CALIBRATIONS OF THIN PLATE ORIFICES FOR FEEDWATER MEASUREMENT IN THE A1W ATOMIC REACTOR PLANTS

Conducted for
Westinghouse Electric Corporation
Idaho Falls, Idaho

by

S. S. Karaki

May 1960

Civil Engineering Section
Colorado State University Research Foundation

CER60SSK29

CALIBRATIONS OF THIN PLATE ORIFICES FOR FEEDWATER MEASUREMENT IN THE A1W ATOMIC REACTOR PLANTS

Conducted for

Westinghouse Electric Corporation

Idaho Falls, Idaho

by

S. S. Karaki

May 1960

Civil Engineering Section

Colorado State University Research Foundation

CER60SSK29

TABLE OF CONTENTS

	Page
SYNOPSIS	1
INTRODUCTION	2
THEORY AND APPLICATION OF THE THIN PLATE ORIFICE	2
CALIBRATION PROCEDURE	4
MEASUREMENT ACCURACIES	5
TABLE 1.	5
CALIBRATION DATA	6
DISCUSSION OF RESULTS	7
USE OF CALIBRATION DATA TO DETERMINE THE DISCHARGE CURVE	9
RECOMMENDATIONS	10
FIGURES	11
TABLES (2 - 4)	21

LIST OF FIGURES

Fig. No.

1. Piping Mock-up for Orifice Calibrations.
2. Plate No. 1. Variation of Flow Coefficients with flow bypass. Before Modification.
3. Orifice Plates 1, 2, and 3. Before Modification.
4. Plate No. 1. Before Modification.
5. Plate No. 1. Variations Between Various Calibrations of the Same Orifice Plate. Before Modification.
6. Plate No. 1. Change of Gaskets. Before Modification.
7. Plates No. 1, 2, and 3. After Modification.
8. Electronic Measuring Equipment of Differential Head.
9. Discharge Curve for Feedwater Flow Measurement.

LIST OF TABLES

Table No.

1. Measurement Accuracies.
2. Calibration Data. Before Modification.
3. Calibration Data. After Modification.
4. Calculations for Discharge Curve.

CALIBRATIONS OF THIN PLATE ORIFICES FOR FEEDWATER MEASUREMENTS IN THE A1W ATOMIC REACTOR PLANTS.

SYNOPSIS

This report contains the results of calibration of thin plate orifices for feedwater flow measurement in the A1W Reactor Plants. The calibrations were conducted in the Hydraulics Laboratory of Colorado State University for the Westinghouse Electric Corporation, Idaho Falls, Idaho. As a result of this study, several modifications were made to improve the reliability of flow measurement. These modifications were:

1. A device to enable concentric placement of the orifice with respect to both upstream and downstream piping.
2. Construction of several piezometer taps located around the pipe circumference which connected to piezometer rings to obtain better average measurements of pressures and to damp pressure fluctuations.
3. Setting straightening vanes upstream of the upstream pressure taps to decrease the turbulence in the approach flow.

The most effective modification was the centering guide for the orifice plates. The increase in number of piezometers, reduction in size of piezometer holes, and the piezometer rings were moderately helpful. The effect of the straightening vanes were not measurable.

Flow coefficients were determined for the orifices and a discharge curve with differential head as a function of feedwater flow at 305^{o}F was calculated.

INTRODUCTION

The calibration of the orifice plates, with necessary tooling, was authorized by Westinghouse Electric Corporation on March 10, 1960, with the issuance of a Purchase Order No. 73-H-4074. This was subsequently amended by a change order dated April 22, 1960, to allow additional tooling modifications to improve the reliability of measurement.

The orifice plates were calibrated in a mock-up of the feedwater piping system of the A1W Reactor Plant, provided by the Westinghouse Electric Corporation. All calibrations were made in the Hydraulics Laboratory at the Colorado State University and in the presence of the Westinghouse representative, Mr. W. M. Pugh. Flow coefficients were determined and calculations were made to establish a discharge curve for feedwater at 305°F. The orifices were calibrated with water at temperatures between 50 and 60°F.

THEORY AND APPLICATION OF THE THIN PLATE ORIFICE

In its most elementary form, a thin plate orifice is a device located in a pipeline which causes flow constriction. Accompanying this flow constriction is a local increase in velocity and reduction in pressure which produces a pressure-head differential between the two sides of the orifice plate.

Using Bernoulli's Equation and the equation of continuity, one can arrive at the following equation for flow through an orifice in a pipeline,

$$q = \frac{Ca}{144} \sqrt{2gh} \left(\frac{1}{\sqrt{1-\beta^4}} \right) \qquad (1)$$

or in terms of gravimetric rate of flow,

$$w = \frac{C}{\sqrt{1-\beta^4}} \quad \frac{a}{144} \gamma \sqrt{2gh} \qquad (2)$$

In Equations (1) and (2), the following nomenclature applies:

q = Volume rate of flow, c.f.s.

C = Coefficient of discharge.

a = Area of the orifice opening, sq. in.

g = Acceleration due to gravity, ft/sec^2.

h = Effective differential head, feet of the fluid.

β = Ratio of the orifice diameter to pipe diameter.

w = Weight rate of flow, lbs per sec.

γ = Specific weight, lb per cubic ft.

By choosing different dimensions of the foregoing terms in a manner more consistent with industrial practice, the following equation is developed for an incompressible fluid:

$$w_h = 358.9 \frac{C}{\sqrt{1-\beta^4}} d^2 \sqrt{\gamma h_w} \tag{3}$$

and by letting

$$K = \frac{C}{\sqrt{1-\beta^4}},$$

and rounding the conversion factor 358.9 to 359,

$$w_h = 359 \ K \ d^2 \sqrt{\gamma h_w} \tag{4}$$

Now,

w_h = Weight ratio of flow, pounds per hour.

K = Flow coefficient.

d = Orifice diameter, inches.

h_w = Differential head across the orifice plate, inches of fluid at 68^{0}F.

In Equation (3) the "theoretical" coefficient of discharge, C, is unity. However, actually, C varies with orifice geometry, the physical location of pressure measuring piezometers, fluid properties, and flow characteristics. Quite conveniently, however, it has been found through experimentation that the significant variables, for any fixed location of pressure taps, can be related to discharge coefficient through a single dimensionless number, R_D , called the "Reynolds Number". Therefore, for any orifice of fixed geometry and location, C and thus, K can be related to the Reynolds Number of flow and from the curve of flow coefficients, w_h can be calculated for any h_w . Since Equation (4) is implicit in terms of w_h and h_w , a trial and error procedure must be adopted to calculate the rate of flow from h_w , or if w_h is chosen as the independent quantity for purpose of calculation only, then h_w can be determined directly.

CALIBRATION PROCEDURE

The orifices were calibrated in the laboratory with a recirculating water system. Water was pumped from the sump by an 8-inch high-head turbine pump, through the piping mock-up, and delivered to the calibration tank or gravimetric system and subsequently returned to the sump. A photograph of the laboratory installation is shown in Fig. 1. The electronic timing device connected to a splitter valve, which controlled the flow either to the measuring system or to the sump, is shown in the background. The pressures were measured with a differential manometer. The square edged orifice was 2.38 inches in diameter and conformed to A.S.T.M. recommendations.

At the beginning of each calibration, sufficient time was allowed to be assured that the approach piping was purged of all air. The manometer lines were also purged of air through bypass valves at the manometer connections. When stable conditions were established, the splitter valve was operated to direct the flow into the measuring system. The timing mechanism automatically operated simultaneously with movement of the splitter valve. The time was always checked with a stop watch throughout the calibrations for measurement of time to 0.1 second. The differential head was then read from the manometer. During long periods of calibration runs, the differential head was read a number of times and averaged. For large flows, the differential head fluctuated considerably and it was necessary to constrict the manometer lines to damp the oscillations. Assurance was made at all times that the constriction did not close the manometer leads completely.

MEASUREMENT ACCURACIES

Accuracies of measurement of time, volume, weight and differential head are tabulated below.

TABLE 1.

MEASUREMENT ACCURACIES

			Total Measurement		Percent Accuracy	
Item	Unit	Accuracy	Min.	Max.	Min.	Max.
Time	Sec.	0.1	180	1200	.056	.008
Volume	gal.	2.5	1400	1900	.131	.104
Weight	lb.	0.25	1800	2100	.013	.011
Head*	in.	0.05	----	----	----	----

*Per cent accuracy of head measurement was dependent upon actual differential head developed by the flow through the orifice and is therefore a dependent quantity. At low discharges, and therefore small differential heads, the manometer was tilted to obtain a greater reading of differential head on the manometer which was subsequently corrected to vertical head readings.

