Flow Rating Analysis for Pump Stations S-382 and S-383
Ten Mile Creek Water Preserve Area

Technical Publication ERA # 444

Mark Wilsnack
Hua Li

October 2006

Stream Gauging, Engineering & Hydraulic Support Unit
Operations & Hydro Data Management Division
South Florida Water Management District

Executive Summary

The standard procedure for conducting hydraulic rating analyses of new pump stations was implemented for pump stations S-382 and S-383, located at the Ten Mile Creek WPA. Since no measured flow data exist, the ratings were based on the manufacturer's pump performance curves along with computed energy losses within the pump stations' piping and appurtenances. At each pump station, differences in flows computed by the rating equations and flows obtained from the pump station performance curves were nearly always less than 1%.

In developing the hydraulic rating equations for the pump stations, some unique circumstances were encountered. Both pump stations discharge into some outlet works situated between the pump station outlets and the tail water monitoring gauge. At S-383, it was determined that head losses within the outlet structures would not affect pump station discharges under the expected range of flows and water levels. This is primarily due to both the elevation at which the discharge pipes were installed and the capacity of the outfall facilities.

At S-382, it was found that the head losses incurred within the outlet structures can be appreciable and result in a significant difference in head between the tail water monitoring site and the discharge pipe outlets. Strictly speaking, the developed case 8 rating equation therefore cannot be applied directly between the measured head water in Ten Mile Creek and the measured tail water locations for S-382. As a solution, a special rating case was developed specifically for S-382 and implemented into the flow program. In this case, the case 8 rating equation itself remains the same while an iterative procedure is used to compute the effective tail water for the pump station outlets. This will enable reliable flow estimates to be made with the developed rating equations along with the stage monitoring network currently proposed.

Acknowledgements

The authors wish to express appreciation to Emile Damise and Matahel Ansar for their support and encouragement throughout this study. Helpful comments were also received from Ziming Chen, Jack Zeng and Juan Gonzales. Special thanks should also go to Maura Merkel and the S-382 operators for supplying much of the necessary data and organizing the site visits.

Table of Contents

Executive Summary ………………………………………………………………….. 1

Acknowledgements ………………………………………………………………… 2

List of Figures …………………………………………………………………….. 4

List of Tables ……………………………………………………………………… 5

Introduction ……………………………………………………………………….. 6

Objectives and Scope ……………………………………………………………… 6

Methodology ………………………………………………………………………. 7

S-383 Rating Analysis …………………………………………………………….. 9
  Station Design ……………………………………………………………….. 9
  Rating Equations …………………………………………………………….. 12
  Monitoring Recommendations ……………………………………………….... 12
  Stream Gauging Needs ……………………………………………………….. 12

S-382 Rating Analysis …………………………………………………………….. 12
  Station Design ……………………………………………………………….. 12
  Rating Equations …………………………………………………………….. 15
  Effects of the Outlet Works on the Rating Equation Implementation …………… 15
  Stream Gauging Needs ……………………………………………………….. 18

Summary and Conclusions ………………………………………………………….. 18

References ………………………………………………………………………... 25

Appendix A. Evaluation of the Head Losses Through S-383 Outlet Works …………….. 26

Appendix B. Head Loss Calculations for Pump Station Piping and Appurtenances …….. 32

List of Figures

Figure 1. Configuration of the Ten Mile Creek WPA 6

Figure 2. Cross Section of S-383 Pump Station …………………………………………... 9

Figure 3a. Performance Curves for the 15 CFS Pump ……………………….……..…. 10

Figure 3b. Performance Curves for the 25 CFS Pump …………………………………. 11

Figure 4. Schematic Cross Section of S-382 Pumps and Discharge Pipes ……….…….. 19

Figure 5. Cross Section of the Outlet Works for S-382 …………………...……….……. 20

Figure 6a. Performance Curves for the 60 cfs Pump at S-382 ……………….....………. 21

Figure 6b. Performance Curves for the 160 cfs Pump at S-382 ………………………… 22

Figure 7a. Adjusted Performance Curve for the 60 cfs Pump at S-382 ……………...… 23

Figure 7b. Adjusted Performance Curve for the 160 cfs Pump at S-382 ……………….. 23

Figure 8. Iterative Procedure for Computing the Effective TW Elevation at S-382 …...... 24

Figure A1. Cross Section of the Outlet Works for S-383 ……………………….……. 27

List of Tables

Table 1. Rating Equation Parameters for S-383 …………………………………………… 12

Table 2a. Evaluation of the Rating Equation for the 15 cfs Pump …............................... 13

Table 2b. Evaluation of the Rating Equation for the 25 cfs Pump …............................... 14

Table 3. Recommended Stream Flow Data for S383 ……………………………………… 12

Table 4. Rating Equation Parameters for S-382 …………………………….…………... 15

Table 5a. Evaluation of the Rating Equation for the 60 cfs Pump 16

Table 5b. Evaluation of the Rating Equation for the 160 cfs Pump 17

Table 6. Recommended Stream Flow Data for S382 ……………………………………… 18

Table B1. S-383 Head Losses with 15 CFS Pump and Minimum Pipe Roughness ……...34

Table B2. S-383 Head Losses with 15 CFS Pump and Maximum Pipe Roughness……...35

Table B3. S-383 Head Losses with 25 CFS Pump and Minimum Pipe Roughness….…...36

Table B4. S-383 Head Losses with 25 CFS Pump and Maximum Pipe Roughness……...37

Table B5. S-382 Head Losses with 60 CFS Pump and Minimum Pipe Roughness……....38

Table B6. S-382 Head Losses with 60 CFS Pump and Maximum Pipe Roughness…..…..39

Table B7. S-382 Head Losses with 160 CFS Pump and Minimum Pipe Roughness……...40

Table B8. S-382 Head Losses with 160 CFS Pump and Maximum Pipe Roughness….....41

Introduction

The Ten Mile Creek Water Preserve Area, located just west of Ft. Pierce in Martin County, consists of a large reservoir adjoined to a Stormwater Treatment Area (figure 1). The reservoir has an effective area of 526 acres while the effective area of the STA is 132 acres. Allowable stages in the reservoir range from about 18.5 feet NGVD to 29.0 feet. The minimum target stage for the STA is about 21.7 feet while the maximum design stage is 24.0 feet.

Inflow to the reservoir occurs exclusively through pump station S-382 whenever the water surface elevation in Ten Mile Creek exceeds 9.7 feet. The transfer of water from the reservoir to the STA occurs through the S-383 culvert whenever sufficient head is available. Otherwise, water transfer occurs through pumping. Additional details on the operational plan for these structures are provided by Goforth (2006).

Figure 1. Configuration of the Ten Mile Creek WPA (from Goforth, 2006)

Objectives and Scope

The purpose of the rating analyses conducted in this study is to enable flows through the pump stations to be estimated using measured head water elevations, tail water elevations and pump engine speeds. The hydraulic rating equations are based on pump performance characteristics, hydraulic properties of the pump station piping and appurtenances, and sound engineering principles. Since S-382 and S-383 became operational only recently, the rating equations could not be calibrated to stream flow measurements.

Methodology

The procedure implemented here for developing the rating curves reflects the standard procedure presented by Imru and Wang (2004). Certain deviations, however, were deemed necessary and are as noted. In particular, the moderately complex outlet works for both pump stations along with unfavorable monitoring gauge locations necessitated additional analyses to either ensure the suitability of the developed ratings or ascertain the required modifications. In the case of S-382, significant alterations to the conventional procedure for computing flows had to be implemented.

For a pump station with little or no measured flow data the established approach for rating analysis essentially consists of the following steps:

1. Obtain the manufacturer's performance curve that depicts the relationship between total dynamic head (TDH) and flow rate.
2. Determine the relationship between total static head (TSH) and flow rate using the results from step 1.
3. Fit the case 8 model to the modified pump performance curve determined in step 2.

TSH versus Discharge Curve

Computation of System Head Losses

The development of this curve is necessary since only TSH is measured in the field. This requires the accurate estimation of head losses within the piping and appurtenances of the pump station. In the past, energy losses due to friction have been estimated with the Hazen-Williams formula. However, a recent investigation by Bombardelli and Garcia (2004) indicates that this formula has a limited range of application and is not as accurate or reliable as conventionally assumed. In particular, it is only applicable within the transition or smooth, turbulent flow regimes. Furthermore, Daugherty and Franzini (1977) indicate that the velocity must be less than 10 ft/s. The various limitations of this equation have been demonstrated by other investigators as well, including Diskin (1960) and Liou (1998), who recommended that it not be used in engineering practice.

Despite these concerns regarding the reliability of the Hazen-Williams formula, it has found a longstanding acceptance in engineering design since any inaccuracies inherent to it may be off set by selecting a conservative value for the coefficient C. In contrast, when analyzing an existing facility for the purpose of estimating discharges as accurately as possible, the engineer does not have this convenient fallback. Consequently, to enhance the reliability of flow estimates while avoiding senseless errors in hydraulic head loss calculations, it is recommended that the Hazen-Williams formula no longer be used in conducting hydraulic rating analyses of the District's pumping stations.

The Darcy-Weisbach equation, when used in conjunction with a Moody diagram, has historically been demonstrated as the most reliable and sound method for computing head losses in pipes. In the transition range between smooth and rough-pipe turbulent flow, Swamee and Jain (1976) proposed the following convenient expression for Darcy-Weisbach friction factor:

$$f = \frac{1}{4\left[\mathrm{Log}_{10}\left(\varepsilon/(3.7D)+5.74/N_R^{0.9}\right)\right]^2} \quad \ldots\ldots(1)$$

In the current study, a water temperature of 75 ^{0}F was assumed when determining the Reynolds number.

Both pump stations discharge through steel pipes with terminal flap gates. According to project specifications, the wall thickness of the steel pipe installed at Ten Mile Creek WPA is 3/8" for outer pipe diameters less than or equal to 36" and ½" for outer diameters greater than 36" but less than or equal to 54". Published values of new steel pipe roughness include 0.00015 ft (Zipparro and Hasen, 1993) and 0.00025 ft (Sanks, 1989). Friction head losses were computed using both roughness values to evaluate the sensitivity of the modified performance curve to pipe roughness. The rating analysis, however, was based on the average head losses. According to early research by Nagler (1923), head losses incurred at the outlet due to the flap gate are expected to be negligible.

Rating Curve Analysis

The Case 8 model for pump station performance previously implemented by Imru and Wang (2004) is:

$$Q = A\left(\frac{N}{N_O}\right) + BH^C\left(\frac{N_O}{N}\right)^{2C-1} \quad \ldots\ldots (2)$$

Where Q is the discharge at N RPM, H is the TSH, N_O is the design engine or pump speed, and A, B and C are coefficients to be determined through regression. The form of this expression was determined through dimensional analysis and is based on the pump affinity laws. For pumps driven by electric motors, $N_O = N$ so the ratios involving these parameters are eliminated.

Due to the absence of measured flow values, equation (2) was fit to each of the modified pump curves reflecting average head losses. To accomplish this, nonlinear regression techniques were applied using the SAS software. In particular, the NONLIN procedure was implemented with the Marquardt technique to find the optimal values of A, B and C. This approach resembles the technique used by PEST (Doherty, 2004) for optimizing the parameters of nonlinear models.

Effects of Outlet Works on Pump Station Flow

Both S-382 and S-383 are unique in that they differ from a typical SFWMD pump station where the tail water elevation is directly measured. Both S-382 and S-383 discharge into a stilling basin whose stage may be sensitive to the discharge rate. Hence, at each location, an additional analysis was carried out to evaluate whether or not flows through the outlet works would incur any appreciable head loss between the pump outlets and the tail water stage monitoring site.

S-383 Rating Analysis

Station Design

Pump station S-383 contains two vertical, axial flow pumps directly driven by vertical hollow shaft electric motors mounted directly on the pumps. The larger of the two pumps has a capacity of 25 cfs at the design static head and an impeller speed of 880 RPM. The smaller pump has a capacity of 15 cfs at a pump speed of 1180 RPM. Each of the electric motors operates at the same speed as the pump it drives.

