TECHNICAL PUBLICATION
EMA # 419

FLOW RATING DEVELOPMENT FOR NEW PUMP STATIONS
(S319, S361, S362, G370, G370S, G372, G372S, S25B, S26, G420, G420S, S332C, S356)

Muluneh Imru
Youchao Wang

August, 2004

South Florida Water Management District
3301 Gun Club Road
West Palm Beach, Fl 33406

EXECUTIVE SUMMARY

This document summarizes the results of flow rating analyses for thirteen new pump stations that were completed in 2004. These new pump stations are S319, S361, S362, S370, S370S, S372, S372S, S25B, S26, G420, G420S, S332C and S356. Seven of the pump stations are associated with Stormwater Treatment Areas (STA-1E and STA-3/4) in Palm Beach County and six of them are located in Miami-Dade County.

In the rating analyses, manufacturers' pump performance curves and data from the record drawings were used to establish preliminary flow equations for these new pump stations. These equations can be improved when flow measurements become available.

The rating equations (4) through (22) have 100% of calculated discharges within ±5% of the discharges from the pump curves for all the pump stations.

The equations developed here are recommended for computing flow through the pumps. It is further recommended that two to three stream flow measurements be used for each pump station from time to time to verify the performance of the rating equations. If the rating equations can not be verified, then up to twelve additional stream flow measurements should be made, for each pump station as needed, to improve the flow rating equations.

TABLE OF CONTENTS

List of Figures iii
List of Tables iv
Acknowledgement vi
1. Introduction 1
2. Methodology 1
3. Rating Analysis for S319 2
4. Rating Analysis for S361 7
5. Rating Analysis for S362 10
6. Rating Analysis for G370 17
7. Rating Analysis for G370S 19
8. Rating Analysis for G372 22
9. Rating Analysis for G372S 24
10. Rating Analysis for S25B 26
11. Rating Analysis for S26 28
12. Rating Analysis for G420 30
13. Rating Analysis for G420S 32
14. Rating Analysis for S332C 35
15. Rating Analysis for S356 39
16. Summary of Rating Analyses 41
17. Conclusion 44
18. Recommendation 44
19. Reference 44

LIST OF FIGURES

Figure 1. Performance curves of the 960 cfs pumps at S319 2
Figure 2. Head and discharge relationship for the 960 cfs pumps at S319 resulting from the performance curve and the rating curve adjusted for losses 4
Figure 3. Performance curves of the 550 cfs pumps at S319 5
Figure 4. Head and discharge relationship for the 550 cfs pumps at S319 resulting from the performance curve and the rating curve adjusted for losses 6
Figure 5. Performance curves of the 25 cfs pumps at S361 7
Figure 6. Head and discharge relationship for the 25 cfs pumps at S361 resulting from the performance curve and the rating curve adjusted for losses 10
Figure 7. Performance curves of the 960 cfs pumps at S362 11
Figure 8. Head and discharge relationship for the 960 cfs pumps at S362 resulting from the performance curve and the rating curve adjusted for losses 12
Figure 9. Performance curves of the 550 cfs pumps at S362 13
Figure 10. Head and discharge relationship for the 550 cfs pumps at S362 resulting from the performance curve and the rating curve adjusted for losses 14
Figure 11. Performance curves of the 110 cfs pumps at S362 15
Figure 12. Head and discharge relationship for the 110 cfs pumps at S362 resulting from the performance curve and the rating curve adjusted for losses 17
Figure 13. Performance curves of the 925 cfs pumps at G370 18
Figure 14. Head and discharge relationship for the 925 cfs pumps at G370 resulting from the performance curve and the rating curve adjusted for losses 19
Figure 15. Performance curves of the 75 cfs pumps at G370S 20
Figure 16. Head and discharge relationship for the 75 cfs pumps at G370S resulting from the performance curve and the rating curve adjusted for losses 21
Figure 17. Performance curves of the 925 cfs pumps at G372 22
Figure 18. Head and discharge relationship for the 925 cfs pumps at G372 resulting from the performance curve and the rating curve adjusted for losses 23
Figure 19. Performance curves of the 75 cfs pumps at G372S 24
Figure 20. Head and discharge relationship for the 75 cfs pumps at G372S resulting from the performance curve and the rating curve adjusted for losses 25
Figure 21. Performance curves of the 200 cfs pumps at S25B 26
Figure 22. Head and discharge relationship for the 200 cfs pumps at S25B resulting from the performance curve and the rating curve adjusted for losses 28
Figure 23. Performance curve of the 200 cfs pumps at S26 28
Figure 24. Head and discharge relationship for the 200 cfs pumps at S26 resulting from the performance curve and the rating curve adjusted for losses 30
Figure 25. Performance curves of the 223 cfs pumps at G420 31
Figure 26. Head and discharge relationship for the 223 cfs pumps at G420 resulting from the performance curve and the rating curve adjusted for losses 32
Figure 27. Performance curve of the 66 cfs pumps at G420S 33
Figure 28. Head and discharge relationship for the 66 cfs pumps at G420S resulting from the performance curve and the rating curve adjusted for losses 35
Figure 29. Performance curve of the 125 cfs pumps at S332C 36
Figure 30. Head and discharge relationship for the 125 cfs pumps at S332C resulting

from the performance curve and the rating curve adjusted for losses 37
Figure 31. Performance curve of the 75 cfs pump at S332C 38
Figure 32. Head and discharge relationship for the 75 cfs pump at S332C resulting from the performance curve and the rating curve adjusted for losses 39
Figure 33. Performance curve of the 125 cfs pumps at S356 40
Figure 34. Head and discharge relationship for the 125 cfs pumps at S356 resulting from the performance curve and the rating curve adjusted for losses 41

LIST OF TABLES

Table 1. Head and discharge values for calibration of the 960 cfs pumps at S319 3
Table 2. Computed discharges, discharges from pump curve, and relative errors for the 960 cfs pumps at S319..... 3
Table 3. Head and discharge values for calibration of the 550 cfs pumps at S319 5
Table 4. Computed discharges, discharges from pump curve, and relative errors for the 550 cfs pumps at S319..... 6
Table 5. Head and discharge values for calibration of the 25 cfs pumps at S361 8
Table 6. Computed discharges, discharges from pump curve, and relative errors for the 25 cfs pumps at S361..... 9
Table 7. Head and discharge values for calibration of the 960 cfs pumps at S362 11
Table 8. Computed discharges, discharges from pump curve, and relative errors for the 960 cfs pumps at S362..... 12
Table 9. Head and discharge values for calibration of the 550 cfs pumps at S362 13
Table 10. Computed discharges, discharges from pump curve, and relative errors for the 550 cfs pumps at S362..... 14
Table 11. Head and discharge values for calibration of the 110 cfs pumps at S362 16
Table 12. Computed discharges, discharges from pump curve, and relative errors for the 110 cfs pumps at S362..... 16
Table 13. Head and discharge values for calibration of the 925 cfs pumps at G370..... 18
Table 14. Computed discharges, discharges from pump curve, and relative errors for the 925 cfs pumps at G370..... 19
Table 15. Head and discharge values for calibration of the 75 cfs pumps at G370S 20
Table 16. Computed discharges, discharges from pump curve, and relative errors for the 75 cfs pumps at G370S..... 21
Table 17. Head and discharge values for calibration of the 925 cfs pumps at G372..... 22
Table 18. Computed discharges, discharges from pump curve, and relative errors for the 925 cfs pumps at G372..... 23
Table 19. Head and discharge values for calibration of the 75 cfs pumps at G372S 24
Table 20. Computed discharges, discharges from pump curve, and relative errors for the 75 cfs pumps at G372S..... 25
Table 21. Head and discharge values for calibration of the 200 cfs pumps at S25B..... 27
Table 22. Computed discharges, discharges from pump curve, and relative errors for the 200 cfs pumps at S25B..... 27
Table 23. Head and discharge values for calibration of the 200 cfs pumps at S26 29
Table 24. Computed discharges, discharges from pump curve, and relative errors for the 200 cfs pumps at S26..... 29

Table 25. Head and discharge values for calibration of the 223 cfs pumps at G420 30
Table 26. Computed discharges, discharges from pump curve, and relative errors for the 223 cfs pumps at G420 32
Table 27. Head and discharge values for calibration of the 66 cfs pumps at G420S 34
Table 28. Computed discharges, discharges from pump curve, and relative errors for the 66 cfs pumps at G420S 34
Table 29. Head and discharge values for calibration of the 125 cfs pumps at S332C 35
Table 30. Computed discharges, discharges from pump curve, and relative errors for the 125 cfs pumps at S332C 36
Table 31. Head and discharge values for calibration of the 75 cfs pump at S332C 37
Table 32. Computed discharges, discharges from pump curve, and relative errors for the 75 cfs pump at S332C 38
Table 33. Head and discharge values for calibration of the 125 cfs pumps at S356 39
Table 34. Computed discharges, discharges from pump curve, and relative errors for the 125 cfs pumps at S356 41
Table 35. Summary of the rating analyses results for the new pump stations 42

ACKNOWLEDGEMENT

The authors would like to acknowledge Emile Damisse, Matahel Ansar, Scott Huebner, and Garth Redfield for their review of the draft and valuable comments. Kathy Conner and Robin Campbell are gratefully acknowledged for assistance in coordinating the review and production of this document.

1. Introduction

There are thirteen new pump stations that were completed in 2004. These new pump stations are S319, S361, S362, S370, S370S, S372, S372S, S25B, S26, G420, G420S, S332C and S356. Seven of the pump stations are associated with Stormwater Treatment Area No. 1 East (STA-1E) and STA-3/4 and six of them are located in Miami-Dade County. The purpose of this flow rating analysis is to use the manufacturers' pump performance curves and data from the record drawings to establish preliminary flow equations for these new pump stations. These equations can be improved when flow measurements become available.

2. Methodology

The pump performance curves supplied by the manufacturers were used to develop the flow rating equations for estimating flows through the pumps. The pump performance curves characterize the relationship between the pump capacity and the total dynamic head. However, in the District's FLOW program, the online flow estimates need the relationship of discharge and static head. The static head is the difference between the total dynamic head and the sum of kinetic head and losses. The total head loss is the sum of pipe friction losses and minor losses including entrance, bend, value, and exit.

Minor losses are determined using the following equation

$$H_{ml} = \sum_{i=1}^{n} K \frac{V^2}{2g} \tag{1}$$

where K = resistance coefficient which depends on design and size of valve or fitting
V = average velocity in pipe of corresponding diameter, ft/s
g = acceleration of gravity, 32.2 ft/s^2

The minor losses in the following calculations were determined using minor loss coefficients obtained from tables (Karassik et al., 1976).

The pipe friction losses in the discharge and the suction piping system can be computed using the Hazen-Williams equation (Damisse, 2000).

$$H_{fl} = \frac{4.72L}{D^{4.86}} \left(\frac{Q}{C} \right)^{1.85} \tag{2}$$

where D = the pipe diameter, ft
Q = the discharge, cfs
C = the roughness coefficient

The roughness coefficient is 130 for new cast iron pipes. The pump diameter and pipe length obtained from record drawings are used to estimate the total losses. The total minor loss and total friction loss are calculated for each pump station.

The standard rating equation is taken from Flow Rating Analysis Procedures for Pumps (Imru and Wang, 2003) and given by

$$Q = A\left[\frac{N}{N_0}\right] + BH^C\left[\frac{N_0}{N}\right]^D \tag{3}$$

where H = head differential, ft

N_0 = design pump or engine speed, rpm

N = field measured pump or engine speed, rpm

A, B, C, and D = regression coefficients.

Equation (3) presents a model based on physical laws that can be used to estimate flow through pumps. This equation describes the relationship between discharge, head differential, and engine speed. Equation (3) was calibrated using the static head and discharge data from the pump performance curves for each pump station. The regression coefficients for Equation (3) were determined based on the least-squares method (Davis, 1986).

3. Rating Analysis for S319

The structure S319 has three 960 cfs pumps and two 550 cfs pumps with a total capacity of 3980 cfs. Figure 1 shows the head-discharge relationship for flows through the 960 cfs pumps at S319 under laboratory conditions at design pump speed (128 rpm). The head and discharge values are summarized in Table 1 for the 960 cfs pumps.

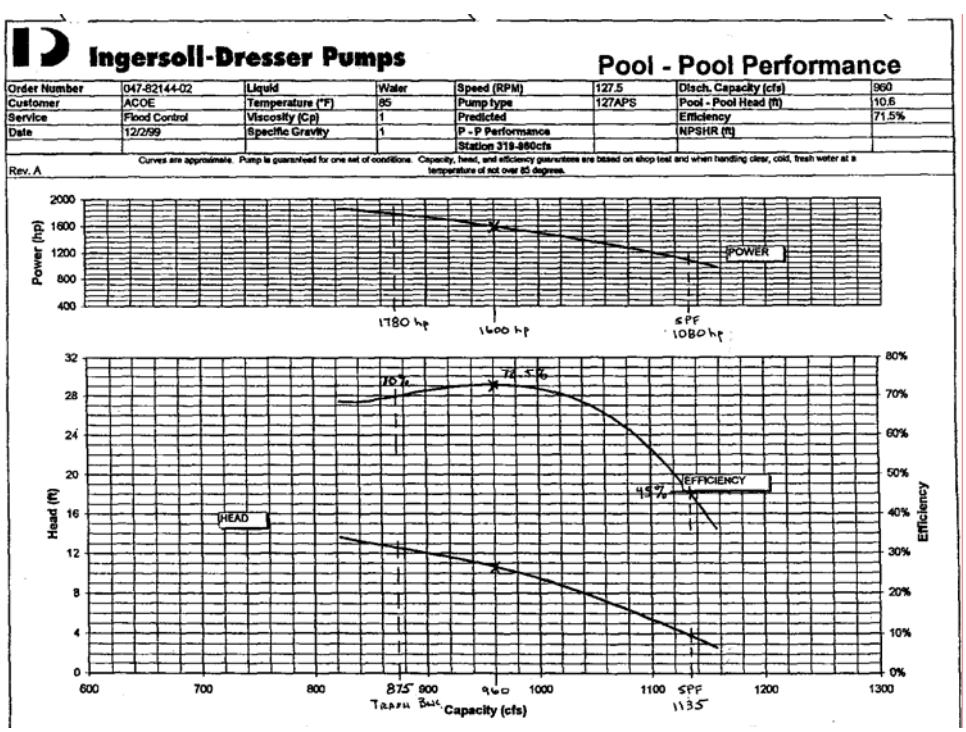

Figure 1. Performance curves of the 960 cfs pumps at S319

Table 1. Head and discharge values for calibration of the 960 cfs pumps at S319

TDH (ft)	Discharge (cfs)	Velocity (ft/s)	$V^2/(2g)$ (ft)	friction loss (ft)	minor loss (ft)	Kinetic head and losses (ft)	Static head (ft)
13.2	840	10.70	1.78	0.16	1.96	2.12	11.08
12.9	860	10.96	1.86	0.17	2.05	2.22	10.68
12.6	875	11.15	1.93	0.18	2.12	2.30	10.30
12	900	11.46	2.04	0.19	2.25	2.43	9.57
11.7	920	11.72	2.13	0.19	2.35	2.54	9.16
11.1	940	11.97	2.23	0.20	2.45	2.65	8.45
10.6	960	12.23	2.32	0.21	2.55	2.77	7.83
10	980	12.48	2.42	0.22	2.66	2.88	7.12
9.5	1000	12.74	2.52	0.23	2.77	3.00	6.50
8.8	1020	12.99	2.62	0.24	2.88	3.12	5.68
8	1040	13.25	2.73	0.24	3.00	3.24	4.76
7.1	1060	13.50	2.83	0.25	3.11	3.37	3.73
6.3	1080	13.76	2.94	0.26	3.23	3.49	2.81
5.5	1100	14.01	3.05	0.27	3.35	3.62	1.88
4.5	1120	14.27	3.16	0.28	3.48	3.76	0.74
3.9	1135	14.46	3.25	0.29	3.57	3.86	0.04

Equation (4) represents the rating equation for flows through the 960 cfs pumps at S319. Table 2 shows computed discharges, discharges from the pump curve, and relative errors.

$$Q = 1135\left[\frac{N}{N_0}\right] - 10.15H^{1.4}\left[\frac{N_0}{N}\right]^{1.8} \tag{4}$$

Table 2. Computed discharges, discharges from pump curve, and relative errors for the 960 cfs pumps at S319

No.	Q (cfs)	H (ft)	$Q_{computed}$ (cfs)	Relative error	Abs. error
1	840	11.08	840.7	0.08%	0.08%
2	860	10.68	855.5	-0.52%	0.52%
3	875	10.30	869.3	-0.66%	0.66%
4	900	9.57	895.3	-0.52%	0.52%
5	920	9.16	909.5	-1.14%	1.14%
6	940	8.45	933.7	-0.67%	0.67%
7	960	7.83	953.8	-0.64%	0.64%
8	980	7.12	976.6	-0.35%	0.35%
9	1000	6.50	995.5	-0.45%	0.45%
10	1020	5.68	1019.5	-0.05%	0.05%
11	1040	4.76	1044.9	0.47%	0.47%
12	1060	3.73	1070.8	1.02%	1.02%
13	1080	2.81	1092.0	1.11%	1.11%
14	1100	1.88	1110.5	0.96%	0.96%
15	1120	0.74	1128.3	0.74%	0.74%
16	1135	0.04	1134.9	-0.01%	0.01%
Average relative error				-0.04%	0.59%

Figure 2 shows head-discharge relationships for the 960 cfs pumps at S319 resulting from the performance curve and the rating curve adjusted for losses. The upper continuous curve represents the manufacturer's pump curve at the rated speed (128 rpm).

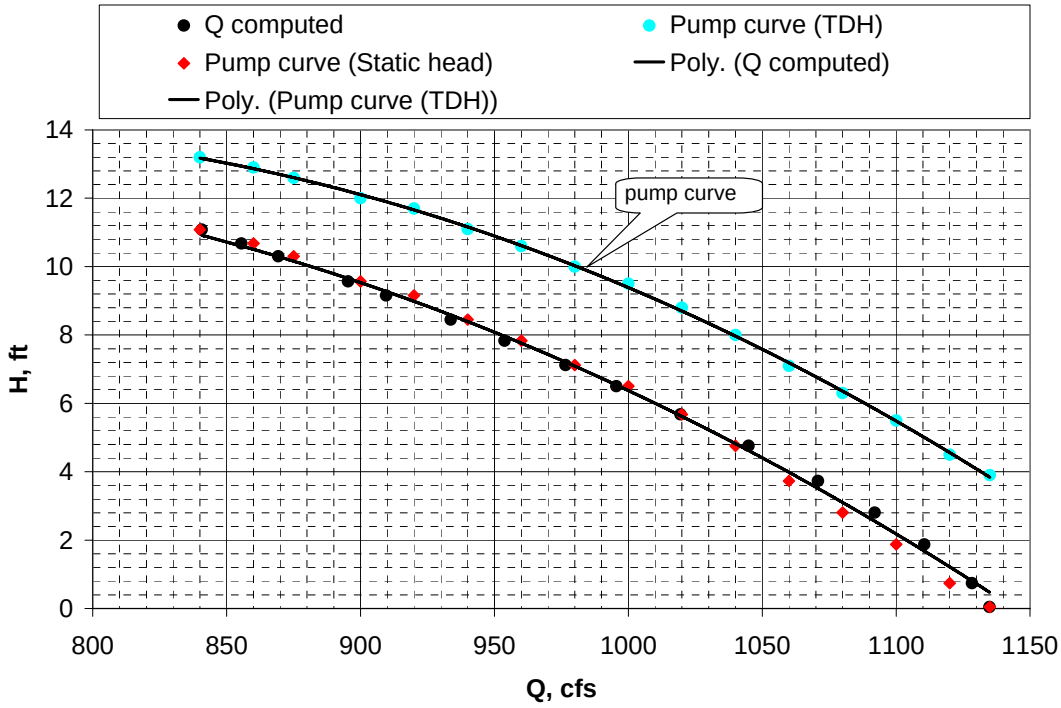

Figure 2. Head and discharge relationship for the 960 cfs pumps at S319 resulting from the performance curve and the rating curve adjusted for losses

Figure 3 shows the head-discharge relationship for flows through the 550 cfs pumps at S319 under laboratory conditions at design pump speed (196 rpm). The pump diameter is 7.5 ft for the 550 cfs pumps at S319 (USACE, 2000). The head and discharge values are summarized in Table 3 for the 550 cfs pumps.

