FLOW AND TORQUE CHARACTERISTICS OF ROCKWELL PERMASPHERE VALVES WITH LARGE DISCHARGES

Prepared for the
Rockwell Manufacturing Company
Pittsburg, Pennsylvania

COLORADO STATE UNIVERSITY
ENGINEERING RESEARCH CENTER
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LIST OF SYMBOLS

A	Area of the pipe using nominal diameter, ft^2
A_p	Area of plug port opening, ft^2
C	Flow coefficient, $Q\sqrt{\Delta p} = 12 C_d A_p \sqrt{\frac{2g}{\gamma}}$
C_d	Discharge coefficient
C_T	Dynamic torque coefficient
D	Valve or pipe diameter, nominal size, ft
E	Modulus of elasticity for steel
f_k	Coefficient of kinetic friction between the seat and the plug
G	Gauge factor for the strain gauges
g	Gravitational acceleration in ft/sec^2
J	Polar moment of inertia, in^4
k	Transverse sensitivity of the strain gauges
K	Flow coefficient $C/A = V/\sqrt{\Delta p}$
N	Number of strain gauges
Δp	Differential pressure across the valve from upstream flange to downstream flange, psi.
Q	Total discharge, cfs
r	Shaft radius, in.
R	Strain gauge resistance (unstrained)
R_c	Calibrating resistance
Re	Pipe Reynolds number
T_c	Torque to close the valve, ft-lbs.
T_D	Dynamic torque, ft-lbs.
T_F	Friction torque, ft-lbs.
T_o	Torque to open the valve, ft-lbs.
u	Poisson's ratio
V	Velocity of flow in the pipe, ft/sec
$\Sigma\Delta v$	Changes in velocity of flow through the valve plug
ϵ	Strain
γ	Unit weight of water, lbs/ft^3
σ	Stress

LIST OF SYMBOLS (cont'd)

ρ	Density of water, slugs/ft^3
θ	Plug position, where $\theta = 0^0$ is wide open and $\theta = 90^0$ is closed.
μ	Dynamic viscosity

SYNOPSIS

A study of Permasphere valves of the Rockwell Manufacturing Company was conducted for three sizes, 36, 24 and 12-in, to determine the flow characteristics through the valve and dynamic torque created by the flow. The study was conducted at the Engineering Research Center, Colorado State University.

The flow coefficient $K = \frac{V}{\sqrt{\Delta p}}$ was found to be the same for all three sizes. A graphical representation of its magnitude as a function of plug position and differential pressure is given in Fig. 14. The flow coefficient enables calculation of discharge through the valve at different pressures across the valve and shows that the head loss through the valve at full open position is very small.

The dynamic torque, or torque exerted on the valve due to the flow through it is presented in Fig. 30 with $C_T = \frac{T_D}{\Delta p D^3}$ expressed as a function of plug position and differential pressure. By adding or subtracting the dynamic torque to the friction torque it is possible to determine the torque which will be required to open the valve or close it. Friction torque is determined in an independent manner, outside the scope of this report, but Figs. 17, 22 and 27 give indications of the magnitudes of friction torque for the three valves tested.

INTRODUCTION

The Rockwell Permasphere valve is a spherical plug valve that rotates 90 degrees from wide open to completely closed positions. The primary component parts consist of a split cast iron body, a spherical nickel plated cast iron plug, and a solid stem from the plug to a worm gear operator which can be driven by a hand wheel, or by an electric motor. Operation with hydraulic or pneumatic cylinders is also possible. There are circular seat rings on both inlet and outlet sides of the plug which renders the valve leak tight in the completely closed position. The valve is manufactured in sizes from 8 to 48 inches with ASA pressure rating classes of 125 and 250 psi. A more complete description and cut-away pictoral views are included in brochure No. V 107 of the Rockwell Manufacturing Company.

Three sizes of valves, 36, 24 and 12 inch diameters, were tested at the Engineering Research Center of Colorado State University. The purpose of the study was to determine discharge characteristics through the valve at various plug positions and to determine the dynamic torque coefficients of permasphere valves due to flow through the valve.

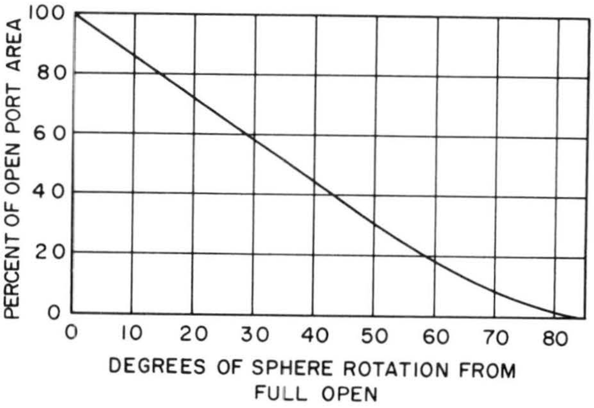

FIG. I CLOSING CHARACTERISTICS OF 24-IN. PERMASHERE VALVE

PRELIMINARY CONSIDERATIONS

Flow Characteristics

The equation for discharge through the valve can be written:

$$Q = C_d A_p \sqrt{\frac{2g\,\Delta p\,(144)}{\gamma}} , \qquad (1)$$

where

Q = discharge, cfs,

A_p = port area, ft^2,

g = gravitational acceleration, ft/sec^2,

Δp = differential pressure across the valve, psi,

γ = unit weight of water lbs/ft^3,

C_d = discharge coefficient.

The discharge coefficient C_d varies with valve position and velocity, hence with differential pressure and includes the coefficient of head or pressure loss due to angularity of the plug. The differential pressure, Δp, as defined herein is the drop in pressure across the valve from the upstream flange to the downstream flange.

Through combination of the constants in Eq. (1) and C_d, discharge may be expressed as

$$Q = C' A_p \sqrt{\Delta p} , \qquad (2)$$

and for a particular plug position, A_p being constant,

$$Q = C \sqrt{\Delta p} , \qquad (3)$$

where

$$C = 12 C_d A_p \sqrt{\frac{2g}{\gamma}} \qquad (4)$$

The value of C will vary with plug position because of changes in C_d and A_p.

The change in port area A_p, with plug position, θ, is presented in Fig. 1. While the curve is for a 24-in. valve, area-position relationships are similar for other valve sizes.

Torque

The torque required to move the spherical plug of the valve depends upon the change in momentum of the flow through the plug and the coefficient of kinetic friction between the plug and the seat rings. Listing the separate variables, torque is dependent upon:

1. Valve diameter, equal to pipe diameter, D,
2. Plug position θ,
3. Changes in flow direction and velocity through the valve plug $\Sigma\Delta v$,
4. Pipe velocity, v,
5. Fluid density ρ,
6. Fluid dynamic viscosity μ,

7. Differential pressure across the plug, Δp,
8. Coefficient of kinetic friction between the seat and the plug, f_k,
9. Direction of plug rotation, towards opening or towards closing.

In symbolic form the torque can be expressed as

$$T = f(D, \theta, \Sigma\Delta v, V, \rho, \mu, \Delta p, f_k, \text{direction of rotation}) \tag{5}$$

Assuming that f_k is dependent upon Δp and seat material then only the gross effects of Δp on friction forces need to be included. The effects of changes in flow direction within the plug is not generally determinable, therefore, that effect will be included implicitly in θ and Δp. Thus for plug rotation in one direction, i. e., opening or closing, Eq. (5) reduces to

$$T = f(D, \theta, V, \rho, \mu, \Delta p) \tag{6}$$

and by combining these terms into significant dimensionless terms,

$$f(\theta, \frac{T}{D^3\Delta p}, \frac{V^2\rho}{\Delta p}, \frac{VD\rho}{\mu}) = 0 \tag{7}$$

Rearranging,

$$\frac{T}{D^3\Delta p} = f'(\theta, \frac{V^2\rho}{\Delta p}, \frac{VD\rho}{\mu}) \tag{8}$$

where

$\frac{VD\rho}{\mu}$ = Re , pipe Reynolds number.

Thus, if we let $C_T = f'(\theta, \frac{V^2\rho}{\Delta p}, \frac{VD\rho}{\mu})$ (9)

then

$$T = C_T D^3 \Delta p. \tag{10}$$

Since the flow is unidirectional while rotation of the valve plug is bi-directional, i. e., closing and opening, then torque to open the valve may be different from torque required to close the valve.

Torque measurements were made with four electrical resistance strain gauges mounted circumferentially on the solid plug shaft. Each strain guage was placed at an angle of 45^0 with respect to the axis of the shaft so that when torque was applied to the shaft, two of the gauges would be in compression and the other two in tension. A typical mounting arrangement of the strain gauges is shown in the photograph of Fig. 2. The gauges were connected in a bridge with the gauges having like deformations placed on opposite legs of the bridge as shown in Fig. 3.

With torque applied to the shaft, two of strain gauges elongate, two shorten, and the bridge becomes unbalanced, resulting in an output which is proportional to the change in resistance of the gauges. The change in resistance is related to the strain on the shaft which is in turn related to the torque applied. A Brush strain gauge amplifier Model RD 5612-11 was used to measure strain, which included a signal generator, amplifier and phase sensitive demodulator.

A general stress diagram of an elementary surface of material is shown in Fig. 4, and the stresses in pure torsion is shown in Fig. 5. The relation between the strains in the x and y directions and the change in resistance of the strain gauges aligned in the x direction is given by:

$$\frac{\Delta R}{R} = G(\epsilon_x + k\epsilon_y), \tag{11}$$

where

ΔR = change in strain gauge resistance
R = Strain gauge resistance unstressed
G = Gauge factor for the strain gauges
ϵ_x = Strain in the x direction
k = Transverse sensitivity of the gauges
ϵ_y = Strain in the y direction

For the general case, strain is related to stress according to

$$\epsilon_x = \frac{\sigma_x}{E} - u\frac{\sigma_y}{E}, \tag{12}$$

where

E = modulus of elasticity,
u = Poisson's ratio,
σ_x = stress in the x direction,
σ_y = stress in the y direction.

In case a shaft is in pure torsion, $\sigma_y = -\sigma_x$ so so that

$$\epsilon_x = \frac{1+u}{E}\sigma_x, \tag{13}$$

and

$$\epsilon_y = \frac{(1+u)}{E}\sigma_y. \tag{14}$$

Shaft torque may be written as

$$T = \frac{\sigma_s J}{12r} \tag{15}$$

where

T = torque, ft-lbs,
J = Polar moment of inertia of the shaft, $= \frac{\pi r^4}{2}$ in^4
r = Shaft radius, in.
σ_s = Shear stress shown in Fig. 5, lbs/in^2 = σ_x.

The Brush strain gauge amplifier did not measure ΔR but gave an output directly proportional to strain. A calibrator was provided with the unit which enabled electrical calibration of the output voltage against strain. The relationship for calibration is

$$\epsilon_x = \frac{R}{GNR_c} \tag{16}$$

where

R = unstressed strain gauge resistance (500 ohms for the gauges used)

N = the number of gauges used in the bridge
R_c = calibrating resistance

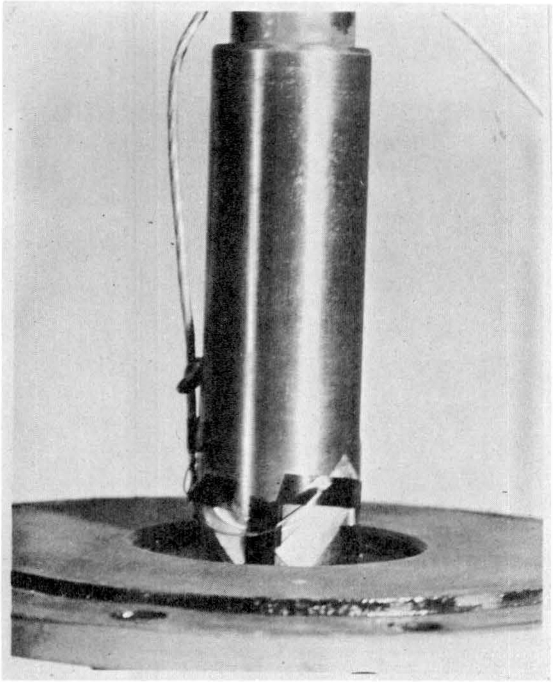

FIG. 2 TYPICAL MOUNTING ARRANGEMENT OF STRAIN GAUGES.

The transverse sensitivity k of the strain gauges was small, $k = 0.008$, while $G = 3.56$, therefore k was ignored for purposes of this study.

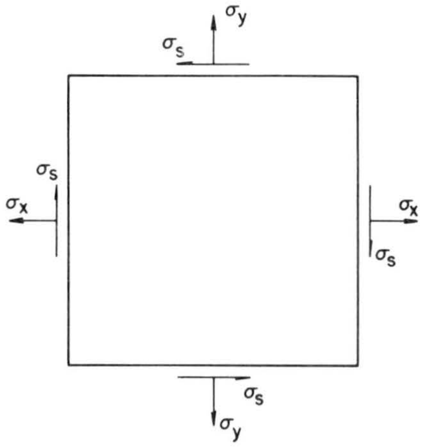

FIG. 4 GENERAL STRESS DIAGRAM

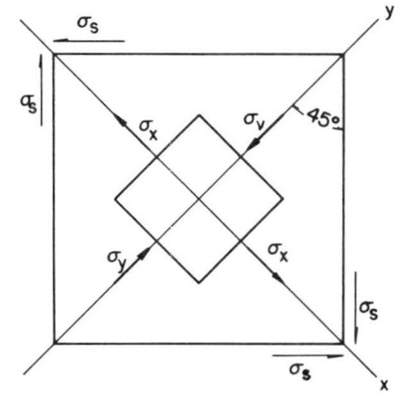

FIG. 5 STRESS DIAGRAM FOR TORSION

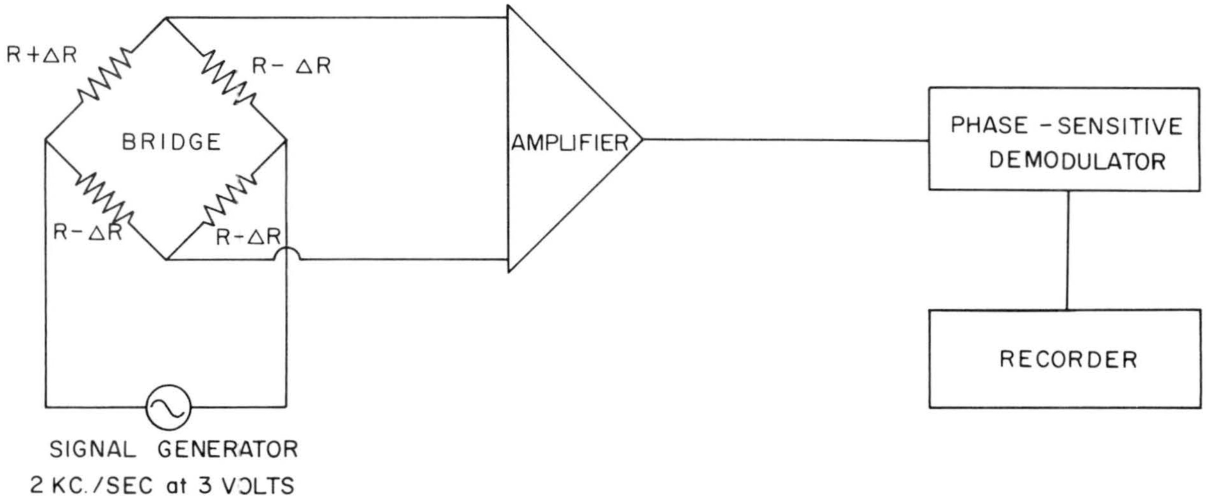

FIG. 3 STRAIN GAUGE BRIDGE CIRCUIT

DESCRIPTION OF THE TEST FACILITY

A plan showing the general arrangement of the laboratory and location of the particular facility used for this test is shown in Fig. 6. A schematic drawing of the test arrangement is given in Fig. 7. The distances between the control valves and the test valves were unchanged for all three that were tested. Tapered transitions were used to adapt from the 36 valves to the 24 and 12-in. pipes.

The total head available to the test facility varied with the water level in Horsetooth reservoir. In general, the pressure was about 100 psi. The pressure in the line upstream of the test valves varied with the discharge rate through the valve and differential pressure across the valve was controlled by adjusting the downstream valve.

The discharge through the system was measured with a calibrated orifice located in the 36-in. diameter supply line near the hydraulic laboratory. The manometers and recording instruments were located within the laboratory building. Pressures upstream and downstream from the test valve were measured with pressure gauges located in the test line shown in Fig. 7, for the 36 and 12 inch valves and with a differential pressure transducer for tests on the 24-in. valve. In chronological order, the 36-in. valve was tested first, the 12-in valve next and the 24-in. valve last. Torque was measured in all tests with strain gauges and the results were recorded on a strip chart.

