Design Calculations for Sucker Rod Pumping Systems (Conventional Units)

API TECHNICAL REPORT 11L
FIFTH EDITION, JUNE 2008

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Upstream Segment

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Foreword

This technical report is under the jurisdiction of the API Standards Subcommittee on Field Operating Equipment (API SC11). This technical report replaces Recommended Practice 11L, *Design Calculations for Sucker Rod Pumping Systems*, 4th Edition. This technical report shall become effective on the date printed on the cover but may be used voluntarily from the date of distribution.

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Suggested revisions are invited and should be submitted to the Standards Department, API, 1220 L Street, NW, Washington, D.C. 20005.

Contents

Design Calculations for Sucker Rod Pumping Systems (Conventional Units)

1 Introduction

1.1 In 1954, a group of users and manufacturers of sucker rod pumping equipment undertook a study in depth of the many complex problems associated with this means of lifting fluid from a well. To control and direct the effort, Sucker Rod Pumping Research, Incorporated, a non-profit organization was created. The services of Midwest Research Institute at Kansas City were retained to perform the work necessary to achieve the objectives of the organization.

1.2 The design calculations are based on correlations of the test data that were obtained during the research phase of the project. Sucker Rod Pumping Research, Inc., before its dissolution, released these correlated test results to the American Petroleum Institute for publication. This technical report for the design calculations of sucker rod pumping systems using conventional pumping units is based on these correlations.

1.3 Three discussions included in the final reports of test results by Midwest Research Institute have been published for permanent reference in API *Drilling and Production Practice* (1968). These discussions include the following topics:

a) vibration characteristics of sucker-rod strings;

b) physical characteristics of sucker rods;

c) dimensional analysis of sucker-rod pumping systems.

1.4 A catalog of over 1100 dynamometer cards derived from the electronic analog computer for many combinations of the independent non-dimensional parameters F_o/Sk_r and N/N_o was included in the material released to API by Sucker Rod Pumping Research, Inc. This catalog has been printed as API 11L2, *Catalog of Analog Computer Dynamometer Cards*.

1.5 Two computer programs have been developed from the data in API 11L. One program developed tabular material calculated for depths of 2000 ft to 12,000 ft in increments of 500 ft and for production rates of 100 barrels/day to over 1500 barrels/day in varying increments. Rod and pump size combinations as listed in Table 4.1 were used, except for the elimination of rod no. 88 and rod no. 99. All API stroke lengths are covered. This material is printed as API 11L3, *Sucker Rod Pumping System Design Book*.

1.6 The other program developed a series of curves for selecting beam pumping units for depths of 1600 ft to 9900 ft and various rates of production and combinations of rod sizes, pump sizes, and speeds. Generally, the limiting factor on the curve is the peak torque rating of the unit. This material was printed as API 11L4, *Curves for Selecting Beam Pumping Units* (withdrawn from publication in 2008).

2 Validity of Calculations

2.1 In a majority of cases, it has been found that the values calculated by the following method have been in reasonably close agreement with measured values. Several groups conducting independent surveys have found this design method to give better results than other methods formerly used. However, since this method is based on the best interpretations of average values, the actual conditions found in individual cases may not always yield valid predictions of pumping system performance.

2.2 The designer must realize that there are a number of unusual conditions which may be present in a well that could cause misleading conclusions from these design calculations. Some of these unusual conditions are:

a) slanted or crooked holes;

b) very viscous fluid;

c) excessive sand production;

d) excessive gas production through the pump; and

e) well flowing-off.

2.3 The research work was limited to simulated problems in which the tubing was assumed as being anchored at the pump. Therefore, the test results reflected only this condition. However, because of the many known cases in which tubing is unanchored, a formula is included which, experience indicates, will give a very close approximation of relative plunger travel with respect to the pump. This value is identified with the symbol S_p. Examination of the formula will reveal that the contraction of the tubing caused by the transfer of the fluid load from the standing valve to the traveling valve is subtracted from the calculated plunger stroke. It is realized that this formula is highly simplified and not mathematically correct, but it is close enough for practical application.

2.4 These design calculations may be used with confidence when applied to the broad category of average, normal pumping wells fitting the assumed conditions outlined in Annex A. Unusual, conditions not fitting the assumptions will cause deviations from calculated performance. The designer must recognize this fact even though he cannot calculate quantitative values for this deviation.

3 Symbols and Formulas

3.1 Symbols, with Units Where Applicable, Used in the Technical Report

3.1.1
CBE
counterweight required, lb

3.1.2
D
plunger diameter, in.

3.1.3
E_r
elastic constant—rods, in./lb-ft (Table 4.1, Column 4).

NOTE E_r represents the inches of elongation caused by the application of a load of 1 lb to a rod 1 ft in length

3.1.4
E_t
elastic constant—tubing, in./lb ft (see Table 4.2, Column 5)

NOTE E_t represents the inches of elongation caused by application of a load of 1 lb to a section of tubing 1 ft in length.

3.1.5
F_1
PPRL factor (see Figure 3.1)

3.1.6
F_2
MPRL factor (see Figure 3.1)

3.1.7
F_c
frequency factor (see Table 4.1, Column 5)

3.1.8
F_o
differential fluid load on full plunger area, lb (see Figure 3.1)

3.1.9
F_3
PRHP factor

3.1.10
G
specific gravity of produced fluid

3.1.11
H
net lift, ft

3.1.12
L
pump depth, ft

3.1.13
$MPRL$
minimum polished rod load, lb (see Figure 3.1)

3.1.14
N
pumping speed, SPM

3.1.15
N_o
natural frequency of straight rod string, SPM

3.1.16
N'_o
natural frequency of tapered rod string, SPM

3.1.17
PD
pump displacement, barrels/day

3.1.18
$PPRL$
peak polished rod load, lb (see Figure 3.1)

3.1.19
PRHP
polished rod horsepower

3.1.20
PT
peak crank torque, lb-in.

3.1.21
S
polished rod stroke, in. (see Figure 3.1)

3.1.22
Sk_r
lb of load necessary to stretch the total rod string an amount equal to the polished rod stroke, *S*

3.1.23
S_p
bottom hole pump stroke, in.

3.1.24
SPM
strokes/minute

3.1.25
T
crank torque, lb-in.

3.1.26
T_a
torque adjustment constant for values of W_{rf}/Sk_r other than 0.3

3.1.27
W
total weight of rods in air, lb

3.1.28
W_r
average unit weight of rods in air, lb/ft (see Table 4.1, Column 3)

3.1.29
W_{rf}
total weight of rods in fluid, lb (see Figure 3.1)

3.1.30
$1/k_r$
elastic constant—total rod string, in./lb

NOTE k_r is the spring constant of the total rod string and represents the load in lb required to stretch the total rod string 1 in.

3.1.31
$1/k_t$
elastic constant—unanchored portion of tubing string, in./lb

NOTE k_t is the spring constant of the unanchored tubing and represents the load in pounds required to stretch the unanchored portion of the tubing, between the anchor and the pump, 1 in.

3.2 Formulas

An understanding of the formulas utilized for the solution of sucker rod pumping problems will be gained by referring to Figure 3.1. The variables F_0, F_1, F_2, W_{rf}, and S are illustrated with this figure.