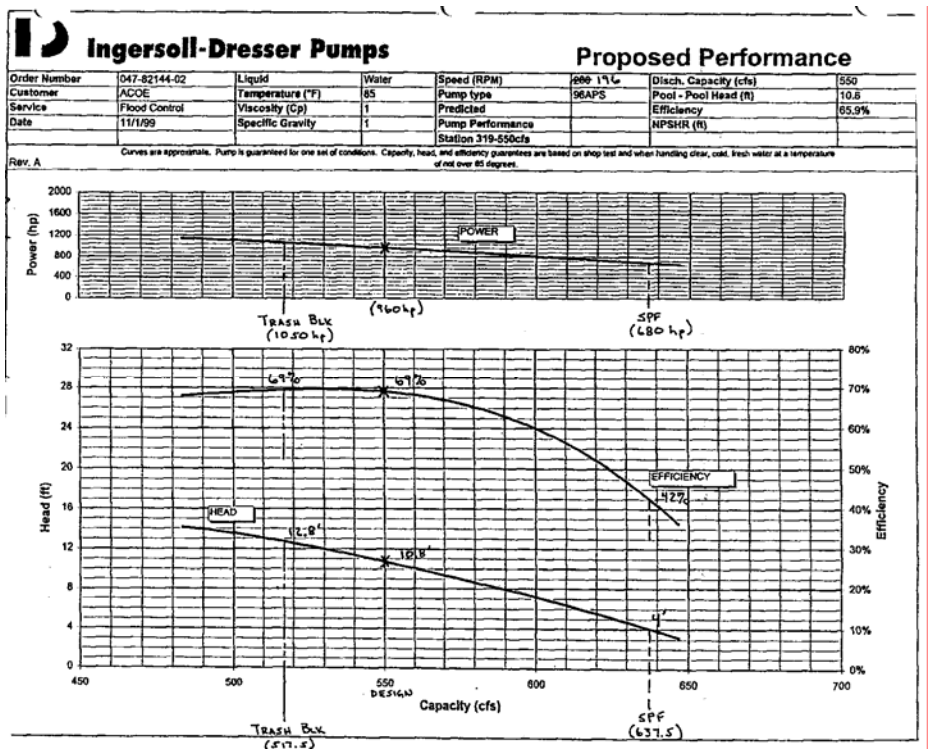

Figure 3. Performance curves of the 550 cfs pumps at S319

Table 3. Head and discharge values for calibration of the 550 cfs pumps at S319

TDH (ft)	Discharge (cfs)	Velocity (ft/s)	$V^2/(2g)$ (ft)	friction loss (ft)	minor loss (ft)	Kinetic head and loss (ft)	Static head (ft)
14	490	11.10	1.91	0.25	2.10	2.35	11.65
13.5	500	11.32	1.99	0.25	2.19	2.45	11.05
13	510	11.55	2.07	0.26	2.28	2.54	10.46
12.6	520	11.78	2.15	0.27	2.37	2.64	9.96
12	530	12.00	2.24	0.28	2.46	2.74	9.26
11.4	540	12.23	2.32	0.29	2.55	2.85	8.55
10.8	550	12.46	2.41	0.30	2.65	2.95	7.85
10	560	12.68	2.50	0.31	2.75	3.06	6.94
9.4	570	12.91	2.59	0.32	2.85	3.17	6.23
8.8	580	13.14	2.68	0.34	2.95	3.28	5.52
8	590	13.36	2.77	0.35	3.05	3.40	4.60
7.1	600	13.59	2.87	0.36	3.15	3.51	3.59
6.5	610	13.81	2.96	0.37	3.26	3.63	2.87
5.8	620	14.04	3.06	0.38	3.37	3.75	2.05
4.9	630	14.27	3.16	0.39	3.48	3.87	1.03

Equation (5) represents the rating equation for flows through the 550 cfs pumps at S319. Table 4 shows computed discharges, discharges from the pump curve, and relative errors. Figure 4 shows head-discharge relationships for the 550 cfs pumps at S319 resulting from the performance curve and the rating curve adjusted for losses.

$$Q = 640\left[\frac{N}{N_0}\right] - 7.81H^{1.2}\left[\frac{N_0}{N}\right]^{1.4} \tag{5}$$

Table 4. Computed discharges, discharges from pump curve, and relative errors for the 550 cfs pumps at S319

No.	Q (cfs)	H (ft)	$Q_{computed}$ (cfs)	Relative error	Abs. error
1	490	11.65	491.3	0.27%	0.27%
2	500	11.05	500.4	0.08%	0.08%
3	510	10.46	509.4	-0.12%	0.12%
4	520	9.96	516.9	-0.60%	0.60%
5	530	9.26	527.2	-0.53%	0.53%
6	540	8.55	537.4	-0.48%	0.48%
7	550	7.85	547.5	-0.46%	0.46%
8	560	6.94	560.2	0.03%	0.03%
9	570	6.23	569.9	-0.02%	0.02%
10	580	5.52	579.4	-0.11%	0.11%
11	590	4.60	591.2	0.20%	0.20%
12	600	3.59	603.8	0.63%	0.63%
13	610	2.87	612.3	0.38%	0.38%
14	620	2.05	621.5	0.24%	0.24%
15	630	1.03	631.9	0.30%	0.30%
Average relative error				0.013%	0.30%

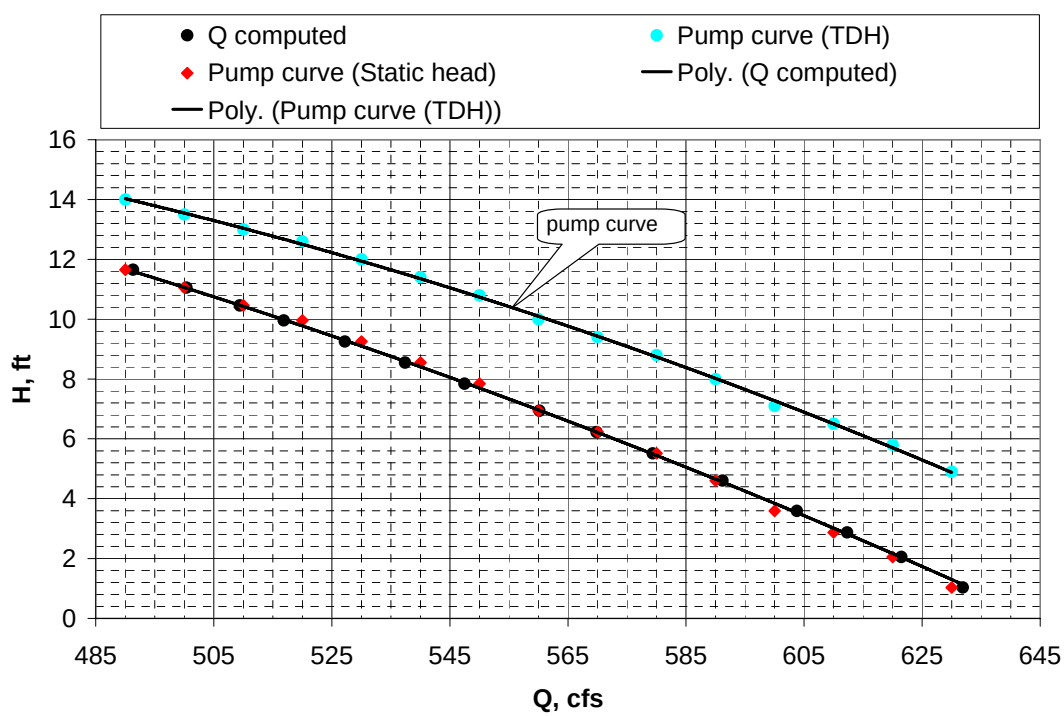

Figure 4. Head and discharge relationship for the 550 cfs pumps at S319 resulting from the performance curve and the rating curve adjusted for losses

4. Rating Analysis for S361

The structure S361 is a three-unit pump station with a total capacity of 75 cfs. Figure 5 shows the head-discharge relationship for flows through the pumps at S361 under laboratory conditions at the design engine speed (884 rpm).

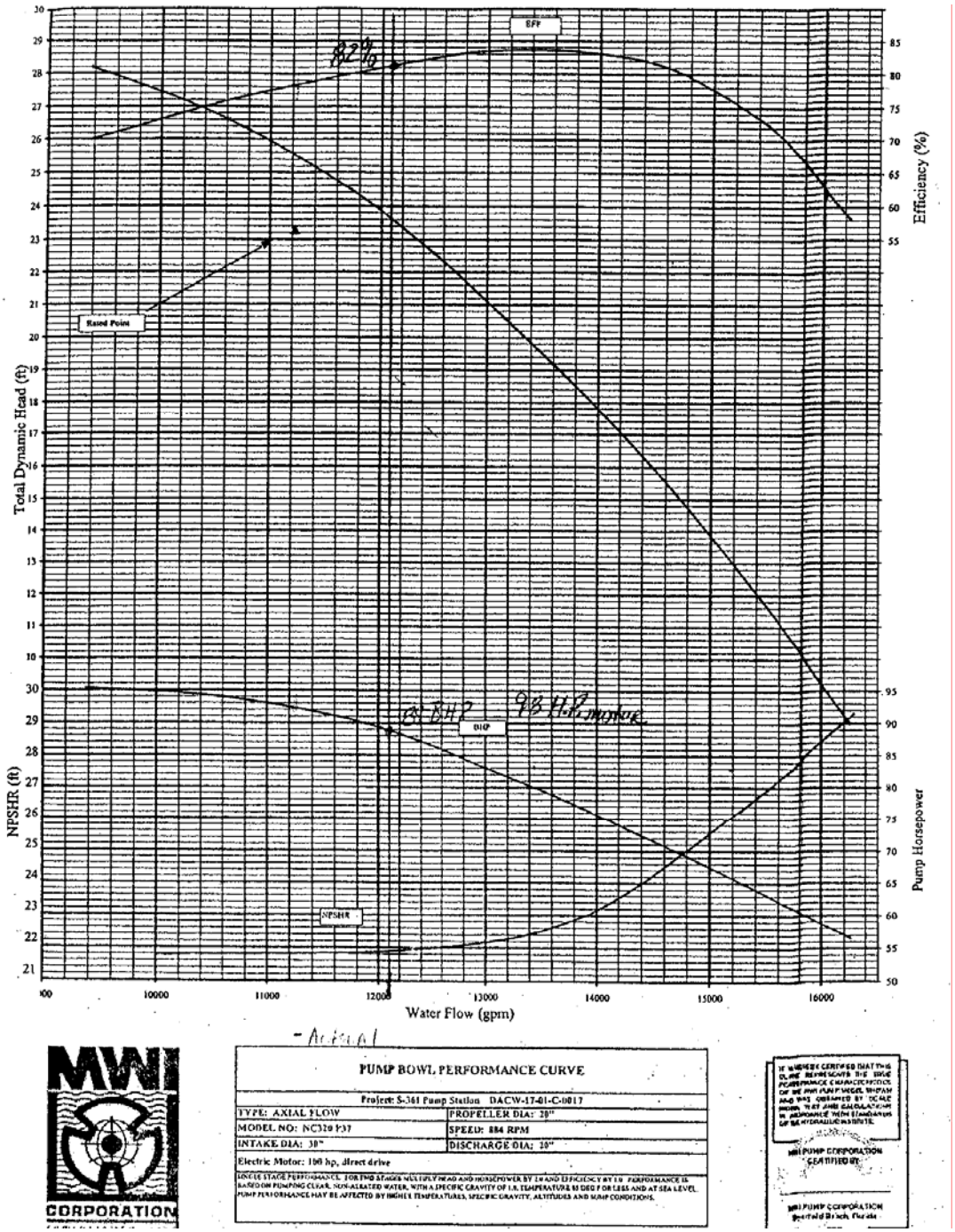

Figure 5. Performance curves of the 25 cfs pumps at S361

The pump diameter is 1.7 ft for pumps at S361 (USACE, 2000). Minor losses and pipe friction losses are calculated using equations (1) and (2). The head and discharge values are summarized in Table 5.

Table 5. Head and discharge values for calibration of the 25 cfs pumps at S361

TDH (ft)	Discharge (gpm)	Discharge (cfs)	Velocity (ft/s)	$V^2/(2g)$ (ft)	Friction loss (ft)	Minor losses (ft)	Kinetic head and losses (ft)	Static head (ft)
27.4	10000	22.3	7.10	0.78	2.12	0.940	3.06	24.34
26.9	10400	23.2	7.39	0.85	2.28	1.017	3.29	23.61
26.6	10600	23.6	7.53	0.88	2.36	1.056	3.42	23.18
26.3	10800	24.1	7.67	0.91	2.44	1.096	3.54	22.76
25.9	11000	24.5	7.81	0.95	2.53	1.137	3.66	22.24
25.6	11200	25.0	7.95	0.98	2.61	1.179	3.79	21.81
25.2	11400	25.4	8.10	1.02	2.70	1.221	3.92	21.28
24.7	11600	25.9	8.24	1.05	2.79	1.265	4.05	20.65
24.3	11800	26.3	8.38	1.09	2.88	1.309	4.19	20.11
23.9	12000	26.8	8.52	1.13	2.97	1.353	4.32	19.58
23.6	12100	27.0	8.59	1.15	3.01	1.376	4.39	19.21
23.4	12200	27.2	8.66	1.17	3.06	1.399	4.46	18.94
22.8	12400	27.7	8.81	1.20	3.15	1.445	4.60	18.20
22.3	12600	28.1	8.95	1.24	3.25	1.492	4.74	17.56
21.7	12800	28.5	9.09	1.28	3.34	1.540	4.88	16.82
21.1	13000	29.0	9.23	1.32	3.44	1.588	5.03	16.07
20.4	13200	29.4	9.37	1.36	3.54	1.64	5.18	15.22
19.8	13400	29.9	9.52	1.41	3.64	1.69	5.33	14.47
19.2	13600	30.3	9.66	1.45	3.74	1.74	5.48	13.72
18.5	13800	30.8	9.80	1.49	3.84	1.79	5.63	12.87
17.8	14000	31.2	9.94	1.54	3.95	1.84	5.79	12.01
17	14200	31.7	10.08	1.58	4.05	1.90	5.95	11.05
16.3	14400	32.1	10.23	1.62	4.16	1.95	6.11	10.19
15.6	14600	32.6	10.37	1.67	4.27	2.00	6.27	9.33

Equation (6) represents the rating equation for flows through the pumps at S361. Table 6 shows computed discharges, discharges from the pump curve, and relative errors for S361.

$$Q = 34\left[\frac{N}{N_0}\right] - 0.019H^2\left[\frac{N_0}{N}\right]^3 \tag{6}$$

Table 6. Computed discharges, discharges from pump curve, and relative errors for the 25 cfs pumps at S361

No.	Q (cfs)	H (ft)	$Q_{computed}$ (cfs)	Relative error	Abs. error
1	22.3	24.34	22.7	1.98%	1.98%
2	23.2	23.61	23.4	0.95%	0.95%
3	23.6	23.18	23.8	0.63%	0.63%
4	24.1	22.76	24.2	0.30%	0.30%
5	24.5	22.24	24.6	0.31%	0.31%
6	25.0	21.81	25.0	-0.05%	0.05%
7	25.4	21.28	25.4	-0.10%	0.10%
8	25.9	20.65	25.9	0.12%	0.12%
9	26.3	20.11	26.3	0.00%	0.00%
10	26.8	19.58	26.7	-0.16%	0.16%
11	27.0	19.21	27.0	0.02%	0.02%
12	27.2	18.94	27.2	-0.08%	0.08%
13	27.7	18.20	27.7	0.19%	0.19%
14	28.1	17.56	28.1	0.16%	0.16%
15	28.5	16.82	28.6	0.29%	0.29%
16	29.0	16.07	29.1	0.36%	0.36%
17	29.4	15.22	29.6	0.55%	0.55%
18	29.9	14.47	30.0	0.46%	0.46%
19	30.3	13.72	30.4	0.31%	0.31%
20	30.8	12.87	30.9	0.26%	0.26%
21	31.2	12.01	31.3	0.13%	0.13%
22	31.7	11.05	31.7	0.04%	0.04%
23	32.1	10.19	32.0	-0.27%	0.27%
24	32.6	9.33	32.3	-0.65%	0.65%
Average relative error				0.24%	0.35%

Figure 6 shows head-discharge relationships for pumps at S361 resulting from the performance curve and the rating curve adjusted for losses. The upper continuous curve represents the manufacturer's pump curve at the rated speed (884 rpm). The lower continuous curve represents the rating curve adjusted for losses. The slope of the rating curve is similar to the performance curve. The head difference between these two curves represents kinetic head and the total system losses.

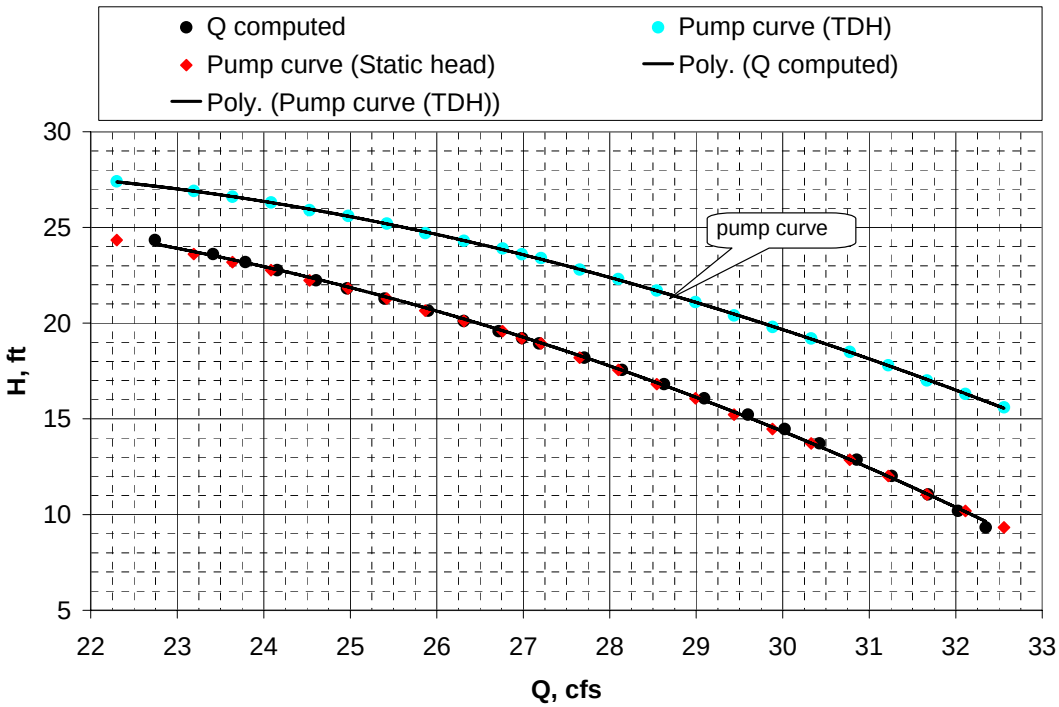

Figure 6. Head and discharge relationship for pumps at S361 resulting from the performance curve and the rating curve adjusted for losses

5. Rating Analysis for S362

The structure S362 consists of seven pumps with a total capacity of 4200 cfs. S362 has three 960 cfs pumps, two 550 cfs pumps, and two 110 cfs pumps. The rated pool-to-pool head is 5.5 ft at S362.