A cross section of S-383 is shown in figure 2. The steel discharge pipes are relatively short (42.5 inches) and have a centerline elevation of 28.0 feet NGVD. Water discharged through the pumps flows through a long 54-inch culvert and into a distribution box consisting of gated weirs and outlet culverts (figures A1, Appendix A). Given that the maximum operating level of the downstream STA is 24.0 feet, the outlet of each pump will remain unsubmerged as long as head losses between the STA entrance and the stilling basin total less than 4 feet. Based on the calculations provided in appendix A, this should generally be the case.
The pump performance curves provided by the manufacturer are provided in figures 3. Figure 3a provides the performance curves for the smaller pump while figure 3b shows the performance curves for the larger pump. The system head losses were computed as explained previously and were subtracted from the TDH versus discharge relationship. Tables B.1 through B.4 of Appendix B provide the head loss calculations. It is evident that the head losses within the

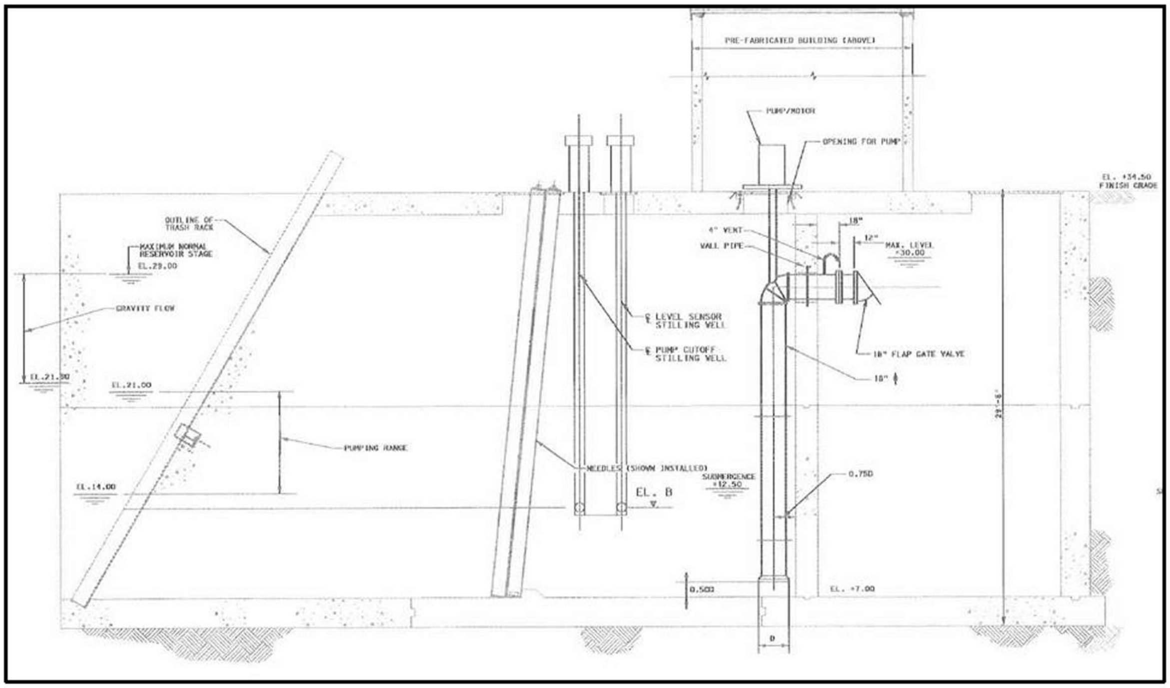
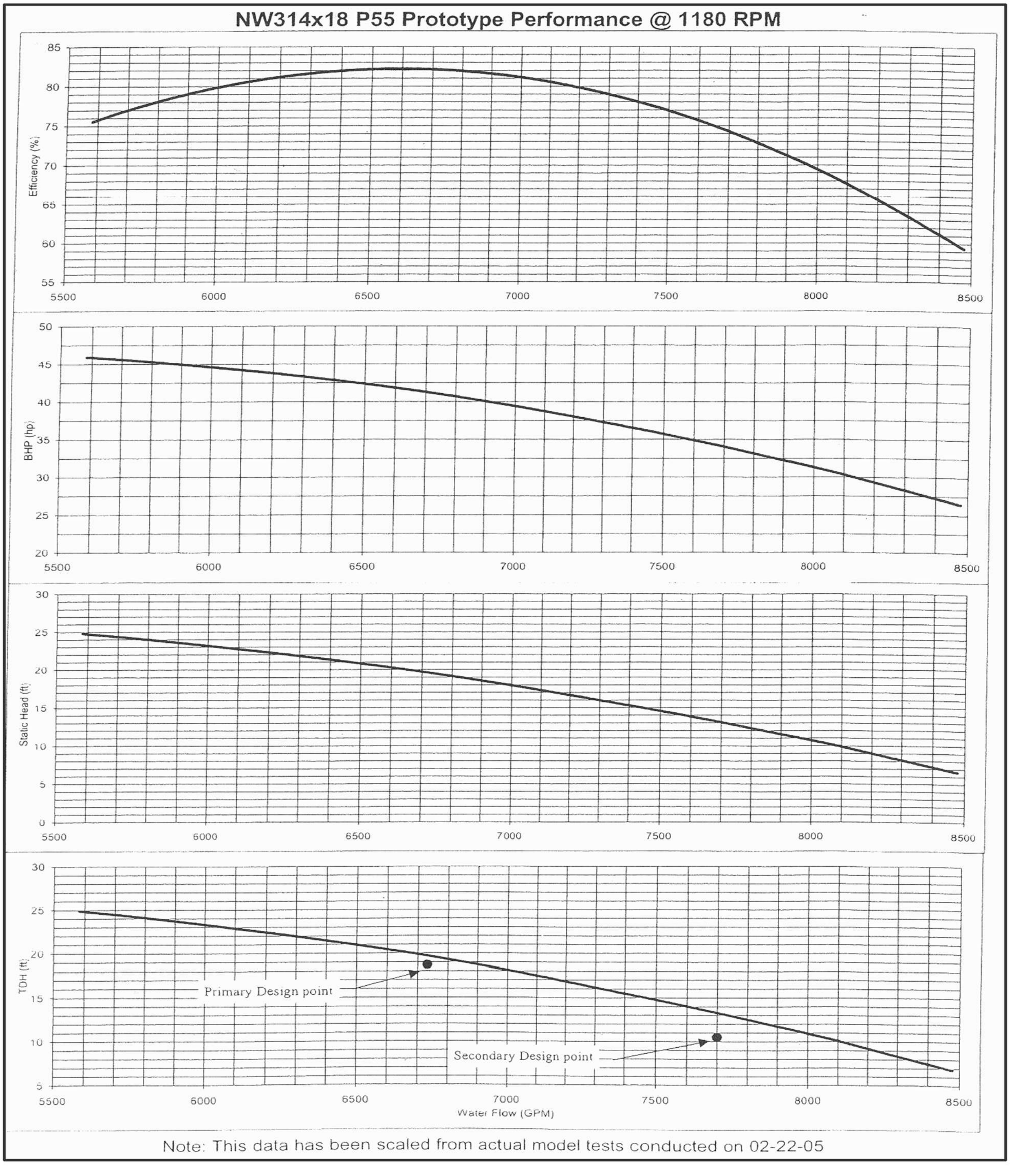


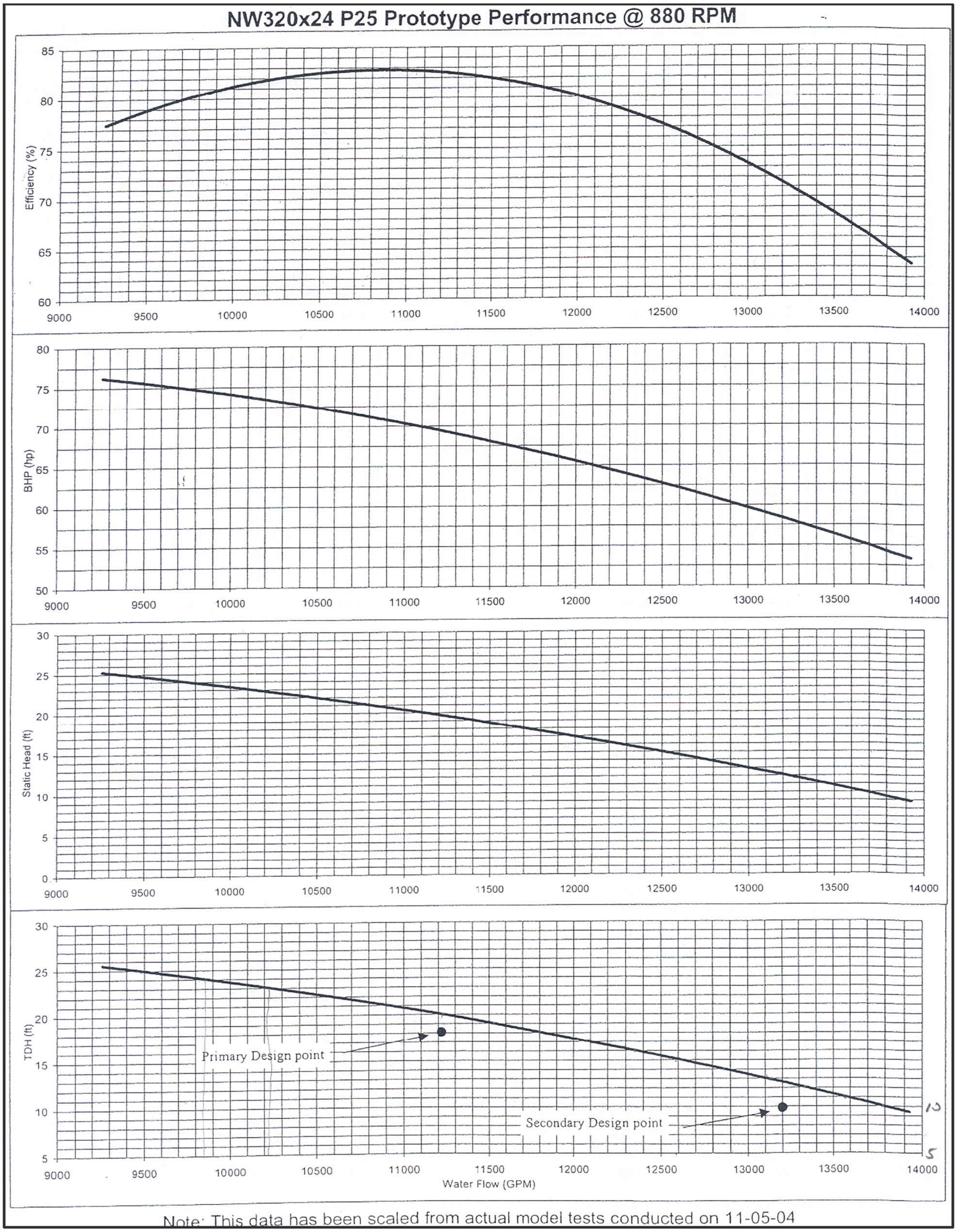
Figure 2. Cross Section of S-383 Pump Station

discharge piping are negligible as expected. Hence the TDH versus discharge relationship and the TSH versus discharge relationship are very similar.



Note: This data has been scaled from actual model tests conducted on 02-22-05

Figure 3a. Performance Curves for the 15 CFS Pump



Note: This data has been scaled from actual model tests conducted on 11-05-04

Figure 3b. Performance Curves for the 25 CFS Pump

Rating Equations

The SAS based, nonlinear regression technique discussed previously was applied to fit each of the adjusted pump performance curves to equation 2. The resultant parameter values along with their approximate 95% confidence intervals are given in table 1.

Table 1. Rating Equation Parameters for S-383

Parameter	**15 CFS Pump**			**25 CFS Pump**		
	Lower 95% C.I.	Expected Value	Upper 95% C.I	Lower 95% C.I.	Expected Value	Upper 95% C.I
A	*19.168*	*19.343*	*19.519*	*33.016*	*33.202*	*33.389*
B	*-0.0249*	*-0.0184*	*-0.0118*	*-0.0589*	*-0.0503*	*-0.0417*
C	*1.733*	*1.838*	*1.943*	*1.651*	*1.700*	*1.749*

A comparison of the discharges computed with these rating equations with those obtained from the modified performance curves is provided in tables 2. It is readily evident that the average error is well within 5%.

Monitoring Recommendations

As mentioned previously, it was determined that the pump outlets are unlikely to ever become submerged under the conditions in which they would operate. However, there is always the possibility of unforeseen events that could cause the pumps to discharge through a submerged outlet. Hence, it is suggested that the monitoring well installed within the stilling basin be equipped with a continuous stage recorder for tail water monitoring purposes.

Recommendations for the Acquisition of Stream Gauging Data

S383 is a new pump station for which no stream flow measurements have been taken. Consequently, the flow rating was based on the pump performance curves along with estimated system head losses. In order to improve the accuracy of the rating, stream gauging data should be acquired at the earliest possible date. Table 3 summarizes the stream gauging needs for the pumps at various head differentials and engine speeds.

Table 3. Recommended Stream Flow Data for S383

Static Head	**RPM**
	Design
0-3.2	5
3.2-6.3	5
6.3-9.5	5

S-382 Rating Analysis

Station Design

S-382 is equipped with three diesel-powered axial pumps with a combined nominal pumping capacity of 380 cfs. Two 54-inch diameter pumps have a nominal capacity of approximately 160 cfs each and one 36-inch pump has a nominal capacity of approximately 60 cfs. The impeller speed of the larger pumps is 400 rpm while the design impeller speed of the smaller pump is 600 rpm. All pumps are driven by diesel engines whose operating speed is 1200 rpm.

A schematic cross section of the 36-inch pump along with its discharge line is shown in figure 4. The corresponding cross section of the 54-inch pumps and their appurtenances is similar. Each

Table 2a. Evaluation of the rating equation for the 15 cfs pump

Flow Computed with Rating Equation			**Adjusted Pump Curve Flow**	**% Error**
lower 95% C.I.	**estimated value**	**upper 95% C.I.**		
12.64	12.58	13.44	12.48	0.83
12.82	12.78	13.63	12.70	0.63
13.04	13.03	13.86	12.92	0.79
13.13	13.12	13.96	13.15	-0.18
13.37	13.39	14.20	13.37	0.12
13.50	13.53	14.34	13.59	-0.49
13.69	13.74	14.53	13.82	-0.58
13.90	13.96	14.75	14.04	-0.54
14.11	14.19	14.96	14.26	-0.52
14.31	14.41	15.16	14.48	-0.54
14.51	14.62	15.36	14.71	-0.59
14.71	14.83	15.56	14.93	-0.66
15.02	15.16	15.86	15.15	0.04
15.16	15.32	16.01	15.38	-0.37
15.46	15.63	16.29	15.60	0.20
15.63	15.82	16.47	15.82	-0.02
15.84	16.04	16.67	16.04	-0.04
16.11	16.32	16.92	16.27	0.33
16.31	16.53	17.11	16.49	0.22
16.50	16.72	17.29	16.71	0.07
16.77	17.01	17.54	16.94	0.43
17.01	17.25	17.76	17.16	0.53
17.20	17.45	17.94	17.38	0.40
17.36	17.61	18.08	17.60	0.06
17.60	17.85	18.29	17.83	0.13
17.82	18.08	18.49	18.05	0.16
18.01	18.26	18.64	18.27	-0.07
18.19	18.44	18.79	18.50	-0.32
18.36	18.61	18.94	18.72	-0.58

pump discharges into a steel pipe approximately 90 feet long that terminates in a stilling basin.

