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SENSITIVITY OF PIPE FLOW CALCULATIONS

USING THE COLEBROOK-WHITE EQUATION

by

T.R.Fietz

Research Report No. 165

September 1985

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USING THE COLEBROOK-WHITE EQUATION

Abstract

The sensitivity of friction factor, discharge, and energy gradient to changes in pipe roughness and diameter is discussed. Results are presented graphically on Moody and Powell pipe charts, and applied to pipe data given in Australian Standard codes.

Notation

C_1, C_2, C_3	Constants
d, d_1, d_2	Pipe diameter (bore)
d_o	Maximum d
d_i	Minimum d
d_m	Mean or nominal pipe diameter
f, f_1, f_2	Darcy friction factor
F	Function of
g	Gravitational acceleration
h_f	Frictional head loss
k, k_1, k_2	Equivalent sand grain roughness
$\underline{k}$, $\underline{k}_1$, $\underline{k}_2$	Relative roughness $= \frac{k}{d}$
ℓ	Pipe length
Q, Q_1, Q_2	Discharge

$\underline{Q}$, $\underline{Q}_1$, $\underline{Q}_2$	Dimensionless discharge parameter $= \frac{Q}{k\nu}$
$\mathbb{R}$, $\mathbb{R}_1$, $\mathbb{R}_2$	Reynolds Number $= \frac{Vd}{\nu}$
S, S_1, S_2	Energy gradient $= \frac{h_f}{\ell}$
$\underline{S}$, $\underline{S}_1$, $\underline{S}_2$	Dimensionless energy gradient parameter $= \frac{Sgk^3}{\nu^2}$
V	Mean velocity $= \frac{4Q}{\pi d^2}$
Δd	Range of pipe diameters $= d_o - d_i$
α	Multiplier for k
ϕ	Function of
ν	Kinematic viscosity

INTRODUCTION

In his book "Internal Flow Systems" (Ref. 15) Miller comments on the "Accuracy of Friction Calculations" (Section 8.1.2). The "accuracy" of estimating friction coefficients (i.e. Darcy friction factors) is apparently the "sensitivity" of the friction factor f to changes in the basic variables pipe diameter d and equivalent sand grain roughness k.

This report looks at the sensitivity of f, Q, and S to changes in d and k. The frictional head loss for steady flow in circular pipes is based on the Colebrook-White equation. Sensitivity is determined numerically and results are presented graphically on Moody and Powell pipe charts. The results are applied to data given in Australian Standard codes.

BASIC EQUATIONS AND PIPE CHARTS

Frictional (or surface resistance) head loss for steady flow under pressure in prismatic circular pipes is given by the Darcy-Weisbach equation:

$$h_f = \frac{f \ell V^2}{d\,2g} \qquad (1)$$

Substituting $S = \frac{h_f}{\ell}$ and $V = \frac{4Q}{\pi d^2}$ gives an alternative form:

$$S = \frac{8 f Q^2}{\pi^2 g d^5} \qquad (2)$$

The friction factor is a function of the relative roughness and the

Reynolds number, i.e. $f = \phi\ (\underline{k}, \mathrm{I\!R})$ and the most popular expression for ϕ is given by the Colebrook-White equation (Ref.11):

$$\frac{1}{\sqrt{f}} = -2 \log_{10}\left(\frac{\underline{k}}{3.7} + \frac{2.51}{\mathrm{I\!R}\sqrt{f}}\right) \qquad (3)$$

The Colebrook-White equation may be plotted as log f vertically against log $\mathrm{I\!R}$ horizontally for parametric values of $\underline{k}$ to give the Moody Chart (Ref. 16). At low $\mathrm{I\!R}$ values equation (3) is asymptotic to the "Smooth Law":

$$\frac{1}{\sqrt{f}} = 2 \log_{10}\left(\mathrm{I\!R}\sqrt{f}\right) - 0.8 \qquad (4)$$

while at high $\mathrm{I\!R}$ values it is asymptotic to the "Rough Law":

$$\frac{1}{\sqrt{f}} = 1.74 + 2 \log_{10}\left(\frac{2}{\underline{k}}\right) \qquad (5)$$

For this report the Moody chart has been replotted to a scale of about three times that shown in text books. The Colebrook-White equation (3) was solved by Yao's method of successive substitution (Ref. 18).

For presenting some sensitivity results the chart due to Powell (Ref. 17) is more convenient than the Moody chart. Powell used the dimensionless terms $\underline{Q} = \frac{Q}{k\nu}$, $\underline{S} = \frac{Sgk^3}{\nu^2}$ and $\frac{d}{k}$. The third term has been inverted to give $\underline{k}$. Using $\underline{Q}$, $\underline{S}$ and $\underline{k}$, the friction factor becomes:

$$f = \frac{\pi^2 \underline{S}}{8 \underline{Q}^2 \underline{k}^5} \qquad (6)$$

and the Reynolds number becomes:

$$\mathbb{R} = \frac{4 \underline{Q} \underline{k}}{\pi} \qquad (7)$$

Using equations (6) and (7) for f and $\mathbb{R}$ in equation (3) gives an alternative expression of the Colebrook-White equation:

$$\underline{Q} = -\frac{\pi}{\sqrt{2}} \sqrt{\underline{S}}\ \underline{k}^{-2.5} \log_{10}\left(\frac{\underline{k}}{3.7} + \frac{2.51}{\sqrt{2\underline{S}}\ \underline{k}^{-1.5}}\right) \qquad (8)$$

Equation (8) is used to plot log S vertically against log Q horizontally for parametric values of k. Choosing k and S, Q is found directly, so avoiding any iteration or approximation required to solve the Colebrook-White equation.

The lower limit of turbulent flow occurs at $\mathbb{R}$ = 4000, so from equation (7):

$$\underline{Q} = 3142\ \underline{k}^{-1} \qquad (9)$$

Following Ackers (Ref. 1) the limit between smooth pipe and transitional flow is taken where there is a 1% difference in velocities calculated by equations (3) and (4). Transforming Ackers' dimensionless groups to the present set gives:

$$\underline{Q} = 14.69\,\underline{S}\,\underline{k}^{-3} \qquad (10)$$

Equation (10) was solved simultaneously with equation (8) using the method of bisection (or interval halving) (Ref. 10). Defining:

$$F(\underline{S}) = \underline{Q}(\underline{S})_{\text{Eqn.(10)}} - \underline{Q}(\underline{S})_{\text{Eqn.(8)}} \qquad (11)$$

For a given value of $\underline{k}$, $F(\underline{S}) = 0$ at the required root $\underline{S}$.

Again following Ackers (Ref. 1) the limit between transitional and rough pipe flow is given by:

$$\underline{Q} = 634\,\underline{k}^{-2} \qquad (12)$$

The Powell Chart, with sufficient scope to cover most practical water supply problems, and including the various flow zone limits, is shown in Figure 1.

To demonstrate the relationship between the Moody and the Powell charts parametric values of $\mathbb{R}$ and f have been plotted on the Powell chart in Figure 2. The parametric $\mathbb{R}$ lines were obtained directly from equation (7). The parametric f lines were obtained by using equation (6) to obtain f for numerous points and then interpolating contours of equal f value.

OPERATING ZONES ON PIPE CHARTS

Pipe Data

k and d values for some typical clean water supply pipes are shown in Table 1. The steel pipe, araldite coated, is included as an example of a modern "super-smooth" material. The remaining data are taken from Australian Standards and commercial references.

The practical problem of selecting k values, which requires "educated engineering judgment" (Ref. 9) or "engineer's judgment" (Ref. 2), is not discussed here, except to note an apparent anomaly in the Australian Standard (Ref. 9). The footnote to Table 1 reproduces the k value selection criteria and implies that higher k values may be selected to allow for increased fitting (or minor) losses. This contrasts with the traditional procedure (Ref. 1) where fitting losses are allowed for by adding an equivalent length of pipe or by using loss coefficients. The range of k values is then used to allow for variation in quality of manufacture or construction, or possibly deterioration with age.

Operating Zones

Using the pipe data from Table 1, operating zones have been plotted on a Moody chart to give Figure 3 and on a Powell chart to give Figure 4. Note the overlap of zones for smoother pipes on the Moody chart. The Powell chart allows better definition of operating zones, as well as better presentation of sensitivity results.

TABLE 1: DATA FOR TYPICAL CLEAN PIPES

Material	k(mm) Range	Ref	d(m) Range	Ref
Steel, araldite coated	0.0015	14	0.2 to 2.7	14
Brass, Copper, UPVC, Polyethylene	0.003 to 0.015	9	0.015 to 0.25	13
Asbestos Cement	0.015 to 0.06	9	0.05 to 0.6	12
Concrete, spun	0.03 to 0.15	9	0.1 to 1.83	5
Steel, cement mortar lined	0.03 to 0.15	9	0.075 to 0.3	3
Cast Iron, bitumen coated	0.06 to 0.3	9	0.08 to 0.625	6
Cast Iron, uncoated	0.15 to 0.6	9	0.08 to 0.625	6

Note: k values from Ref. 9 are for "pipes concentrically jointed and clean". Also "lowest values of k - - - are for straight lines and few fittings".

METHOD OF PRESENTING SENSITIVITY RESULTS

The following procedure has been used to plot sensitivity results:

(1) At a point on a pipe chart the variables have subscript 1, e.g. k_1, d_1, Q_1, S_1, f_1.

(2) Make a change in one of the independent variables, say change k_1 to $k_2 = \alpha\, k_1$, where α is a multiplier used throughout.

(3) Find the new value of one of the dependent variables, say S_2.

(4) Plot S_2/S_1 at the point on the chart.

(5) Repeat for numerous points on the chart and plot contour lines of equal S_2/S_1 value.

Contour lines have been found by linear interpolation between plotted points. The pipe charts are plotted to logarithmic scales, however, so an error is introduced by linear interpolation. This error may be reduced by taking a finer mesh of points.

The dependent variables have been taken as f, S, and Q, and the independent variables as k and d. Results are presented on both the Moody and Powell Pipe Charts.

SENSITIVITY RESULTS SHOWN ON THE MOODY CHART

k Changed, Find Change in S for Q and d Constant

From equation (2):

$$S_1 = f_1 \cdot \frac{8Q^2}{\pi^2 g d^5} = f_1 C_1 \qquad (13)$$

and $$S_2 = f_2 C_1 \qquad (14)$$

so $$\frac{S_2}{S_1} = \frac{f_2}{f_1} \qquad (15)$$

For example, say $\alpha = 2$, then $k_2 = k_1 \times 2$, and f_2 is found for $\mathbb{R}_1$ and $\underline{k}_2 = \underline{k}_1 \times 2$, from equation (3), solved by Yao's method (Ref. 18).