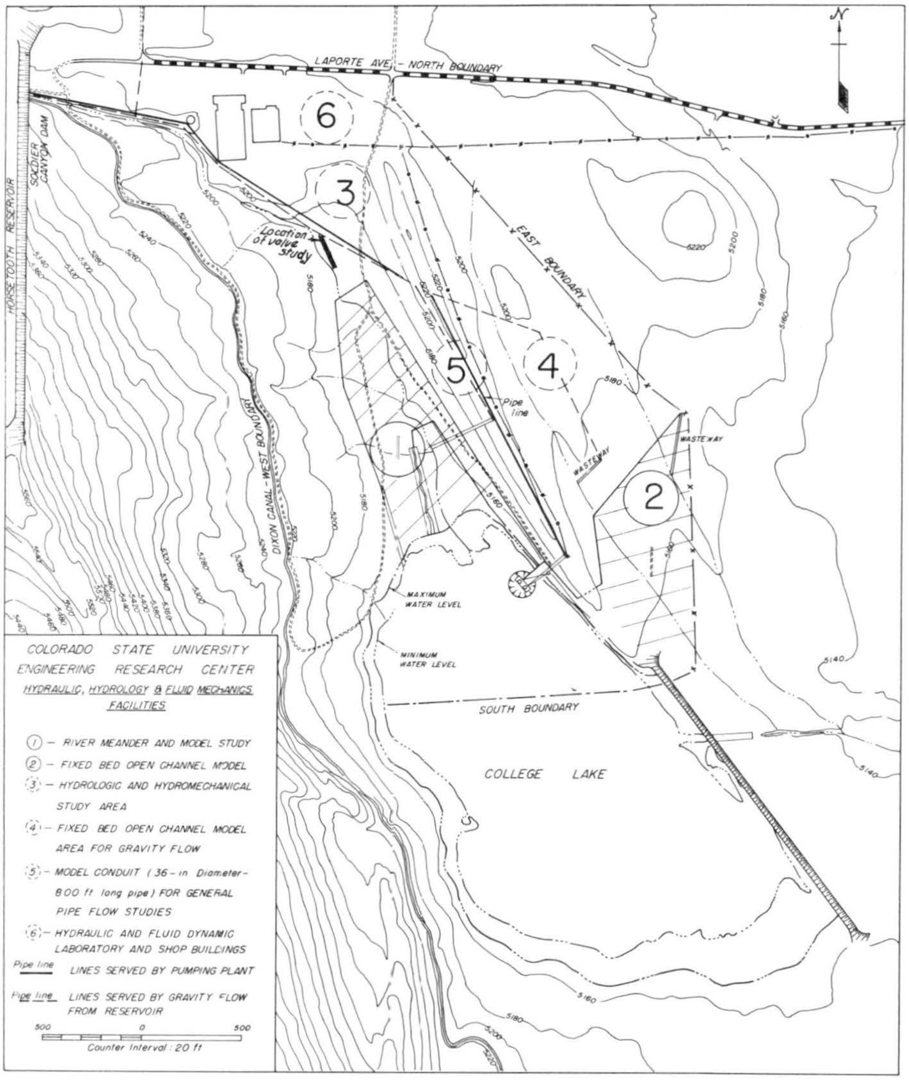

FIG. 6 GENERAL ARRANGEMENT OF THE ENGINEERING RESEARCH CENTER

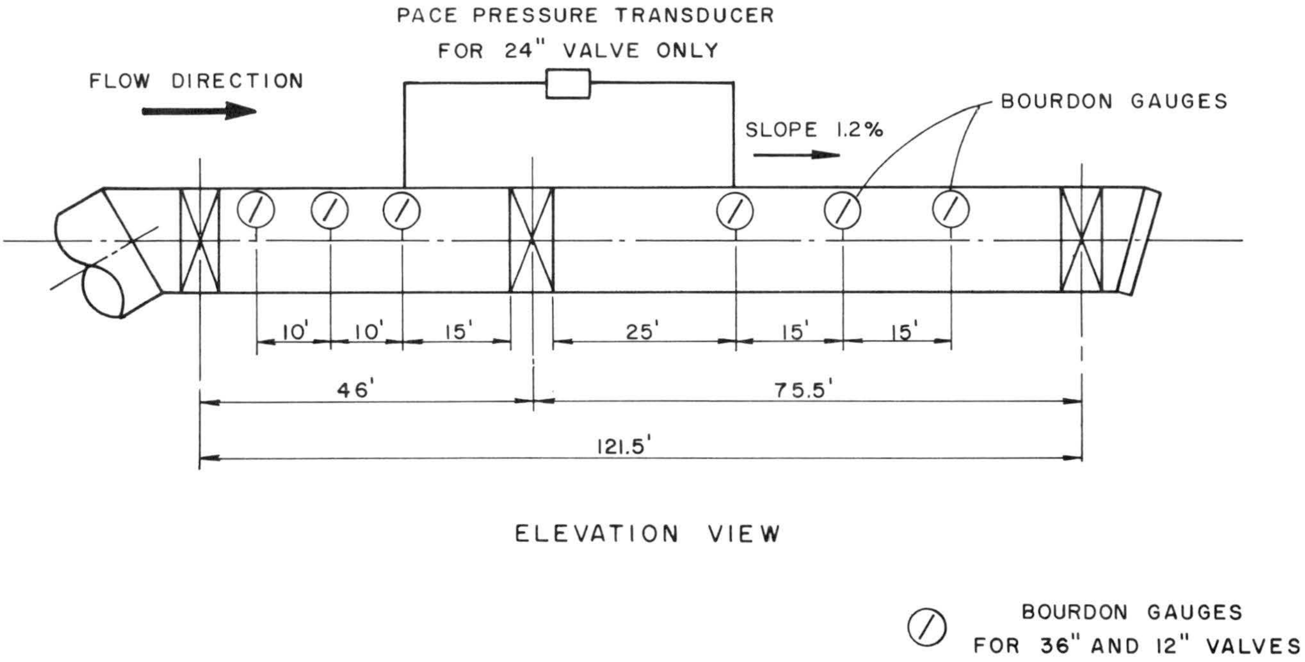

FIG. 7 LOCATION OF PRESSURE TAPS

TEST RESULTS AND DISCUSSION

Flow Characteristics

According to Eq. (3), for a given valve position, discharge is a function of the differential pressure across the valve and a variable coefficient C. Differential pressures were measured between two points, the first 15 ft upstream from the upstream flange of the test valve and the second 25 ft downstream from the downstream flange, for all three valves. Corrections were applied to measured values of Δp to indicate differential pressure across the valve from flange to flange. This was done by using a calculated pipe friction slope assuming the roughness elements in the pipe to be 0.00015 ft and with measured discharges.

By dividing both sides of Eq. (3) by the cross-sectional area of the approach pipe, A, we obtain:

$$V = K\sqrt{\Delta p} \,. \tag{17}$$

which is the relationship between average velocity V in the pipe and Δp across the valve for a given plug position.

Observation of all plotted data for the 36-in. valve (see Fig. 8) indicated that within the limits of accuracy, C_d, was essentially constant for all values of V at a particular plug position, and a straight line could be drawn through the data having a slope of 1/2, consistent with the exponent of Δp in Eq. (17). Data were taken at plug positions of full open, 15, 25, 35, 45, 55, 60, 65, 70, 75, 78 and 81 degrees. Relationships for other plug positions shown in Fig. 8 were established by interpolation. The values of K for the 36-in. valve are shown in Fig. 9. The data for Figs. 8 and 9 are tabulated in Table 1 of the Appendix.

The curves of V vs Δp for different plug positions for the 24-in. valve are shown in Fig. 10, and a curve for K is given in Fig. 11. The data for the two figures are given in Table 2 of the Appendix.

Figures 12 and 13 similarly shows the relationships between velocity, differential pressure and flow coefficient at various plug positions for the 12-in. valve. The curves of K for all three valves are replotted in Fig. 14. This comparison clearly shows that except for very small valve openings the flow coefficients for the three valves are practically identical. This is to be expected because of the geometrical similarity of the three valves. Some variation is noted at very small openings, (θ near 90 degrees). This is principally because the three valves did not close at identical values of θ. The differences are insignificant however, and a single curve of K may be applied to all three valves.