Figure 7 shows the head-discharge relationship for flows through the 960 cfs pumps at S362 under laboratory conditions at design pump speed (117 rpm). The pump diameter is 10 ft for the 960 cfs pumps at S362 (USACE, 2000). Minor losses and pipe friction losses are calculated using equations (1) and (2). The head and discharge values are summarized in Table 7 for the 960 cfs pumps.

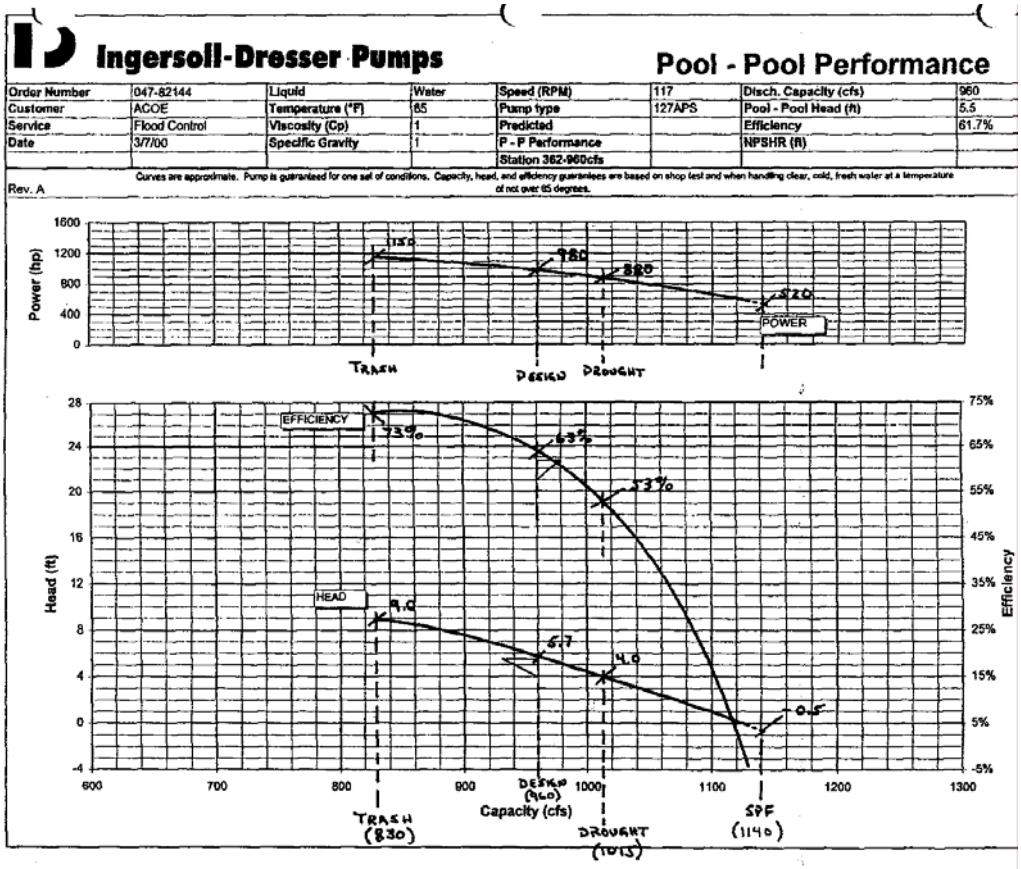

Figure 7. Performance curves of the 960 cfs pumps at S362

Table 7. Head and discharge values for calibration of the 960 cfs pumps at S362

TDH (ft)	Discharge (cfs)	Velocity (ft/s)	$V^2/(2g)$ (ft)	friction loss (ft)	minor loss	Kinetic head and losses (ft)	Static head (ft)
8.9	840	10.70	1.78	0.10	1.78	1.88	7.02
8.5	860	10.96	1.86	0.11	1.86	1.97	6.53
8	880	11.21	1.95	0.11	1.95	2.06	5.94
7.5	900	11.46	2.04	0.12	2.04	2.16	5.34
7	920	11.72	2.13	0.12	2.13	2.25	4.75
6.4	940	11.97	2.23	0.13	2.23	2.35	4.05
5.7	960	12.23	2.32	0.13	2.32	2.45	3.25
5	980	12.48	2.42	0.14	2.42	2.56	2.44
4.4	1000	12.74	2.52	0.14	2.52	2.66	1.74
3.8	1020	12.99	2.62	0.15	2.62	2.77	1.03
3	1040	13.25	2.73	0.15	2.73	2.88	0.12

Equation (7) represents the rating equation for flows through the 960 cfs pumps at S362. Table 8 shows computed discharges, discharges from the pump curve, and relative errors.

$$Q = 1040\left[\frac{N}{N_0}\right] - 19.05H^{1.2}\left[\frac{N_0}{N}\right]^{1.4} \tag{7}$$

Table 8. Computed discharges, discharges from pump curve, and relative errors for the 960 cfs pumps at S362

No.	Q (cfs)	H (ft)	$Q_{computed}$ (cfs)	Relative error	Abs. error
1	840	7.02	842.6	0.30%	0.30%
2	860	6.53	859.0	-0.12%	0.12%
3	880	5.94	878.5	-0.17%	0.17%
4	900	5.34	897.7	-0.25%	0.25%
5	920	4.75	916.6	-0.37%	0.37%
6	940	4.05	938.0	-0.21%	0.21%
7	960	3.25	961.7	0.18%	0.18%
8	980	2.44	984.4	0.44%	0.44%
9	1000	1.74	1003.0	0.30%	0.30%
10	1020	1.03	1020.2	0.02%	0.02%
11	1040	0.12	1038.5	-0.15%	0.15%
Average relative error				-0.001%	0.23%

Figure 8 shows head-discharge relationships for the 960 cfs pumps at S362 resulting from the performance curve and the rating curve adjusted for losses. The upper continuous curve represents the manufacturer's pump curve at the rated speed (117 rpm).

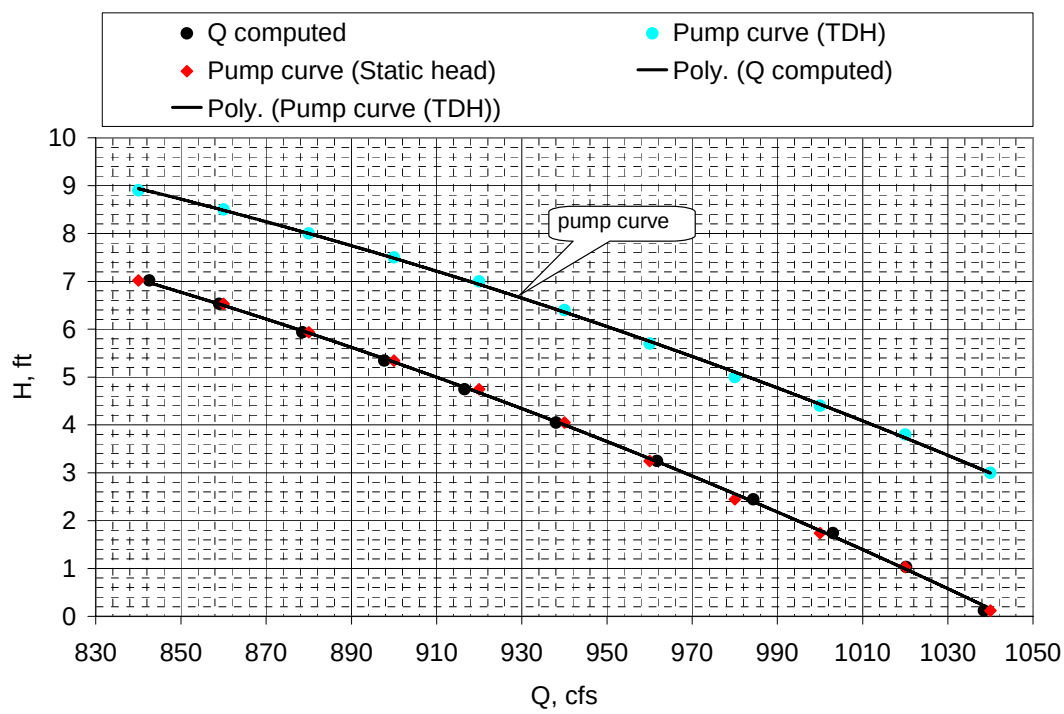

Figure 8. Head and discharge relationship for the 960 cfs pumps at S362 resulting from the performance curve and the rating curve adjusted for losses

Figure 9 shows the head-discharge relationship for flows through the 550 cfs pumps at S362 under laboratory conditions at design pump speed (179 rpm). The head and discharge values are summarized in Table 9 for the 550 cfs pumps.

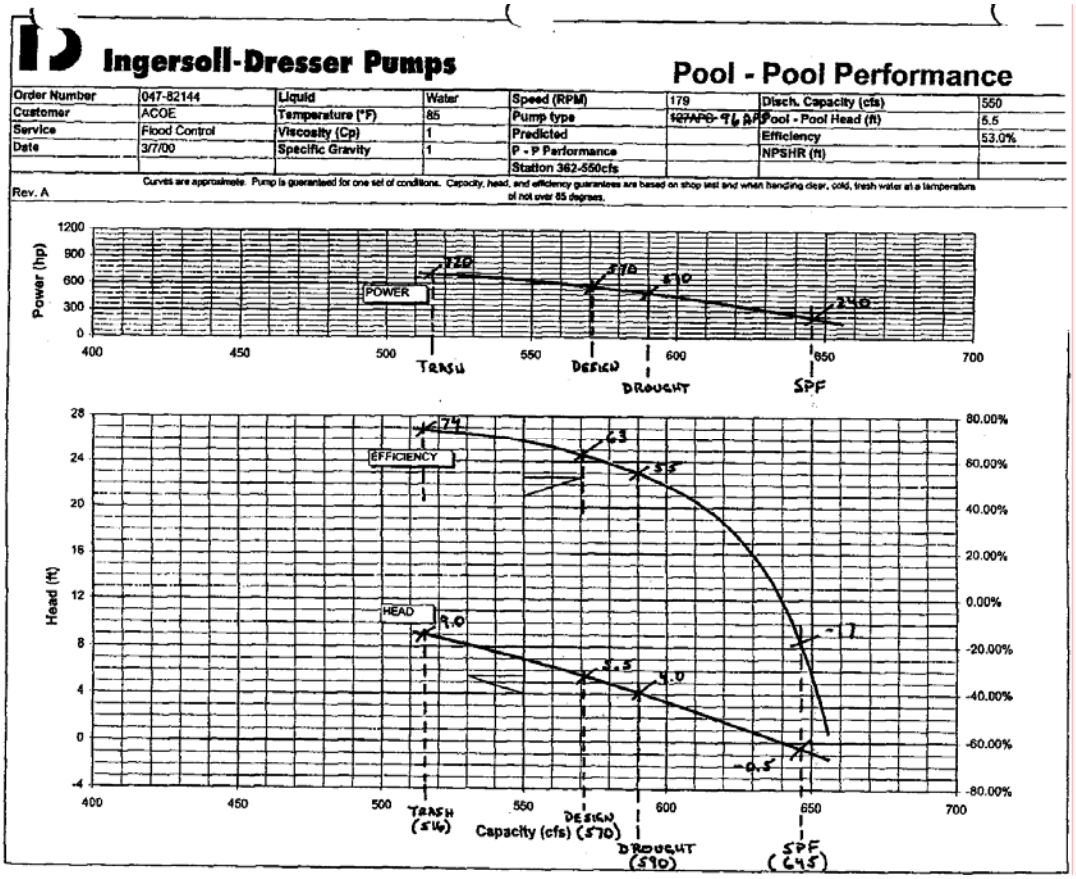

Figure 9. Performance curves of the 550 cfs pumps at S362

Table 9. Head and discharge values for calibration of the 550 cfs pumps at S362

TDH (ft)	Discharge (cfs)	Velocity (ft/s)	$V^2/(2g)$ (ft)	Friction loss (ft)	Minor losses (ft)	Kinetic head and losses (ft)	Static head (ft)
8.9	520	11.78	2.15	0.17	2.15	2.32	6.58
8.1	530	12.00	2.24	0.18	2.24	2.41	5.69
7.7	540	12.23	2.32	0.18	2.32	2.51	5.19
7	550	12.46	2.41	0.19	2.41	2.60	4.40
6.4	560	12.68	2.50	0.20	2.50	2.69	3.71
5.6	570	12.91	2.59	0.20	2.59	2.79	2.81
5	580	13.14	2.68	0.21	2.68	2.89	2.11
4	590	13.36	2.77	0.22	2.77	2.99	1.01
3.4	600	13.59	2.87	0.22	2.87	3.09	0.31

Equation (8) represents the rating equation for flows through the 550 cfs pumps at S362. Table 10 shows computed discharges, discharges from pump curve, and relative errors.

$$Q = 602\left[\frac{N}{N_0}\right] - 8.84H^{1.2}\left[\frac{N_0}{N}\right]^{1.4} \tag{8}$$

Table 10. Computed discharges, discharges from pump curve, and relative errors for the 550 cfs pumps at S362

No.	Q (cfs)	H (ft)	$Q_{computed}$ (cfs)	Relative error	Abs. error
1	520	6.58	517.3	-0.52%	0.52%
2	530	5.69	530.9	0.16%	0.16%
3	540	5.19	538.2	-0.34%	0.34%
4	550	4.40	549.7	-0.06%	0.06%
5	560	3.71	559.4	-0.10%	0.10%
6	570	2.81	571.5	0.26%	0.26%
7	580	2.11	580.3	0.06%	0.06%
8	590	1.01	593.0	0.52%	0.52%
9	600	0.31	599.8	-0.03%	0.03%
Average relative error				-0.007%	0.23%

Figure 10 shows head-discharge relationships for the 550 cfs pumps at S362 resulting from the performance curve and the rating curve adjusted for losses. The upper continuous curve represents the manufacturer's pump curve at the rated speed (179 rpm).

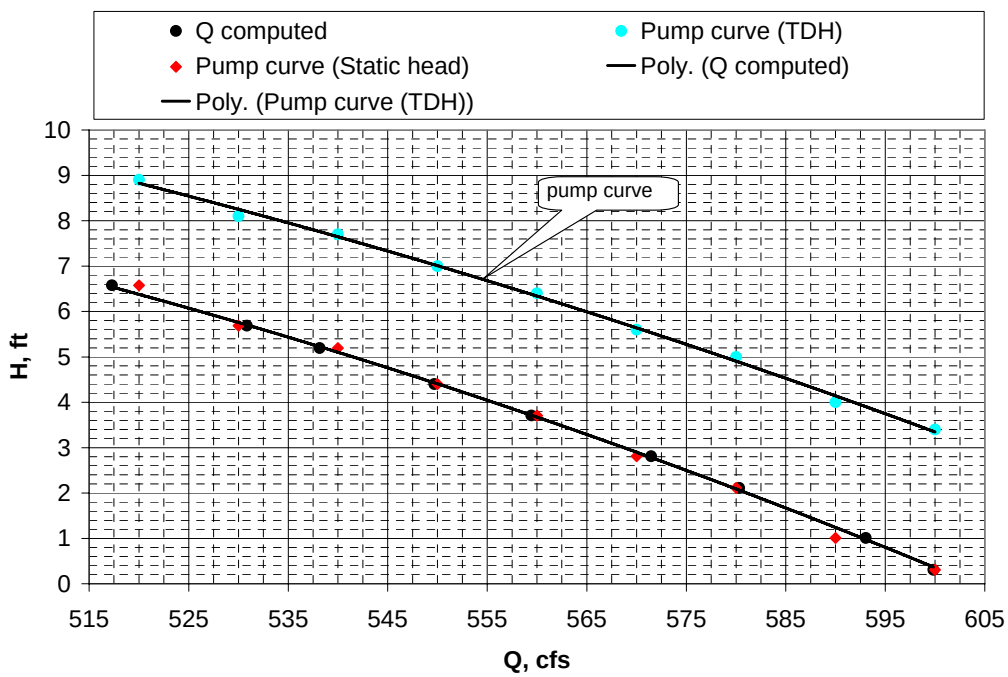

Figure 10. Head and discharge relationship for the 550 cfs pumps at S362 resulting from the performance curve and the rating curve adjusted for losses

Figure 11 shows the head-discharge relationship for flows through the 110 cfs pumps at S362 under laboratory conditions at design engine speed (442 rpm). The performance evaluation obtained from the performance curve shows that the flow rate is between 75 cfs and 125 cfs for this pump. The head and discharge values are summarized in Table 11 for the 110 cfs pumps.

