THE EFFECT OF INLET PORT ELBOWS ON INTAKE OF THE INTERNAL COMBUSTION ENGINE

by

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PURPOSE

Engine output is determined to a large extent by the amount of charge it is possible to take into the cyclinder through the intake port and valve. The intake port determines the amount of charge which can be taken into the cyclinder per unit time. In other words, the output of the engine depends upon the efficiency of the intake port elbow and its effect upon the intake flow.

In this thesis, the authors tried to find out what effect port elbow shape had upon the flow through the intake valve. First of all it was proposed that the authors, by experiment, find the best elbow for a given radius of curvature of intake port. Second, when that elbow was found, experiments were to be run for determining the effect on the flow of varying the radius of curvature of the elbow.

PERTINENT REFERENCES

Doroff and Ryder:-

In this thesis a study was made of an actual Wright Aeronautical Corporation cylinder head and barrel. The flow thru the intake and exhaust valves was restricted by the use of plasticene. Doroff and Ryder wanted to determine whether or not the diameter of a radial engine could be effectively reduced by reducing the size of intake and exhaust valves. Their results showed:

1. Both inlet and exhause port may be reduced in size considerably without causing an appreciable decrease in flow.

2. At low valve lifts when the port is restricted the air flow shows a tendency to increase.

Le Blanc:-

Using an Indian motor cycle head, flow thru the valve was varied both by putting various fillets on the valve and also on the valve seat. Le Blanc was concerned chiefly with the steamlining of the immediate vicinity of the valve and seat.

Hunter:-

By the use of fillets, Hunter varied both upsteam and downstream shapes of both the valve itself and its port. He used a straight intake port. He found that:

1. Small fillets on upsteam side of valve which remove shaft discontinuities at valve opening are desirable.

2. These fillets should be kept small.

3. Small amount of streamlining on port removing discontinuities of flow are very important for good flow at high lifts.

R. J. Durley:-

In the Transactions of the A. S. M. E. 1905-1906, Mr. Durley tells of his experiments with square edged flat plate orifices. He gives several useful curves and formulae for calculating orifice coefficients.

A.S.M.E. Research Committee on Fluid Meters:-

A very thorough study of the theory and application of fluid meters. From this study was taken the fundamental equation that we used in measuring the flow through our port elbows.

APPARATUS AND PROCEDURE

The apparatus for this series of tests was arranged as shown in the accompanying photostat. A detail drawing of the intake valve and seat, both with streamlining is also shown.

The chamber which represents the cylinder and which contains the valve is the same one that Hunter used in his thesis*. It is made of aluminum alloy and machined to correct dimensions. Attached to this chamber is the micrometer screw and scale for setting the valve lift.

Built by the authors, the orifice box was formerly a fifty gallon oil drum. Holes for measuring pressure differences were cut as shown and an approach orifice was put at the exit end of the box. The entrance or metering orifice is clamped to the front of the box by a wooden frame secured by four bolts. The orifice may be changed at will.

One manometer measured the pressured across the metering orifice, the other manometer measured the pressure difference across the valve.

Controlling the pressure difference across the poppet valve were two cut-off valves, one opening to the suction pump, the other opening to the atmosphere. The valve opening to the atmosphere was used for fine adjust-

*See Bibliography

ments of the pressure across the poppet valve.

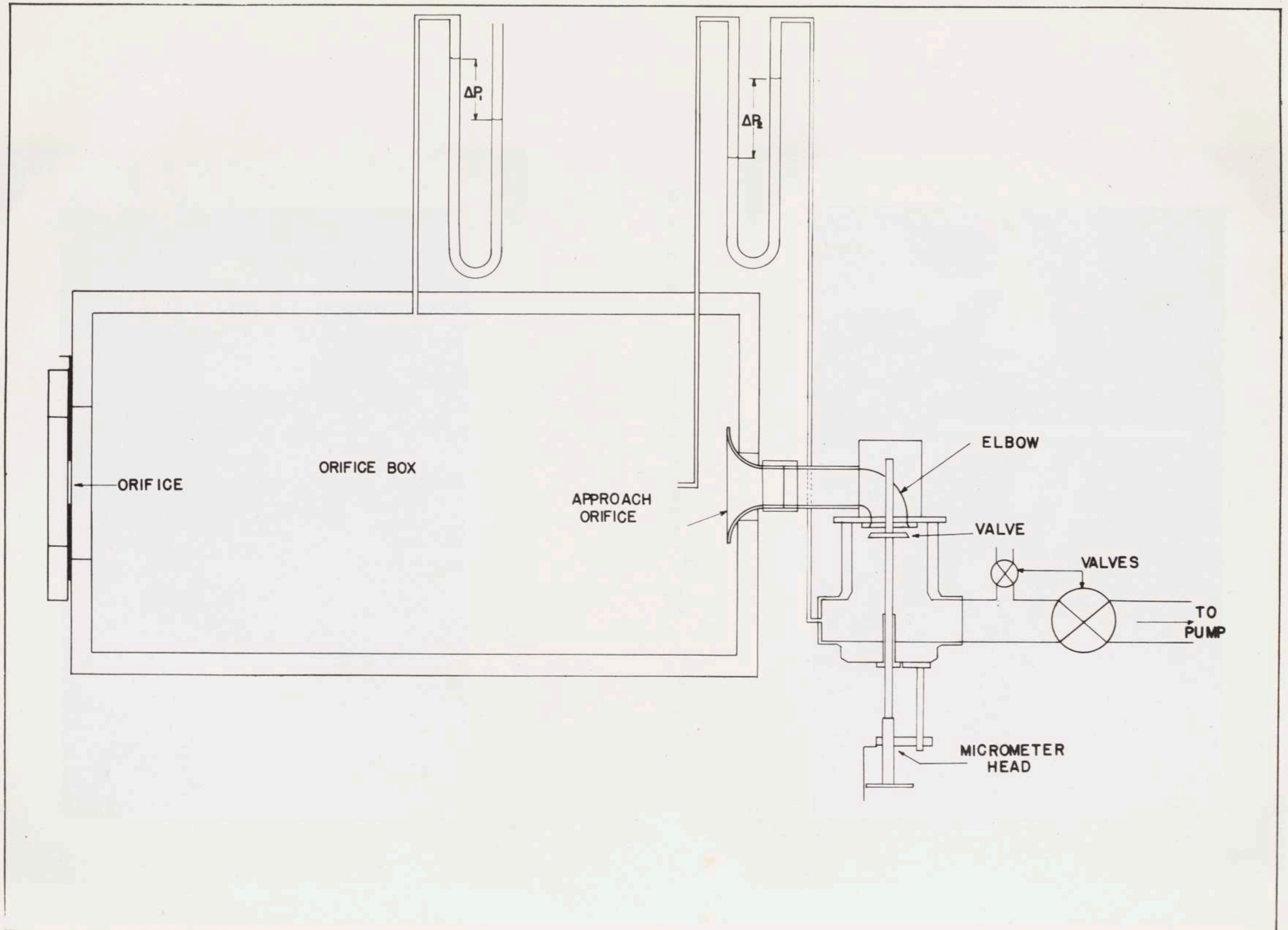
As is shown in the diagram, the elbow to be tested was placed in position and clamped down. Port elbows were made of plaster of paris. The authors found that this was a very workable and easily cut material, ideal for experimental purposes.

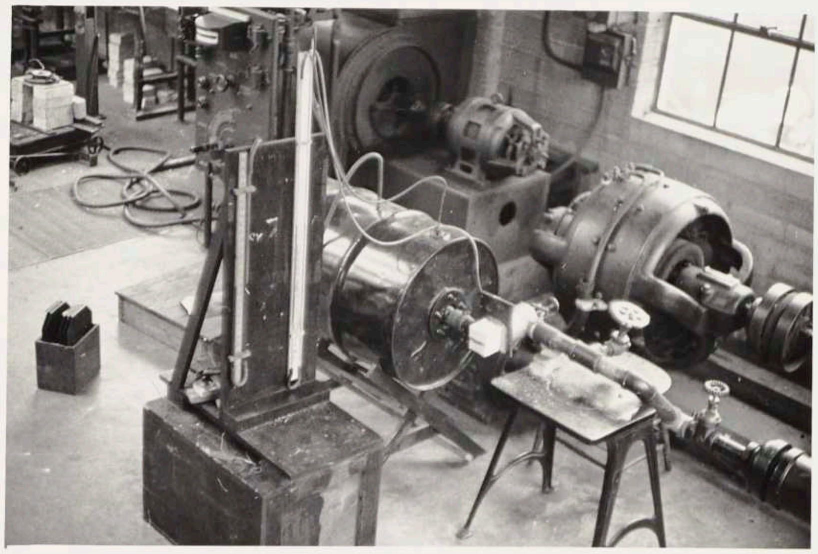
First, the elbow to be tested was modeled in plasticene. (See accompanying photographs.) The plasticene elbow was made in halves, each half being laid on a flat surface, varnished, then covered with plaster of paris. When the plaster hardened, the plasticene was removed, and the two halves were then clamped together forming the elbow.

In making test runs, the authors first tried a perfectly straight intake and took manometer readings with constant pressure differences of five, ten, and fifteen inches of alcohol across the intake port. Readings were taken at lift readings such that the ratio of valve lift to valve diameter came out, .1, .12, .14, etc.

Because the difference in orifice coefficients due to increased pressure across the valve is small, the authors used the run at 10 inches of alcohol as a basis of comparison, and made all experimental runs at this pressure difference. They went ahead and built several elbows of different shapes and radii of curvature. They then took the elbow giving best results and tried to improve it. After improving it to the best of their ability, they then built similar elbows with various radii of curvature, and tested them to determine precisely the difference in flow caused by the reduction in radius of curvature.

In determining the best elbow, both valve port and valve were filleted and streamlining was used behind the valve stem on the down stream side. The results were plotted with orifice coefficients as ordinates and the ratio of valve lift to valve diameter as abcissae. In the final runs for a basis of comparison for determining the best elbow, the curve obtained by Wood and Hunter for the same diameter straight intake is plotted on the same graph as the curve for the elbow in question.


ΔP1
ΔP2
ORIFICE
ORIFICE BOX
APPROACH
ORIFICE
ELBOW
VALVE
VALVES
TO
PUMP
MICROMETER
HEAD



General Arrangement of Apparatus

Elbow

Modeled in plasticene, Cast in plaster of Paris

CALCULATIONS

From the report of the Fluid Meters Committee of the A.S.M.E.* we get the basic relation for flow through orifices (equation 175, page 128)

$$W = A\,(n\,K\,Y)\sqrt{2d_1\,(\Delta P_1)} \qquad (1)$$

where

- W = weight of flow per second
- A = area of the orifice
- n = A numerical constant that takes account of the units used.
- K = Flow coefficient
- Y = Expansibility effect
- d = Density of fluid
- ΔP = Pressure drop across orifice

By the nature of the apparatus

$$W_{orifice} = W_{valve} \qquad (2)$$

Hence we may write

$$\frac{W_{orifice}}{W_{valve}} = \frac{A_1 n_1 K_1 Y_1 \sqrt{2d_1 \Delta P_1}}{A_2 n_2 K_2 Y_2 \sqrt{2d_2 \Delta P_2}} = 1 \qquad (3)$$

Solving for K_2 and cancelling n_1 and n_2 because we are using consistent units

$$K_2 = \frac{A_1 K_1}{A_2}\;\frac{Y_1}{Y_2}\;\sqrt{\frac{d_1}{d_2}}\;\sqrt{\frac{\Delta P_1}{\Delta P_2}} \qquad (4)$$

On making our first three runs we found that changing ΔP_2

* See Bibliography #5

changed our results only slightly, hence in all subsequent runs we used a ΔP_2 of ten inches of alcohol. Because we had no way of calculating the compressibility effect (Y_2) through the valve, and, since the pressure drop across the valve was constant, we assumed that the compressibility effect through the valve was constant and very nearly unity.

$$Y = \text{constant} = 1 \text{ (very nearly)} \tag{5}$$

Let

$$N = \frac{A_1 K_1}{A_2} \tag{6}$$

Where

A_1 = area of orifice

K_1 = orifice coefficient

A_2 = area of valve port

From the report by R. J. Durley* and the thesis by George Wood*, we found the following values of K_1, the coefficient of a square edged flat plate orifice. These coefficients do vary slightly with differences in pressure drop across the orifice, but it was felt to be beyond the accuracy of the experiments to use other than the average value.

$A_2 = \pi \frac{1.75^2}{4}$ in all cases.

Orifice	K	N
$\frac{1}{2}''$	0.610	0.0498
$1''$	0.605	0.1976
$1\frac{1}{2}''$	0.605	0.4445
$2''$	0.601	0.786
$2\frac{1}{2}''$	0.600	1.224

* See Bibliography #4

Assuming adiabatic flow through the orifice

$$\frac{P_1}{P_2} = \frac{d_1}{d_2} \quad \text{simple gas laws} \qquad (7)$$

Let

$$Y_1\sqrt{\frac{d_1}{d_2}} = Y_1\sqrt{\frac{P_1}{P_2}} = R \qquad (8)$$

From Fig. 72 Fluid Meters Committee Report *

$$Y = 1-(0.41 + 0.035\ B^4)\ \frac{X}{K_G} \qquad (9)$$

where $B = \frac{\text{Diameter of orifice}}{\text{Diameter of orifice box}}$

$$X = \frac{\Delta P_1}{P_1}$$

$$K_G = \text{Gas constant} = \frac{C_p}{C_v} = 1.4$$

For our purpose B=0 because our apparatus is arranged so that the manometer connection on the upstream side of the valve is put in as an impact tube and hence reads total pressure instead of static pressure. By use of this stratagem we may assume that the diameter of the orifice box equals infinity rather than thirty inches as is the actual case and B is reduced from less than one to zero.

$\frac{\Delta P_1}{P_1}$	Y	R
0	1.0000	1.0000
.01	↑	1.0006
.02	↑	1.0013
.03	↑	
.04	↑	1.0028

* See Bibliography #5

P_1	Y	R
.05	Straight Line Variation	1.0036
.06	↓	1.0044
.07		
.08		1.0061
.10	.9707	1.0088

Combining and simplifying equations 4,6, and 8

$$K_2 = N\ R \sqrt{\frac{\Delta P_1}{\Delta P_2}} \qquad (10)$$

In carrying out our calculation we found that the inclusion of R only effected the fourth significant figure and since this is beyond the accuracy of our results all calculations after the first three runs assume R = 1.

K_2 , the valve coefficient, is the ratio of the amount of air flowing through the valve and elbow to the amount of air that would flow through an orifice of the same diameter as the valve port if a perfect gas were used.

RESULTS

1. Within experimental error, the amount of bulge (Dimension "D" in diagrams) is dependent upon the diameter of the valve stem . Roughly the diameter of the valve stem should equal 2 D. If the expansion chamber of the elbow is too large (2 D$>$stem diameter) the flow is worse than if the expansion bulge is too small. (2 D$<$stem diameter),

2. The larger the radius of curvature, "R" the better the flow characteristics of the elbow. With "R" equal diameter of the elbow, and with the optimum bulge, "D", and a stream-line fillet, the flow thru the elbow is within 10% of that through a straight inlet port at a valve lift to diameter ratio of .21 .

3. If the ratio of radius of curvature of the elbow to port diameter is reduced below .85, then each subsequent reduction of 14% reduces the flow about 8%. Any increase above 8.5 in the ratio of radius of curvature to port diameter, has no worthwhile effect in bettering flow characteristics.

SUGGESTIONS FOR FURTHER INVESTIGATIONS

1. Effect of pulsating flow on intake.

   (In our thesis, only steady flow was considered.)

2. Precise effect of valve stem diameter on flow.

3. Further study about the effects on flow of complex curvatures in port elbows.

P = Press. drop across metering orif.
D = Bulge ($\frac{1}{2}$ total bulge)
R = radius of port elbo

DESCRIPTION OF ELBOWS

Runs 1, 2,3 -

Straight intake elbow, 1 3/4 inches in diameter.
Run 1 taken with P 10" alcohol, Run 2 with P 5" alcohol, and Run 3 P 15" alcohol.

Each run, 4 through 21, taken with P = 10" alcohol.

Runs 4,5,6

See diagrams

Run 7

See diagram. In Run 7, D = 0, R = 1 3/4"
Streamline fillet behind valve stem.

Runs 8 & 9

The bulge in the elbow tested started at a point just before the valve stem.
See diagram. Run 9 like 8 except a streamline fillet was inserted behind the valve stem.

Run 10

Run 10 like 7 but with D = 3/16

Run 11

Like Run 10, but with streamline valve stem fillet.

Run 12

Like run 11, except the valve seat were streamlined as shown in diagram.

Run 13

Like run 7, but with D = 3/8"

Run 14

Like run 13, but with streamline fillet behind valve stem.