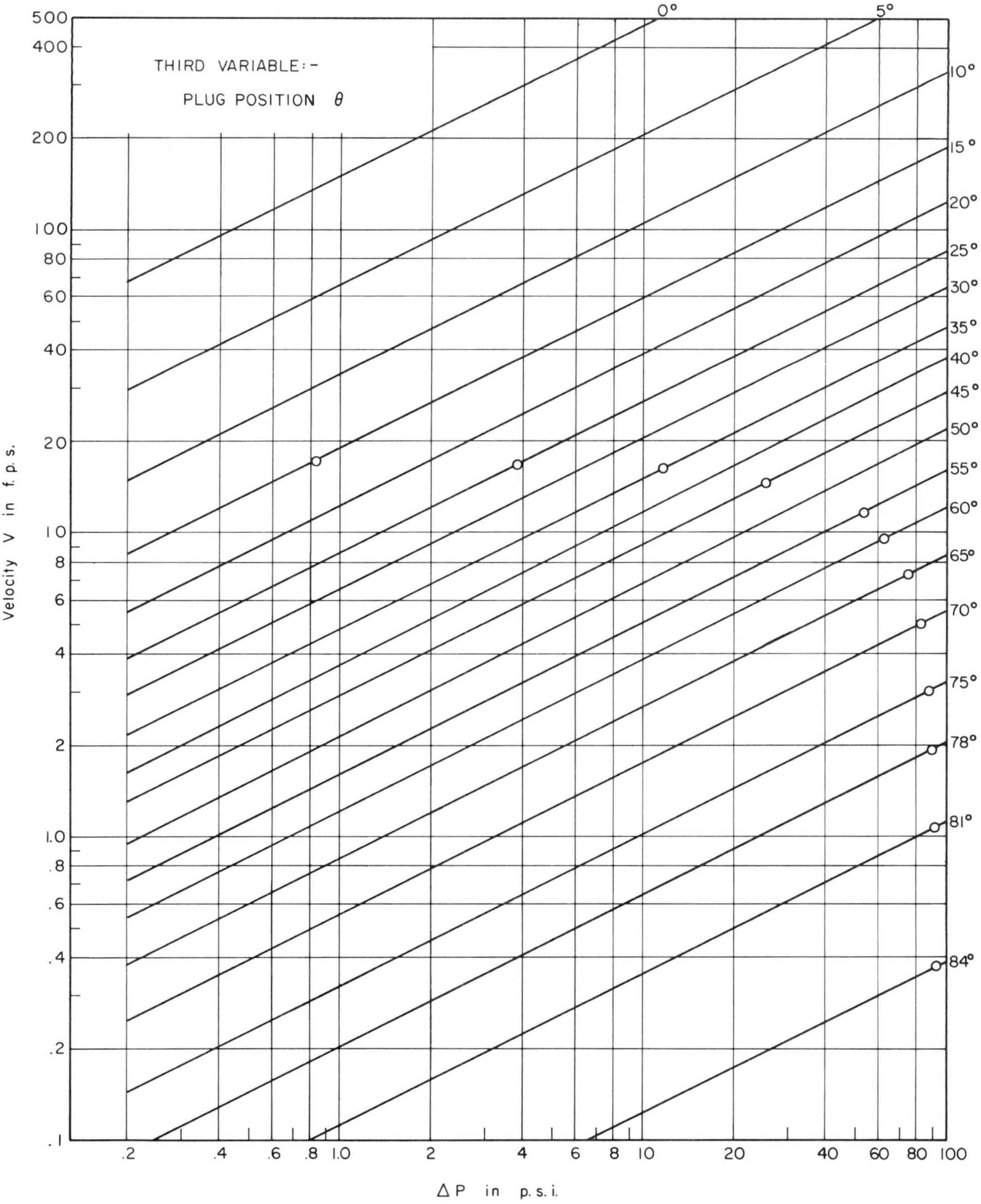

FIG. 8 VELOCITY - PRESSURE RELATIONSHIP FOR 36" VALVE

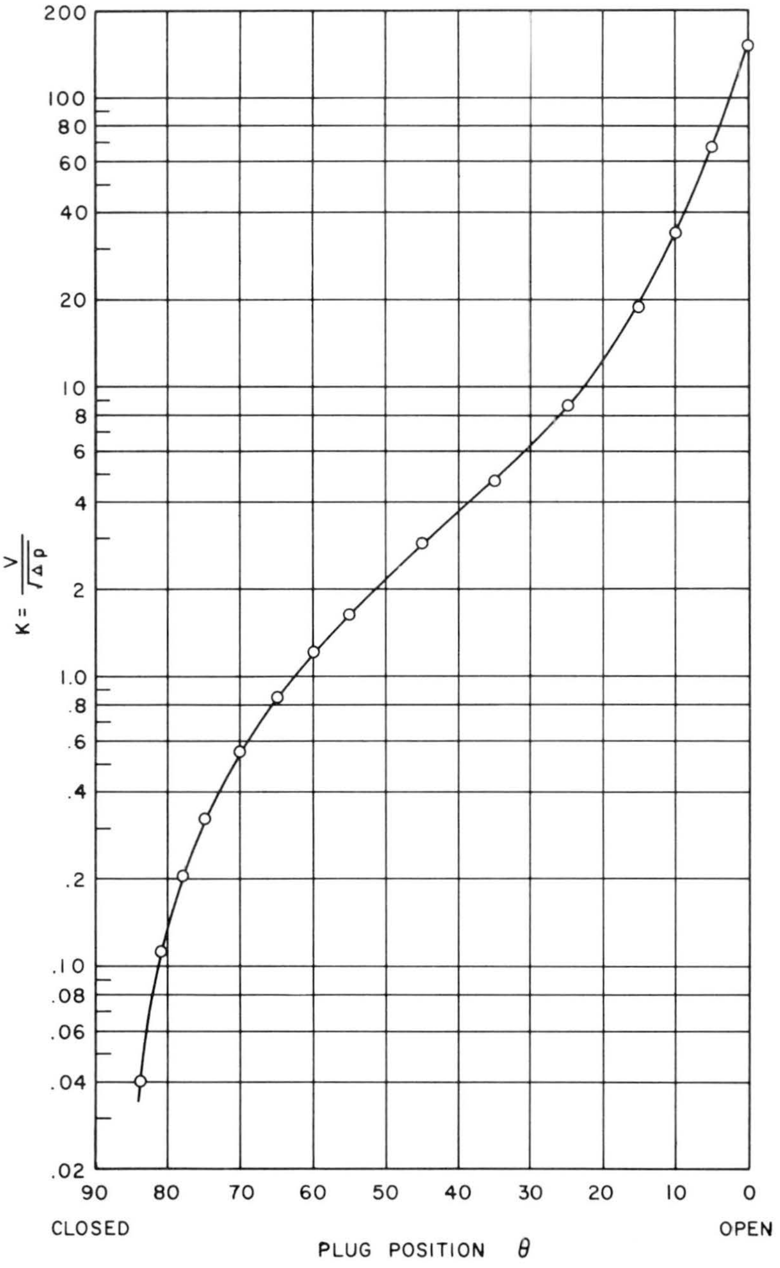

FIG. 9 FLOW COEFFICIENT FOR 36-IN VALVE

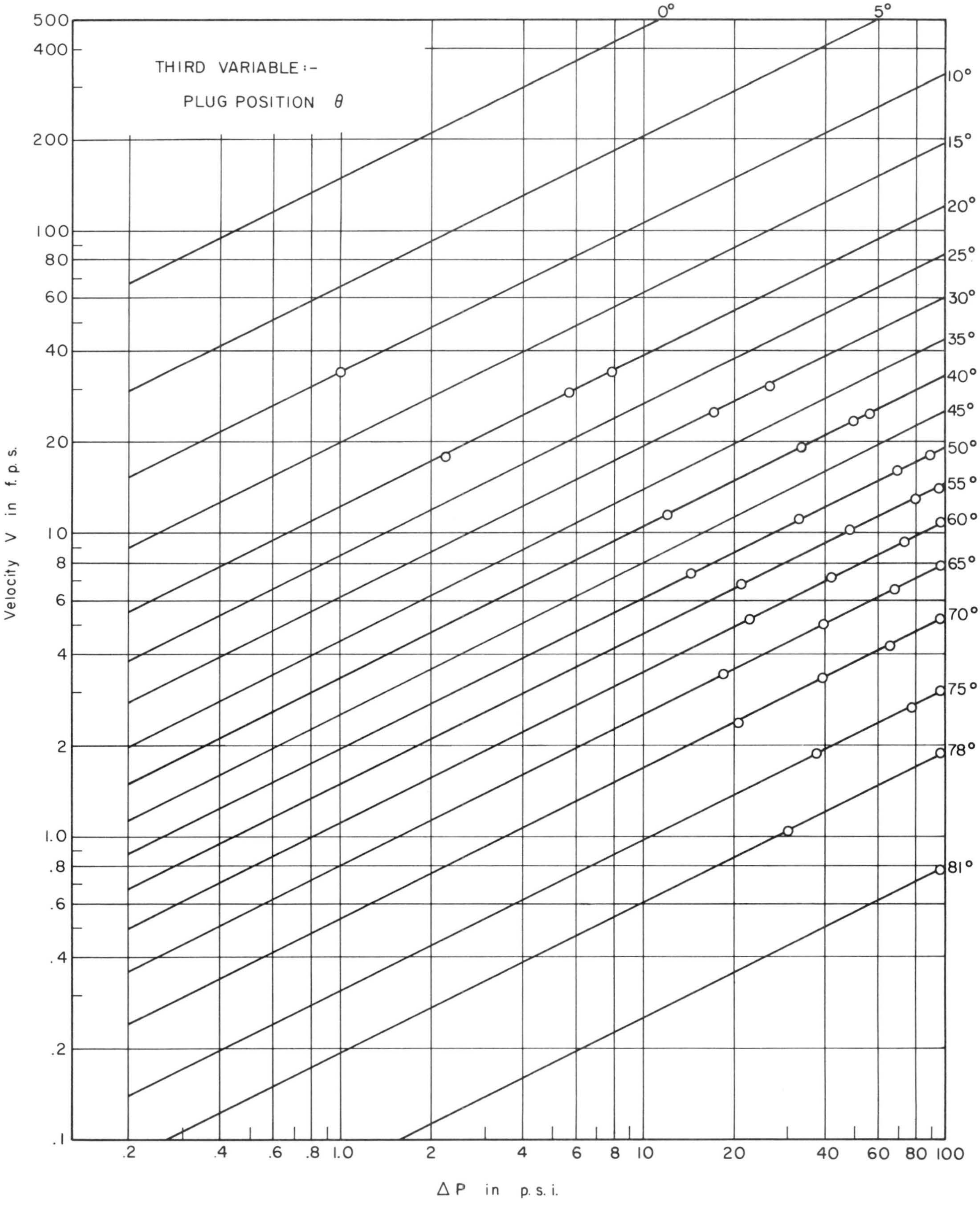

FIG. 10 VELOCITY - PRESSURE RELATIONSHIP FOR 24" VALVE

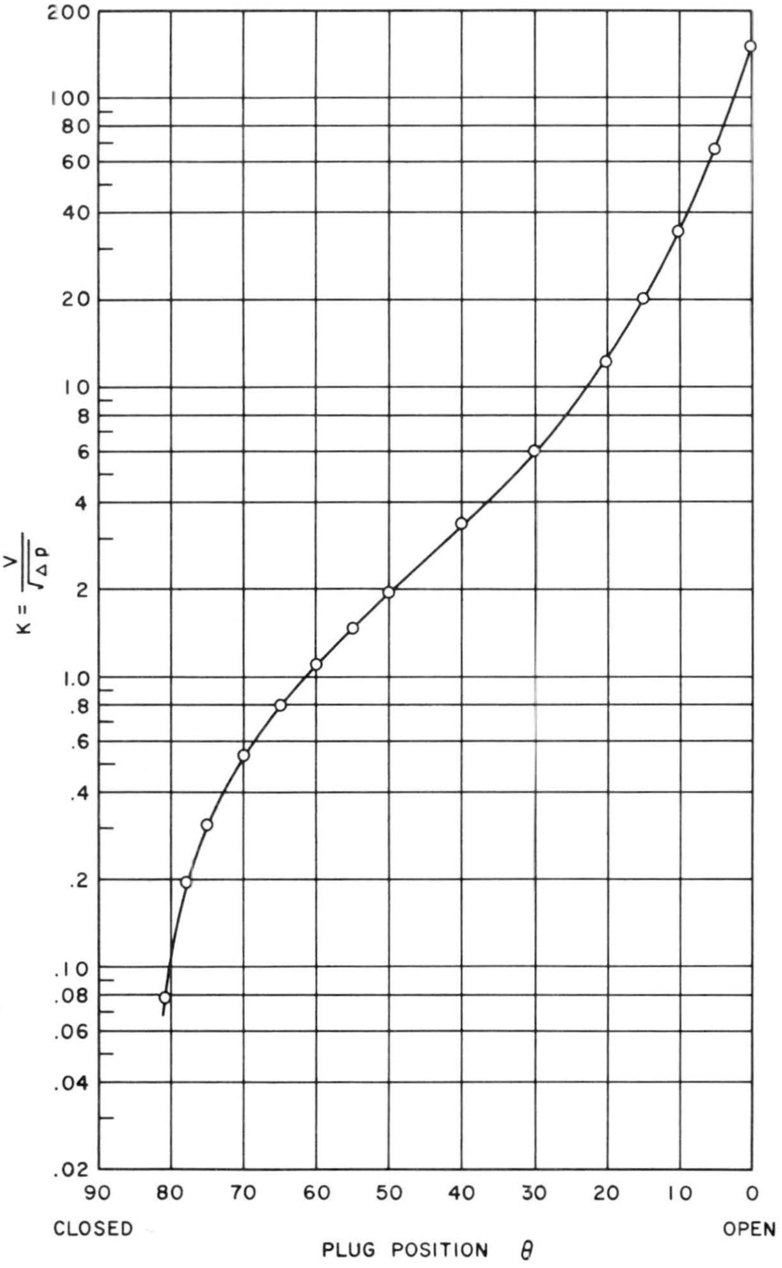

FIG. 11 FLOW COEFFICIENT FOR 24-IN VALVE

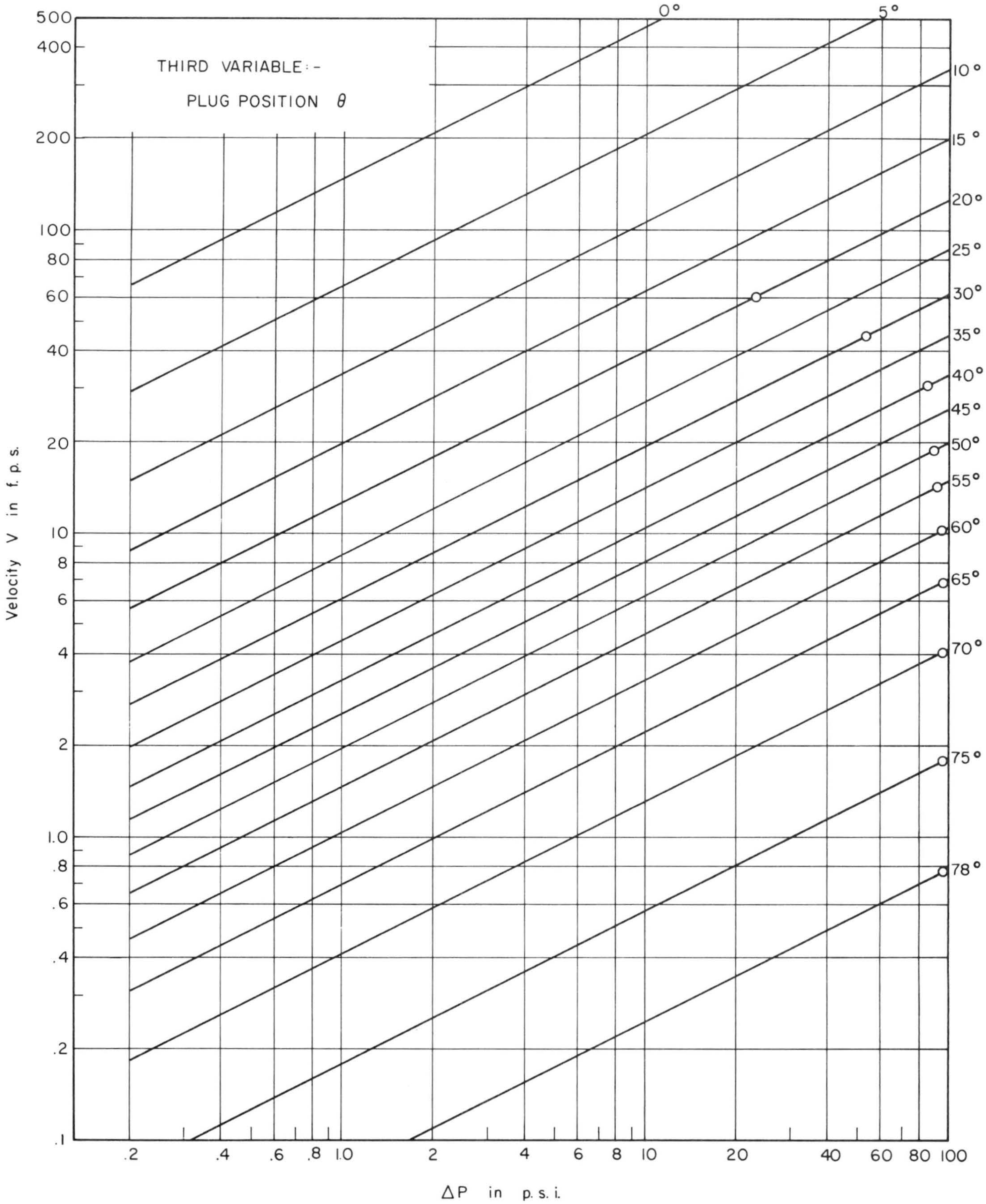

FIG. 12 VELOCITY - PRESSURE RELATIONSHIP FOR 12" VALVE

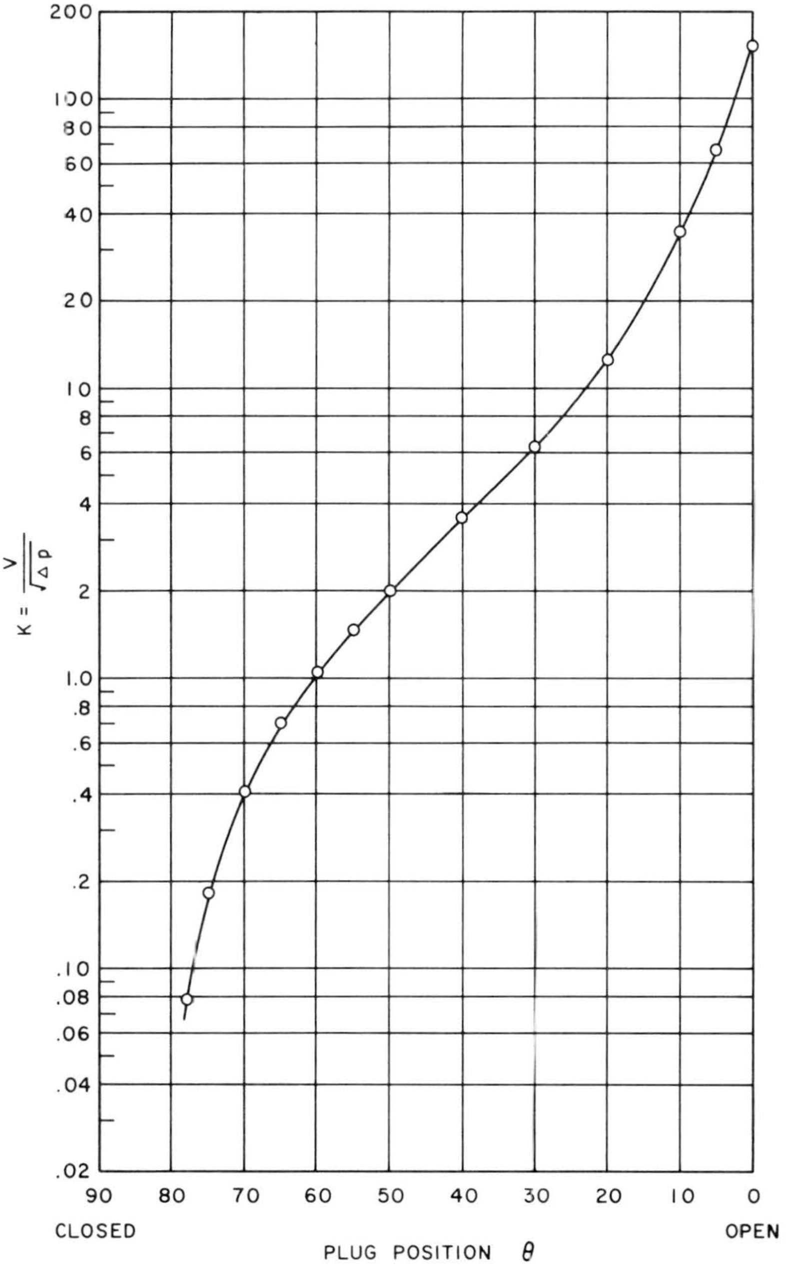

FIG. 13 FLOW COEFFICIENT FOR 12-IN VALVE

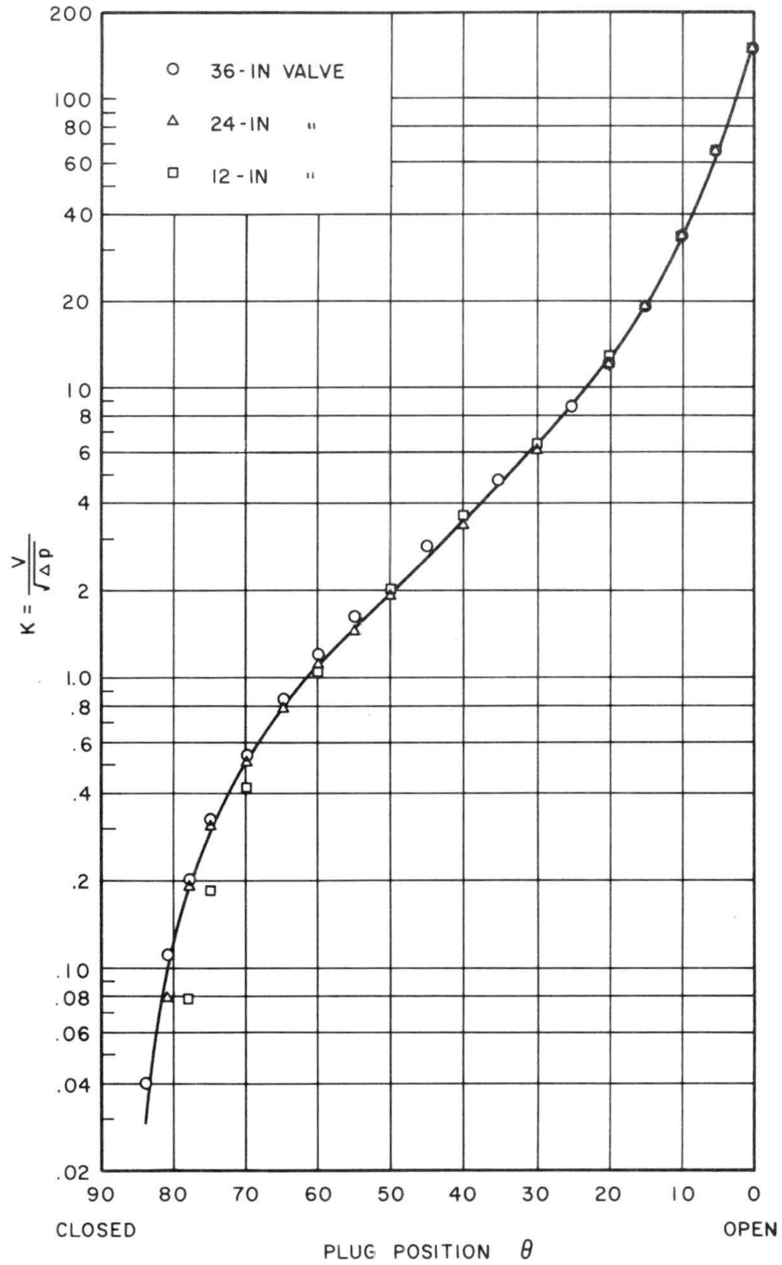

FIG. 14 FLOW COEFFICIENT PERMASPHERE VALVES

Torque Characteristics

The relationships for torque was developed in Eq. (10) and was shown to be a function of the valve size, differential pressure across the valve, plug position, discharge and a torque coefficient. Further, the coefficient of torque was theorized in Eq. (9) to be a function of plug position, discharge and Reynolds number to flow. As will be discussed later, the torque coefficient was better related to differential pressure across the valve rather than with the Reynolds number.

The torque to open the valve was in general greater than the torque required to close the valve, indicating that in the main, the dynamic torque acted in a direction which tended to close the valve. The dynamic torque should always act in the same direction at a particular discharge and plug position, whether the valve is being opened or closed, but friction forces always act in a direction which opposes motion. Thus, if it is assumed that at a given differential pressure and plug position and with constant speed of plug rotation, the friction torque (or torque required to overcome friction), is the same, then friction torque and dynamic torque can be determined from opening and closing torques in the following manner:

$$T_D = \frac{T_o - T_c}{2} \qquad (18)$$

and

$$T_F = \frac{T_o + T_c}{2}, \qquad (19)$$

where

T_o = torque required to open the valve,

T_c = torque required to close the valve,

T_D = dynamic torque,

T_F = friction torque.