Results for the change in S produced by taking $\alpha = 0.5$, 2 and 5 are shown as Figures 5, 6, and 7, respectively. Comparison of Figures 5 and 6 indicates that halving <u>k</u> has much less effect on S than doubling it. Subsequent results are given for increase in <u>k</u> only, i.e. for $\alpha = 2$ and 5.

k Changed, Find Change in Q for S and d Constant

Combining equation (1) and $\mathbb{R} = \frac{Vd}{\nu}$ gives

$$S = f\,\mathbb{R}^2 \frac{\nu^2}{2gd^3} = f\,\mathbb{R}^2 C_2 \qquad (16)$$

As S is constant it follows:

$$f_1\,\mathbb{R}_1^2 = f_2\,\mathbb{R}_2^2 \qquad (17)$$

Now $\dfrac{Q_2}{Q_1} = \dfrac{\mathbb{R}_2}{\mathbb{R}_1}$ is required.

f_1 and $\mathbb{R}_1$ are known at the given point, so equation (17) may be rearranged to give:

$$F(\mathbb{R}_2) = f_1\,\mathbb{R}_1^2 - f_2(\mathbb{R}_2)\,\mathbb{R}_2^2 \qquad (18)$$

Using the method of bisection, $F(\mathbb{R}_2) = 0$ at the required root $\mathbb{R}_2$.

Results for the change in Q produced by taking $\alpha = 2$ and 5 are shown as Figures 8 and 9, respectively.

d Changed, Find Change in S for Q and k Constant

From equation (2):

$$S_1 = f_1 \frac{Q_1^2}{d_1^5} C_3 \tag{19}$$

Similarly $$S_2 = f_2 \frac{Q_2^2}{d_2^5} C_3 \tag{20}$$

As $Q_1 = Q_2$:

$$\frac{S_2}{S_1} = \frac{f_2(d_2)}{f_1(d_1)} \left(\frac{d_1}{d_2}\right)^5 \tag{21}$$

Figure 10 shows $\frac{f_2}{f_1}$ for $d_2 = 1.1d_1$, i.e. a 10% increase in pipe diameter. Figure 10 indicates that f is relatively insensitive to d change. For normal operating zones (Figure 3) $\frac{f_2}{f_1}$ is greatest at $\mathbb{R} = 10^4$ and $\underline{k} = 0.01$. Values of $\frac{f_2}{f_1}$ have been taken at this point for a range of $\frac{d_2}{d_1}$ values to plot Figure 11.

Ignoring the effect of the f variation gives the approximate relation:

$$\frac{S_2}{S_1} = \left(\frac{d_1}{d_2}\right)^5, \text{ within } \pm 4\% \text{ for } 0.9 < \left(\frac{d_2}{d_1}\right) < 1.1 \qquad (22)$$

d Changed, Find Change in Q for S and k Constant

In equations (18) and (19), $S_1 = S_2$ so:

$$\frac{Q_2}{Q_1} = \sqrt{\frac{f_1(Q_1)}{f_2(Q_2)}} \left(\frac{d_2}{d_1}\right)^{2.5} \qquad (23)$$

Again taking maximum $\frac{f_2}{f_1}$ values at $\mathbb{R} = 10^4$ and $\underline{k} = 0.01$, equation (23) is plotted as Figure 12.

Ignoring the effect of the f variation gives the approximate relation:

$$\frac{Q_2}{Q_1} = \left(\frac{d_2}{d_1}\right)^{2.5}, \text{ within } \pm 2\% \text{ for } 0.9 < \left(\frac{d_2}{d_1}\right) < 1.1 \qquad (24)$$

SENSITIVITY RESULTS SHOWN ON THE POWELL CHART

k Changed, Find Change in S for Q and d Constant

Taking $k_2 = \alpha \times k_1$ then $\underline{Q}_1 = \frac{Q}{k_1 \nu}$ and $\underline{Q}_2 = \frac{Q}{k_2 \nu} = \frac{Q}{\alpha k_1 \nu}$.

It follows:

$$\underline{Q}_2 = \frac{\underline{Q}_1}{\alpha} \qquad (25)$$

Similarly, from the definitions of $\underline{S}_1$ and $\underline{S}_2$ it follows:

$$\frac{S_2}{S_1} = \frac{\underline{S}_2\,\alpha^{-3}}{\underline{S}_1} \qquad (26)$$

To find $\underline{S}_2$ equation (8) is rearranged and substitutions for $\underline{Q}_2$ and $\underline{k}_2$ made from above:

$$F(\underline{S}_2) = \frac{\underline{Q}_1}{\alpha} + \frac{\pi}{\sqrt{2}}\sqrt{\underline{S}_2}\,(\alpha\,\underline{k}_1)^{-2.5}\log_{10}\left(\frac{\alpha\,\underline{k}_1}{3.7} + \frac{2.51}{\sqrt{2\underline{S}_2}\,(\alpha\,\underline{k}_1)^{-1.5}}\right)$$

The method of bisection is used to find the root of $\underline{S}_2$ of equation (27).

Results for the change in S produced by taking α = 2 and 5 are shown as Figures 13 and 14, respectively.

<u>k Changed, Find Change in Q for S and d Constant</u>

Taking $k_2 = \alpha \times k_1$, then from the definition of $\underline{S}$:

$$\underline{S}_2 = \alpha^3\,\underline{S}_1 \qquad (28)$$

$\underline{Q}_2$ is found from equation (8), using $\underline{k}_2 = \alpha \times \underline{k}_1$, and $\underline{S}_2$ from equation

(28). From the definition of $\underline{Q}$:

$$\frac{\underline{Q}_1}{Q_2} = \frac{\alpha \underline{Q}_2}{\underline{Q}_1} \qquad (29)$$

Results for the change in Q produced by taking $\alpha = 2$ and 5 are shown as Figures 15 and 16, respectively.

<u>d Change, Powell Chart</u>

Figures 11 and 12 show adequately the effects of d change on S and Q respectively. There is no advantage in showing equivalent information on Powell Charts.

APPLICATION OF SENSITIVITY CHARTS

To Predict the Effect of k Change

For a given clean pipe the upper values of k are usually four or five times the lower values, as shown in Table 1. This corresponds to $\alpha = 5$ and is covered by the sensitivity charts labelled $\underline{k}\times5$. Intermediate values are covered by the charts labelled $\underline{k}\times2$.

Combination of the operating zone charts (Figures 3 and 4) with the relevant sensitivity chart shows quantitatively the effect of k change. This may guide selection of initial k value for new pipes and show which pipes are more sensitive to k increase with age.

To Predict the Effect of d Change

Variations in pipe diameter in manufacture to Australian Standards are shown in Table 2. The internal diameter, or bore, of a pipe may range from d_o maximum to d_i minimum, with a mean value d_m. The mean d_m is normally used for pipe flow calculations.

If the pipe manufacturer works to the lower limit of diameter d_i, while d_m is used for calculations, then the $-\frac{\Delta d}{2d_m}$ % values in Table 2 apply. For smaller pipes $\frac{\Delta d}{2d_m}$ is between -4% and -5% and this corresponds to $\frac{d_2}{d_1}$ of 0.96 and 0.95, respectively, for using Figures 11 and 12.

Alternatively d_i could be taken for calculations in which case $\frac{\Delta d}{d_i}$ % in Table 2 gives the percentage increase in diameter from d_i to d_o. $\frac{\Delta d}{d_i}$ may approach +10% for smaller pipes. The corresponding value of $\frac{d_2}{d_1}$ is 1.1 for use of Figures 11 and 12.

Other possible diameter variations include those due to ovality of plastic pipes, and distortions due to soil loading of buried, thin walled pipes.

To Derive General Sensitivity Rules

Figures 6, 7, 8 and 9 indicate that the closer the operating point on the Moody chart is to the smooth pipe line, then the less sensitive f, S and Q are to k change.

If the small variation in f with change in d is ignored, then S and Q

TABLE 2: PIPE DIAMETER VARIATIONS IN MANUFACTURE

Material	Nominal Size (mm)	Class	Diameter or Bore d_o max (mm)	d_i min (mm)	d_m mean (mm)	$\Delta d = d_o - d_i$ (mm)	$\frac{\Delta d}{2}$ (mm)	$\frac{\Delta d}{d_i}\%$	$\frac{\Delta d}{2d_m}\%$	Ref
UPVC	15	18	18.3	17.2	17.75	1.1	0.55	+6.39	±1.55	8
	200	18	191.6	187.2	189.4	4.4	2.2	+2.35	±1.16	
	575	18	535.8	524.8	530.3	11	5.5	+2.1	±1.04	
Polyethylene	75	15	45.2	41.2	43.2	4	2	+9.71	±4.63	7
(Type 30)	710	4.5	615.7	599.8	607.75	15.9	7.95	+2.65	±1.31	
Asbestos Cement	75	F	72.77	66.42	69.6	6.35	3.18	+9.56	±4.57	4
	610	C	585.1	569.21	577.16	15.89	7.95	+2.79	±1.38	
Cast Iron,	75	D	84.33	78.74	81.54	5.59	2.8	+7.1	±3.43	6
Uncoated	610	D	629.16	622.3	625.73	6.86	3.43	+1.1	±0.55	
Cast Iron, Cement	75	D, Light	75.18	68.83	72.01	6.35	3.18	+9.23	±4.42	6
Mortar Lined	610	D, Light	613.03	600.33	606.68	12.7	6.35	+2.12	±1.05	

sensitivity to change in d may be taken as independent of pipe material.

The general rules for f variation proposed by Miller (Ref. 14) could not be verified. For example, Miller states that "At high Reynolds numbers an error of 100 percent in a roughness value causes about a 10 percent error in friction coefficient". Figures 5 and 6 show that the "error" in f varies throughout the chart. The "10 percent error" line, (corresponding to $f_2/f_1 = 0.9$ or 1.1 on Figures 5, 6 and 7), is approximately parallel to the smooth pipe line so a 10 percent error may occur over a wide range of Reynolds numbers.

Miller also specifies f "accuracy" zones, as shown in Fig. 17. The variation in f is apparently due to variation in roughness k, as "the pipe diameter is known to within 0.5 percent". There is no correlation between Fig. 17 and Figs. 5, 6 and 7, which show f variation for $\frac{k}{2}$, $\underline{k}\times 2$, and $\underline{k}\times 5$ respectively.