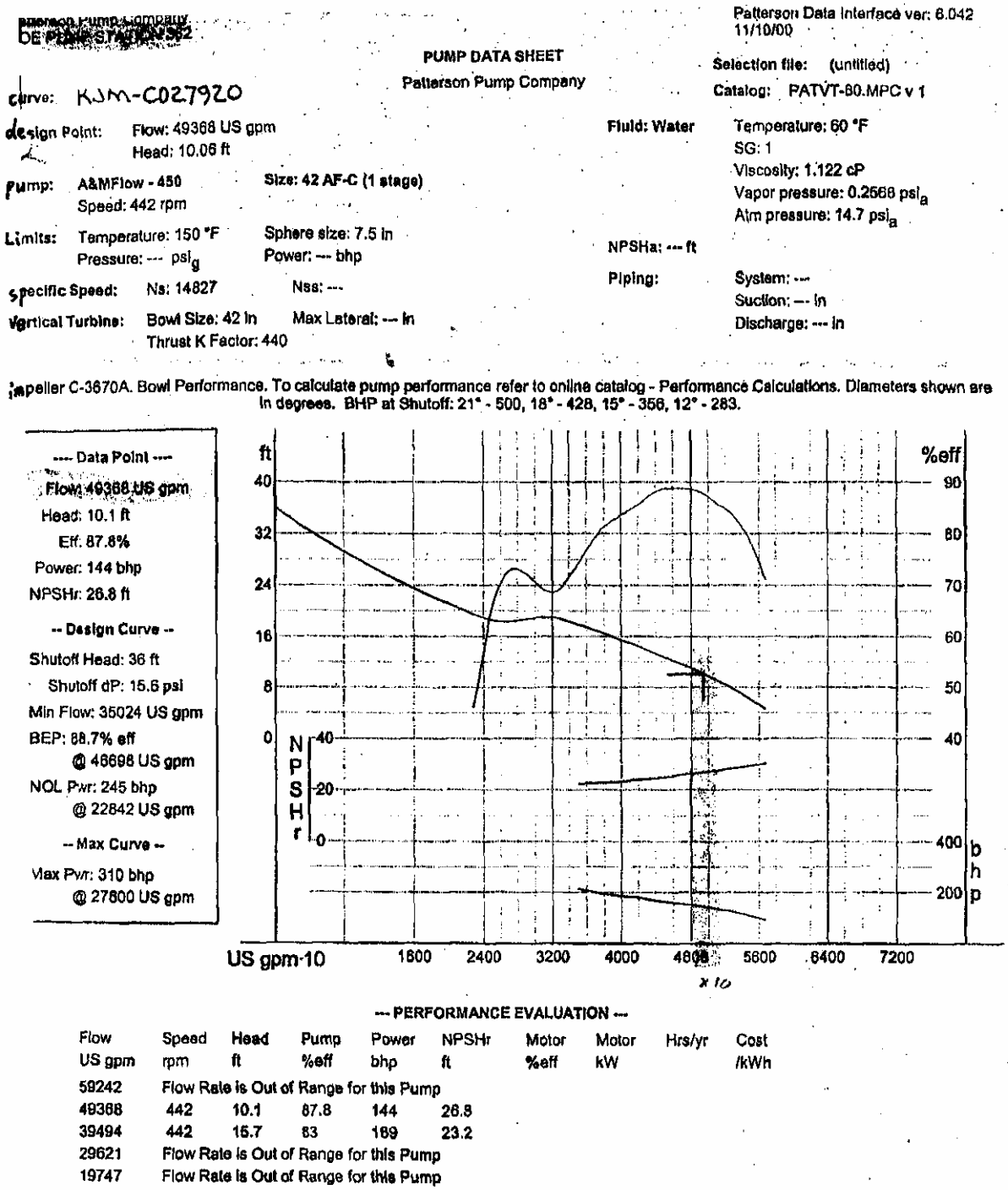

Figure 11. Performance curves of the 110 cfs pumps at S362

Table 11. Head and discharge values for calibration of the 110 cfs pumps at S362

TDH (ft)	Discharge (gpm)	Discharge (cfs)	Velocity (ft/s)	$V^2/(2g)$ (ft)	Friction loss (ft)	Minor loss (ft)	Kinetic head and losses (ft)	Static head (ft)
18.5	34000	75.8	7.88	0.97	0.20	0.97	1.16	17.34
17.5	36000	80.3	8.35	1.08	0.22	1.08	1.30	16.20
16.5	38000	84.7	8.81	1.21	0.24	1.21	1.45	15.05
15.7	39494	88.1	9.16	1.30	0.26	1.30	1.56	14.14
15.2	40000	89.2	9.28	1.34	0.27	1.34	1.60	13.60
14.5	42000	93.7	9.74	1.47	0.29	1.47	1.76	12.74
13.3	44000	98.1	10.20	1.62	0.32	1.62	1.93	11.37
12	46000	102.6	10.67	1.77	0.35	1.77	2.11	9.89
11	48000	107.0	11.13	1.92	0.37	1.92	2.30	8.70
10.1	49368	110.1	11.45	2.04	0.39	2.04	2.43	7.67
8	52000	116.0	12.06	2.26	0.43	2.26	2.69	5.31
6.5	54000	120.4	12.52	2.44	0.46	2.44	2.90	3.60
5.5	56000	124.9	12.99	2.62	0.50	2.62	3.12	2.38

Equation (9) represents the rating equation for flows through the 110 cfs pumps at S362. Table 12 shows computed discharges, discharges from pump curve, and relative errors for the 110 cfs pumps.

$$Q = 129\left[\frac{N}{N_0}\right] - 1.7H^{1.2}\left[\frac{N_0}{N}\right]^{1.4} \tag{9}$$

Table 12. Computed discharges, discharges from pump curve, and relative errors for the 110 cfs pumps at S362

No.	Q (cfs)	H (ft)	$Q_{computed}$ (cfs)	Relative error	Abs. error
1	75.8	17.34	76.9	1.36%	1.36%
2	80.3	16.20	80.9	0.82%	0.82%
3	84.7	15.05	85.0	0.30%	0.30%
4	88.1	14.14	88.2	0.12%	0.12%
5	89.2	13.60	90.0	0.94%	0.94%
6	93.7	12.74	93.0	-0.72%	0.72%
7	98.1	11.37	97.6	-0.55%	0.55%
8	102.6	9.89	102.4	-0.16%	0.16%
9	107.0	8.70	106.2	-0.79%	0.79%
10	110.1	7.67	109.4	-0.63%	0.63%
11	116.0	5.31	116.4	0.38%	0.38%
12	120.4	3.60	121.1	0.56%	0.56%
13	124.9	2.38	124.2	-0.56%	0.56%
Average relative error				0.083%	0.561%

Figure 12 shows head-discharge relationships for the 110 cfs pumps at S362 resulting from the performance curve and the rating curve adjusted for losses. The upper continuous curve represents the manufacturer's pump curve at the rated speed (442 rpm).

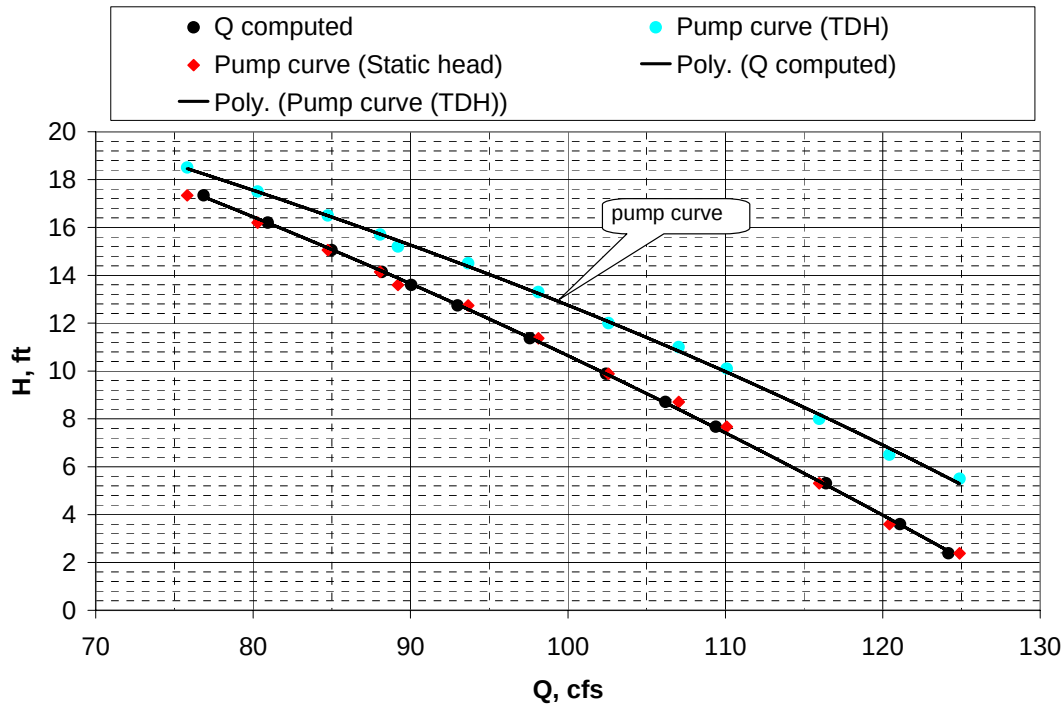

Figure 12. Head and discharge relationship for the 110 cfs pumps at S362 resulting from the performance curve and the rating curve adjusted for losses

6. Rating Analysis for G370

The structure G370 has three 925 cfs pumps. Figure 13 shows the head-discharge relationship for flows through the pumps at G370 under laboratory conditions at design pump speed (113 rpm). The performance curve is parabolic with concave down suggesting that a polynomial function with a power higher than one maybe appropriate to compute flow for pumps at G370. Minor losses and pipe friction losses are calculated using equations (1) and (2). The head and discharge values are summarized in Table 13 for the 925 cfs pumps.

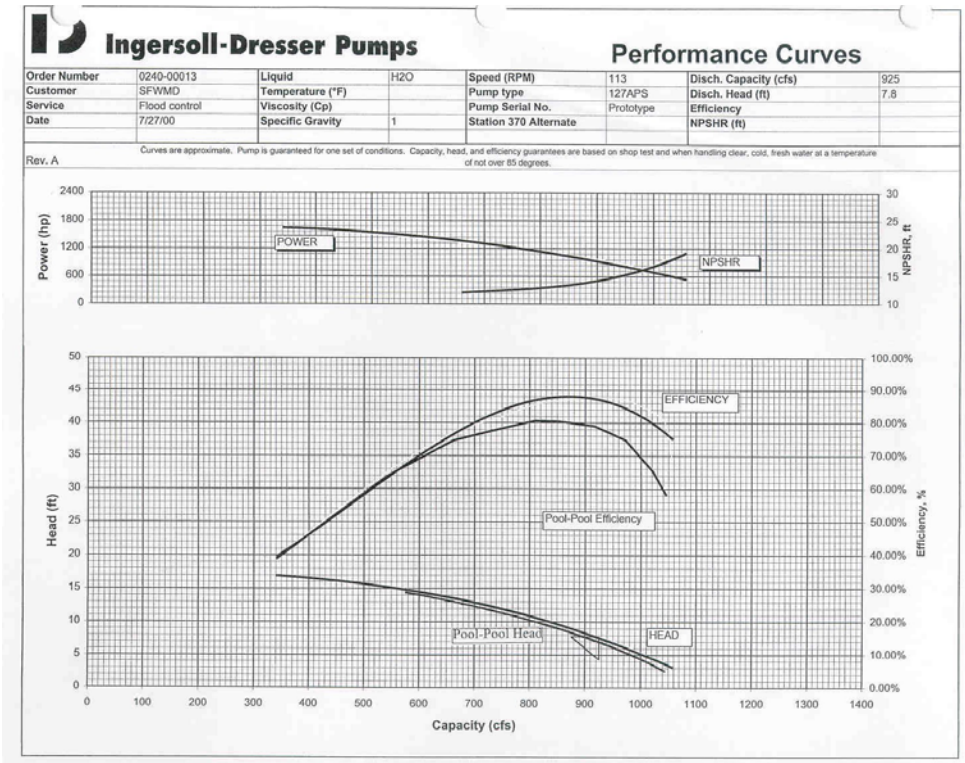

Figure 13. Performance curves of the 925 cfs pumps at G370

Table 13. Head and discharge values for calibration of the 925 cfs pumps at G370

TDH (ft)	Q (cfs)	Velocity (ft/s)	$V^2/(2g)$	Friction loss (ft)	Minor loss (ft)	Kinetic head and loss	Static head (ft)
14.0	600	5.31	0.44	0.11	0.66	0.77	13.23
13.1	650	5.75	0.51	0.13	0.77	0.90	12.20
12.5	700	6.19	0.60	0.15	0.89	1.04	11.46
11.4	750	6.63	0.68	0.17	1.03	1.20	10.20
10.1	800	7.08	0.78	0.19	1.17	1.36	8.74
9.0	850	7.52	0.88	0.21	1.32	1.53	7.47
8.0	900	7.96	0.99	0.24	1.48	1.72	6.28
7.0	925	8.18	1.04	0.25	1.56	1.81	5.19
6.1	950	8.40	1.10	0.26	1.65	1.91	4.19
4.4	1000	8.85	1.22	0.29	1.82	2.11	2.29

Equation (10) represents the rating equation for flow through pumps at G370. Table 14 shows computed discharges, discharges from the pump curve, and relative errors for the 925 cfs pumps.

$$Q = 1020\left[\frac{N}{N_0}\right] - 6.67H^{1.6}\left[\frac{N_0}{N}\right]^{2.2} \tag{10}$$

Table 14. Computed discharges, discharges from pump curve, and relative errors for the 925 cfs pumps at G370

No.	Q (cfs)	H (ft)	$Q_{computed}$ (cfs)	Relative error	abs. error
1	600	13.23	604.4	0.73%	0.73%
2	650	12.20	655.0	0.78%	0.78%
3	700	11.46	689.9	-1.44%	1.44%
4	750	10.20	745.7	-0.57%	0.57%
5	800	8.74	805.9	0.74%	0.74%
6	850	7.47	853.6	0.42%	0.42%
7	900	6.28	893.7	-0.70%	0.70%
8	925	5.19	927.0	0.22%	0.22%
9	950	4.19	954.0	0.42%	0.42%
10	1000	2.29	994.9	-0.51%	0.51%
Average relative error				0.01%	0.65%

Figure 14 shows head-discharge relationships for the 925 cfs pumps at G370 resulting from the performance curve and the rating curve adjusted for losses. The upper continuous curve represents the manufacturer's pump curve at rated speed (113 rpm).

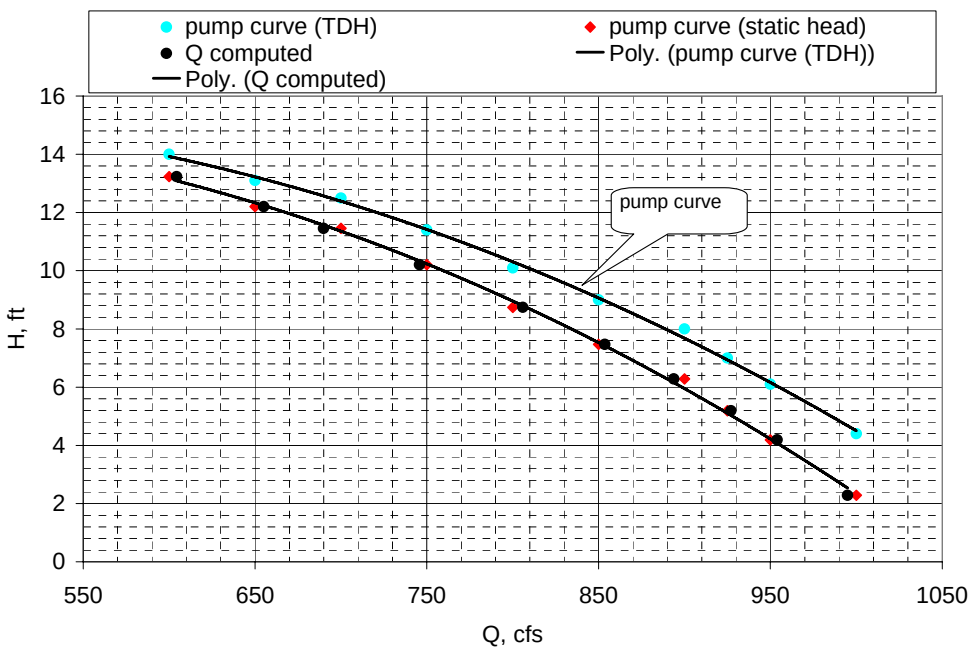

Figure 14. Head and discharge relationship for the 925 cfs pumps at G370 resulting from the performance curve and the rating curve adjusted for losses

7. Rating Analysis for G370S

The structure G370S has three 75 cfs pumps. The performance curves for the 75 cfs pumps are shown in Figure 15. As shown in Figure 15, the pump performance curves can be divided into two parts. The shape of the upper part suggests that a cubic equation may be applicable to

compute flow for the higher head range, and the lower part is parabolic with concave down suggesting that the standard rating equation may be suitable for the lower head range. The inflection point with a head of 14 ft is determined to separate these two parts. The rated capacity is 75 cfs at static head 7.8 ft. In this study, the standard rating equation is used to estimate the discharges for the total head equal to or less than 14 ft. The head and discharge values are summarized in Table 15 for the 75 cfs pumps for the head equal to or less than 14 ft.

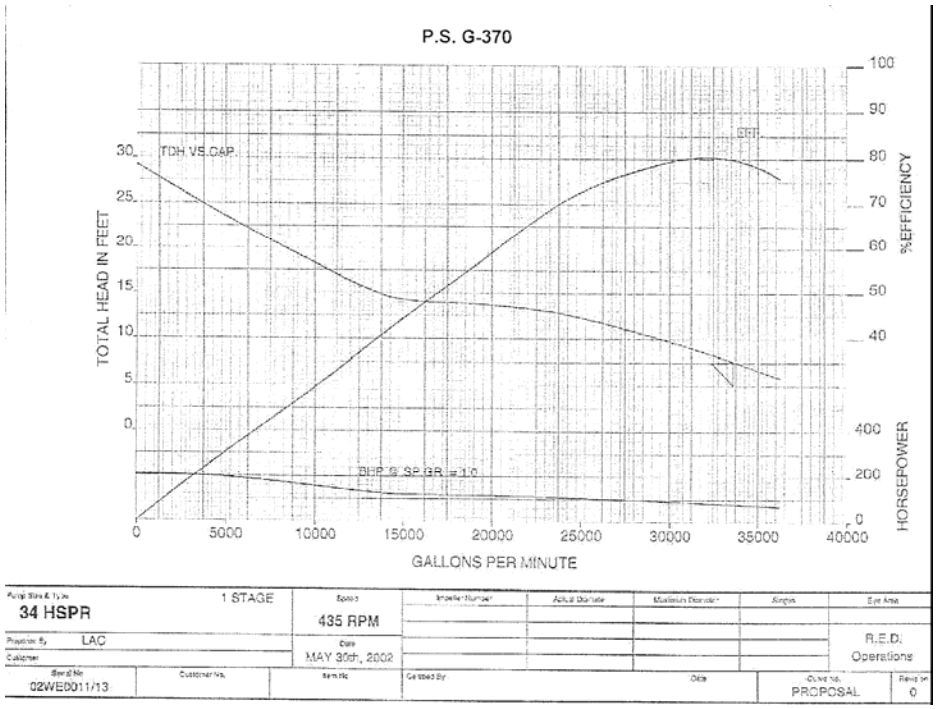

Figure 15. Performance curves of the 75 cfs pumps at G370S

Table 15. Head and discharge values for calibration of the 75 cfs pumps at G370S

TDH (ft)	Discharge (cfs)	Velocity	$V^2/(2g)$	Friction Loss	Minor Loss	Kinetic head and losses	Static Head (ft)
14.0	39.0	1.75	0.05	0.006	0.07	0.08	13.9
13.7	44.6	2.00	0.06	0.008	0.09	0.10	13.5
13.0	50.1	2.25	0.08	0.009	0.12	0.13	12.8
12.2	55.7	2.50	0.10	0.011	0.15	0.16	11.9
11.1	61.3	2.75	0.12	0.014	0.18	0.19	10.8
9.8	66.8	3.00	0.14	0.016	0.21	0.23	9.4
7.5	75.1	3.37	0.18	0.020	0.26	0.28	7.0
6.5	78.0	3.50	0.19	0.021	0.29	0.31	6.0

Equation (11) represents the rating equation for flow through G370S for total head equal to or less than 14 ft. Table 16 shows computed discharges, discharges from the pump curve, and relative errors for pumps at G370S.

$$Q = 83\left[\frac{N}{N_0}\right] - 0.057H^{2.5}\left[\frac{N_0}{N}\right]^4 \tag{11}$$

Table 16. Computed discharges, discharges from pump curve, and relative errors for the 75 cfs pumps at G370S

No.	H (ft)	Q (cfs)	$Q_{computed}$ (cfs)	relative error	abs. error
1	13.5	44.6	44.57	0.02%	0.02%
2	12.8	50.13	49.63	-1.0%	1.01%
3	11.9	55.7	54.88	-1.5%	1.46%
4	10.8	61.3	61.19	-0.1%	0.14%
5	9.4	66.8	67.41	0.9%	0.86%
6	7.0	75.1	75.51	0.6%	0.56%
7	6.0	78.0	77.97	0.0%	0.01%
Average relative error				-0.17%	0.58%

Figure 16 shows head-discharge relationships for the 75 cfs pumps at G370S resulting from the performance curve and the rating curve adjusted for losses for head differential less than 14 ft. The upper continuous curve represents the manufacturer's pump curve at rated speed (435 rpm).