Runs 15 - 21 see diagram

Run 15

D = 1/4"; R = 1 1/2"

Run 16

D = 3/16"; R = 1 1/2"

Run 17

D = 1/8"; R = 1 1/2"

Run 18

D = 1/16"; R = 1 1/2"

Run 19 =

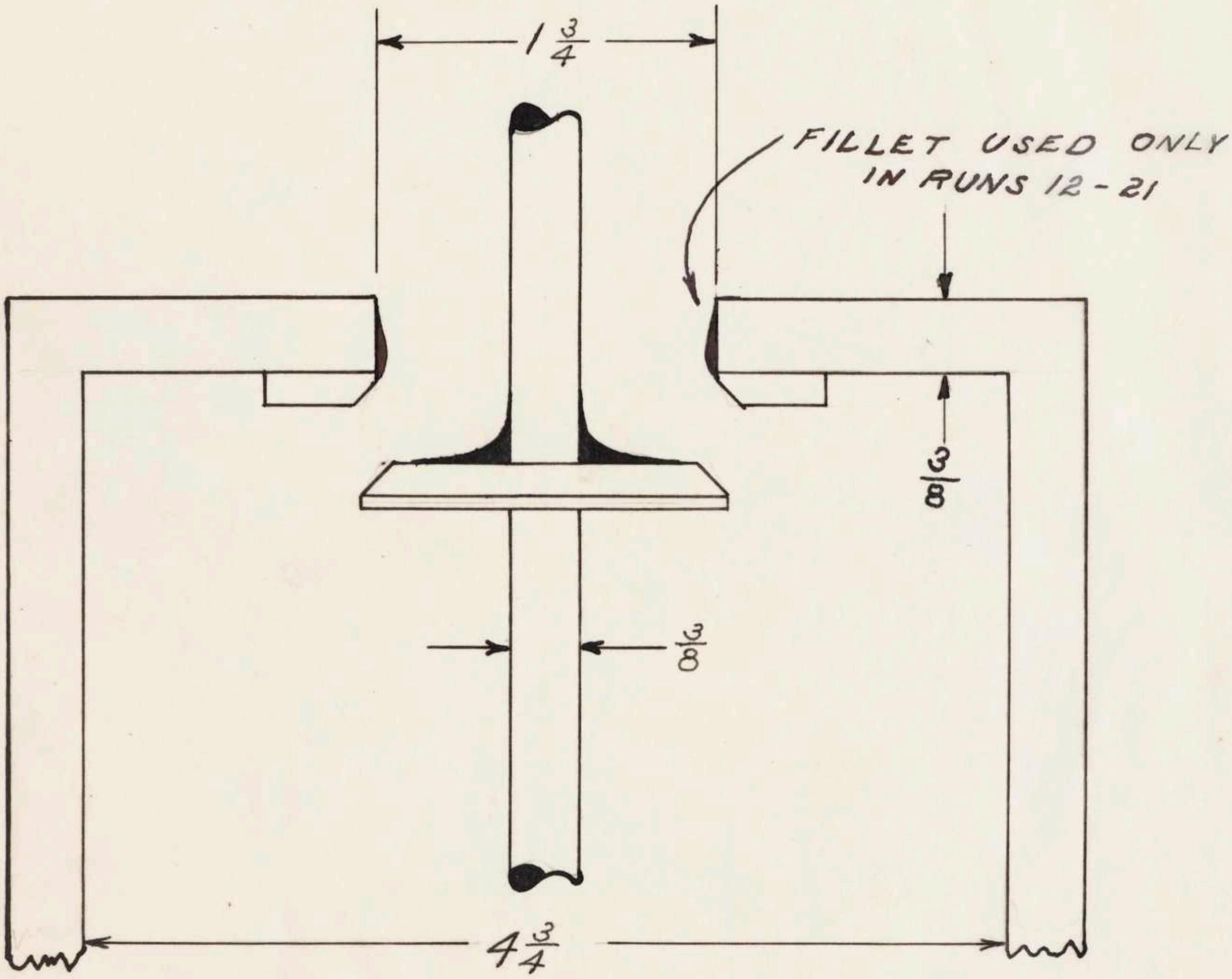
D = 5/16"; R = 1 1/2"

Run 20

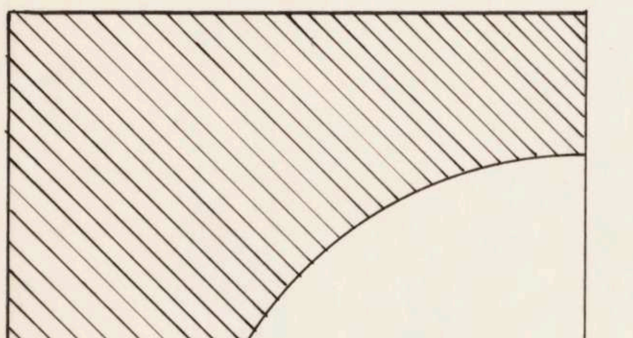
D = 3/16"; R = 1 1/4"

Run 21

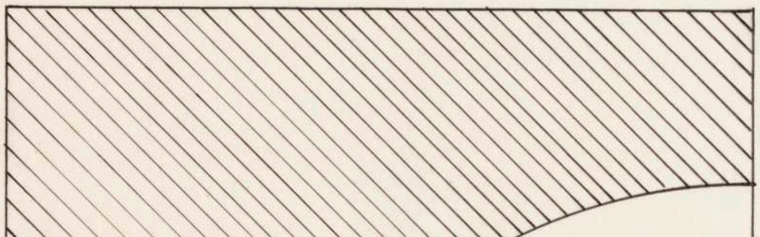
D = 3/16"; R = 1"



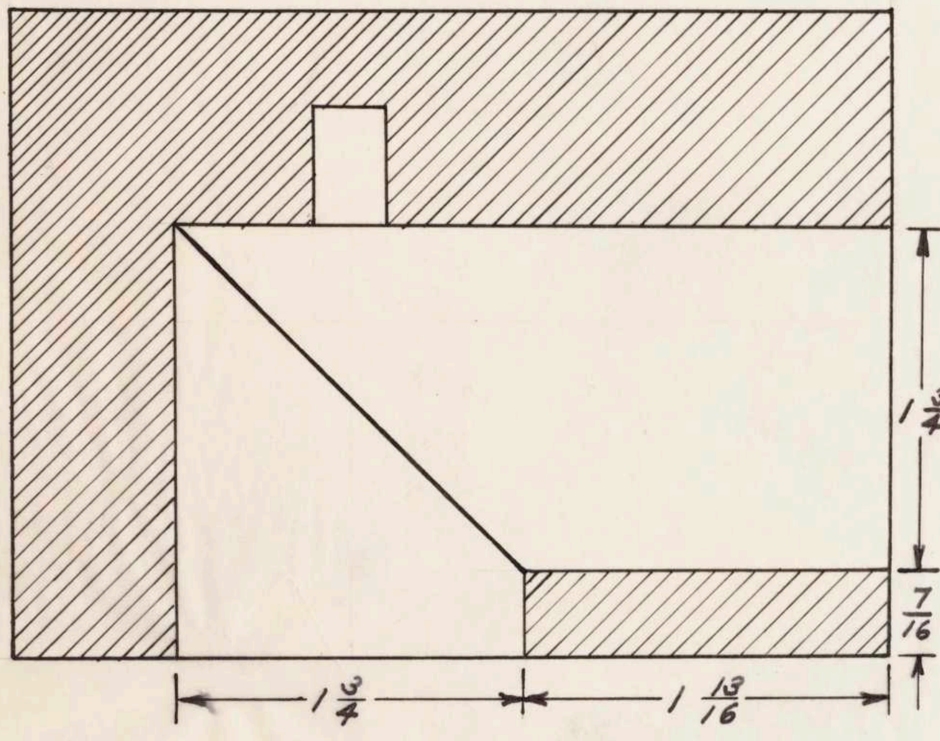
DETAIL OF VALVE
SHOWING PLASTICENE FILLETS