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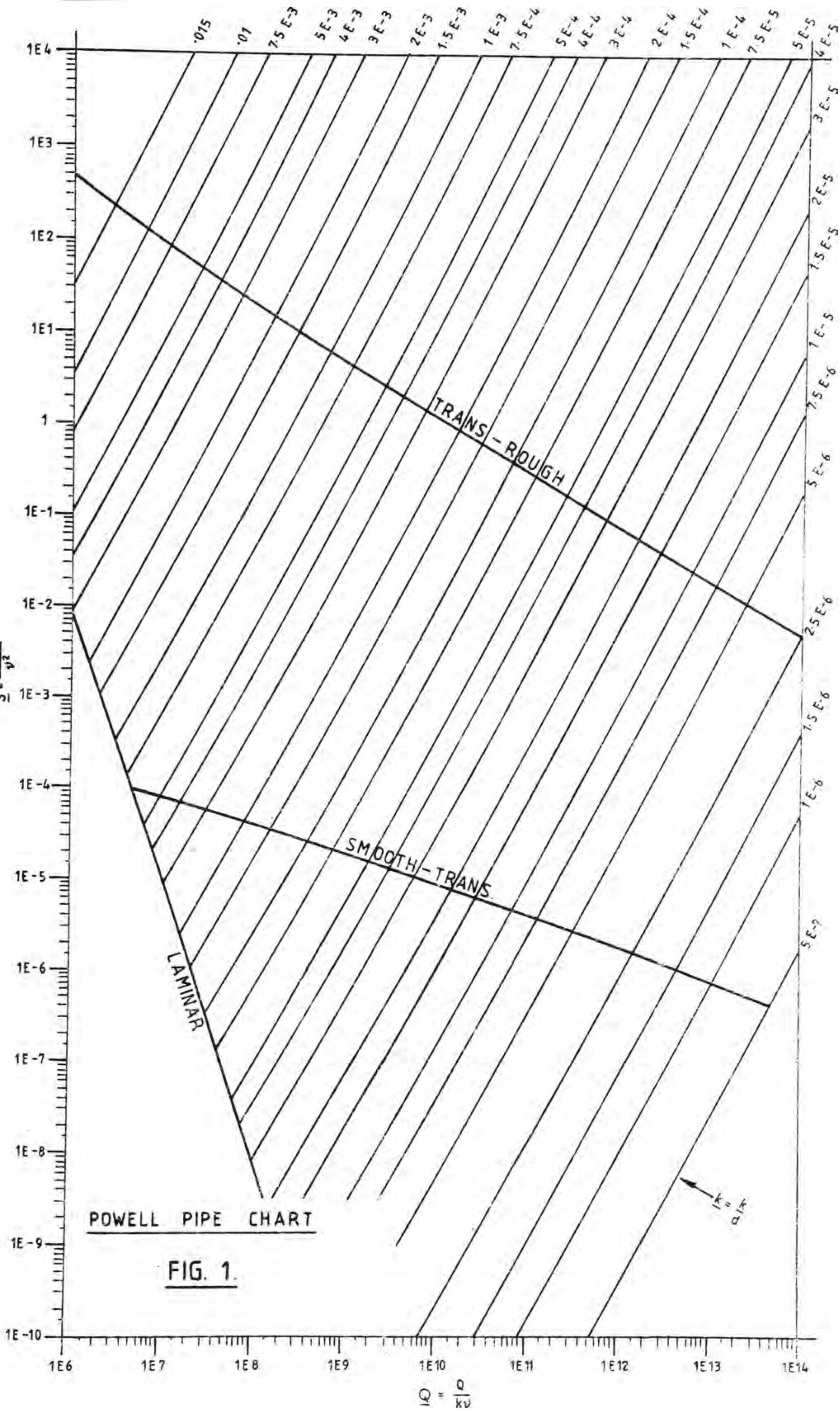
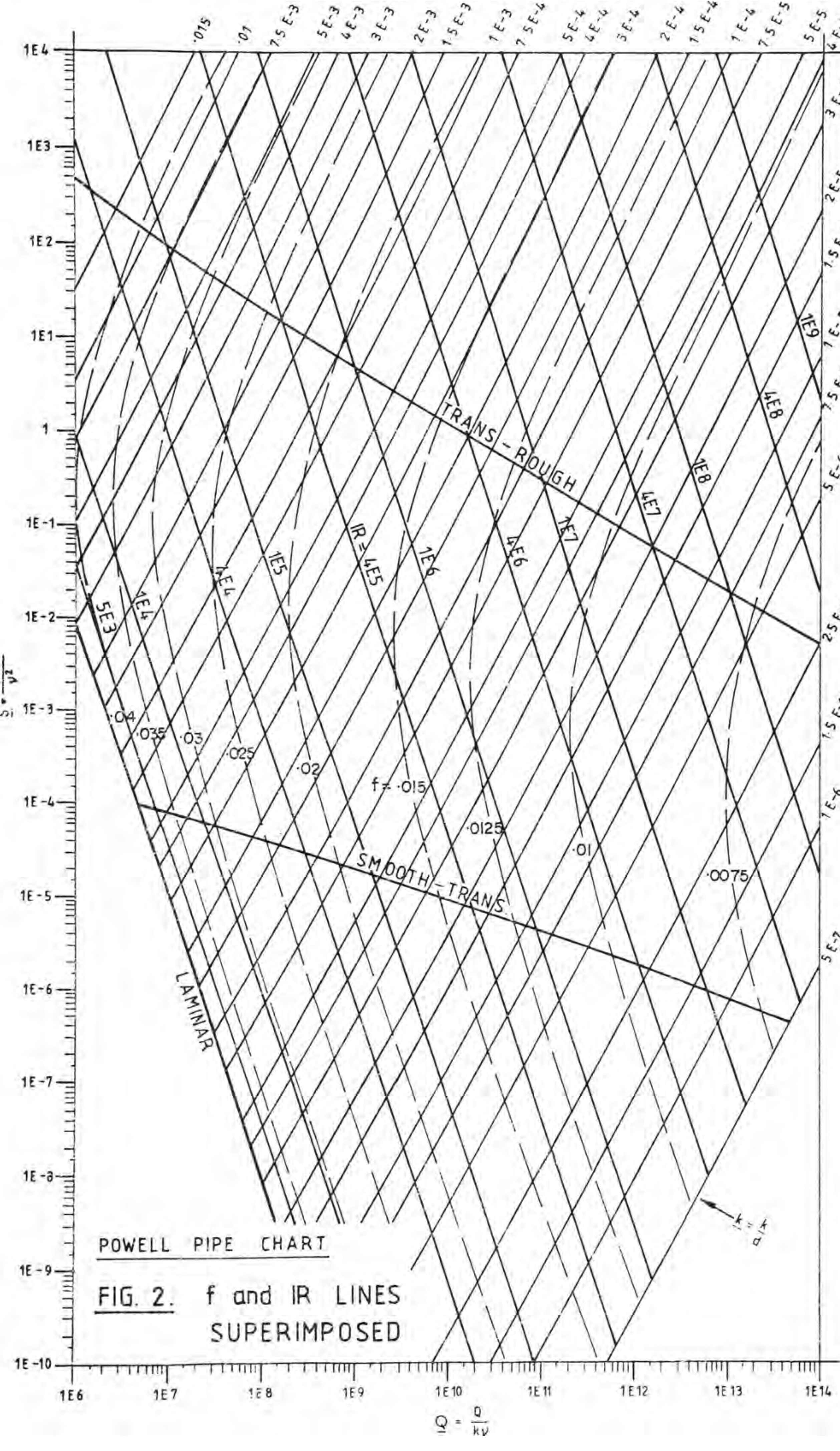


POWELL PIPE CHART

FIG. 1.