Table 2b. Evaluation of the rating equation for the 25 cfs pump

Flow Computed with Rating Equation			Adjusted Pump Curve Flow	% Error
lower 95% C.I.	estimated value	upper 95% C.I.		
20.66	20.91	21.38	20.72	0.91
20.90	21.16	21.62	20.95	1.01
21.06	21.32	21.79	21.17	0.71
21.22	21.48	21.95	21.39	0.42
21.45	21.72	22.19	21.61	0.50
21.69	21.96	22.43	21.84	0.56
21.84	22.12	22.59	22.06	0.26
22.00	22.28	22.75	22.28	-0.04
22.22	22.51	22.98	22.51	0.01
22.53	22.82	23.29	22.73	0.39
22.68	22.97	23.44	22.95	0.08
22.97	23.27	23.74	23.17	0.42
23.12	23.42	23.89	23.40	0.11
23.34	23.65	24.12	23.62	0.11
23.49	23.79	24.26	23.84	-0.21
23.77	24.09	24.56	24.07	0.08
24.06	24.37	24.84	24.29	0.35
24.20	24.52	24.98	24.51	0.02
24.41	24.73	25.20	24.73	-0.02
24.72	25.04	25.51	24.96	0.35
24.82	25.15	25.61	25.18	-0.13
25.09	25.42	25.88	25.40	0.07
25.36	25.69	26.15	25.63	0.26
25.49	25.83	26.28	25.85	-0.09
25.75	26.09	26.55	26.07	0.07
26.04	26.38	26.84	26.29	0.33
26.20	26.54	26.99	26.52	0.10
26.49	26.83	27.27	26.74	0.32
26.70	27.04	27.49	26.96	0.30
26.95	27.29	27.73	27.19	0.38
27.19	27.53	27.97	27.41	0.45
27.36	27.71	28.14	27.63	0.28
27.60	27.94	28.37	27.85	0.32
27.83	28.17	28.60	28.08	0.34
28.00	28.34	28.76	28.30	0.15
28.28	28.62	29.03	28.52	0.33
28.47	28.81	29.22	28.75	0.22
28.71	29.05	29.45	28.97	0.27
28.97	29.31	29.71	29.19	0.39
29.10	29.43	29.83	29.41	0.06
29.37	29.71	30.09	29.64	0.23
29.52	29.85	30.23	29.86	-0.03
29.76	30.09	30.46	30.08	0.02
29.95	30.27	30.64	30.31	-0.11
30.18	30.50	30.86	30.53	-0.10
30.40	30.71	31.07	30.75	-0.12
30.61	30.92	31.27	30.97	-0.17

The cross section of the outlet works is shown in figure 5. Just downstream of the discharge pipe terminus is a baffle with a bottom opening that is 2 feet wide. Immediately downstream of the stilling basin is a baffled chute with a crest elevation equal to the discharge pipe centerline elevation. The pump performance curves provided by the manufacturer are given in figures 6. The system head losses were computed as explained previously and were subtracted from the TDH versus discharge relationship. Tables B.5 through B.8 provide the head loss calculations while figures 7 provide the pump station performance curves that relate TSH to discharge. The computed friction head losses do not appear to be sensitive to the value of pipe roughness within its estimated range.

Rating Equations

The SAS based, nonlinear regression technique discussed previously was applied to fit each of the adjusted pump performance curves to equation 2. The resultant parameter values along with their approximate 95% confidence intervals are given in table 4.

A comparison of the discharges computed with these rating equations with those obtained from the modified performance curves is provided in tables 5. It is readily evident that the average error is well within 5%.

Table 4. Rating Equation Parameters for S-382

Parameter	**60 CFS Pump**			**160 CFS Pumps**		
	Lower 95% C.I.	Expected Value	Upper 95% C.I	Lower 95% C.I.	Expected Value	Upper 95% C.I
A	*81.336*	*82.079*	*82.822*	*195.4*	*196.7*	*198.1*
B	*-0.0926*	*-0.0687*	*-0.0447*	*-0.116*	*-0.0824*	*-0.049*
C	*1.745*	*1.845*	*1.945*	*1.871*	*1.990*	*2.109*

Effects of the Outlet Works on the Rating Equation Implementation

It is apparent from the design of the outlet works (figure 5) that unless water levels are monitored at the upstream end of the stilling basin, measured tail water elevations will not reflect the water level at the pump outlets. These stages are needed to implement the rating equations. Unfortunately, the closest stage recorders specified in the current monitoring plan are located in the reservoir. Currently, a stilling well installed near the downstream end of the stilling basin could be monitored continuously if funds are available. Hydraulic conditions at this and other locations, however, may not be conducive to obtaining accurate stages.

If stages cannot be monitored at the upstream end of the stilling basin, the tail water elevation at the pump outlets will have to be estimated from the discharge rate along with the hydraulic properties of the outlet works. In particular, the tail water elevation at the pump outlets depends on the discharge rate and vice versa. This necessitates classifying S-382 as a special case in the flow program. This case differs from case 8 in that an iterative technique must be used to compute both the discharge rate and the tail water elevation at the pump outlets.

The technique developed is illustrated in figure 7. Initially, the tail water elevation at the pump outlets is taken to be either at the centerline of the pump outlets or the measured reservoir level, whichever is higher. Using this tail water elevation, the flow rate through S-382 is computed using the rating equations presented earlier. This computed discharge rate is subsequently used to establish the energy grade line elevation above the crest of the baffle chute. This is accomplished by first setting the hydraulic grade line elevation at this location to either critical depth or the tail

Table 5a. Evaluation of the Rating Equation for the 60 cfs Pump

Flow Computed from Rating Equation			**Adjusted Pump Curve Flow**	**% Error**
lower 95% C.I.	**estimated value**	**upper 95% C.I.**		
50.00	49.62	53.33	48.58	2.14
50.56	50.23	53.92	49.47	1.54
50.83	50.53	54.20	50.36	0.34
51.67	51.45	55.09	51.25	0.39
52.70	52.56	56.15	52.14	0.81
52.87	52.75	56.33	53.03	-0.53
53.69	53.65	57.18	53.93	-0.51
54.69	54.73	58.21	54.82	-0.16
55.04	55.11	58.57	55.71	-1.07
56.02	56.17	59.57	56.60	-0.76
56.80	57.02	60.37	57.49	-0.82
57.58	57.86	61.17	58.38	-0.90
58.60	58.96	62.20	59.27	-0.53
59.27	59.68	62.88	60.17	-0.80
60.43	60.92	64.04	61.06	-0.22
60.92	61.44	64.53	61.95	-0.82
62.20	62.81	65.80	62.84	-0.05
62.75	63.39	66.35	63.73	-0.53
63.82	64.53	67.41	64.62	-0.13
64.80	65.57	68.36	65.51	0.09
65.61	66.42	69.15	66.40	0.03
66.55	67.41	70.05	67.30	0.16
67.32	68.22	70.80	68.19	0.04
68.48	69.42	71.90	69.08	0.50
69.34	70.32	72.71	69.97	0.50
70.17	71.18	73.49	70.86	0.45
71.22	72.26	74.46	71.75	0.71
72.00	73.06	75.18	72.64	0.57
72.75	73.82	75.86	73.54	0.39
73.80	74.88	76.80	74.43	0.61
74.58	75.67	77.49	75.32	0.47
75.33	76.42	78.15	76.21	0.28
76.04	77.13	78.76	77.10	0.04
76.89	77.96	79.48	77.99	-0.04
77.59	78.65	80.06	78.88	-0.30
78.32	79.34	80.65	79.77	-0.54
78.91	79.91	81.12	80.67	-0.94

Table 5b. Evaluation of the Rating Equation for the 160 cfs Pumps

Flow Computed from Rating Equation			Adjusted Pump Curve Flow	% Error
lower 95% C.I.	estimated value	upper 95% C.I.		
142.41	141.13	149.32	140.53	0.43
146.50	145.68	153.54	145.29	0.27
150.50	150.11	157.63	150.64	-0.35
154.28	154.27	161.45	155.09	-0.53
157.85	158.17	165.01	158.66	-0.31
161.27	161.89	168.39	162.22	-0.20
164.54	165.43	171.58	165.79	-0.22
167.60	168.71	174.52	168.46	0.15
170.57	171.89	177.34	172.03	-0.08
173.33	174.81	179.93	174.70	0.06
175.94	177.56	182.33	177.38	0.10
178.41	180.13	184.57	180.16	-0.02
180.66	182.45	186.56	181.83	0.34
182.79	184.63	188.43	184.17	0.25
184.76	186.63	190.11	186.29	0.18
186.58	188.45	191.64	188.52	-0.04
188.24	190.09	192.99	190.75	-0.34
188.69	190.53	193.35	191.08	-0.29

water depth induced by the reservoir, whichever is higher. The exit head loss from the stilling basin is then added to the energy grade line elevation at the chute crest and is used as an estimate of the energy grade line elevation within the portion of the stilling basin downstream of the concrete baffle. The energy grade line elevation on the upstream side of the baffle is then initially estimated using the specified flow rate, the energy grade line elevation on the downstream side and an orifice equation. If, however, the hydraulic grade line elevation on the downstream side is within a certain tolerance of the baffle crest elevation, both a weir and orifice equation are used. Similarly, if the baffle head water elevation computed with the orifice equation alone is above the baffle crest, then the computation is repeated with both an orifice and weir formulation. The resultant energy grade line elevation on the upstream side of the concrete baffle constitutes a revised estimate of the pump station tail water elevation. If this estimate of the pump station tail water elevation does not agree with the starting estimate, both estimates are used to determine a revised initial estimate and the entire procedure is repeated until two consecutive pump station tail water elevations agree within a specified tolerance. When such a convergence has been achieved, the corresponding discharge rate is the flow rate returned by the flow program and associated with the measured head water and tail water elevations for the entire facility. The primary consequence of implementing this procedure to estimate the effective tail water elevation of the pump station is a reduction in the accuracy of the computed flows and an increase in the number of measured flows needed to calibrate the entire procedure. The latter effect is due to an increase in the number of parameters associated with the entire rating procedure (i.e. the orifice and weir coefficients must be considered). Fortunately, an inspection of the pump station performance curves reveals that an error of one foot in the computed pump station tail water elevation would result in an error of about 3% or less in the computed flow rate.

Recommendations for the Acquisition of Stream Gauging Data

S382 is a new pump station for which no stream flow measurements have been taken. Consequently, the flow rating was based on the pump performance curves along with estimated system head losses. In order to improve the accuracy of the rating, stream gauging data should be acquired at the earliest possible date. Table 6 summarizes the stream gauging needs for the pumps at various head differentials and engine speeds.

Table 6. Recommended Stream Flow Data for S382

Static Head	**RPM**		
	600-800	*800-1000*	*1000-1200*
12-14.5	5	5	5
14.5-17	5	5	5
17-19.5	5	5	5

Summary and Conclusions

The standard procedure for conducting hydraulic rating analyses of new pump stations was implemented for pump stations S-382 and S-383, located at the Ten Mile Creek WPA. Since no measured flow data exist, the ratings were based on the manufacturer's pump performance curves along with computed energy losses within the pump stations' piping and appurtenances. At each pump station, differences in flows computed by the rating equations and flows obtained from the pump station performance curves were nearly always less than 1%.

In developing the hydraulic rating equations for the pump stations, some unique circumstances were encountered. Both pump stations discharge into some outlet works situated between the pump station outlets and the tail water monitoring gauge. At S-383, it was determined that head losses within the outlet structures would not affect pump station discharges under the expected range of flows and water levels. This is primarily due to both the elevation at which the discharge pipes were installed and the capacity of the outfall facilities.

At S-382, it was found that the head losses incurred within the outlet structures can be appreciable and result in a significant difference in head between the tail water monitoring site and the discharge pipe outlets. Consequently, the developed case 8 rating equation cannot be applied directly between the measured head water and tail water locations for S-382. As a solution, a special rating case was developed specifically for S-382 and implemented into the flow program. In this case, the case 8 rating equation itself remains the same while an iterative procedure is used to compute the effective tail water for the pump station. This special case can be modified or eliminated altogether by moving the tail water monitoring site to a more favorable location.