The basic data from the tests of the 36-in valve are given in Table 4 of the Appendix, and the results are plotted in Figs. 15 and 16 for opening and closing torques respectively. In each of these figures lines of constant Δp are drawn to the limits of the data. It can be seen that as the differential pressure increases across the valve, the torque required to operate the valve increases. This bears direct relationship to increase in friction torque and dynamic torque. From these data, the friction and dynamic torques were calculated at constant differential pressures. These results are shown in Figs. 17 and 18. The dynamic torque coefficients C_T were calculated and plotted in Fig. 19. Calculations are given in Table 7.

The coefficient of dynamic torque increases with increasing opening of the valve because the discharge hence dynamic torque increases with increase in valve opening. The coefficient also increases with differential pressure. There was a maximum value for torque coefficient at 60 psi. The coefficients for 70, 80 and 90 psi were very close to the maximum curve at 60 psi. Within the range of pressures in this study therefore, there appears to be a maximum torque coefficient for the valve.

The results of the tests for the 24-in valve are similarly shown in Figs. 20 through 24. The data are given in Tables 5 and 8 of the Appendix. The torque coefficients for the 24-in valve were almost identical to those of the 36-in valve. Comparison of the calculated values of C_T in Tables 7 and 8 will indicate that the magnitudes of differences were slight.

The test results and analysis of torques for the 12-in valve are given in Figs. 25 through 29 and Tables 6 and 9. Comparison of torque coefficients for all three valves indicated that dynamic torque coefficients were similar and that they could be presented on one set of curves of C_T as a function of plug position and Δp as in Fig. 30.