POWELL PIPE CHART

FIG. 2. f and IR LINES SUPERIMPOSED

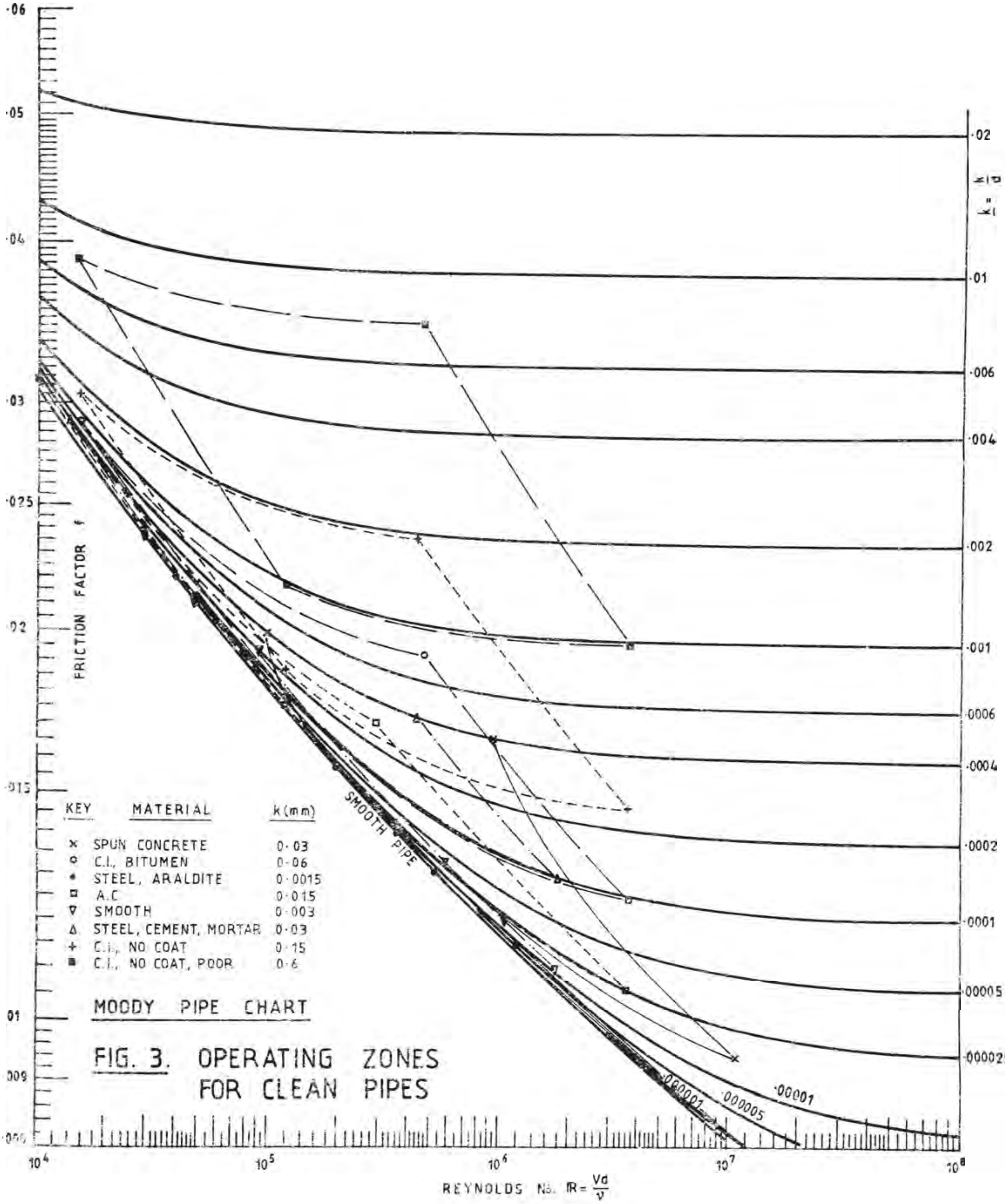
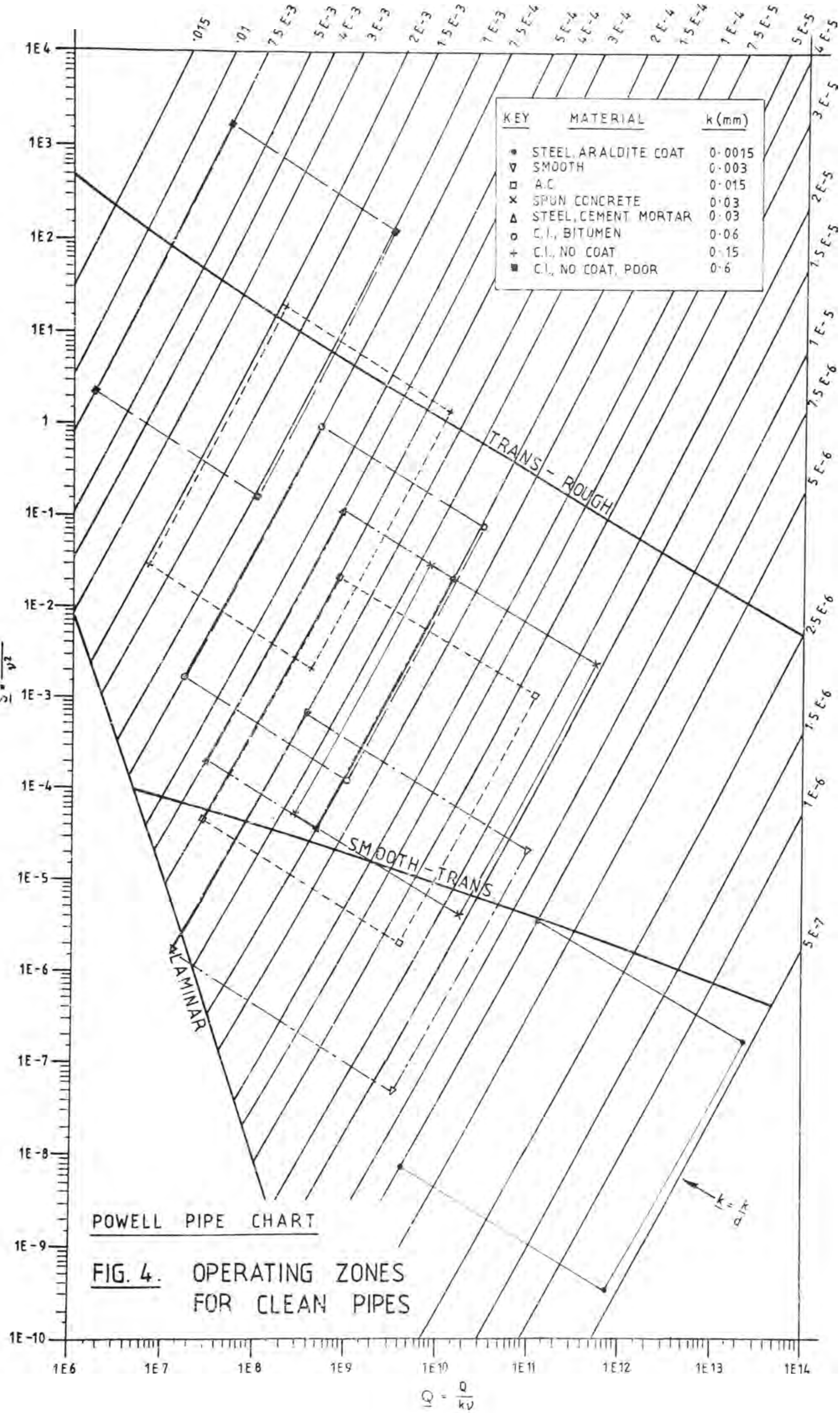
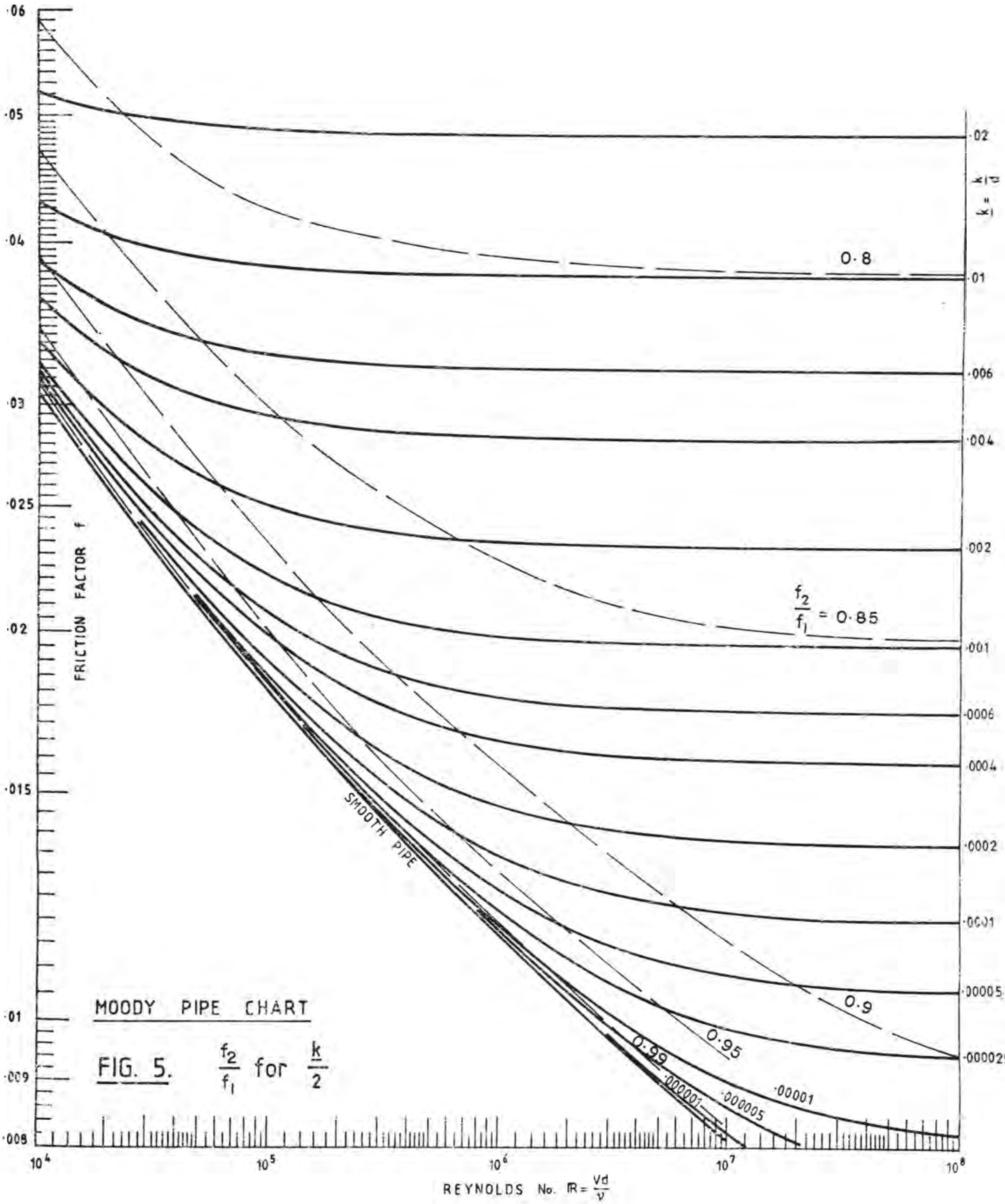