CALIBRATION DATA

The experimental data for the orifice calibrations are appended to this report. The calibrations were made in two phases. The first phase included calibration of orifice plates Nos. 1, 2, and 3 without a positive centering guide for the orifice and with non-standard gaskets. A standard gasket herein refers to gaskets used with the orifice plates in the Westinghouse plant in Idaho Falls, Idaho. The non-standard gaskets used were asbestos fibre gaskets 1/16-inch thick and rubber gaskets 3/32-inch thick. Single pressure taps were used to determine differential head across the orifice plate. The second phase included calibrations after modifications were made to the piping mock-up using centering guides for the orifice and standard gaskets.

Modifications to the testing equipment for the second phase included:

(1) Construction of seven piezometers, each 3/32-inch in diameter in the same plane for each upstream and downstream pressure measuring tap. The piezometers were connected to a piezometer ring 1/2-inch in diameter with a single manometer lead connected to each piezometer ring. Seven piezometers were used, where normally there would have been eight, because the original piezometer was left undisturbed. It was desirable to make comparisons of the effect of single taps and multiple piezometer taps with rings on the differential pressure fluctuations. The original piezometer sizes were 3/4-inch in diameter for the upstream and 1/2-inch in diameter for the downstream tap.

(2) Installation of a honeycombed straightening vane upstream of the orifice and pressure tap for the purpose of damping turbulent fluctuations in the flow. The honeycomb consisted of three pipes welded together to fit inside the approach pipe.

DISCUSSION OF RESULTS

The results of the first phase of the calibrations are shown in Figs. 2 to 6. Calibrations of orifice plate No. 1 with no bypass flow at the tee, with flow bypass equal to the flow through the orifice, and with flow bypass equal to twice the flow through the orifice are shown in Fig. 2. The trend of flow coefficients, with due regard to normal scatter of data, shows no systematic effect of flow bypass at the tee on the calibration of the orifice. The data for this study was taken without removal or otherwise disturbing the orientation of the orifice plate. Asbestos fibre gaskets were used with the orifice plate.

Fig. 3 shows the results of the calibrations for orifice plates 1, 2, and 3. The scatter of calibration coefficients made it impossible to determine quantitatively, the deviation of coefficients for the three plates. Lines are drawn for each orifice on the figure to identify the data and to show the apparent trend for the different plates. They are not to be construed as representing the correct coefficients. The results of the study indicated need for additional studies to be made to determine the cause of the deviation in calibration for the single orifice and between the three orifice plates.

Accordingly, a series of calibrations were made with the orifice plate placed non-concentrically to the approach and downstream piping. The results, shown in Fig. 4, indicate the differences in the flow coefficients due to the different orientation of the orifice with respect to the pipe. However, it must be pointed out that the scatter of data is no greater than that of Fig. 3. Within this analysis, neither the amount nor direction of deviation can be related positively with the position of the orifice. A more extensive study is needed to establish such relationship; time was not available for such a conclusive study to be conducted at this time.

The calibration results for a number of repetitions for orifice plate No. 1 is shown in Fig. 5. There is a large random deviation for any calibration. This was due to the fact that the orifice could not be located in the same position for each calibration without the aid of some physical guide, as the orifice plate was removed and reinserted for each test run. Rubber gaskets were used instead of asbestos fibre gaskets. The difference in the results are shown in Fig. 6.

The results of the first phase indicated a need for some modifications to be made to the feedwater piping and orifice. First, centering guides were constructed for orifice plates Nos. 1, 2, and 3 to effect positive means of centering the orifice with respect to the pipe, both upstream and downstream. Second, the gaskets were changed to the actual gaskets used by the Westinghouse Corporation in the feedwater-flow system. Third, the large diameter single piezometers used to measure pressures were changed to several small piezometers connected to a common ring to register better average pressures and to damp the oscillations. Also, in a portion of the second phase of the study, straightening vanes, comprised of three small pipes in a honeycomb, were installed as previously described.

The results of calibrations for orifice plates 1, 2, and 3 are shown in Fig. 7. The data on this curve include a number of different calibrations for the orifice plates made by completely removing and reinserting the orifice plates. The curves show that the calibrations can be repeated and that the flow coefficients are the same for all three orifice plates. It also indicates that the accuracy of an orifice in measuring flow rate is about $\pm$ 0.5 per cent.

Electronic differential pressure gages with appropriate instrumentation were used to determine the beneficial effects of the increased number of piezometers and the piezometer rings. The instrumentation shown in Fig. 8 was provided by the Westinghouse Corporation. The data from this study was recorded on the strip chart of the recorder and is not included as part of this report. The strip chart was retained by the Westinghouse representative from Idaho Falls. In general, there was some indication of less flow pulsation and differential pressure fluctuation, particularily at the high discharges.

The effect of straightening vanes was also tested with the electronic differential pressure gages. There was no observable effect, either on the calibrations or improvement of pressure fluctuation by installing the straightening vanes. The recorded results were also retained by the Westinghouse representative and is therefore not included as part of this report.

USE OF CALIBRATION DATA TO DETERMINE THE DISCHARGE CURVE

The calibration results of Fig. 7 were used to develop a discharge curve for feedwater flow at a temperature of 305°F. The calculated data is tabulated in Table 4 and the curve is plotted in Fig. 9. In order to make this conversion, the flow coefficients of Fig. 7 were used in conjunction with Equation (4):

$$w_s = 359 \; K F_a d^2 \sqrt{\gamma_s h_w}\,, \qquad (4)$$

where the subscript s refers to ship or actual feedwater conditions.

To enable direct solutions, w_s was used as the independent quantity, for purposes of constructing the discharge curve, and h_w was calculated. It was also necessary to extrapolate the flow coefficient curve beyond the data taken in the laboratory. The extrapolation is shown on Fig. 7 as a dashed line, and the coefficient was assumed constant for Reynolds Numbers greater than one million.

RECOMMENDATIONS

The results of this study indicate that certain modifications should be adopted for the feedwater system of the Westinghouse A1W Reactor Plant in Idaho Falls. The recommended modifications are:

1. Constructing centering guides for the orifice plates to eliminate the possibility of installing orifices in a position other than that for which it was calibrated.

2. Providing multiple piezometers to determine better average pressures. The size of the piezometer taps will be governed by the amount of foreign material suspended in the flow, but should not be much greater than 3/32-inch in diameter.

3. Construct a piezometer ring to which the piezometer should be connected. The ring should be continuous and approximately 3/4-inch inside diameter. The ring will damp pressure fluctuations at the high discharges and thus, enable more accurate determinations of average pressures. The ring should be placed higher than the piezometer taps and sloped so that air cannot be entrapped.

