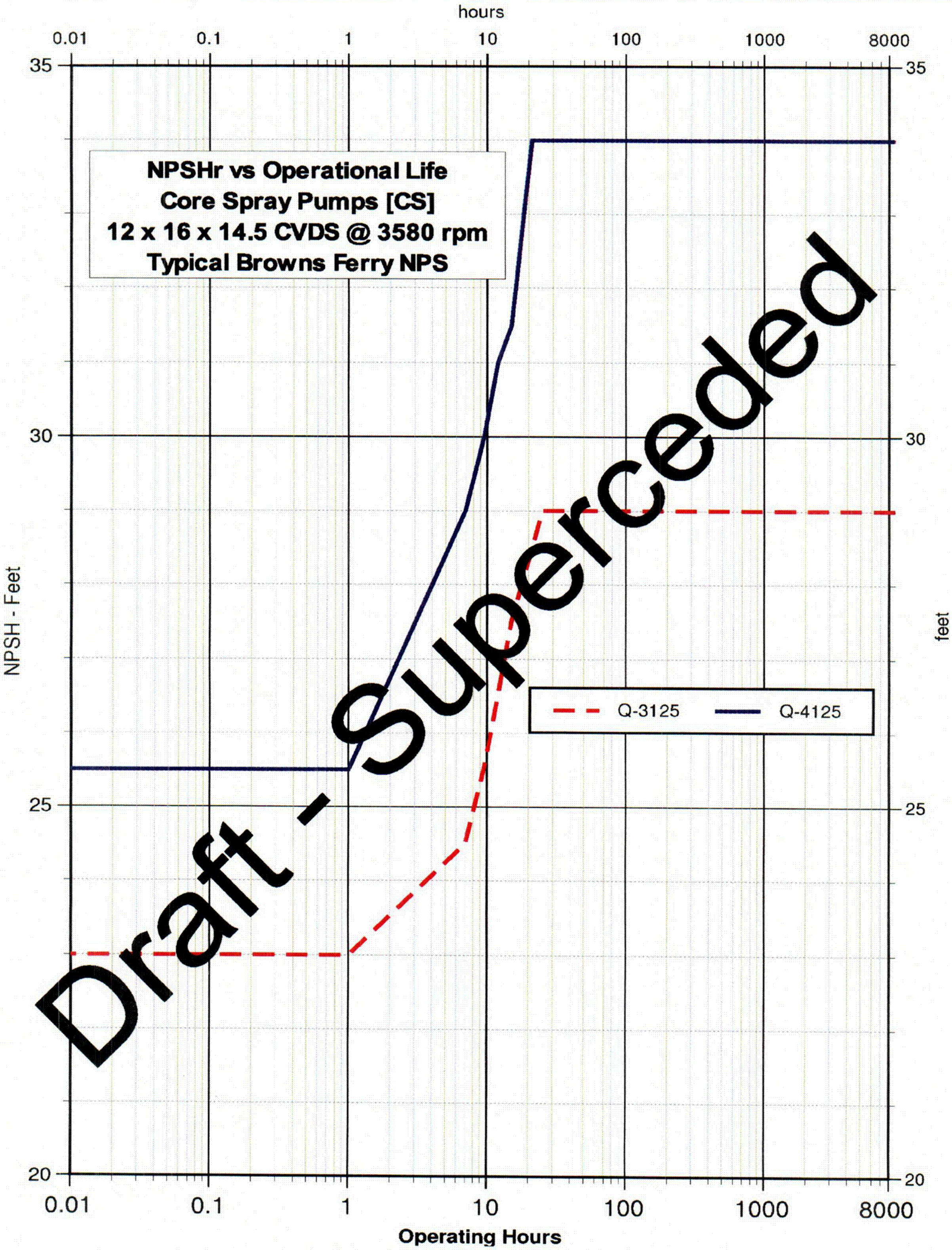
When the previously tabulated transient NPSHa cases are compared to the plots of CS II, it is seen that the minimum NPSHa value both events are equal, or greater, than the (standard) 3% curve at the same flow:

- The LOCA for 3125 gpm is above the 1% head loss curve;
- The LOCA for 4125 gpm is just above the 3% head loss curve

Since some cavitation exists at reduced NPSHa scenarios, a graph defining NPSHr vs. Operating Life (Curve 6 - as follows) based on mechanical damage (erosion) estimates has been developed in addition to the preceding NPSH analysis.

8000 hours (~1 year) has been selected as an adequate post transient event operational life. This is an estimate of the minimum life expectancy that will produce similar damage (during low NPSHa events) as that expected from an impeller operating with NPSHa above the "recommended" (40,000 hour) NPSHr curve:

- At the graphical NPSHr values for the origin (.01 hours) these are high suction energy pumps. The resulting lack of sufficient NPSH margin would result in life reduction (due to cavitation damage) if operated continually in the suppressed state;
    - Sulzer's graph provides a guideline for operating at the lowest possible NPSHa, while requiring an increase, over time, adequately removing enough energy from the pump to prevent catastrophic failure;
    - The recommended minimum NPSHr (time .01 hours), at all flows, range from slightly above 3% up to 6% head loss.
- Based on post test inspection of the tested pumps the graph is conservative since the inspected impellers showed no damage;
    - Pumps were run for extended periods (2-3 hours) at 1% to 6% head loss without losing suction, despite surging, noise and increased vibration;
    - Several tests included NPSHa reduction to initiate loss of suction. Pump recovered, with no damage, after NPSH was restored;
    - NPSHa increase over time, as dictated by the graph at a given flow, insures that recommended NPSH levels/duration will be less severe than that experienced during testing.



Curve 6: CS NPSHr vs. Operating Life

CS Results and Conclusions:

The subject pumps have been analyzed and found to be suitable for reduced NPSHa operation, as described above, with equipment in "as new" condition.