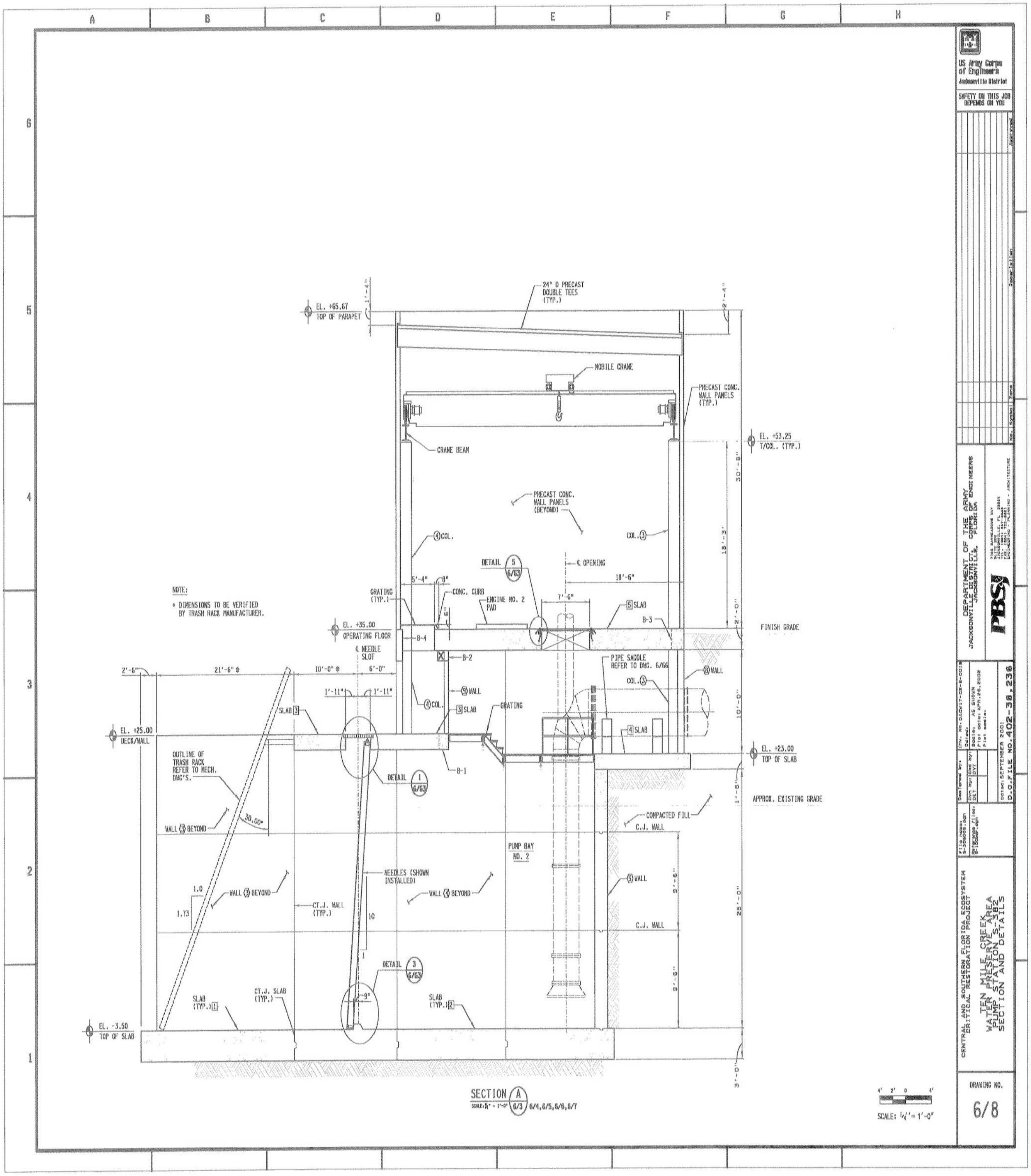


Figure 4. Schematic Cross Section of S-382 Pumps and Discharge Pipes

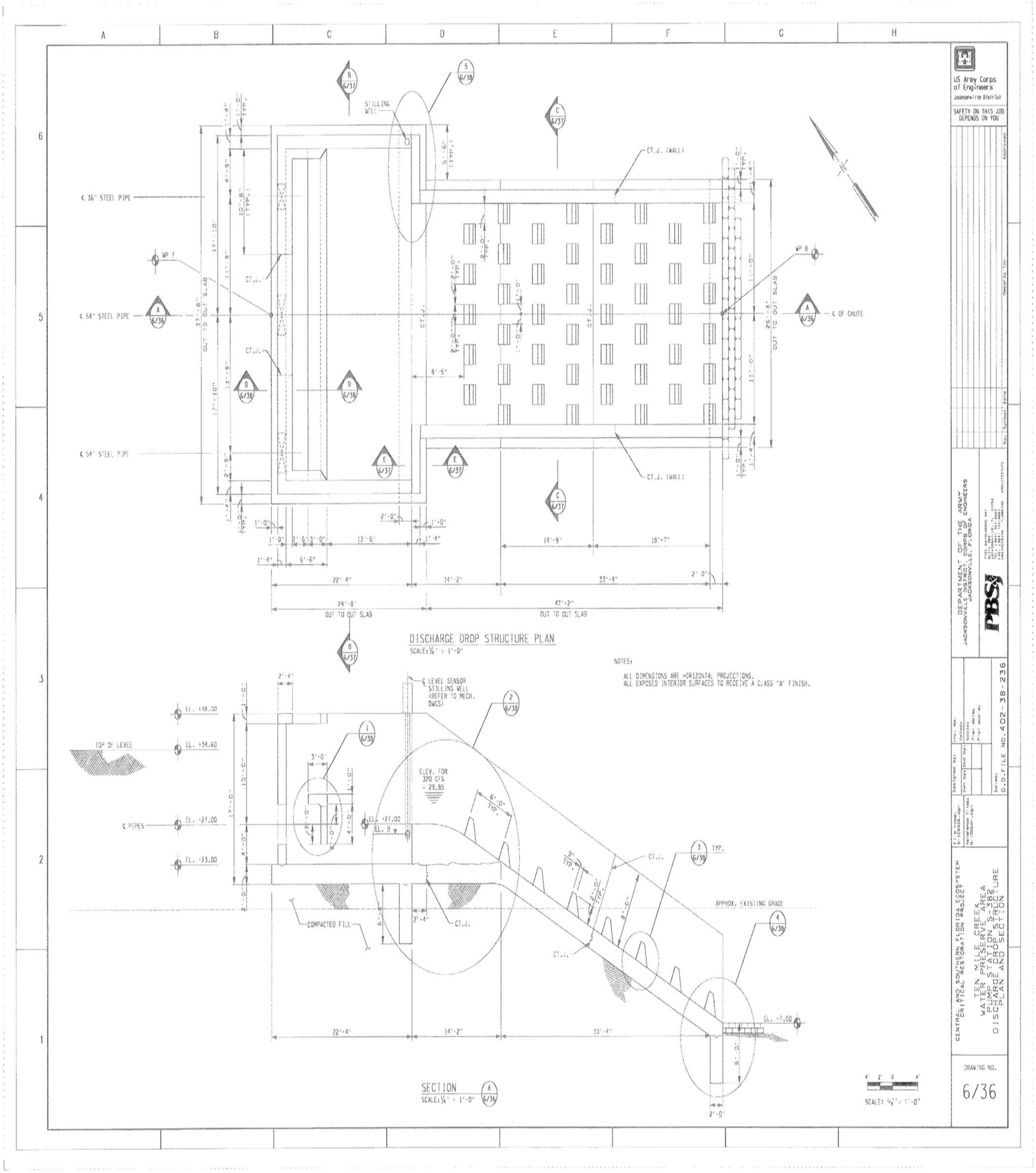


Figure 5. Cross Section of the Outlet Works for S-382

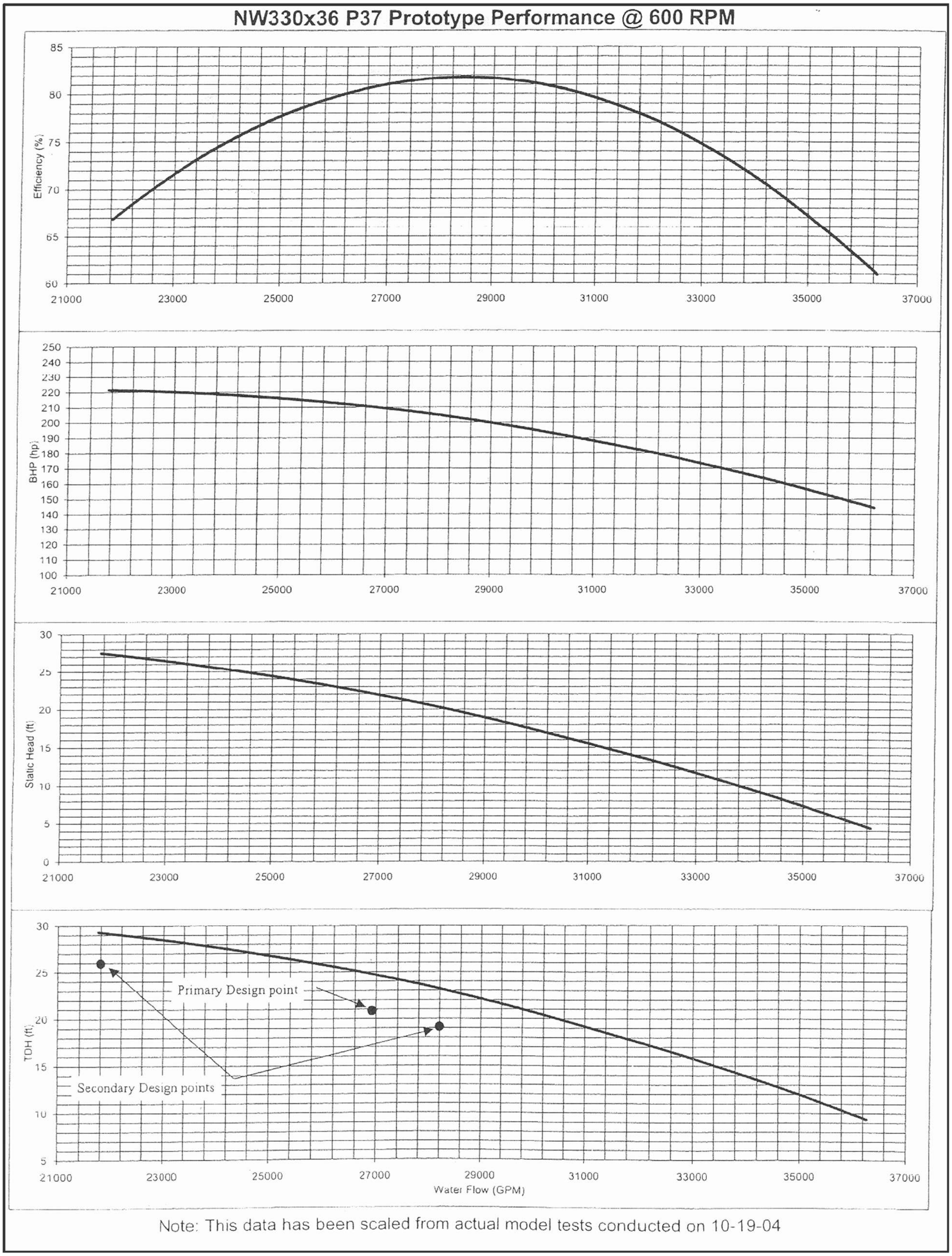
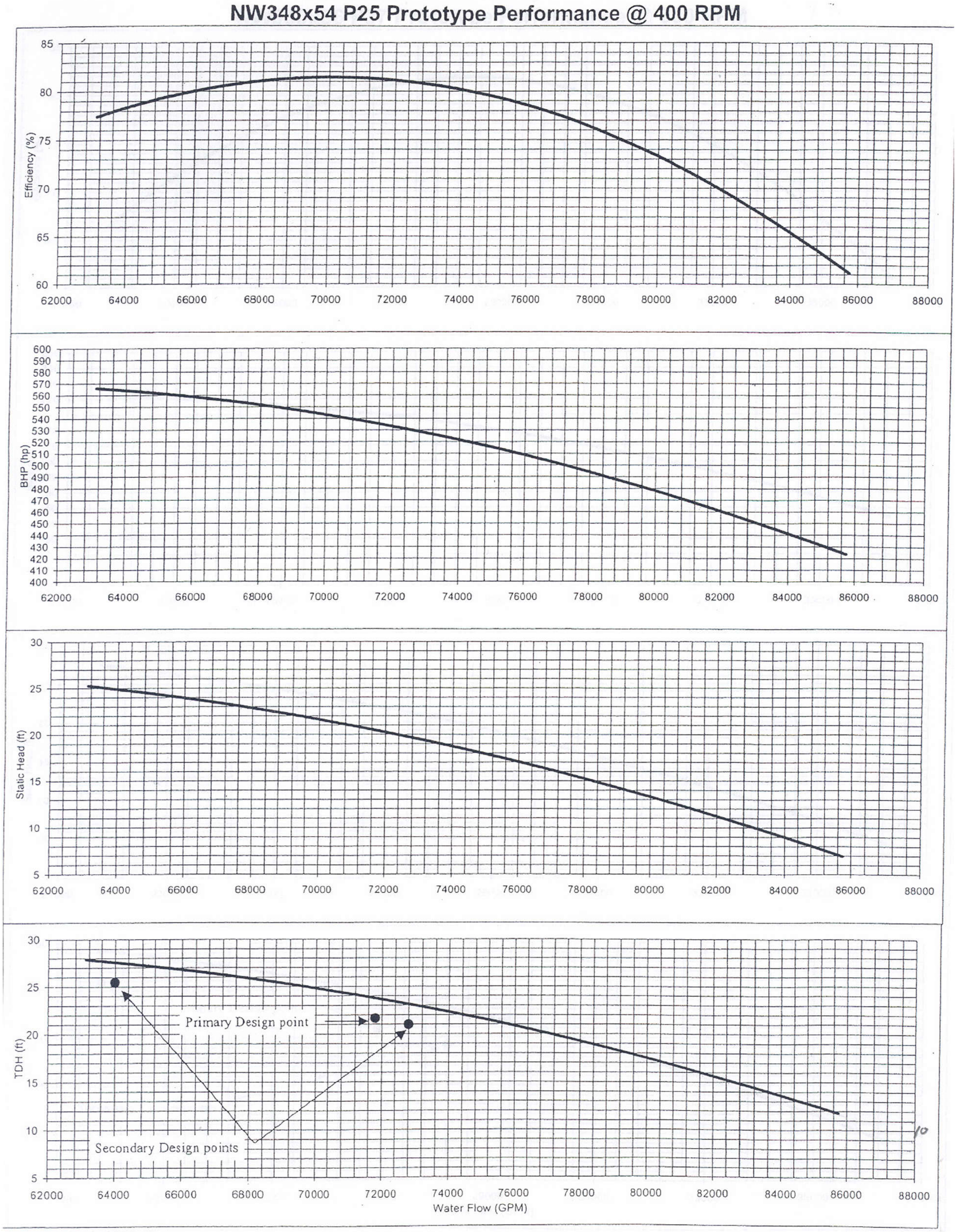