FIGURES

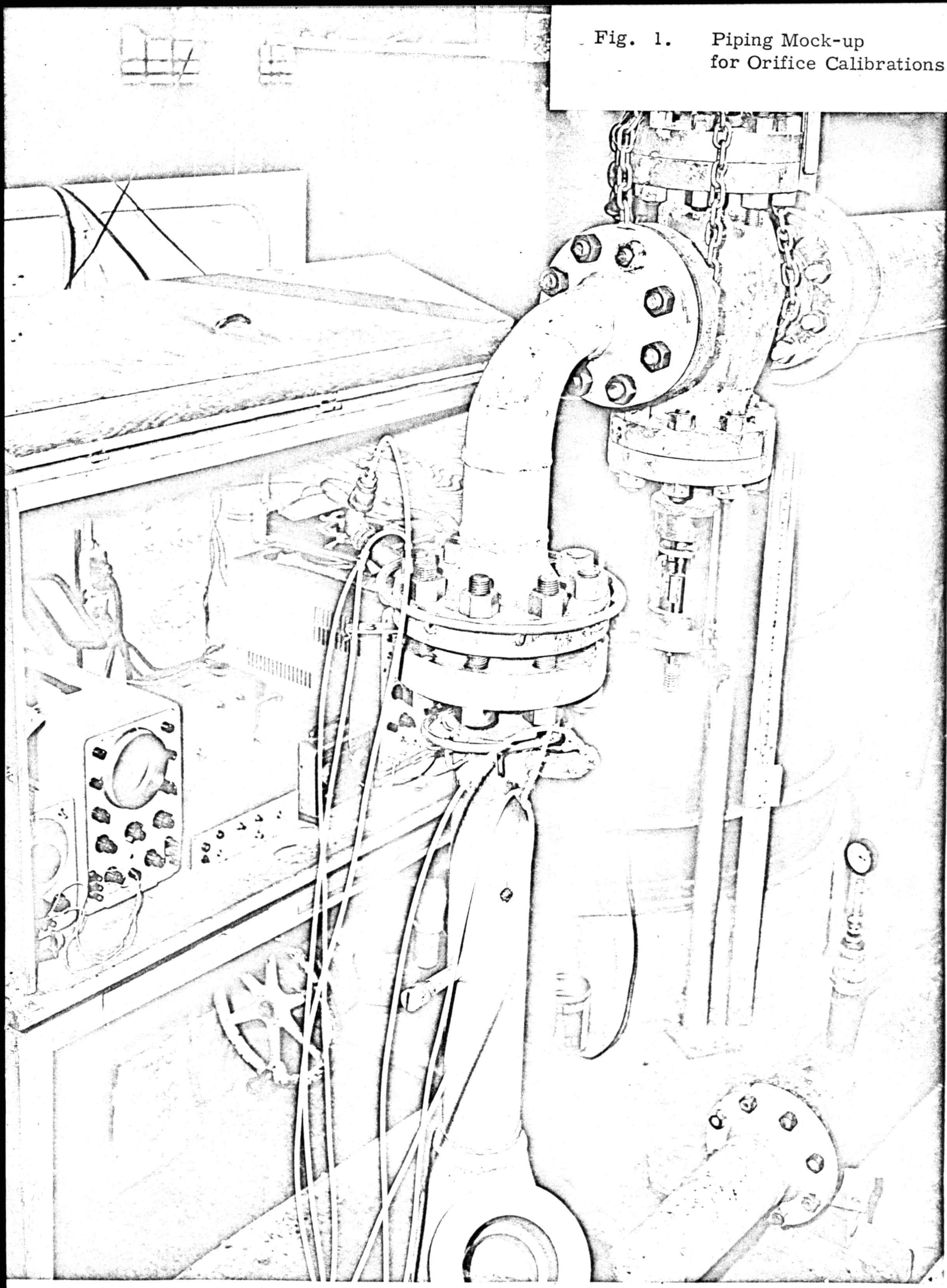


Fig. 1. Piping Mock-up for Orifice Calibrations

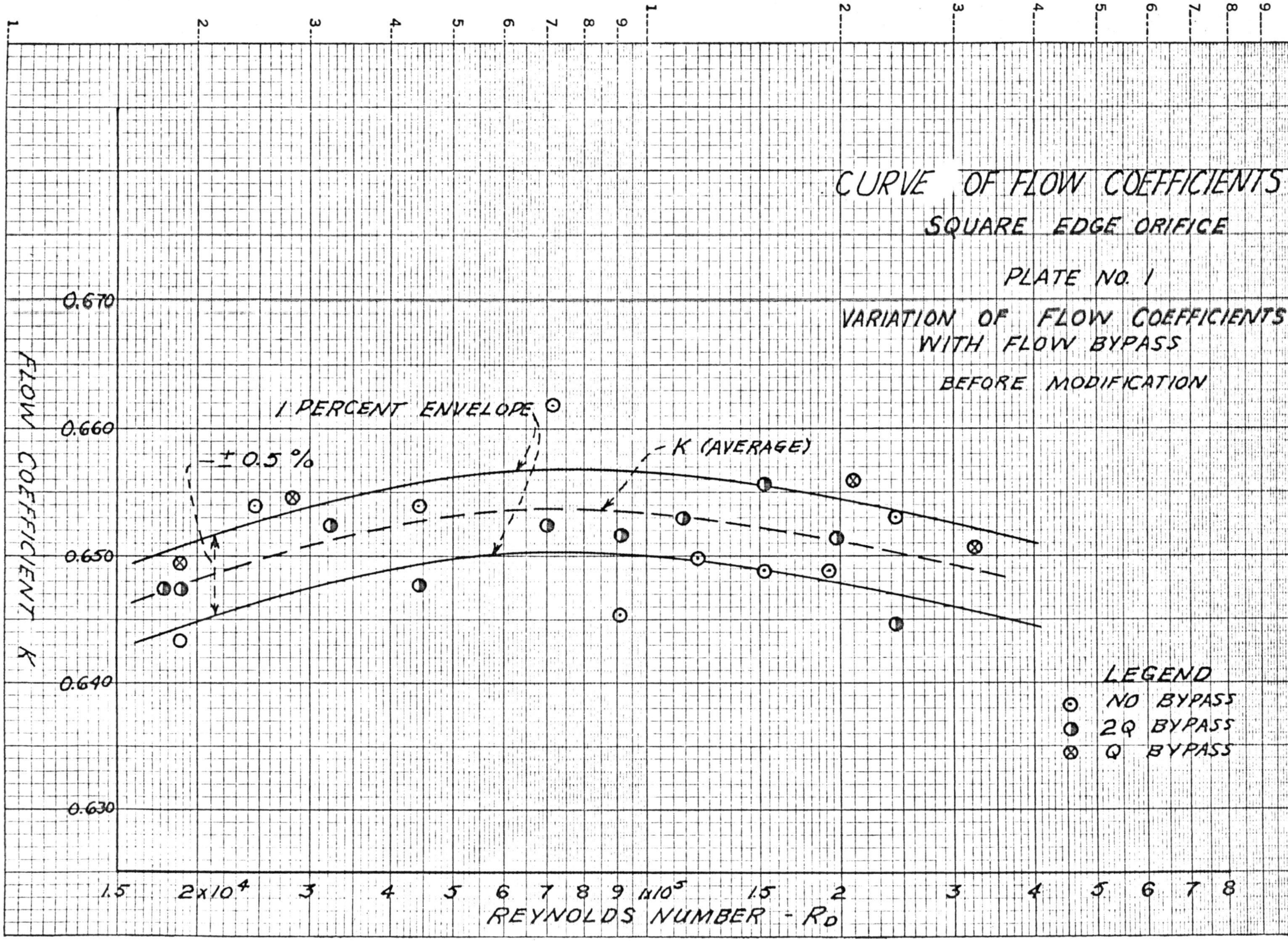

CURVE OF FLOW COEFFICIENTS
SQUARE EDGE ORIFICE
PLATE NO. 1
VARIATION OF FLOW COEFFICIENTS WITH FLOW BYPASS
BEFORE MODIFICATION
1 PERCENT ENVELOPE
K (AVERAGE)
± 0.5 %
0.670
0.660
0.650
0.640
0.630
FLOW COEFFICIENT K
1.5
2x10⁴
3
4
5
6
7
8
9
1x10⁵
1.5
2
3
4
5
6
7
8
REYNOLDS NUMBER - R_D
LEGEND
NO BYPASS
2Q BYPASS
Q BYPASS