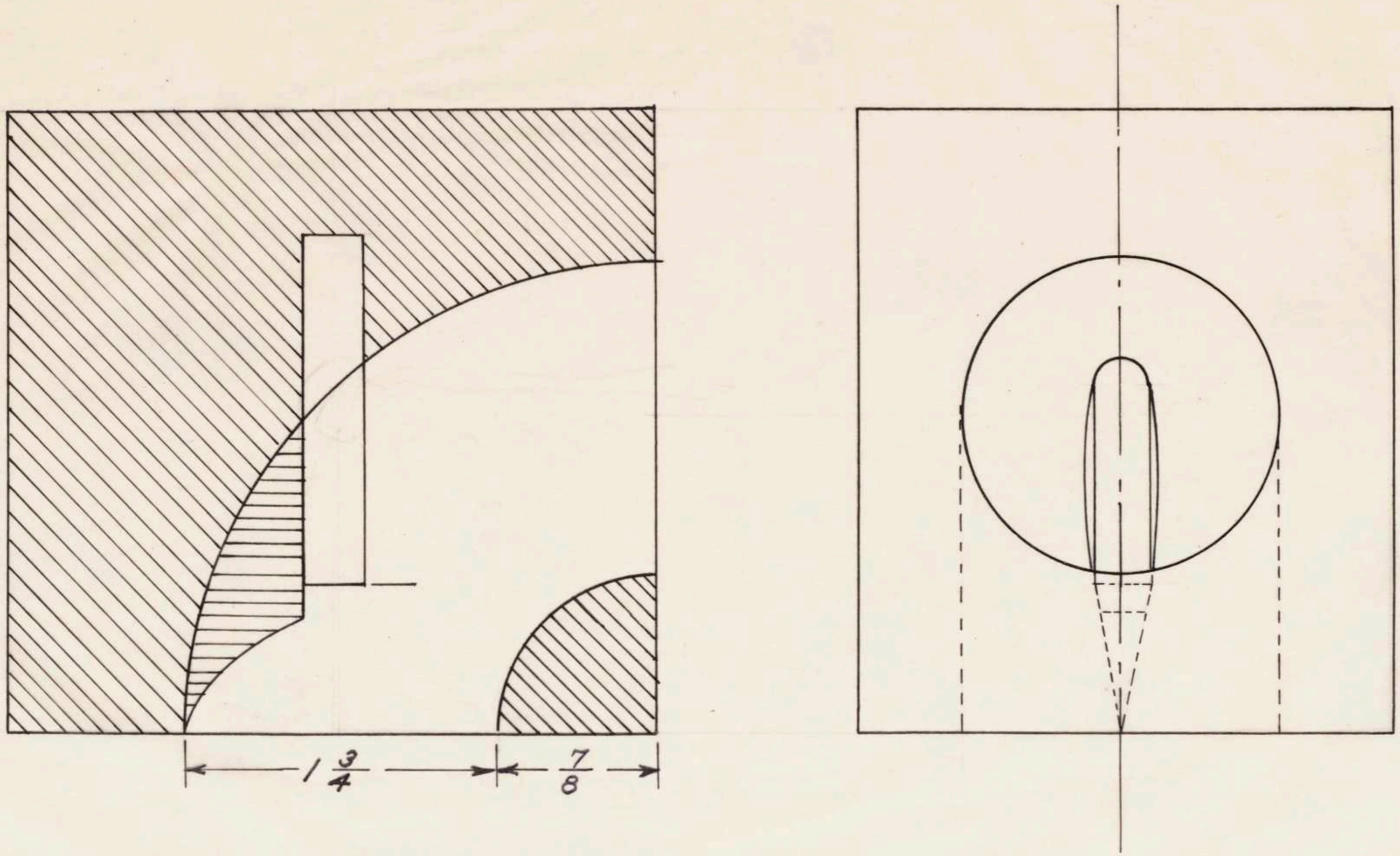
RUN 4



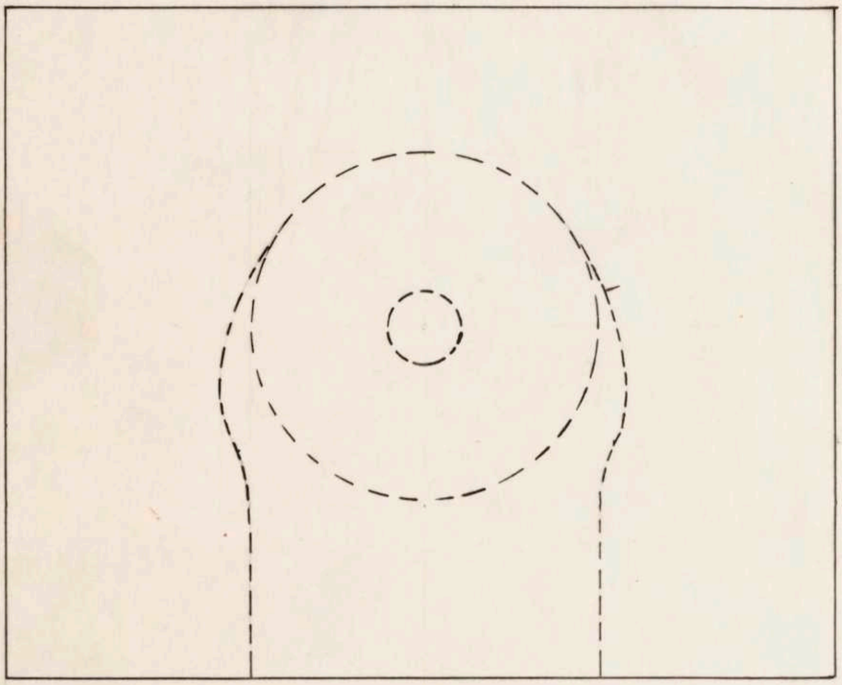
RUN 5



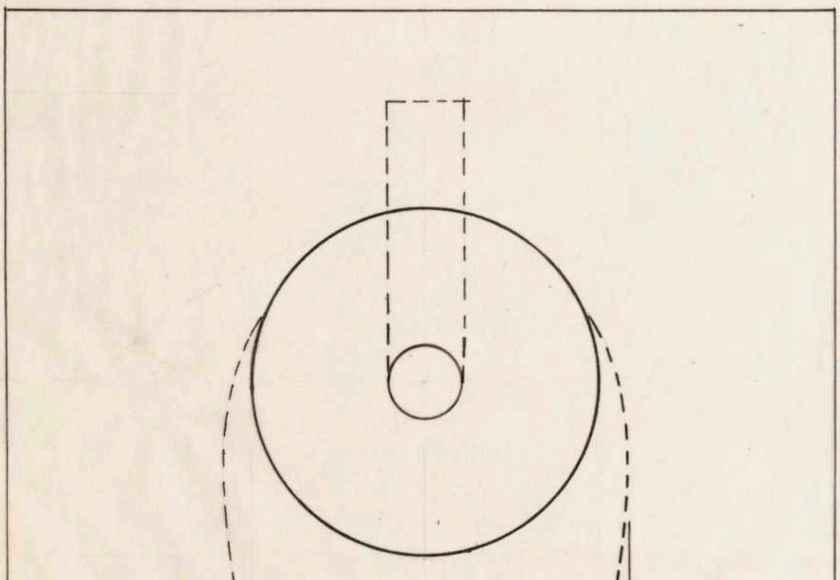
RUN 6



RUN 7

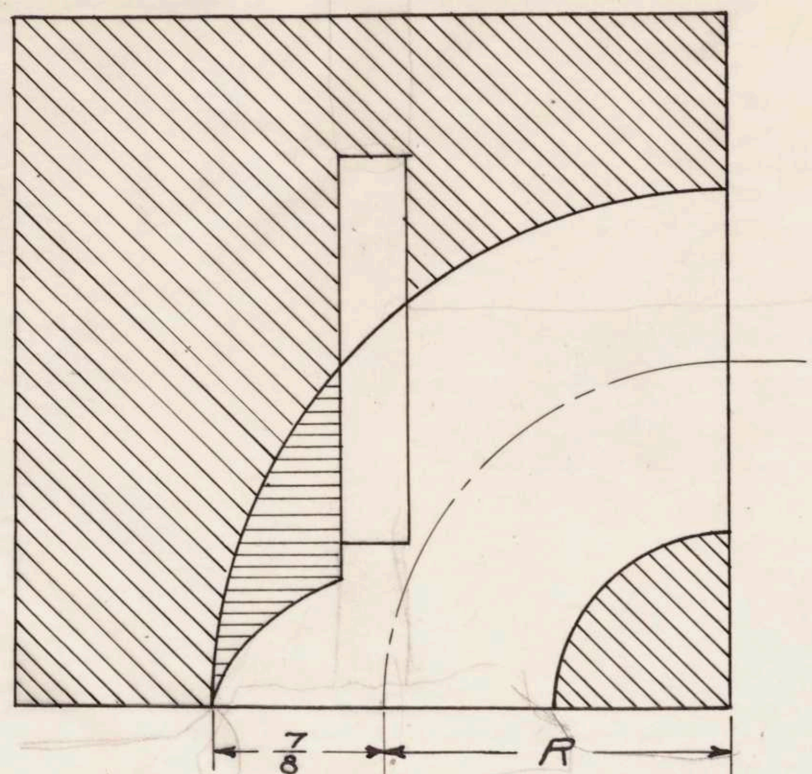


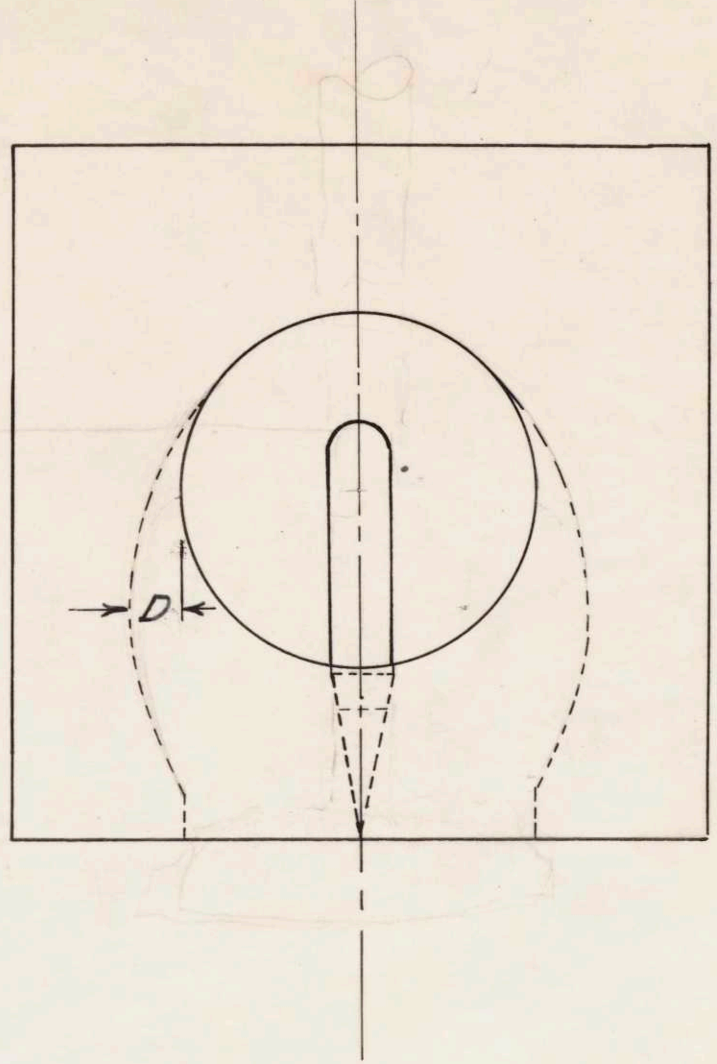
TOP VIEW



FRONT VIEW

RUN 8





RUNS 10-21

DATA RUN #1

Reading	P_1 Manometer Left	P_1 Manometer Right	P_2	Micrometer	Orifice
1	15	15		.806	½"
2	15.2	14.8		.806	"
3	22.1	5.6	10	.756	"
4				.706	1 "
5	15.0	15.0		.800	½"
6	25.2	1.9		.750	"
7	15.6	14.1		.750	1"
8	18.0	11.2	10	.700	1"
9	22.6	4.9		.650	1"
10	16.5	13.1		.650	1½"
11	17.8	11.4		.600	"
12	19.1	9.7		.550	"
13	19.9	8.7		.500	"
14	20.9	7.2	10	.450	"
15	22.3	5.6		.400	"
16	17.3	12.1		.400	2"
17	17.8	11.4		.350	"
18	18.3	10.9	10	.300	"
19	18.7	10.4		.250	"
20	19.2	9.7		.200	"
21	18.0	11.2		.700	1"
22	16.6	13.0		.725	"
23	15.7	14.2		.750	"
24	17.3	12.0		.775	½"
25	15.0	15.0		.800	"

DATA RUN #2 (Straight Inlet)

Reading	P_1 Manometer Left	P_1 Manometer Right	P_2	Micrometer	Orifice Used
0	14.9	14.9		0.800	
1	14.9	14.9		0.800	1/2
2	17.3	11.7		0.765	
3	15.0	14.6		0.765	
4	15.6	13.9		0.730	
5	16.6	12.6		0.695	1"
6	18.1	10.5		0.660	
7	20.0	8.1		0.625	
8	22.9	4.2		0.590	
9	16.4	12.7		0.590	
10	17.0	12.1		0.555	
11	17.2	11.8	5	0.515	
12	17.6	11.3		0.480	
13	18.0	10.8		0.445	
14	18.6	10.0		0.410	
15	19.1	9.3		0.375	1 1/2"
16	19.7	8.6		0.340	
17	20.2	8.0		0.305	
18	20.7	7.2		0.270	
19	21.1	6.6		0.235	
20	21.7	5.7		0.200	
21	22.1	5.2		0.165	
22	22.6	4.8		0.130	
23	23.0	4.3		0.095	

RUN #4 Curved Elbow

Reading	P_1 Manometer Left	P_1 Manometer Right	P_2 Left	P_2 Right	Micrometer	Orifice
1	14.5	14.5	.6	.6	.825	1/2"
2	12.2	17.3	5.6	4.4	.790	
3	14.2	14.8	"	"	.790	
4	13.3	15.9	"	"	.755	1"
5	11.8	17.9	"	"	.720	
6	9.1	21	"	"	.685	
7	13.3	15.9	"	"	.685	
8	12.6	16.8	"	"	.650	
9	11.7	17.9	"	"	.615	
10	10.8	19.1	"	"	.580	
11	10.2	19.8	"	"	.545	
12	9.6	20.4	"	"	.510	1 1/2"
13	9.0	21.2	"	"	.475	
14	8.4	21.9	"	"	.440	
15	7.7	22.7	"	"	.405	
16	7.1	23.2	"	"	.370	
17	6.8	23.8	"	"	.335	
18	6.5	24.0	"	"	.300	
19	6.3	24.2	"	"	.265	
20	6.2	24.3	"	"	.230	
21	6.1	24.4	"	"	.195	
Check:-						
22	12.2	17.3	"	"	.370	2"
23	12.1	17.4	"	"	.335	

RUN #5 Curved Elbow

Reading	P_1 Manometer Left	P_1 Manometer Right	P_2 Left	P_2 Right	Micrometer	Orifice
1	15	15	≠ .05	≠ .05	.830	1/2"
2	11.9	18.7	5.5	4.5	.795	
3	14.7	15.2	10"		.795	
4	13.8	16.4	"		.760	1"
5	12.0	18.6	"		.725	
6	9.2	22.0	"		.690	
7	13.8	16.4	"		.690	
8	13.0	17.4	"		.655	
9	12.0	18.6	"		.620	
10	11.0	19.9	"		.585	
11	10.3	20.7	"		.550	1 1/2"
12	9.8	21.3	"		.515	
13	9.2	22.2	"		.480	
14	8.3	23.1	"		.445	
15	7.4	24.1	"		.410	
16	12.5	17.9	"		.410	
17	12.3	18.2	"		.375	
18	12.1	18.6	"		.340	
19	11.9	18.8	"		.305	
20	11.6	19.1	"		.270	2"
21	11.4	19.4	"		.235	
22	11.2	19.6	"		.200	
23	11.1	19.8	"		.165	
24	10.9	20.0	"		.130	

RUN #6 Square Elbow

Reading	P_1 Manometer Left	P_1 Manometer Right	P_2 Left		P_2 Right	Micrometer	Orifice
1	15	15	0	-	0	.830	1/2"
2	14.8	15.3	5	-	5	.795	
3	13.9	16.4		"		.760	1"
4	12.3	18.5		"		.725	
5	9.8	21.5		"		.690	
6	13.9	16.4		"		.690	
7	13.3	17.2		"		.655	
8	12.4	18.4		"		.620	
9	11.5	19.4		"		.585	
10	11.0	20.0		"		.550	
11	11.6	21.6		"		.515	
12	9.9	21.3		"		.480	1 1/2"
13	9.4	21.9		"		.445	
14	9.1	22.3		"		.410	
15	8.7	22.8		"		.375	
16	8.2	23.2		"		.340	
17	8.1	23.5		"		.305	
18	7.9	23.6		"		.270	
19	7.7	23.9		"		.235	
20	7.6	24.0		"		.200	
21	7.4	24.1		"		.165	
22	7.3	24.2		"		.130	

RUN #7

Curved Elbow and Streamlined
Valve Guide

Reading NO.	P_1 Manometer Left	P_1 Manometer Right	P_2 Left	P_2 Right	Micrometer	Orifice
1	15	15	.1	.1	.830	
2	13.4	17.0	10"		.665	
3	13.2	17.2			.655	
4	12.3	18.3			.620	
5	11.4	19.4			.585	1.5"
6	10.8	20.1			.550	
7	10.3	20.7			.515	
8	9.7	21.5			.480	
9	9.1	22.1			.445	
10	8.5	22.9			.410	
11	7.9	23.6			.375	
12	12.6	17.7			.375	
13	12.5	18.0			.340	
14	12.3	18.2			.305	
15	12.2	18.4			.270	2.0"
16	12.0	18.6			.235	
17	11.9	18.7			.200	
18	11.9	18.8			.165	

RUN #8

Reading No.	P_1 Manometer Left	P_1 Manometer Right	P_2 Left	P_2 Right	Micrometer	Orifice
1	0	0.	10		830	
2	13.1	17.4	"		655	
3	12.2	18.6	"		620	
4	11	20	"		585	1.5"
5	10.2	20.8	"		550	
6	9.6	21.5	"		515	
7	8.9	22.4	"		480	
8	8.1	23.4	"		445	
9	7.3	24.4	"		410	1.5"
10	12.5	18.1	"		410	2.0"
11	12.3	18.5	"		375	
12	12.0	18.8	"		340	
13	11.8	19.1	"		305	
14	11.5	19.4	"		270	2.0"
15	11.3	19.8	"		235	
16	11.1	20.0	"		200	
17	10.8	20.2	"		165	
18	10.6	20.4	"		130	

RUN #9

Reading No.	P_1 Manometer Left	P_1 Manometer Right	P_2	Micrometer	Orifice
1	13.1	17.2	10"	655	1.5"
2	12.2	18.3		620	
3	11.1	19.6		585	
4	10.5	20.4		550	
5	9.9	21.1		515	
6	9.2	21.9		480	
7	8.5	22.8		445	
8	7.6	23.8		410	
9	12.5	17.9		410	2.0"
10	12.2	18.2		375	
11	12.0	18.5		340	
12	11.7	18.8		305	
13	11.5	19.1		270	
14	11.3	19.3		235	
15	11.2	19.5		200	
16	11.0	19.8		165	
17	10.8	20.0		130	

RUN #11

Reading No.	P_1 Manometer Left	Right	P_2	Micrometer	Orifice
0	15.	15.0	10"	.830	1 1/2"
1	13.0	17.5	"	.655	
2	12.0	18.6	"	.620	
3	11.0	19.9	"	.585	
4	10.2	20.9	"	.550	
5	9.5	21.7	"	.515	
6	8.7	22.7	"	.480	
7	13.1	17.4	"	.480	2"
8	12.8	17.7	"	.445	
9	12.5	18.0	"	.410	
10	12.2	18.4	"	.375	
11	11.9	18.7	"	.340	
12	11.7	19.0	"	.305	
13	11.4	19.4	"	.270	
14	11.2	19.7	"	.235	
15	11.0	19.9	"	.200	
16	10.8	20.2	"	.165	
17	10.6	20.4	"	.130	

RUN #12

Reading No.	P_1 Manometer Left	P_1 Manometer Right	P_2	Micrometer	Orifice
0	15.0	15.0	10"	.830	1 1/2"
1	13.2	17.3		.655	
2	12.3	18.4		.620	
3	11.1	19.8		.585	
4	9.7	21.5		.550	
5	8.2	23.3		.515	
6	6.8	24.9		.480	
7	12.3	18.2		.480	2"
8	12.1	18.5		.445	
9	12.1	18.6	10"	.410	
0	12.1	18.6		.375	
1	12.2	18.5		.340	
2	12.2	18.5		.305	
3	12.1	18.7		.270	
4	11.9	18.8		.235	
5	11.8	18.9		.200	
6	11.8	19.0		.165	
7	11.7	19.1		.130	

RUN 13

ading No.	P_1 Manometer Left	P_1 Manometer Right	P_2	Micrometer	Orifice
0	15	15.2	10"	.830	↑
1	13.1	17.2	↓	.655	
2	12.2	18.4		.620	
3	11.1	19.7		.585	
4	9.8	21.2		.550	1.5"
5	8.7	22.5		.515	
6	8.0	23.4	↓	.480	
7	8.0	23.4	10"	.445	
8	7.9	23.5	↓	.410	
9	7.6	23.8		.375	
10	7.4	24.1		.340	↓
11	7.1	24.4		.304	---------
12	12.3	18.2		.305	↑
13	12.2	18.3		.270	2"
14	12.1	18.4		.235	
15	12.1	18.5		.200	
16	12.0	18.5		.165	
17	12.0	18.6	↓	.130	↓

RUN 14

Reading No.	P_1 Manometer Left	P_1 Manometer Right	P_2	Micrometer	Orifice
1	13	17.3	10"	.655	
2	12	18.6		.620	
3	10.8	20.1		.585	
4	9.3	21.8		.550	1.5"
5	7.9	23.5		.516	
6	6.6	24.9		.480	
7	12.3	18.1		.480	
8	12.3	18.1	10"	.445	
9	12.3	18.2		.410	
10	12.2	18.3		.375	2.0"
11	12.1	18.4		.340	
12	12.0	18.5		.305	
13	11.9	18.6		.270	
14	11.9	18.7		.235	
15	11.8	18.7		.200	
16	11.7	18.8		.165	
17	11.7	18.9		.130	

RUN 15

Reading No.	P_1 Manometer Left	P_1 Manometer Right	P_2	Micrometer	Orifice
1	12.8	16.7	10"	.655	1.5"
2	11.9	17.8		.620	
3	10.8	19.2		.585	
4	9.6	20.6		.550	
5	8.3	22.2		.515	
6	7.2	23.5		.480	
7	12.0	17.6	10"	.480	2"
8	11.9	17.8		.445	
9	12.0	17.7		.410	
10	11.9	17.8		.375	
11	11.9	17.8		.340	
12	11.8	17.9		.305	
13	11.7	19.0		.270	
14	11.7	18.1		.235	
15	11.6	18.2		.200	
16	11.6	18.3		.165	
17	11.5	18.4		.130	

RUN 16

ading o.	P_1 Manometer Left	Right	P_2	Micrometer	Orifice
	13	17	10"	.655	
	12.1	18.2		.620	
	10.9	19.7		.585	
	9.5	21.3		.550	1.5"
	8.0	23.1		.515	
	6.6	24.7		.480	
	12.2	18.1	10"	.480	
	12.0	18.3		.445	
	12.0	18.3		.410	
	12.0	18.4		.375	
	12.0	18.4		.340	
	11.9	18.4		.305	2.0"
	11.8	18.5		.270	
	11.8	18.6		.235	
	11.7	18.7		.200	
	11.7	18.8		.165	
	11.6	18.9		.130	

RUN 17

Reading No.	P_1 Manometer Left	P_1 Manometer Right	P2	Micrometer	Orifice
1	13	17.1	10"	.655	1.5"
2	12.1	18.2		.620	
3	10.9	19.7		.585	
4	9.4	21.4		.550	
5	8.0	23.1		.515	
6	6.5	24.7		.480	
7	12.2	18.1		.480	
8	12.0	18.3	10"	.445	2.0"
9	12.1	18.2		.410	
10	12.1	18.2		.375	
11	12.0	18.3		.340	
12	12.0	18.4		.305	
13	11.9	18.4		.270	
14	11.8	18.5		.235	
15	11.7	18.6		.200	
16	11.6	18.7		.165	
17	11.6	18.8		.130	

RUN 18

ading o.	P_2 Manometer Left	P_2 Manometer Right	P_2	Micrometer	Orifice
	11.6	15.7	10"	.655	
	10.7	16.8		.620	
	9.5	18.2		.585	
	8.2	19.8		.550	1.5"
	6.9	21.3		.515	
	5.8	22.7		.480	
	5.5	23.0		.445	
	10.8	16.7	10"	.445	
	10.9	16.6		.410	
	10.9	16.6		.375	
	10.9	16.7		.340	
	10.8	16.8		.305	
	10.7	16.9		.270	2.0"
	10.6	17.0		.235	
	10.5	17.1		.200	
	10.4	17.2		.165	
	10.3	17.3		.130	

RUN 19

ading o.	P_2 Manometer Left	P_2 Manometer Right	P_2	Micrometer	Orifice
	11.6	15.7	10"	.655	
	10.6	16.9		.620	
	9.6	18.1		.585	
	8.5	19.5		.550	
	7.4	20.7		.515	
	7.0	21.2		.480	1.5"
	6.9	21.4		.445	
	6.8	21.4		.410	
	6.6	21.7		.375	
	6.3	22.0	10"	.340	
	6.1	22.3		.305	
	5.8	22.6		.270	
	5.7	22.8		.235	
	5.5	23.0		.200	
	5.3	23.2		.165	
	5.1	23.5		.130	

RUN 20

Reading No.	P_1 Manometer Left	P_1 Manometer Right	P_2	Micrometer	Orifice
1	11.6	14.7	10"	.655	↑
2	10.8	15.6	↓	.620	
3	9.7	16.8		.585	
4	8.7	18.2		.550	
5	7.6	19.5		.515	
6	6.5	20.9		.480	
7	5.8	21.7	↓	.445	
			10"		1 1/2"
8	5.7	21.8	↓	.410	
9	5.8	21.6		.375	
10	5.8	21.6		.340	
11	5.6	21.8		.305	
12	5.4	22.0		.270	
13	5.2	22.2		.235	
14	5.1	22.4		.200	
15	5.0	22.5		.165	
16	4.9	22.7	↓	.130	↓