Figure 6a. Performance Curves for the 60 cfs Pump at S-382



Note: This data has been scaled from actual model tests conducted on 11-05-04

Figure 6b. Performance Curves for the 160 cfs Pump at S-382

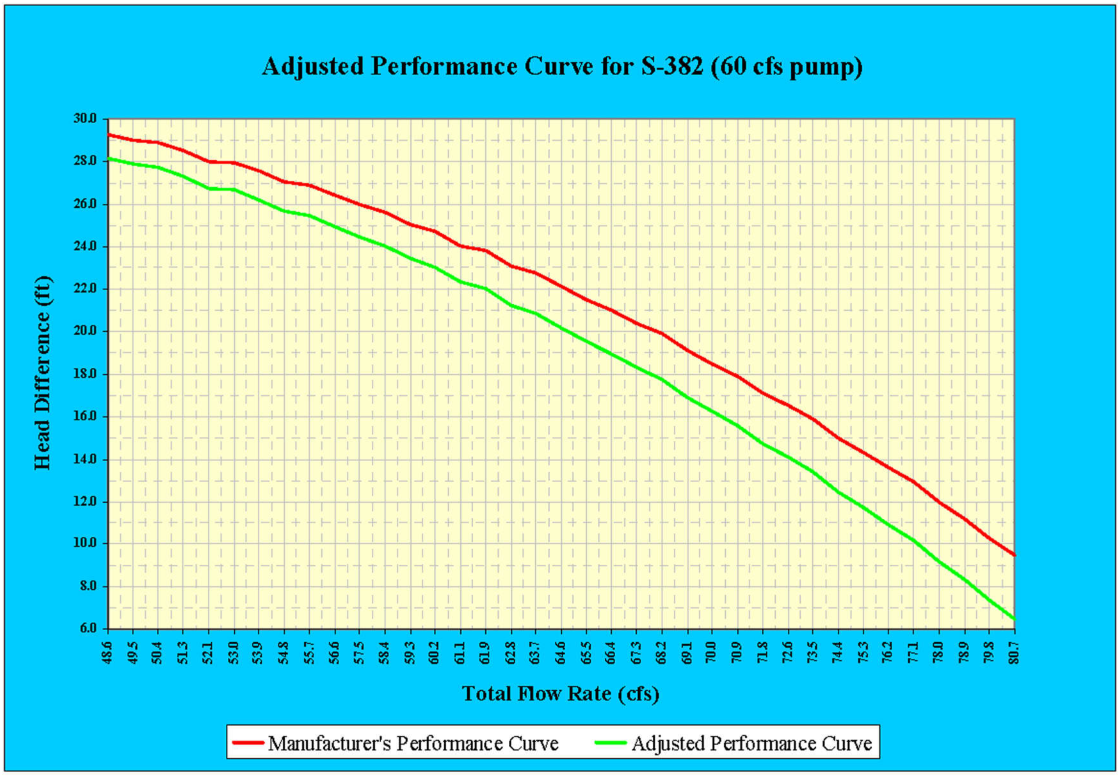


Figure 7a. Adjusted Performance Curve for the 60 cfs Pump at S-382

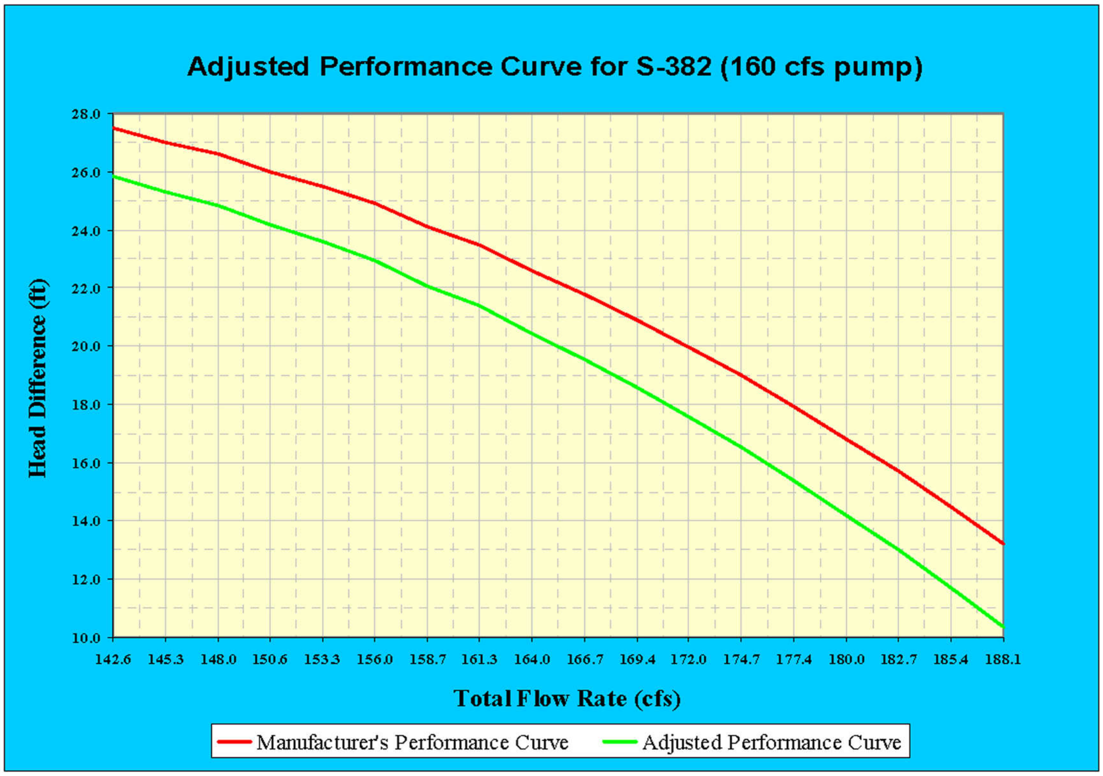


Figure 7b. Adjusted Performance Curve for the 160 cfs Pump at S-382

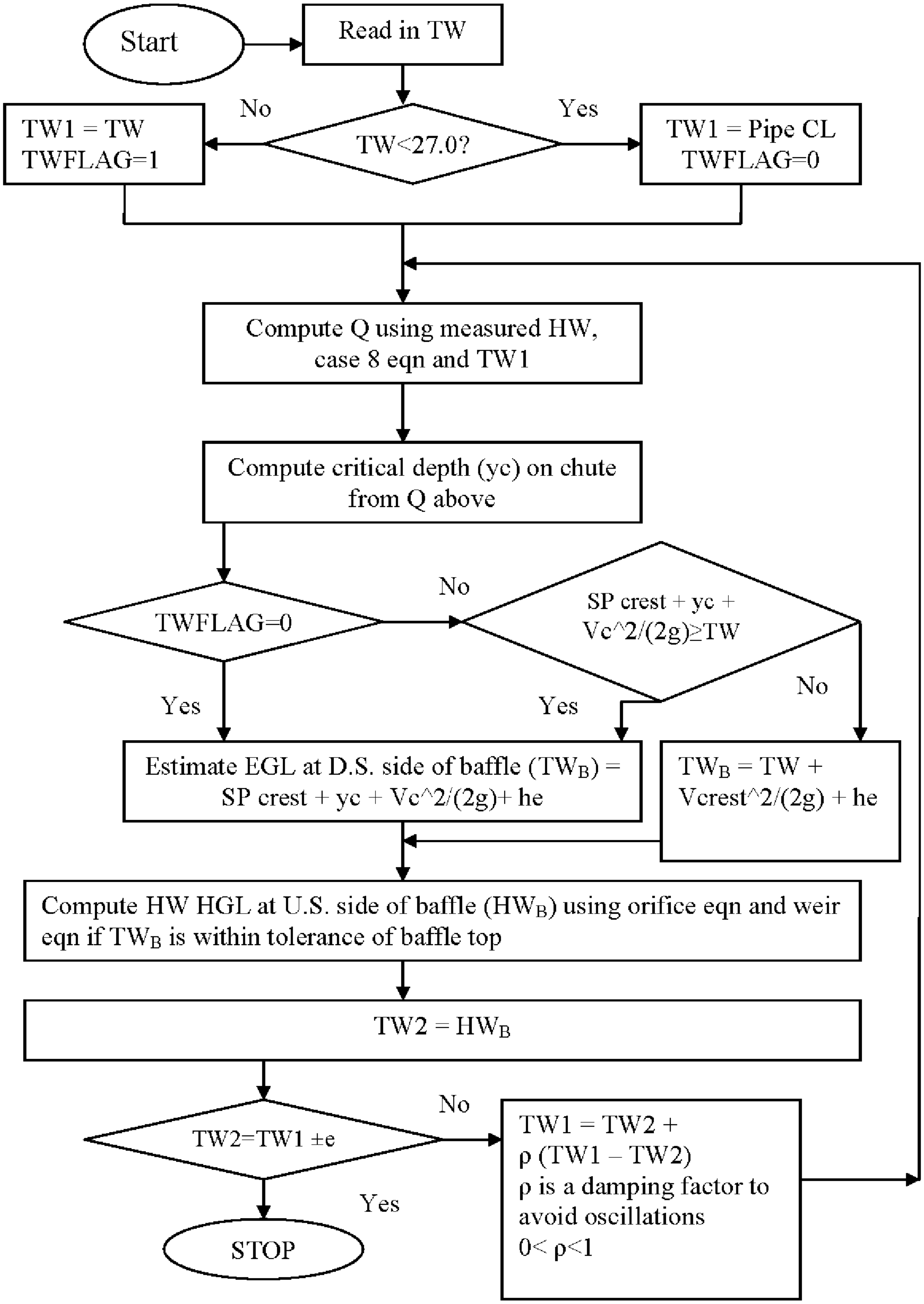


Figure 8. Iterative Procedure for Computing the Effective Tail Water Elevation at S-382

References

Bombardelli, F. A. and M. H. Garcia. 2003. "Hydraulic Design of Large Diameter Pipes." *Journal of Hydraulic Engineering, ASCE*, 129(11), 839-846.

Daugherty, R. L. and Franzini, J. B. 1977. *Fluid Mechanics with Engineering Applications, 7th Ed.* McGraw-Hill, New York.

Diskin, M. H. 1960. "The limits of applicability of the Hazen-Williams formula." *Houille Blanche*, 6, 720-723.

Doherty, J. E. 2004. PEST Model-Independent Parameter Estimation, User's Manual: 5th edition. Watermark Numerical Computing, Brisbane, Australia, 336 pp.

Goforth, G. F. 2006. Operation Plan : Ten Mile Creek Water Preserve Area. South Florida Water Management District, West Palm Beach, Florida, 48 pp.

Imru, M. and Y. Wang. 2004. Flow Rating Development for New Pump Stations. Technical Publication EMA # 419, South Florida Water Management District, West Palm Beach, Florida, 44 pp.

Liou, C. P. 1998. "Limitations and proper use of the Hazen-Williams equation." *Journal of Hydraulic Engineering, ASCE*, 124(9), 951-954.

Nagler, F. A. 1923. "Hydraulic tests of Calco automatic drainage gates." *The Transit, State University of Iowa,* vol 27.

Sanks, R. L. 1989. *Pumping Station Design.* Butterworth Publishers, Stoneham, MA.

Swamee, P. K. and A. K. Jain. 1976. "Explicit equations for pipe flow problems." *Journal of The Hydraulics Division, ASCE*, 102(5), 657-664.

Zipparro, V. J. and H. Hasen. 1993. *Davis' Handbook of Applied Hydraulics.* McGraw-Hill, New York.