FIG 2

KEUFFEL & ESSER CO. MADE IN U.S.A.
2 CYCLES X 70 DIVISIONS

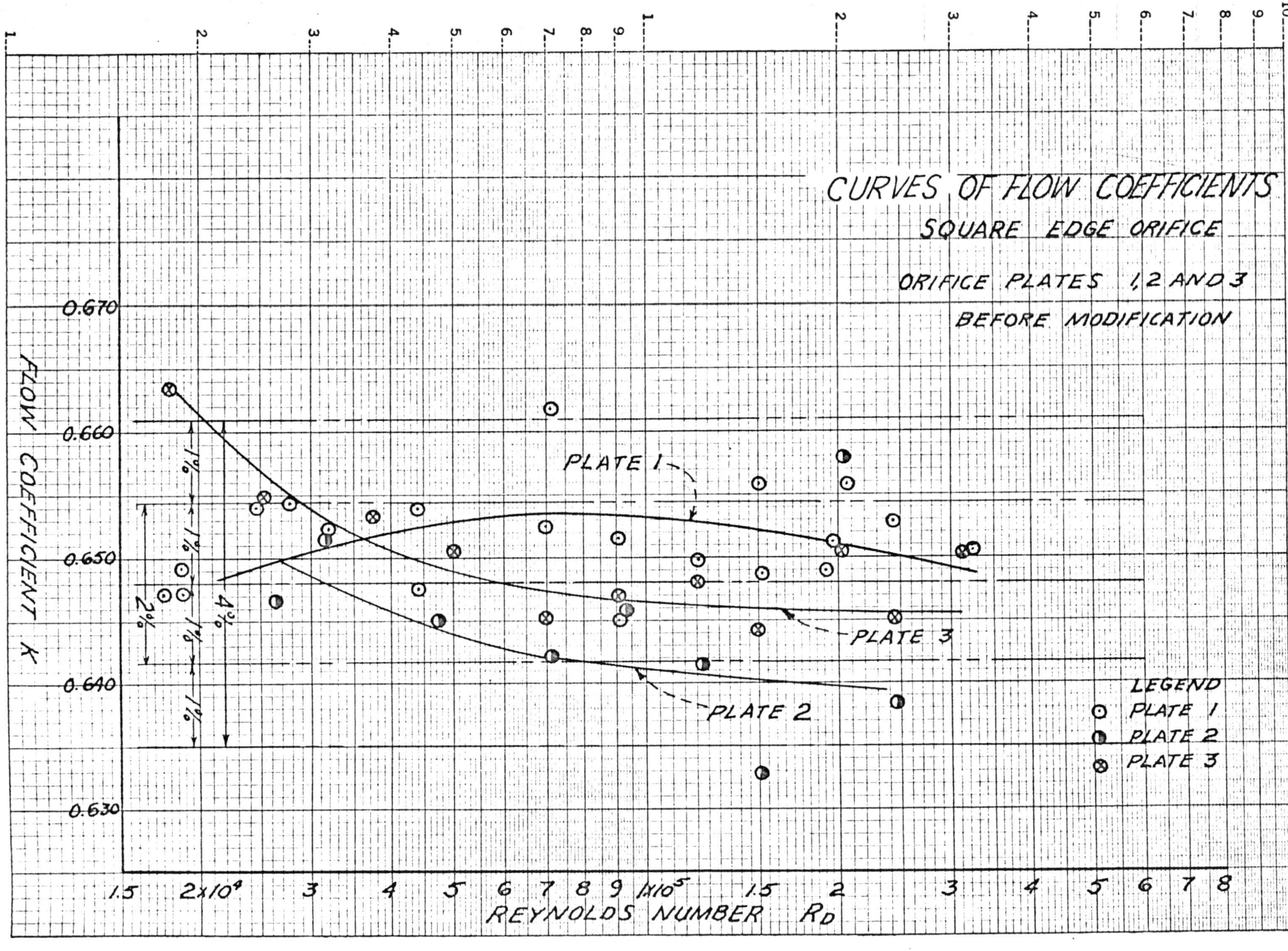


FIG. 3

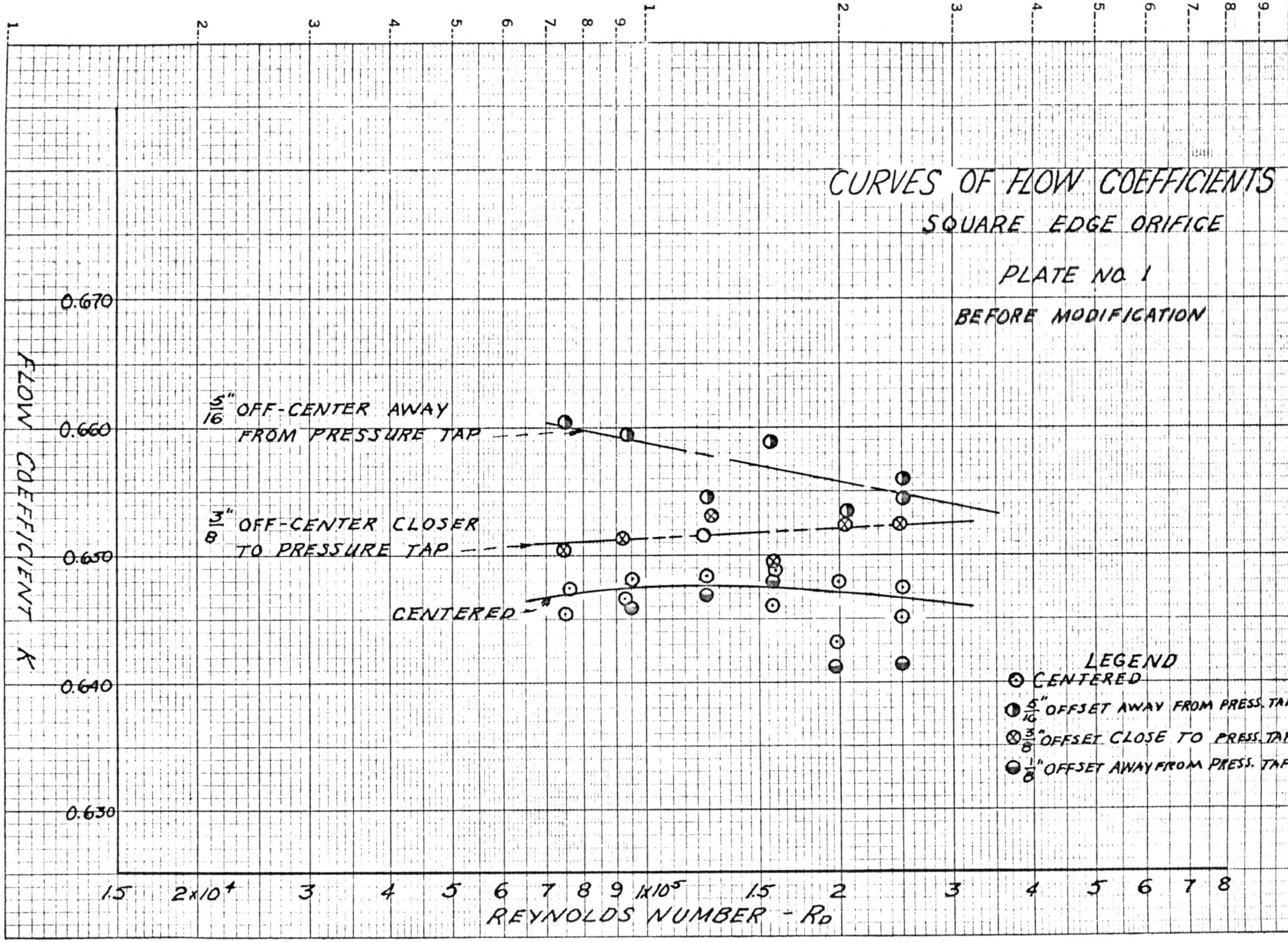
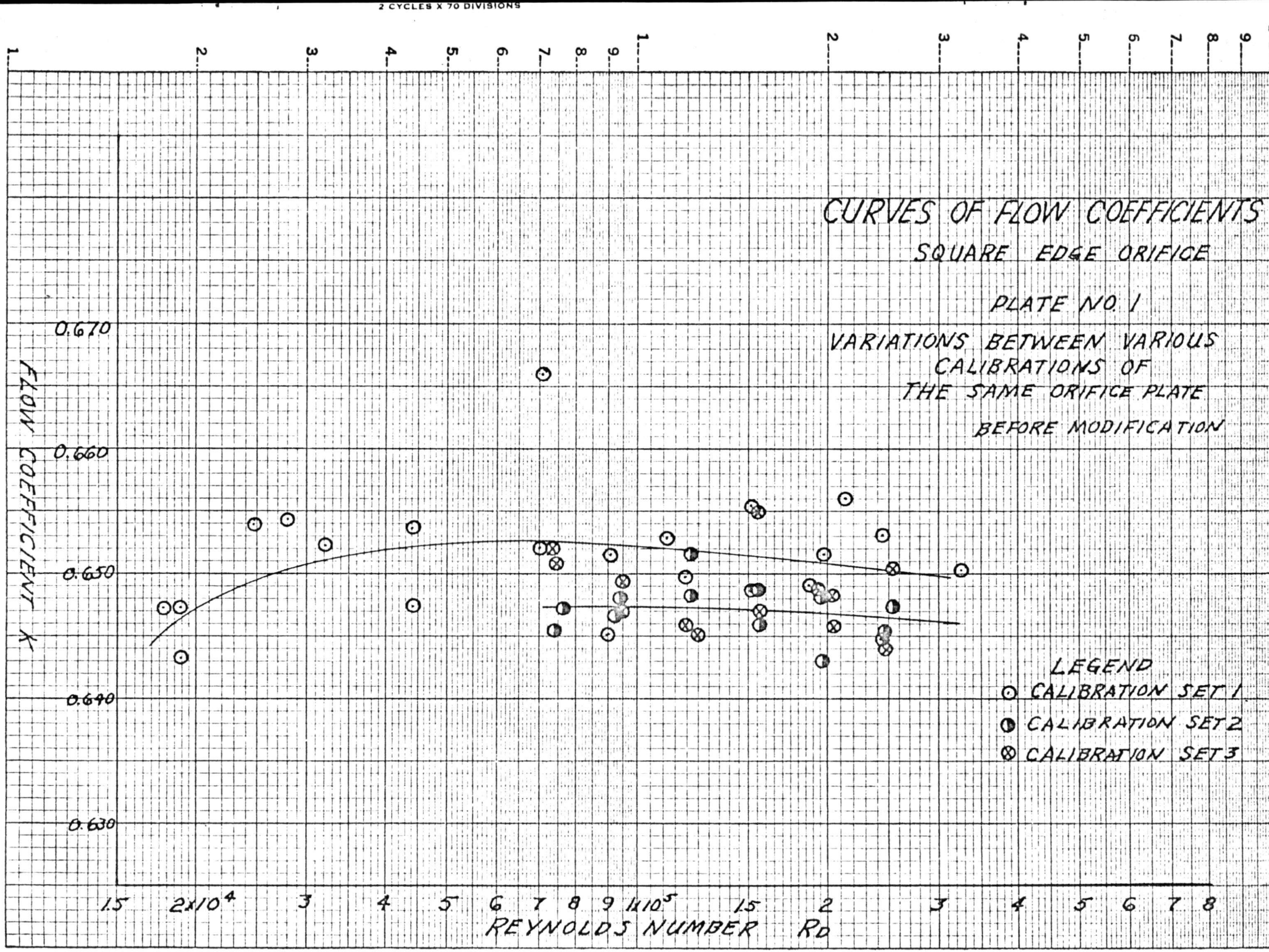