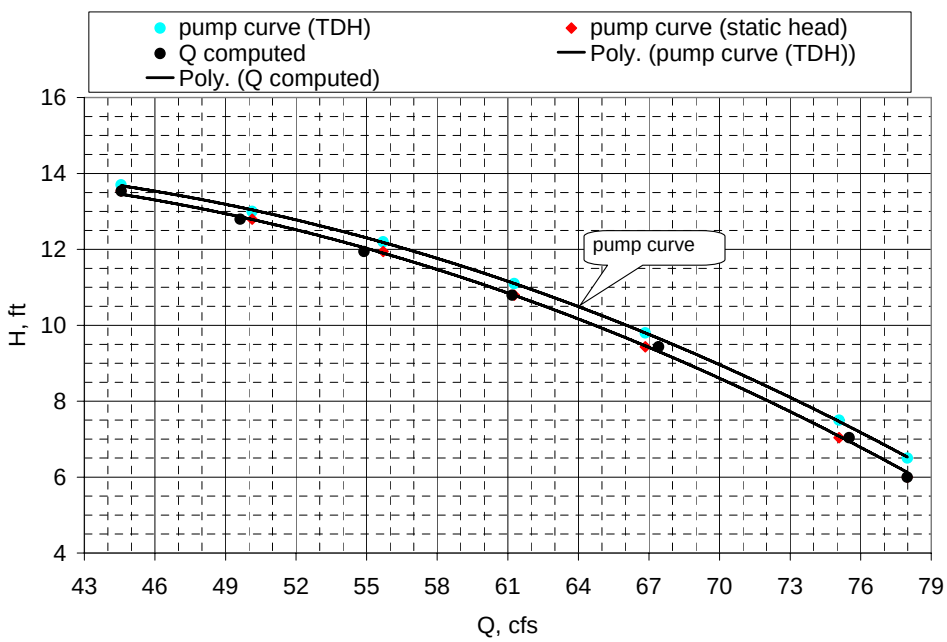

Figure 16. Head and discharge relationship for the 75 cfs pumps at G370S resulting from the performance curve and the rating curve adjusted for losses

Equation (12) is used for estimate flows for total head more than 14 ft for pumps at G370S.

$$Q = 278.93 - 34.505H + 1.5797H^2 - 0.0253H^3 \tag{12}$$

8. Rating Analysis for G372

The structure G372 has four 925 cfs pumps. The performance curves for the 925 cfs pumps are shown in Figure 17. The head and discharge values are summarized in Table 17.

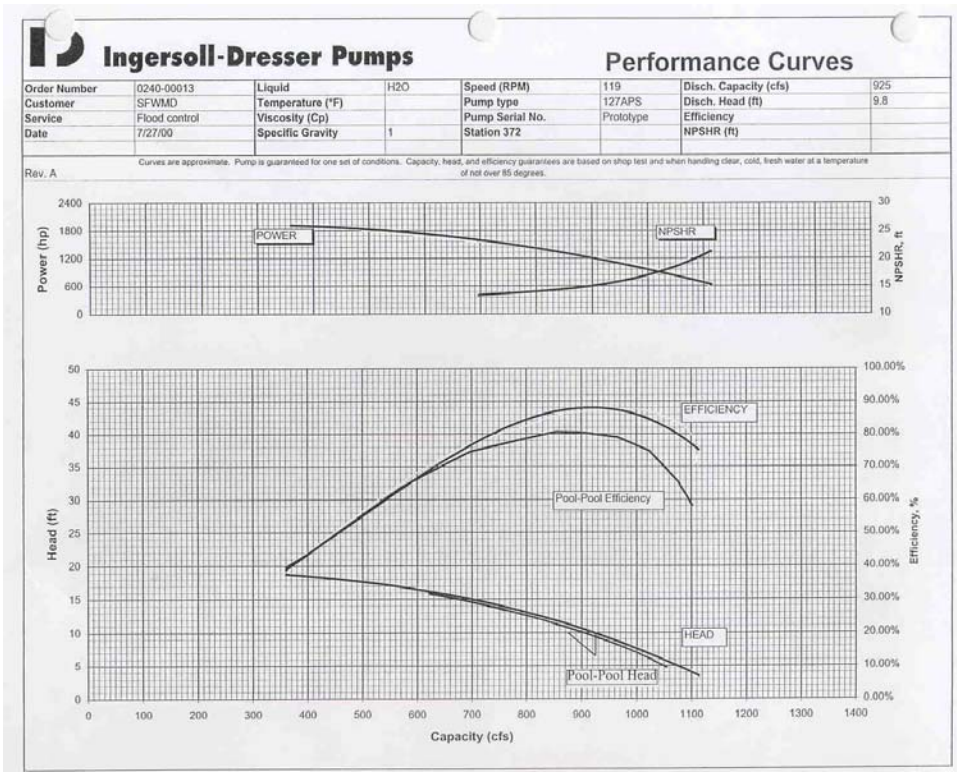

Figure 17. Performance curves of the 925 cfs pumps at G372

Table 17. Head and discharge values for calibration of the 925 cfs pumps at G372

TDH (ft)	Discharge (cfs)	Velocity	$V^2/(2g)$	Friction Loss	Minor Loss (ft)	Kinetic head and losses	Static Head (ft)
15.6	640	5.66	0.50	0.34	0.25	1.09	14.51
15.0	680	6.02	0.56	0.38	0.28	1.23	13.77
14.5	700	6.19	0.60	0.41	0.30	1.30	13.20
13.8	750	6.63	0.68	0.46	0.34	1.49	12.31
12.7	800	7.08	0.78	0.52	0.39	1.69	11.01
11.4	850	7.52	0.88	0.58	0.44	1.90	9.50
10.0	900	7.96	0.98	0.64	0.49	2.12	7.88
9.3	925	8.18	1.04	0.68	0.52	2.24	7.06
8.7	950	8.40	1.10	0.71	0.55	2.36	6.34
7.0	1000	8.85	1.22	0.78	0.61	2.61	4.39

Equation (13) represents the rating equation for flow through G372. Table 18 shows computed discharges, discharges from the pump curve, and relative errors.

$$Q = 1050\left[\frac{N}{N_0}\right] - 5.5H^{1.6}\left[\frac{N_0}{N}\right]^{2.2} \tag{13}$$

Table 18. Computed discharges, discharges from pump curve, and relative errors for the 925 cfs pumps at G372

No.	Q (cfs)	H (ft)	$Q_{computed}$ (cfs)	Relative error	Abs .error
1	640	14.51	652.8	2.00%	2.00%
2	680	13.77	684.6	0.67%	0.67%
3	700	13.20	708.5	1.22%	1.22%
4	750	12.31	744.5	-0.73%	0.73%
5	800	11.01	794.4	-0.70%	0.70%
6	850	9.50	848.2	-0.21%	0.21%
7	900	7.88	900.5	0.05%	0.05%
8	925	7.06	924.5	-0.05%	0.05%
9	950	6.34	944.3	-0.60%	0.60%
10	1000	4.39	991.3	-0.87%	0.87%
Average relative error				0.08%	0.71%

Figure 18 shows head-discharge relationships for the 925 cfs pumps at G372 resulting from the performance curve and the rating curve adjusted for losses. The upper continuous curve represents the manufacturer's pump curve at the rated speed (119 rpm).

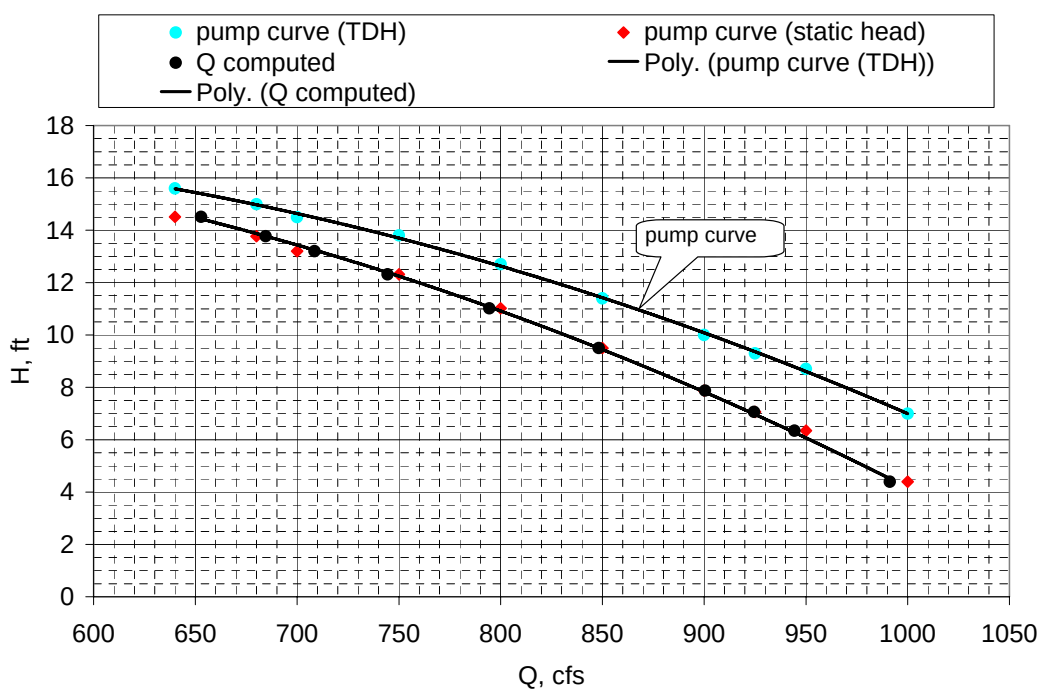

Figure 18. Head and discharge relationship for the 925 cfs pumps at G372 resulting from the performance curve and the rating curve adjusted for losses

9. Rating Analysis for G372S

The structure G372S has three 75 cfs pumps. The performance curves for the 75 cfs pumps are shown in Figure 19. As shown in Figure 19, the pump performance curves can be divided into two parts. The shape of the upper part suggests that a cubic equation may be applicable to compute flow for the higher head range, and the lower part is parabolic with concave down suggesting that the standard rating equation (Case 8) may be suitable for the lower head range. The inflection point with a head of 15 ft is determined to separate these two parts. The head and discharge values are summarized in Table 19 for the head equal to or less than 15 ft.

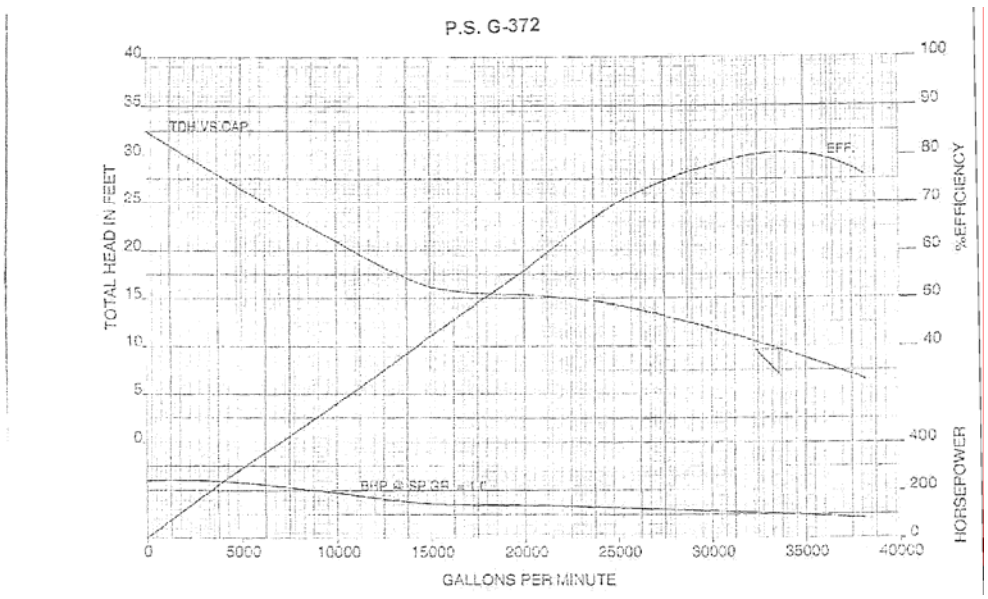

Figure 19. Performance curves of the 75 cfs pumps at G372S

Table 19. Head and discharge values for calibration of the 75 cfs pumps at G372S

TDH (ft)	Discharge (cfs)	Velocity	$V^2/(2g)$	Friction Loss	Minor Loss	Kinetic head and losses	Static Head (ft)
15.0	50.1	2.2	0.08	0.009	0.12	0.21	14.79
14.6	55.7	2.5	0.10	0.011	0.15	0.25	14.35
13.2	61.3	2.7	0.12	0.014	0.18	0.31	12.89
11.8	66.8	3.0	0.14	0.016	0.21	0.37	11.43
9.8	75.1	3.4	0.18	0.020	0.26	0.46	9.34
8.7	78.0	3.5	0.19	0.021	0.29	0.50	8.20
7.0	83.6	3.7	0.22	0.024	0.33	0.57	6.43

Equation (14) represents the rating equation for flow through G372S for total head equal to or less than 15 ft. Table 20 shows computed discharges, discharges from the pump curve, and relative errors for pumps at G372S at heads less than 15 ft.

$$Q = 90.0\left[\frac{N}{N_0}\right] - 0.18H^{2.0}\left[\frac{N_0}{N}\right]^{3.0} \tag{14}$$

Table 20. Computed discharges, discharges from pump curve, and relative errors for the 75 cfs pumps at G372S

No.	H (ft)	Q (cfs)	$Q_{computed}$ (cfs)	Relative error	abs. error
1	14.79	50.13	50.6	0.9%	0.94%
2	14.35	55.70	54.5	-2.2%	2.18%
3	12.89	61.27	60.1	-1.9%	1.94%
4	11.43	66.84	66.5	-0.6%	0.56%
5	9.34	75.08	74.3	-1.0%	1.05%
6	8.20	77.98	77.9	-0.1%	0.12%
7	6.43	83.55	82.6	-1.2%	1.19%
Average relative error				-0.87%	1.14%

Figure 20 shows head-discharge relationships for the 75 cfs pumps at G372S resulting from the performance curve and the rating curve adjusted for losses at heads less than 15 ft.

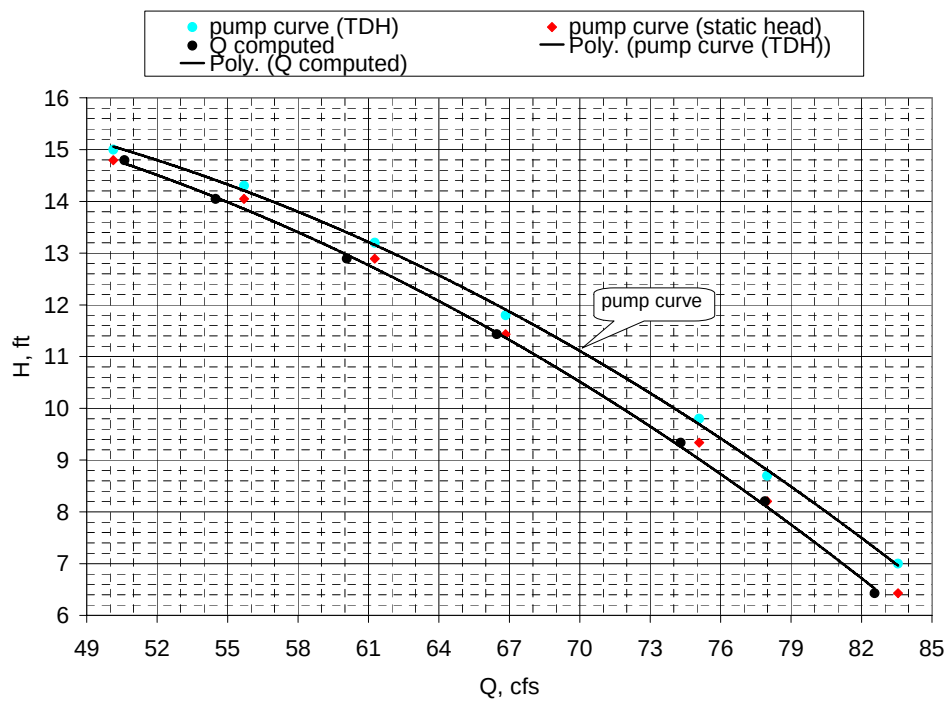

Figure 20. Head and discharge relationship for the 75 cfs pumps at G372S resulting from the performance curve and the rating curve adjusted for losses

Equation (15) is used for estimate flows for total head more than 15 ft for pumps at G372S.

$$Q = 364.89 - 42.551H + 1.7944H^2 - 0.0261H^3 \tag{15}$$

10. Rating Analysis for S25B

The structure S25B has three 200 cfs pumps. Figure 21 shows the head-discharge relationship for flows through the pumps at S25B. The head and discharge values are summarized in Table 21. The recorded drawing shows the capacity is 200 cfs at static head 7.5 ft for pumps at S25B.

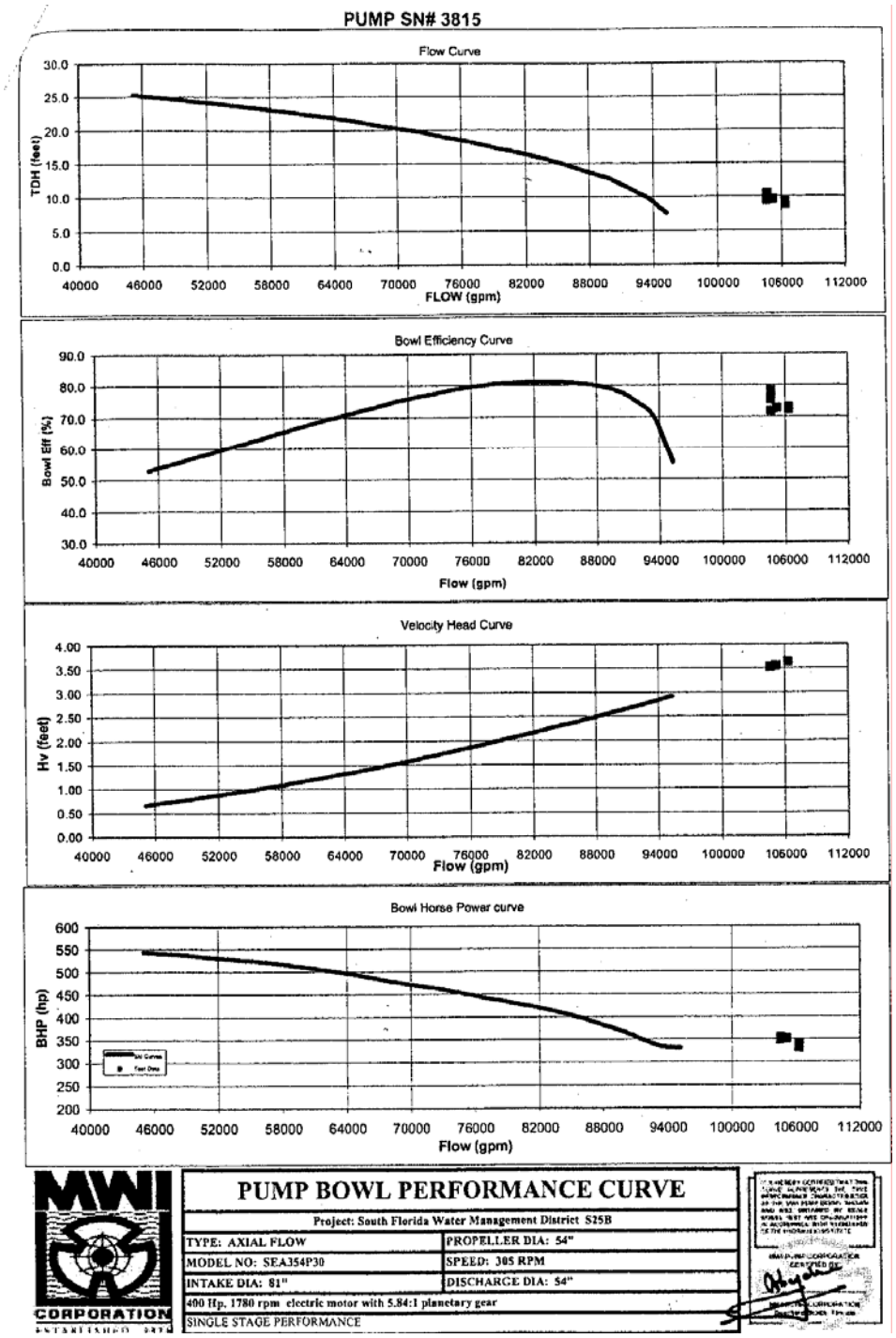

Figure 21. Performance curves of the 200 cfs pumps at S25B

Table 21. Head and discharge values for calibration of the 200 cfs pumps at S25B

TDH (ft)	Discharge (gpm)	Discharge (cfs)	Velocity (ft/s)	$V^2/(2g)$	friction loss (ft)	minor loss	kinetic head and losses	Static head (ft)
25.1	46000	102.6	6.45	0.65	0.08	1.36	1.44	23.66
24	52000	116.0	7.29	0.83	0.10	1.74	1.84	22.16
23.4	58000	129.3	8.14	1.03	0.13	2.16	2.28	21.12
22.1	64000	142.7	8.98	1.25	0.15	2.63	2.78	19.32
20	70000	156.1	9.82	1.50	0.18	3.14	3.32	16.68
18.5	76000	169.5	10.66	1.77	0.21	3.71	3.91	14.59
16.5	82000	182.9	11.50	2.05	0.24	4.32	4.55	11.95
15	85000	189.6	11.92	2.21	0.25	4.64	4.89	10.11
13.5	88000	196.2	12.35	2.37	0.27	4.97	5.24	8.26
13	89800	200.3	12.60	2.46	0.28	5.18	5.46	7.54
12	91000	202.9	12.77	2.53	0.29	5.31	5.60	6.40
11	92000	205.2	12.91	2.59	0.29	5.43	5.73	5.27
10.5	93000	207.4	13.05	2.64	0.30	5.55	5.85	4.65
9.4	94000	209.6	13.19	2.70	0.31	5.67	5.98	3.42