FIG. 3. OPERATING ZONES FOR CLEAN PIPES



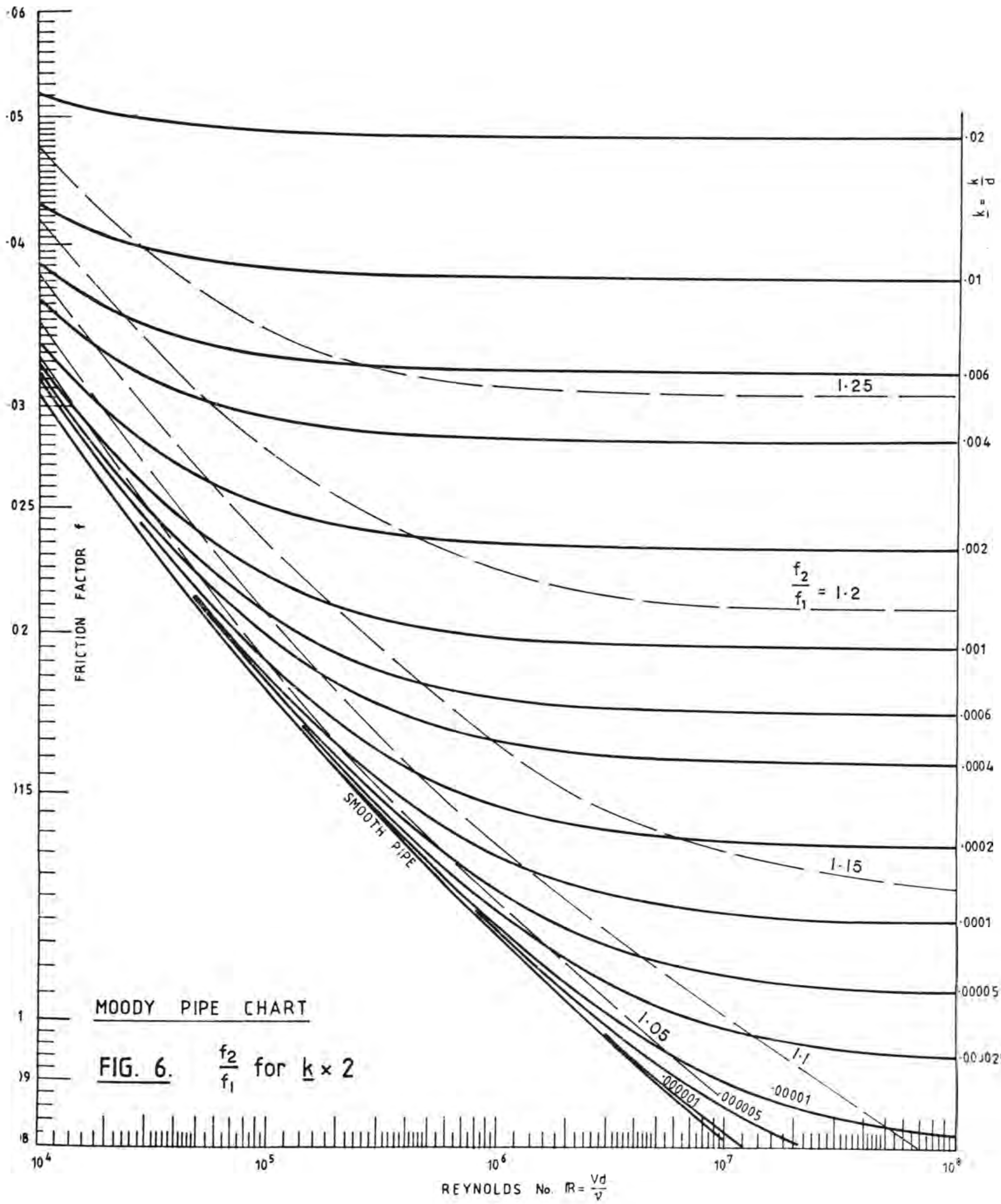
POWELL PIPE CHART

FIG. 4. OPERATING ZONES FOR CLEAN PIPES



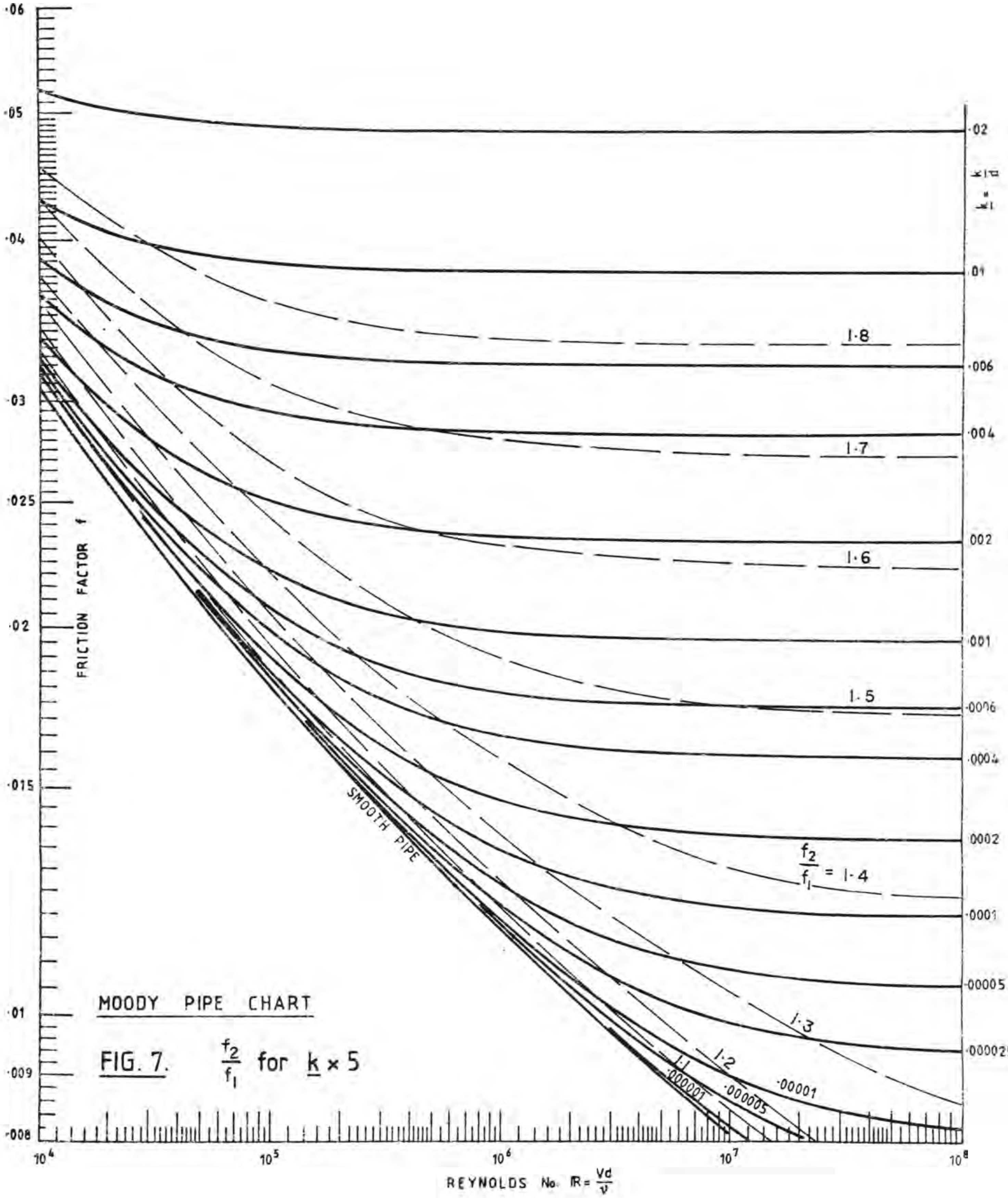
MOODY PIPE CHART

FIG. 5. $\frac{f_2}{f_1}$ for $\frac{k}{2}$



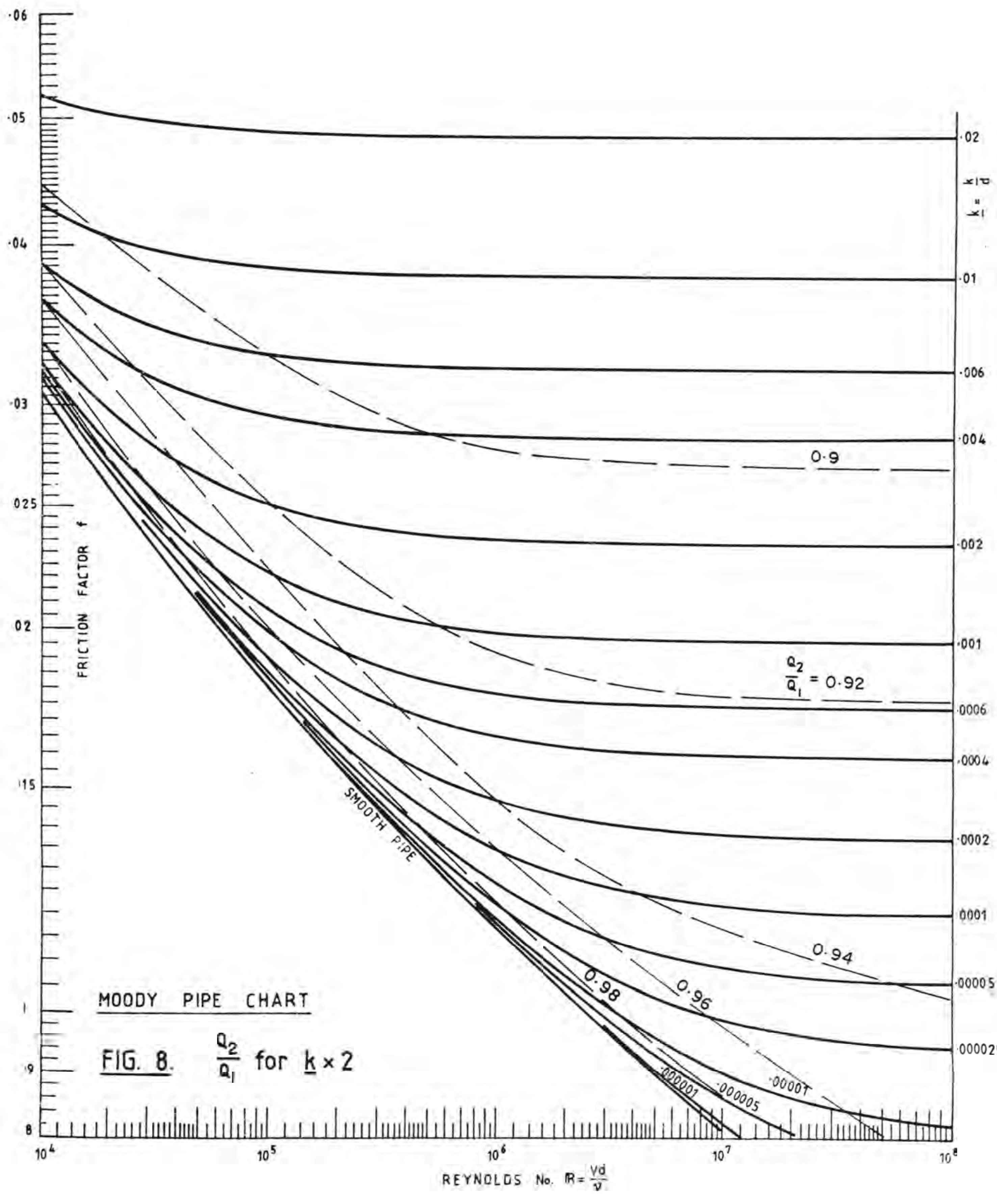
MOODY PIPE CHART

FIG. 6. $\frac{f_2}{f_1}$ for $\underline{k} \times 2$



MOODY PIPE CHART

FIG. 7. $\frac{f_2}{f_1}$ for $\underline{k} \times 5$



MOODY PIPE CHART
FIG. 8. $\frac{Q_2}{Q_1}$ for $\underline{k} \times 2$
FRICTION FACTOR f
REYNOLDS No. $R = \frac{Vd}{\nu}$
$\frac{k}{d} = \frac{k}{d}$
$\frac{Q_2}{Q_1} = 0{\cdot}92$
0·9
0·94
0·96
0·98
SMOOTH PIPE
·06
·05
·04
·03
·025
·02
·015
·01
·009
·008
10^4
10^5
10^6
10^7
10^8
·02
·01
·006
·004
·002
·001
·0006
·0004
·0002
·0001
·00005
·000025
·00001
·000005
·000001

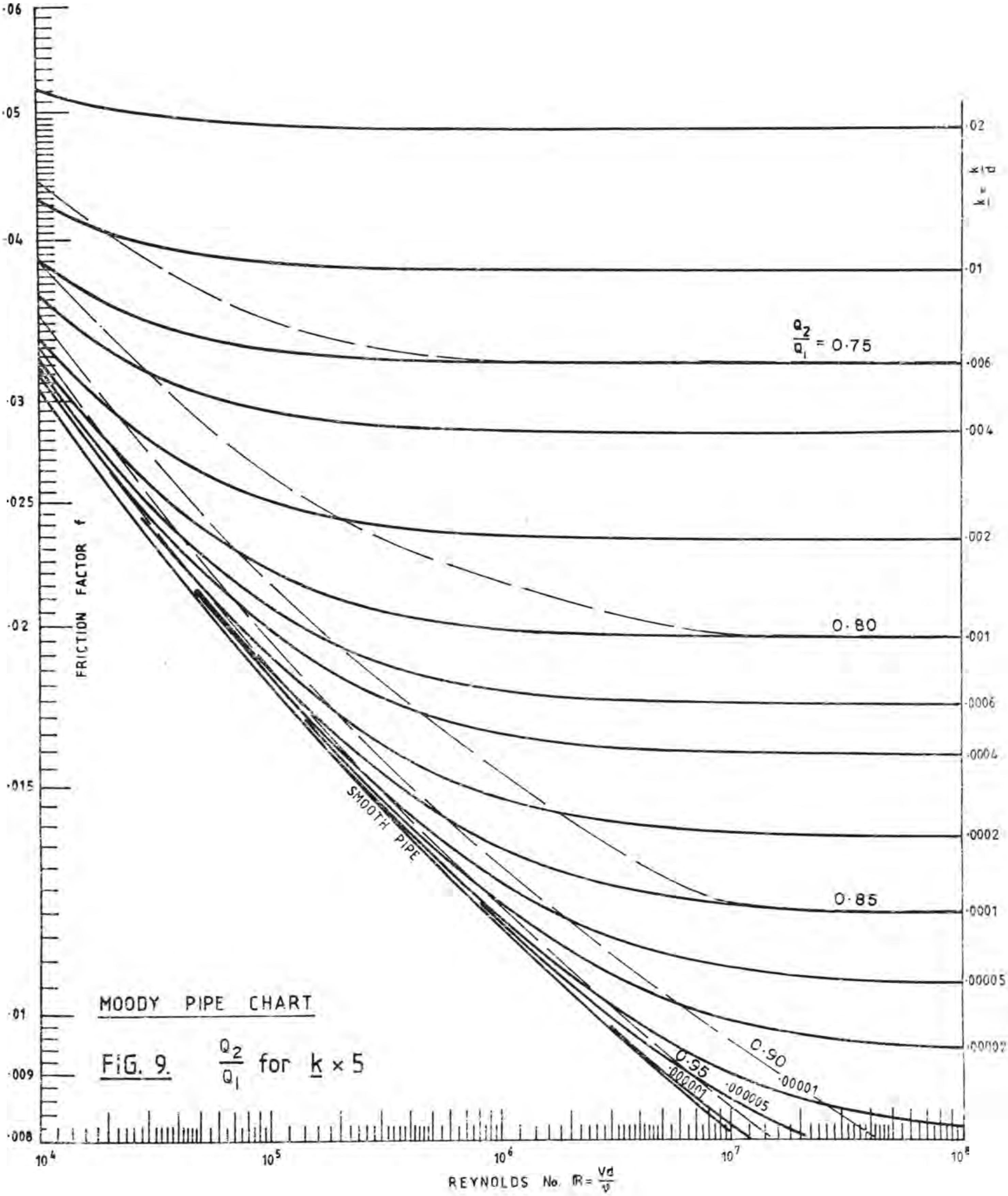


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FIG. 9. $\frac{Q_2}{Q_1}$ for $\underline{k} \times 5$