CURVES OF FLOW COEFFICIENTS
SQUARE EDGE ORIFICE
PLATE NO. 1
BEFORE MODIFICATION
5/16" OFF-CENTER AWAY FROM PRESSURE TAP
3/8" OFF-CENTER CLOSER TO PRESSURE TAP
CENTERED
LEGEND
CENTERED
5/16" OFFSET AWAY FROM PRESS. TAP
3/8" OFFSET CLOSE TO PRESS. TAP
1/8" OFFSET AWAY FROM PRESS. TAP
FLOW COEFFICIENT K
0.670
0.660
0.650
0.640
0.630
1.5
2×10⁴
3
4
5
6
7
8
9
1×10⁵
1.5
2
3
4
5
6
7
8
REYNOLDS NUMBER - RD

FIG 4



2 CYCLES X 70 DIVISIONS
CURVES OF FLOW COEFFICIENTS
SQUARE EDGE ORIFICE
PLATE NO. 1
VARIATIONS BETWEEN VARIOUS CALIBRATIONS OF THE SAME ORIFICE PLATE
BEFORE MODIFICATION
FLOW COEFFICIENT K
0.670
0.660
0.650
0.640
0.630
LEGEND
CALIBRATION SET 1
CALIBRATION SET 2
CALIBRATION SET 3
1.5
2x10^4
3
4
5
6
7
8
9
1x10^5
15
2
3
4
5
6
7
8
REYNOLDS NUMBER R_D