Appendix A. Head Loss Calculations for S-383 Outlet Structures

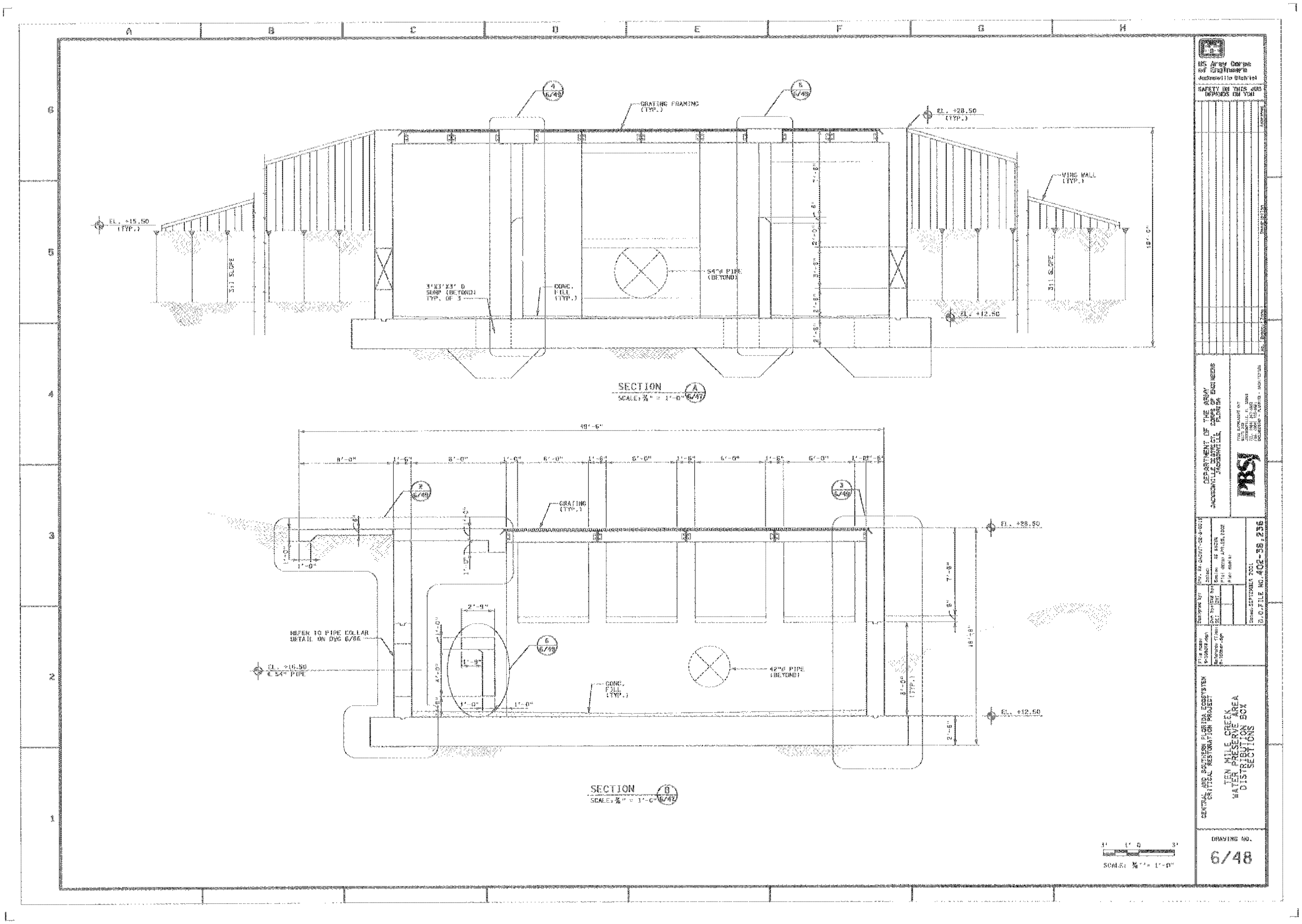


Figure A1. Cross Section of the Outlet Works for S-383

South Florida Water Management District
OPERATIONS & HYDRO DATA MANAGEMENT DIVISION

Calculations

Form #0230
Rev.11/97

Project: S-383 RATING ANALYSIS
Subject: HEAD LOSSES THRU OUTLET WORKS
Engineer: WILSNACK
Sheet No. 1 of 5
Job No. / Program Code:
Date: 10/3/06 Checked By: LI

ESTIMATE HYDRAULIC PROFILE THROUGH OUTLET WORKS @ MAXIMUM FLOW, TAILWATER:

$Q_{MAX} = 40$ CFS ± MAX STA LEVEL = 24.0 FT

Q PER SIDE = 20 CFS

DISCHARGE THROUGH OUTLET PORTS $\approx CA\sqrt{2g(h_d - 24)}$

$C \approx 0.6$ $A = \frac{\pi(3.5)^2}{4}$

$$20 = (0.6)\left[\frac{\pi(3.5)^2}{4}\right]\sqrt{2g(h_d - 24)} \Rightarrow h_d = 24.19 \text{ FT}$$

DOWNSTREAM OF WEIRS

DISCHARGE PER SIDE WEIR $\simeq 20/4 = 5$ CFS

$$5 \simeq C_d L H^n \left[1 - \left(\frac{h}{H}\right)^n\right]^{0.385}$$

$C_d \simeq 3.13$ $L = 6'$ $n = 3/2$

H = UPSTREAM HEAD ON WEIR CREST
h = DOWNSTREAM " " "

$$5 = (3.13)(6)H^{3/2}\left[1 - \left(\frac{24.19 - 21}{H}\right)^{3/2}\right]^{0.385}$$

South Florida Water Management District
OPERATIONS & HYDRO DATA MANAGEMENT DIVISION

Calculations

Form #0230
Rev.11/97

Project: S-383 RATING ANALYSIS Sheet No. 2 of 5
Subject: HEAD LOSSES THRU OUTLET WORKS Job No. / Program Code:
Engineer: WILSNACK Date: 10/3 Checked By: LI

$$0.27 = H^{3/2}\left[1-\left(\frac{3.19}{H}\right)^{3/2}\right]^{0.385}$$

$$H^{3/2} = 5.70 + \frac{0.032}{H^{2.4}} \Rightarrow H \approx 3.19?$$

∴ HEAD LOSSES ACROSS SIDE DISCHARGE WEIRS ARE VERY LOW

@ PEAK FLOW THRU P.S. ONLY, W.S. ELEV IN THE DISTRIBUTION BOX ≈ 24.2 FT DOWNSTREAM OF THE BAFFLE

HEAD LOSS ACROSS BAFFLE:

TOP OF BAFFLE @ 19.25 FT → SUBMERGED OVERFLOW

$h_B = 24.2 - 19.25 = 4.95$ FT

BAFFLE WIDTH = 2.75 FT $= W_c$

$\frac{h_B}{W_c} = 1.80$ → SHOULD ACT AS SHARP CRESTED WEIR FOR OVERTOPPING (ANSAR + ALEXIS, 2003)

ORIFICE FLOW: $Q_o = CA\sqrt{2g(H_B - h_B)}$

WEIR FLOW: $Q_W = C_d L H_B^{n}\left[1-\left(\frac{h_B}{H_B}\right)^{n}\right]^{0.385}$

South Florida Water Management District
OPERATIONS & HYDRO DATA MANAGEMENT DIVISION

Calculations

Form #0230
Rev.11/97

Project: S-383 RATING ANALYSIS
Sheet No. 3 of 5
Subject: HEAD LOSSES THRU OUTLET WORKS
Job No. / Program Code:
Engineer: WILSNACK
Date: 10/3
Checked By: LI

$C \simeq 0.7$ (ZIPPARRO + HASEN, 1993)

$A = (1.75)(10) = 17.5 \text{ FT}^2$ $L = 10'$

$n = 3/2$ (ANSAR + ALEXIS, 2003)

$Cd = 3.13$

$$40 = (0.7)(17.5)(\sqrt{2g})\sqrt{H_B - 4.95} + (3.13)(10)\,H_B^{3/2}\left[1 - \left(\frac{4.95}{H_B}\right)^{3/2}\right]^{0.385}$$

$$1.28 = 3.14\sqrt{H_B - 4.95} + H_B^{3/2}\left[1 - \frac{11.01}{H_B^{3/2}}\right]^{0.385}$$

$H_B \simeq 4.956'$ $\Rightarrow$ HEAD LOSS ACROSS BAFFLE IS NEGLIGIBLE!

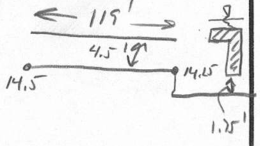
$\therefore$ TAKE W.S. ELEV THROUGHOUT DIST BOX $\simeq 24.2$ FT = TW DEPTH FOR CULVERT

South Florida Water Management District
OPERATIONS & HYDRO DATA MANAGEMENT DIVISION

Calculations

Form #0230
Rev.11/97

Project S-383 RATING ANALYSIS Sheet No. 4 of 5
Subject: HEAD LOSSES THRU OUTLET WORKS Job No. / Program Code: ___
Engineer: WILSNACK Date: 10/3 Checked By: LI



FLOW THROUGH DISCHARGE CULVERT:

$Q = 40$ CFS (PUMPS ONLY)

$$Q_f = \left(\frac{1.49}{0.012}\right)\left(\frac{\pi}{4}\right)\left(\frac{81}{4}\right)\left(\frac{9}{8}\right)^{2/3}\sqrt{0.0021} = 98 \text{ CFS}$$

$$\frac{Q}{Q_f} = \frac{40}{98} = 0.41 \Rightarrow \frac{y_n}{D} = 0.51$$

$$Z = \frac{Q}{\sqrt{g}} = \frac{40}{\sqrt{32.2}} = 7.05$$

$$\frac{Z}{D^{2.5}} = 0.16 \Rightarrow \frac{y_c}{D} = 0.40$$

$y_n > y_c \rightarrow$ CULVERT SLOPE IS MILD

OUTLET TW ELEV = 24.2 FT

CROWN @ OUTLET IS AT ELEV 18.75
" " INLET " " " 19.0

OUTLET IS SUBMERGED

$\therefore$ PIPE WILL FLOW FULL

$$h_l = \frac{4.64\, n^2 Q^2 L}{D^{16/3}} = \frac{(4.64)(0.012)^2(40)^2(119)}{(4.5)^{16/3}}$$

South Florida Water Management District
OPERATIONS & HYDRO DATA MANAGEMENT DIVISION

Calculations

Form #0230
Rev.11/97

Project: S-383 RATING ANALYSIS
Sheet No. 5 of 5
Subject: HEAD LOSSES THRU OUTLET WORKS
Job No. / Program Code:
Engineer: WILSNACK
Date: 10/3
Checked By: LL

$hl = 0.04$ FT

BARREL AREA = $\frac{81\pi}{16} = 15.90$ FT^2

$V = \frac{40}{15.90} = 2.52$ FT/S $\qquad \frac{V^2}{2g} = 0.1$ FT

$h_{ex} = 0.1$ FT

$h_{ent} = (0.5)(0.1) = 0.05$ FT

TOTAL HEAD LOSS THROUGH CULVERT = $0.1 + 0.04 + 0.05$

$= 0.19$ FT

≈ 0.2 FT

W.S. ELEV IN STILLING BASIN

$= 24.2 + 0.2 = 24.4$ FT

PUMP DISCHARGE ℄ ELEV = 28.0 FT

∴ NOT LIKELY THAT PUMP OUTLETS WILL BE SUBMERGED UNDER THE CONDITIONS THAT THE PUMPS WOULD TYPICALLY OPERATE.

Appendix B. Head Loss Calculations for S-382, S-382 Performance Curves

Table B1. S-383 Head Losses with 15 CFS Pump and Minimum Pipe Roughness

1180 RPM						Swamee & Jain(1976)				
TDH(ft)	Q (GPM)	Q(cfs)	V(ft/s)	N_R	$V^2/2g$ (ft)	f	$h_l = f(L/D)V^2/2g$	$h_m = \Sigma KV^2/2g$	Total Head Loss (ft)	Static Head (ft)
24.90	5600	12.48	7.69	1105275	0.92	0.01346	0.03	0.00	0.03	24.9
24.50	5700	12.70	7.83	1125012	0.95	0.01345	0.03	0.00	0.03	24.5
24.00	5800	12.92	7.96	1144749	0.98	0.01343	0.03	0.00	0.03	24.0
23.80	5900	13.15	8.10	1164486	1.02	0.01341	0.03	0.00	0.03	23.8
23.25	6000	13.37	8.24	1184223	1.05	0.01339	0.03	0.00	0.03	23.2
22.95	6100	13.59	8.38	1203961	1.09	0.01338	0.04	0.00	0.04	22.9
22.50	6200	13.82	8.51	1223698	1.13	0.01336	0.04	0.00	0.04	22.5
22.00	6300	14.04	8.65	1243435	1.16	0.01335	0.04	0.00	0.04	22.0
21.50	6400	14.26	8.79	1263172	1.20	0.01333	0.04	0.00	0.04	21.5
21.00	6500	14.48	8.92	1282909	1.24	0.01332	0.04	0.00	0.04	21.0
20.50	6600	14.71	9.06	1302646	1.28	0.01330	0.04	0.00	0.04	20.5
20.00	6700	14.93	9.20	1322383	1.31	0.01329	0.04	0.00	0.04	20.0
19.20	6800	15.15	9.34	1342120	1.35	0.01327	0.04	0.00	0.04	19.2
18.80	6900	15.38	9.47	1361857	1.39	0.01326	0.05	0.00	0.05	18.8
18.00	7000	15.60	9.61	1381594	1.43	0.01325	0.05	0.00	0.05	18.0
17.50	7100	15.82	9.75	1401331	1.48	0.01324	0.05	0.00	0.05	17.5
16.90	7200	16.04	9.89	1421068	1.52	0.01322	0.05	0.00	0.05	16.9
16.10	7300	16.27	10.02	1440805	1.56	0.01321	0.05	0.00	0.05	16.0
15.50	7400	16.49	10.16	1460542	1.60	0.01320	0.05	0.00	0.05	15.4
14.90	7500	16.71	10.30	1480279	1.65	0.01319	0.05	0.00	0.05	14.8
14.00	7600	16.94	10.43	1500016	1.69	0.01318	0.05	0.00	0.05	13.9
13.20	7700	17.16	10.57	1519753	1.74	0.01316	0.06	0.00	0.06	13.1
12.50	7800	17.38	10.71	1539491	1.78	0.01315	0.06	0.00	0.06	12.4
11.90	7900	17.60	10.85	1559228	1.83	0.01314	0.06	0.00	0.06	11.8
11.00	8000	17.83	10.98	1578965	1.87	0.01313	0.06	0.00	0.06	10.9
10.05	8100	18.05	11.12	1598702	1.92	0.01312	0.06	0.00	0.06	10.0
9.25	8200	18.27	11.26	1618439	1.97	0.01311	0.06	0.00	0.06	9.2
8.40	8300	18.50	11.40	1638176	2.02	0.01310	0.07	0.00	0.07	8.3
7.50	8400	18.72	11.53	1657913	2.07	0.01309	0.07	0.00	0.07	7.4