RUN 21

Reading No.	P_2 Manometer Left	P_2 Manometer Right	P_2	Micrometer	Orifice
1	11.6	14.6	10"	.655	
2	10.8	15.5		.620	
3	9.8	16.7		.585	
4	8.7	18.0		.550	
5	7.6	19.3		.515	
6	6.8	20.3		.480	
7	6.8	20.3		.445	
8	6.8	20.3		.410	
9	6.7	20.4	10"	.375	1 1/2"
10	6.5	20.6		.340	
11	6.2	20.9		.305	
12	6.2	21.0		.270	
13	6.2	21.1		.235	
14	5.9	21.3		.200	
15	5.9	21.4		.165	
16	5.8	21.5		.130	

CALCULATIONS RUN #1

Reading	P_1	N	K_2	L/D
1	23.3	.0498	.0766	.0286
2	1.5	.1976	.0766	.0286
3	6.8		.163	.0572
4	17.7		.264	.0857
5	3.4		.269	.0857
6	6.6		.356	.1143
7	9.4	.4445	.431	.1430
8	11.2		.470	.1712
9	13.7		.520	.200
10	16.7		.574	.2285
11	5.2		.567	.2285
12	6.4		.630	.257
13	7.4	.786	.676	.286
14	8.3		.716	.314
15	9.5		.767	.333
16	6.8		.163	.0572
17	3.6	.1976	.119	.0429
18	1.5		.0764	.0286
19	5.3	.0498	.0363	.0143

CALCULATIONS RUN #2

...ading	P_1	N	K	L/D
0	0		0	0
1	0	.0498	0	
2	5.6		.0528	.02
3	0.4		.0559	.02
4	1.7		.115	.04
5	4.0	.1976	.175	.06
6	7.6		.243	.08
7	11.9		.304	.10
8	18.7		.381	.12
9	3.7		.382	.12
0	4.9		.440	.14
1	5.4		.462	.163
2	6.3		.497	.183
3	7.2		.533	.203
4	8.6	.4445	.582	.223
5	9.8		.617	.243
6	11.1		.662	.263
7	12.2		.693	.283
8	13.5		.733	.303
9	14.5		.755	.323
0	16.0		.790	.343
1	16.9		.817	.363
2	17.8		.840	.383
3	18.7		.858	.403

CALCULATIONS RUN # 3

Reading	P_1	N	K	L/D
1	.05	.0498	.0025	0
2	16.5		.0523	.02
3	1.1		.0535	.02
4	4.6	.1976	.109	.04
5	11.3		.172	.06
6	21.2		.235	.08
7	4.3		.238	.08
8	7.0		.304	.10
9	10.4	.4445	.370	.12
10	13.7		.424	.19
11	14.9		.443	.16
12	17.0		.471	.18
13	19.4		.504	.20
14	6.3		.510	.20
15	7.2		.544	.22
16	8.3		.585	.24
17	9.4		.621	.26
18	10.4		.655	.28
19	11.5	.786	.688	.30
20	12.5		.719	.32
21	13.5		.746	.34
22	14.5		.773	.36
23	16.0		.812	.38
24	16.4		.822	.40
25	17.0		.836	.42
26	17.8		.858	.44
27	18.3		.869	.46
28	10.6	1.224	1.03	

CALCULATIONS RUN #4

Reading	P_1	N	K	L/D
1	0	0.498	0	
2	5.1		.0356	.02
3	.6		.0484	.02
4	2.6	.1976	.101	.04
5	6.1		.154	.06
6	11.9		.216	.08
7	2.4		.218	.08
8	4.2		.288	.10
9	6.2		.350	.12
10	8.3		.404	.14
11	9.6	.4445	.435	.16
12	10.8		.462	.18
13	12.2		.490	.20
14	13.5		.516	.22
15	15.0		.544	.24
16	16.1		.565	.26
17	17.0		.580	.28
18	17.5		.587	.30
19	17.9		.594	.32
20	18.1		.597	.34
21	18.2		.600	.36
22	5.1	.786	.563	.26
23	5.3		.573	.28

CALCULATIONS RUN #5

ding	P_1	N	K	L/D
.	0			
:		.0498		
)	6.8	--------	.0411	.02
4	.5	↑	.0443	.02
5	2.6	.1976	.101	.04
6	6.6	↓	.160	.06
7	11.8	--------	.214	.08
8	2.6	↑	.226	.08
9	3.4		.259	.10
0	6.6		.361	.12
1	8.9	.4445	.419	.14
2	10.4		.458	.16
3	11.5		.476	.18
4	13.0		.506	.20
5	14.8	↓	.540	.22
6	16.7	--------	.574	.24
7	5.2	↑	.567	.24
8	5.9		.605	.26
9	6.5		.634	.28
0	6.9		.653	.3
1	7.5	.786	.681	.32
2	8.0		.703	.34
3	8.4		.720	.36
4	8.7		.732	.38
5	9.1	↓	.750	.40

CALCULATIONS RUN #6

P_1	N	K	L/D
0	.0498	0	0
6.1		.0388-	.02
.5		.0443	.02
2.5	.1976	.0988	.04
6.2		.155	.06
11.7		.213	.08
2.5		.222	.08
3.9		.278	.10
6.0		.344	.12
7.9		.395	.14
9.0		.421	.16
10.0	.4445	.444	.18
11.4		.473	.20
12.5		.492	.22
13.2		.510	.24
14.1		.528	.26
15.0		.544	.28
15.4		.551	.30
15.7		.556	.32
16.2		.565	.34
16.4		.568	.36
16.7		.574	.38
16.9		.578	.40

CALCULATIONS RUN #7

adings	Pl	N	K_2	L/D
1	0			
2	3.6		.267	x
3	4.0		.281	.1
4	6.0		.344	.12
5	8.0	.4445	.397	.14
6	9.3		.429	.16
7	10.4		.453	.18
8	11.8		.483	.20
9	13.0		.506	.22
0	14.4		.533	.24
1	15.7		.556	.26
2	5.1		.562	.26
3	5.5		.583	.28
4	5.9		.603	.30
5	6.2	.786	.619	.32
6	6.6		.630	.34
7	6.8		.649	.36
8	6.9		.653	.38
9				

CALCULATIONS RUN #8

P_1	N	K	L/D
0		.0	.0
4.3		.291	.10
6.4		.356	.12
9	.4445	.421	.14
10.6		.458	.16
11.9		.485	.18
13.5		.516	.20
15.3		.549	.22
17.1		.581	.24
5.6		.588	.24
6.2		.618	.26
6.8		.648	.28
7.3		.671	.30
7.9	.786	.699	.32
8.5		.724	.34
8.9		.741	.36
9.4		.762	.38
9.8		.777	.40

CALCULATIONS RUN #9

P_1	N	K	L/D
4.1		.284	.1
6.1		.347	.12
8.5		.410	.14
9.9	.4445	.442	.16
11.2		.471	.18
12.7		.502	.20
14.3		.530	.22
16.2		.565	.24
5.4		.578	.24
6.0		.609	.26
6.5		.634	.28
7.1	.786	.661	.30
7.6		.700	.32
8.0		.705	.34
8.3		.712	.36
8.8		.737	.38
9.2		.754	.40

CALCULATIONS RUN #10

Reading	P/I	N	K	L/D
1	4.3	↑	.291	.10
2	6.5		.358	.12
3	8.5	.4445	.410	.14
4	10.0		.4445	.16
5	11.4		.475	.18
6	13.0		.506	.20
7	14.6	↓	.538	.22
8	4.7	↑	.539	
9	5.4		.578	.24
10	6.0		.610	.26
11	6.5	.786	.634	.28
12	7.1		.662	.30
13	7.6		.685	.32
14	8.0		.704	.34
15	8.4		.720	.36
16	8.9		.742	.38
17	9.3	↓	.757	.40

CALCULATIONS # 11

ding	P_1	N	K	L/D
[illegible]	4.5		.670	.1
[illegible]	6.6	.4445	.361	.12
[illegible]	8.9		.419	.14
4	10.7		.460	.16
[illegible]	12.2		.490	.18
[illegible]	14.0		.526	.20
[illegible]	4.3		.524	.20
3	4.9		.550	.22
9	5.5		.741	.24
0	6.2		.620	.26
1	6.8	.786	.650	.28
2	7.3		.672	.30
3	8.0		.703	.32
4	8.5		.725	.34
5	8.9		.742	.36
6	9.4		.763	.38
7	9.8		.779	.40

CALCULATIONS RUN #12

Reading	P_1	N	K	L/D
1	4.1		.284	.10
2	6.1		.347	.12
3	8.7	.4445	.415	.14
4	11.8		.483	.16
5	15.1		.545	.18
6	18.1		.597	.20
7	5.9		.604	.20
8	6.4		.630	.22
9	6.5	.786	.635	.24
10	6.5		.635	.26
11	6.3		.625	.28
12	6.3		.625	.30
13	6.6		.640	.32
14	6.9		.654	.34
15	7.1		.663	.36
16	7.2		.667	.38
17	7.4		.676	.40

CALCULATIONS #13

ding	P_1	N	K	L/D
	4.1	↑	.288	.10
	6.2		.35	.12
	8.6		.412	.14
	11.4	.4445	.475	.16
	13.8		.523	.18
	15.4		.551	.20
	15.4		.551	.22
	15.6		.555	.24
	16.2		.565	.26
	16.7	↓	.574	.28
	17.3	--------	.585	.30
	5.9	↑	.604	.30
	6.1		.614	.32
	6.3		.624	.34
	6.4	.786	.630	.36
	6.5		.635	.38
7	6.6	↓	.639	.40

CALCULATIONS RUN #14

Reading	$\frac{P}{l}$	N	K	L/D
1	4	.4445	.281	.10
2	6.6		.361	.12
3	9.3		.429	.14
4	12.5		.497	.16
5	15.6		.555	.18
6	18.3		.601	.20
7	5.8	.786	.599	.20
8	5.8		.599	.22
9	5.9		.604	.24
10	6.1		.614	.26
11	6.3		.624	.28
12	6.5		.634	.30
13	6.7		.643	.32
14	6.8		.649	.34
15	6.9		.654	.36
16	7.1		.663	.38
17	7.2		.667	.40

CALCULATIONS RUN #15

Reading	P_1	N	K	L/D
1	3.9		.278	.10
2	5.9	.4445	.337	.12
3	8.4		.407	.14
4	11.0		.466	.16
5	13.9		.525	.18
6	16.3		.568	.20
7	5.6		.588	.20
8	5.9		.604	.22
9	5.7	.786	.594	.24
10	5.9		.604	.26
11	5.9		.604	.28
12	6.1		.614	.30
13	6.3		.624	.32
14	6.4		.630	.34
15	6.6		.639	.36
16	6.7		.644	.38
17	6.9		.654	.40

CALCULATIONS RUN #16

Reading	P_1	N	K	L/D
1	4.0		.281	.10
2	7.1		.373	.12
3	8.8	.4445	.417	.14
4	11.8		.483	.16
5	15.1		.546	.18
6	18.1		.598	.20
7	5.9		.604	.20
8	6.3		.625	.22
9	6.3		.625	.24
10	6.4		.630	.26
11	6.4	.786	.630	.28
12	6.5		.634	.30
13	6.7		.644	.32
14	6.8		.648	.34
15	7.0		.658	.36
16	7.1		.662	.38
17	7.3		.672	.40

CALCULATIONS RUN#17

Reading	P_1	N	K	L/D
1	4.1		.284	.10
2	6.1	.4445	.347	.12
3	8.8		.417	.14
4	12.0		.487	.16
5	15.1		.546	.18
6	18.2		.600	.20
7	5.9		.604	.20
8	6.3		.625	.22
9	6.1		.614	.24
10	6.1	.786	.614	.26
11	6.3		.625	.28
12	6.4		.630	.30
13	6.5		.634	.32
14	6.7		.644	.34
15	6.9		.653	.36
16	7.1		.662	.40
17	7.2		.671	.42

CALCULATIONS #18

Reading	P_1	N	K	L/D
1	4.1		.284	.10
2	6.1	.4445	.346	.12
3	8.7		.413	.14
4	11.6		.480	.16
5	14.4		.523	.18
6	16.9		.576	.20
7	17.5		.586	.22
8	5.9		.604	.22
9	5.7		.593	.24
10	5.7		.593	.26
11	5.8	.786	.600	.28
12	6.0		.609	.30
13	6.2		.618	.32
14	6.4		.628	.34
15	6.6		.638	.36
16	6.8		.647	.38
17	7.0		.657	.40

CALCULATIONS RUN #19

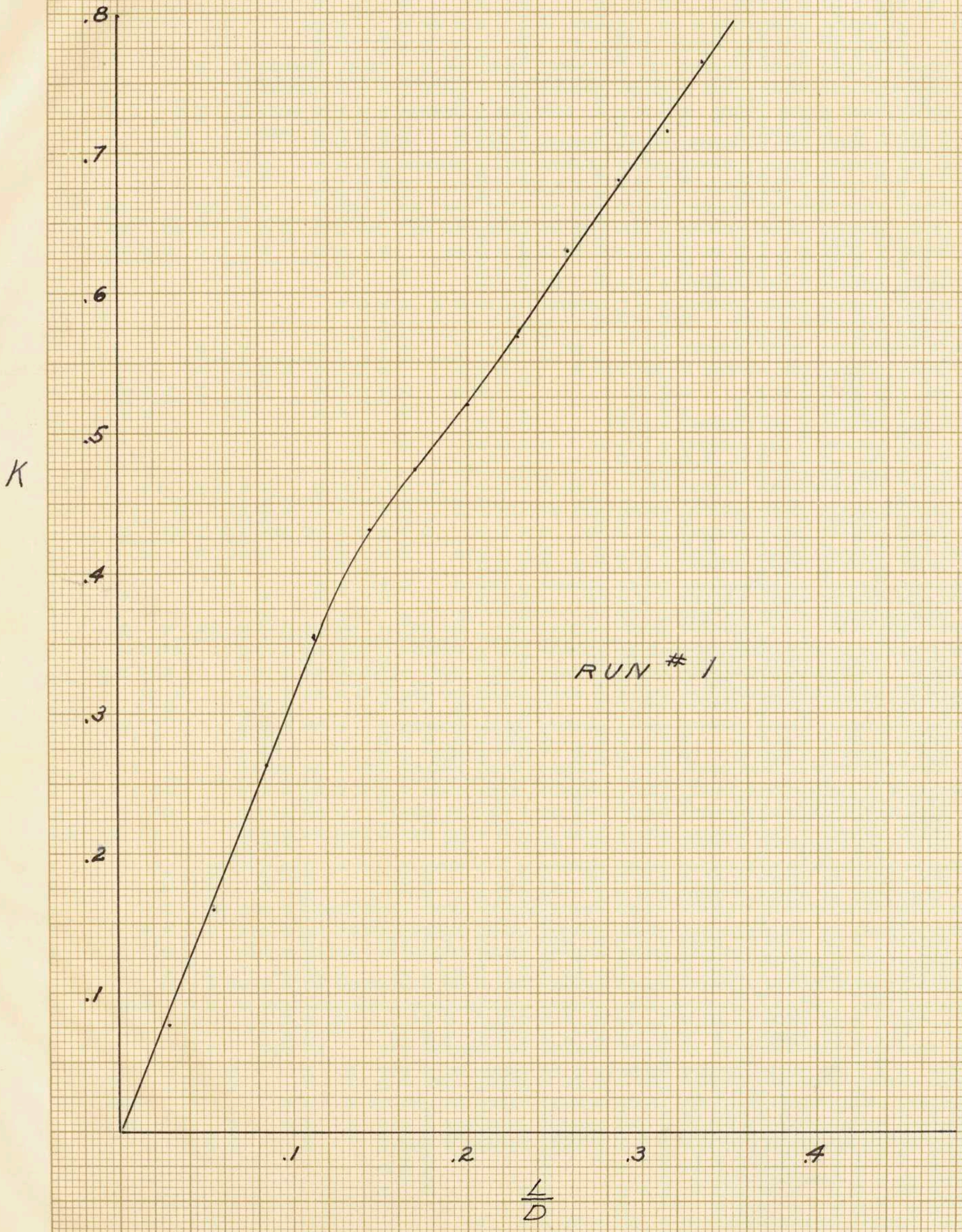
Reading	P_1	N	K	L/D
1	4.1		.284	.10
2	6.3		.352	.12
3	8.5		.409	.14
4	11.0		.466	.16
5	13.3		.510	.18
6	14.2	.4445	.528	.20
7	14.5		.532	.22
8	14.6		.537	.24
9	15.1		.546	.26
10	15.7		.555	.28
11	16.2		.564	.30
12	16.8		.576	.32
13	17.1		.581	.34
14	17.5		.586	.36
15	17.9		.592	.38
16	18.4		.602	.40

CALCULATIONS RUN #20

Reading	P_1	N	K	L/D
1	3.1		.247	.10
2	4.8		.308	.12
3	7.1		.374	.14
4	9.5		.433	.16
5	11.9		.484	.18
6	14.4		.533	.20
7	15.9	.4445	.560	.22
8	16.1		.563	.24
9	15.8		.555	.26
10	15.8		.555	.28
11	16.2		.565	.30
12	16.6		.572	.32
13	17.0		.580	.34
14	17.3		.585	.36
15	17.5		.588	.38
16	17.8		.594	.40