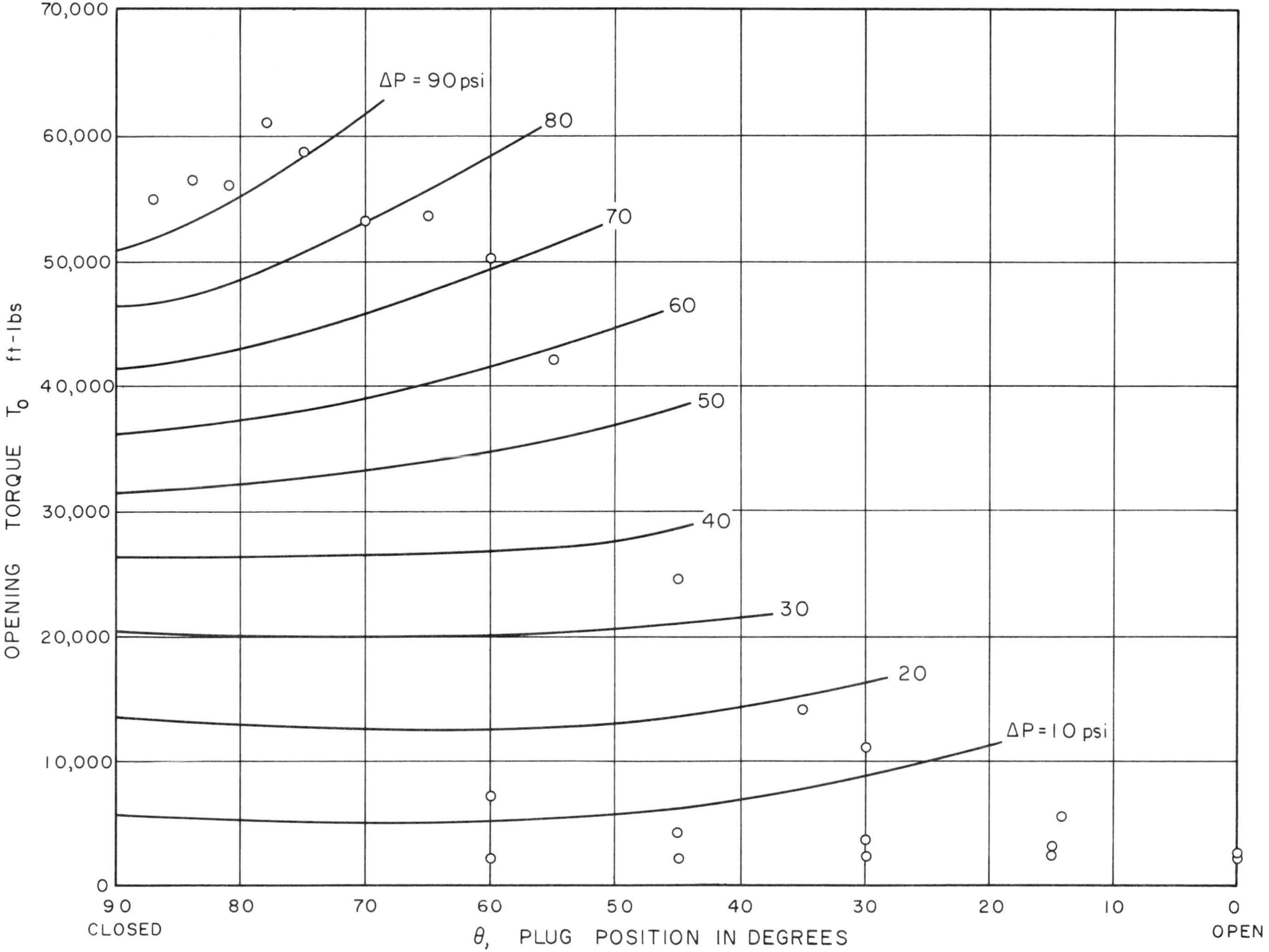

FIG. 15 OPENING TORQUE 36-IN. VALVE

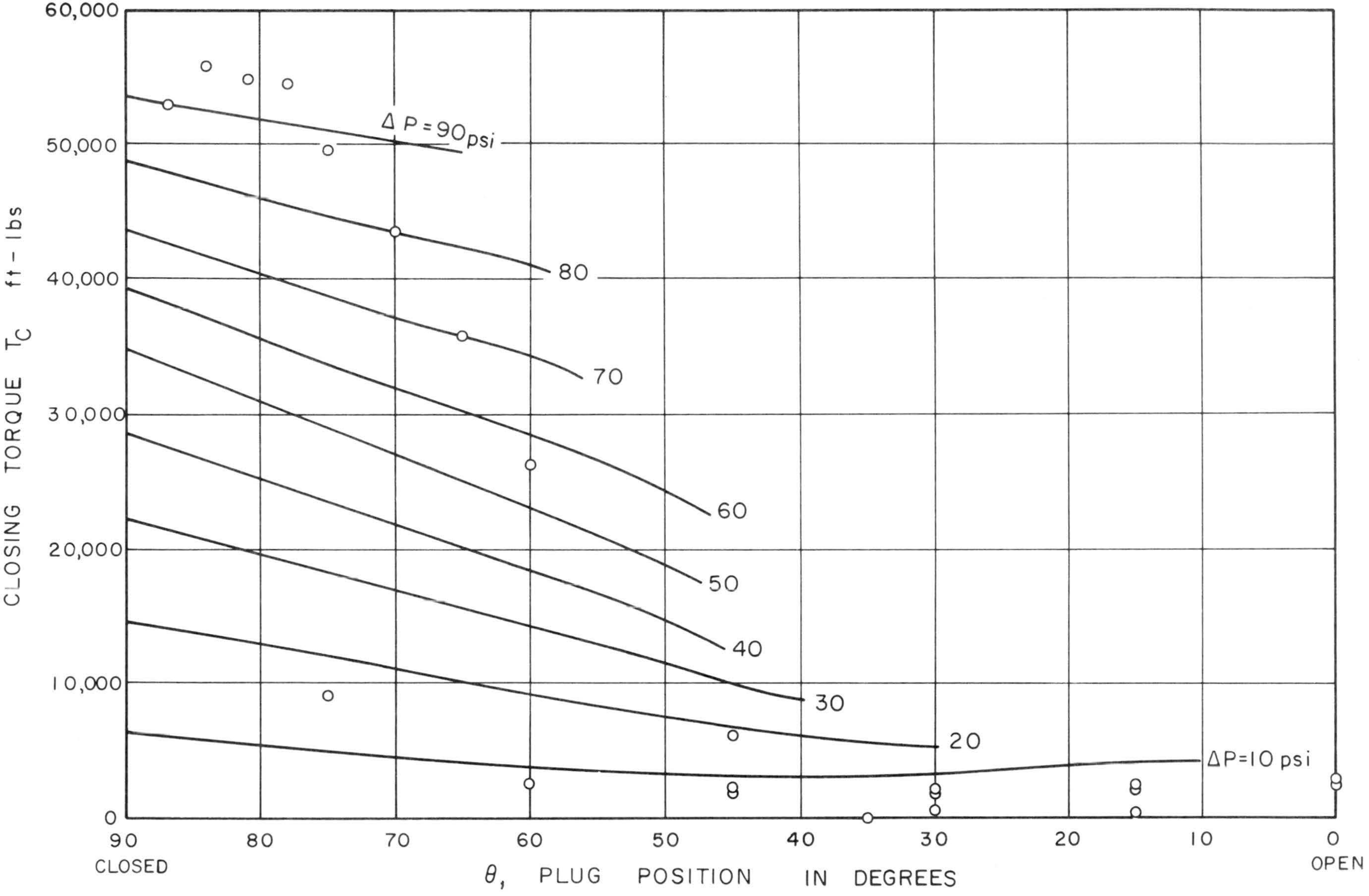

FIG. 16 CLOSING TORQUE 36 - IN VALVE

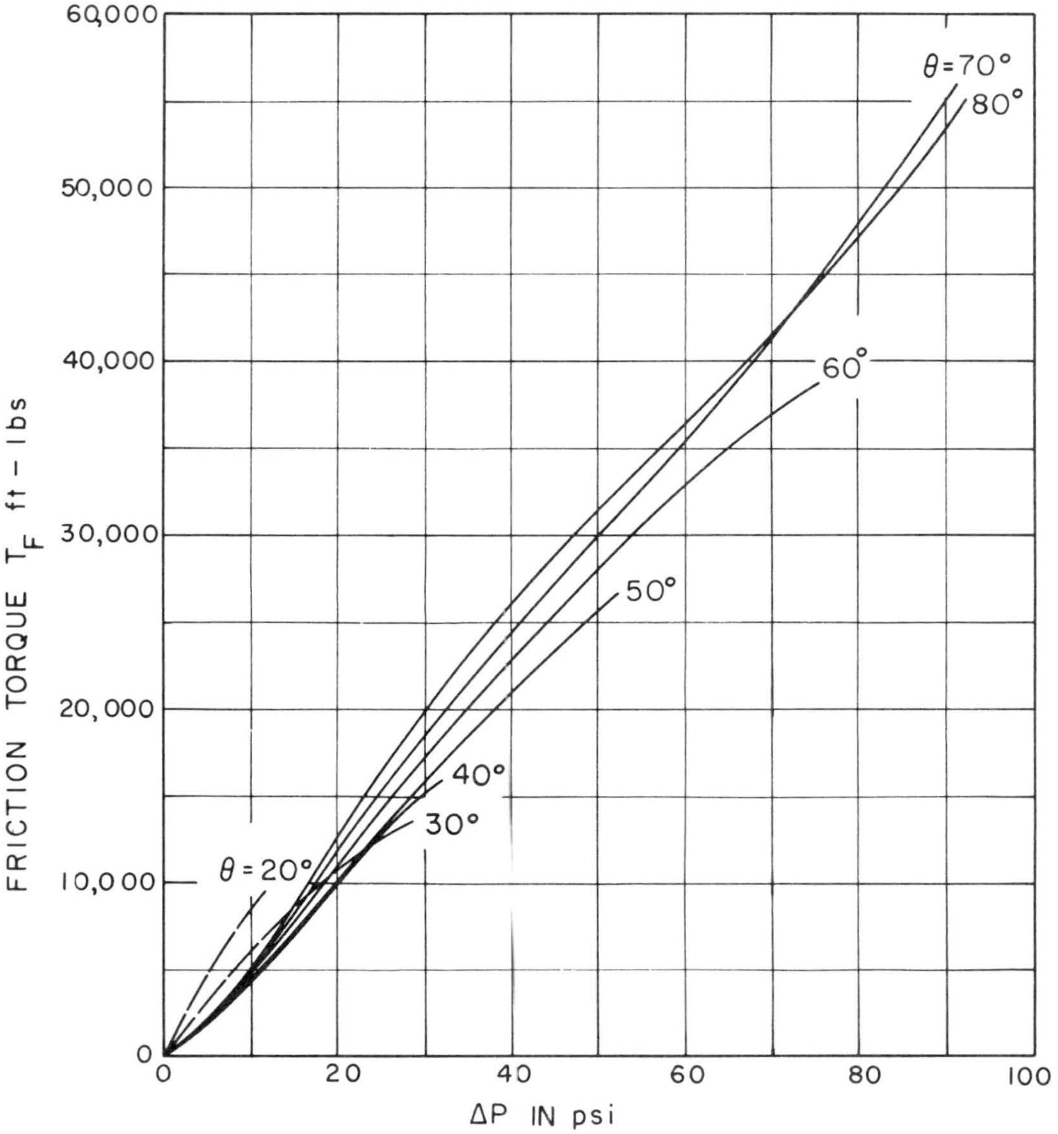

FIG. 17 FRICTION TORQUE 36 - IN VALVE

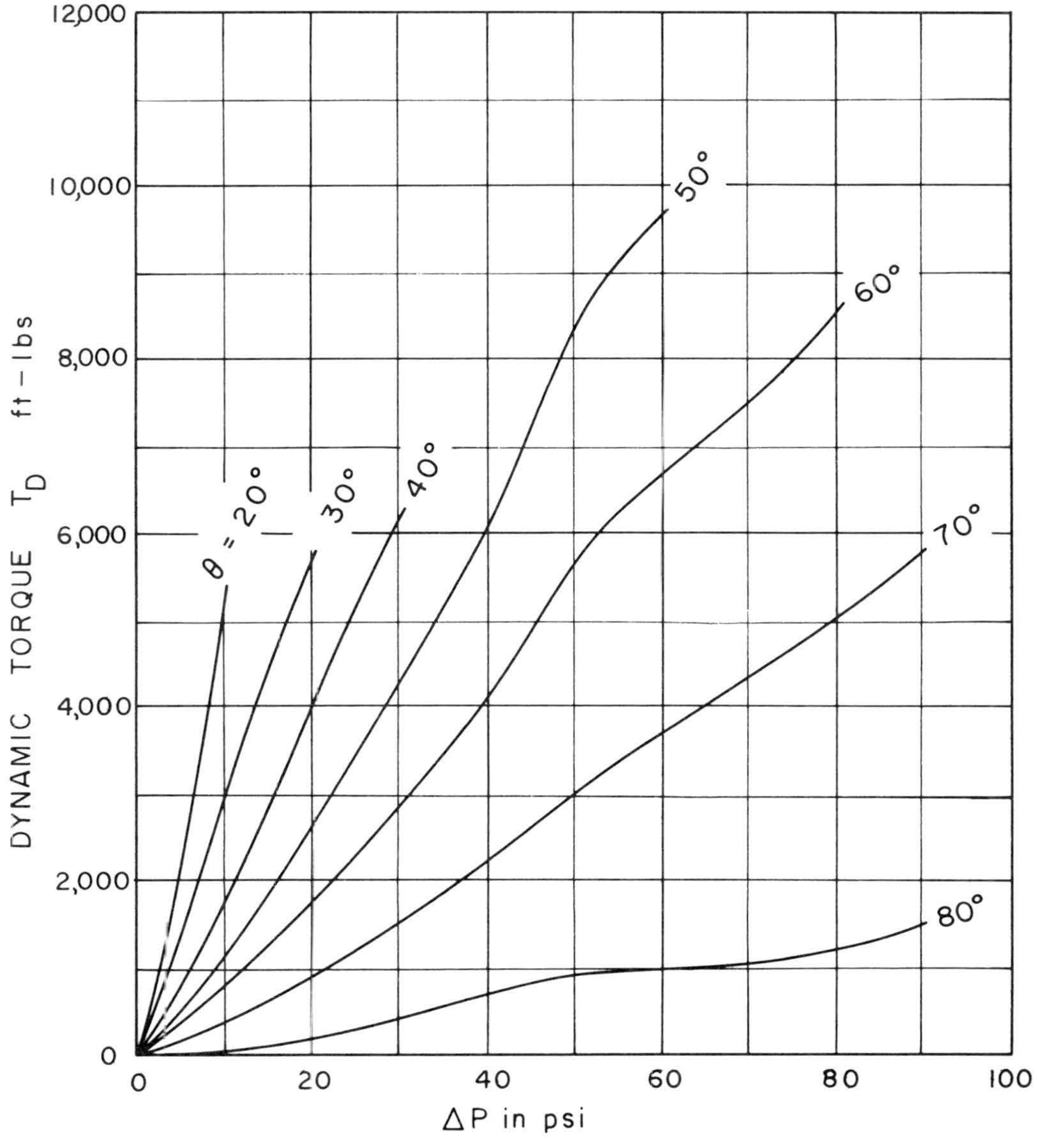

FIG. 18 DYNAMIC TORQUE 36 - IN VALVE

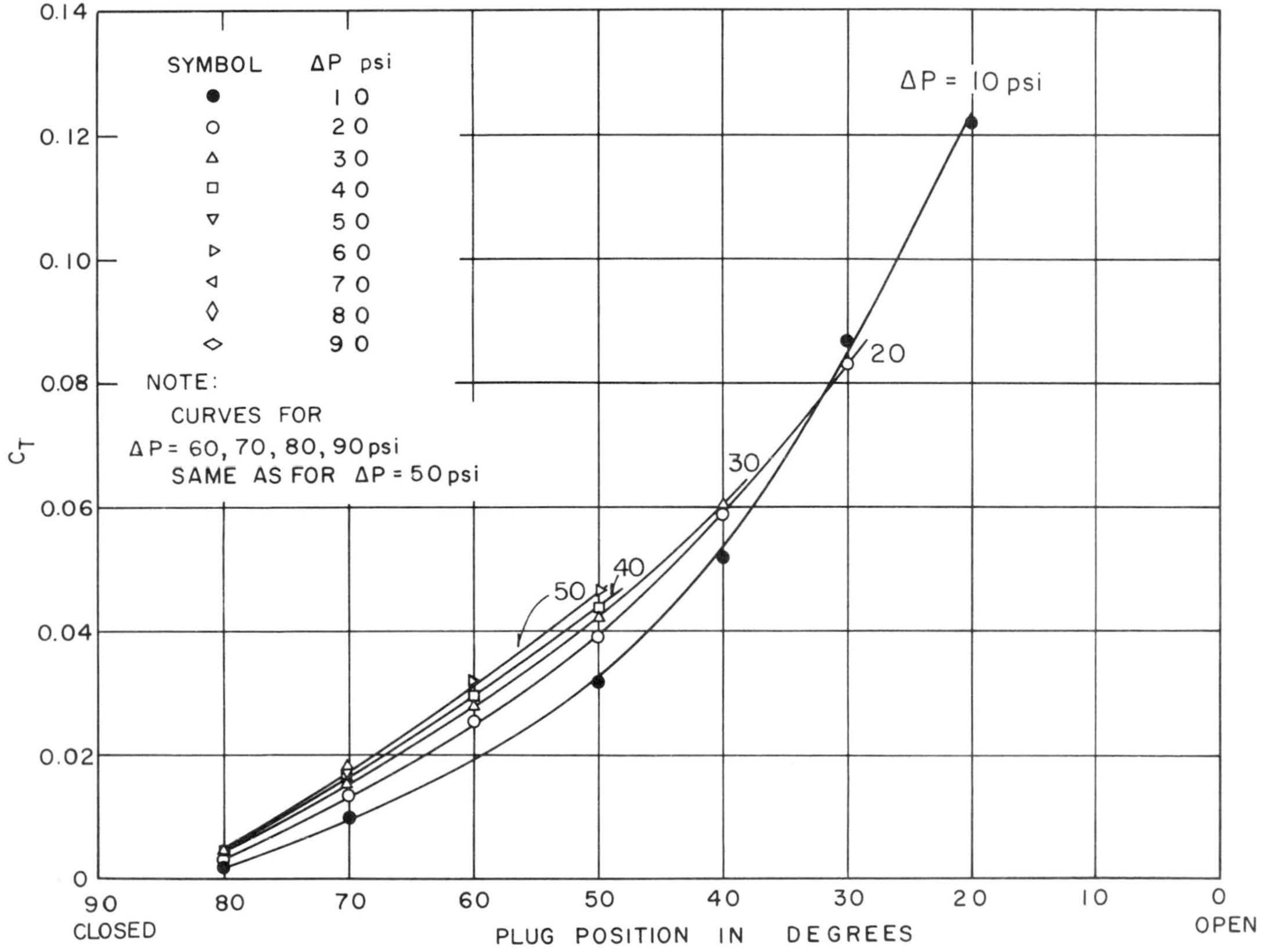

FIG. 19 DYNAMIC TORQUE COEFFICIENT 36-IN VALVE

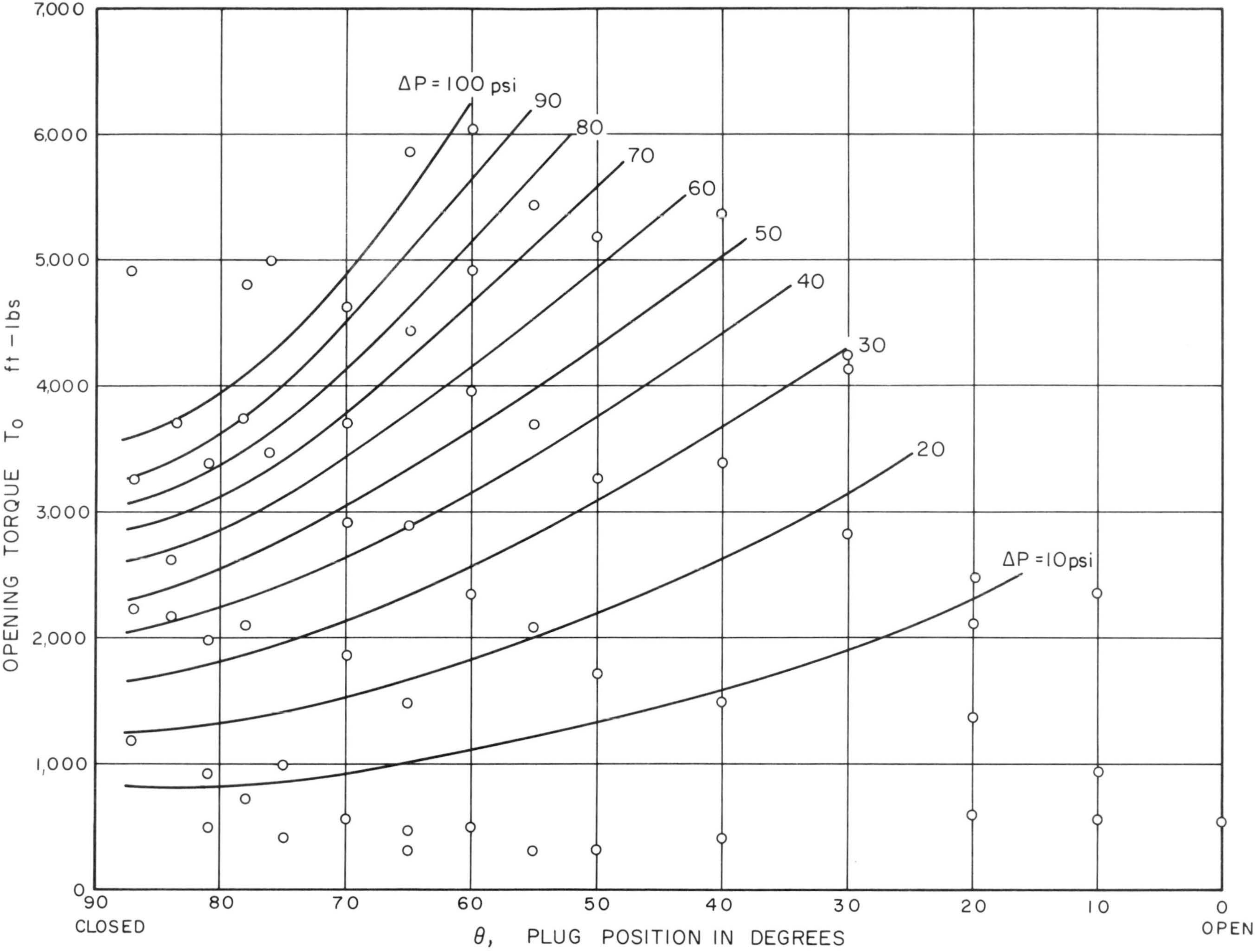

FIG. 20 OPENING TORQUE 24 - IN VALVE

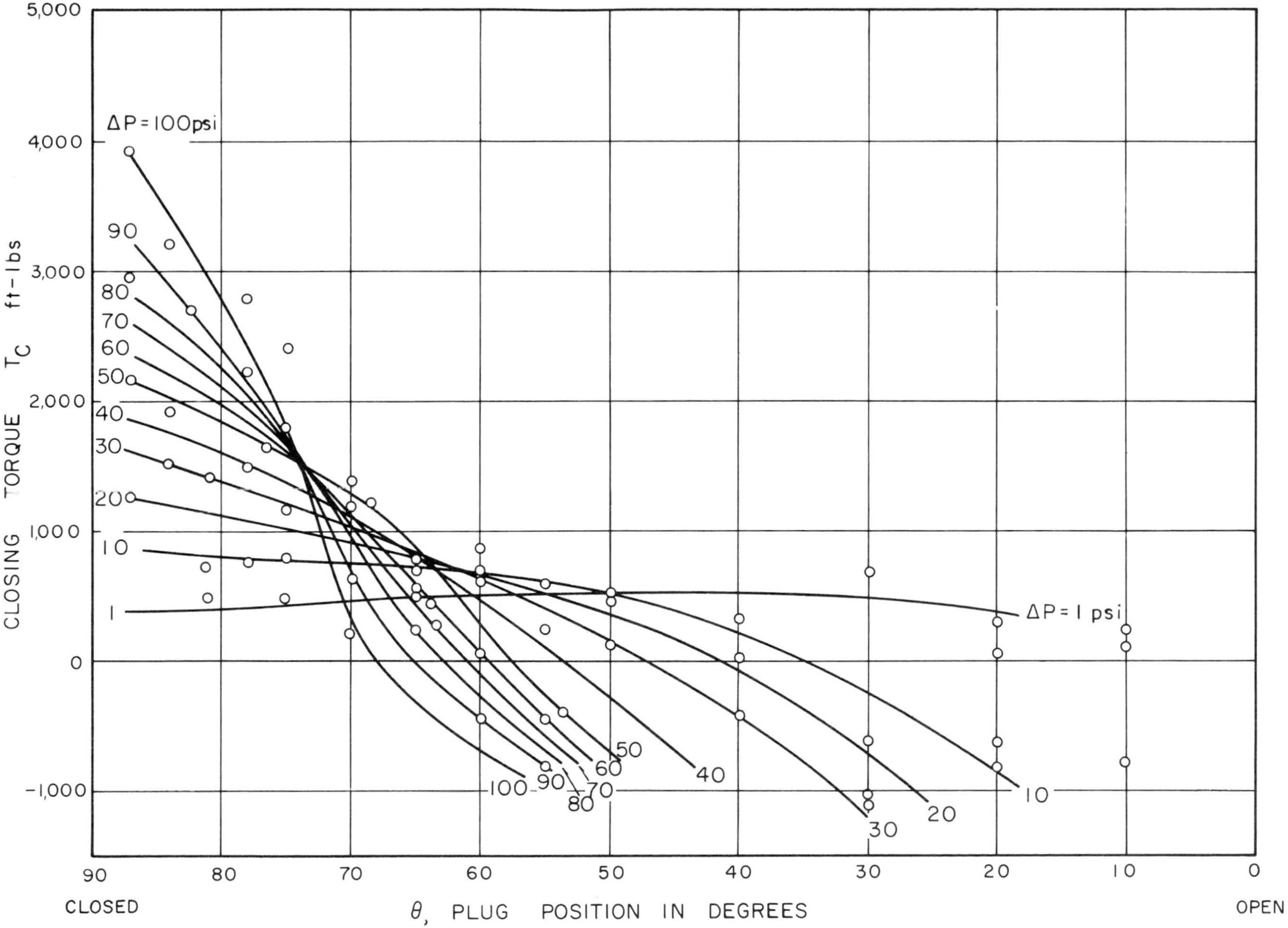

FIG. 21 CLOSING TORQUE 24 – IN VALVE

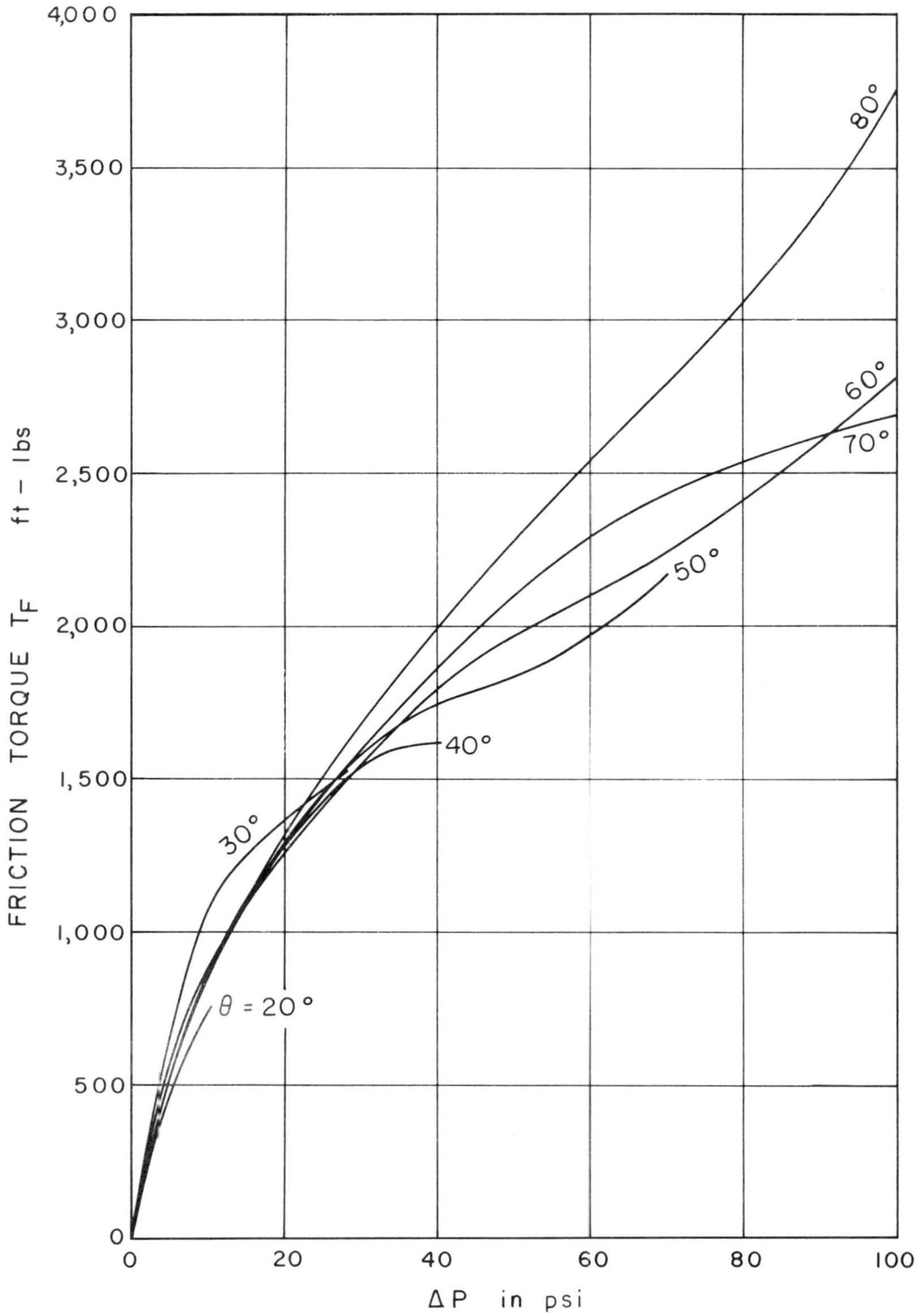

FIG. 22 FRICTION TORQUE 24 - IN VALVE

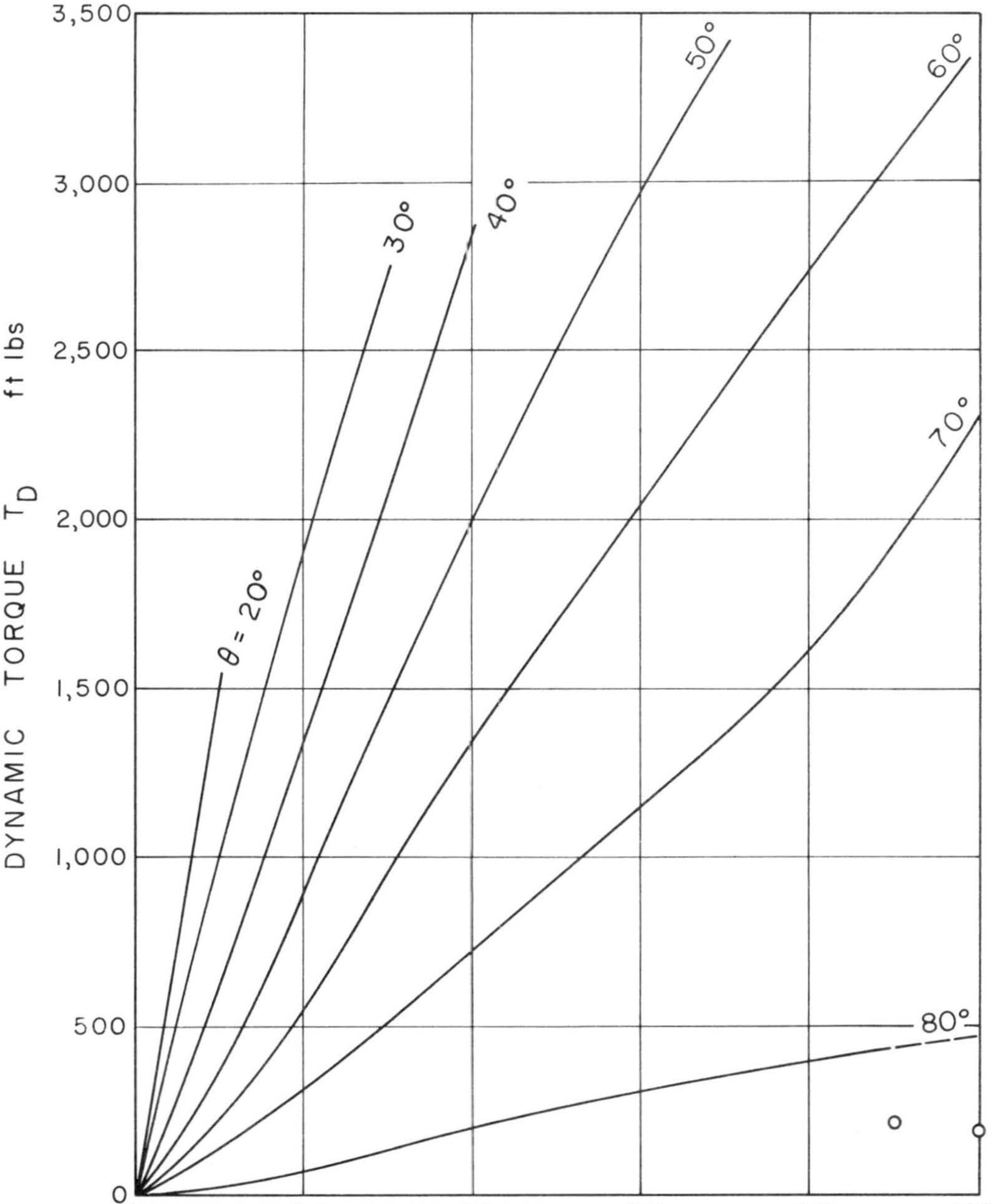

FIG. 23 DYNAMIC TORQUE 24-IN VALVE

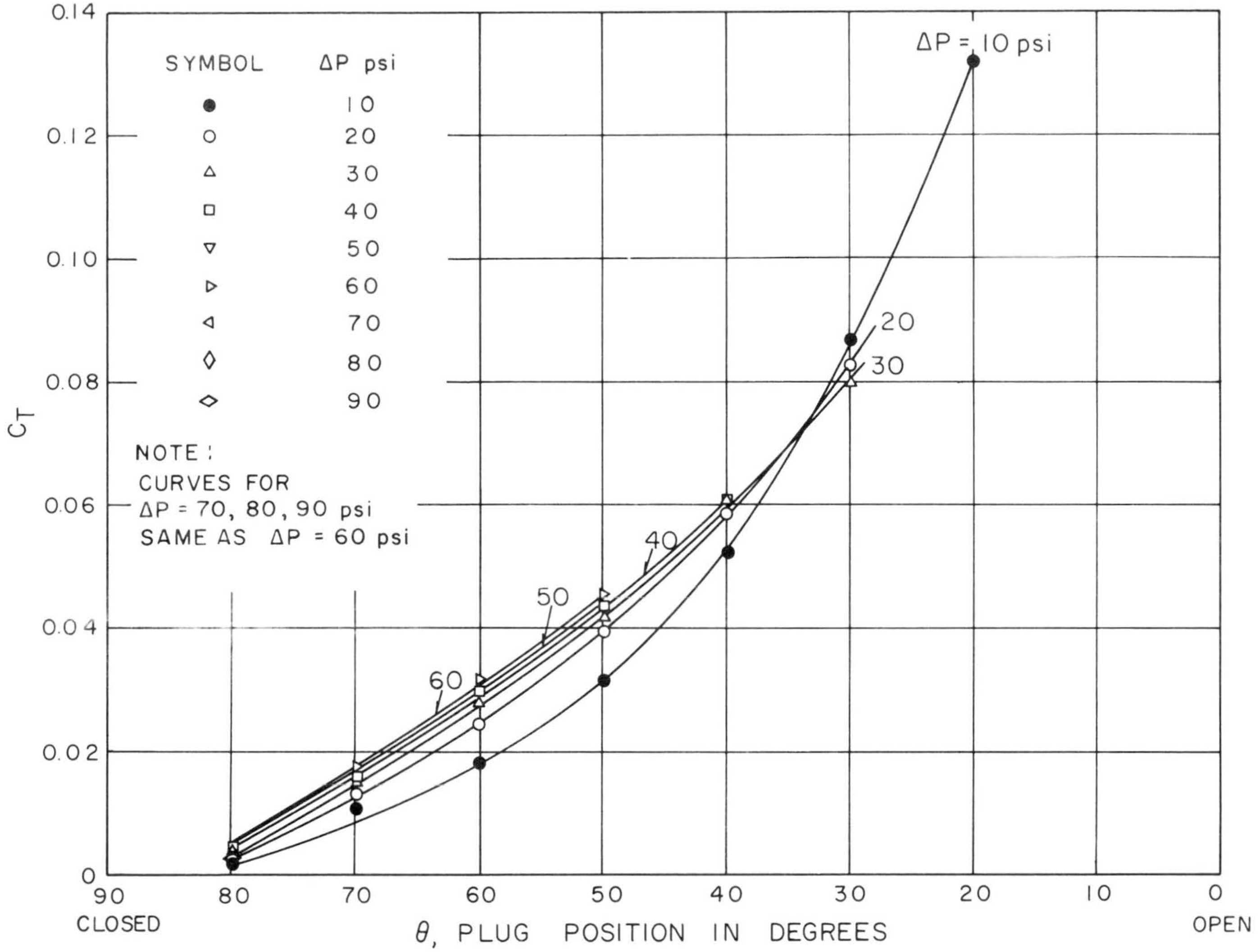

FIG. 24 DYNAMIC TORQUE COEFFICIENT 24 — IN VALVE

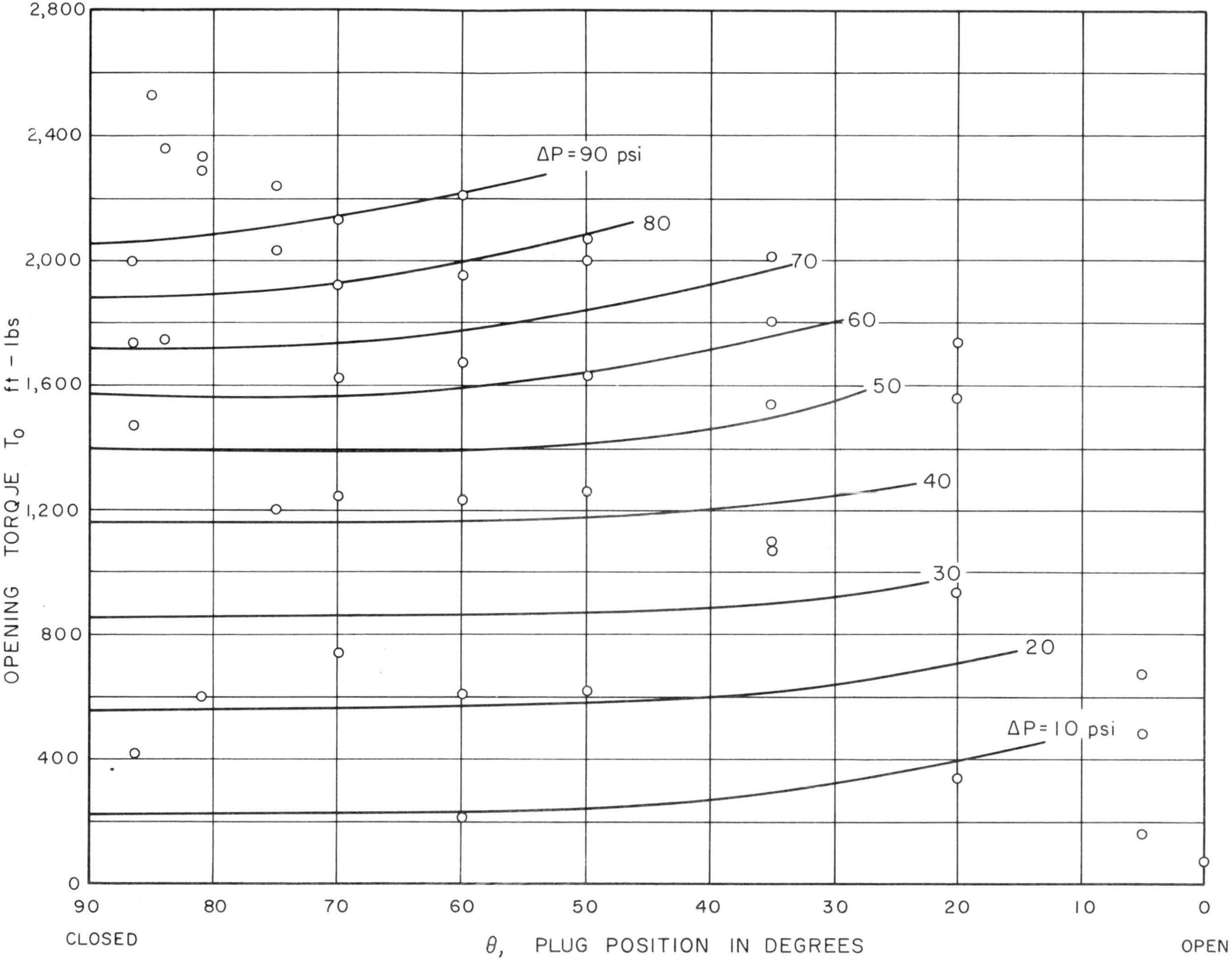

FIG. 25 OPENING TORQUE 12 - IN VALVE

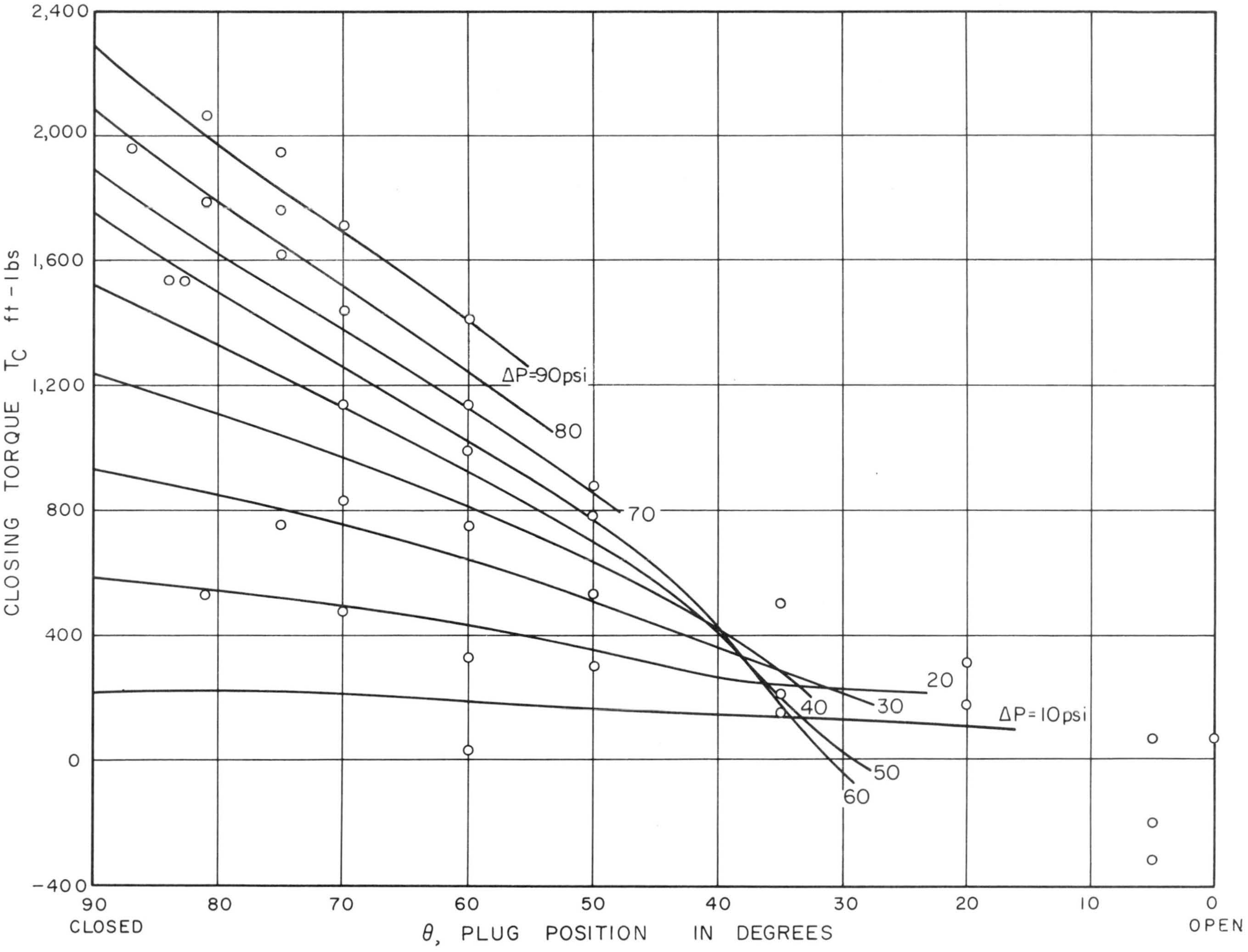

FIG. 26 CLOSING TORQUE 12 - IN VALVE

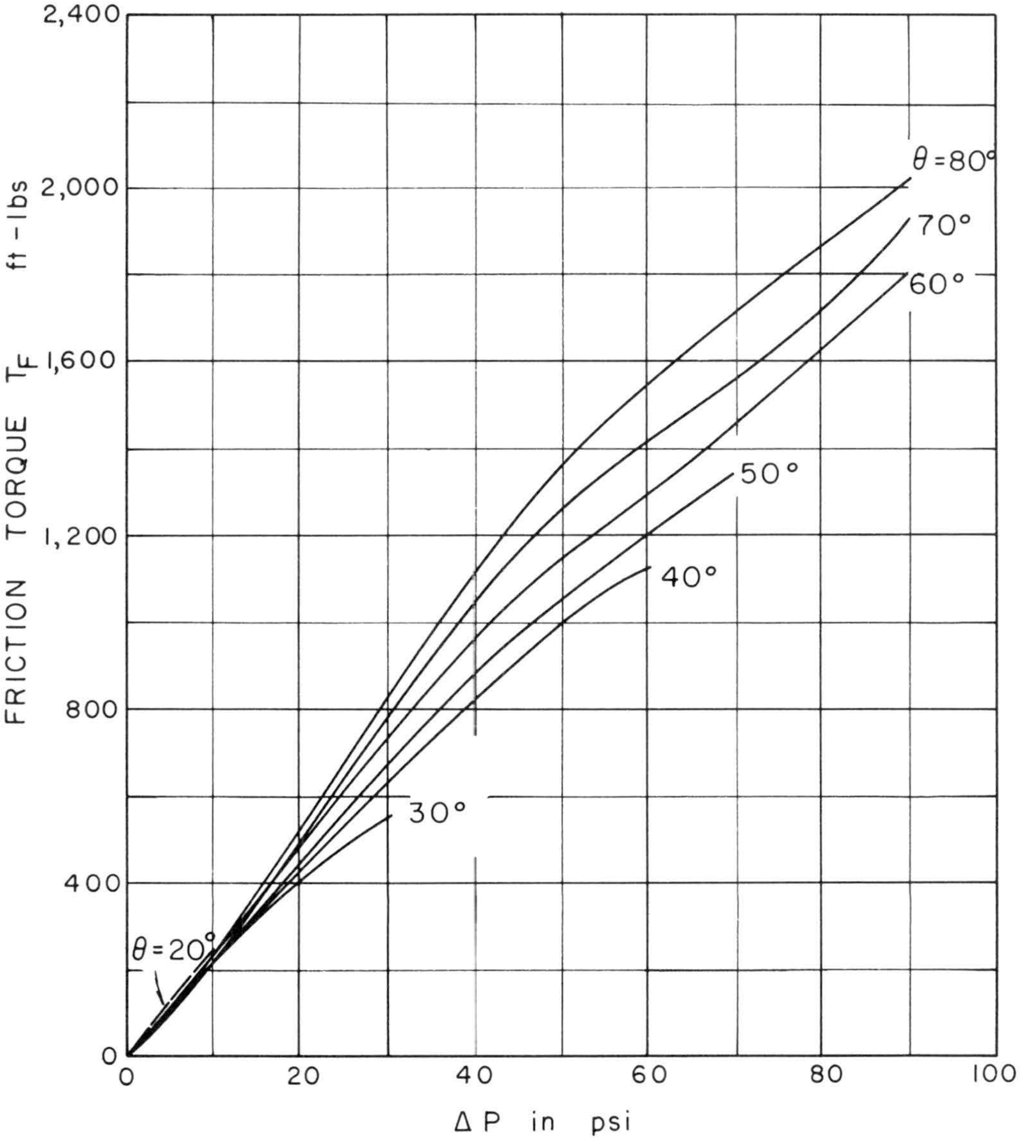

FIG. 27 FRICTION TORQUE 12 – IN VALVE

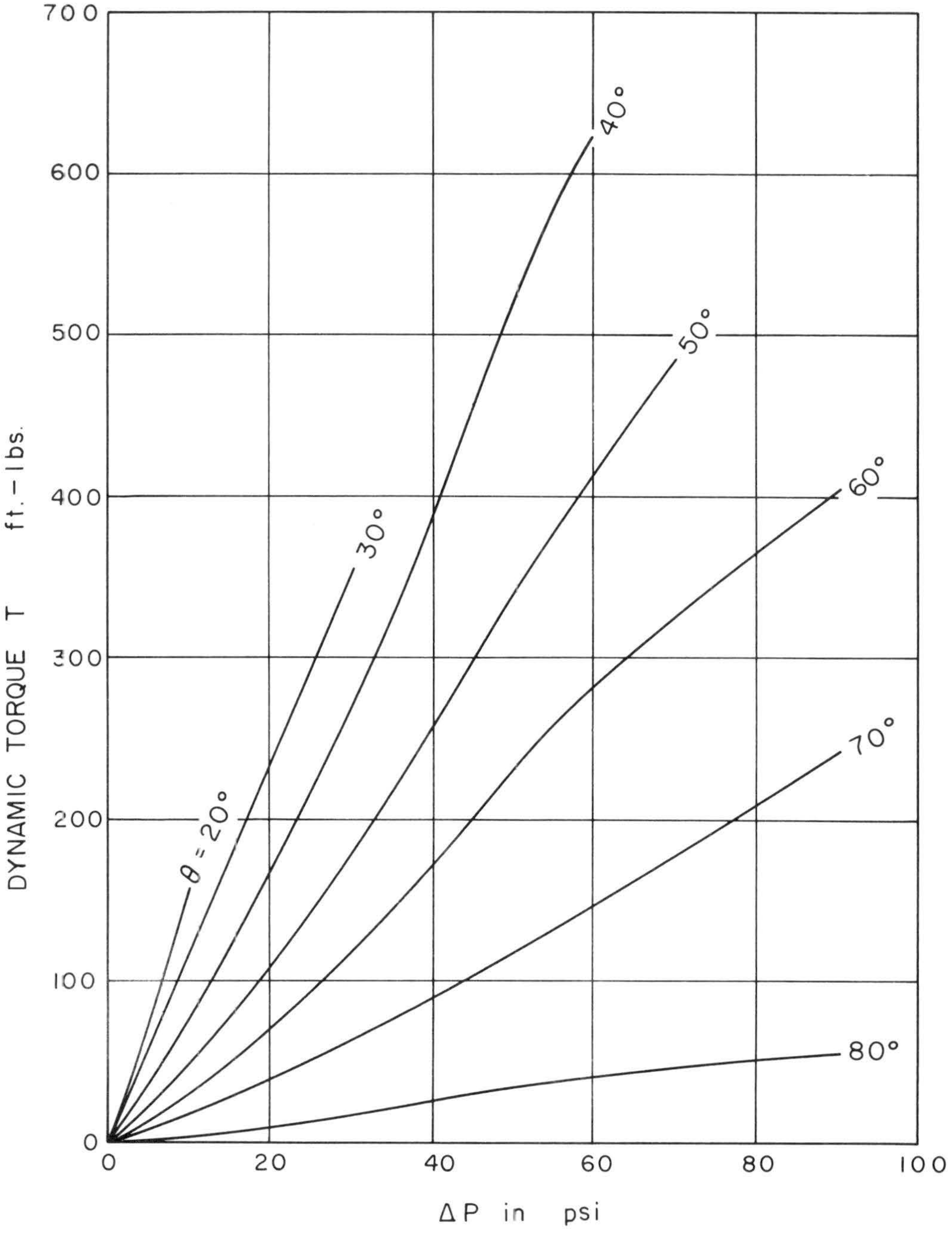

FIG. 28 DYNAMIC TORQUE 12-IN VALVE

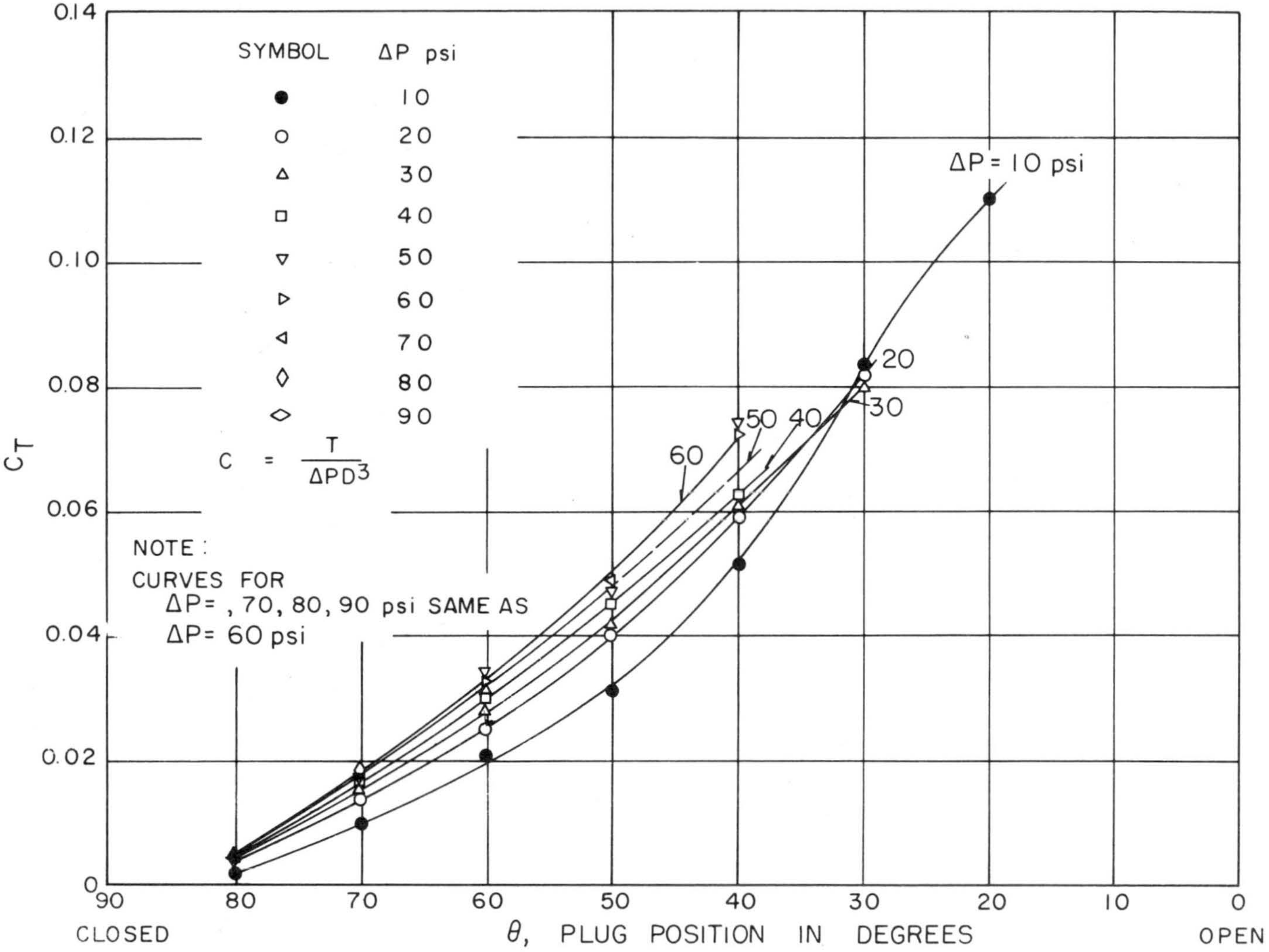

FIG. 29 DYNAMIC TORQUE COEFFICIENT 12 -IN VALVE

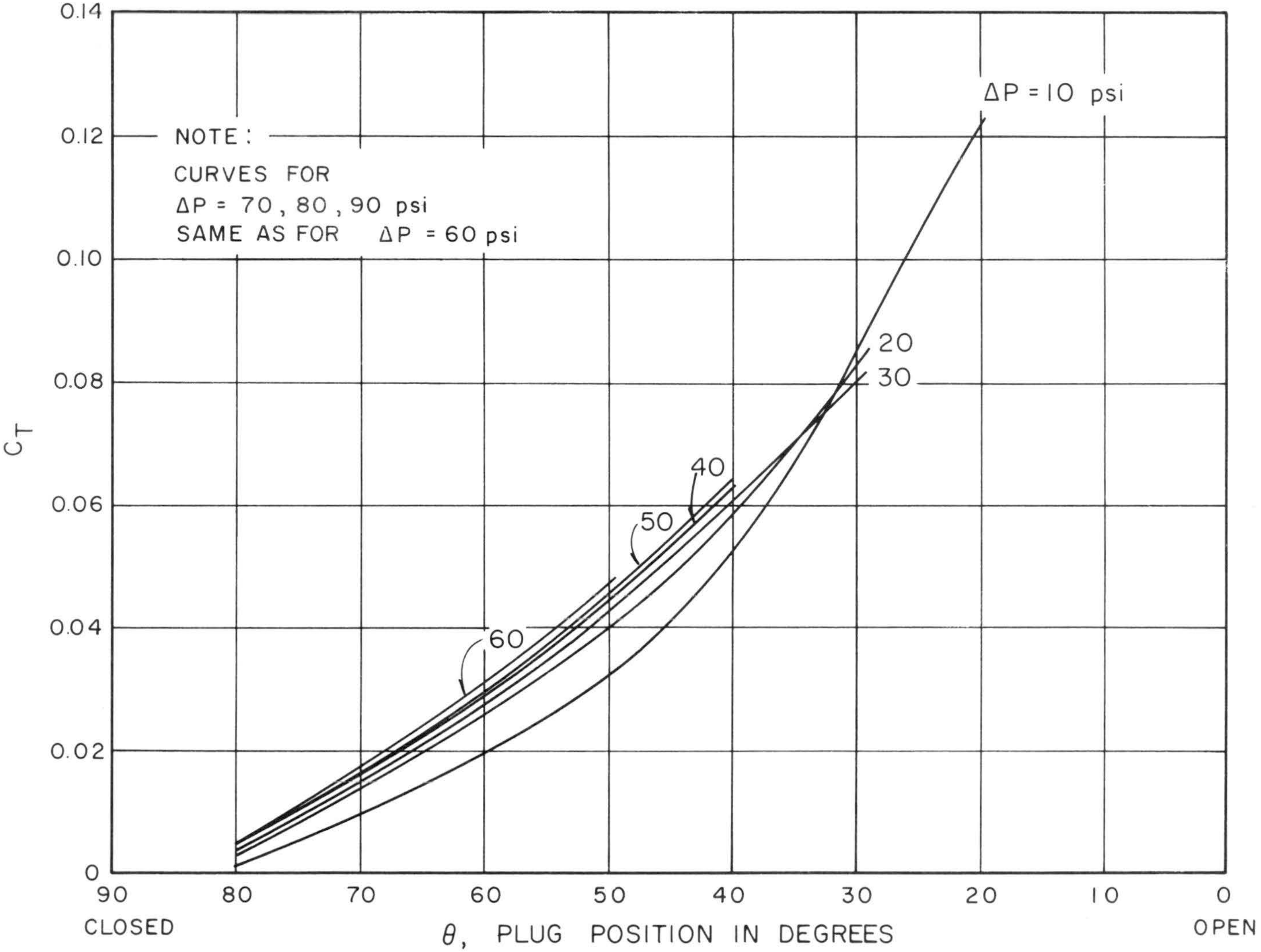

FIG. 30 DYNAMIC TORQUE COEFFICIENT PERMASPHERE VALVES

CONCLUSION

The flow coefficients K and dynamic torque coefficients C_T were found to be similar for all three sizes of values tested (36, 24 and 12-in). This was because the values are geometrically similar, (with only minor discrepancies) in so far as flow through the valve is concerned. Because both flow coefficient