Curve 6 provides a guideline for operational life vs. NPSHa as a general recommendation for operation when the pumps may be subject to transient events outside of their original scope.

Recommendations are also provided specifically to address the potential transient events provided by TVA Browns Ferry:

- Both potential LOCA events (as tabulated) provide NPSHa values above the minimum established NPSHr (as established in the operating life graph) and are acceptable - i.e. they meet the criteria for determining operational life vs. NPSHa from the graph (curve 6).

Analysis methodology compared test derived NPSHr values with those predicted theoretically. The pumps were evaluated against this comparative basis in order to predict the remaining operational life of a pump in the aftermath of a transient event;

- An 8000 hour post-transient operational lifetime was developed, based on similar cavitation damage to the 40,000 hour "recommended" NPSHr curve; the curve is well supported by the NPSH analysis and mechanical response on the test stand;
  - Graphical NPSHa levels and duration are less severe than that actually experienced on the test stand;
  - Empirical test information has been verified by one of the original test Engineers;
  - Despite NPSH testing that was more severe than the "recommended" curve, post-test inspection revealed no damage.

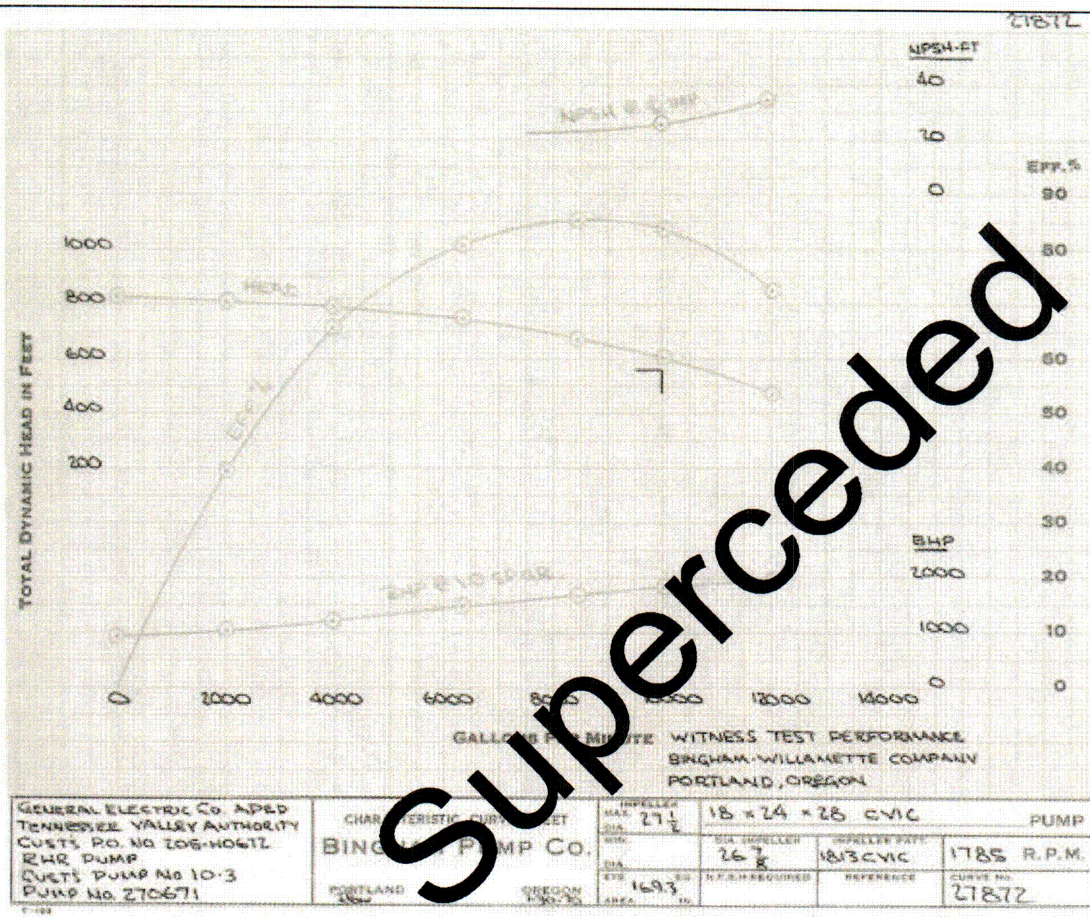
When pumps are in "undamaged" condition they can be operated in accordance within the NPSHa guidelines provided with the expectation of the 8000 hour life described.

The tabulated transients are acceptable scenarios within the operating recommendations established in curve 6:

- Although vibration and noise may increase as a result of severe transients, the units should continue pumping;
- Damage is likely, due to a transient event, but will not be catastrophic. If the operational life graph is followed the pumps will continue to function.

APPENDIX A - TEST DATA AND CALCULATIONS

RHR Performance Curve:



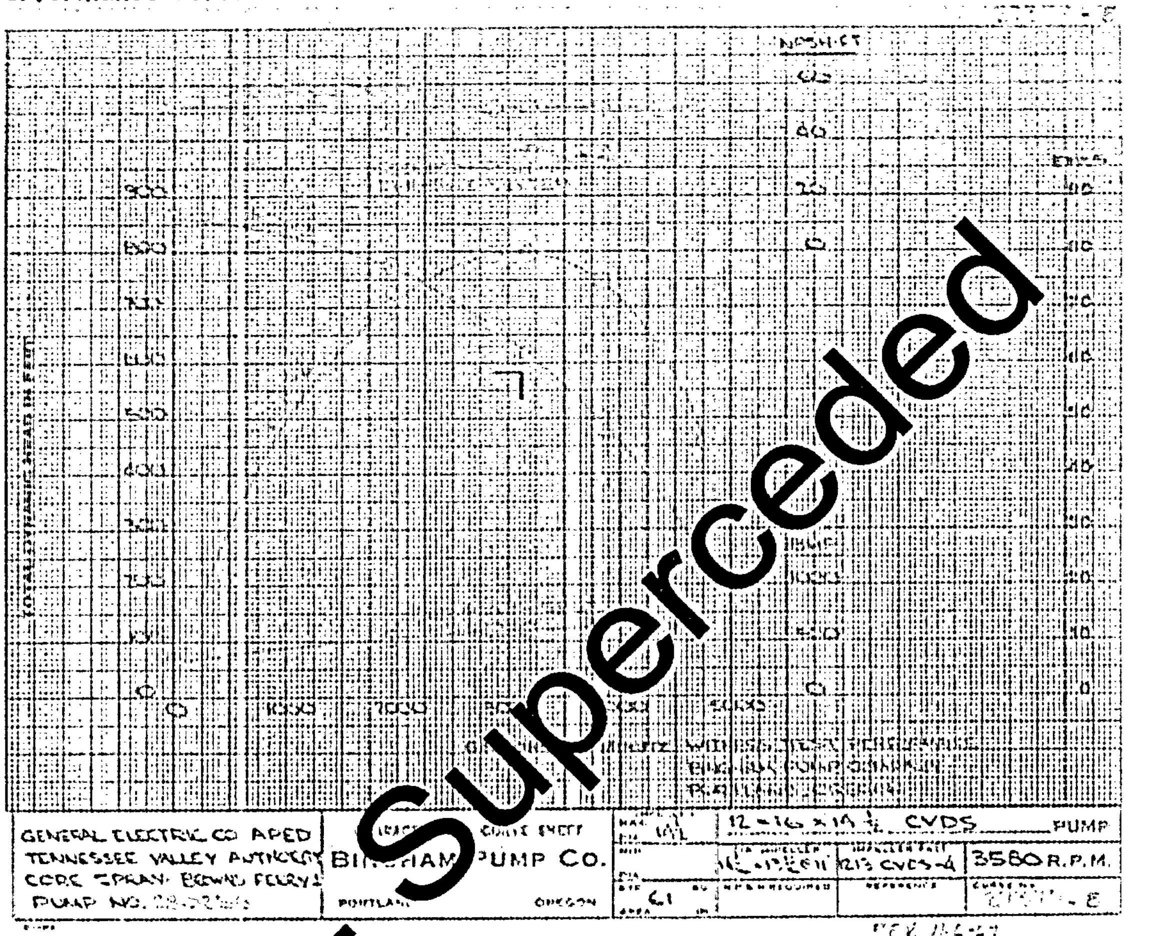
Customer Curve 27872: Typical RHR Witness Test Performance Curve

RHR NPSH Test Data:

RHR NPSH test data is tabulated as follows:

Test	Flow	NPSH For Various Head Losses 1% Loss	3% Loss	6% Loss	Comments
270685-A	7,512	30.0 ft.	15.6 ft.	Untested	Test stopped at 15.6 feet NPSH-
	10,015	30.3 ft.	23.4 ft.	23.2 ft.	7512 gpm drop still only 2.3%.
270685-B	5,004	34.0 ft.	19 ft.	Untested	Test stopped at 19 feet NPSH -
	10,009	37.0 ft.	28.5 ft.	20.8 ft.	5004 gpm drop still only at 2.7%.
270685	5,000	34.2 ft.	19.5	Untested	5000 - 2.5% drop at 19.5 feet.
	7,505	31.0 ft.	15.9 ft.	Untested	
	10,000	31.5 ft.	20.8 ft.	20 ft.	
	12,000	47.5 ft.	40.7 ft.	36.2 ft.	

CS Performance Curve:



Customer Curve 27379-B: Typical CS Witness Test Performance Curve

CS NPSH TEST Data:

CS NPSH test data is tabulated as follows:

Test	Flow	NPSH For Various Head Losses			Comments
		1% Loss	3% Loss	6% Loss	
270427	3,110	21.3 ft.	21.2 ft.	21.0 ft.	Sharp knee @ 3110. NPSHr must
	4,510	43.0 ft.	31.5 ft.	26.0 ft.	be above knee.
270427	2,013	30.0 ft.	23.0 ft.	Untested	Test stopped - 1.6% @ 23 feet.

RHR Cavitation Free NPSH Calculations:

"CAVITATION FREE" NPSHr CALCULATION

Q =	5000	(GPM)	Flow.
N =	1785	(rpm)	
A-B =	368.2	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E =	169.3	(in^2)	Impeller eye area.
B_1 =	11	(deg.)	Blade inlet angle.
$(A-B)/A_E$ =	217.48	(%)	Area ratio (From Lobanoff and Ross).
K_1 =	1.58		From Lobanoff & Ross Figure 8-18.
D_t =	15.25	(in.)	Impeller eye diameter
C_{M1} =	9.4802	(ft./sec.)	Average meridianal velocity at blade inlet (.321Q/A_E).
U_T =	118.87	(ft./sec.)	Peripheral velocity of impeller blade (D_TN/229).
Tan(θ) =	0.0798		Impeller inlet velocity ratio (C_{M1}/U_T)
θ =	4.5598	(deg.)	Angle of flow approaching blade.
α =	6.4402	(deg.)	Angle of incidence (B_1-theta).
K_2 =	0.46		From Lobanoff & Ross Figure 8-19.
C_B =	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr =	96.5	(ft.)	Lobanoff&Ross equation 8-2 {[$(K_1+K_2)C$[illegible] K_2[illegible]$/2g]C_B$}

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application
2nd Edition, Gulf Publishing, 1992