Table B2. S-383 Head Losses with 15 CFS Pump and Maximum Pipe Roughness

880 RPM						Swamee & Jain(1976)				
TDH(ft)	Q (GPM)	Q(cfs)	V(ft/s)	N_R	$V^2/2g$ (ft)	f	$h_l = f(L/D)V^2/2g$	$h_m = \Sigma KV^2/2g$	Total Head Loss (ft)	Static Head (ft)
24.90	5600	12.48	7.69	1105275	0.92	0.01439	0.03	0.00	0.03	24.9
24.50	5700	12.70	7.83	1125012	0.95	0.01437	0.03	0.00	0.03	24.5
24.00	5800	12.92	7.96	1144749	0.98	0.01436	0.03	0.00	0.03	24.0
23.80	5900	13.15	8.10	1164486	1.02	0.01435	0.04	0.00	0.04	23.8
23.25	6000	13.37	8.24	1184223	1.05	0.01433	0.04	0.00	0.04	23.2
22.95	6100	13.59	8.38	1203961	1.09	0.01432	0.04	0.00	0.04	22.9
22.50	6200	13.82	8.51	1223698	1.13	0.01431	0.04	0.00	0.04	22.5
22.00	6300	14.04	8.65	1243435	1.16	0.01430	0.04	0.00	0.04	22.0
21.50	6400	14.26	8.79	1263172	1.20	0.01428	0.04	0.00	0.04	21.5
21.00	6500	14.48	8.92	1282909	1.24	0.01427	0.04	0.00	0.04	21.0
20.50	6600	14.71	9.06	1302646	1.28	0.01426	0.04	0.00	0.04	20.5
20.00	6700	14.93	9.20	1322383	1.31	0.01425	0.05	0.00	0.05	20.0
19.20	6800	15.15	9.34	1342120	1.35	0.01424	0.05	0.00	0.05	19.2
18.80	6900	15.38	9.47	1361857	1.39	0.01423	0.05	0.00	0.05	18.8
18.00	7000	15.60	9.61	1381594	1.43	0.01422	0.05	0.00	0.05	17.9
17.50	7100	15.82	9.75	1401331	1.48	0.01421	0.05	0.00	0.05	17.4
16.90	7200	16.04	9.89	1421068	1.52	0.01420	0.05	0.00	0.05	16.8
16.10	7300	16.27	10.02	1440805	1.56	0.01419	0.05	0.00	0.05	16.0
15.50	7400	16.49	10.16	1460542	1.60	0.01418	0.06	0.00	0.06	15.4
14.90	7500	16.71	10.30	1480279	1.65	0.01417	0.06	0.00	0.06	14.8
14.00	7600	16.94	10.43	1500016	1.69	0.01416	0.06	0.00	0.06	13.9
13.20	7700	17.16	10.57	1519753	1.74	0.01415	0.06	0.00	0.06	13.1
12.50	7800	17.38	10.71	1539491	1.78	0.01414	0.06	0.00	0.06	12.4
11.90	7900	17.60	10.85	1559228	1.83	0.01414	0.06	0.00	0.06	11.8
11.00	8000	17.83	10.98	1578965	1.87	0.01413	0.07	0.00	0.07	10.9
10.05	8100	18.05	11.12	1598702	1.92	0.01412	0.07	0.00	0.07	10.0
9.25	8200	18.27	11.26	1618439	1.97	0.01411	0.07	0.00	0.07	9.2
8.40	8300	18.50	11.40	1638176	2.02	0.01411	0.07	0.00	0.07	8.3
7.50	8400	18.72	11.53	1657913	2.07	0.01410	0.07	0.00	0.07	7.4

Table B3. S-383 Head Losses with 25 CFS Pump and Minimum Pipe Roughness

880 RPM						Swamee & Jain(1976)				
TDH(ft)	Q (GPM)	Q(cfs)	V(ft/s)	N_R	$V^2/2g$ (ft)	f	$h_l = f(L/D)V^2/2g$	$h_m = \Sigma KV^2/2g$	Total Head Loss (ft)	Static Head (ft)
25.50	9300	20.72	7.03	1361857	0.77	0.01281	0.02	0.00	0.02	25.5
25.20	9400	20.95	7.10	1376501	0.78	0.01280	0.02	0.00	0.02	25.2
25.00	9500	21.17	7.18	1391144	0.80	0.01279	0.02	0.00	0.02	25.0
24.80	9600	21.39	7.26	1405788	0.82	0.01278	0.02	0.00	0.02	24.8
24.50	9700	21.61	7.33	1420432	0.83	0.01277	0.02	0.00	0.02	24.5
24.20	9800	21.84	7.41	1435075	0.85	0.01276	0.02	0.00	0.02	24.2
24.00	9900	22.06	7.48	1449719	0.87	0.01275	0.02	0.00	0.02	24.0
23.80	10000	22.28	7.56	1464362	0.89	0.01274	0.02	0.00	0.02	23.8
23.50	10100	22.51	7.63	1479006	0.90	0.01273	0.02	0.00	0.02	23.5
23.10	10200	22.73	7.71	1493650	0.92	0.01272	0.02	0.00	0.02	23.1
22.90	10300	22.95	7.78	1508293	0.94	0.01271	0.02	0.00	0.02	22.9
22.50	10400	23.17	7.86	1522937	0.96	0.01270	0.02	0.00	0.02	22.5
22.30	10500	23.40	7.94	1537581	0.98	0.01269	0.02	0.00	0.02	22.3
22.00	10600	23.62	8.01	1552224	1.00	0.01268	0.02	0.00	0.02	22.0
21.80	10700	23.84	8.09	1566868	1.02	0.01267	0.02	0.00	0.02	21.8
21.40	10800	24.07	8.16	1581511	1.03	0.01266	0.02	0.00	0.02	21.4
21.00	10900	24.29	8.24	1596155	1.05	0.01266	0.02	0.00	0.02	21.0
20.80	11000	24.51	8.31	1610799	1.07	0.01265	0.02	0.00	0.02	20.8
20.50	11100	24.73	8.39	1625442	1.09	0.01264	0.03	0.00	0.03	20.5
20.05	11200	24.96	8.46	1640086	1.11	0.01263	0.03	0.00	0.03	20.0
19.90	11300	25.18	8.54	1654729	1.13	0.01262	0.03	0.00	0.03	19.9
19.50	11400	25.40	8.62	1669373	1.15	0.01261	0.03	0.00	0.03	19.5
19.10	11500	25.63	8.69	1684017	1.17	0.01261	0.03	0.00	0.03	19.1
18.90	11600	25.85	8.77	1698660	1.19	0.01260	0.03	0.00	0.03	18.9
18.50	11700	26.07	8.84	1713304	1.21	0.01259	0.03	0.00	0.03	18.5
18.05	11800	26.29	8.92	1727948	1.24	0.01258	0.03	0.00	0.03	18.0
17.80	11900	26.52	8.99	1742591	1.26	0.01258	0.03	0.00	0.03	17.8
17.35	12000	26.74	9.07	1757235	1.28	0.01257	0.03	0.00	0.03	17.3
17.00	12100	26.96	9.15	1771878	1.30	0.01256	0.03	0.00	0.03	17.0
16.60	12200	27.19	9.22	1786522	1.32	0.01255	0.03	0.00	0.03	16.6
16.20	12300	27.41	9.30	1801166	1.34	0.01255	0.03	0.00	0.03	16.2
15.90	12400	27.63	9.37	1815809	1.36	0.01254	0.03	0.00	0.03	15.9
15.50	12500	27.85	9.45	1830453	1.39	0.01253	0.03	0.00	0.03	15.5
15.10	12600	28.08	9.52	1845097	1.41	0.01253	0.03	0.00	0.03	15.1
14.80	12700	28.30	9.60	1859740	1.43	0.01252	0.03	0.00	0.03	14.8
14.30	12800	28.52	9.67	1874384	1.45	0.01251	0.03	0.00	0.03	14.3
13.95	12900	28.75	9.75	1889027	1.48	0.01251	0.03	0.00	0.03	13.9
13.50	13000	28.97	9.83	1903671	1.50	0.01250	0.03	0.00	0.03	13.5
13.00	13100	29.19	9.90	1918315	1.52	0.01249	0.03	0.00	0.03	13.0
12.75	13200	29.41	9.98	1932958	1.55	0.01249	0.04	0.00	0.04	12.7
12.20	13300	29.64	10.05	1947602	1.57	0.01248	0.04	0.00	0.04	12.2
11.90	13400	29.86	10.13	1962246	1.59	0.01248	0.04	0.00	0.04	11.9
11.40	13500	30.08	10.20	1976889	1.62	0.01247	0.04	0.00	0.04	11.4
11.00	13600	30.31	10.28	1991533	1.64	0.01246	0.04	0.00	0.04	11.0
10.50	13700	30.53	10.35	2006176	1.66	0.01246	0.04	0.00	0.04	10.5
10.00	13800	30.75	10.43	2020820	1.69	0.01245	0.04	0.00	0.04	10.0
9.50	13900	30.97	10.51	2035464	1.71	0.01245	0.04	0.00	0.04	9.5

Table B5. S-382 Head Losses with 60 CFS Pump and Minimum Pipe Roughness

	1200 RPM					Swamee & Jain(1976)				
TDH(ft)	Q (GPM)	Q(cfs)	V(ft/s)	N_R	$V^2/2g$ (ft)	f	$h_l = f(L/D)V^2/2g$	$h_m = \Sigma KV^2/2g$	Total Head Loss (ft)	Static Head (ft)
29.25	21800	48.58	7.17	2105566	0.80	0.01185	0.29	0.80	1.09	28.2
29.00	22200	49.47	7.30	2144200	0.83	0.01183	0.30	0.83	1.13	27.9
28.90	22600	50.36	7.43	2182835	0.86	0.01181	0.31	0.86	1.17	27.7
28.50	23000	51.25	7.56	2221469	0.89	0.01180	0.32	0.89	1.21	27.3
28.00	23400	52.14	7.69	2260103	0.92	0.01178	0.33	0.92	1.25	26.7
27.95	23800	53.03	7.83	2298737	0.95	0.01177	0.34	0.95	1.29	26.7
27.55	24200	53.93	7.96	2337372	0.98	0.01175	0.35	0.98	1.34	26.2
27.05	24600	54.82	8.09	2376006	1.02	0.01174	0.37	1.02	1.38	25.7
26.90	25000	55.71	8.22	2414640	1.05	0.01173	0.38	1.05	1.43	25.5
26.40	25400	56.60	8.35	2453274	1.08	0.01171	0.39	1.08	1.47	24.9
26.00	25800	57.49	8.48	2491909	1.12	0.01170	0.40	1.12	1.52	24.5
25.60	26200	58.38	8.61	2530543	1.15	0.01169	0.41	1.15	1.56	24.0
25.05	26600	59.27	8.75	2569177	1.19	0.01167	0.42	1.19	1.61	23.4
24.70	27000	60.17	8.88	2607811	1.22	0.01166	0.44	1.22	1.66	23.0
24.05	27400	61.06	9.01	2646446	1.26	0.01165	0.45	1.26	1.71	22.3
23.80	27800	61.95	9.14	2685080	1.30	0.01164	0.46	1.30	1.76	22.0
23.05	28200	62.84	9.27	2723714	1.34	0.01163	0.48	1.34	1.81	21.2
22.75	28600	63.73	9.40	2762348	1.37	0.01162	0.49	1.37	1.86	20.9
22.10	29000	64.62	9.54	2800983	1.41	0.01161	0.50	1.41	1.91	20.2
21.50	29400	65.51	9.67	2839617	1.45	0.01160	0.52	1.45	1.97	19.5
21.00	29800	66.40	9.80	2878251	1.49	0.01158	0.53	1.49	2.02	19.0
20.40	30200	67.30	9.93	2916885	1.53	0.01157	0.54	1.53	2.07	18.3
19.90	30600	68.19	10.06	2955519	1.57	0.01156	0.56	1.57	2.13	17.8
19.10	31000	69.08	10.19	2994154	1.61	0.01156	0.57	1.61	2.18	16.9
18.50	31400	69.97	10.32	3032788	1.66	0.01155	0.59	1.66	2.24	16.3
17.90	31800	70.86	10.46	3071422	1.70	0.01154	0.60	1.70	2.30	15.6
17.10	32200	71.75	10.59	3110056	1.74	0.01153	0.61	1.74	2.36	14.7
16.50	32600	72.64	10.72	3148691	1.78	0.01152	0.63	1.78	2.41	14.1
15.90	33000	73.54	10.85	3187325	1.83	0.01151	0.64	1.83	2.47	13.4
15.00	33400	74.43	10.98	3225959	1.87	0.01150	0.66	1.87	2.53	12.5
14.30	33800	75.32	11.11	3264593	1.92	0.01149	0.68	1.92	2.59	11.7
13.60	34200	76.21	11.25	3303228	1.96	0.01148	0.69	1.96	2.65	10.9
12.90	34600	77.10	11.38	3341862	2.01	0.01148	0.71	2.01	2.72	10.2
12.00	35000	77.99	11.51	3380496	2.06	0.01147	0.72	2.06	2.78	9.2
11.20	35400	78.88	11.64	3419130	2.10	0.01146	0.74	2.10	2.84	8.4
10.30	35800	79.77	11.77	3457765	2.15	0.01145	0.76	2.15	2.91	7.4
9.50	36200	80.67	11.90	3496399	2.20	0.01145	0.77	2.20	2.97	6.5