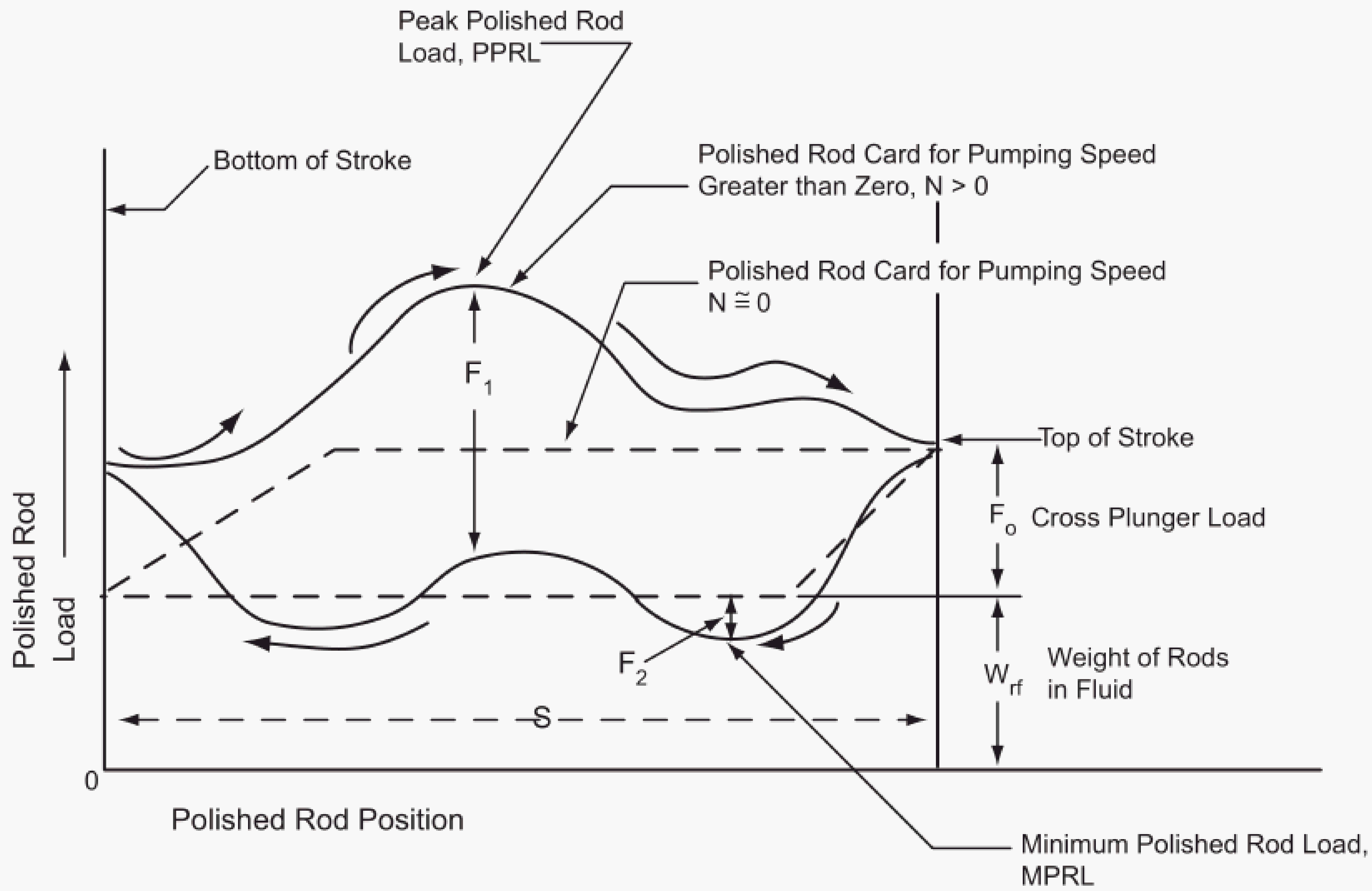

Figure 3.1—Basic Dynagraph Card

a) At pumping speed, $N \cong 0$

peak polished rod load, $PPRL = W_{rf} + F_o$
minimum polished rod load, $MPRL = W_{rf}$

b) For pumping speed, $N > 0$

peal polished rod load, $PPRL = W_{rf} + F_1$
minimum polished rod load, $MPRL = W_{rf} - F_2$

3.2.1 The problem is generalized by using parameters of variables that are non-dimensional.

a) The independent non-dimensional variables are:

N/N_o (Dimensionally = SPM/SPM = 1), and

F_o/S_{kr} (Dimensionally $= \frac{\text{lb}}{\text{in.} \times \text{lb/in.}} = 1$)

where

N is SPM
N_o is SPM at natural frequency of rod string
S is surface stroke
k_r is spring constant of rod string

b) The dependent non-dimensional variables are:

peak polished rod load, $PPRL$:	F_1/Sk_r
minimum polished rod load, $MPRL$:	F_2/Sk_r
peak torque, PT:	$2T/S^2k_r$
polished rod horsepower, $PRHP$:	F_3/Sk_r
plunger stroke, S_p:	S_p/S

3.2.2 In the research project the sucker rod pumping system was simulated by an electronic analog computer. Computer runs were made for many combinations of N/N_o and F_o/Sk_r with the dependent non-dimensional variables being measured on each test. Test results were correlated by plotting the families of curves shown in Figures 4.1 through 4.5. From these curves, values for the various non-dimensional variables may be determined for substitution in the following design calculation formulas:

plunger stroke,
$S_p = [(S_p/S) \times S] - [F_o \times 1/k_t]$

NOTE When tubing is anchored, the value of $1/k_t$ equals zero, therefore the formula for Sp with anchored tubing becomes $(S_p/S) \times S$.

pump displacement,
$PD = 0.1166 \times S_p \times N \times D^2$

peak polished rod load,
$PPRL = W_{rf} + [(F_1/Sk_r) \times Sk_r]$

minimum polished rod load,
$MPRL = W_{rf} - [(F_2/Sk_r) \times Sk_r]$

peak torque,
$PT = (2T/S^2k_r) \times Sk_r \times S/2 \times T_a$

polished rod horsepower,
$PRHP = (F_3/Sk_r) \times Sk_r \times S \times N \times 2.53 \times 10^{-6}$

counterweight required,
$CBE = 1.06\ (W_{rf} + {}^1/_2\ F_o)$

4 Design Procedure

4.1 The final solution to this design problem is reached through trial and error methods. Generally, three steps are required in designing an installation.

a) A preliminary selection of components for the installation must be made.

b) The operating characteristics of the preliminary selection are calculated by use of the formulas, tables, and figures presented herein.

c) The calculated pump displacement and loads are compared with the volumes, load ratings, stresses, and other limitations of the preliminary selection.

It will usually be found necessary to make more than one calculation to bring the limitations of the various components of the installation into agreement.

4.2 The minimum amount of information which must be known (or assumed) for a particular sucker rod pumping unit installation design calculation must include:

— fluid level—H, the net lift in ft;

— pump depth—L, ft;

— pumping speed—N, SPM;

— length of surface stroke—S, in.;

— pump, plunger diameter—D, in.;

— specific gravity of the fluid—G;

— the nominal tubing diameter and whether it is anchored or hanging free;

— sucker rod size and design.

4.3 With these factors, the designer will be able to calculate the following:

— plunger stroke—S_p, in.;

— pump displacement—PD, barrels/day;

— peak polished rod load—$PPRL$, lb;

— minimum polished rod load—$MPRL$, lb;

— peak crank torque—PT, lb-in.;

— polished rod horsepower—$PRHP$;

— counterweight required—CBE, lb.

4.4 Accumulate the known (or assumed) factors on a data sheet or similar document. An example of a completed design calculations form is included in this document (see Data Sheet 11L).

4.5 Refer to Table 4.1, use the sucker rod string designation in Column 1 and the plunger diameter in Column 2 as guides, read and record the values for W_r, E_r, and F_c found in Columns 3, 4, and 5 respectively. Table 4.2, Column 5 will give the value of E_t. This factor becomes significant only when working with an unanchored tubing string. If the tubing is anchored, E_t need not be recorded.

NOTE The values of rod percentages, rod weights, elastic constants, and frequency factors shown in Table 4.1 differ from those in previous editions of this document and those shown in Tables 1 and 2, API 11L3, First Edition, May 1970. Values in current Table 4.1 were adopted at the June 1976 Standardization Conference, based on the article by A. B. Neely. Changed rod percentages have negligible effect upon values calculated in API 11L3 except for the weight of rods in fluid (W_{rf}).

4.6 Perform the indicated mathematical operations indicated through step 11 (per example Data Sheet 11L). If the tubing is anchored, $1/k_t$ (step 11) is equal to zero and need not be calculated. The values are now available with which the bottom hole pump stroke, S_p, and the pump displacement, PD, may be calculated.

4.7 With the calculated values of F_o/Sk_r and N/N'_o, record the value of S_p/S from figure 4.1 and solve for S_p and *PD* in steps 13 and 14 (per example Data Sheet 11L). Pump displacement is the first test being made to see if the preliminary selection of components for the installation is satisfactory. If the pump displacement calculated in step 14 fails to satisfy known or anticipated requirements, appropriate adjustments must be made in the assumed data and steps 1 through 14 repeated. When the calculated pump displacement is acceptable, proceed with the design calculations by performing steps 15, 16 and 17.