Equation (16) represents the rating equation for flows through the pumps at S25B. Table 22 shows computed discharges, discharges from the pump curve, and relative errors.

$$Q = 210\left[\frac{N}{N_0}\right] - 0.19H^2\left[\frac{N_0}{N}\right]^3 \tag{16}$$

Table 22. Computed discharges, discharges from pump curve, and relative errors for the 200 cfs pumps at S25B

No.	Q (cfs)	H (ft)	$Q_{computed}$ (cfs)	Relative error	Abs. error
1	102.6	23.66	103.6	1.03%	1.03%
2	116.0	22.16	116.7	0.62%	0.62%
3	129.3	21.12	125.3	-3.14%	3.14%
4	142.7	19.32	139.1	-2.56%	2.56%
5	156.1	16.68	157.1	0.67%	0.67%
6	169.5	14.59	169.6	0.05%	0.05%
7	182.9	11.95	182.9	0.01%	0.01%
8	189.6	10.11	190.6	0.54%	0.54%
9	196.2	8.26	197.0	0.41%	0.41%
10	200.3	7.54	199.2	-0.53%	0.53%
11	202.9	6.40	202.2	-0.35%	0.35%
12	205.2	5.27	204.7	-0.22%	0.22%
13	207.4	4.65	205.9	-0.72%	0.72%
14	209.6	3.42	207.8	-0.88%	0.88%
Average relative error				-0.36%	0.84%

Figure 22 shows head-discharge relationships for pumps at S25B resulting from the performance curve and the rating curve adjusted for losses. The upper continuous curve represents the manufacturer's pump curve at the rated speed (305 rpm).

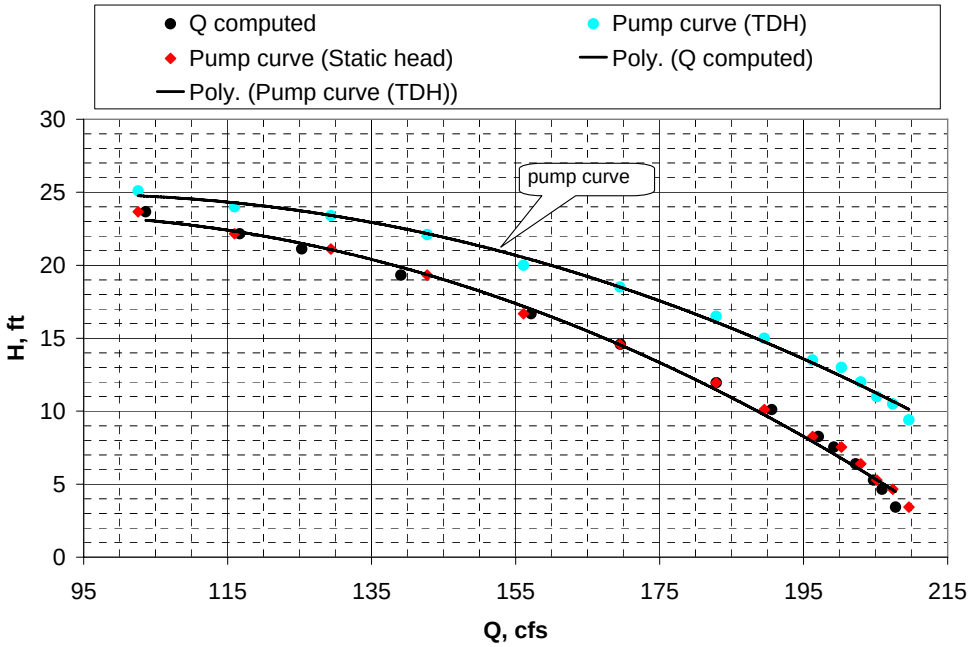

Figure 22. Head and discharge relationship for the 200 cfs pumps at S25B resulting from the performance curve and the rating curve adjusted for losses

11. Rating Analysis for S26

The structure S26 has three 200 cfs pumps. Figure 23 shows the head-discharge relationship for flows through the pumps at S26. The head and discharge values are summarized in Table 23. The drawing shows the capacity is 200 cfs at static head 7.5 ft for pumps at S26.

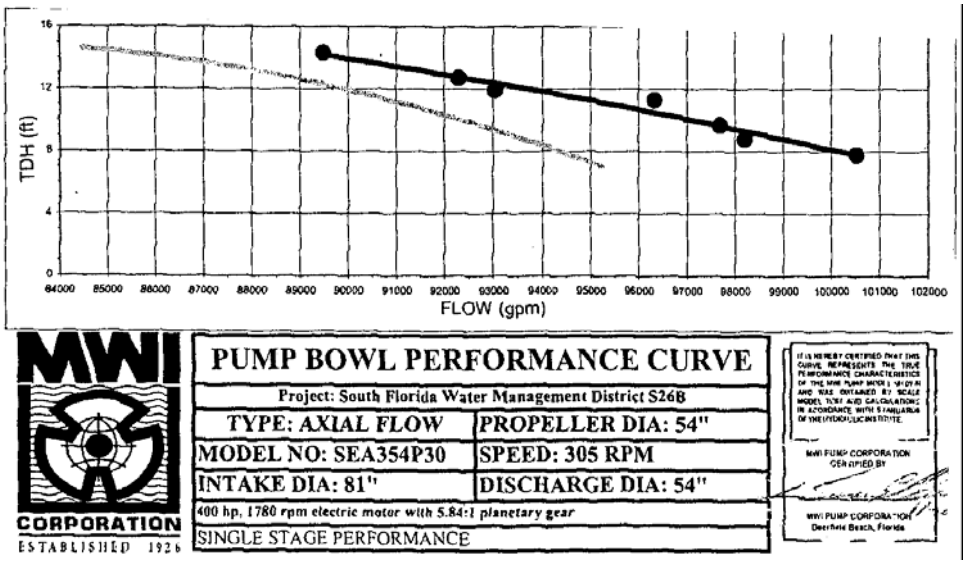

Figure 23. Performance curve for the 200 cfs pumps at S26

Table 23. Head and discharge values for calibration of the 200 cfs pumps at S26

Total Head (ft)	Discharge (gpm)	Discharge (cfs)	Velocity	$V^2/(2g)$	friction loss (ft)	minor loss	Kinetic head and losses	Static head (ft)
14	89500	199.6	12.56	2.45	0.28	6.022	6.30	7.70
13.9	89800	200.3	12.60	2.46	0.28	6.062	6.34	7.56
13.8	90000	200.7	12.63	2.48	0.28	6.089	6.37	7.43
13.3	91000	202.9	12.77	2.53	0.29	6.225	6.51	6.79
13	92000	205.2	12.91	2.59	0.29	6.363	6.66	6.34
12.5	93000	207.4	13.05	2.64	0.30	6.502	6.80	5.70
12	94000	209.6	13.19	2.70	0.31	6.642	6.95	5.05
11.1	95000	211.9	13.33	2.76	0.31	6.784	7.10	4.00
10.7	96000	214.1	13.47	2.82	0.32	6.928	7.25	3.45
9.9	97000	216.3	13.61	2.88	0.32	7.073	7.40	2.50
9.2	98000	218.5	13.75	2.93	0.33	7.22	7.55	1.65
8.7	99000	220.8	13.89	3.00	0.34	7.37	7.70	1.00
8.1	100000	223.0	14.03	3.06	0.34	7.52	7.86	0.24

Equation (17) represents the rating equation for flows through the pumps at S26. Table 24 shows the computed discharges, the discharges from the pump curve, and relative errors.

$$Q = 223\left[\frac{N}{N_0}\right] - 2.01H^{1.2}\left[\frac{N_0}{N}\right]^{1.4} \tag{17}$$

Table 24. Computed discharges, discharges from pump curve, and relative errors for the 200 cfs pumps at S26

No.	Q (cfs)	H (ft)	$Q_{computed}$ (cfs)	Relative error	Abs. error
1	199.6	7.70	199.7	0.07%	0.07%
2	200.3	7.56	200.2	-0.01%	0.01%
3	200.7	7.43	200.7	0.00%	0.00%
4	202.9	6.79	203.0	0.03%	0.03%
5	205.2	6.34	204.6	-0.30%	0.30%
6	207.4	5.70	206.8	-0.30%	0.30%
7	209.6	5.05	209.0	-0.31%	0.31%
8	211.9	4.00	212.4	0.25%	0.25%
9	214.1	3.45	214.1	0.01%	0.01%
10	216.3	2.50	217.0	0.30%	0.30%
11	218.5	1.65	219.3	0.36%	0.36%
12	220.8	1.00	221.0	0.10%	0.10%
13	223.0	0.24	222.6	-0.16%	0.16%
Average relative error				0.004%	0.17%

Figure 24 shows head-discharge relationships for pumps at S26 resulting from the performance curve and the rating curve adjusted for losses. The upper continuous curve represents the manufacturer's pump curve at the rated speed (305 rpm).

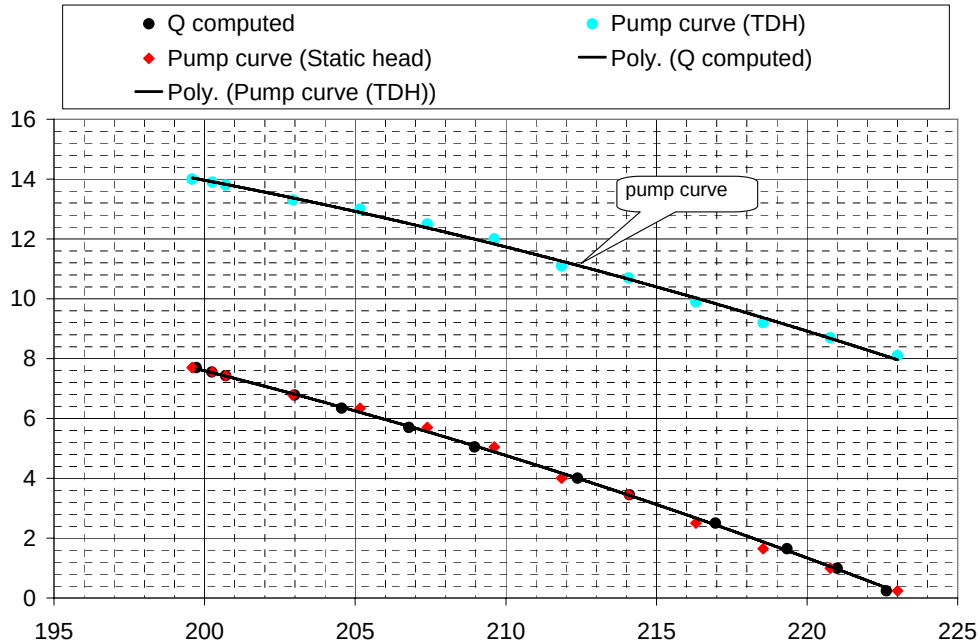

Figure 24. Head and discharge relationship for the 200 cfs pumps at S26 resulting from the performance curve and the rating curve adjusted for losses

12. Rating Analysis for G420

The structure G420 is a three-unit new pump station. The rated capacity is 223 cfs at 11.5 ft for pumps at G420. Figure 25 shows the head-discharge relationship for flows through the pumps at G420 under laboratory conditions at the design engine speed (1324 rpm). The performance curve is parabolic with concave down suggesting that a polynomial function with a power higher than one may be appropriate to compute flow for pumps at G420. The pump diameter is 5 ft for pumps at G420. The roughness coefficient is 130 for new pipes. The head and discharge values are summarized in Table 25.

Table 25. Head and discharge values for calibration of the 223 cfs pumps at G420

TDH (ft)	Discharge (cfs)	Velocity (ft/s)	$V^2/(2g)$ (ft)	friction loss (ft)	minor loss (ft)	Kinetic head and losses (ft)	Static head (ft)
14.8	204	10.38	1.67	0.22	1.67	1.89	12.87
14.1	209	10.63	1.76	0.23	1.76	1.98	12.13
13.1	214	10.92	1.85	0.24	1.85	2.09	11.03
12.1	220	11.21	1.95	0.25	1.95	2.20	9.94
11.5	223	11.35	2.00	0.26	2.00	2.26	9.23
10.8	226	11.52	2.06	0.26	2.06	2.32	8.51
9.8	231	11.77	2.15	0.27	2.15	2.42	7.42
8.5	237	12.05	2.26	0.29	2.26	2.54	5.99
8.2	238	12.13	2.28	0.29	2.28	2.57	5.63

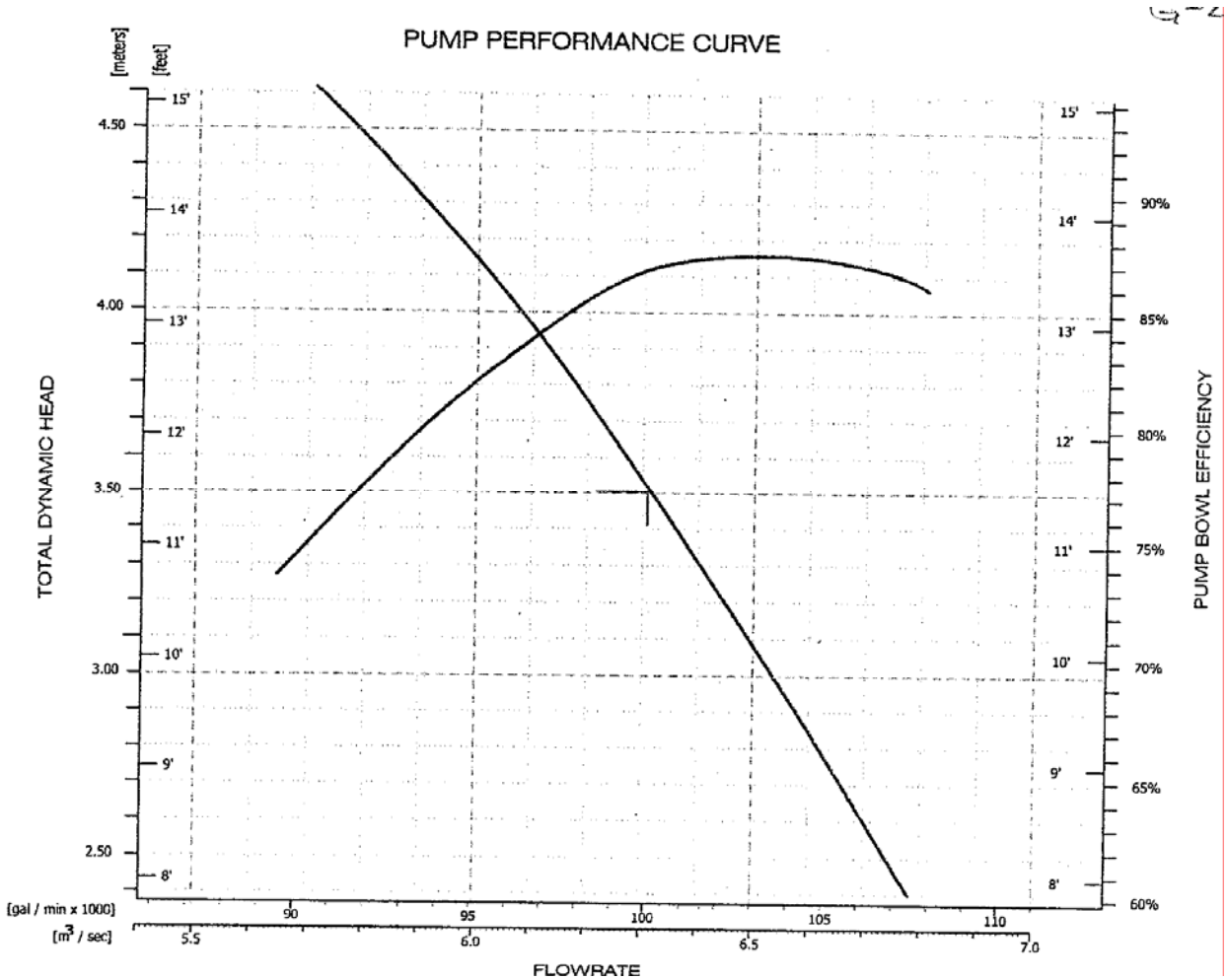

Figure 25. Performance curve of the 223 cfs pumps at G420

Equation (18) represents the rating equation for flow through pumps at G420. Table 26 shows computed discharges, discharges from the pump curve, and relative errors for G420.

$$Q = 250\left[\frac{N}{N_0}\right] - 0.77H^{1.6}\left[\frac{N_0}{N}\right]^{2.2} \tag{18}$$

where Q = discharge, cfs
H = head differential, ft
N_0 = the design engine speed, rpm
N = the field engine speed, rpm

Table 26. Computed discharges, discharges from pump curve, and relative errors for the 223 cfs pumps at G420

No.	H (ft)	$Q_{pump\ curve}$ (cfs)	$Q_{computed}$ (cfs)	Relative error	Abs. error
1	12.87	204	204	0.17%	0.17%
2	12.13	209	208	-0.20%	0.20%
3	11.03	214	214	-0.10%	0.10%
4	9.94	220	220	-0.15%	0.15%
5	9.23	223	223	0.11%	0.11%
6	8.51	226	226	0.16%	0.16%
7	7.42	231	231	0.03%	0.03%
8	5.99	237	237	-0.03%	0.03%
9	5.63	238	238	-0.09%	0.09%
Average relative error				-0.011%	0.11%

Figure 26 shows head-discharge relationships for pumps at G420 resulting from the performance curve and the rating curve adjusted for losses. The upper continuous curve represents the manufacturer's pump curve at rated speed (1324 rpm).