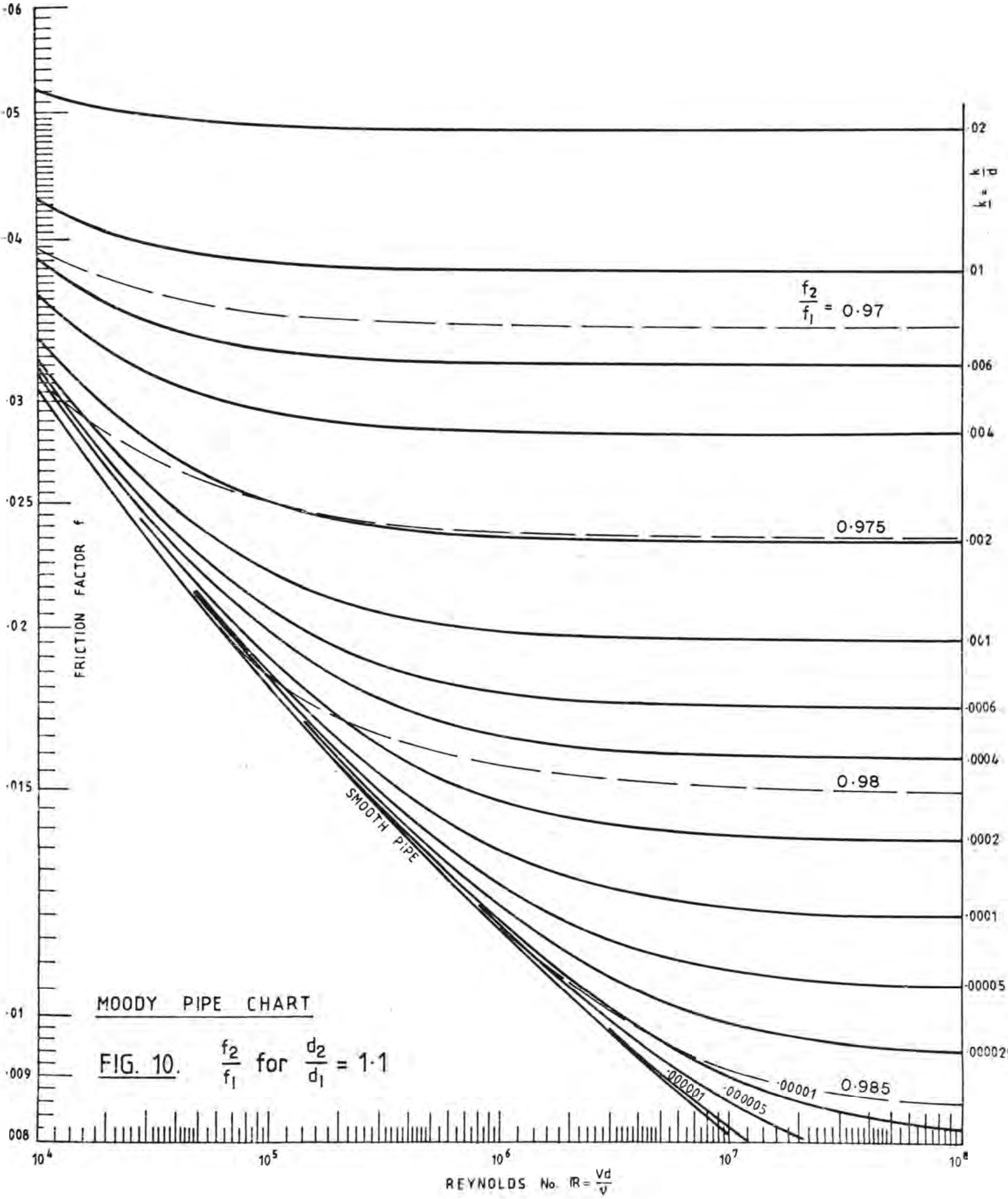


FIG. 10. $\frac{f_2}{f_1}$ for $\frac{d_2}{d_1} = 1{\cdot}1$

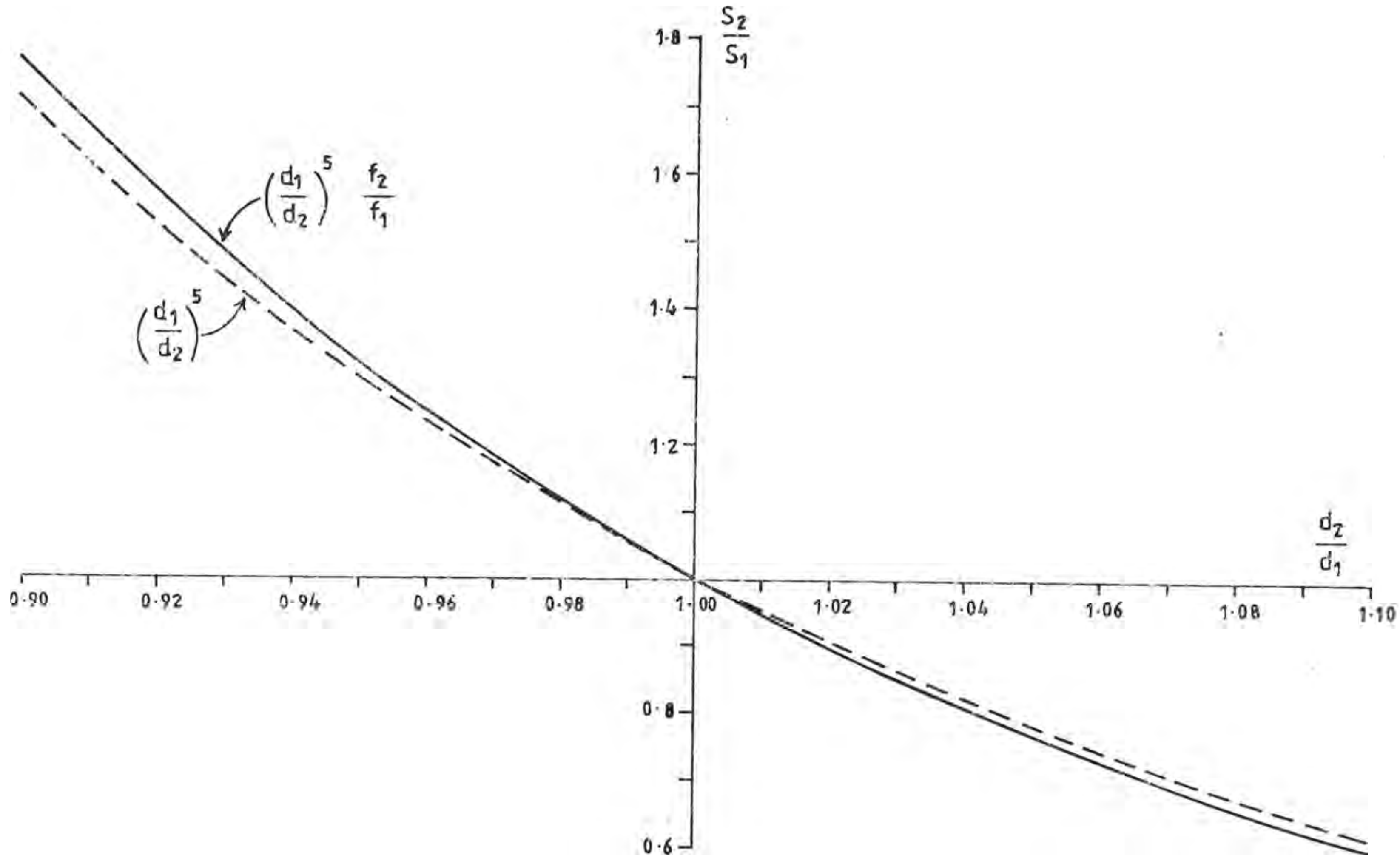
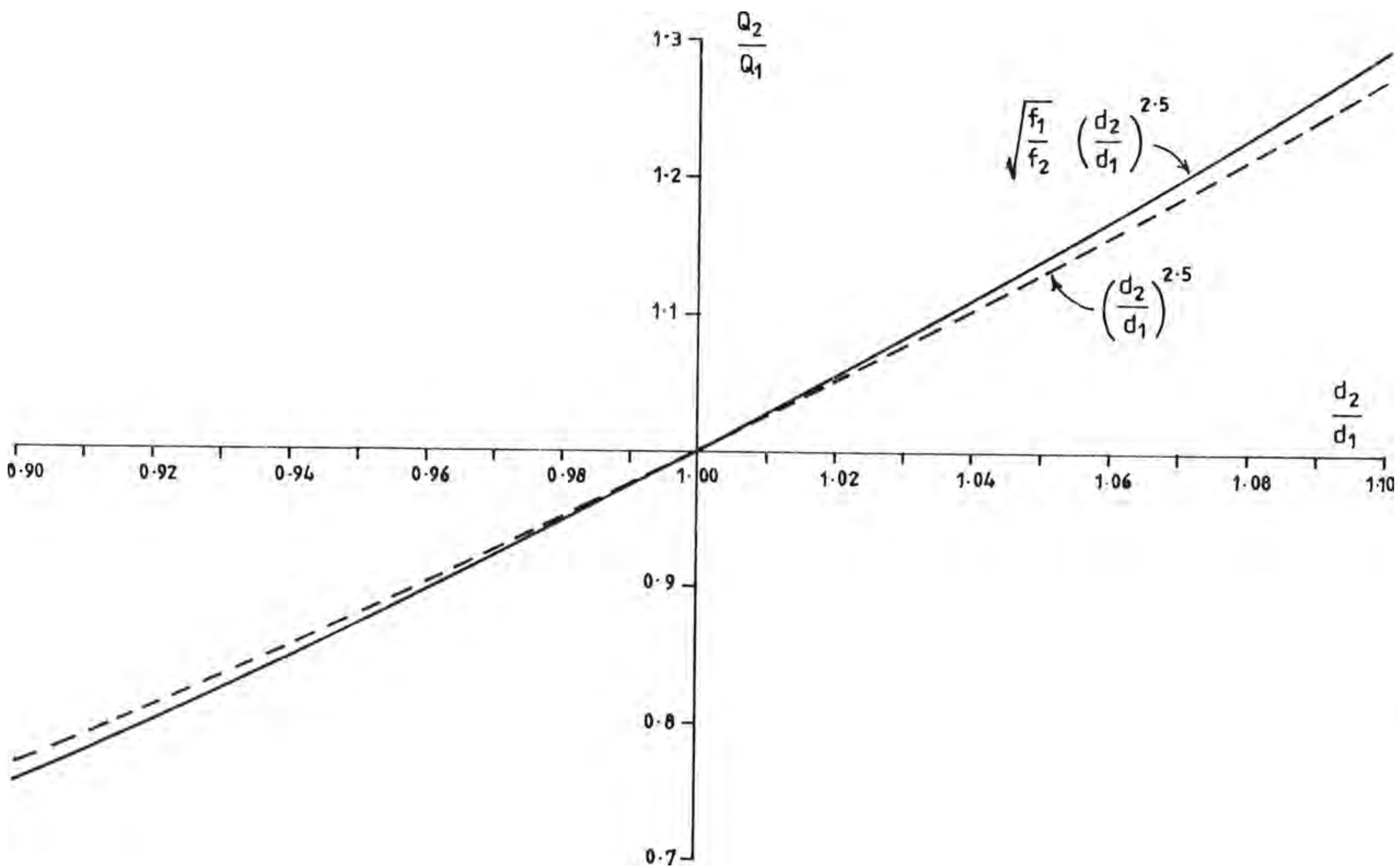