CALCULATIONS RUN # 21

Reading	P_1	N	K	L/D
1	3.0		.243	.10
2	4.7		.302	.12
3	6.9		.368	.14
4	9.3		.427	.16
5	11.7		.479	.18
6	13.5		.515	.20
7	13.5	.4445	.515	.22
8	13.5		.515	.24
9	13.7		.519	.26
10	14.1		.527	.28
11	14.7		.538	.30
12	14.8		.540	.32
13	15.1		.545	.34
14	15.4		.551	.36
15	15.5		.552	.38
16	15.7		.555	.40



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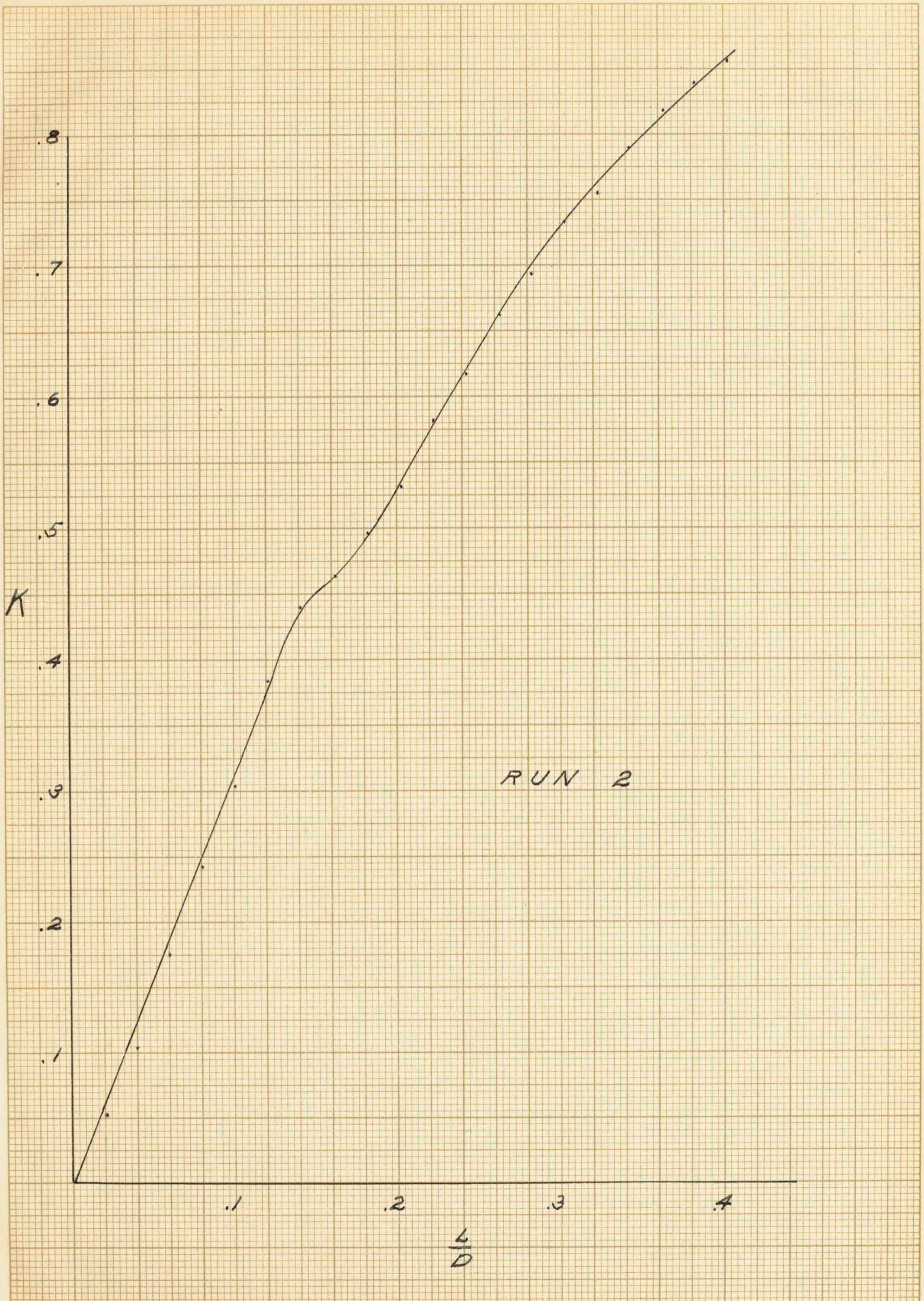

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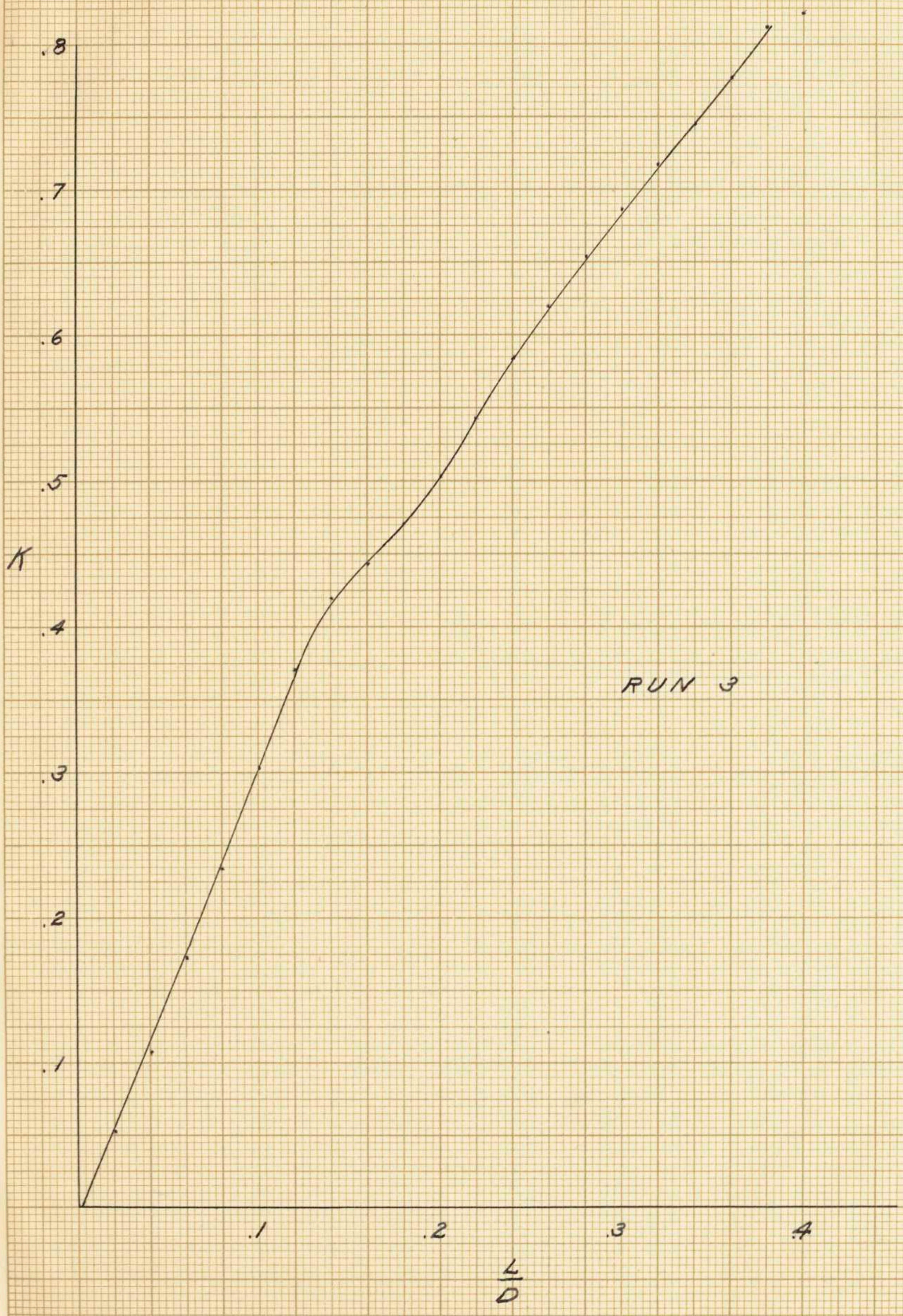

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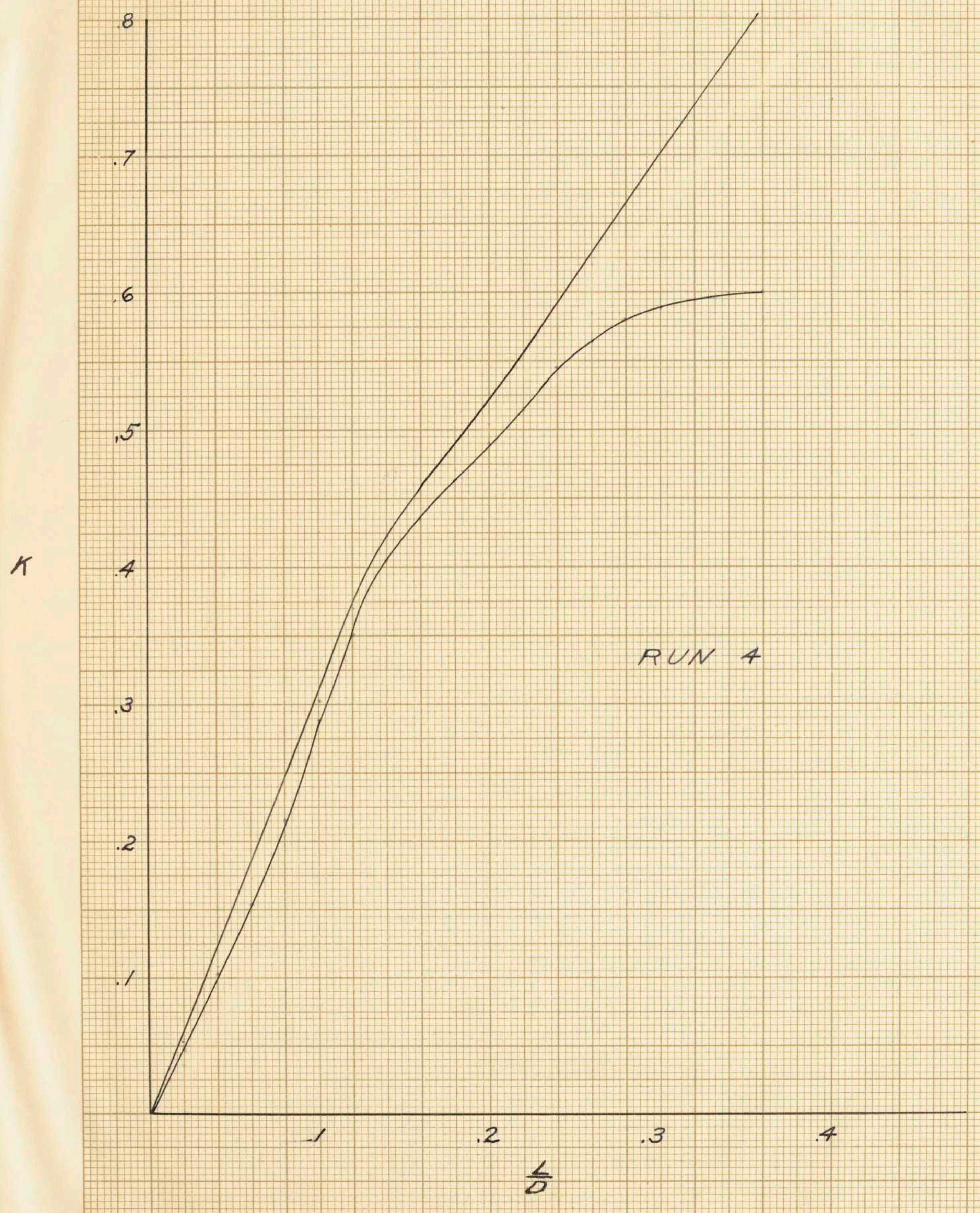

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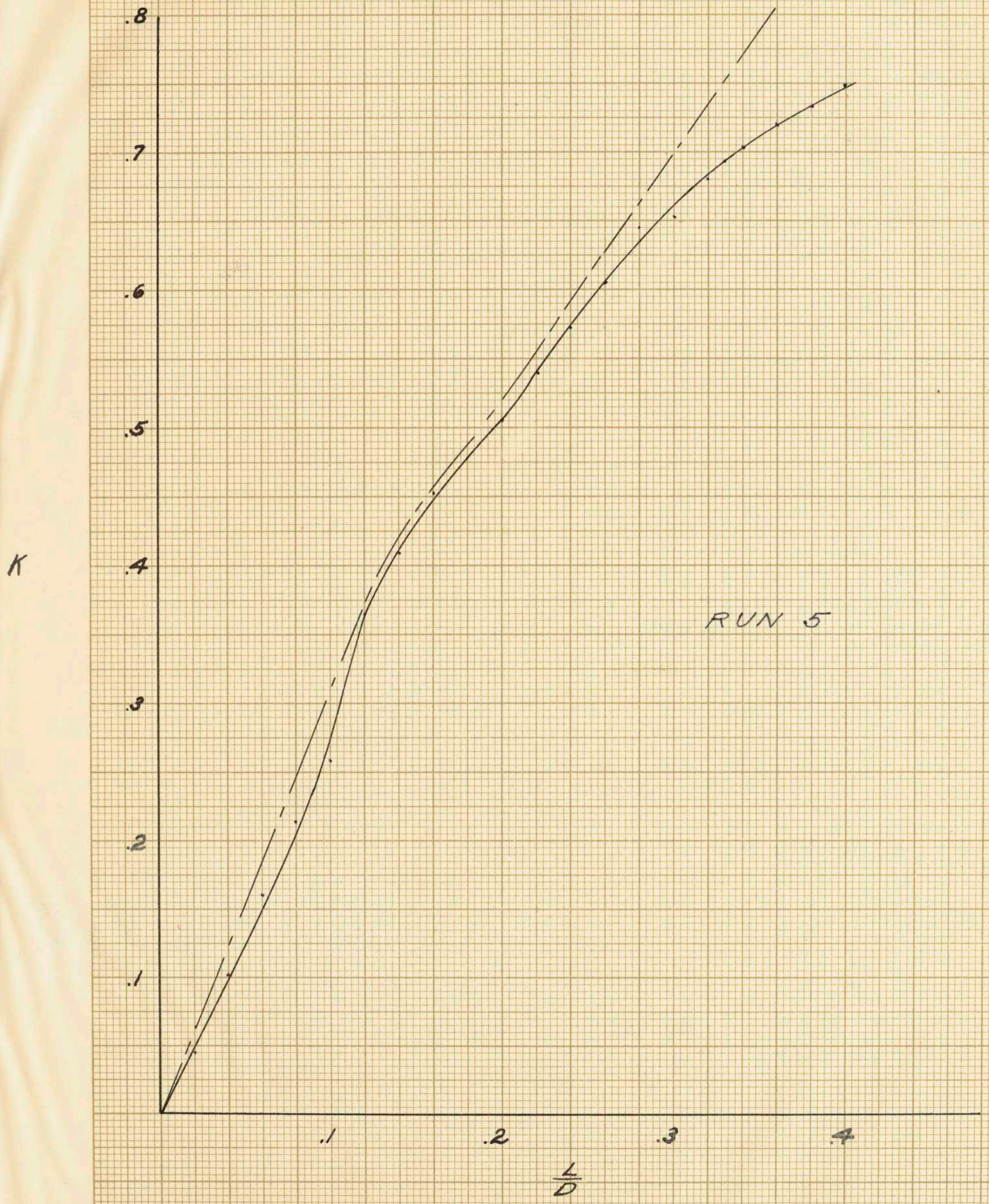