RHR PUMP @5000 GPM

"CAVITATION FREE" NPSHr CALCULATION

Q =	7000	(GPM)	Flow.
N =	1785	(rpm)	
A-B =	368.2	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E =	169.3	(in^2)	Impeller eye area.
B_1 =	[illegible]	[illegible])	Blade inlet angle.
$(A-B)/A_E$ =	217.4[illegible]	(%)	[illegible]a ratio (From Lobanoff and Ross).
K_1 =	[illegible]		From Lobanoff & Ross Figure 8-18.
D_t =	1[illegible]25	[illegible]n.)	Impeller eye diameter
C_{M1} =	13.2[illegible]2	(ft./sec.)	Average meridianal velocity at blade inlet (.321Q/A_E).
[illegible] =	[illegible]18.87	(ft./sec.)	Peripheral velocity of impeller blade (D_TN/229).
Tan([illegible] =	0.1117		Impeller inlet velocity ratio (C_{M1}/U_T)
θ =	6.3709	(deg.)	Angle of flow approaching blade.
α =	4.6291	(deg.)	Angle of incidence (B_1-theta).
K_2 =	0.345		From Lobanoff & Ross Figure 8-19.
C_B =	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr =	75.3	(ft.)	Lobanoff&Ross equation 8-2 {[$(K_1+K_2)C_{M1}{}^2/2g + K_2U_T{}^2/2g]C_B$}

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application"
2nd Edition, Gulf Publishing, 1992

RHR PUMP @ 7000 GPM

"CAVITATION FREE" NPSHr CALCULATION

Q	=	9000	(GPM)	Flow.
N	=	1785	(rpm)	
A-B	=	368.2	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	169.3	(in^2)	Impeller eye area.
B_t	=	11	(deg.)	Blade inlet angle.
$(A-B)/A_E$	=	217.48	(%)	Area ratio (From Lobanoff and Ross).
K_1	=	1.58		From Lobanoff & Ross Figure 8-18.
D_t	=	15.25	(in.)	Impeller eye diameter
C_{M1}	=	17.064	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	118.87	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
Tan(θ)	=	0.1436		Impeller inlet velocity ratio (C_{M1}/U_T)
θ	=	8.1693	(deg.)	Angle of flow approaching blade.
α	=	2.8307	(deg.)	Angle of incidence (B_t-theta).
K_2	=	0.31		From Lobanoff & Ross Figure 8-19.
C_B	=	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr	=	71.2	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application"
2nd Edition, Gulf Publishing, 1992

RHR PUMP @ 9000 GPM

"CAVITATION FREE" NPSHr CALCULATION

Q	=	10500	(GPM)	Flow.
N	=	1785	(rpm)	
A-B	=	368.2	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	169.3	(in^2)	Impeller eye area.
B_t	=	[illegible]	(deg.)	Blade inlet angle.
$(A-B)/A_E$	=	[illegible]	(%)	Area ratio (From Lobanoff and Ross).
K_1	=	[illegible]		From Lobanoff & Ross Figure 8-18.
D_t	=	[illegible]	(in.)	Impeller eye diameter
C_{M1}	=	19.908	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	118.87	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
Tan(θ)	=	0.1675		Impeller inlet velocity ratio (C_{M1}/U_T)
θ	=	9.5077	(deg.)	Angle of flow approaching blade.
α	=	1.4923	(deg.)	Angle of incidence (B_t-theta).
K_2	=	0.31		From Lobanoff & Ross Figure 8-19.
C_B	=	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr	=	74.1	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application"
2nd Edition, Gulf Publishing, 1992

RHR PUMP @ 10500 GPM

"CAVITATION FREE" NPSHr CALCULATION

Q	=	*12000*	(GPM)	Flow.
N	=	*1785*	(rpm)	
A-B	=	*368.2*	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E	=	*169.3*	(in^2)	Impeller eye area.
B_1	=	*11*	(deg.)	Blade inlet angle.
$(A\text{-}B)/A_E$	=	217.48	(%)	Area ratio (From Lobanoff and Ross).
K_1	=	*1.58*		From Lobanoff & Ross Figure 8-18.
D_t	=	*15.25*	(in.)	Impeller eye diameter
C_{M1}	=	22.753	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T	=	118.87	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
Tan(θ)	=	0.1914		Impeller inlet velocity ratio (C_{M1}/U_T)
θ	=	10.836	(deg.)	Angle of flow approaching blade.
α	=	0.1643	(deg.)	Angle of incidence (B_1-theta).
K_2	=	*0.3*		From Lobanoff & Ross Figure 8-19.
C_B	=	*0.93*		From Lobanoff & Ross Figure 8-20.
NPSHr	=	**75.3**	(ft.)	Lobanoff&Ross equation 8-2 {[$(K_1+K_2)C_{M1}^2/2g$ [illegible]$_2U_T^2/2$[illegible]

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application"
2nd Edition, Gulf Publishing, 1992

RHR PUMP @ 12000 GPM

CS Cavitation Free NPSH Calculations:

"CAVITATION FREE" NPSHr CALCULATION

Q =	2000	(GPM)	Flow.
N =	3580	(rpm)	
A-B =	122.4	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E =	61.04	(in^2)	Impeller eye area.
B_1 =	16	(deg.)	Blade inlet angle.
$(A\text{-}B)/A_E$ =	200.52	(%)	Area ratio (From Lobanoff and Ross).
K_1 =	1.48		From Lobanoff & Ross Figure 8-18.
D_1 =	6.875	(in.)	Impeller eye diameter
C_{M1} =	10.518	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T =	107.48	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
$Tan(\theta)$ =	0.0979		Impeller inlet velocity ratio (C_{M1}/U_T)
θ =	5.5891	(deg.)	Angle of flow approaching blade.
α =	10.411	(deg.)	Angle of incidence (B_1-theta).
K_2 =	0.93		From Lobanoff & Ross Figure 8-19.
C_B =	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr =	159.0	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application" 2nd Edition, Gulf Publishing, 1992