FIG. 11. $\frac{S_2}{S_1}$ as $f\left(\frac{d_2}{d_1}\right)$



<u>FIG. 12.</u> $\frac{Q_2}{Q_1}$ as $f\left(\frac{d_2}{d_1}\right)$

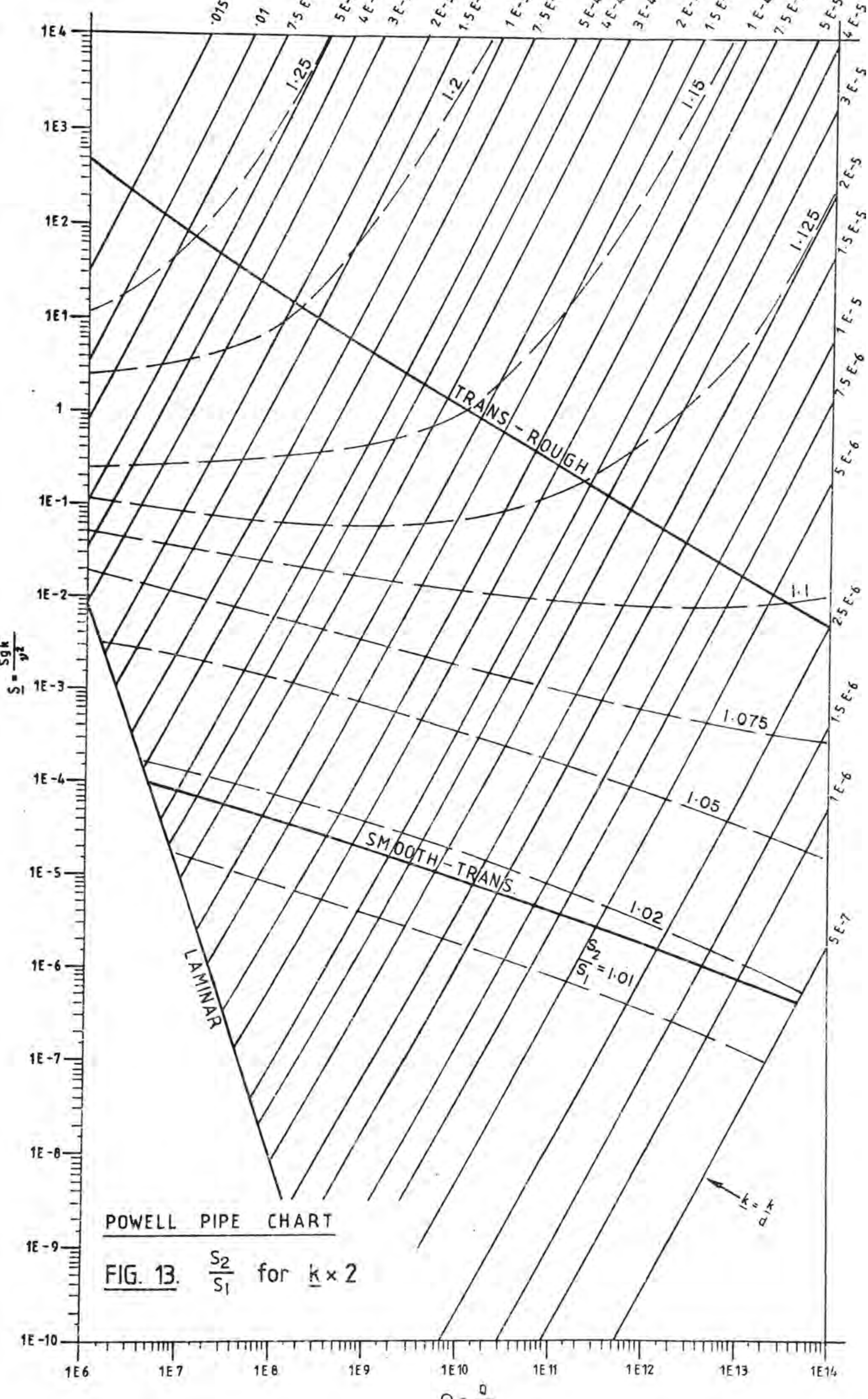


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FIG. 13. $\frac{S_2}{S_1}$ for $\underline{k} \times 2$

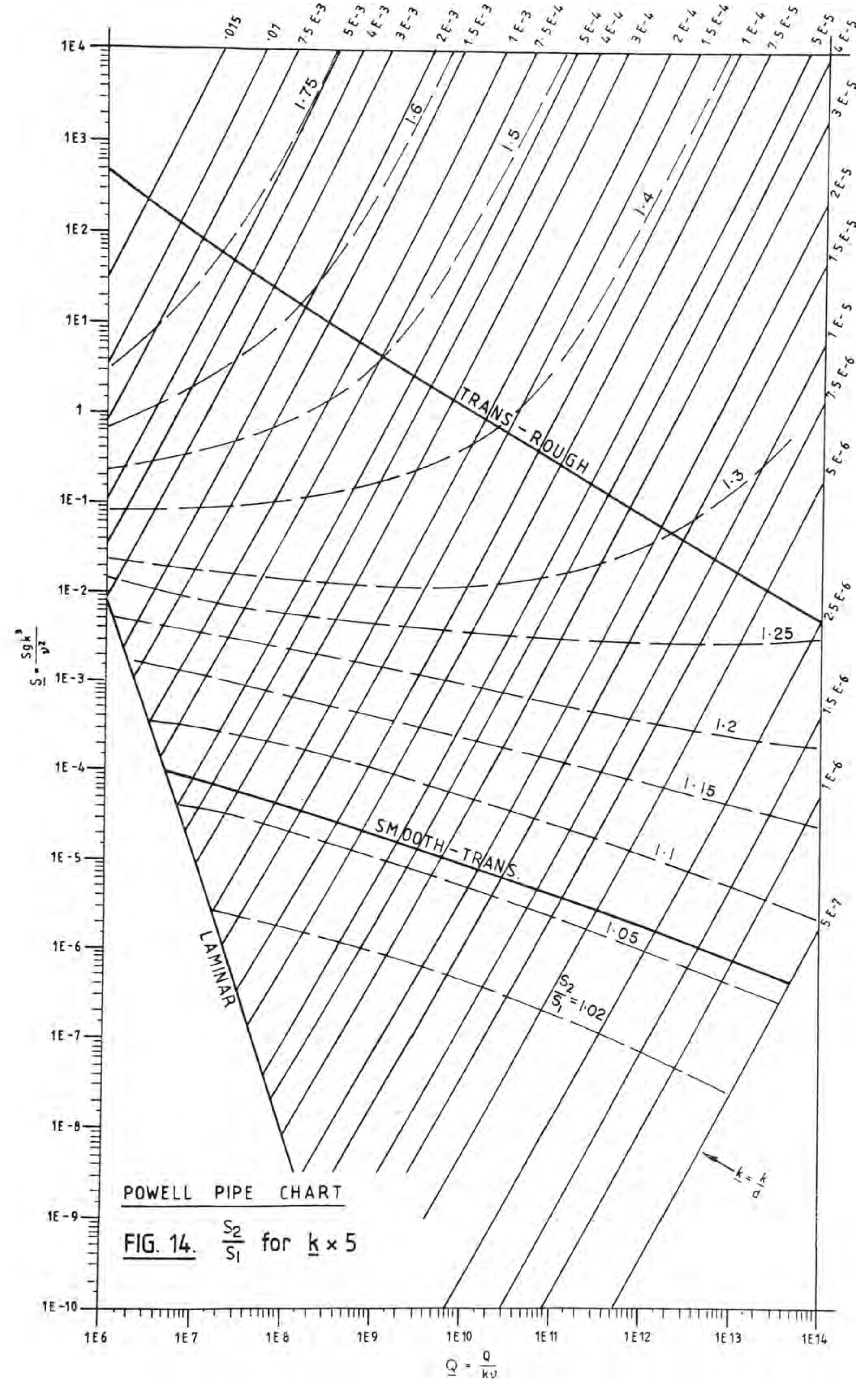

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FIG. 14. $\frac{S_2}{S_1}$ for $\underline{k} \times 5$