FIG 5

2 CYCLES X 70 DIVISIONS

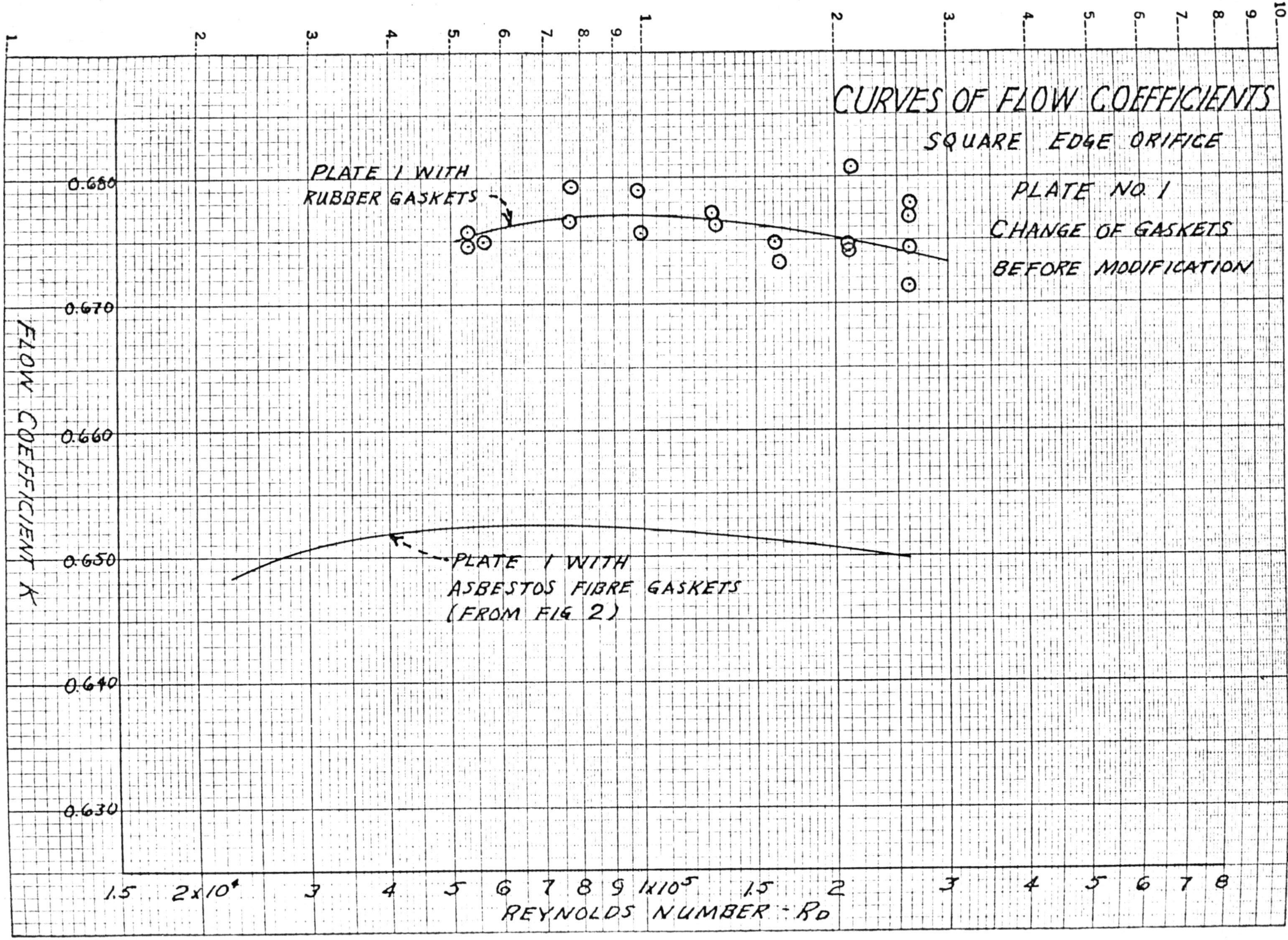


FIG 6

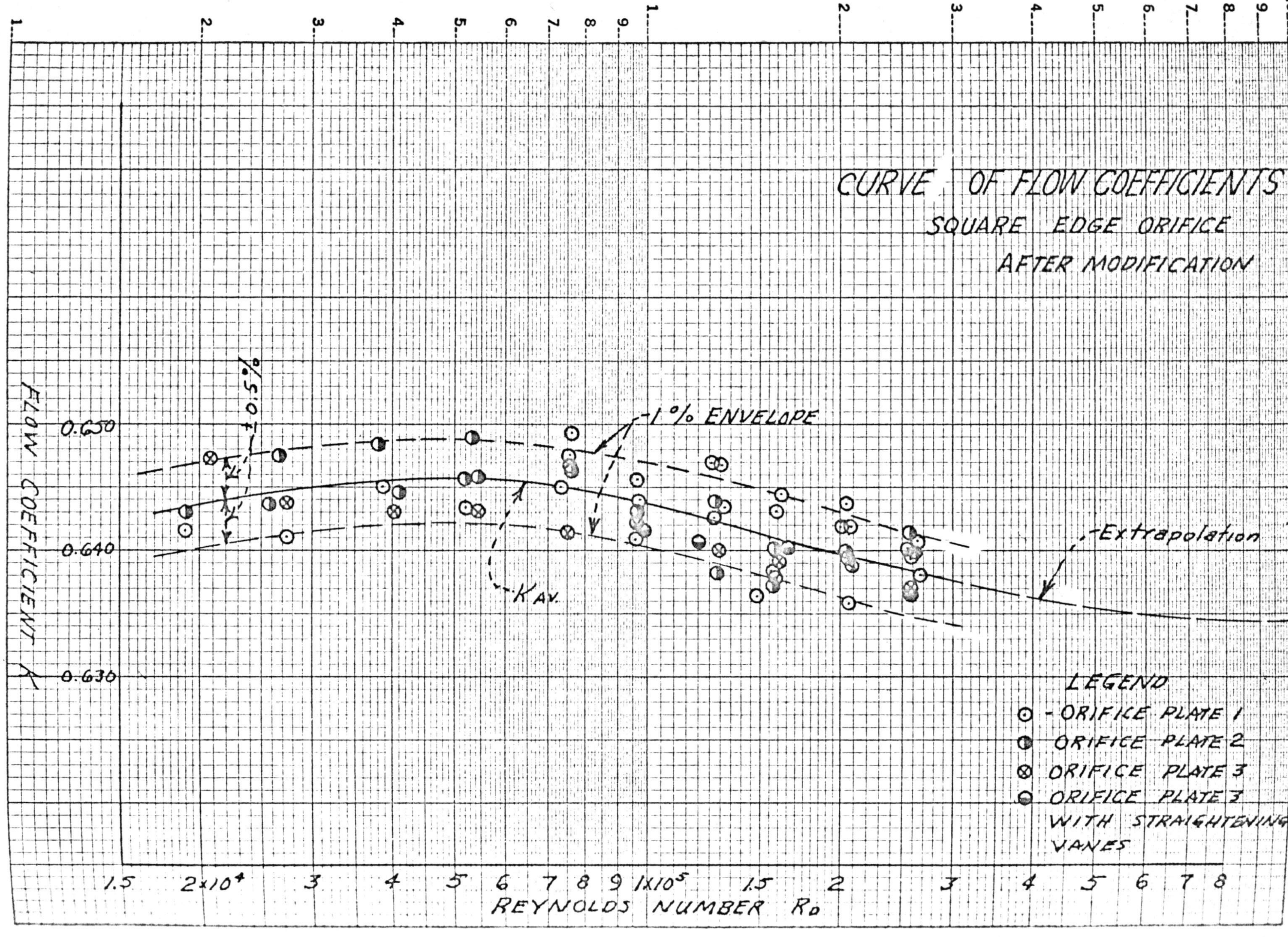

CURVE OF FLOW COEFFICIENTS
SQUARE EDGE ORIFICE
AFTER MODIFICATION
FLOW COEFFICIENT K
0.650
0.640
0.630
1% ENVELOPE
±.5% OF
Extrapolation
KAV.
LEGEND
- ORIFICE PLATE 1
ORIFICE PLATE 2
ORIFICE PLATE 3
ORIFICE PLATE 3 WITH STRAIGHTENING VANES
1.5
2×10⁴
3
4
5
6
7
8
9
1X10⁵
1.5
2
3
4
5
6
7
8
REYNOLDS NUMBER RD

FIG. 7

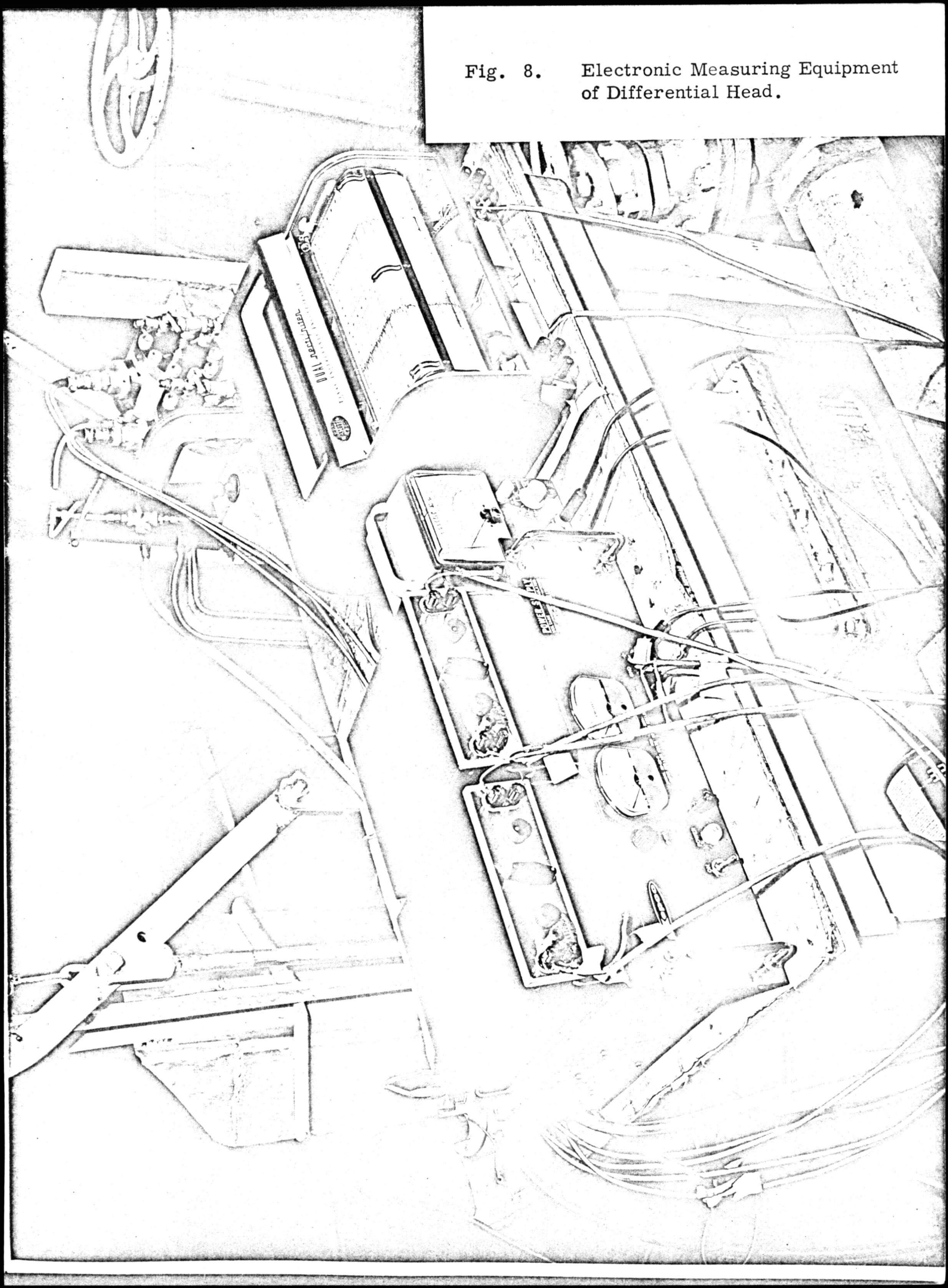


Fig. 8. Electronic Measuring Equipment of Differential Head.