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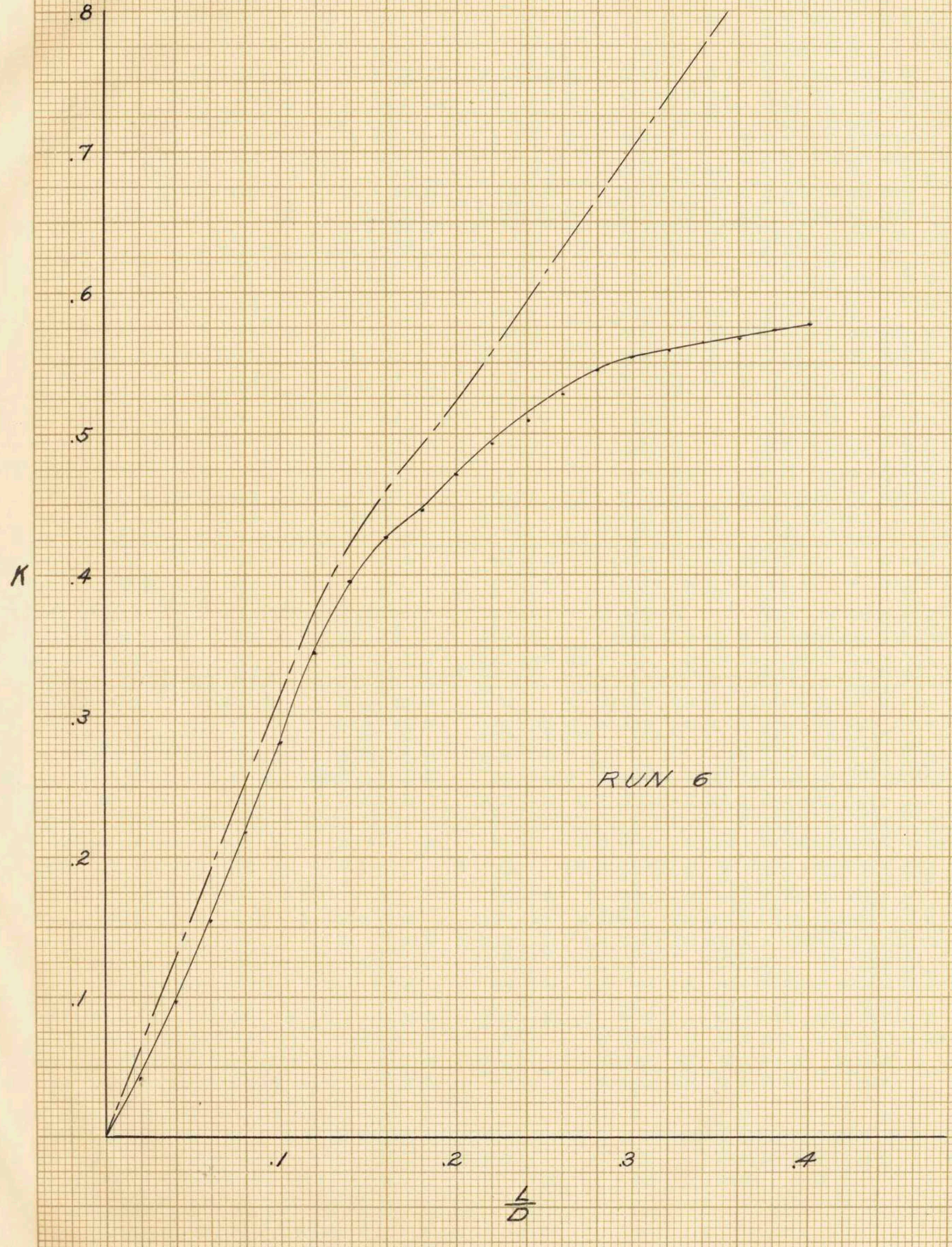

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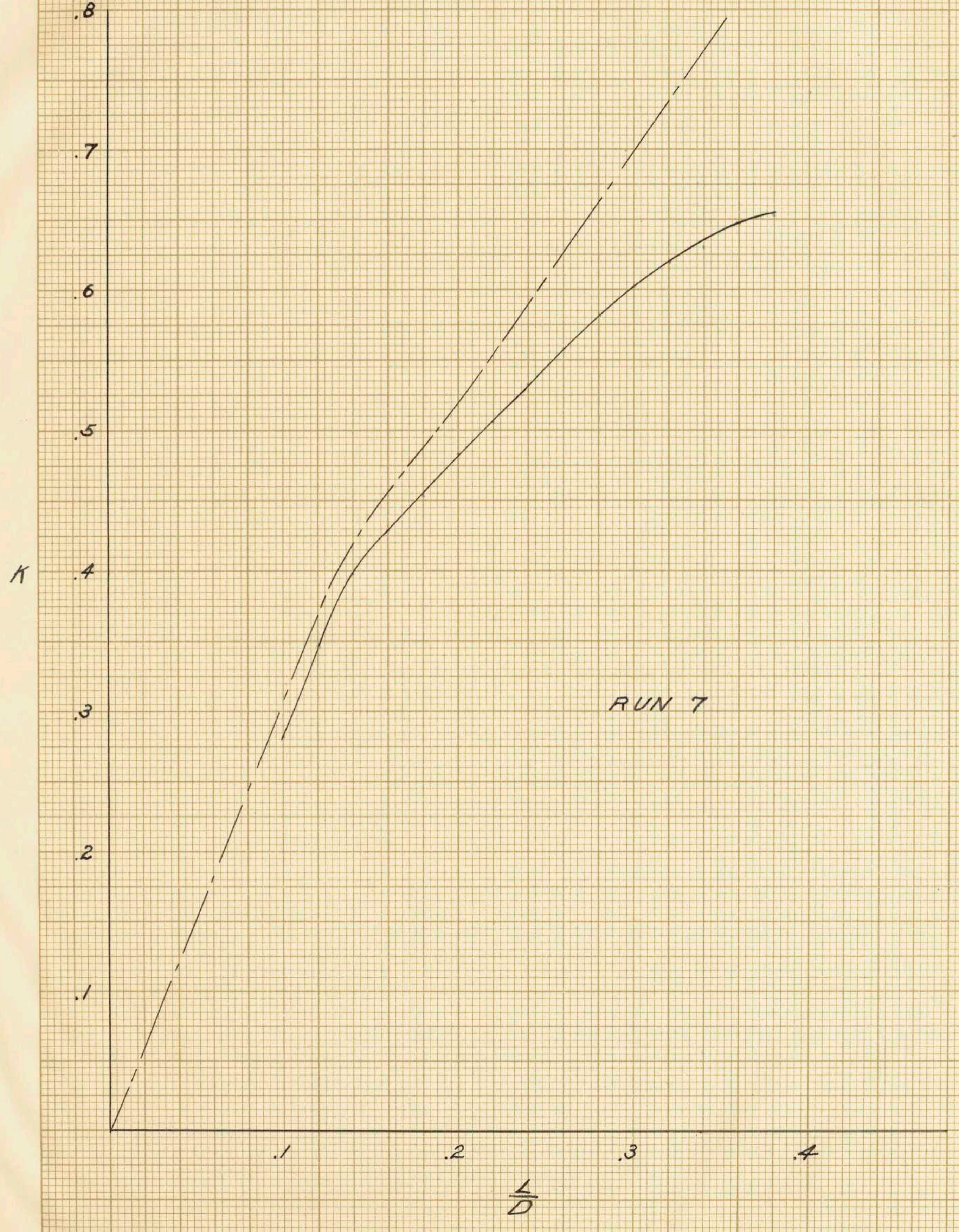

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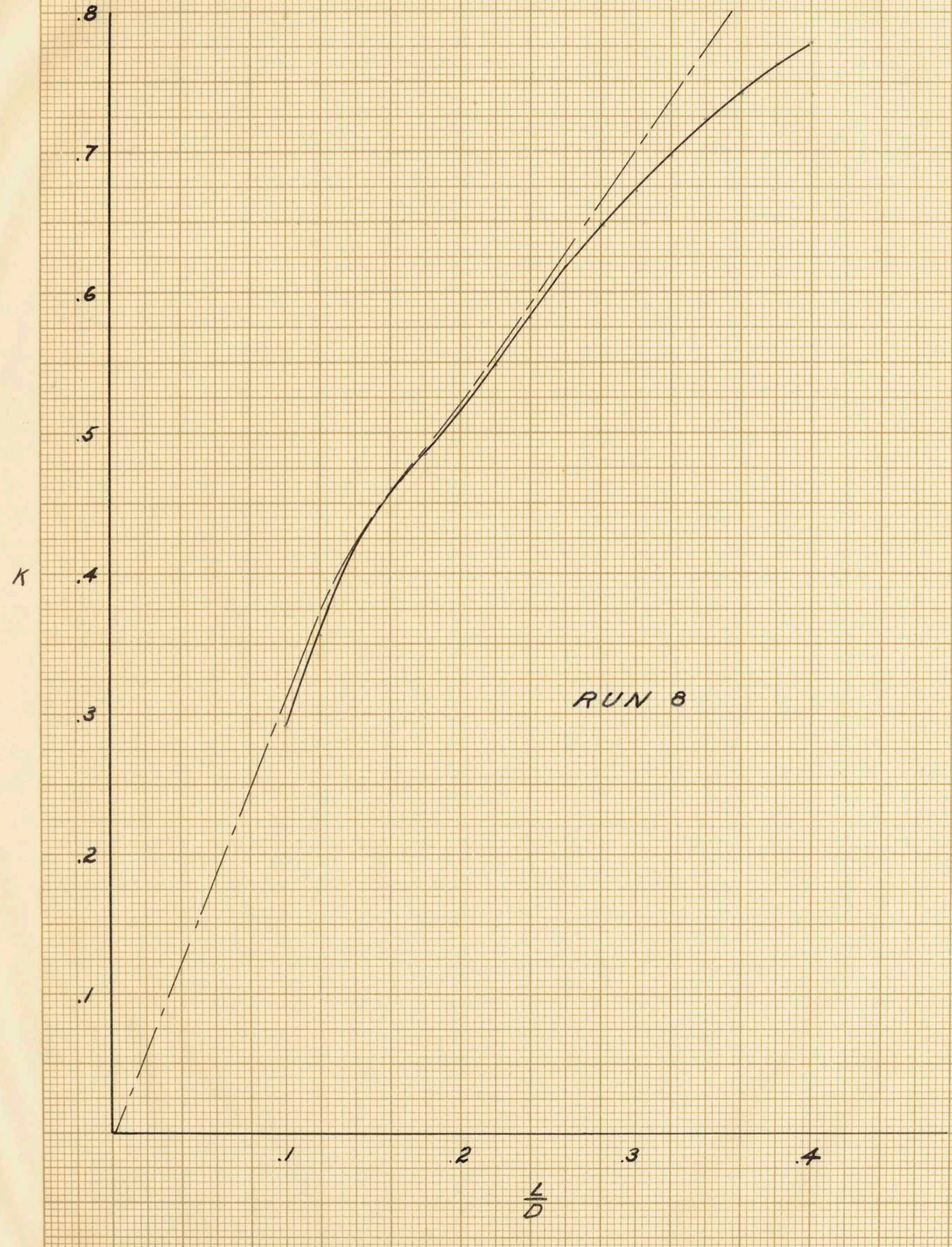

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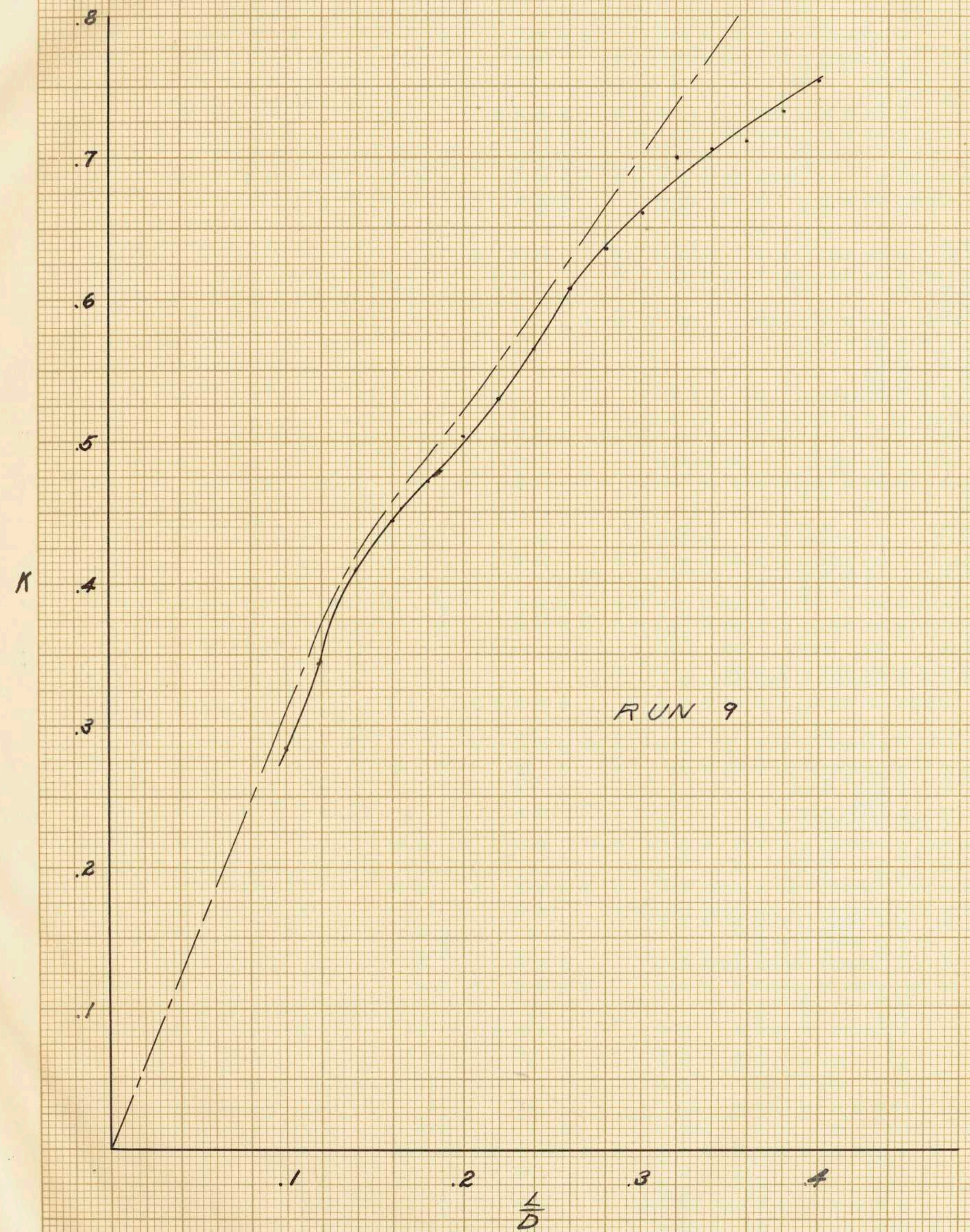

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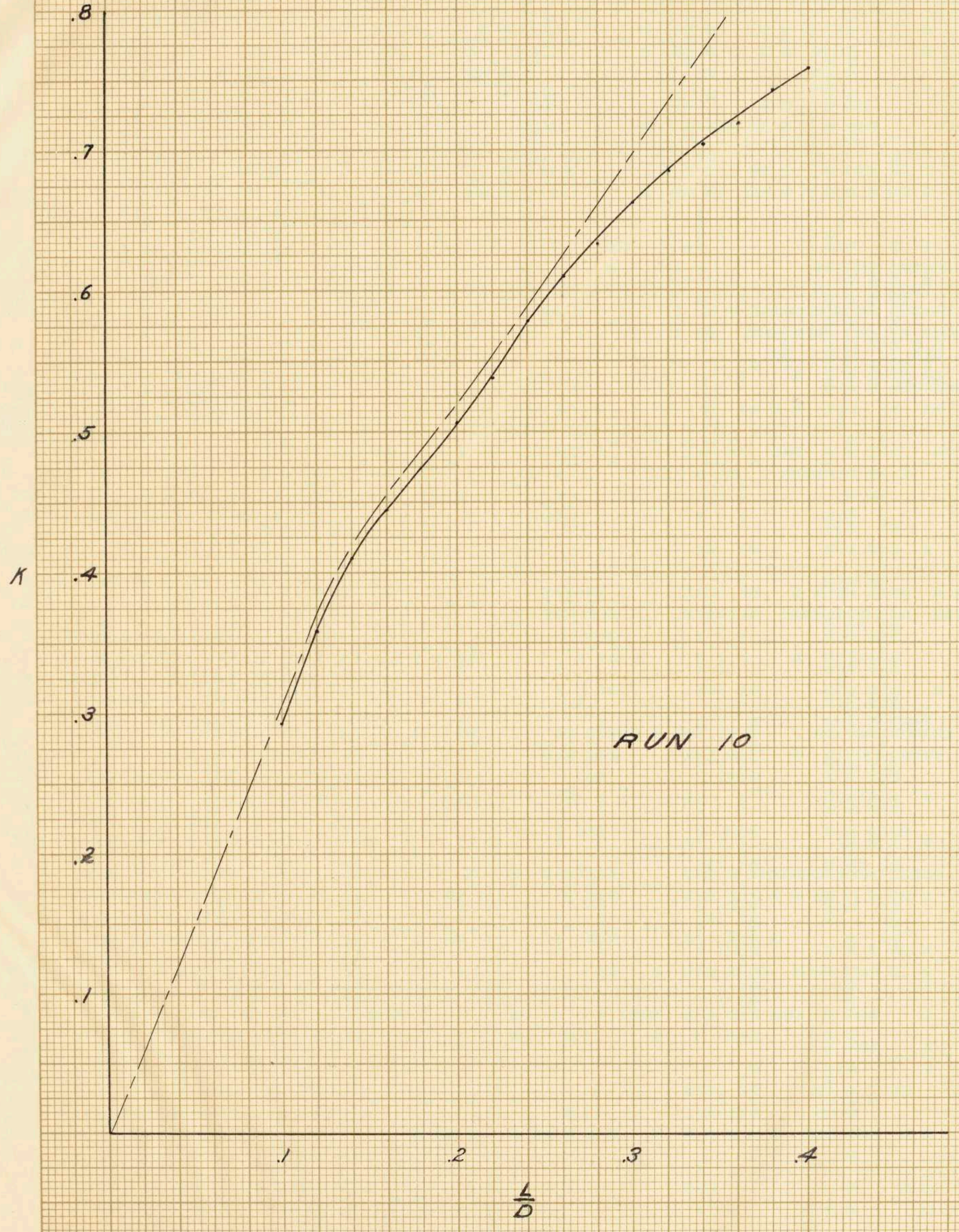