4.8 By using the calculated values of F_o/Sk_r and N/N_o, the values of F_1/Sk_r (see Figure 4.2), F_2/Sk_r (see Figure 4.3), $2T/S^2k_r$ (see Figure 4.4), and F_3/Sk_r (see Figure 4.5) are read from the curves and recorded. When referring to Figures 4.1 and 4.6 to determine S_p/S and T_a, the value of N/N'_o must be used. Record the value of T_a.

4.9 Substitution of the appropriate values in the various formulas and performance of the indicated mathematics in steps 23 through 27 of the example Data Sheet 11L will yield the various loads to be expected from the preliminary selection of equipment. It is now necessary to compare these calculated loads with limitations imposed by the preliminary selection. Calculate the stress in the sucker rods to determine if it is within acceptable limits.

4.10 Generally, more than one selection of equipment and calculation of operating conditions is necessary before the optimum selection can be made.. .

EXAMPLE DESIGN CALCULATIONS
CONVENTIONAL SUCKER ROD PUMPING SYSTEM

Object: To solve for—Sp, PD, PPRL, MPRL, PT, PRHP, and CBE

Known or Assumed Data:

Fluid Level, H = 4,500 ft. Pumping Speed, N = 16 SPM Plunger Diameter, D = 1.50 in.

Pump Depth, L = 5,000 ft. Length of Stroke, S = 54 in. Spec. Grav. of Fluid, G = 0.9

Tubing Size 2 in. Is it anchored? Yes, (No) Sucker Rods 33.8 % – 7/8" & 66.2 % – 3/4"

Record Factors from Tables 4.1 & 4.2:

1. W_r = 1.833 (Table 4.1, Column 3)
2. E_r = .804 x 10⁻⁶ (Table 4.1, Column 4)
3. F_c = 1.082 (Table 4.1, Column 5)
4. E_t = .307 x 10⁻⁶ (Table 4.2, Column 5)

Calculate Non-Dimensional Variables:

5. $F_o = .340 \times G \times D^2 \times H$ = .340 x 0.9 x 2.25 x 4500 = 3,098 lbs.
6. $1/k_r = E_r \times L$ = .804 x 10⁻⁶ x 5,000 = 4.020 x 10⁻³ in/lb.
7. $Sk_r = S \div 1/k_r$ = 54 ÷ 4.020 x 10⁻³ = 13,433 lbs.

   F_o/Sk_r = 3,098 ÷ 13,433 = .231
9. $N/N_o = NL \div 245{,}000$ = 16 x 5,000 ÷ 245,000 = .326
10. $N/N_o' = N/N_o \div F_c$ = .326 ÷ 1.082 = .301
11. $1/k_t = E_t \times L$ = .307 x 10⁻⁶ x 5,000 = 1.535 x 10⁻³ in/lb.

Solve for S_p and PD:

12. S_p/S = .86 (Figure 4.1)
13. $S_p = [(S_p/S) \times S] - [F_o \times 1/k_t]$ = [.86 x 54] – [3,098 x 1.535 x 10⁻³] = 41.7 in.
14. $PD = 0.1166 \times S_p \times N \times D^2$ = 0.1166 x 41.7 x 16 x 2.25 = 175 barrels per day

If the calculated pump displacement fails to satisfy known or anticipated requirements, appropriate adjustments must be made in the assumed data and steps 1 through 14 repeated. When the calculated pump displacement is acceptable, proceed with the Design Calculation.

Determine Non-Dimensional Parameters:

15. $W = W_r \times L$ = 1.833 x 5,000 = 9,165 lbs.
16. $W_{rf} = W[1 - (.128G)]$ = 9,165 [1–(.128 x .9)] = 8,110 lbs.
17. W_{rf}/Sk_r = 8,110 ÷ 13,433 = .604

Record Non-Dimensional Factors from Figures 4.2 through 4.6:

18. F_1/Sk_r = .465 (Figure 4.2)
19. F_2/Sk_r = .213 (Figure 4.3)
20. $2T/S^2k_r$ = .37 (Figure 4.4)
21. F_3/Sk_r = .29 (Figure 4.5)
22. T_a = .997 (Figure 4.6)

Solve for Operating Characteristics:

23. $PPRL = W_{rf} + [(F_1/Sk_r) \times Sk_r]$ = 8,110 + [.465 x 13,433] = 14,356 lbs.
24. $MPRL = W_{rf} - [(F_2/Sk_r) \times Sk_r]$ = 8,110 – [.22 x 13,433] = 5,249 lbs.
25. $PT = (2T/S^2k_r) \times Sk_r \times S/2 \times T_a$ = .37 x 13,433 x 27 x .997 = 133,793 lb inches
26. $PRHP = (F_3/Sk_r) \times Sk_r \times S \times N \times 2.53 \times 10^{-6}$ = .29 x 13,433 x 54 x 16 x 2.53 x 10⁻⁶ = 8.5
27. $CBE = 1.06(W_{rf} + 1/2\,F_o)$ = 1.06 x (8,110 + 1,549) = 10,239 lbs.

Data Sheet 11L—Example Design Calculation*

* The technical report calculations are merely examples for illustration purposes only (each company should develop its own approcach). They are not to be considered exclusive or exhaustive in nature. API makes no warranties, express or implied for reliance on or any omissions from the information contained in this document.

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Table 4.1—Rod and Pump Data (See 4.5)

1	2	3	4	5	6	7	8	9		
Rod No.	Plunger Diameter in. D	Rod Weight lb/ft W_r	Elastic Constant in./lb-ft E_r	Frequency Factor F_c	Rod String, % of each size					
					1 1/8	1	7/8	3/4	5/8	1/2
44	All	0.726	1.990×10^{-6}	1.000	—	—	—	—	—	100.0
54	1.06	0.908	1.668×10^{-6}	1.138	—	—	—	—	44.6	55.4
54	1.25	0.929	1.633×10^{-6}	1.140	—	—	—	—	49.5	50.5
54	1.50	0.957	1.584×10^{-6}	1.137	—	—	—	—	56.4	43.6
54	1.75	0.990	1.525×10^{-6}	1.122	—	—	—	—	64.6	35.4
54	2.00	1.027	1.460×10^{-6}	1.095	—	—	—	—	73.7	26.3
54	2.25	1.067	1.391×10^{-6}	1.061	—	—	—	—	83.4	16.6
54	2.50	1.108	1.318×10^{-6}	1.023	—	—	—	—	93.5	6.5
55	All	1.135	1.270×10^{-6}	1.000	—	—	—	—	100.0	—
64	1.06	1.164	1.382×10^{-6}	1.229	—	—	—	33.3	33.1	33.5
64	1.25	1.211	1.319×10^{-6}	1.215	—	—	—	37.2	35.9	26.9
64	1.50	1.275	1.232×10^{-6}	1.184	—	—	—	42.3	40.4	17.3
64	1.75	1.341	1.141×10^{-6}	1.145	—	—	—	47.4	45.2	7.4
65	1.06	1.307	1.138×10^{-6}	1.098	—	—	—	34.4	65.6	—
65	1.25	1.321	1.127×10^{-6}	1.104	—	—	—	37.3	62.7	—
65	1.50	1.343	1.110×10^{-6}	1.110	—	—	—	41.8	58.2	—
65	1.75	1.369	1.090×10^{-6}	1.114	—	—	—	46.9	53.1	—
65	2.00	1.394	1.070×10^{-6}	1.114	—	—	—	52.0	48.0	—
65	2.25	1.426	1.045×10^{-6}	1.110	—	—	—	58.4	41.6	—
65	2.50	1.460	1.018×10^{-6}	1.099	—	—	—	65.2	34.8	—
65	2.75	1.497	0.990×10^{-6}	1.082	—	—	—	72.5	27.5	—
65	3.25	1.574	0.930×10^{-6}	1.037	—	—	—	88.1	11.9	—
66	All	1.634	0.883×10^{-6}	1.000	—	—	—	100.0	—	—
75	1.06	1.566	0.997×10^{-6}	1.191	—	—	27.0	27.4	45.6	—
75	1.25	1.604	0.973×10^{-6}	1.193	—	—	29.4	29.8	40.8	—
75	1.50	1.664	0.935×10^{-6}	1.189	—	—	33.3	33.3	33.3	—
75	1.75	1.732	0.892×10^{-6}	1.174	—	—	37.8	37.0	25.1	—
75	2.00	1.803	0.847×10^{-6}	1.151	—	—	42.4	41.3	16.3	—
75	2.25	1.875	0.801×10^{-6}	1.121	—	—	46.9	45.8	7.2	—
76	1.06	1.802	0.816×10^{-6}	1.072	—	—	28.5	71.5	—	—
76	1.25	1.814	0.812×10^{-6}	1.077	—	—	30.6	69.4	—	—
76	1.50	1.833	0.804×10^{-6}	1.082	—	—	33.8	66.2	—	—
76	1.75	1.855	0.795×10^{-6}	1.088	—	—	37.5	62.5	—	—
76	2.00	1.880	0.785×10^{-6}	1.093	—	—	41.7	58.3	—	—
76	2.25	1.908	0.774×10^{-6}	1.096	—	—	46.5	53.5	—	—
76	2.50	1.934	0.764×10^{-6}	1.097	—	—	50.8	49.2	—	—
76	2.75	1.967	0.751×10^{-6}	1.094	—	—	56.5	43.5	—	—
76	3.25	2.039	0.722×10^{-6}	1.078	—	—	68.7	31.3	—	—