CS PUMP @ 2000 GPM

"CAVITATION FREE" NPSHr CALCULATION

Q =	3000	(GPM)	Flow.
N =	3580	(rpm)	
A-B =	122.4	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E =	61.04	(in^2)	Impeller eye area.
B_1 =	[illegible]	(deg.)	Blade inlet angle.
$(A\text{-}B)/A_E$ =	200.5[illegible]	(%)	Area ratio (From Lobanoff and Ross).
K_1 =	[illegible]		From Lobanoff & Ross Figure 8-18.
D_1 =	6.[illegible]75	(in.)	Impeller eye diameter
C_{M1} =	15.777	(ft./sec.)	Average meridianal velocity at blade inlet ($.321Q/A_E$).
U_T =	107.48	(ft./sec.)	Peripheral velocity of impeller blade ($D_TN/229$).
$Tan(\theta)$ =	0.1468		Impeller inlet velocity ratio (C_{M1}/U_T)
θ =	8.3507	(deg.)	Angle of flow approaching blade.
α =	7.6493	(deg.)	Angle of incidence (B_1-theta).
K_2 =	0.71		From Lobanoff & Ross Figure 8-19.
C_B =	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr =	126.3	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application" 2nd Edition, Gulf Publishing, 1992

CS PUMP @ 3000 GPM

"CAVITATION FREE" NPSHr CALCULATION

Symbol	Value	Unit	Description
Q =	3750	(GPM)	Flow.
N =	3580	(rpm)	
A-B =	122.4	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E =	61.04	(in^2)	Impeller eye area.
B_1 =	16	(deg.)	Blade inlet angle.
$(A-B)/A_E$ =	200.52	(%)	Area ratio (From Lobanoff and Ross).
K_1 =	1.48		From Lobanoff & Ross Figure 8-18.
D_t =	6.875	(in.)	Impeller eye diameter
C_{M1} =	19.721	(ft./sec.)	Average meridianal velocity at blade inlet (.321Q/A_E).
U_T =	107.48	(ft./sec.)	Peripheral velocity of impeller blade (D_TN/229).
Tan(θ) =	0.1835		Impeller inlet velocity ratio (C_{M1}/U_T)
θ =	10.397	(deg.)	Angle of flow approaching blade.
α =	5.6027	(deg.)	Angle of incidence (B_1-theta).
K_2 =	0.46		From Lobanoff & Ross Figure 8-19.
C_B =	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr =	87.6	(ft.)	Lobanoff&Ross equation 8-2 {[(K_1+K_2)C[illegible] K_2 [illegible]^2/2g]C_B}

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application[illegible]
2nd Edition, Gulf Publishing, 1992

CS PUMP @ 3750 GPM

"CAVITATION FREE" NPSHr CALCULATION

Symbol	Value	Unit	Description
Q =	4500	(GPM)	Flow.
N =	3580	(rpm)	
A-B =	122.4	(in^2)	Suction area. Lobanoff & Ross and Sulzer drawing Z06196.
A_E =	61.0[illegible]		Impeller eye area.
B_1 =	1[illegible]	(deg.)	Blade inlet angle.
$(A-B)/A_E$ =	[illegible]	(%)	Area ratio (From Lobanoff and Ross).
K_1 =	[illegible]48		From Lobanoff & Ross Figure 8-18.
D_t =	6.875	(in.)	Impeller eye diameter
C_{M1} =	23.665	(ft./sec.)	Average meridianal velocity at blade inlet (.321Q/A_E).
U_T =	107.48	(ft./sec.)	Peripheral velocity of impeller blade (D_TN/229).
Tan(θ) =	0.2202		Impeller inlet velocity ratio (C_{M1}/U_T)
θ =	12.417	(deg.)	Angle of flow approaching blade.
α =	3.5826	(deg.)	Angle of incidence (B_1-theta).
K_2 =	0.37		From Lobanoff & Ross Figure 8-19.
C_B =	0.93		From Lobanoff & Ross Figure 8-20.
NPSHr =	76.7	(ft.)	Lobanoff&Ross equation 8-2 $\{[(K_1+K_2)C_{M1}^2/2g + K_2U_T^2/2g]C_B\}$

References: Lobanoff & Ross, "Centifugal Pumps: Design & Application"
2nd Edition, Gulf Publishing, 1992

CS PUMP @ 4500 GPM

RHR Recommended NPSH Calculations:

"NPSH RECOMMENDED" CALCULATION

Q =	5000	(GPM)	From performance curve
Q_{BEP} =	8600	(GPM)	From performance curve
Q/Q_{BEP} =	0.5814		
S_N =	1.84		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN} =	1.12		Function of pumpage and $NPSH_R$(3%)
S_T =	0.97		Function of temperature and $NPSH_R$(3%)
S_M =	1		Function of impeller material and pumpage
S_{LG} =	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
N_{SS}(3%) =	13390		Suction specific speed at 3%
N_{SS}(REF) =	9300		Suction specific speed at reference
F_S =	1.1999		{sqrt(N_{ss}(3%) / N_{ss}(REF))} for water if N_{ss}(3%) > 9300 = N_{ss}(R[illegible])
$NPSH_R$(3%) =	19	(ft)	From performance curve
F_{CT} =	1		F_{CT} ? 1.0 ; avoids adding margin on to margin i[illegible]sted [illegible]urve has Been increased by $1/F_{CT}$ to allow for Casting a[illegible]easuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$ =	45.6	(ft)	$NPSH_{REC} = S_N$ x S_{EN} x S_T x S_m x S_{LG} x [illegible]PS[illegible](3%) x F_{CT}

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

RHR PUMP @500[illegible]