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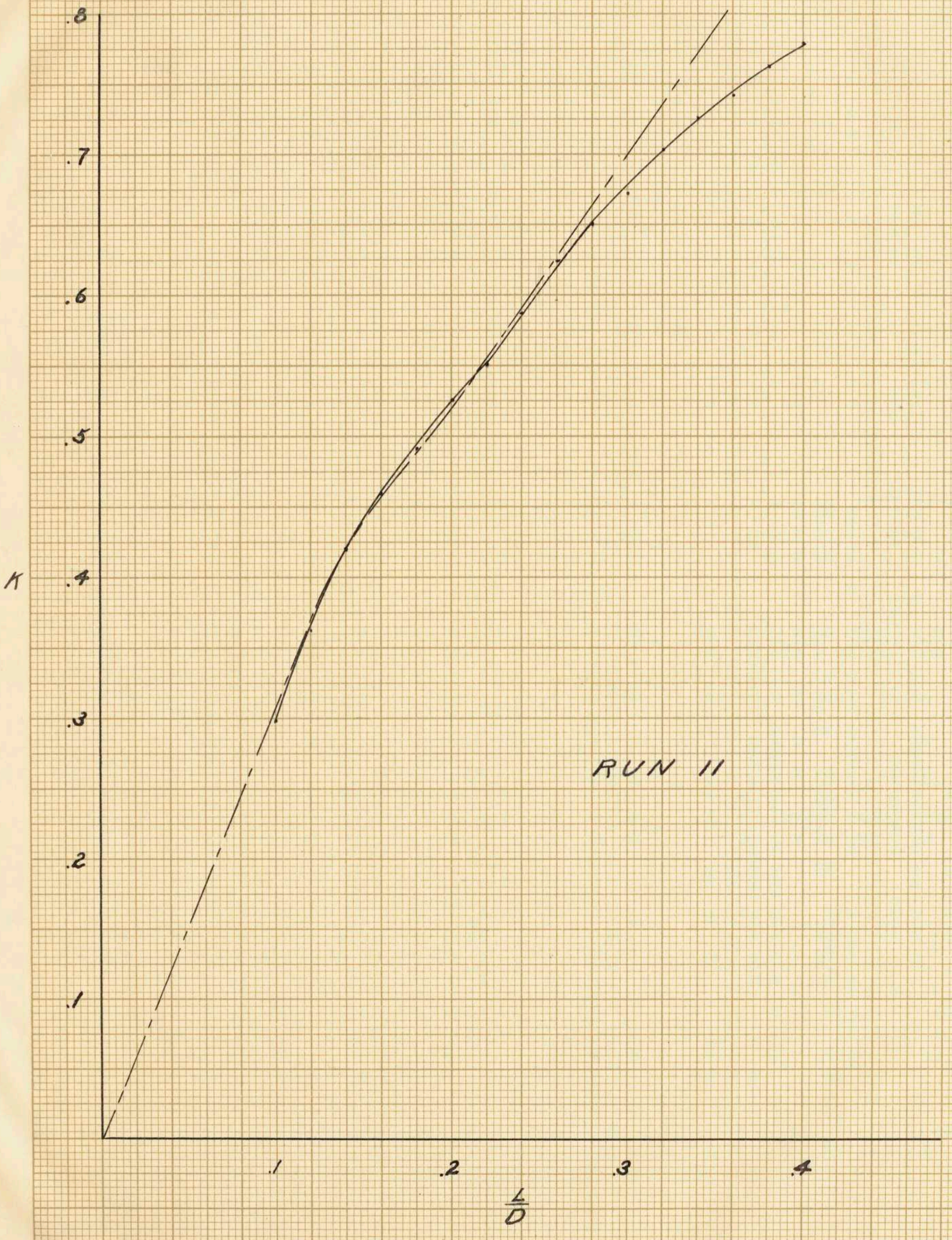

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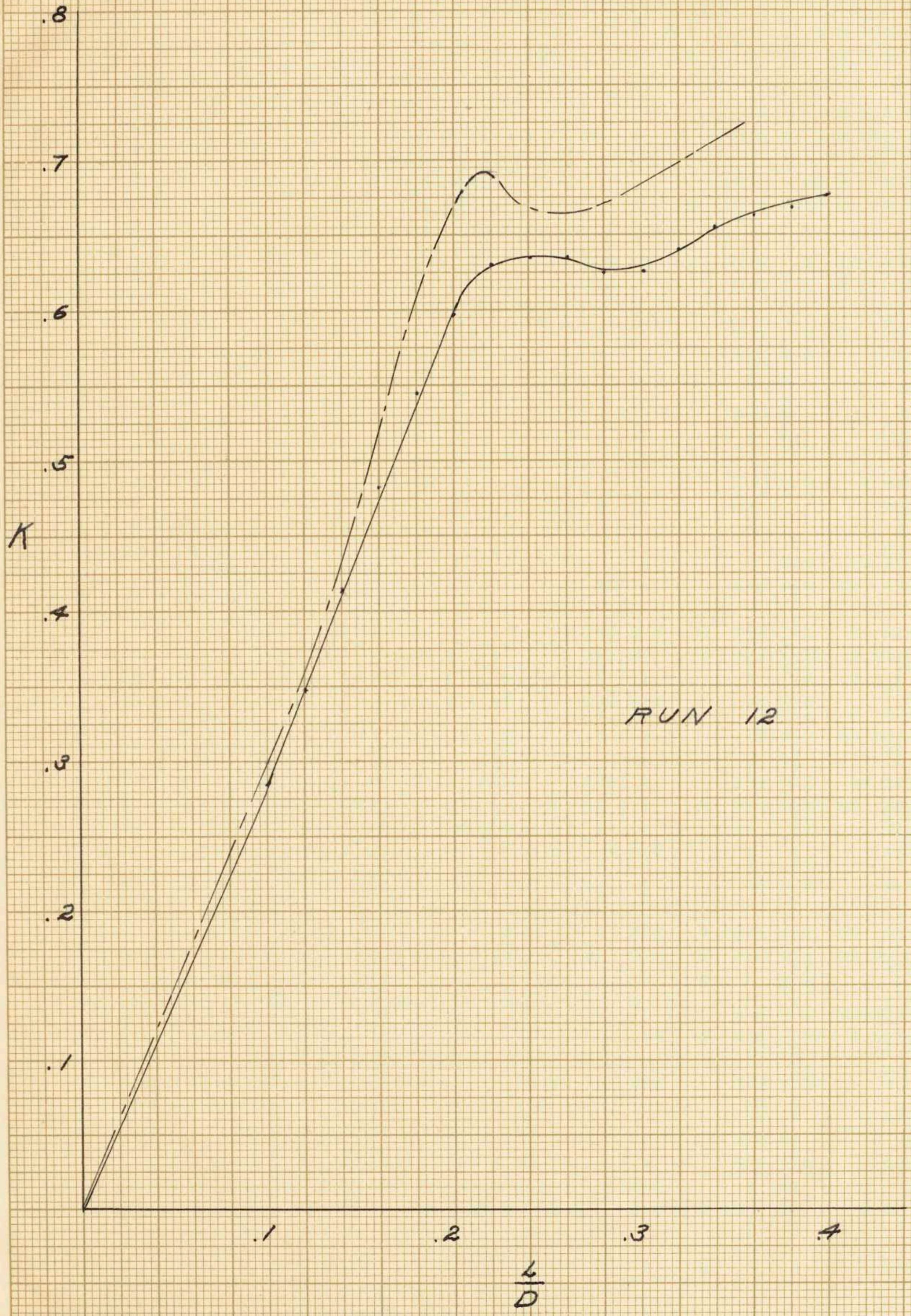

FORM 1 T


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K
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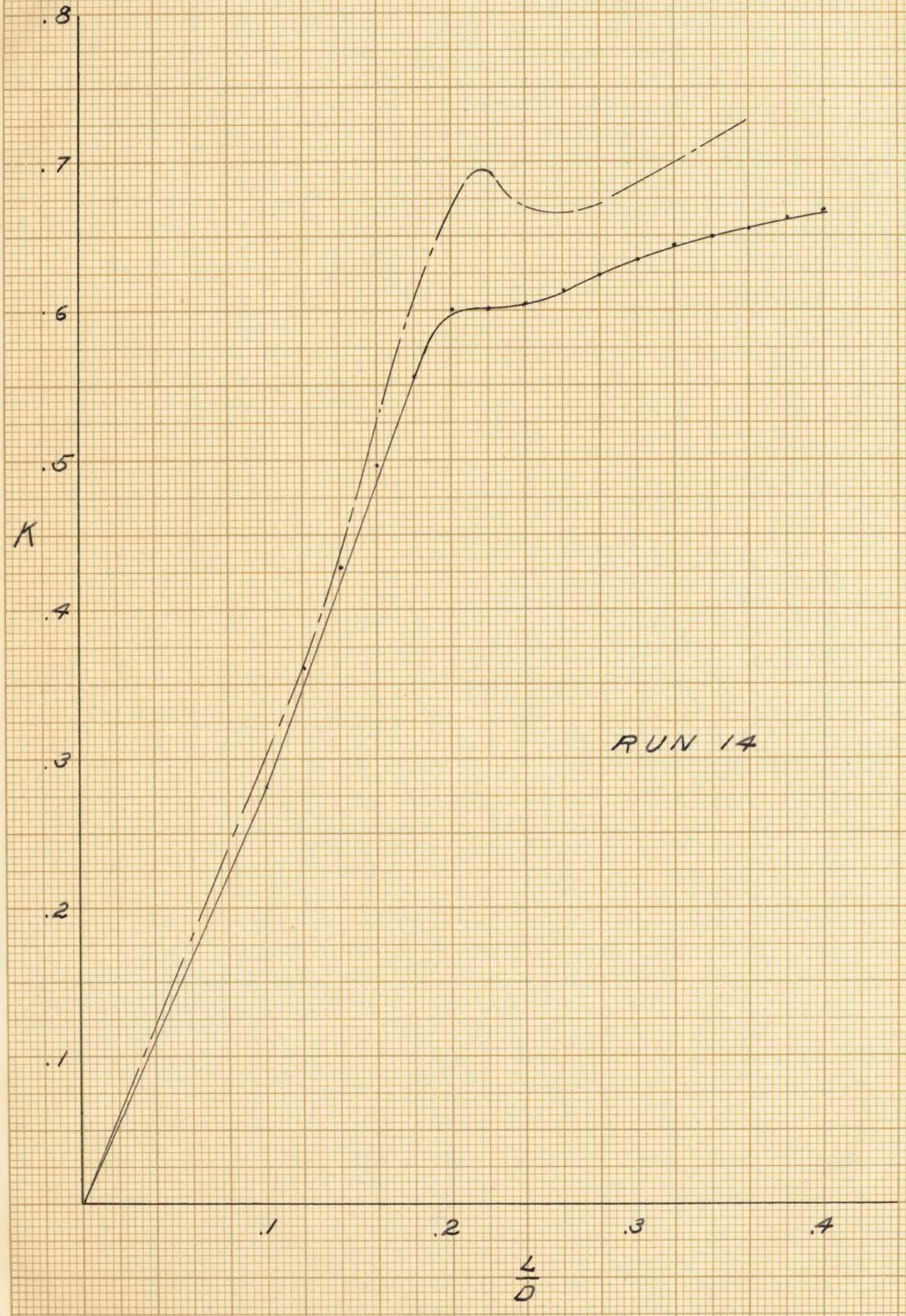
L/D
RUN 13



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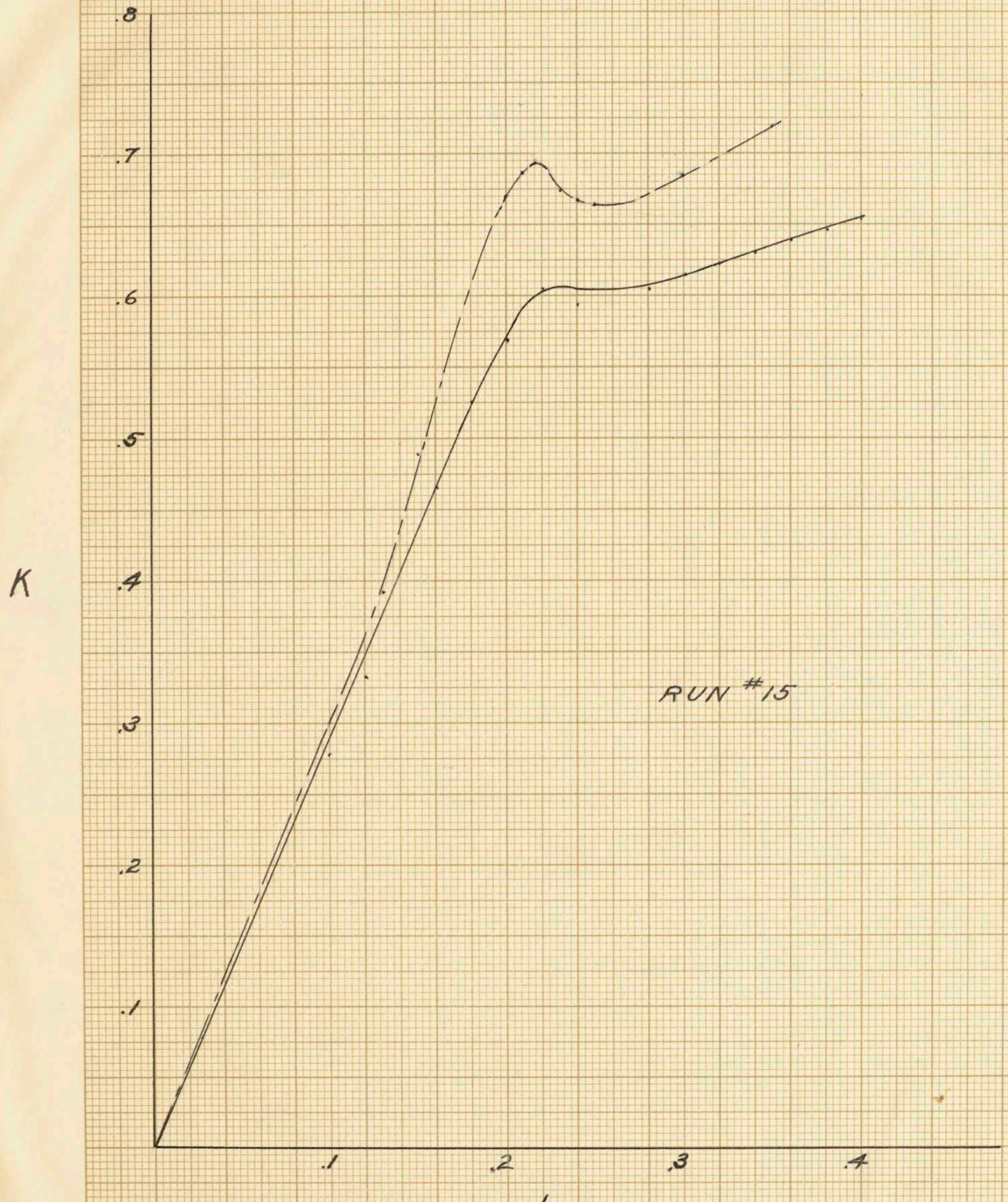