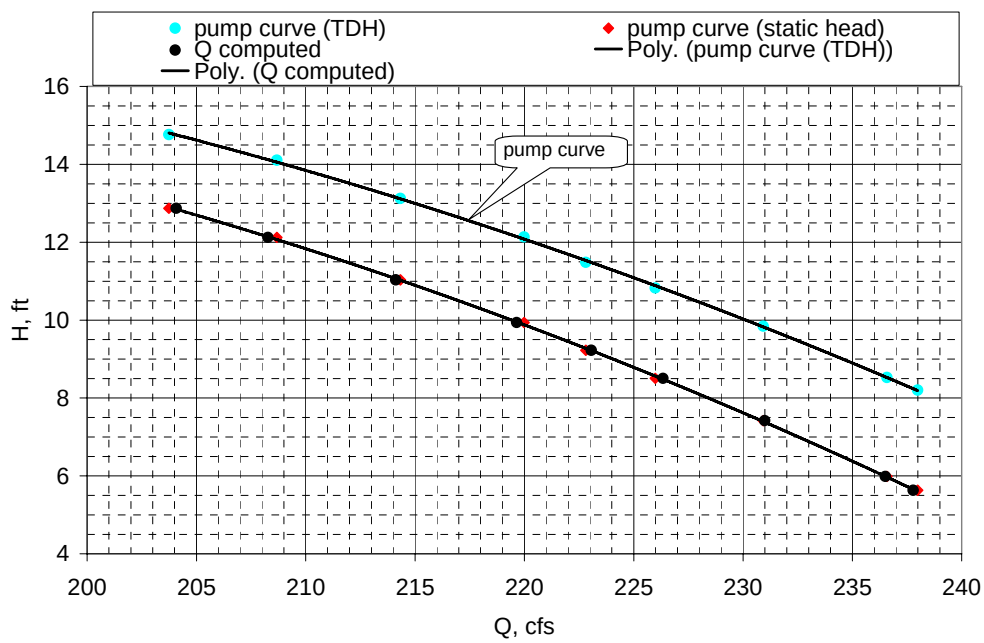

Figure 26. Head and discharge relationship for the 223 cfs pumps at G420 resulting from the performance curve and the rating curve adjusted for losses

13. Rating Analysis for G420S

The structure G420S is a new seepage pump station. The rated capacity is 66 cfs at 10.6 ft static head for pumps at G420S. Figure 27 shows the head-discharge relationship for flows through the

pumps at G420S under laboratory conditions at the design pump speed (297 rpm). The performance curve is parabolic with concave down suggesting that a polynomial function with a power higher than one may be appropriate to compute flow for pumps at G420S. The pump diameter is 3.5 ft for pumps at G420S. The roughness coefficient is 130 for new pipes. The head and discharge values are summarized in Table 27.

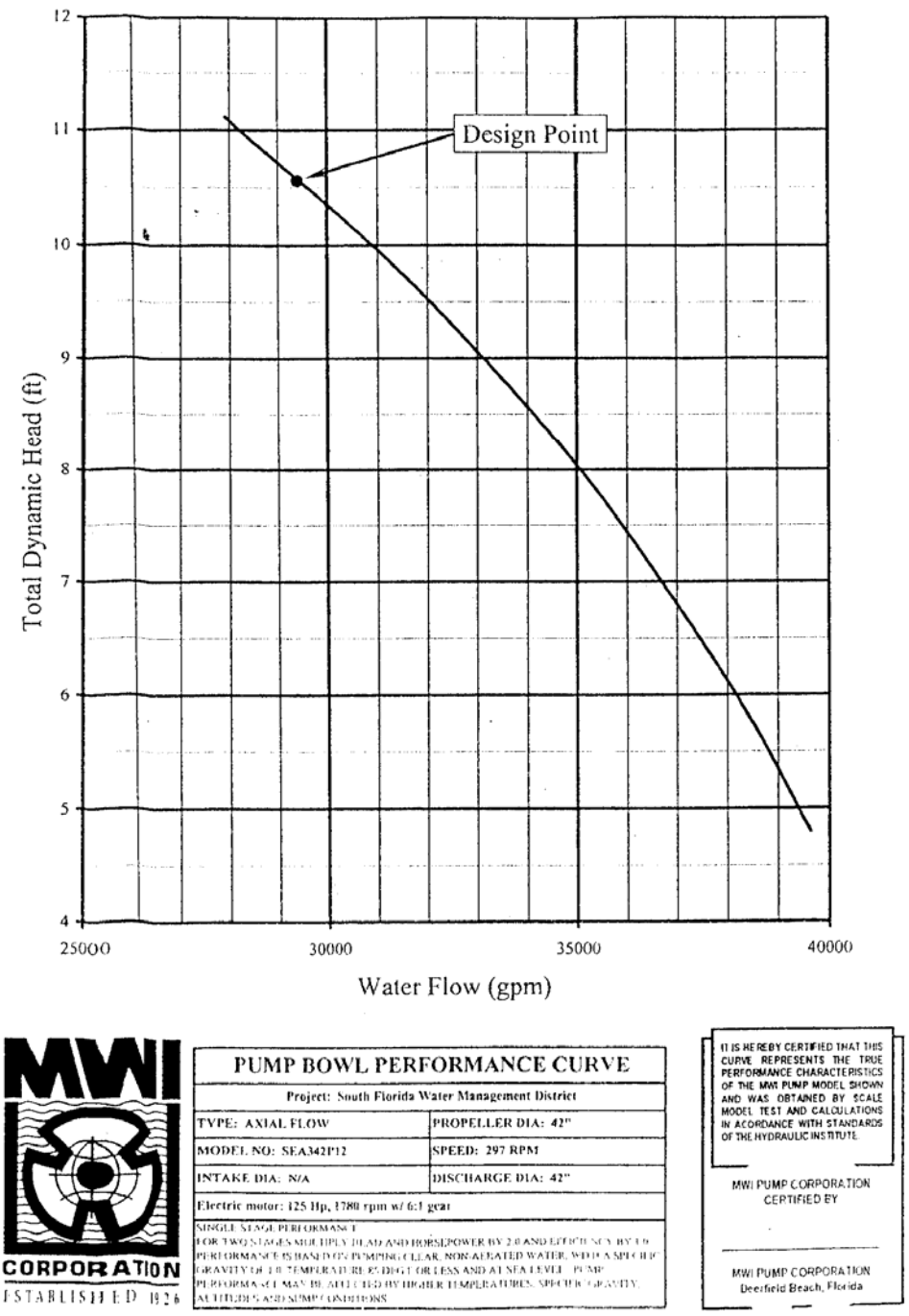

Figure 27. Performance curve for the 66 cfs pumps at G420S

Table 27. Head and discharge values for calibration of the 66 cfs pumps at G420S

TDH (ft)	Q (gpm)	Q (cfs)	Velocity (ft/s)	$V^2/(2g)$	friction loss	minor loss	kinetic head and losses	static head (ft)
11.0	28200	62.9	6.54	0.66	0.14	0.33	1.14	9.86
10.7	29000	64.7	6.73	0.70	0.15	0.35	1.20	9.52
10.6	29400	65.6	6.82	0.72	0.15	0.36	1.23	9.32
10.4	30000	66.9	6.96	0.75	0.16	0.38	1.28	9.12
9.9	31000	69.1	7.19	0.80	0.17	0.40	1.37	8.53
9.5	32000	71.4	7.42	0.86	0.18	0.43	1.46	8.05
9.1	33000	73.6	7.65	0.91	0.19	0.45	1.55	7.55
8.6	34000	75.8	7.88	0.97	0.20	0.48	1.65	6.95
8.1	35000	78.1	8.12	1.02	0.21	0.51	1.74	6.31
7.4	36000	80.3	8.35	1.08	0.22	0.54	1.84	5.59
6.8	37000	82.5	8.58	1.14	0.23	0.57	1.95	4.85
6.2	38000	84.7	8.81	1.21	0.24	0.60	2.05	4.10
5.4	39000	87.0	9.04	1.27	0.25	0.64	2.16	3.19

Equation (19) represents the rating equation for flow through pumps at G420S. Table 28 shows computed discharges, discharges from the pump curve, and relative errors for G420S.

$$Q = 90\left[\frac{N}{N_0}\right] - 0.44H^{1.8}\left[\frac{N_0}{N}\right]^{2.6} \tag{19}$$

Table 28. Computed discharges, discharges from pump curve, and relative errors for the 66 cfs pumps at G420S

No.	H (ft)	$Q_{\text{pump curve}}$ (cfs)	Q_{computed} (cfs)	Relative error	Abs .error
1	9.86	62.9	62.9	0.04%	0.04%
2	9.52	64.7	64.6	-0.12%	0.12%
3	9.32	65.6	65.6	0.00%	0.00%
4	9.12	66.9	66.5	-0.60%	0.60%
5	8.53	69.1	69.1	0.03%	0.03%
6	8.05	71.4	71.2	-0.21%	0.21%
7	7.55	73.6	73.3	-0.44%	0.44%
8	6.95	75.8	75.6	-0.34%	0.34%
9	6.31	78.1	77.9	-0.21%	0.21%
10	5.59	80.3	80.3	-0.02%	0.02%
11	4.85	82.5	82.4	-0.08%	0.08%
12	4.10	84.7	84.4	-0.37%	0.37%
13	3.19	87.0	86.4	-0.60%	0.60%
Average relative error				-0.23%	0.24%

Figure 28 shows head-discharge relationships for pumps at G420S resulting from the performance curve and the rating curve adjusted for losses. The upper continuous curve represents the manufacturer's pump curve at rated speed (297 rpm).

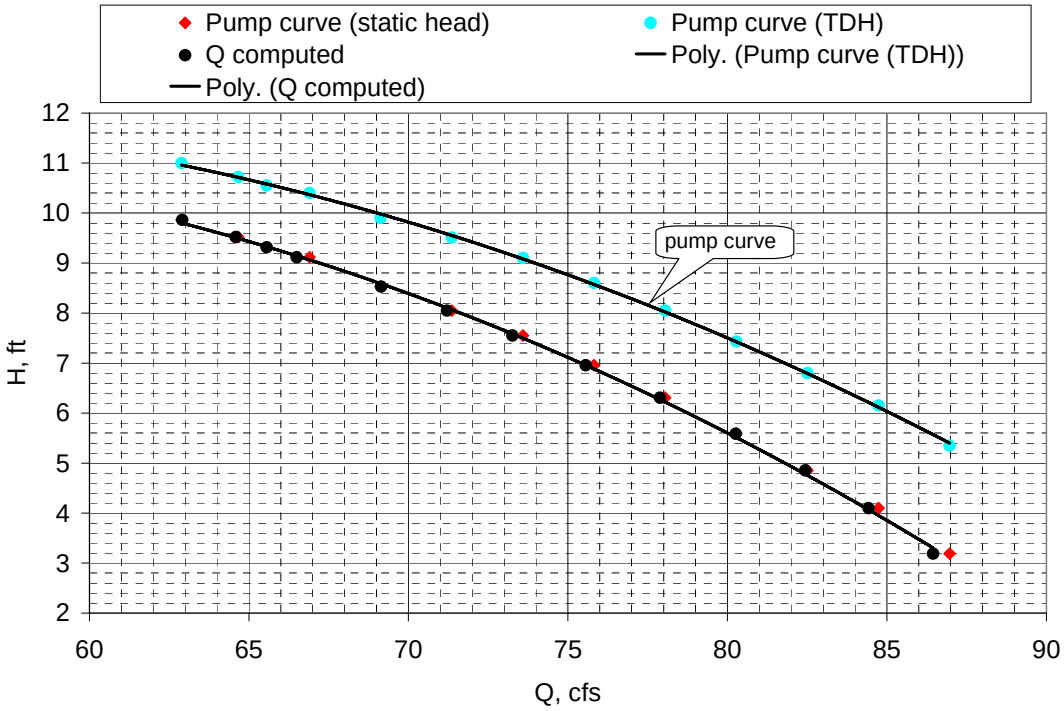

Figure 28. Head and discharge relationship for the 66 cfs pumps at G420S resulting from the performance curve and the rating curve adjusted for losses

14. Rating Analysis for S332C

The structure S332C has four 125 cfs pumps and one 75 cfs pump with a total capacity of 575 cfs. Figure 29 shows the head-discharge relationship for flows through the 125 cfs pumps at S332C under laboratory conditions at design pump speed (404 rpm). The pumping system losses for rated head, maximum head and minimum head are provided by the MWI Couch Pump Company. The head and discharge values are summarized in Table 29 for the 125 cfs pumps.

Table 29. Head and discharge values for calibration of the 125 cfs pumps at S332C

TDH (ft)	Discharge (gpm)	Discharge (cfs)	Intake losses	friction losses	velocity head	minor losses	kinetic head and losses	static head (ft)
16.9	54800	122.2	0.7	2.48	0.31	0.42	3.91	13.00
16.5	55500	123.8	0.72	2.54	0.31	0.43	4.01	12.49
16.0	56100	125.1	0.74	2.6	0.32	0.44	4.10	11.90
15.0	57500	128.2	0.78	2.73	0.34	0.46	4.31	10.69
14.0	58650	130.8	0.81	2.84	0.35	0.48	4.48	9.52
13.1	59500	132.7	0.81	2.92	0.36	0.48	4.57	8.50
12.0	60500	134.9	0.86	3.02	0.37	0.51	4.77	7.23
11.0	61200	136.5	0.88	3.09	0.38	0.52	4.88	6.12
10.0	61850	137.9	0.90	3.16	0.39	0.53	4.98	5.02
9.0	62350	139.0	0.91	3.21	0.40	0.54	5.06	3.94

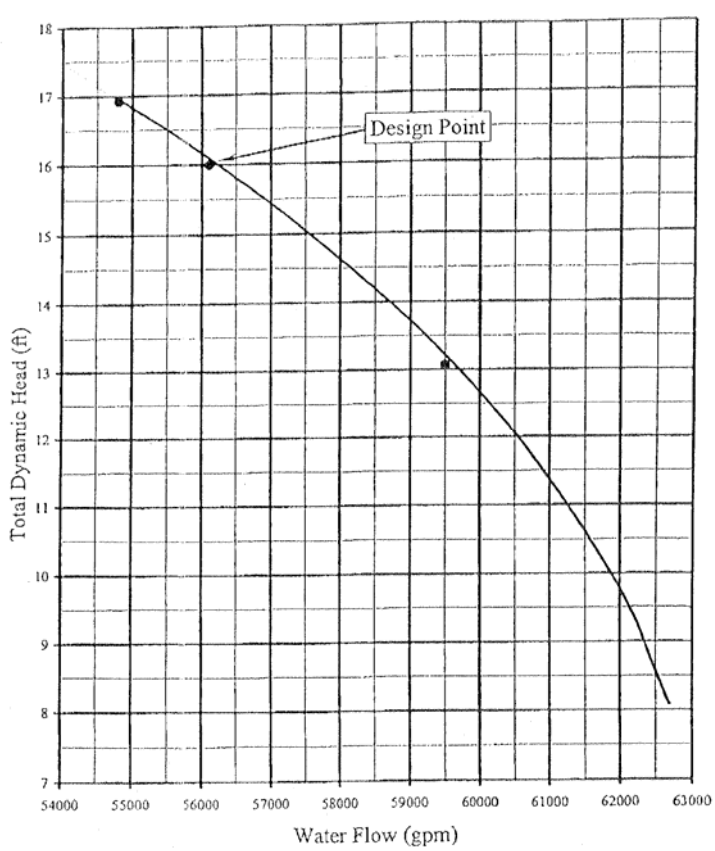

Figure 29. Performance curve of the 125 cfs pumps at S332C

Equation (20) represents the rating equation for flows through the 125 cfs pumps at S332C. Table 30 shows computed discharges, discharges from the pump curve, and relative errors.

$$Q = 141\left[\frac{N}{N_0}\right] - 0.113H^2\left[\frac{N_0}{N}\right]^3 \tag{20}$$

Table 30. Computed discharges, discharges from pump curve, and relative errors for the 125 cfs pumps at S332C

No.	Q (cfs)	H (ft)	$Q_{computed}$ (cfs)	Relative error	Abs. error
1	122.2	13.00	121.9	-0.25%	0.25%
2	123.8	12.49	123.4	-0.31%	0.31%
3	125.1	11.90	125.0	-0.08%	0.08%
4	128.2	10.69	128.1	-0.11%	0.11%
5	130.8	9.52	130.8	-0.02%	0.02%
6	132.7	8.50	132.8	0.11%	0.11%
7	134.9	7.23	135.1	0.13%	0.13%
8	136.5	6.12	136.8	0.21%	0.21%
9	137.9	5.02	138.2	0.17%	0.17%
10	139.0	3.94	139.2	0.15%	0.15%
Average relative error				0.00%	0.16%

Figure 30 shows head-discharge relationships for the 125 cfs pumps at S332C resulting from the performance curve and the rating curve adjusted for losses. The upper continuous curve represents the manufacturer's pump curve at the rated speed (404 rpm).

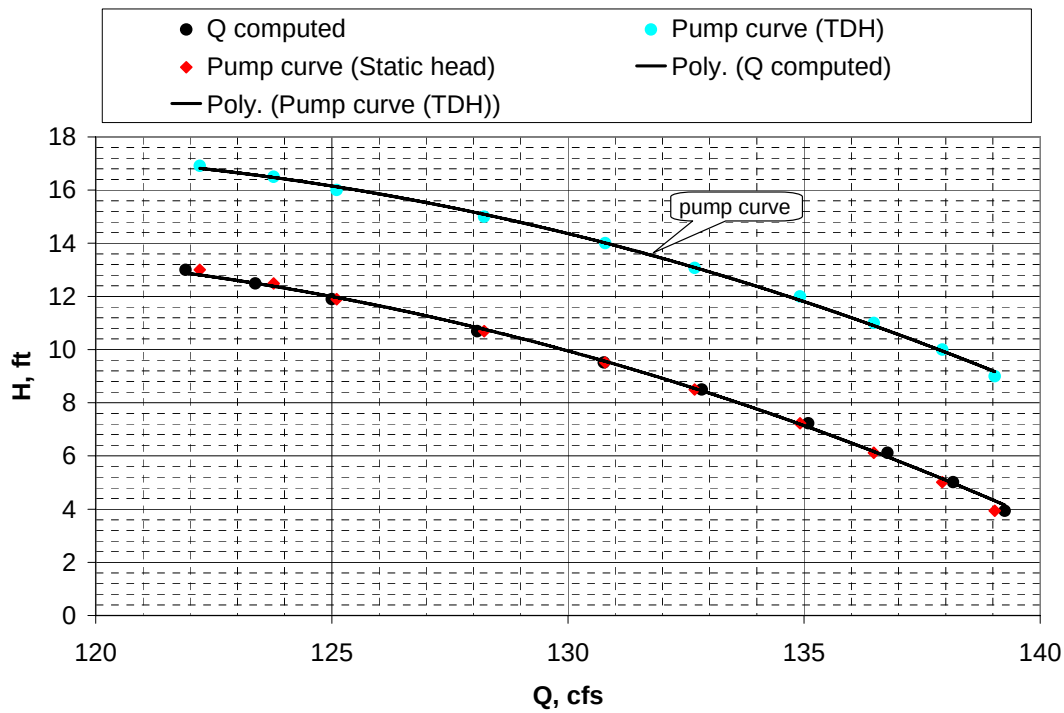

Figure 30. Head and discharge relationship for the 125 cfs pumps at S332C resulting from the performance curve and the rating curve adjusted for losses

Figure 31 shows the head-discharge relationship for flows through the 75 cfs pump at S332C under laboratory conditions at design pump speed (620 rpm). The pumping system losses for rated head, maximum head and minimum head are provided by the MWI Couch Pump Company. The head and discharge values are summarized in Table 31 for the 75 cfs pump.