Table 4.1—Rod and Pump Data (See 4.5) (Continued)

1	2	3	4	5	6	7	8	9		
Rod No.	Plunger Diameter in. D	Rod Weight lb/ft W_r	Elastic Constant in./lb-ft E_r	Frequency Factor F_c	Rod String, % of each size					
					1 1/8	1	7/8	3/4	5/8	1/2
76	3.75	2.119	0.690×10^{-6}	1.047	—	—	82.3	17.7	—	—
77	All	2.224	0.649×10^{-6}	1.000	—	—	100.0	—	—	—
85	1.06	1.883	0.873×10^{-6}	1.261	—	22.2	22.4	22.4	33.0	—
85	1.25	1.943	0.841×10^{-6}	1.253	—	23.9	24.2	24.3	27.6	—
85	1.50	2.039	0.791×10^{-6}	1.232	—	26.7	27.4	26.8	19.2	—
85	1.75	2.138	0.738×10^{-6}	1.201	—	29.6	30.4	29.5	10.5	—
86	1.06	2.058	0.742×10^{-6}	1.151	—	22.6	23.0	54.3	—	—
86	1.25	2.087	0.732×10^{-6}	1.156	—	24.3	24.5	51.2	—	—
86	1.50	2.133	0.717×10^{-6}	1.162	—	26.8	27.0	46.3	—	—
86	1.75	2.185	0.699×10^{-6}	1.164	—	29.4	30.0	40.6	—	—
86	2.00	2.247	0.679×10^{-6}	1.161	—	32.8	33.2	33.9	—	—
86	2.25	2.315	0.656×10^{-6}	1.153	—	36.9	36.0	27.1	—	—
86	2.50	2.385	0.633×10^{-6}	1.138	—	40.6	39.7	19.7	—	—
86	2.75	2.455	0.610×10^{-6}	1.119	—	44.5	43.3	12.2	—	—
87	1.06	2.390	0.612×10^{-6}	1.055	—	24.3	75.7	—	—	—
87	1.25	2.399	0.610×10^{-6}	1.058	—	25.7	74.3	—	—	—
87	1.50	2.413	0.607×10^{-6}	1.062	—	27.7	72.3	—	—	—
87	1.75	2.430	0.603×10^{-6}	1.066	—	30.3	69.7	—	—	—
87	2.00	2.450	0.598×10^{-6}	1.071	—	33.2	66.8	—	—	—
87	2.25	2.472	0.594×10^{-6}	1.075	—	36.4	63.6	—	—	—
87	2.50	2.496	0.588×10^{-6}	1.079	—	39.9	60.1	—	—	—
87	2.75	2.523	0.582×10^{-6}	1.082	—	43.9	56.1	—	—	—
87	3.25	2.575	0.570×10^{-6}	1.084	—	51.6	48.4	—	—	—
87	3.75	2.641	0.556×10^{-6}	1.078	—	61.2	38.8	—	—	—
87	4.75	2.793	0.522×10^{-6}	1.038	—	83.6	16.4	—	—	—
88	All	2.904	0.497×10^{-6}	1.000	—	100.0	—	—	—	—
96	1.06	2.382	0.670×10^{-6}	1.222	19.1	19.2	19.5	42.3	—	—
96	1.25	2.435	0.655×10^{-6}	1.224	20.5	20.5	20.7	38.3	—	—
96	1.50	2.511	0.633×10^{-6}	1.223	22.4	22.5	22.8	32.3	—	—
96	1.75	2.607	0.606×10^{-6}	1.213	24.8	25.1	25.1	25.1	—	—
96	2.00	2.703	0.578×10^{-6}	1.196	27.1	27.9	27.4	17.6	—	—
96	2.25	2.806	0.549×10^{-6}	1.172	29.6	30.7	29.8	9.8	—	—
97	1.06	2.645	0.568×10^{-6}	1.120	19.6	20.0	60.3	—	—	—
97	1.25	2.670	0.563×10^{-6}	1.124	20.8	21.2	58.0	—	—	—
97	1.50	2.707	0.556×10^{-6}	1.131	22.5	23.0	54.5	—	—	—
97	1.75	2.751	0.548×10^{-6}	1.137	24.5	25.0	50.4	—	—	—
97	2.00	2.801	0.538×10^{-6}	1.141	26.8	27.4	45.7	—	—	—
97	2.25	2.856	0.528×10^{-6}	1.143	29.4	30.2	40.4	—	—	—

Table 4.1—Rod and Pump Data (See 4.5) (Continued)

1	2	3	4	5	6	7	8	9		
Rod No.	Plunger Diameter in. D	Rod Weight lb/ft W_r	Elastic Constant in./lb-ft E_r	Frequency Factor F_c	Rod String, % of each size					
					1 1/8	1	7/8	3/4	5/8	1/2
97	2.50	2.921	0.515×10^{-6}	1.141	32.5	33.1	34.4	—	—	—
97	2.75	2.989	0.503×10^{-6}	1.135	36.1	35.3	28.6	—	—	—
97	3.25	3.132	0.475×10^{-6}	1.111	42.9	41.9	15.2	—	—	—
98	1.06	3.068	0.475×10^{-6}	1.043	21.2	78.8	—	—	—	—
98	1.25	3.076	0.474×10^{-6}	1.045	22.2	77.8	—	—	—	—
98	1.50	3.089	0.472×10^{-6}	1.048	23.8	76.2	—	—	—	—
98	1.75	3.103	0.470×10^{-6}	1.051	25.7	74.3	—	—	—	—
98	2.00	3.118	0.468×10^{-6}	1.055	27.7	72.3	—	—	—	—
98	2.25	3.137	0.465×10^{-6}	1.058	30.1	69.9	—	—	—	—
98	2.50	3.157	0.463×10^{-6}	1.062	32.7	67.3	—	—	—	—
98	2.75	3.180	0.460×10^{-6}	1.066	35.6	64.4	—	—	—	—
98	3.25	3.231	0.453×10^{-6}	1.071	42.2	57.8	—	—	—	—
98	3.75	3.289	0.445×10^{-6}	1.074	49.7	50.3	—	—	—	—
98	4.75	3.412	0.428×10^{-6}	1.064	65.7	34.3	—	—	—	—
99	All	3.676	0.393×10^{-6}	1.000	100.0	—	—	—	—	—
107	1.06	2.977	0.524×10^{-6}	1.184	16.9	16.8	17.1	49.1	—	—
107	1.25	3.019	0.517×10^{-6}	1.189	17.9	17.8	18.0	46.3	—	—
107	1.50	3.085	0.506×10^{-6}	1.195	19.4	19.2	19.5	41.9	—	—
107	1.75	3.158	0.494×10^{-6}	1.197	21.0	21.0	21.2	36.9	—	—
107	2.00	3.238	0.480×10^{-6}	1.195	22.7	22.8	23.1	31.4	—	—
107	2.25	3.336	0.464×10^{-6}	1.187	25.0	25.0	25.0	25.0	—	—
107	2.50	3.435	0.447×10^{-6}	1.174	26.9	27.7	27.1	18.2	—	—
107	2.75	3.537	0.430×10^{-6}	1.156	29.1	30.2	29.3	11.3	—	—
108	1.06	3.325	0.447×10^{-6}	1.097	17.3	17.8	64.9	—	—	—
108	1.25	3.345	0.445×10^{-6}	1.101	18.1	18.6	63.2	—	—	—
108	1.50	3.376	0.441×10^{-6}	1.106	19.4	19.9	60.7	—	—	—
108	1.75	3.411	0.437×10^{-6}	1.111	20.9	21.4	57.7	—	—	—
108	2.00	3.452	0.432×10^{-6}	1.117	22.6	23.0	54.3	—	—	—
108	2.25	3.498	0.427×10^{-6}	1.121	24.5	25.0	50.5	—	—	—
108	2.50	3.548	0.421×10^{-6}	1.124	26.5	27.2	46.3	—	—	—
108	2.75	3.603	0.415×10^{-6}	1.126	28.7	29.6	41.6	—	—	—
108	3.25	3.731	0.400×10^{-6}	1.123	34.6	33.9	31.6	—	—	—
108	3.75	3.873	0.383×10^{-6}	1.108	40.6	39.5	19.9	—	—	—
109	1.06	3.839	0.378×10^{-6}	1.035	18.9	81.1	—	—	—	—
109	1.25	3.845	0.378×10^{-6}	1.036	19.6	80.4	—	—	—	—
109	1.50	3.855	0.377×10^{-6}	1.038	20.7	79.3	—	—	—	—
109	1.75	3.867	0.376×10^{-6}	1.040	22.1	77.9	—	—	—	—
109	2.00	3.880	0.375×10^{-6}	1.043	23.7	76.3	—	—	—	—