K
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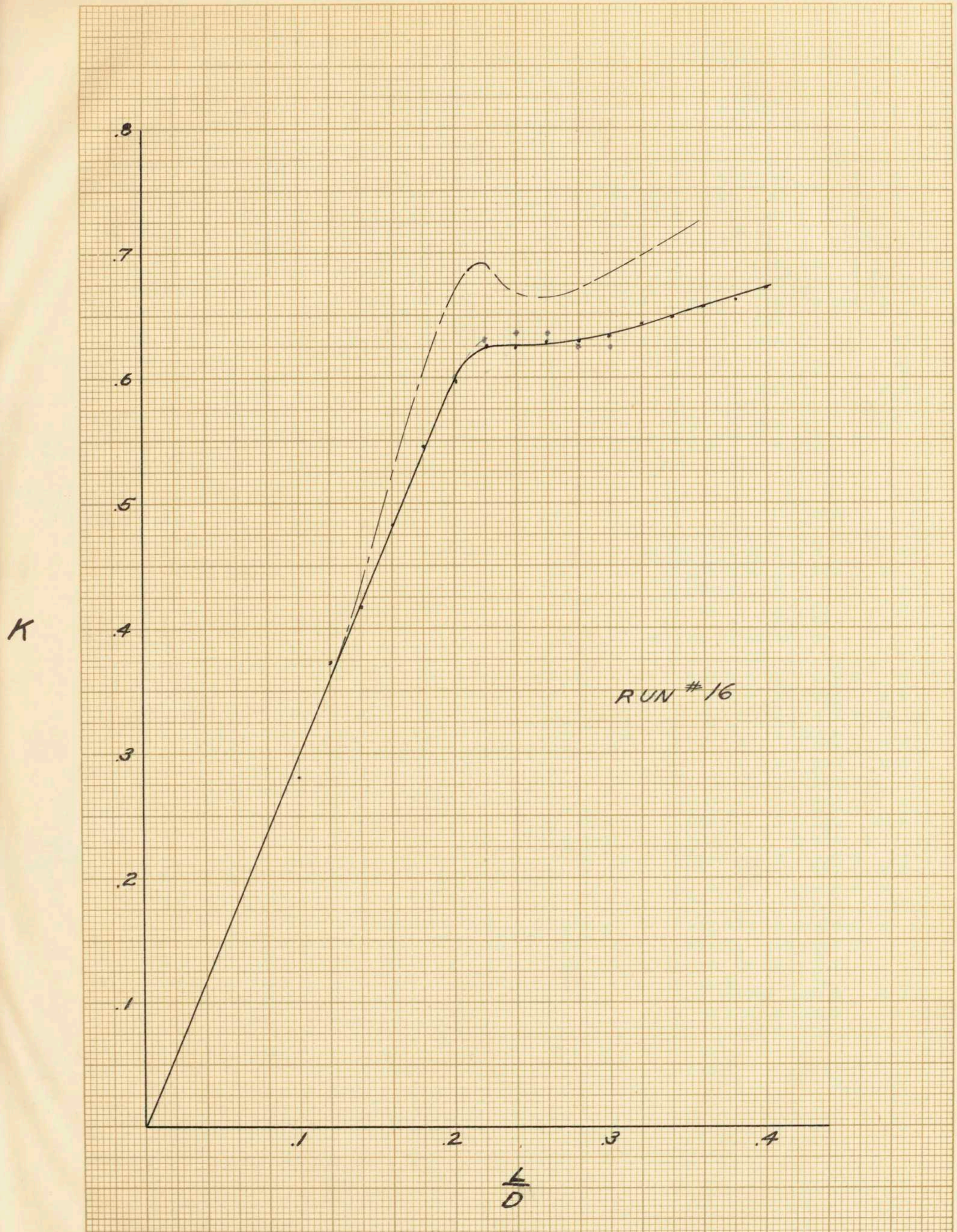
L/D
RUN #15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K
RUN #16
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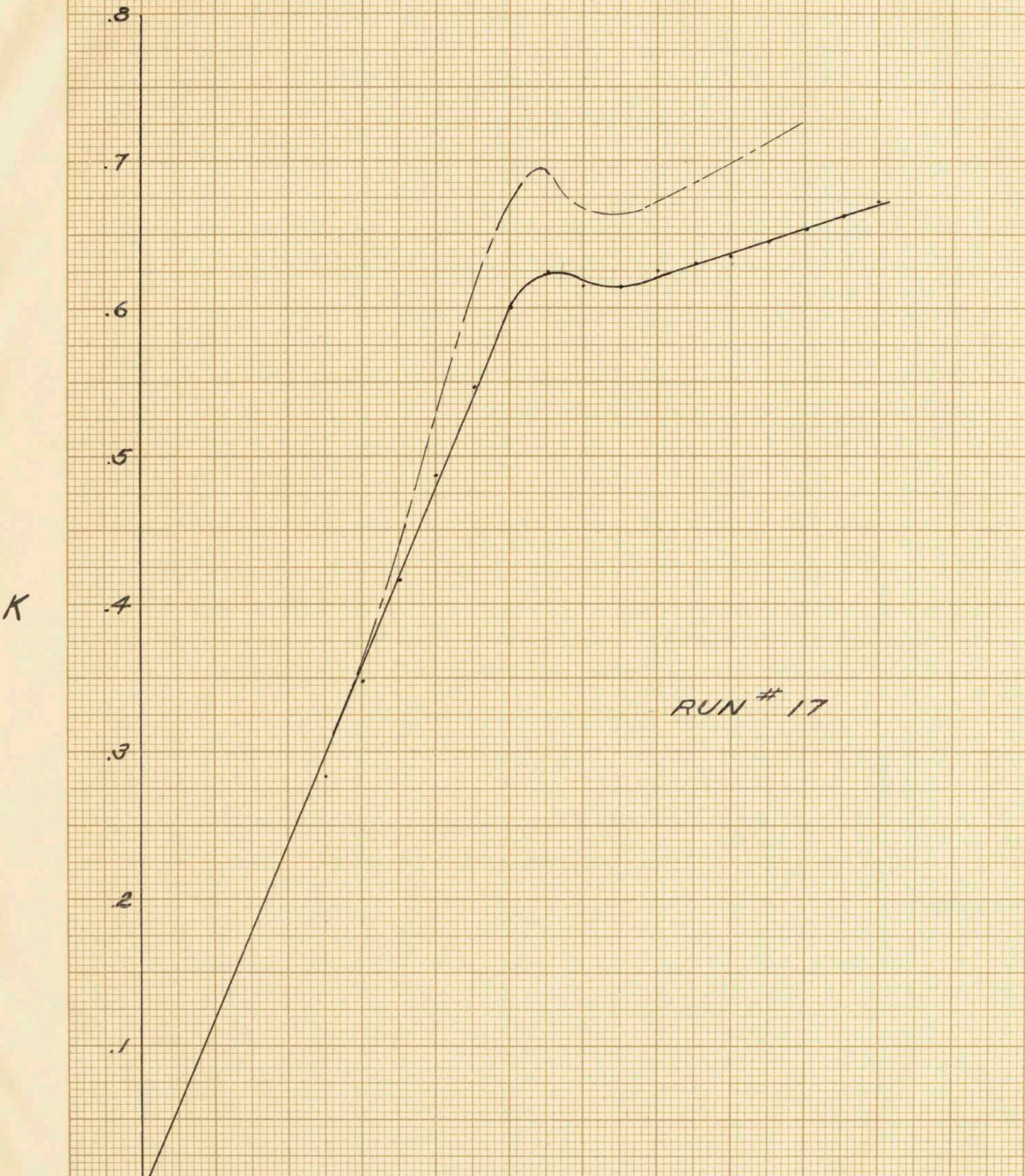
L
D



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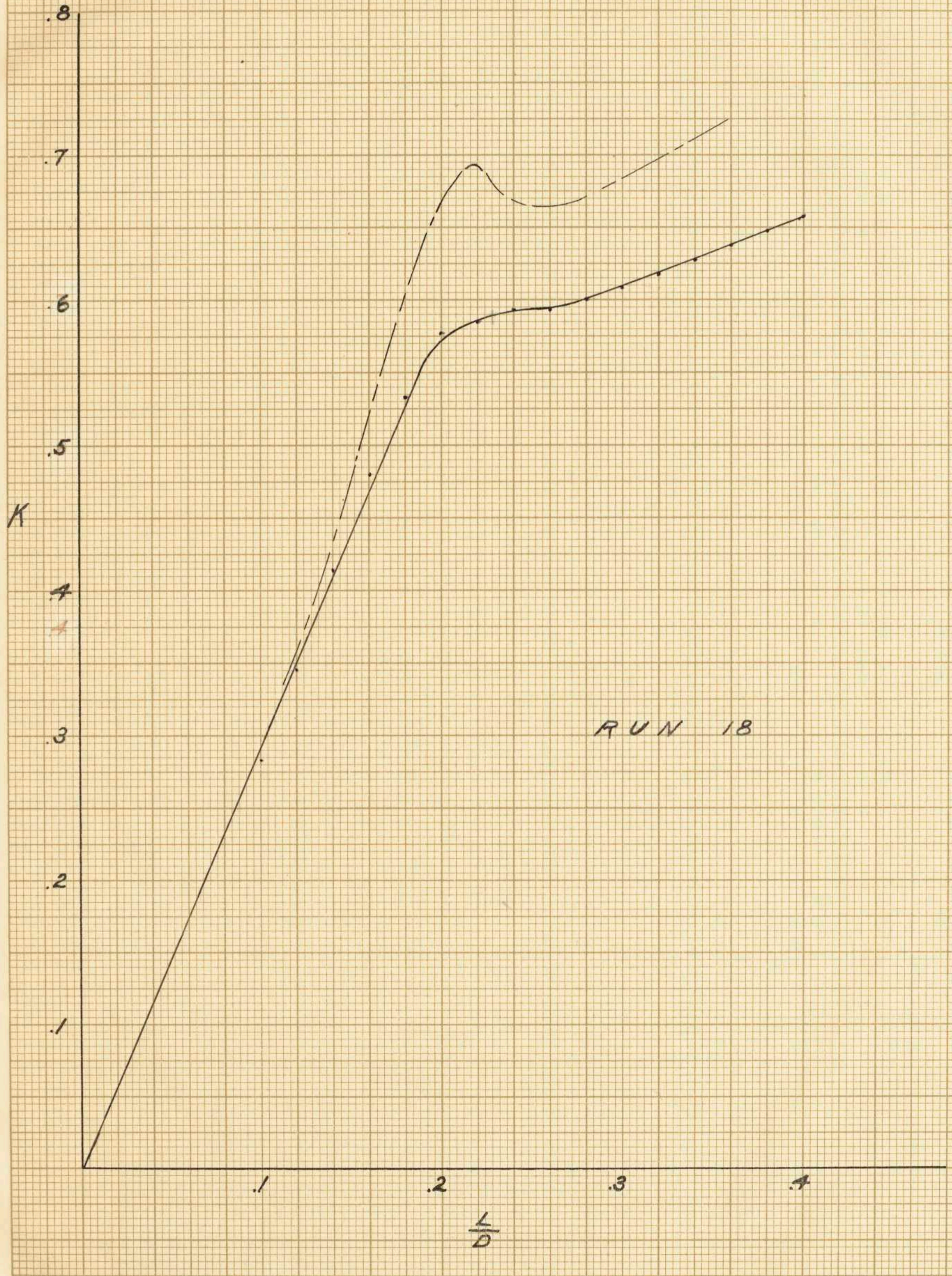

FORM 1 T

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K
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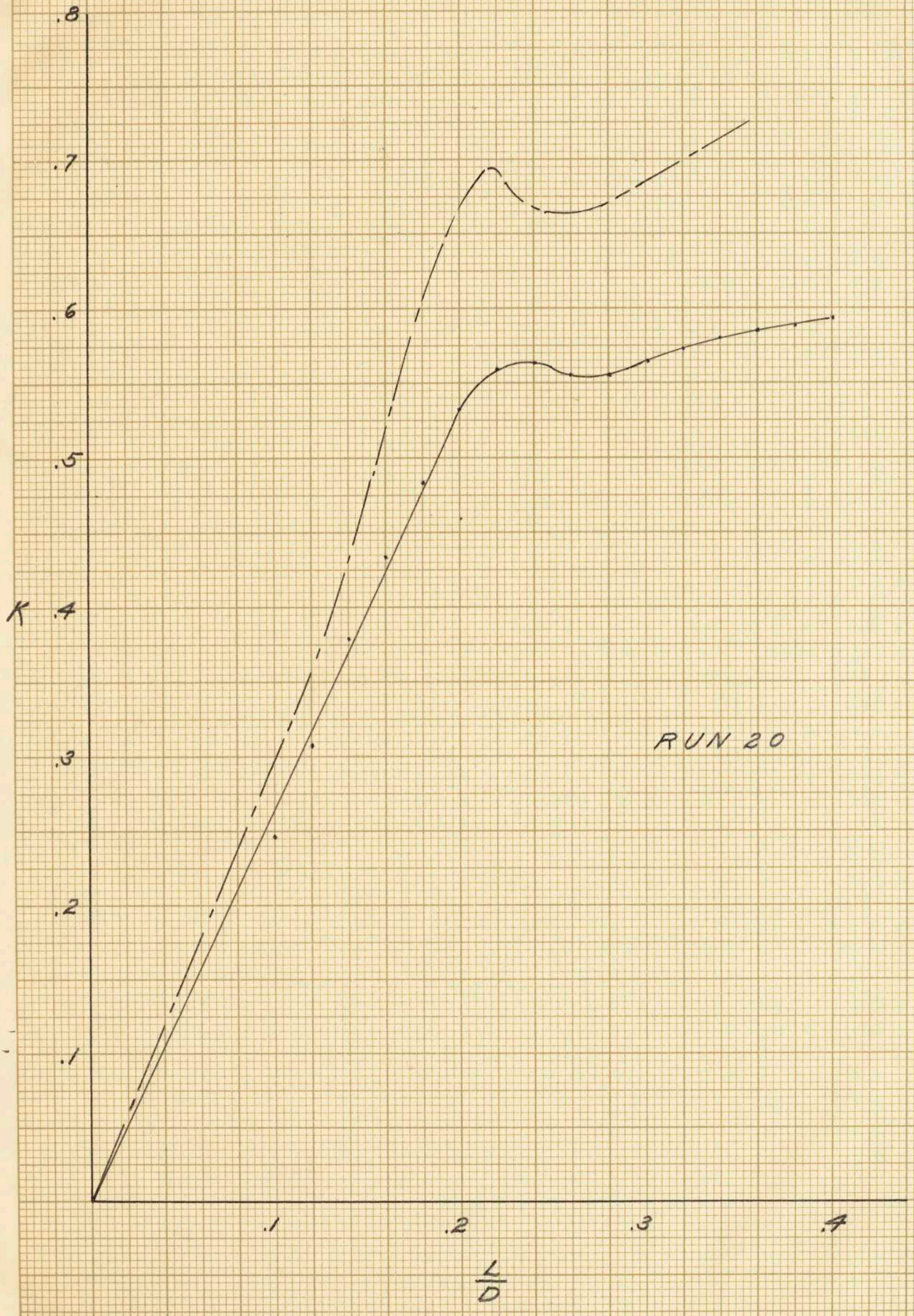
.4
L/D
RUN 19



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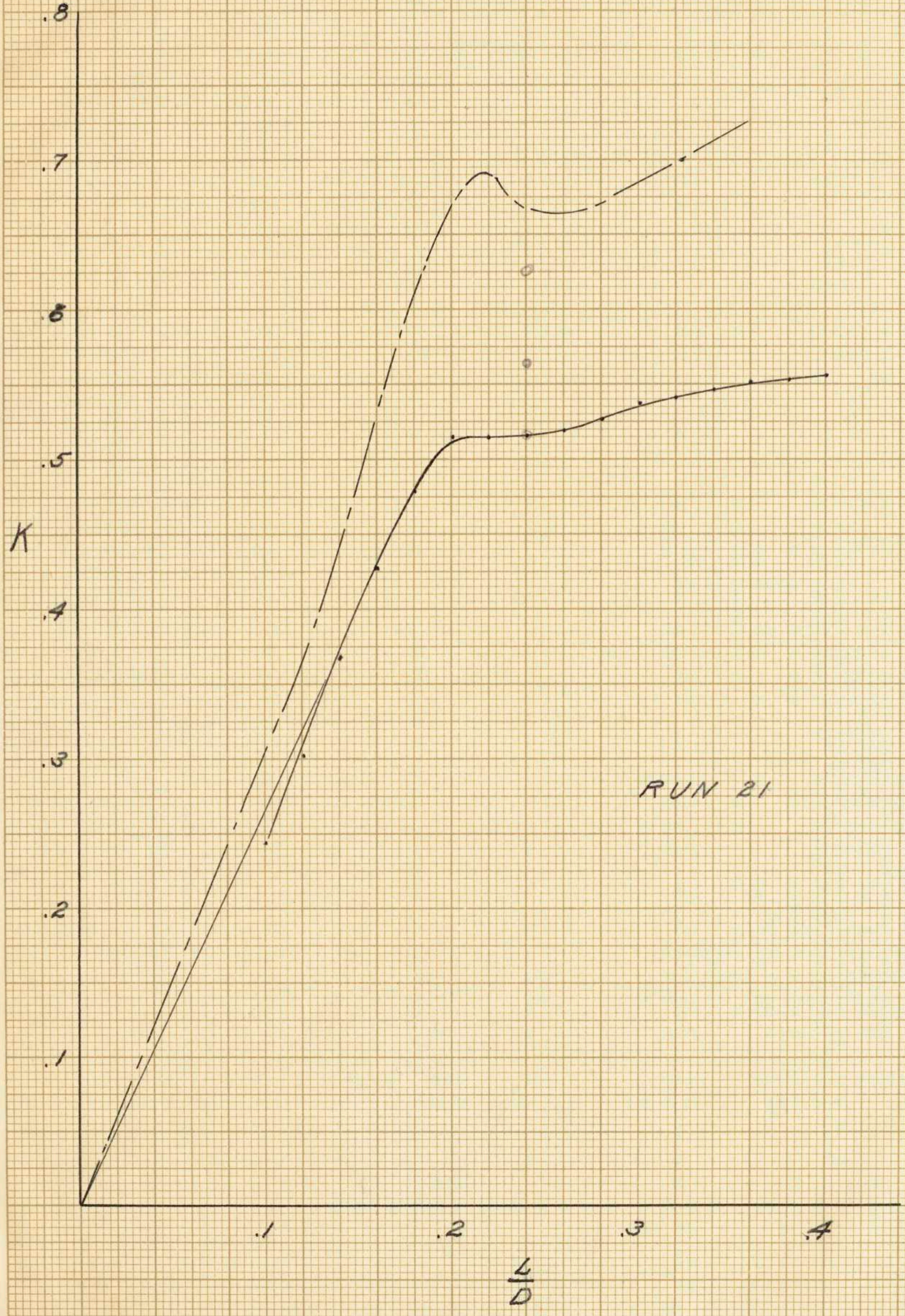

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