K and dynamic torque coefficient C are dependent on the flow through the valve they should be similar in characteristic. Thus as long as similarity is maintained, then the results may be used for valve sizes other than those on which these tests were made. The flow coefficients are given in Fig. 14 and the torque coefficients in Fig. 30.

The results of this study can be used to determine quantity of discharge that will flow through a permisphere valve at a given opening and differential pressure. Thus, knowing either discharge or pressure conditions required for a given installation, the proper piping and valve size can be determined. The dynamic torque coefficients will then enable determination of properly sized operating equipment to be adapted to the valve and to be assured that component parts of the valve are consistent to withstand the forces to which the valve will be subjected.

LIST OF TABLES

TABLE 1

FLOW DATA FOR 36-IN PERMASPHERE VALVE

Valve Position	Measured		Adjusted			
	Q	Δp*	Q	V	Δp	K = V/√Δp
90	0	92.5	0		92.50	0
87	0	92.5	0		92.50	0
84	--	92.0	2.72	0.385	92.10	.040
81	7.1	91.3	7.56	7.072	91.30	.112
78	14.7	89.2	13.72	1.942	89.78	.205
75	21.2	87.9	21.2	3.000	87.77	.320
70	35.3	82.2	35.3	5.000	82.34	.550
65	51.5	74.7	51.5	7.300	74.47	.846
60	67.5	63.0	67.5	9.550	62.77	1.207
55	81.5	50.7	81.7	11.560	50.38	1.628
45	105.	26.2	103.8	14.680	25.78	2.890
35	114.	11.2	114.7	16.250	11.58	4.780
25	120.	4.75	119.7	16.920	3.86	8.630
15	121.	1.7	121.2	17.200	0.83	18.89
0	122.	---	122.0	17.280	0.014	146.5

*Measured Δp between points 15 ft upstream from the upstream flange of the valve and 25 ft for downstream from the downstream flange.