Table B4. S-383 Head Losses with 25 CFS Pump and Maximum Pipe Roughness

	880 RPM					Swamee & Jain(1976)				
TDH(ft)	Q (GPM)	Q(cfs)	V(ft/s)		$V^2/2g$ (ft)	f	$h_l = f(L/D)V^2/2g$	$h_m = \Sigma KV^2/2g$	Total Head Loss (ft)	Static Head (ft)
25.50	9300	20.72	7.03	[illegible]	0.77	0.01363	0.02	0.00	0.02	25.5
25.20	9400	20.95	7.10	[illegible]	0.78	0.01362	0.02	0.00	0.02	25.2
25.00	9500	21.17	7.18	[illegible]	0.80	0.01361	0.02	0.00	0.02	25.0
24.80	9600	21.39	7.26	[illegible]	0.82	0.01361	0.02	0.00	0.02	24.8
24.50	9700	21.61	7.33	[illegible]	0.83	0.01360	0.02	0.00	0.02	24.5
24.20	9800	21.84	7.41	[illegible]	0.85	0.01359	0.02	0.00	0.02	24.2
24.00	9900	22.06	7.48	[illegible]	0.87	0.01358	0.02	0.00	0.02	24.0
23.80	10000	22.28	7.56	[illegible]	0.89	0.01357	0.02	0.00	0.02	23.8
23.50	10100	22.51	7.63	[illegible]	0.90	0.01357	0.02	0.00	0.02	23.5
23.10	10200	22.73	7.71	[illegible]	0.92	0.01356	0.02	0.00	0.02	23.1
22.90	10300	22.95	7.78	[illegible]	0.94	0.01355	0.02	0.00	0.02	22.9
22.50	10400	23.17	7.86	[illegible]	0.96	0.01354	0.02	0.00	0.02	22.5
22.30	10500	23.40	7.94	[illegible]	0.98	0.01354	0.02	0.00	0.02	22.3
22.00	10600	23.62	8.01	[illegible]	1.00	0.01353	0.02	0.00	0.02	22.0
21.80	10700	23.84	8.09	[illegible]	1.02	0.01352	0.03	0.00	0.03	21.8
21.40	10800	24.07	8.16	[illegible]	1.03	0.01351	0.03	0.00	0.03	21.4
21.00	10900	24.29	8.24	[illegible]	1.05	0.01351	0.03	0.00	0.03	21.0
20.80	11000	24.51	8.31	[illegible]	1.07	0.01350	0.03	0.00	0.03	20.8
20.50	11100	24.73	8.39	[illegible]	1.09	0.01349	0.03	0.00	0.03	20.5
20.05	11200	24.96	8.46	[illegible]	1.11	0.01349	0.03	0.00	0.03	20.0
19.90	11300	25.18	8.54	[illegible]	1.13	0.01348	0.03	0.00	0.03	19.9
19.50	11400	25.40	8.62	[illegible]	1.15	0.01347	0.03	0.00	0.03	19.5
19.10	11500	25.63	8.69	[illegible]	1.17	0.01347	0.03	0.00	0.03	19.1
18.90	11600	25.85	8.77	[illegible]	1.19	0.01346	0.03	0.00	0.03	18.9
18.50	11700	26.07	8.84	[illegible]	1.21	0.01346	0.03	0.00	0.03	18.5
18.05	11800	26.29	8.92	[illegible]	1.24	0.01345	0.03	0.00	0.03	18.0
17.80	11900	26.52	8.99	[illegible]	1.26	0.01344	0.03	0.00	0.03	17.8
17.35	12000	26.74	9.07	[illegible]	1.28	0.01344	0.03	0.00	0.03	17.3
17.00	12100	26.96	9.15	[illegible]	1.30	0.01343	0.03	0.00	0.03	17.0
16.60	12200	27.19	9.22	[illegible]	1.32	0.01343	0.03	0.00	0.03	16.6
16.20	12300	27.41	9.30	[illegible]	1.34	0.01342	0.03	0.00	0.03	16.2
15.90	12400	27.63	9.37	[illegible]	1.36	0.01342	0.03	0.00	0.03	15.9
15.50	12500	27.85	9.45	[illegible]	1.39	0.01341	0.03	0.00	0.03	15.5
15.10	12600	28.08	9.52	[illegible]	1.41	0.01341	0.03	0.00	0.03	15.1
14.80	12700	28.30	9.60	[illegible]	1.43	0.01340	0.04	0.00	0.04	14.8
14.30	12800	28.52	9.67	[illegible]	1.45	0.01340	0.04	0.00	0.04	14.3
13.95	12900	28.75	9.75	[illegible]	1.48	0.01339	0.04	0.00	0.04	13.9
13.50	13000	28.97	9.83	[illegible]	1.50	0.01339	0.04	0.00	0.04	13.5
13.00	13100	29.19	9.90	[illegible]	1.52	0.01338	0.04	0.00	0.04	13.0
12.75	13200	29.41	9.98	[illegible]	1.55	0.01338	0.04	0.00	0.04	12.7
12.20	13300	29.64	10.05	[illegible]	1.57	0.01337	0.04	0.00	0.04	12.2
11.90	13400	29.86	10.13	[illegible]	1.59	0.01337	0.04	0.00	0.04	11.9
11.40	13500	30.08	10.20	[illegible]	1.62	0.01336	0.04	0.00	0.04	11.4
11.00	13600	30.31	10.28	[illegible]	1.64	0.01336	0.04	0.00	0.04	11.0
10.50	13700	30.53	10.35	[illegible]	1.66	0.01335	0.04	0.00	0.04	10.5
10.00	13800	30.75	10.43	[illegible]	1.69	0.01335	0.04	0.00	0.04	10.0
9.50	13900	30.97	10.51	2035464	1.71	0.01334	0.04	0.00	0.04	9.5

Table B6. S-382 Head Losses with 60 CFS Pump and Maximum Pipe Roughness

29.25	21800	48.58	7.17	2105566	0.80	0.01257	0.31	0.80	1.11	28.1
29.00	22200	49.47	7.30	2144200	0.83	0.01256	0.32	0.83	1.15	27.9
28.90	22600	50.36	7.43	2182835	0.86	0.01254	0.33	0.86	1.19	27.7
28.50	23000	51.25	7.56	2221469	0.89	0.01253	0.34	0.89	1.23	27.3
28.00	23400	52.14	7.69	2260103	0.92	0.01252	0.35	0.92	1.27	26.7
27.95	23800	53.03	7.83	2298737	0.95	0.01251	0.36	0.95	1.32	26.6
27.55	24200	53.93	7.96	2337372	0.98	0.01249	0.38	0.98	1.36	26.2
27.05	24600	54.82	8.09	2376006	1.02	0.01248	0.39	1.02	1.40	25.6
26.90	25000	55.71	8.22	2414640	1.05	0.01247	0.40	1.05	1.45	25.4
26.40	25400	56.60	8.35	2453274	1.08	0.01246	0.41	1.08	1.50	24.9
26.00	25800	57.49	8.48	2491909	1.12	0.01245	0.43	1.12	1.54	24.5
25.60	26200	58.38	8.61	2530543	1.15	0.01244	0.44	1.15	1.59	24.0
25.05	26600	59.27	8.75	2569177	1.19	0.01243	0.45	1.19	1.64	23.4
24.70	27000	60.17	8.88	2607811	1.22	0.01242	0.47	1.22	1.69	23.0
24.05	27400	61.06	9.01	2646446	1.26	0.01241	0.48	1.26	1.74	22.3
23.80	27800	61.95	9.14	2685080	1.30	0.01240	0.49	1.30	1.79	22.0
23.05	28200	62.84	9.27	2723714	1.34	0.01239	0.51	1.34	1.84	21.2
22.75	28600	63.73	9.40	2762348	1.37	0.01239	0.52	1.37	1.89	20.9
22.10	29000	64.62	9.54	2800983	1.41	0.01238	0.54	1.41	1.95	20.2
21.50	29400	65.51	9.67	2839617	1.45	0.01237	0.55	1.45	2.00	19.5
21.00	29800	66.40	9.80	2878251	1.49	0.01236	0.56	1.49	2.06	18.9
20.40	30200	67.30	9.93	2916885	1.53	0.01235	0.58	1.53	2.11	18.3
19.90	30600	68.19	10.06	2955519	1.57	0.01235	0.59	1.57	2.17	17.7
19.10	31000	69.08	10.19	2994154	1.61	0.01234	0.61	1.61	2.22	16.9
18.50	31400	69.97	10.32	3032788	1.66	0.01233	0.63	1.66	2.28	16.2
17.90	31800	70.86	10.46	3071422	1.70	0.01232	0.64	1.70	2.34	15.6
17.10	32200	71.75	10.59	3110056	1.74	0.01232	0.66	1.74	2.40	14.7
16.50	32600	72.64	10.72	3148691	1.78	0.01231	0.67	1.78	2.46	14.0
15.90	33000	73.54	10.85	3187325	1.83	0.01230	0.69	1.83	2.52	13.4
15.00	33400	74.43	10.98	3225959	1.87	0.01230	0.71	1.87	2.58	12.4
14.30	33800	75.32	11.11	3264593	1.92	0.01229	0.72	1.92	2.64	11.7
13.60	34200	76.21	11.25	3303228	1.96	0.01228	0.74	1.96	2.70	10.9
12.90	34600	77.10	11.38	3341862	2.01	0.01228	0.76	2.01	2.77	10.1
12.00	35000	77.99	11.51	3380496	2.06	0.01227	0.77	2.06	2.83	9.2
11.20	35400	78.88	11.64	3419130	2.10	0.01226	0.79	2.10	2.89	8.3
10.30	35800	79.77	11.77	3457765	2.15	0.01226	0.81	2.15	2.96	7.3
9.50	36200	80.67	11.90	3496399	2.20	0.01225	0.83	2.20	3.03	6.5

Table B7. S-382 Head Losses with 160 CFS Pump and Minimum Pipe Roughness

880 RPM						Swamee & Jain(1976)				
TDH(ft)	Q (GPM)	Q(cfs)	V(ft/s)	N_R	$V^2/2g$ (ft)	f	$h_l = f(L/D)V^2/2g$	$h_m = \Sigma KV^2/2g$	Total Head Loss (ft)	Static Head (ft)
28.00	63066	140.53	9.17	4051268	1.31	0.01150	0.31	1.31	1.61	26.4
27.00	65200	145.29	9.48	4188353	1.40	0.01148	0.33	1.40	1.72	25.3
26.00	67600	150.64	9.83	4342525	1.50	0.01146	0.35	1.50	1.85	24.1
25.00	69600	155.09	10.12	4471002	1.59	0.01145	0.37	1.59	1.96	23.0
24.00	71200	158.66	10.36	4573784	1.67	0.01144	0.39	1.67	2.05	21.9
23.00	72800	162.22	10.59	4676566	1.74	0.01143	0.40	1.74	2.15	20.9
22.00	74400	165.79	10.82	4779347	1.82	0.01141	0.42	1.82	2.24	19.8
21.00	75600	168.46	11.00	4856434	1.88	0.01141	0.44	1.88	2.31	18.7
20.00	77200	172.03	11.23	4959215	1.96	0.01140	0.45	1.96	2.41	17.6
19.00	78400	174.70	11.40	5036301	2.02	0.01139	0.47	2.02	2.49	16.5
18.00	79600	177.38	11.58	5113388	2.08	0.01138	0.48	2.08	2.56	15.4
17.00	80850	180.16	11.76	5193686	2.15	0.01137	0.50	2.15	2.64	14.4
16.00	81600	181.83	11.87	5241865	2.19	0.01137	0.51	2.19	2.69	13.3
15.00	82650	184.17	12.02	5309315	2.24	0.01136	0.52	2.24	2.76	12.2
14.00	83600	186.29	12.16	5370342	2.30	0.01136	0.53	2.30	2.83	11.2
13.00	84600	188.52	12.30	5434580	2.35	0.01135	0.54	2.35	2.89	10.1
12.00	85600	190.75	12.45	5498819	2.41	0.01135	0.55	2.41	2.96	9.0
11.70	85750	191.08	12.47	5508455	2.42	0.01135	0.56	2.42	2.97	8.7

Table B8. S-382 Head Losses with 160 CFS Pump and Maximum Pipe Roughness

1200 RPM						Swamee & Jain(1976)				
TDH(ft)	Q (GPM)	Q(cfs)	V(ft/s)	N_R	$V^2/2g$ (ft)	f	$h_l = f(L/D)V^2/2g$	$h_m = \Sigma KV^2/2g$	Total Head Loss (ft)	Static Head (ft)
28.00	63066	140.53	9.17	4051268	1.31	0.01083	0.29	1.31	1.59	26.4
27.00	65200	145.29	9.48	4188353	1.40	0.01080	0.31	1.40	1.70	25.3
26.00	67600	150.64	9.83	4342525	1.50	0.01078	0.33	1.50	1.83	24.2
25.00	69600	155.09	10.12	4471002	1.59	0.01076	0.35	1.59	1.94	23.1
24.00	71200	158.66	10.36	4573784	1.67	0.01074	0.36	1.67	2.03	22.0
23.00	72800	162.22	10.59	4676566	1.74	0.01073	0.38	1.74	2.12	20.9
22.00	74400	165.79	10.82	4779347	1.82	0.01071	0.40	1.82	2.21	19.8
21.00	75600	168.46	11.00	4856434	1.88	0.01070	0.41	1.88	2.29	18.7
20.00	77200	172.03	11.23	4959215	1.96	0.01069	0.43	1.96	2.38	17.6
19.00	78400	174.70	11.40	5036301	2.02	0.01068	0.44	2.02	2.46	16.5
18.00	79600	177.38	11.58	5113388	2.08	0.01067	0.45	2.08	2.53	15.5
17.00	80850	180.16	11.76	5193686	2.15	0.01066	0.47	2.15	2.61	14.4
16.00	81600	181.83	11.87	5241865	2.19	0.01065	0.47	2.19	2.66	13.3
15.00	82650	184.17	12.02	5309315	2.24	0.01065	0.49	2.24	2.73	12.3
14.00	83600	186.29	12.16	5370342	2.30	0.01064	0.50	2.30	2.79	11.2
13.00	84600	188.52	12.30	5434580	2.35	0.01063	0.51	2.35	2.86	10.1
12.00	85600	190.75	12.45	5498819	2.41	0.01063	0.52	2.41	2.93	9.1
11.70	85750	191.08	12.47	5508455	2.42	0.01062	0.52	2.42	2.94	8.8