Table 4.1—Rod and Pump Data (See 4.5) (Continued)

1	2	3	4	5	6	7	8	9		
Rod No.	Plunger Diameter in. D	Rod Weight lb/ft W_r	Elastic Constant in./lb-ft E_r	Frequency Factor F_c	Rod String, % of each size					
					1 1/8	1	7/8	3/4	5/8	1/2
109	2.25	3.896	0.374×10^{-6}	1.046	25.4	74.6	—	—	—	—
109	2.50	3.911	0.372×10^{-6}	1.048	27.2	72.8	—	—	—	—
109	2.75	3.930	0.371×10^{-6}	1.051	29.4	70.6	—	—	—	—
109	3.25	3.971	0.367×10^{-6}	1.057	34.2	65.8	—	—	—	—
109	3.75	4.020	0.363×10^{-6}	1.063	39.9	60.1	—	—	—	—
109	4.75	4.120	0.354×10^{-6}	1.066	51.5	48.5	—	—	—	—
1010	All	4.538	0.318×10^{-6}	1.000	100.00	—	—	—	—	—

* Rod No. shown in first column refers to the largest and smallest rod size in eighths of an inch. For example, Rod No. 76 is a two-way taper of 7/8 and 6/8 rods. Rod No. 85 is a four-way taper of 8/8, 7/8, 6/8 and 5/8 rods. Rod No. 109 is a two-way taper of 1 1/4 and 1 1/8 rods. Rod No. 77 is a straight string of 7/8 rods, etc.

Table 4.2—Tubing Data

1	2	3	4	5
Tubing Size	Outside Diameter, in.	Inside Diameter, in.	Metal Area, sq. in.	Elastic Constant in./lb-ft E_t
1.900	1.900	1.610	0.800	0.500×10^{-6}
2 3/8	2.375	1.995	1.304	0.307×10^{-6}
2 7/8	2.875	2.441	1.812	0.221×10^{-6}
3 1/2	3.500	2.992	2.590	0.154×10^{-6}
4	4.000	3.476	3.077	0.130×10^{-6}
4 1/2	4.500	3.958	3.601	0.111×10^{-6}

Table 4.3—Sucker Rod Data

1	2	3	4
Rod Size	Metal Area Sq. in.	Rod Weight in air, lb/ft W_r	Elastic Constant, in./lb-ft E_r
1/2	0.196	0.72	1.990×10^{-6}
5/8	0.307	1.13	1.270×10^{-6}
3/4	0.442	1.63	0.883×10^{-6}
7/8	0.601	2.22	0.649×10^{-6}
1	0.785	2.90	0.497×10^{-6}
1 1/8	0.994	3.67	0.393×10^{-6}

Table 4.4—Pump Constants

1	2	3	4
Plunger Diameter, in. D	**Plgr. Diam, Squared Sq. in.** D^2	**Fluid Factor lb/ft** $(.340 \times D^2)$	**Load Pump Factor,** $(.1166 \times D^2)$
1 1/16	1.1289	0.384	0.132
1 1/4	1.5625	0.531	0.182
1 1/2	2.2500	0.765	0.262
1 3/4	3.0625	1.041	0.357
2	4.0000	1.360	0.466
2 1/4	5.0625	1.721	0.590
2 1/2	6.2500	2.125	0.728
2 3/4	7.5625	2.571	0.881
3 3/4	14.0625	4.781	1.640
4 3/4	22.5625	7.671	2.630