TABLE 2

FLOW DATA FOR 24-IN PERMASPHERE VALVE

Valve Position	Measured		Adjusted			
	Q	Δp*	Q	V	Δp	K = $V/\sqrt{\Delta p}$
81	2.4	95.8	2.40	.765	95.8	.0782
78	5.9	96.4	5.90	1.88	96.4	.1915
	5.9	180.2	6.06	1.93	100.2	.193
	3.4	30.0	3.27	1.04	30.0	.190
75	5.9	38.0	5.90	1.88	37.98	.305
	8.0	77.0	8.42	2.68	77.96	.304
	9.5	97.4	9.50	3.02	97.36	.306
70	16.5	97.4	16.50	5.25	97.29	.532
	13.0	66.0	13.51	4.31	65.97	.531
	11.0	39.7	10.40	3.31	39.64	.526
	8.5	20.8	7.53	2.39	20.73	.526
65	11.0	18.5	10.72	3.42	18.45	.777
	15.9	39.6	15.71	5.01	39.50	.795
	19.2	68.5	20.70	6.58	68.33	.805
	24.5	97.6	24.65	7.85	97.36	.796
60	34.2	98.4	34.20	10.90	97.95	1.101
	28.3	74.0	29.50	9.40	73.66	1.095
	22.5	42.6	22.50	7.16	42.20	1.107
	17.0	22.6	16.33	5.20	22.48	1.098
55	22.2	21.4	21.38	6.79	21.22	1.475
	32.2	48.8	32.20	10.25	48.40	1.476
	39.2	80.5	40.85	13.00	79.85	1.46
	44.0	95.8	44.00	14.00	95.05	1.435
50	54.5	90.4	57.10	18.18	89.16	1.922
	48.5	70.0	50.60	16.10	69.01	1.935
	36.5	33.5	35.20	11.20	33.01	1.946
	24.4	14.7	23.25	7.40	14.48	1.946
40	36.0	11.0	36.0	11.45	12.12	3.32
	60.0	35.0	60.0	19.11	33.61	3.29
	74.0	52.0	74.0	23.55	49.94	3.33
	78.0	60.0	78.0	24.90	56.21	3.32
30	96.0	29.5	96.0	30.60	26.07	6.00
	79.0	19.5	79.0	25.20	17.15	6.09
	48.3	7.4	48.3	15.35	6.60	5.98
20	56.5	3.8	56.5	18.00	2.22	12.09
	93.0	8.7	93.0	29.60	5.76	12.30
	107.5	12.2	107.5	34.20	7.86	12.21
10	119.	6.1	119.0	37.90	1.25	30.3
0	110.0	3.1	110.0	35.00	0.053	152.0
	121.0	3.8	121.0	38.50	0.064	152.1

---

*Measured Δp between points 15 ft upstream from the upstream flange of the valve and 25 ft for downstream from the downstream flange.