"NPSH RECOM[illegible]ALCULATION

Q =	7000	(GPM)	From performance [illegible]ve
Q_{BEP} =	8600	(GPM)	From performance curve
Q/Q_{BEP} =	0.814		
S_N =	[illegible].35		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN} =	[illegible]		[illegible]unction of pumpage and $NPSH_R$(3%)
S_T =	[illegible]97		Function of temperature and $NPSH_R$(3%)
[illegible] =	[illegible]		Function of impeller material and pumpage
[illegible] =	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
N_{SS}([illegible]%) =	13390		Suction specific speed at 3%
[illegible](REF) =	9300		Suction specific speed at reference
F_S =	1.1999		{sqrt(N_{ss}(3%) / N_{ss}(REF))} for water if N_{ss}(3%) > 9300 = N_{ss}(REF)
$NPSH_R$(3%) =	18.3	(ft)	From performance curve
F_{CT} =	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by $1/F_{CT}$ to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$ =	31.9	(ft)	$NPSH_{REC} = S_N$ x S_{EN} x S_T x S_m x S_{LG} x F_s x $NPSH_R$(3%) x F_{CT}

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

RHR PUMP @ 7000 GPM

"NPSH RECOMMENDED" CALCULATION

Q	=	9000	(GPM)	From performance curve
Q_{BEP}	=	8600	(GPM)	From performance curve
Q/Q_{BEP}	=	1.0465		
S_N	=	1.2		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN}	=	1.11		Function of pumpage and $NPSH_R$(3%)
S_T	=	0.97		Function of temperature and $NPSH_R$(3%)
S_M	=	1		Function of impeller material and pumpage
S_{LG}	=	1.2	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
N_{SS}(3%)	=	13390		Suction specific speed at 3%
N_{SS}(REF)	=	9300		Suction specific speed at reference
F_S	=	1.1999		{sqrt(N_{ss}(3%) / N_{ss}(REF))} for water if N_{ss}(3%) > 9300 = N_{ss}(REF)
$NPSH_R$(3%)	=	18	(ft)	From performance curve
F_{CT}	=	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by 1/F_{CT} to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$	=	33.5	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

RHR PUMP @ 9000 GPM

"NPSH RECOMMENDED" CALCULATION

Q	=	10500	(GPM)	From performance curve
Q_{BEP}	=	8600	(GPM)	From performance curve
Q/Q_{BEP}	=	1.2209		
S_N	=	[illegible]85		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN}	=	[illegible]		Function of pumpage and $NPSH_R$(3%)
S_T	=	[illegible]98		Function of temperature and $NPSH_R$(3%)
S_M	=	[illegible]		Function of impeller material and pumpage
S_{LG}	=	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
N_{SS}(3%)	=	13390		Suction specific speed at 3%
N_{SS}(REF)	=	9300		Suction specific speed at reference
F_S	=	1.1999		{sqrt(N_{ss}(3%) / N_{ss}(REF))} for water if N_{ss}(3%) > 9300 = N_{ss}(REF)
$NPSH_R$(3%)	=	23.9	(ft)	From performance curve
F_{CT}	=	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by 1/F_{CT} to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$	=	42.9	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

RHR PUMP @ 10500 GPM

"NPSH RECOMMENDED" CALCULATION

Q	=	12000	(GPM)	From performance curve
Q_{BEP}	=	8600	(GPM)	From performance curve
Q/Q_{BEP}	=	1.3953		
S_N	=	1.74		$\{NPSH_R - 0\% / NPSH_R\text{-}3\%\}$ = Function of Q/Q_{BEP}
S_{EN}	=	1.22		Function of pumpage and $NPSH_R(3\%)$
S_T	=	0.98		Function of temperature and $NPSH_R(3\%)$
S_M	=	1		Function of impeller material and pumpage
S_{LG}	=	1	(deg.)	$S_{LG} = 1.2$; Guarantee of 40,000 hours impeller life at BEP flow $S_{LG} = 1.0$; at min. flow and runout flow (40,000 hour are not required)
$N_{SS}(3\%)$	=	13390		Suction specific speed at 3%
$N_{SS}(REF)$	=	9300		Suction specific speed at reference
F_S	=	1.1999		$\{sqrt(N_{ss}(3\%) / N_{ss}(REF))\}$ for water if $N_{ss}(3\%) > 9300 = N_{ss}(REF)$
$NPSH_R(3\%)$	=	40	(ft)	From performance curve
F_{CT}	=	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by $1/F_{CT}$ to allow for Casting and Measuring Tolerances. $F_{CT} = 1.0$ In this study
$NPSH_{REC}$	=	99.8	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_S \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

RHR PUMP @ 115[illegible] GPM

CS Recommended NPSH Calculations:

"NPSH RECOMMENDED" CALCULATION

Q =	2000	(GPM)	From performance curve
Q_{BEP} =	3000	(GPM)	From performance curve
Q/Q_{BEP} =	0.6667		
S_N =	1.62		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN} =	1.16		Function of pumpage and $NPSH_R(3\%)$
S_T =	0.98		Function of temperature and $NPSH_R(3\%)$
S_M =	1		Function of impeller material and pumpage
S_{LG} =	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
$N_{SS}(3\%)$ =	13890		Suction specific speed at 3%
$N_{SS}(REF)$ =	9300		Suction specific speed at reference
F_S =	1.2221		{sqrt($N_{ss}(3\%)$ / $N_{ss}(REF)$)} for water if $N_{ss}(3\%)$ > 9300 = $N_{ss}(REF)$
$NPSH_R(3\%)$ =	28.5	(ft)	From performance curve
F_{CT} =	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by $1/F_{CT}$ to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$ =	64.1	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