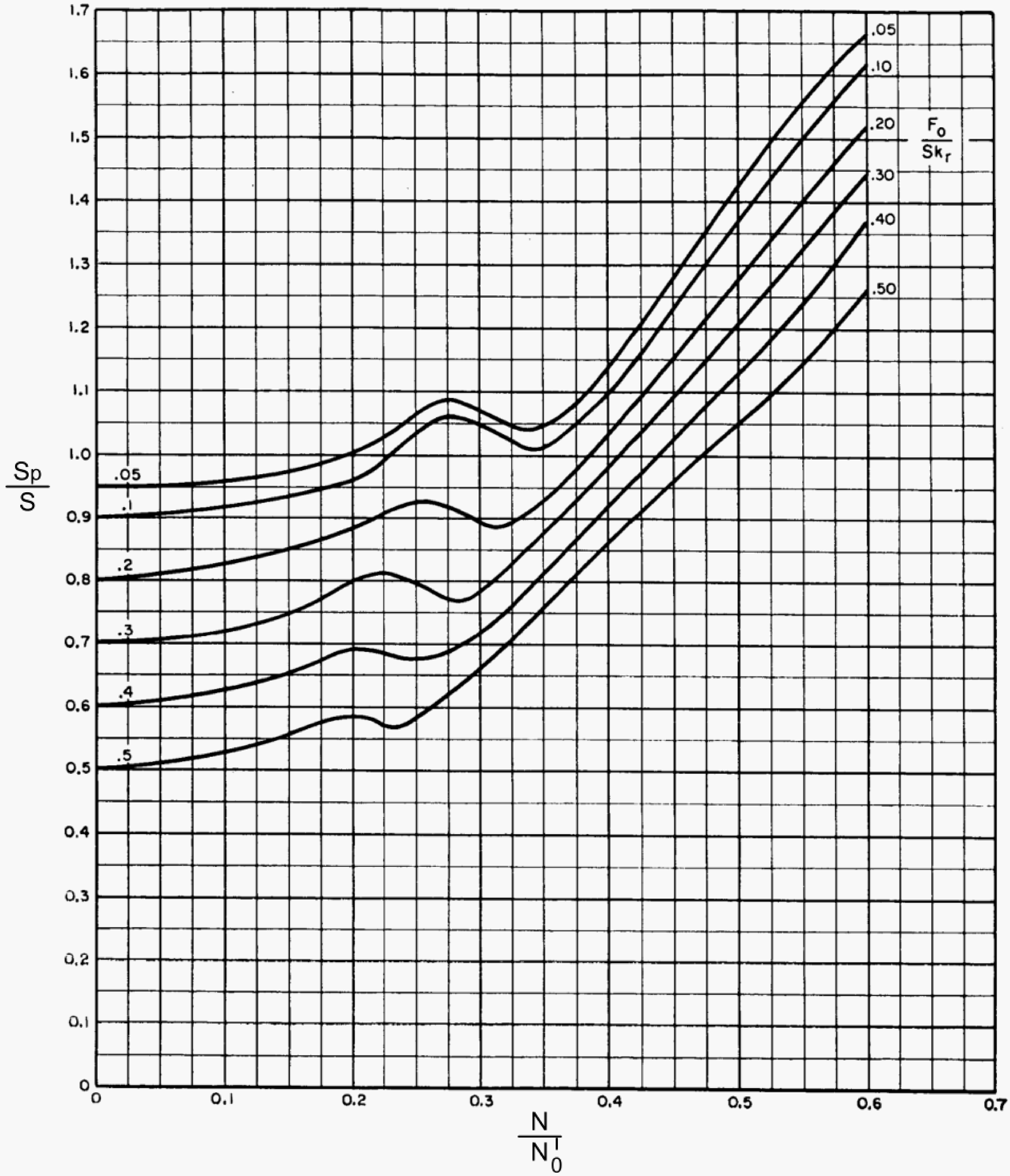


Figure 4.1— $\frac{S_p}{S}$**, Plunger Stroke Factor**

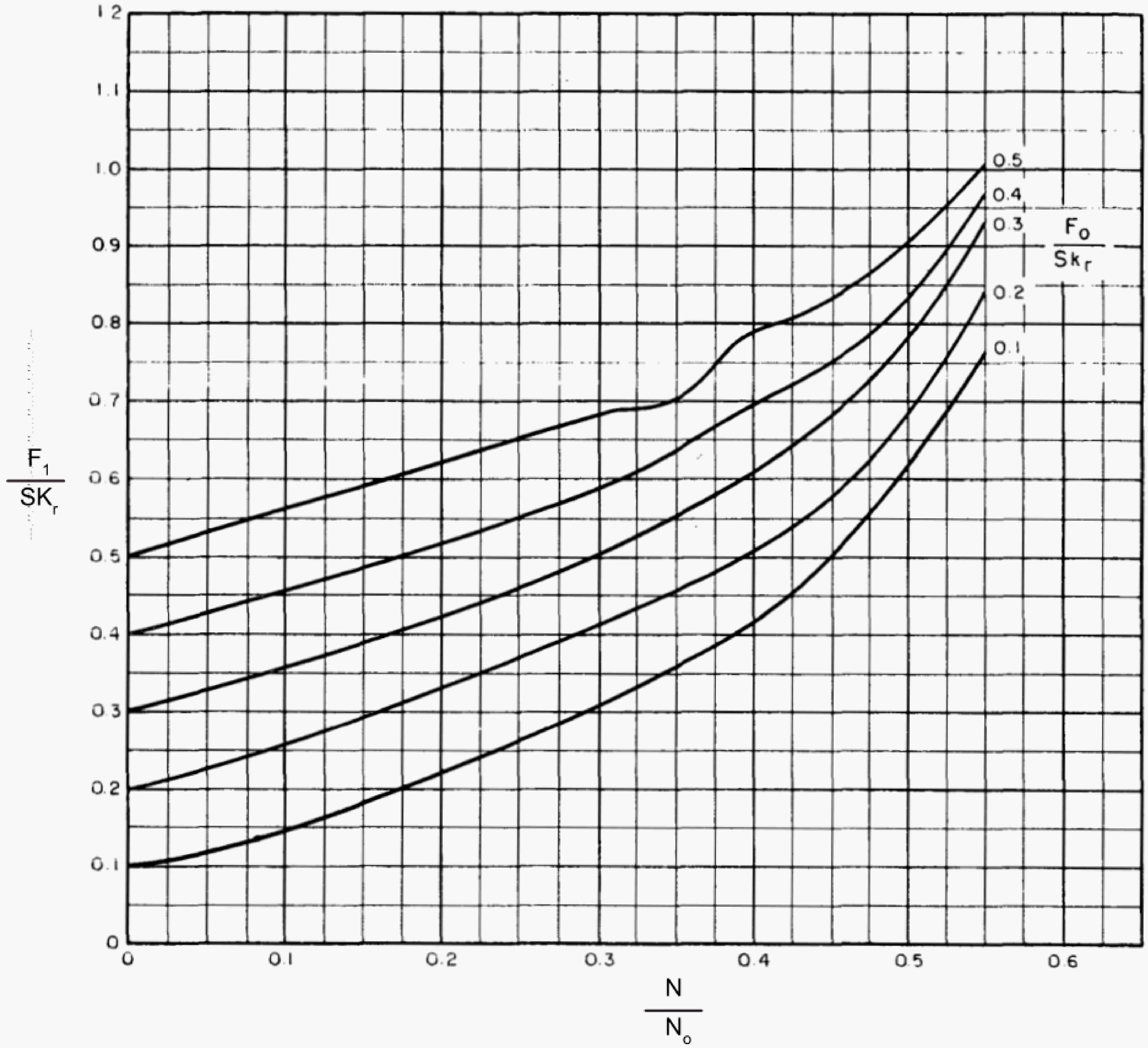
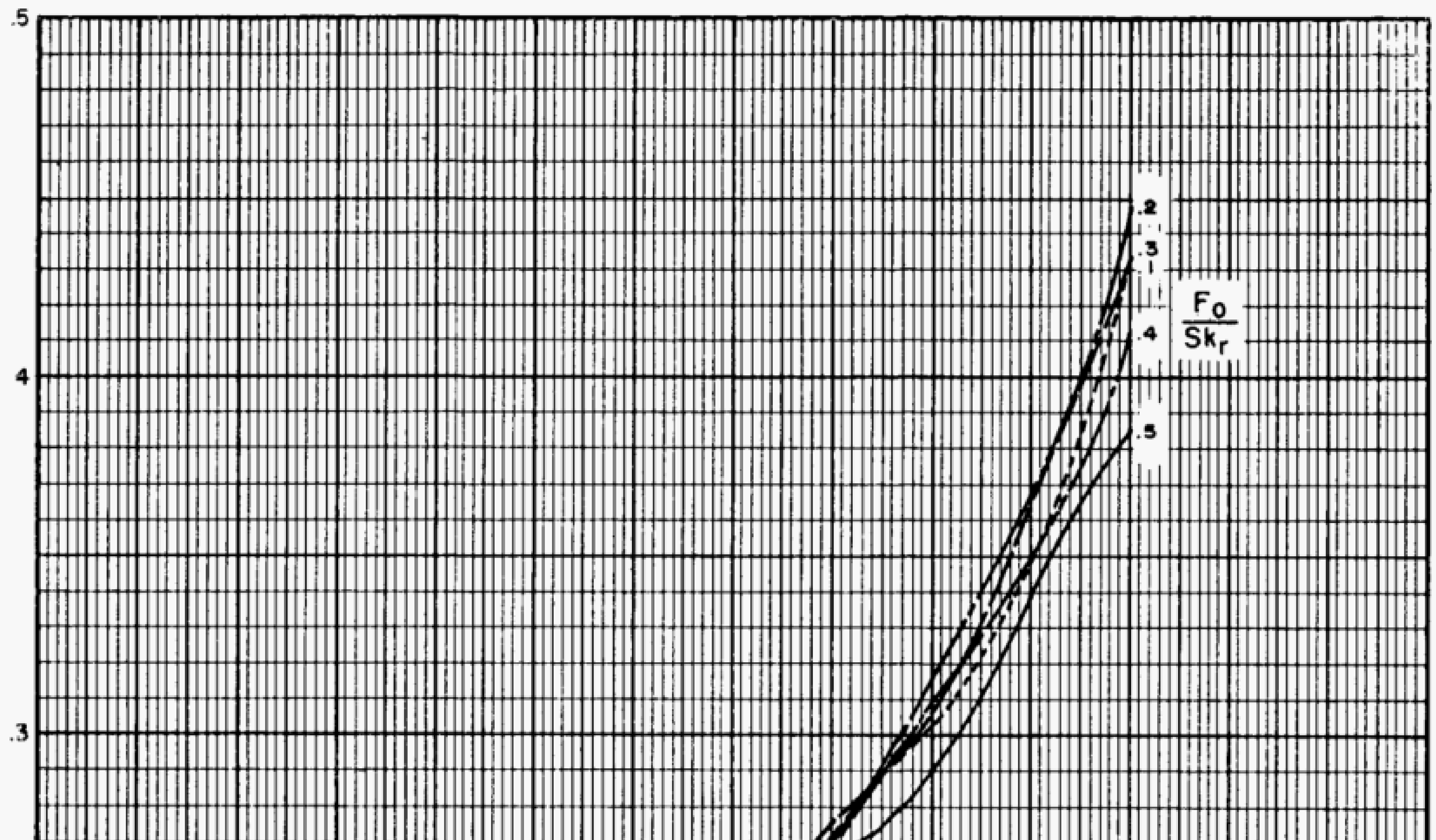