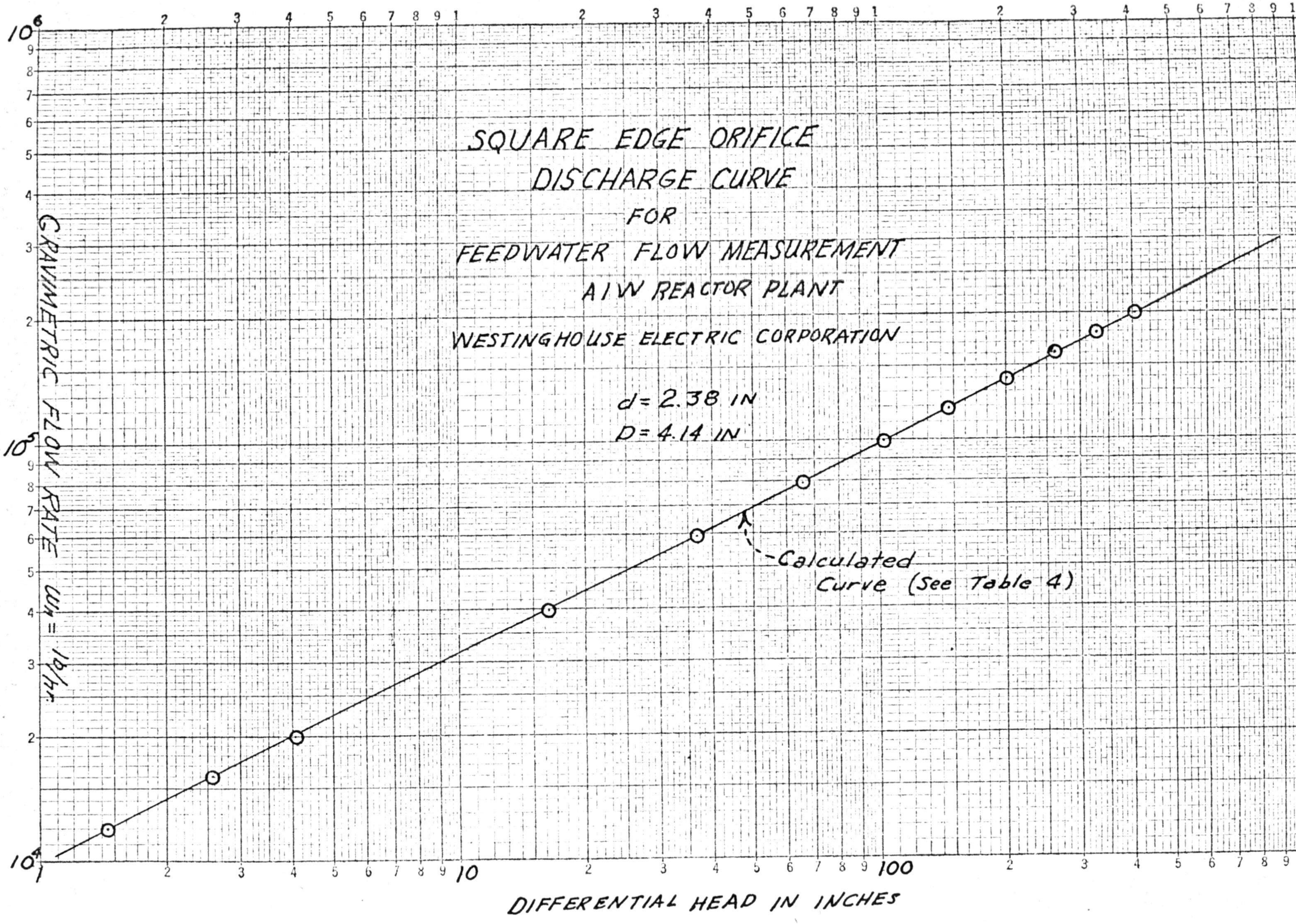

SQUARE EDGE ORIFICE
DISCHARGE CURVE
FOR
FEEDWATER FLOW MEASUREMENT
A1W REACTOR PLANT
WESTINGHOUSE ELECTRIC CORPORATION
d= 2.38 IN
D= 4.14 IN
Calculated Curve (See Table 4)
GRAVIMETRIC FLOW RATE Wh = lb/hr.
DIFFERENTIAL HEAD IN INCHES
10^6
10^5
10^4
1
10
100

FIG 9

TABLES

TABLE 2

CALIBRATION DATA

Before Modification

PLATE 1 - No Bypass Flow at Tee Through 5" Line

Run No.	Temp °F	h_w in.	h_{w68} in.	W_m lbs/min	K	R_D
1	51.5	3.826	3.831	342.65	.654	$.247\times10^5$
1'	52.0	3.815	3.820	342.05	.6538	.249
2	52.0	12.094	12.111	609.25	.6539	.444
3	52.0	30.5	30.542	979.25	.6619	.714
4	52.0	52.2	52.272	1249.16	.6453	.911
5	53.0	87.99	88.018	1632.60	.6499	1.202
6	53.0	143.3	143.346	2079.90	.6489	1.531
7	53.0	228.8	228.873	2628.10	.6489	1.934
8	52.5	362.0	362.116	3327.30	.6531	2.440
PLATE 1 - 2Q Bypass Flow at Tee Through 5" Line						
1	53.0	378.0	378.12	3356.7	.6448	2.471×10^5
2	53.0	241.9	241.98	2713.6	.6516	1.997
3	53.0	138.6	138.64	2067.1	.6557	1.521
4	53.0	79.25	79.35	1557.4	.6530	1.146
5'	54.5	49.2	49.26	1224.4	.6516	0.917
7	54.0	11.80	11.82	596.1	.6477	0.444
8	55.0	1.88	1.88	237.6	.6474	0.179
8'	53.5	2.23	2.233	257.31	.6433	0.190
8"	54.0	2.14	2.143	253.8	.6476	0.189
9	54.0	6.20	6.208	435.3	.6525	0.324
6'	54.25	28.90	28.936	939.5	.6524	0.702
PLATE 1 - Q Bypass Flow at Tee Through 5" Line						
1	55.0	2.10	2.102	252.1	.6495	$.190\times10^5$
2	55.0	4.55	4.555	374.0	.6547	.282
4	56.0	247.6	247.679	2763.9	.6560	2.107×10^5
5	56.0	607.3	607.494	4292.6	.6506	3.273
PLATE 1 - Orifice Offset 5/16 in. Away from Downstream Pressure Tap						
1	53.0	370.4	370.441	3381.5	.6562	2.489×10^5
2	53.5	250.7	250.728	2771.0	.6537	2.051
3	53.75	139.9	139.915	2087.0	.6590	1.549
4	54.0	88.8	88.810	1652.4	.6549	1.230
5	55.25	49.2	49.258	1239.4	.6597	0.937
6	55.25	31.2	31.237	988.3	.6605	0.748

TABLE 2 (cont'd)

Run No.	Temp °F	h_w in.	$h_{w}68$ in.	W_m lbs/min	K	R_D
PLATE 1 - Orifice Offset 3/8 in. Closer to Downstream Pressure Tap						
1'	54.5	355.30	355.339	3294.70	.6529	2.483×10^5
2'	54.5	236.25	236.276	2684.90	.6525	2.023
3'	54.5	143.01	143.026	2081.10	.6500	1.568
4'	54.5	90.09	90.100	1659.84	.6532	1.251
5'	55.0	49.1	49.158	1222.73	.6515	.916
6'	55.0	32.1	32.138	987.53	.6507	.740
PLATE 1 - Centered						
1	55.0	380.5	380.542	3380.9	.6474	2.548
2	55.0	231.84	231.866	2621.7	.6431	1.975
3	55.0	141.75	141.766	2068.8	.6490	1.559
4	55.0	86.31	86.319	1621.0	.6517	1.221
5	56.0	50.45	50.507	1233.5	.6483	0.941
6	56.0	33.0	33.037	996.5	.6476	0.760
PLATE 1 - Centered Repeat						
1'	55.5	361.62	361.660	3287.2	.6457	2.496
2'	55.5	228.06	228.085	2605.1	.6481	1.978
3'	56.0	140.49	140.505	2050.7	.6462	1.564
4'	56.0	87.57	87.580	1624.3	.6484	1.239
5'	56.5	48.75	48.803	1209.8	.6469	0.924
6'	56.5	31.9	31.934	976.7	.6457	0.746
PLATE 1 - Orifice Offset 1/8 in. from Center Away from Downstream Pressure Tap						
1	55.5	362.88	362.920	3273.2	.6418	2.486×10^5
2	55.5	230.58	230.605	2627.2	.6462	1.995
3	56.0	137.97	137.985	2038.7	.6483	1.555
4	56.25	86.31	86.319	1609.6	.6472	1.228
5	57.0	50.15	50.202	1225.4	.6461	0.944
PLATE 1 - Rubber Gaskets						
1	56.0	356.58	356.619	3427.6	.6780	2.614×10^5
2	56.0	235.62	235.646	2798.2	.6809	2.134
3	56.0	362.88	362.920	3423.8	.6713	2.611
4	56.0	362.88	362.920	3452.5	.6770	2.633
5	56.0	232.60	232.626	2754.7	.6747	2.108
6	56.25	139.86	139.875	2137.6	.6752	1.631
7	56.0	86.31	86.319	1684.6	.6773	1.285
8	56.5	51.65	51.706	1301.1	.6759	0.994
9	56.5	30.05	30.082	997.6	.6794	0.762
10	57.0	14.65	14.665	691.8	.6749	0.533
11	57.0	14.65	14.665	692.8	.6759	0.534
12	57.0	14.65	14.665	696.2	.6792	0.536

TABLE 2 (cont'd)

PLATE 1 - Rubber Gaskets Repeat

Run No.	Temp °F	h_w in.	h_{w68} in.	w_m lbs/min	K	R_D
1	56.5	359.1	359.140	3422.1	.6746	2.614×10^5
2	56.5	236.88	236.906	2777.9	.6742	2.122
3	56.5	141.75	141.766	2147.1	.6736	1.640
4	57.0	87.57	87.580	1694.1	.6763	1.305
5	57.0	49.20	49.251	1275.7	.6791	0.983
6	57.0	30.90	30.932	1007.4	.6766	0.776
7	57.0	16.75	16.767	740.1	.6752	0.570
PLATE 1 - Asbestos Fibre Gaskets Repeat						
1	56.5	361.62	361.660	3304.4	.6491	2.525×10^5
2	57.0	141.75	141.766	2042.4	.6408	1.573
1	57.0	361.62	361.660	3278.9	.6441	2.525
2	57.0	360.36	360.400	3288.6	.6471	2.533
1	57.0	359.10	359.140	3262.4	.6431	2.513
1	57.0	370.44	370.481	3301.7	.6408	2.543
1	57.0	360.36	360.400	3306.7	.6507	2.547×10^5
2	57.0	229.32	229.345	2628.7	.6484	2.025
3	57.0	139.61	139.625	2046.3	.6470	1.576
4	57.0	88.20	88.210	1622.3	.6453	1.249
5	57.0	50.5	50.553	1236.8	.6498	0.953
6	57.0	30.95	30.982	970.1	.6511	0.747
1	56.5	360.99	361.030	3275.5	.6440	2.502×10^5
2	56.75	235.62	235.646	2655.5	.6462	2.037
3	56.5	135.45	135.465	2041.1	.6551	1.559
4	56.75	88.83	88.840	1631.0	.6464	1.251
5	56.5	51.10	51.155	1238.7	.6470	0.946
6	56.5	30.70	30.733	467.7	.6521	0.739
PLATE 2 - No Bypass **F**low at Tee Through 5" Line						
1	56.0	367.3	367.418	3276.0	.6384	2.498×10^5
2	56.0	231.8	231.874	2683.0	.6582	2.046
3'	56.0	141.1	141.145	2012.5	.6328	1.535
4	56.0	88.2	88.228	1613.8	.6418	1.231
5	56.5	49.7	49.754	1220.1	.6461	0.932
6	56.5	29.1	29.131	933.2	.6422	0.713
7	55.5	13.2	13.215	627.7	.6451	0.477
8	54.0	6.20	6.208	434.8	.6517	0.316
9	54.0	4.24	4.245	356.7	.6468	0.266