Table 31. Head and discharge values for calibration of the 75 cfs pump at S332C

TDH (ft)	Discharge (gpm)	Discharge (cfs)	intake losses	friction losses	velocity head	minor losses	kinetic head and losses	static head (ft)
17.00	32875	73.3	0.97	1.88	0.15	0.27	3.27	13.73
16.00	33260	74.2	1.00	1.92	0.16	0.27	3.35	12.65
15.87	33300	74.3	1.00	1.93	0.16	0.28	3.37	12.50
14.84	33662	75.1	1.02	1.97	0.16	0.28	3.43	11.41
14.50	33750	75.3	1.03	1.98	0.16	0.28	3.45	11.05
14.00	33900	75.6	1.03	2.00	0.16	0.28	3.48	10.52
13.00	34200	76.3	1.05	2.03	0.17	0.29	3.54	9.46
12.00	34400	76.7	1.07	2.06	0.17	0.29	3.58	8.42
11.60	34500	76.9	1.07	2.06	0.17	0.3	3.60	8.00
10.50	34750	77.5	1.09	2.10	0.17	0.30	3.66	6.84

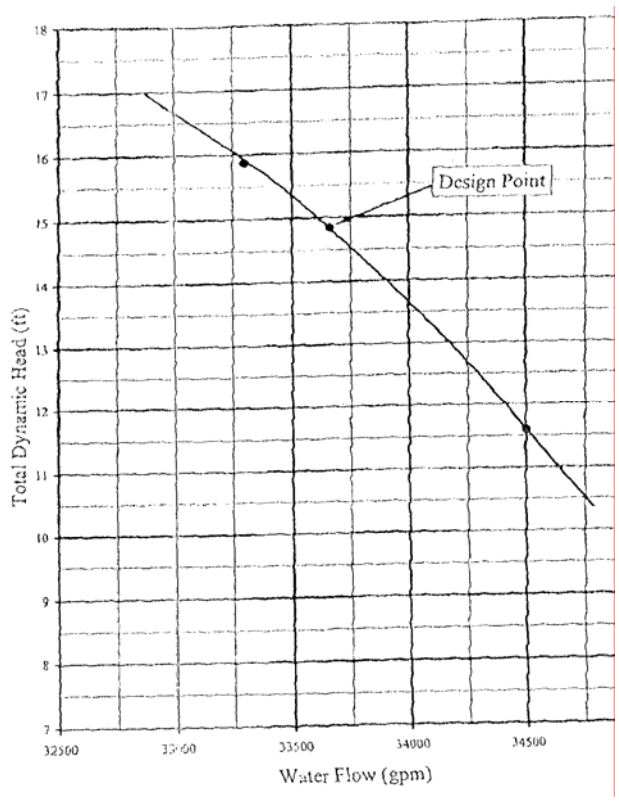

Figure 31. Performance curve of the 75 cfs pump at S332C

Equation (21) represents the rating equation for flows through the 75 cfs pump at S332C. Table 32 shows computed discharges, discharges from the pump curve, and relative errors. Figure 32 shows head-discharge relationships for the 75 cfs pump at S332C resulting from the performance curve and the rating curve adjusted for losses.

$$Q = 79\left[\frac{N}{N_0}\right] - 0.031H^2\left[\frac{N_0}{N}\right]^3 \tag{21}$$

Table 32. Computed discharges, discharges from pump curve, and relative errors for the 75 cfs pump at S332C

No.	Q (cfs)	H (ft)	$Q_{computed}$ (cfs)	Relative error	Abs. error
1	73.3	13.73	73.2	-0.21%	0.21%
2	74.2	12.65	74.0	-0.18%	0.18%
3	74.3	12.50	74.2	-0.14%	0.14%
4	75.1	11.41	75.0	-0.14%	0.14%
5	75.3	11.05	75.2	-0.07%	0.07%
6	75.6	10.52	75.6	-0.04%	0.04%
7	76.3	9.46	76.2	-0.05%	0.05%
8	76.7	8.42	76.8	0.12%	0.12%
9	76.9	8.00	77.0	0.11%	0.11%
10	77.5	6.84	77.5	0.07%	0.07%
Average relative error				-0.052%	0.11%

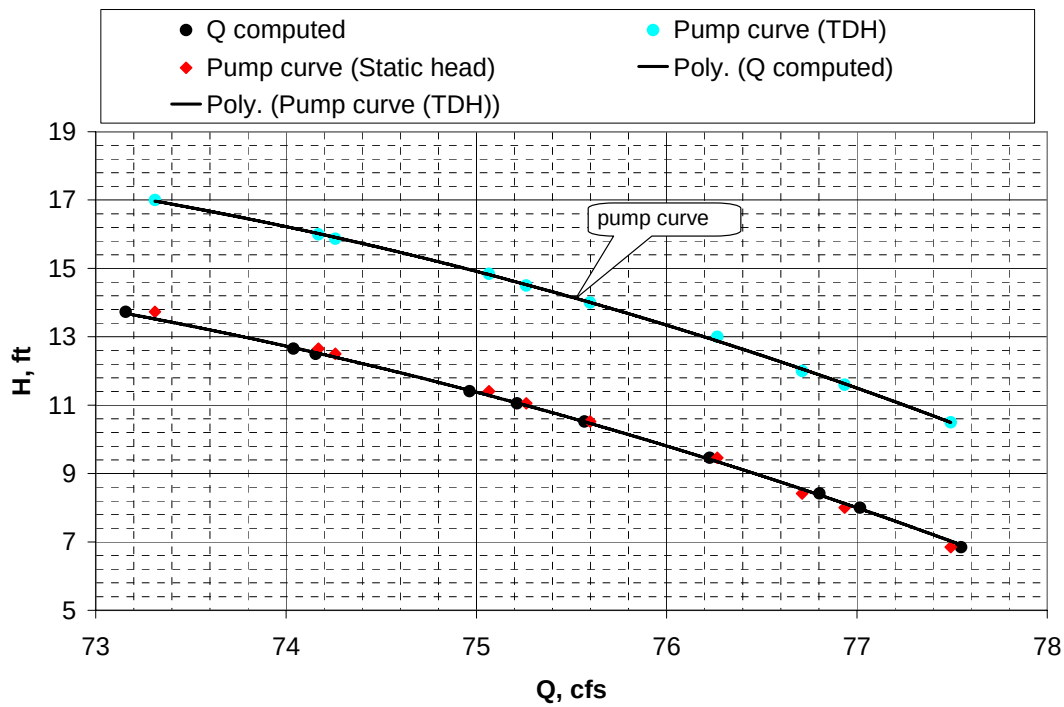

Figure 32. Head and discharge relationship for the 75 cfs pump at S332C resulting from the performance curve and the rating curve adjusted for losses

15. Rating Analysis for S356

The structure S356 has four 125 cfs pumps with a total capacity of 500 cfs. Figure 33 shows the head-discharge relationship for flows through the 125 cfs pumps at S356 under laboratory conditions at design pump speed (404 rpm). The pumping system losses for rated head, maximum head and minimum head are provided by the MWI Couch Pump Company. The head and discharge values are summarized in Table 33 for the 125 cfs pumps.

Table 33. Head and discharge values for calibration of the 125 cfs pumps at S356

TDH (ft)	Q (gpm)	Q (cfs)	intake losses	friction loss	velocity head	minor losses	kinetic head and loss	static head (ft)
19.33	50500	112.6	0.6	1.08	1.35	2.3	5.33	14.00
18.83	51500	114.8	0.62	1.12	1.41	2.39	5.55	13.28
18.05	53000	118.2	0.66	1.19	1.49	2.53	5.87	12.18
17.45	54000	120.4	0.69	1.23	1.55	2.63	6.10	11.35
16.46	55600	124.0	0.73	1.31	1.64	2.79	6.47	9.99
16.08	56100	125.1	0.74	1.33	1.67	2.84	6.58	9.50
15.45	57000	127.1	0.76	1.37	1.72	2.93	6.79	8.66
14.63	58000	129.3	0.79	1.42	1.79	3.04	7.03	7.60
13.7	59000	131.6	0.82	1.47	1.85	3.14	7.28	6.42

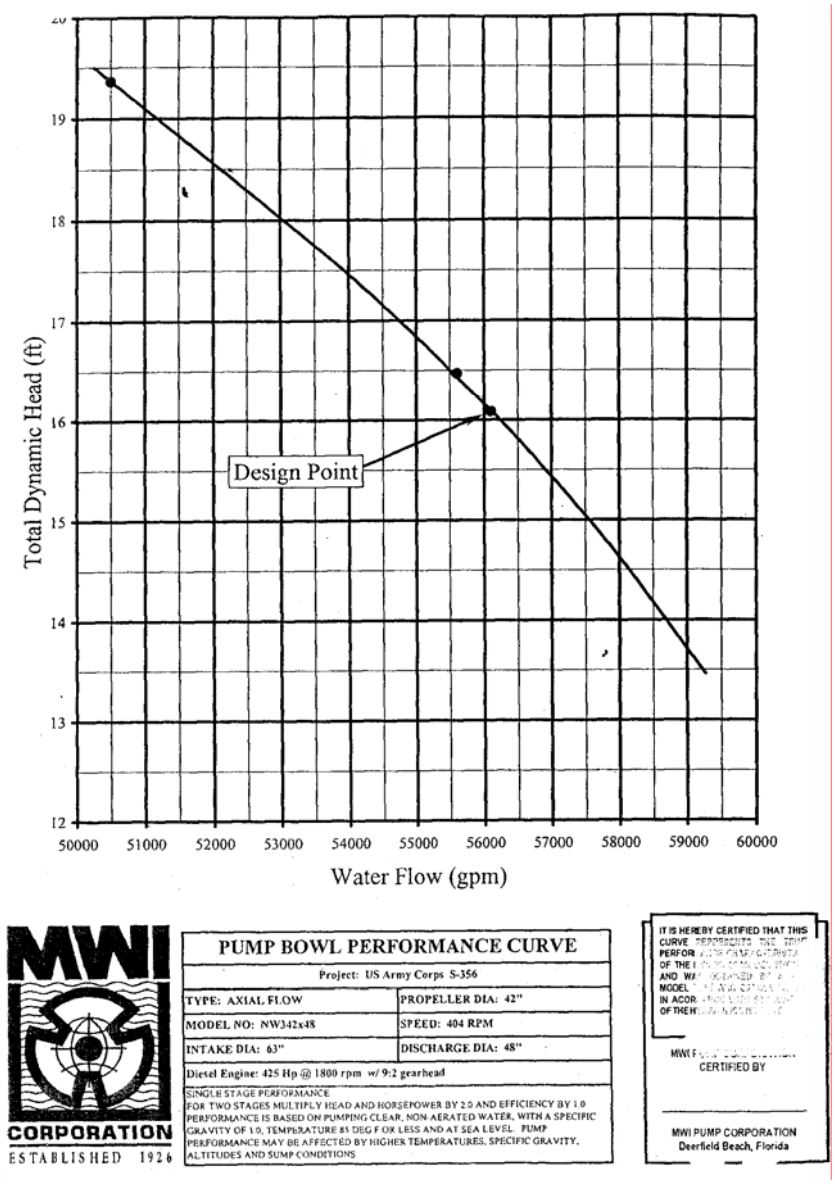

Figure 33. Performance curve of the 125 cfs pumps at S356

Equation (22) represents the rating equation for flows through the 125 cfs pumps at S356. Table 34 shows computed discharges, discharges from the pump curve, and relative errors.

$$Q = 136\left[\frac{N}{N_0}\right] - 0.12H^2\left[\frac{N_0}{N}\right]^3 \tag{22}$$

Table 34. Computed discharges, discharges from pump curve, and relative errors for the 125 cfs pumps at S356

No.	Q (cfs)	H (ft)	$Q_{computed}$ (cfs)	relative error	abs. error
1	112.6	14.00	112.5	-0.12%	0.12%
2	114.8	13.28	114.8	-0.02%	0.02%
3	118.2	12.18	118.2	0.01%	0.01%
4	120.4	11.35	120.5	0.09%	0.09%
5	124.0	9.99	124.0	0.03%	0.03%
6	125.1	9.50	125.2	0.05%	0.05%
7	127.1	8.66	127.0	-0.08%	0.08%
8	129.3	7.60	129.1	-0.21%	0.21%
9	131.6	6.42	131.1	-0.39%	0.39%
Average relative error				-0.07%	0.11%

Figure 34 shows head-discharge relationships for the 125 cfs pumps at S356 resulting from the performance curve and the rating curve adjusted for losses. The upper continuous curve represents the manufacturer's pump curve at the rated speed (404 rpm).

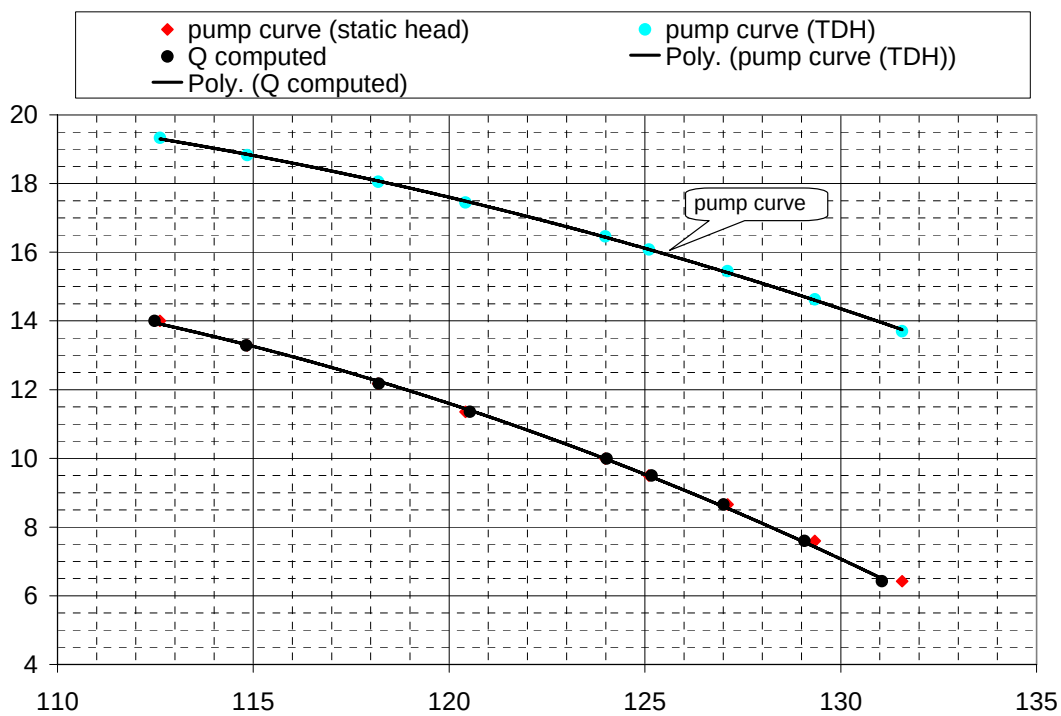

Figure 34. Head and discharge relationship for the 125 cfs pumps at S356 resulting from the performance curve and the rating curve adjusted for losses

16. Summary of Rating Analyses

The rating analysis results for the thirteen new pump stations are summarized in Table 35.

Table 35. Summary of the rating analyses results for the new pump stations

No.	Pump Station	Unit No.	Power source	Design flow (cfs)	Design head (ft)	Pump diameter (ft)	Case No.	pump or engine speed (N0*)	A	B	C	D=2C-1	Abs. error	Project area	Comments
1	S319_P	1	diesel	960	10.6	10	8	128 (pump)	1135	-10.15	1.4	1.8	0.59%	STA-1E	
		2													
		3													
		4	diesel	550	10.6	7.5	8	196 (pump)	640	-7.81	1.2	1.4	0.30%		
		5													
2	S361_P	1	electric	25	22	1.7	8	884	34	-0.019	2	3	0.35%		
		2													
		3													
3	S362_P	1	diesel	960	5.5	10	8	117 (pump)	1040	-19.05	1.2	1.4	0.23%		
		2													
		3													
		4	diesel	550	5.5	7.5	8	179 (pump)	602	-8.84	1.2	1.4	0.23%		
		5													
		6	electric	110	10.6	3.5	8	442	129	-1.7	1.2	1.4	0.61%		
		7													
4	G370_P	1	diesel	925	7.8	9.2	8	113 (pump)	1020	-6.67	1.6	2.2	0.65%	STA-3/4	average pump diameter
		2													
		3													
5	G370S_P	1	electric	75	7.8	5.3	8	435	83	-0.057	2.5	4	0.58%		For H<14 ft only
		2													
		3													
6	G372_P	1	diesel	925	9.8	9.2	8	119 (pump)	1050	-5.5	1.6	2.2	0.71%		average pump diameter
		2													
		3													
		4													
7	G372S_P	1	electric	75	9.8	5.3	8	435	90	-0.18	2	3	1.14%		For H<15 ft only
		2													
		3													
8	S25B_P	1	electric	200	7.5	4.5	8	305 (pump)	210	-0.19	2	3	0.84%	MIAMI	
		2													
		3													
9	S26_P	1	electric	200	7.5	4.5	8	305 (pump)	223	-2.01	1.2	1.4	0.17%		
		2													
		3													
10	G420_P	1	diesel	223	11.5	5	8	1324 (engine)	250	-0.77	1.6	2.2	0.11%		
		2													
		3													
11	G420S_P		electric	66	10.6	3.5	8	297 (pump)	90	-0.44	1.8	2.6	0.24%		

Table 35. Summary of the rating analyses results for the new pump stations

No.	Pump Station	Unit No.	Power source	Design flow (cfs)	Design head (ft)	Pump diameter (ft)	Case No.	pump or engine speed (N0*)	A	B	C	D=2C-1	Abs. error	Project area	Comments
12	S356_P	1	diesel	125	16	3.5	8	404 (pump)	136	-0.12	2	3	0.11%	MIAMI	
		2													
		3													
		4													
13	S332C_P	1	diesel	125	16	3.5	8	404 (pump)	141	-0.113	2	3	0.16%	HMSTD	
		2													
		4													
		5													
		3	electric	75	14.8	2.5	8	620 (pump)	79	-0.031	2	3	0.11%		

17. Conclusion

The rating equations (4) through (22) have 100% of calculated discharge within ±5% of the discharge from the pump curve for all the pump stations. The rating equations developed here can be used to estimate flow for pumps at these new pump stations.

18. Recommendation

The equations (4) through (22) are recommended for computing flow through pumps. It is recommended that the rating equations developed here be validated using streamflow measurements.

19. Reference

Damisse, E., 2000, Flow Rating Development for G335 Pump Station in STA-2, Hydrology and Hydraulics Division, South Florida Water Management District, West Palm Beach, Florida.

Davis, J.C., 1986, Statistics and Data Analysis in Geology, p 176-186, John Wiley & Sons, Inc.

Imru, M., and Y. Wang, 2003, Flow Rating Analysis Procedures for Pumps, Technical Publication EMA #413, South Florida Water Management District, West Palm Beach, Florida.

Karassik I. J., W. C. Krutzsch, W. H. Fraser and J. P. Messina, 1976, Pump Handbook, p 9-37. McGraw-Hill Book Company.

U.S. Army Corps of Engineers (USACE), 2000, Operation Plan, Stormwater Treatment Area No. 1 East (Draft), U.S. Army Corps of Engineers Jacksonville District.