CS PUMP @ 2000 GPM

"NPSH RECOMMENDED" CALCULATION

Q =	3000	(GPM)	From performance curve
Q_{BEP} =	3000	(GPM)	From performance curve
Q/Q_{BEP} =	1		
S_N =	1.2[illegible]		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN} =	[illegible]		Function of pumpage and $NPSH_R(3\%)$
S_T =	[illegible]		Function of temperature and $NPSH_R(3\%)$
S_M =	1		Function of impeller material and pumpage
S_{LG} =	1.2	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
$N_{SS}(3\%)$ =	13890		Suction specific speed at 3%
$N_{SS}(REF)$ =	9300		Suction specific speed at reference
F_S =	1.2221		{sqrt($N_{ss}(3\%)$ / $N_{ss}(REF)$)} for water if $N_{ss}(3\%)$ > 9300 = $N_{ss}(REF)$
$NPSH_R(3\%)$ =	21.5	(ft)	From performance curve
F_{CT} =	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by $1/F_{CT}$ to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$ =	41.9	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

CS PUMP @ 3000 GPM

"NPSH RECOMMENDED" CALCULATION

Q =	3750	(GPM)	From performance curve
Q_{BEP} =	3000	(GPM)	From performance curve
Q/Q_{BEP} =	1.25		
S_N =	1.4		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN} =	1.13		Function of pumpage and $NPSH_R$(3%)
S_T =	0.975		Function of temperature and $NPSH_R$(3%)
S_M =	1		Function of impeller material and pumpage
S_{LG} =	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
N_{SS}(3%) =	13890		Suction specific speed at 3%
N_{SS}(REF) =	9300		Suction specific speed at reference
F_S =	1.2221		{sqrt(N_{ss}(3%) / N_{ss}(REF))} for water if N_{ss}(3%) > 9300 = N_{ss}(REF)
$NPSH_R$(3%) =	23	(ft)	From performance curve
F_{CT} =	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by 1/F_{CT} to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$ =	43.4	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

CS PUMP @ 3750 GPM

"NPSH RECOMMENDED" CALCULATION

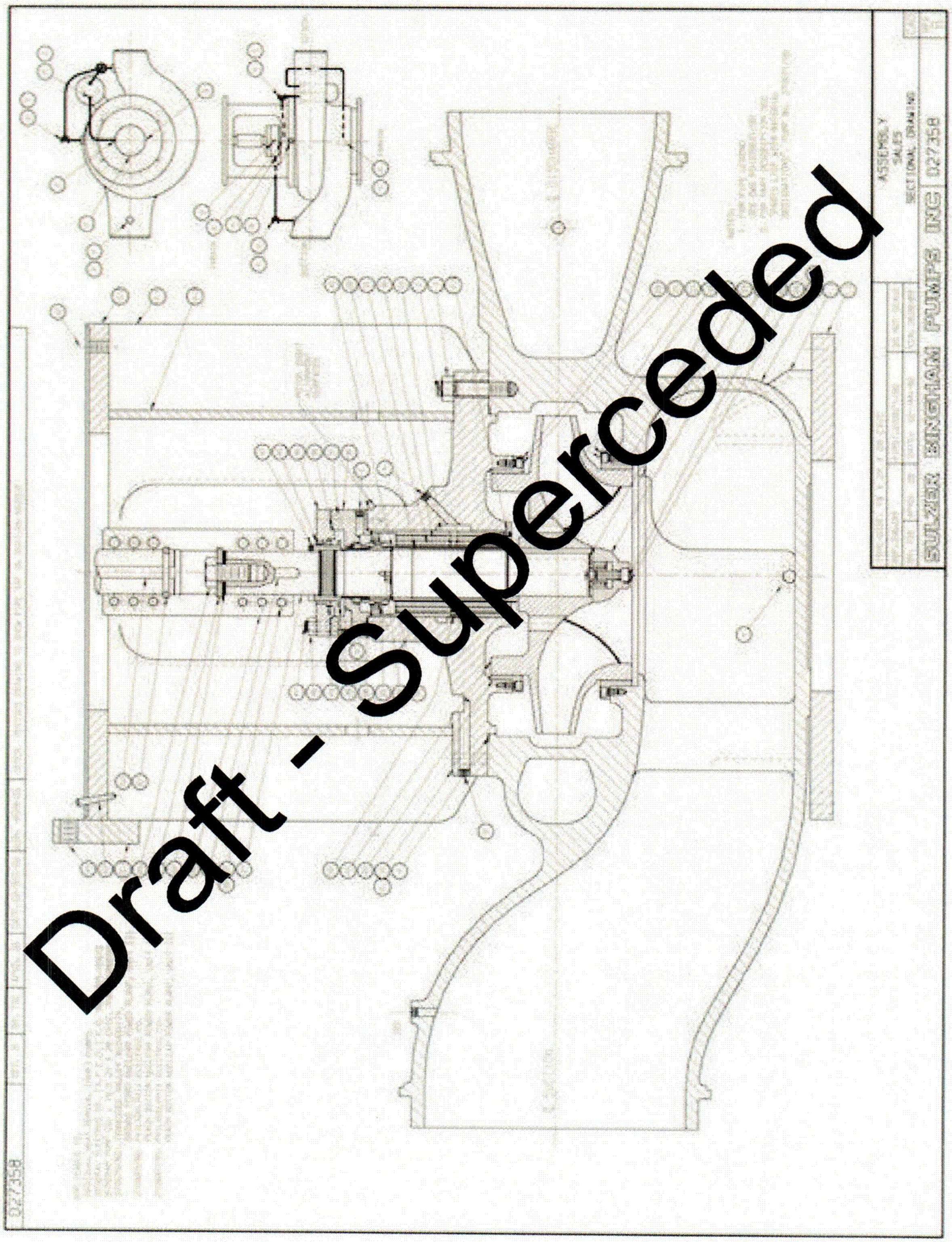
Q =	4500	(GPM)	From performance curve
Q_{BEP} =	3000	(GPM)	From performance curve
Q/Q_{BEP} =	1.5		
S_N =	[illegible]		{$NPSH_R$ - 0% / $NPSH_R$-3%} = Function of Q/Q_{BEP}
S_{EN} =	[illegible]		Function of pumpage and $NPSH_R$(3%)
S_T =	[illegible]		Function of temperature and $NPSH_R$(3%)
S_M =	[illegible]		Function of impeller material and pumpage
S_{LG} =	1	(deg.)	S_{LG} = 1.2 ; Guarantee of 40,000 hours impeller life at BEP flow S_{LG} = 1.0 ; at min. flow and runout flow (40,000 hour are not required)
N_{SS}(3%) =	13890		Suction specific speed at 3%
N_{SS}(REF) =	9300		Suction specific speed at reference
F_S =	1.2221		{sqrt(N_{ss}(3%) / N_{ss}(REF))} for water if N_{ss}(3%) > 9300 = N_{ss}(REF)
$NPSH_R$(3%) =	31.5	(ft)	From performance curve
F_{CT} =	1		F_{CT} ? 1.0 ; avoids adding margin on to margin if tested NPSH curve has Been increased by 1/F_{CT} to allow for Casting and measuring Tolerances. F_{CT} = 1.0 In this study
$NPSH_{REC}$ =	85.9	(ft)	$NPSH_{REC} = S_N \times S_{EN} \times S_T \times S_m \times S_{LG} \times F_s \times NPSH_R(3\%) \times F_{CT}$