TABLE 2 (cont'd)

PLATE 3 - No Bypass Flow at Tee Through 5" Line

Run No.	Temp °F	h_w in.	h_{w68} in.	w_m lbs/min	K	R_D
1	54.0	1.84	1.842	241.2	.6639	$.180 \times 10^5$
2	54.0	3.74	3.745	339.2	.6548	.253
3	54.0	8.32	8.330	504.8	.6534	.376
4	54.0	15.0	15.019	675.0	.6507	.503
5	54.0	30.1	30.138	948.4	.6453	.706
6	55.0	48.8	48.858	1211.1	.6472	.913
7	55.0	85.7	85.727	1607.2	.6484	1.211
8	55.0	140.5	140.545	2045.5	.6445	1.541
9	55.0	234.4	234.475	2668.2	.6509	2.010
10	55.0	357.8	357.914	3269.5	.6455	2.457
11	55.0	573.3	573.483	4172.0	.6508	3.144

TABLE 3

CALIBRATION DATA

After Modification

PLATE 1 - Original

Run No.	Temp °F	h_w in.	h_{w68} in.	w_m lbs/min	K	R_D
1	56.5	366.66	367.06	3283.51	.6402	2.509×10^5
2	56.5	234.36	234.61	2632.18	.6420	2.011
3	56.5	131.67	131.81	1956.83	.6367	1.495
4	57.0	88.20	88.29	1627.68	.6471	1.254
5	57.5	50.80	50.85	1223.76	.6411	0.954
6	57.5	29.8	29.83	943.24	.6451	0.735
7	58.0	375.48	375.84	3326.01	.6409	2.636
8	57.0	244.44	244.69	2688.21	.6420	2.070
9	57.0	143.26	143.41	2061.84	.6432	1.588
PLATE 1 - Repeat						
1	57.0	364.77	365.15	3270.38	.6393	2.519×10^5
2	57.0	234.99	235.23	2635.92	.6420	2.030
3	57.0	143.64	143.79	2050.91	.6389	1.580
4	57.5	89.71	89.80	1630.38	.6428	1.271
5	57.5	50.30	50.35	1226.10	.6455	0.956
6	58.0	30.55	30.58	957.54	.6469	0.759
PLATE 1 - Repeat						
1	51.5	360.99	361.35	3266.09	.6419	2.546×10^5
2	57.5	231.84	232.07	2625.57	.6439	2.047
3	57.5	142.38	142.52	2039.24	.6381	1.590
4	58.0	91.35	91.44	1655.92	.6470	1.312
5	58.0	51.50	51.55	1237.89	.6441	0.981
6	58.5	30.10	30.13	954.08	.6494	0.761
PLATE 1 - Repeat						
1	58.0	355.32	355.66	3221.45	.6382	2.553×10^5
2	58.0	234.36	234.59	2607.63	.6360	2.067
3	58.0	141.12	141.26	2050.18	.6444	1.625
4	58.0	92.61	92.70	1658.34	.6435	1.314
5	58.0	49.00	49.05	1210.88	.6459	0.959
6	58.0	30.00	30.03	950.04	.6477	0.753
7	58.5	14.764	14.777	662.07	.6435	0.528
8	58.5	7.976	7.983	487.92	.6453	0.389
9	58.5	4.001	4.005	343.30	.6410	0.274
10	59.0	1.947	1.949	239.72	.6415	0.192

TABLE 3 (cont'd)

PLATE 2 - Original

Run No.	Temp °F	h_w in.	h_{w68} in.	w_m lbs/min	K	R_D
1	58.0	357.84	357.96	3240.62	.6399	2.568×10^5
2	58.0	227.43	227.51	2584.36	.6401	2.048
3	58.0	133.56	133.61	1981.22	.6403	1.570
4	58.0	91.98	92.01	1638.74	.6382	1.299
5	58.0	50.50	50.55	1222.89	.6426	0.969
6	58.0	30.00	30.03	949.04	.6470	0.752
7	58.5	14.45	14.46	657.26	.6457	0.524
8	58.5	9.699	7.676	481.14	.6487	0.384
9	58.5	3.722	3.725	334.63	.6477	0.384
10	58.5	1.928	1.930	241.32	.6491	0.192
PLATE 2 - Repeat						
1	58.0	15.089	15.104	675.24	.6492	0.535×10^5
2	58.0	9.169	9.178	522.86	.6447	0.414
3	58.0	3.762	3.766	334.61	.6440	0.265
4	58.0	1.955	1.957	239.80	.6431	0.190
1'	58.0	15.830	15.845	688.54	.6462	0.546
5	58.0	31.10	31.130	965.51	.6465	0.765
6	58.0	50.70	50.749	1226.55	.6432	0.972
9	58.0	231.21	231.284	2603.37	.6395	2.063
10	58.0	356.58	356.694	3243.13	.6415	2.570
7'	57.5	91.35	91.379	1647.89	.6440	1.285
8'	57.5	138.60	138.644	2008.39	.6372	1.566
PLATE 3 - Original						
1	59.5	15.072	15.085	668.77	.6433	0.544×10^5
2	59.5	8.210	8.217	493.61	.6432	0.401
3	60.0	3.898	3.901	340.25	.6437	0.278
4	60.5	2.123	2.125	252.71	.6476	0.209
5	58.5	355.70	356.031	3217.79	.6371	2.566
6	58.5	233.10	233.317	2613.09	.6391	2.084
7	58.5	139.23	139.359	2020.06	.6393	1.611
8	58.5	88.83	88.913	1615.82	.6402	1.289
9	58.5	49.40	49.446	1209.40	.6425	0.964
10	58.5	30.30	30.328	945.66	.6415	0.754
PLATE 3 - With Straightening Vanes						
1	58.0	360.36	361.48	3240.46	.6367	2.368×10^5
3	58.0	144.90	144.946	2064.77	.6407	1.636
4	58.5	77.49	77.515	1510.17	.6408	1.204
5	59.0	51.66	51.677	1235.12	.6419	0.990

TABLE 4

CALCULATIONS FOR DISCHARGE CURVE

Square Edge Orifice

Feedwater Flow Measurement @ 305°F

w_h lbs/hr	V ft/sec	R_D	K	$\frac{w_{hs}}{K}$	$(h_w)^{1/2}$	h_w in.
200,000	10.366	1.63×10^6	.6346	315,160	20.37	414.9
180,000	9.330	1.47×10^6	.6346	283,643	18.33	336.0
160,000	8.293	1.30×10^6	.6346	252,127	16.30	265.7
140,000	7.256	1.14×10^6	.6346	220,612	14.26	203.3
120,000	6,220	9.76×10^5	.6346	189,095	12.22	149.3
100,000	5.183	8.14×10^5	.6348	157,530	10.18	103.6
80,000	4.146	6.51×10^5	.635	125,984	8.143	66.3
60,000	3.110	4.88×10^5	.636	94,340	6.097	37.17
40,000	2.073	3.25×10^5	.6375	62,745	4.055	16.44
20,000	1.036	1.63×10^5	.6412	31,192	2.016	4.06
16,000	0.829	1.30×10^5	.6425	24,903	1.610	2.59
12,000	0.622	9.76×10^4	.644	18,634	1.204	1.45
8,000	0.415	6.51×10^4	.6453	12,397	0.801	0.64
4,000	0.207	3.25×10^4	.645	6,202	0.401	0.16
0						