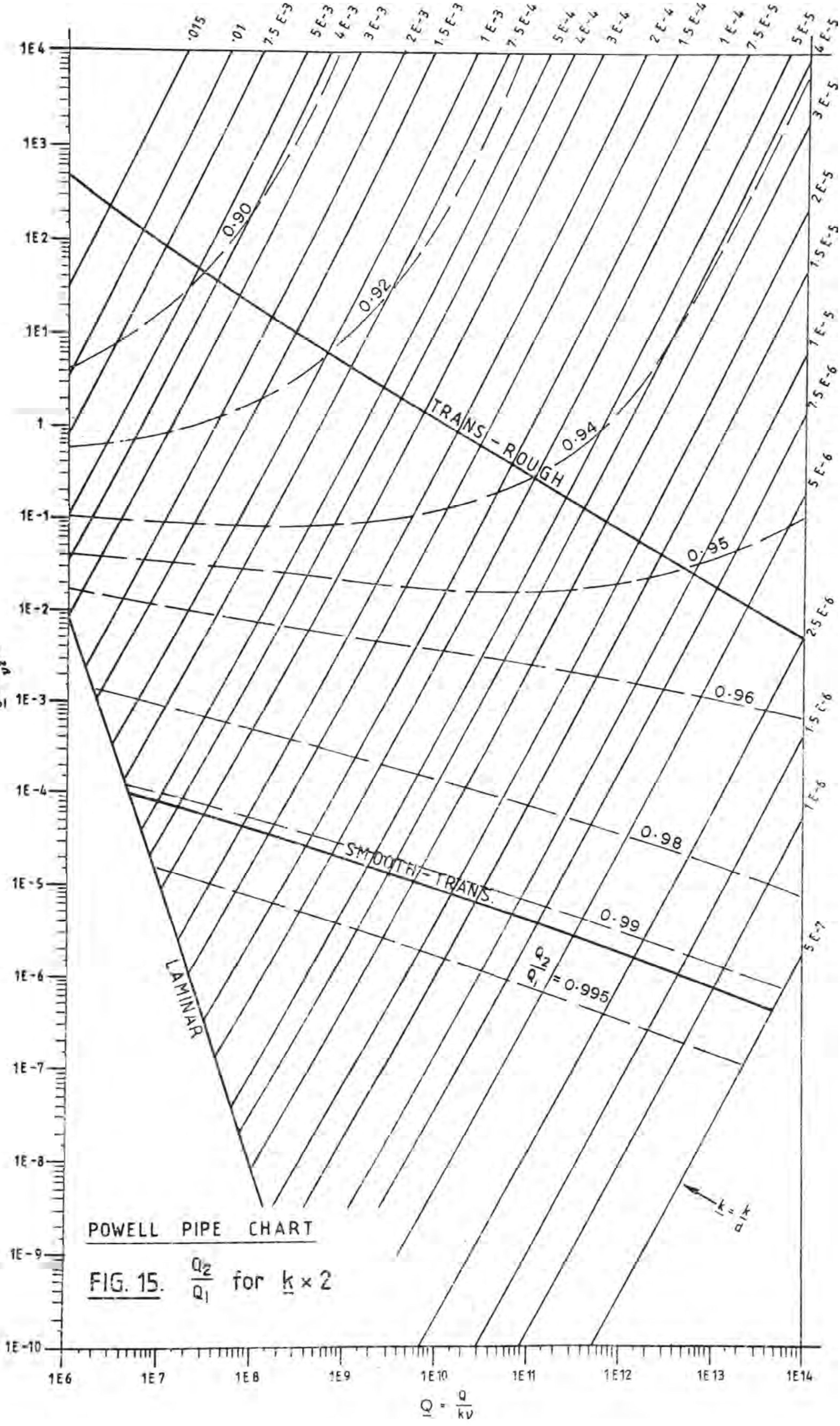

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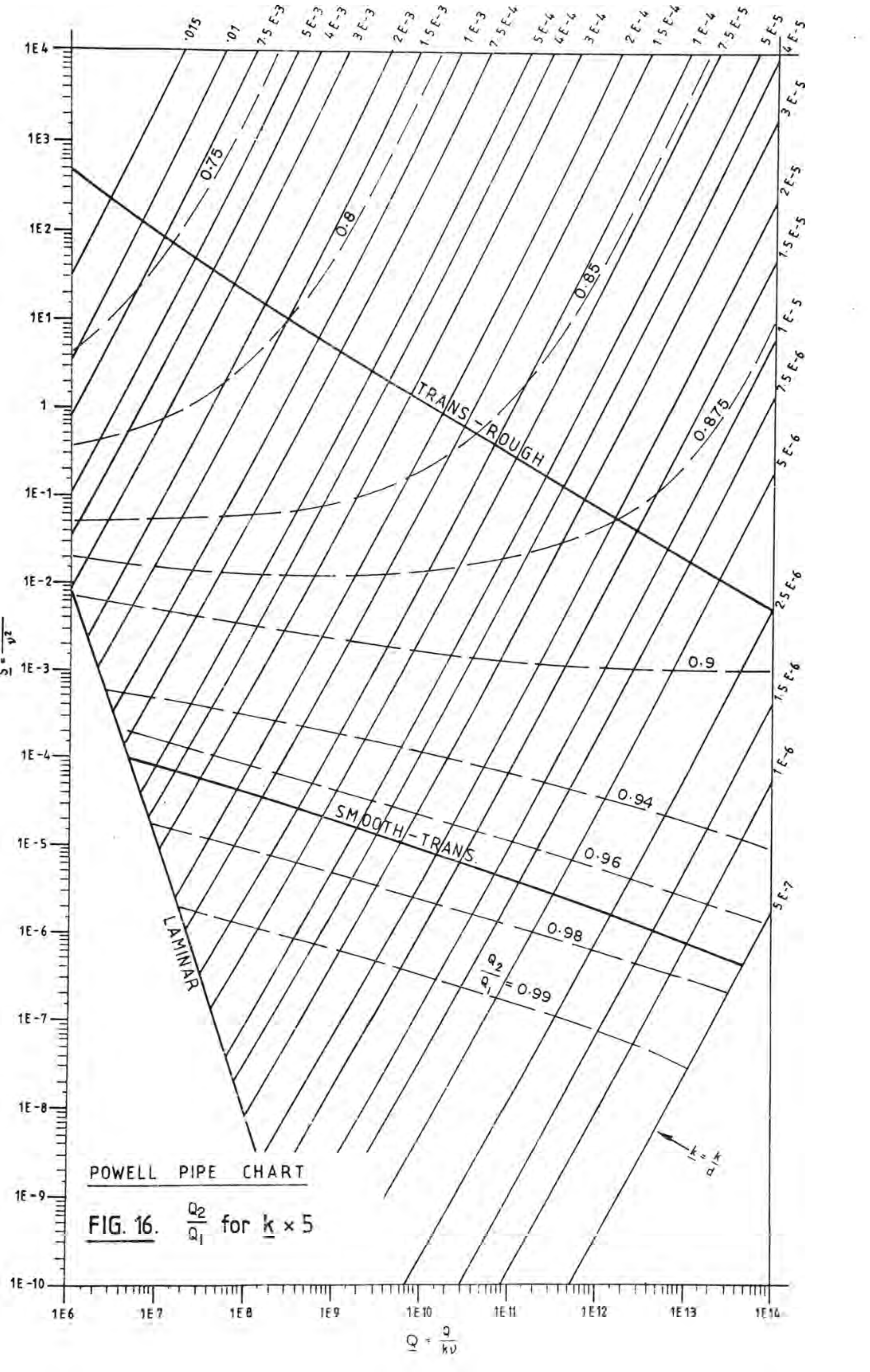
FIG. 15. $\frac{Q_2}{Q_1}$ for $\underline{k} \times 2$



POWELL PIPE CHART

FIG. 16. $\frac{Q_2}{Q_1}$ for $\underline{k} \times 5$

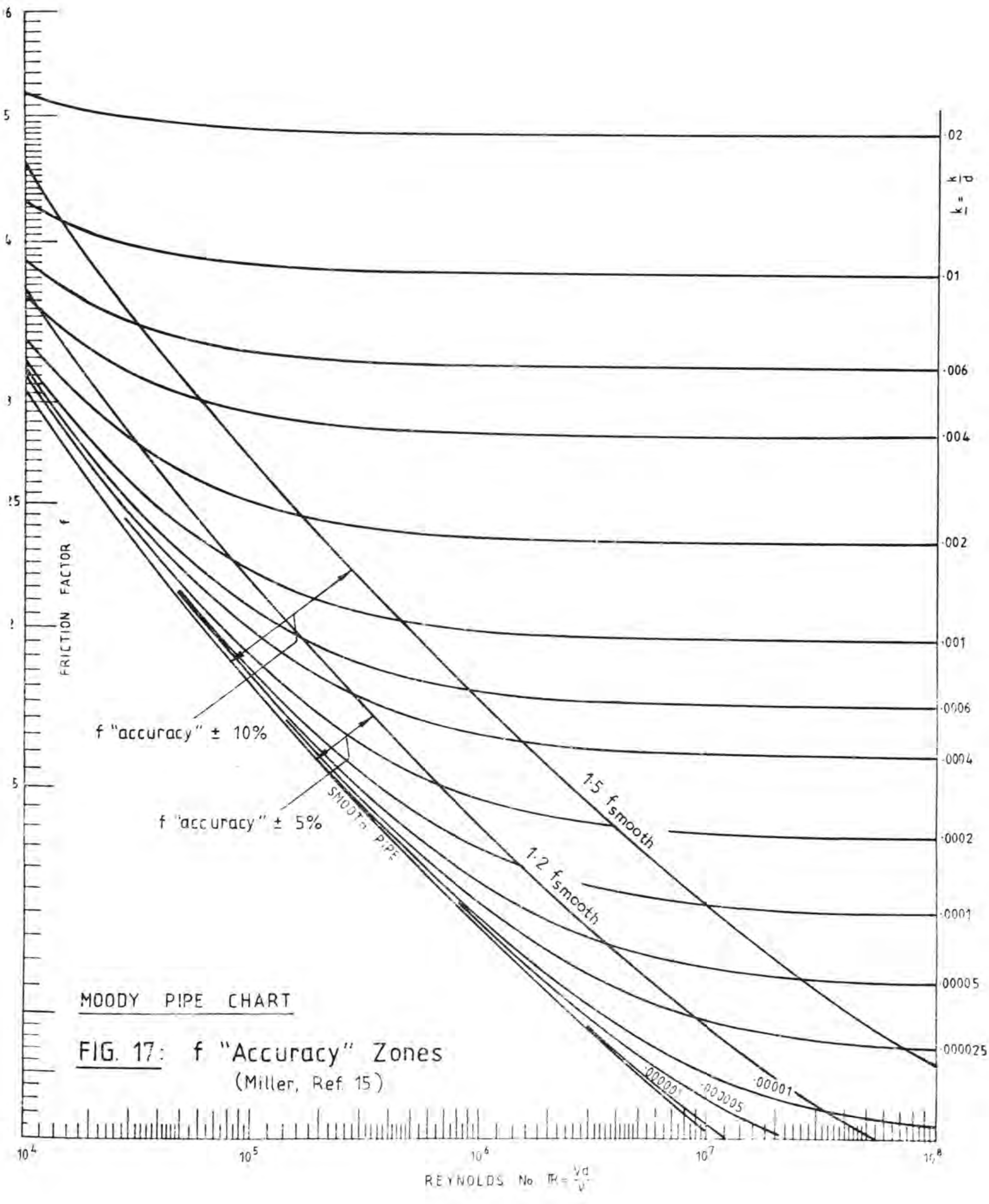


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FIG. 17: f "Accuracy" Zones
(Miller, Ref. 15)