References: Hydraulic Review: E12.5.522 page 7
Hydraulics 1.008.002 pages 1 - 5

CS PUMP @ 4500 GPM

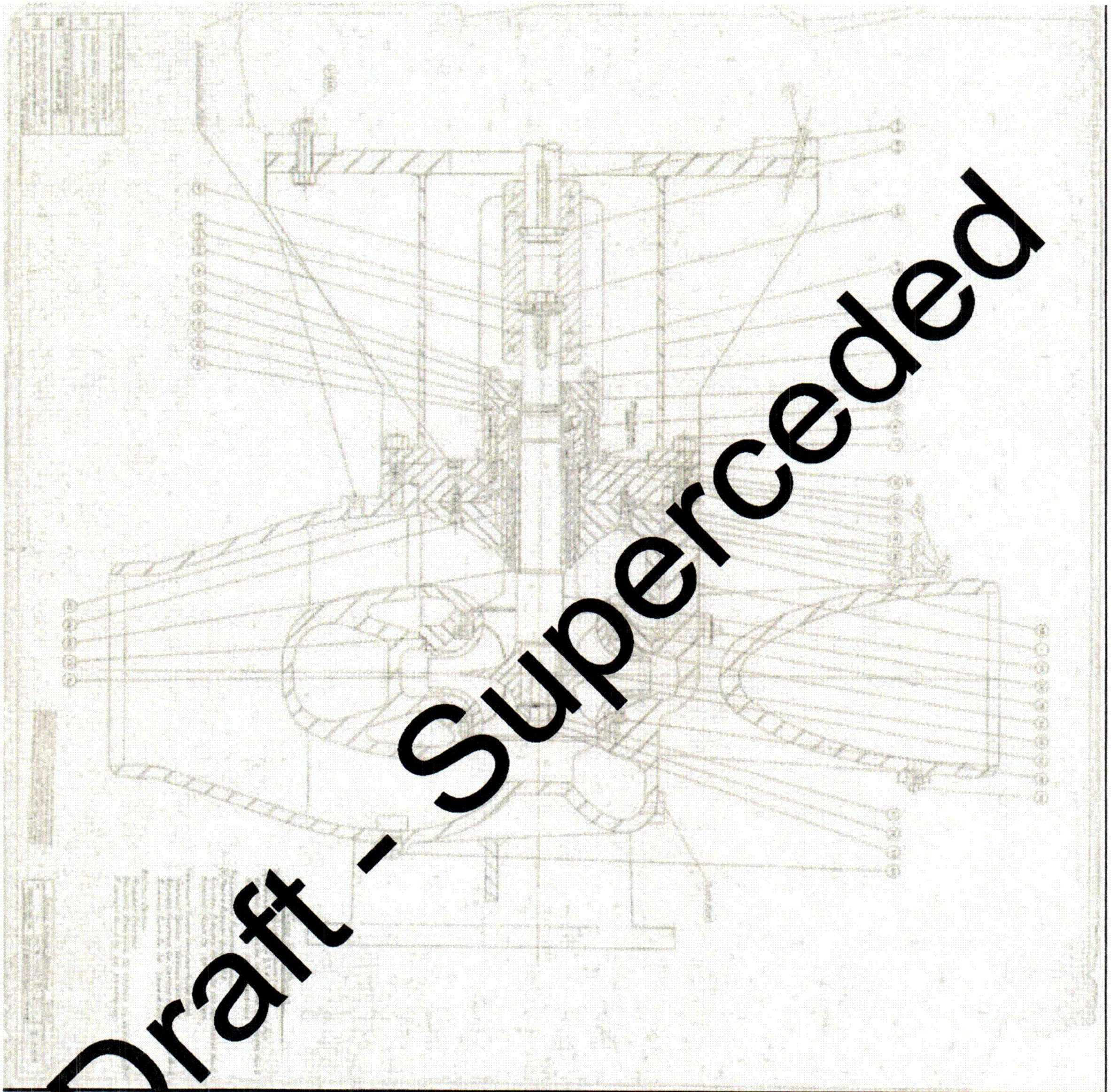
APPENDIX B - PUMP CROSS SECTIONS

RHR Pump Cross Sectional Drawing:



Sulzer Drawing D27358: RHR Pump Cross Sectional Drawing

CS Pump Cross Sectional Drawing:



Sulzer Drawing Z6315: CS Pump Cross Sectional Drawing