Figure 4.2—$\frac{F_1}{Sk_r}$, Peak Polished Rod Load



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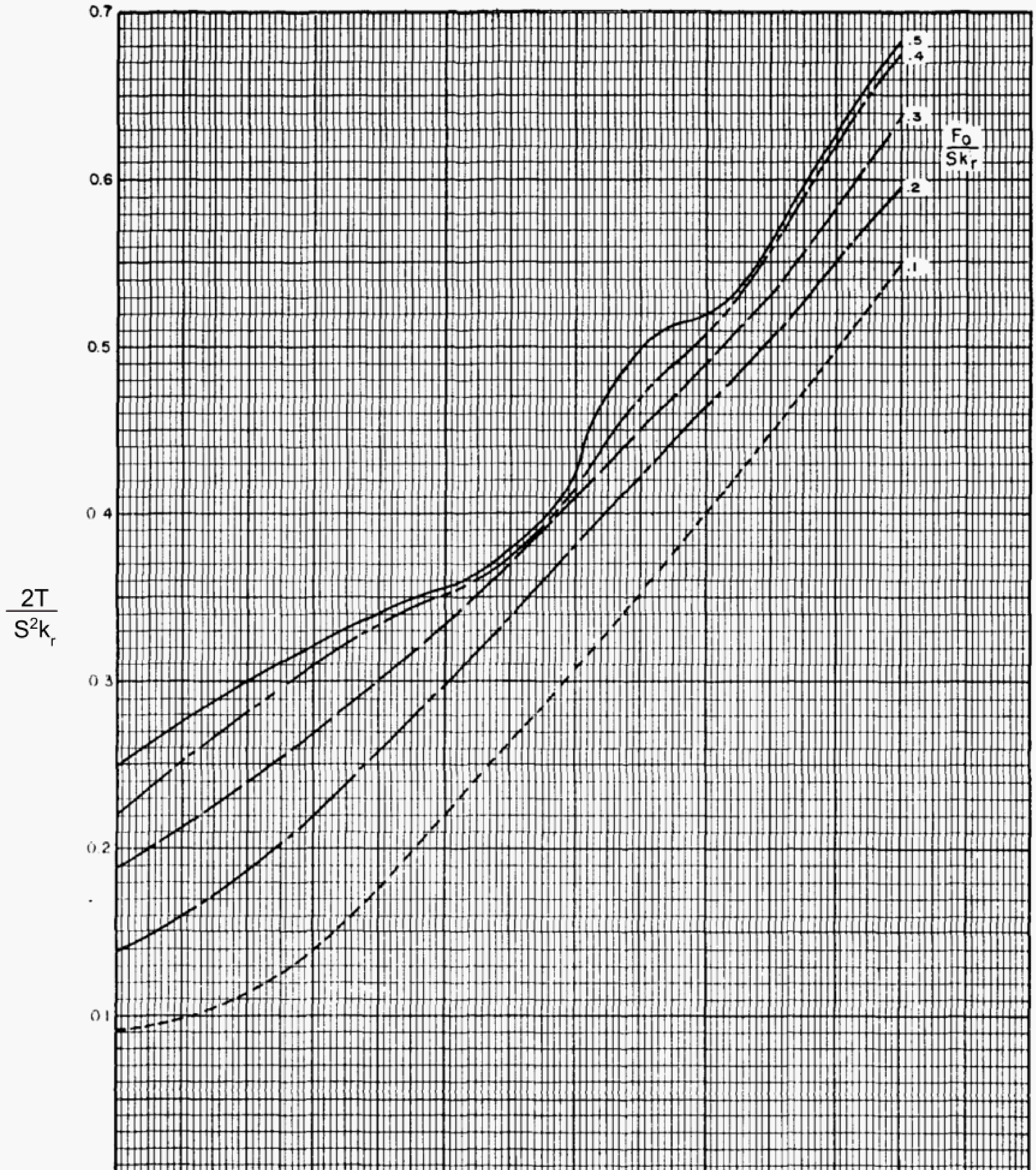

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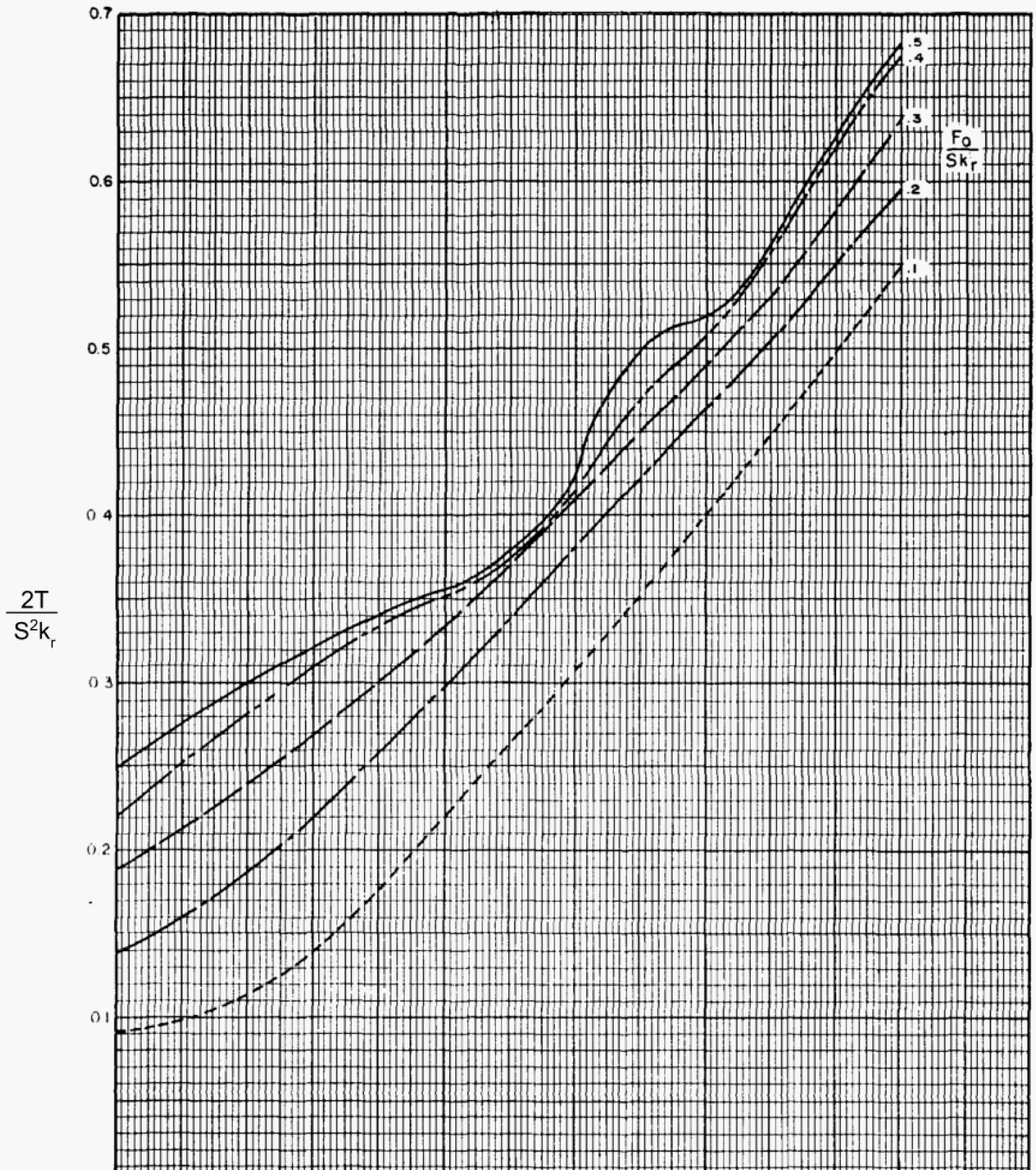