TABLE 3

FLOW DATA FOR 12-IN PERMASPHERE VALVE

Valve Position	Measured		Adjusted			
	Q	Δp*	Q	V	Δp	K = V/ Δp
90	0.	96.	0		96.0	
87	0.	96.	0		96.0	
84	0.	96.	0		96.0	
81		96.	0		96.0	
78		96.	0.60	.765	96.0	.078
75		96.	1.40	1.783	95.96	.182
70		96.	3.20	4.08	95.87	.417
65	5.8	96.	5.40	6.88	95.16	.705
60	6.35	95.	8.00	10.20	94.07	1.050
55	10.7	93.	11.10	14.13	91.95	1.478
50	16.7	92.	14.80	18.88	88.96	2.000
40	26.2	85.	24.20	30.80	77.12	3.510
30	30.5	72.5	36.00	45.80	53.80	6.260
20	47.5	51.5	47.20	60.10	23.30	12.45
10	54.5	35.5	54.5	69.50	4.20	33.90
0	58.	20.0	58.0	73.80	0.25	147.6

*Measured Δp between points 15 ft upstream from the upstream flange of the valve and 25 ft downstream from the downstream flange.

TABLE 4

36-IN PERMASPHERE VALVE MEASURED TORQUE

Plug Posit.	Q	V	Δp	T_o	T_c
89	0	0	92.5	51,100	
87	0	0	92.5	54,900	52,900
84	2.7	0.382	92.1	56,500	56,800
81	7.5	1.06	91.2	56,100	54,900
78	13.7	1.94	89.8	61,000	54,600
75	21.2	3.00	87.0	58,800	49,700
75	8.12	1.15	12.6	13,040	9,350
70	35.3	5.00	82.3	53,400	44,000
65	51.5	7.29	74.7	53,600	35,900
60	67.5	9.56	62.5	50,400	26,300
60	12.9	1.824	2.3	2,170	3,200
60	27.3	3.86	10.0	7,380	3,020
55	81.8	11.58	53.0	42,250	15,700
45	103.8	14.70	25.5	24,600	5,900
45	23.7	3.35	1.3	2,130	2,170
45	50.8	7.19	6.1	4,375	1,780
35	104.7	14.83	9.6	14,200	0
30	107.7	15.26	5.6	11,000	500
30	35.5	5.02	0.6	2,480	2,240
30	78.5	11.1	2.9	3,640	1,860
15	121.1	17.18	0.83	5,200	460
15	79.0	11.18	0.35	3,020	2,010
15	47.75	6.75	0.13	2,530	2,480
0	122.0	17.28	0.135	2,500	2,560
0	79.5	11.24	0.056	2,400	2,480
0	48.0	6.79	0.02	2,440	2,480

TABLE 5

24-IN PERMASPHERE VALVE MEASURED TORQUE

Plug Posit.	Q	V	Δp	T_o	T_c
87	0	0	100.5	4,920	3,940
87	0	0	49.2	2,220	2,160
87	0	0	20.8	1,170	
87	0	0	12.2		1,230
87	0	0	87.7	3,260	2,960
84	0	0	100.5	3,700	3,200
84	0	0	66.0	2,610	
84	0	0	46.2		1,910
84	0	0	42.6	2,160	
84	0	0	28.0		1,540
81	0.52	0.165	4.5	492	
81	0.48	0.152	3.8		492
81	0.97	0.31	14.6	922	
81	0.72	0.23	8.4		740
81	1.87	0.595	57.0	1,970	
81	1.41	0.45	32.5		1,420
81	2.37	0.755	92.0	3,390	
81	2.31	0.735	86.0		2,340
78	5.9	1.88	96.5	3,750	
78	5.96	1.90	100.00		2,220
78	5.99	1.91	100.2	4,800	2,790
78	3.2	1.02	30.0	2,095	1,480
78	1.32	0.42	4.8	740	740
75	1.25	0.397	1.7	460	
75	1.35	0.43	2.0		492
75	3.32	1.06	12.0	985	800
75	5.4	1.72	32.1	2,030	1,170
75	8.16	2.6	72.0	3,450	
75	8.5	2.71	78.0		1,725
75	9.48	3.02	97.4	4,990	
75	9.57	3.05	99.4		2,400
70	16.5	5.25	97.5	4,620	185
70	13.34	4.25	66.0	3,700	
70	13.8	4.40	69.0		1,354
70	10.7	3.40	41.0	2,900	1,354
70	7.67	2.41	21.0	1,850	1,170
70	1.98	0.63	1.4	555	678
65	2.4	0.765	0.90	308	555
65	4.87	1.55	3.8	370	615
65	10.9	3.47	10.0	1,480	676
65	15.7	5.0	39.6	2,900	
65	16.3	5.2	42.0		740
65	20.6	6.55	68.2	4,430	
65	21.2	6.75	72.6		492
65	24.5	7.8	97.6	5,850	
65	24.8	7.9	100.0		146
60	33.6	10.7	96.5	6,030	
60	33.9	10.8	99.4		-431
60	29.0	9.25	71.6	4,920	
60	30.8	9.8	80.5		62
60	22.0	7.0	41.0	3,690	
60	22.9	7.3	44.0		615
60	16.0	5.1	22.0	2,340	862
60	5.25	1.67	2.3	492	676
55	6.50	2.07	2.0	307	591
55	21.4	6.8	21.2	2,090	

TABLE 5 (cont'd)

24-IN PERMASPHERE VALVE MEASURED TORQUE

Plug Posit.	Q	V	Δp	T_o	T_c
55	22.6	7.2	24.3		221
55	31.4	10.0	46.4	3,690	
55	32.9	10.5	52.0		-370
55	40.5	12.9	78.5	5,420	
55	38.0	12.1	69.2		-431
55	37.7	14.0	90.0	6,150	
55	38.5	14.3	94.0		-800
50	47.9	17.8	84.0	5,910	
50	50.3	18.7	94.0		-1,540
50	41.7	15.5	66.0	5,170	
50	39.3	14.6	56.0		-676
50	29.4	10.9	32.2	3,260	
50	30.7	11.4	35.0		123
50	22.6	7.2	14.1	1,725	
50	23.5	7.5	15.2		555
50	7.74	2.87	2.2	308	
50	8.25	3.06	2.5		492
40	14.4	4.60	1.9	401	316
40	28.9	10.7	10.7	1,490	
40	29.9	11.1	11.1		57
40	46.1	17.1	26.0	3,390	
40	49.4	18.3	32.2		-431
40	59.6	22.1	44.0	5,350	
40	66.3	24.6	56.7		-1,480
40	78.0	26.9	67.5	5,550	
40	76.9	26.5	66.0		-1,480
30	98.0	31.3	26.0	4,120	-1,046
30	94.0	30.0	24.5	4,250	
30		32.2	27.0		-1,108
30	77.0	24.5	16.8	2,830	
30	83.1	26.5	19.0		-615
30	50.5	16.1	7.0	1,292	
30	51.2	16.3	7.3		308
30	21.4	6.8	1.3	370	675
20	36.4	11.6	0.9	581	295
20	65.0	20.7	2.9	1,360	50
20	93.2	29.7	5.9	2,120	
20	96.1	30.6	6.3		-631
20	108.3	34.5	7.9	2,640	
20	110.5	35.2	8.4		-830
20	112.	35.6	8.5	2,470	-802
10	113.0	36.0	1.1	2,350	-802
10	55.9	17.8	0.26	919	115
10	47.7	15.2	0.20	531	232
0	59.6	19.0	.015	531	432
0	110.0	35.0	.053	531	515
0	121.0	38.5	.064	432	500

TABLE 6

12-IN PERMASPHERE VALVE MEASURED TORQUE

Plug Posit.	Q	V	Δp	T_o	T_c
86.5	0	0	9.2	420	
86.5	0	0	48.2	1,470	
86.5	0	0	60.	1,740	
86.5	0	0	71.2	2,000	
85	0	0	90.3	2,550	
87	0	0			1,140
87	0	0			1,620
87	0	0			1,860
87	0	0	72.4		1,960
87	0	0			2,460
87	0	0			2,640
84	0	0		1,420	
84	0	0	57.4	1,750	
84	0	0	89.2	2,360	
84	0	0			2,490
84	0	0			2,180
84	0	0	57.4		1,520
84	0	0			1,330
84	0	0			450
81	0	0	27.3	600	
81	0	0		1,510	
81	0	0	88.5	2,290	1,790
81	0	0	94.3	2,330	2,065
81	0	0	27.3		550
81	0	0			2,340
75	.78	1.0	30.3	1,200	750
75	1.24	1.58	76.0	2,030	1,620
75	1.41	1.80	99.0	2,240	1,950
75	0.98	1.25	48.0		1,760
70	3.12	3.98	92.0	2,130	1,710
70	2.80	3.57	76.5	1,920	1,440
70	2.38	3.04	54.0	1,620	1,140
70	1.85	2.35	33.4	1,240	830
70	1.33	1.70	17.4	740	480
60	1.73	2.20	4.4	210	30
60	3.34	4.25	16.7	610	330
60	4.98	6.35	36.5	1,230	750
60	6.2	7.90	56.5	1,670	990
60	7.1	9.05	75.0	1,950	1,140
60	7.86	10.01	94.0	2,210	1,410
50	14.2	18.1	83.0	2,070	760
50	13.3	16.9	73.0	2,000	880
50	11.2	14.3	53.5	1,630	680
50	9.1	11.6	34.0	1,260	550
50	6.2	7.9	16.5	620	300
35	30.2	38.5	73.0	2,010	
35	27.2	34.7	60.0	1,800	150
35	22.9	29.2	42.0	1,540	210
35	17.8	22.7	25.0	1,070	250
35	11.47	14.6	11.0	1,100	450
20	46.3	59.	22.5	1,560	310
20	38.1	48.5	15.0	1,740	180
20	31.0	39.5	10.0	930	160
20	16.8	21.4	2.9	340	
5	24.9	31.7	0.24	160	70
5	47.1	60.	0.84	480	-200
5	55.7	71.	1.20	670	-320
0	57.6	73.5	20.24	70	70

TABLE 7

CALCULATION FOR DYNAMIC TORQUE COEFFICIENT

36-IN VALVE

Plug Posit.	Δp	T_o	T_c	T_D	T_F	C_T
80	10	5,390	5,300	45	5,340	.00132
	20	13,170	12,800	185	12,980	.0027
	30	20,300	19,500	400	19,900	.0040
	40	26,200	25,000	600	25,600	.0044
	50	32,300	30,500	900	31,400	.0046
	60	37,500	35,600	950	36,550	.0046
	70	42,600	40,500	1,050	41,550	.0044
	80	48,700	46,200	1,250	47,450	.0045
	90	55,000	52,000	1,500	53,500	.0048
70	10	5,260	4,500	380	4,880	.0100
	20	13,000	11,200	900	12,100	.0136
	30	19,720	16,600	1,560	18,160	.0150
	40	26,540	22,000	2,270	24,270	.0164
	50	33,260	27,000	3,130	30,130	.0162
	60	38,800	31,800	3,500	35,300	.0169
	70	45,800	37,200	4,300	41,500	.0176
	80	53,500	43,500	5,000	48,500	.0180
	90	62,000	50,400	5,800	55,200	.0186
60	10	5,500	3,800	850	4,650	.0246
	20	12,980	9,500	1,740	11,220	.0255
	30	20,320	14,500	2,910	17,420	.0280
	40	26,700	18,500	4,100	22,600	.0295
	50	34,000	22,600	5,730	28,300	.0297
	60	41,800	28,500	6,650	35,150	.0320
	70	49,500	34,500	7,500	42,000	.0306
	80	58,500	41,500	8,500	50,000	.0308
50	10	5,700	3,500	1,100	4,600	.0317
	20	13,200	7,800	2,700	10,500	.0390
	30	20,300	11,700	4,340	16,000	.0418
	40	27,100	15,000	6,050	21,050	.0437
	50	36,400	19,500	8,450	27,950	.0439
	60	44,500	25,200	9,650	34,850	.0466
40	10	6,600	3,000	1,800	4,800	.052
	20	14,300	6,200	4,050	10,250	.059
	30	21,400	9,000	6,200	15,200	.060
30	10	9,220	3,200	3,010	6,210	.087
	20	16,500	5,100	5,700	10,800	.083
20	10	11,700	3,300	4,200	7,500	.122

TABLE 8

CALCULATION FOR DYNAMIC TORQUE COEFFICIENT

24-IN VALVE

Plug Posit.	Δp	T_o	T_c	T_D	T_F	C_T
80	10	880	850	15	865	.0013
	20	1,360	1,230	65	1,295	.00282
	30	1,810	1,540	135	1,675	.00392
	40	2,210	1,800	205	2,005	.00445
	50	2,550	2,030	260	2,290	.00452
	60	2,860	2,230	315	2,545	.00484
	70	3,130	2,430	350	2,780	.00435
	80	3,470	2,660	405	3,065	.00440
	90	3,640	3,010	215	3,225	.00208
	100	3,950	3,580	185	3,765	.00161
70	10	980	730	125	855	.0109
	20	1,560	940	310	1,250	.0135
	30	2,110	1,070	520	1,590	.0151
	40	2,610	1,140	735	1,875	.0160
	50	3,040	1,180	930	2,110	.0161
	60	3,440	1,160	1,140	2,300	.0175
	70	3,780	1,080	1,350	2,430	.0167
	80	4,130	930	1,600	2,530	.0174
	90	4,540	690	1,925	2,615	.0186
	100	5,000	400	2,300	2,700	.0200
60	10	1,120	700	210	910	.0181
	20	1,830	690	570	1,260	.0248
	30	2,530	600	965	1,565	.0280
	40	3,150	450	1,350	1,800	.0293
	50	3,670	270	1,700	1,970	.0296
	60	4,150	50	2,050	2,100	.0315
	70	4,640	-150	2,395	2,245	.0297
	80	5,150	-320	2,735	2,415	.0297
	90	5,670	-480	3,075	2,595	.0297
	100	6,230	-610	3,420	2,810	.0297
50	10	1,270	540	365	905	.0317
	20	2,200	370	915	1,285	.0398
	30	3,050	150	1,450	1,600	.0420
	40	3,750	-250	2,000	1,750	.0435
	50	4,350	-700	2,525	1,825	.0439
	60	4,930	-1000	2,965	1,965	.0455
	70	5,580	-1250	3,415	2,165	.0423
40	10	1,500	300	600	900	.0521
	20	2,650	-50	1,350	1,300	.0586
	30	3,650	-550	2,100	1,550	.0609
	40	4,450	-1180	2,815	1,635	.0610
30	10	1,900	100	1,000	1,100	.0869
	20	3,250	-550	1,900	1,350	.0825
	30	4,300	-1200	2,750	1,550	.0797
20	10	2,300	-800	1,530	750	.132

TABLE 9

CALCULATION FOR DYNAMIC TORQUE COEFFICIENT

12-IN VALVE

Plug Posit.	Δp	T_o	T_c	T_D	T_F	C_T
80	10	224	220	2	222	.00140
	20	560	540	10	550	.0035
	30	854	820	170	837	.004
	40	1,160	1,110	25	1,135	.0045
	50	1,380	1,310	35	1,345	.0045
	60	1,560	1,480	40	1,570	.00475
	70	1,700	1,610	45	1,655	.00445
	80	1,890	1,790	50	1,840	.00442
	90	2,080	1,970	55	2,025	.0040
70	10	230	200	15	215	.0105
	20	560	480	40	520	.01400
	30	850	720	65	785	.0151
	40	1,160	970	95	1,080	.0164
	50	1,390	1,150	120	1,270	.0165
	60	1,560	1,260	150	1,410	.0173
	70	1,730	1,380	175	1,555	.0175
	80	1,930	1,510	210	1,720	.0181
	90	2,170	1,690	240	1,930	.0187
60	10	240	180	30	210	.0208
	20	570	425	73	497	.0250
	30	860	620	120	740	.0280
	40	1,160	820	170	990	.0294
	50	1,390	900	245	1,145	.0340
	60	1,580	1,020	280	1,300	.0321
	70	1,780	1,130	325	1,455	.0322
	80	1,990	1,240	350	1,615	.0304
	90	2,210	1,400	405	1,805	.0310
50	10	250	160	45	225	.0318
	20	580	350	115	465	.040
	30	860	500	180	680	.0420
	40	1,170	650	260	910	.0450
	50	1,400	720	340	1,060	.047
	60	1,620	790	415	1,205	.0478
	70	1,830	860	485	1,345	.0488
40	10	290	140	75	215	.0521
	20	600	260	170	430	.0588
	30	880	350	265	615	.0610
	40	1,200	440	380	820	.0620
	50	1,460	400	530	1,030	.0735
	60	1,700	450	625	1,125	.072
30	10	350	110	120	230	.0840
	20	650	180	235	415	.0820
	30	910	210	350	560	.0800
20	10	410	100	155	255	.110