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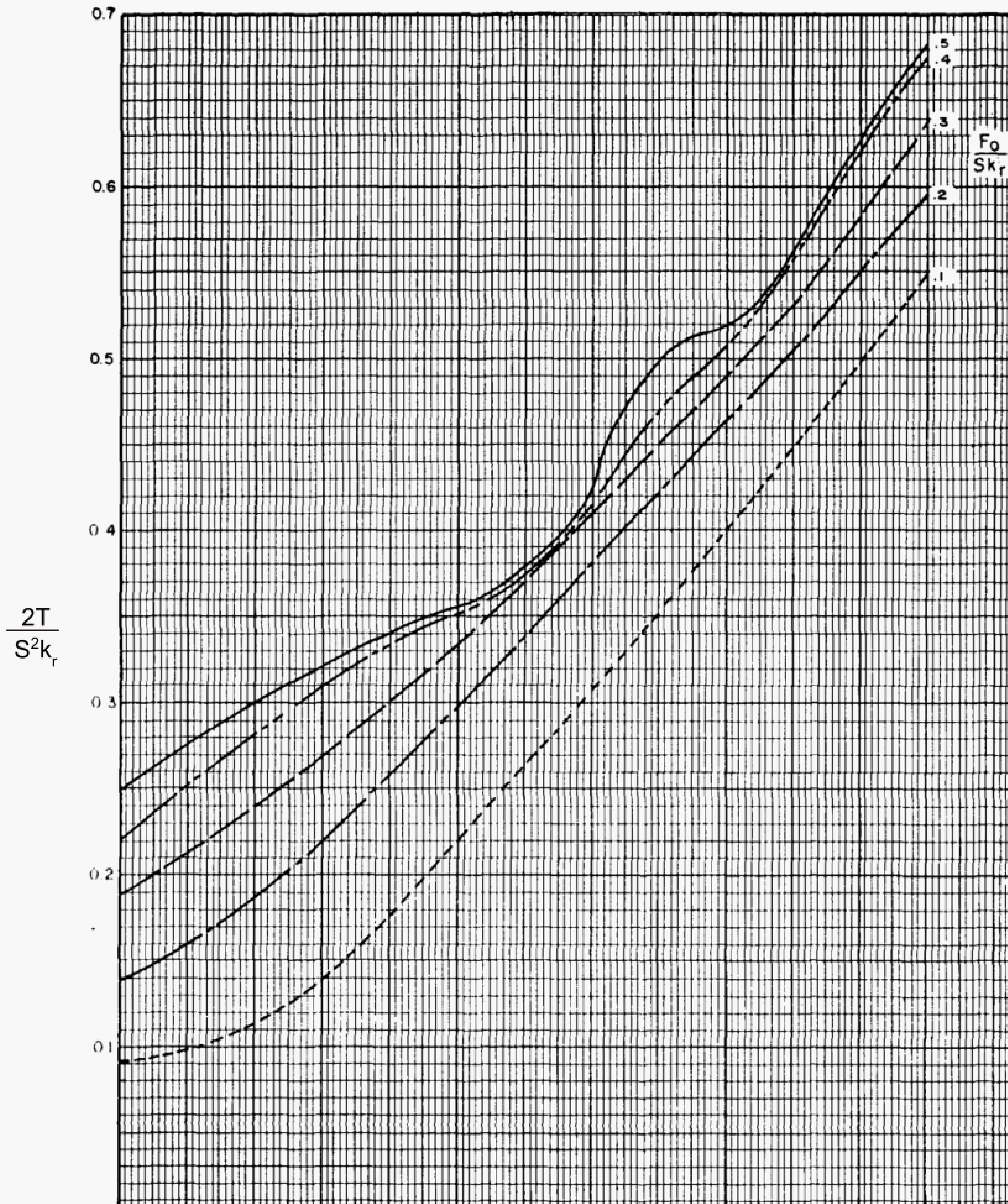

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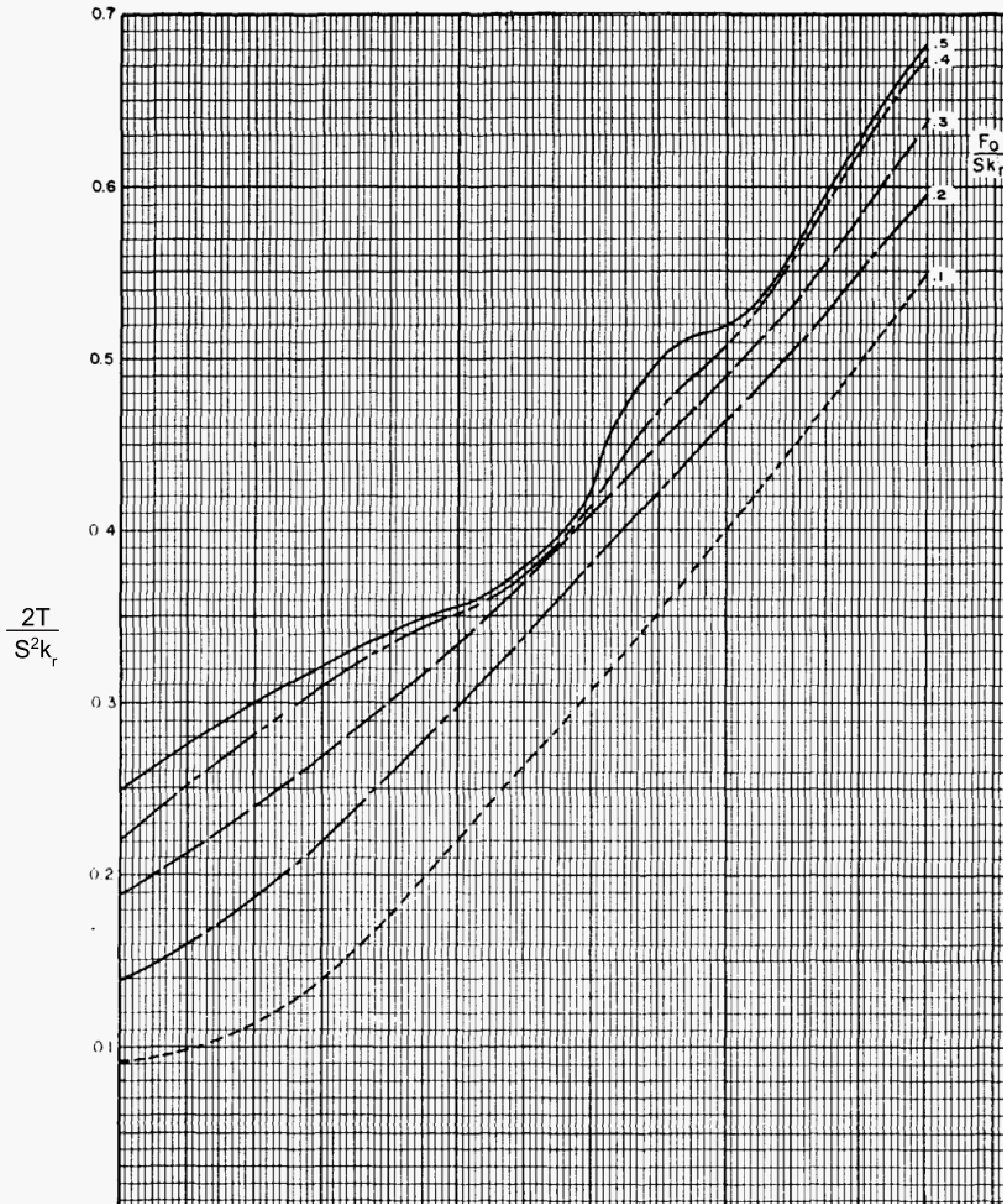

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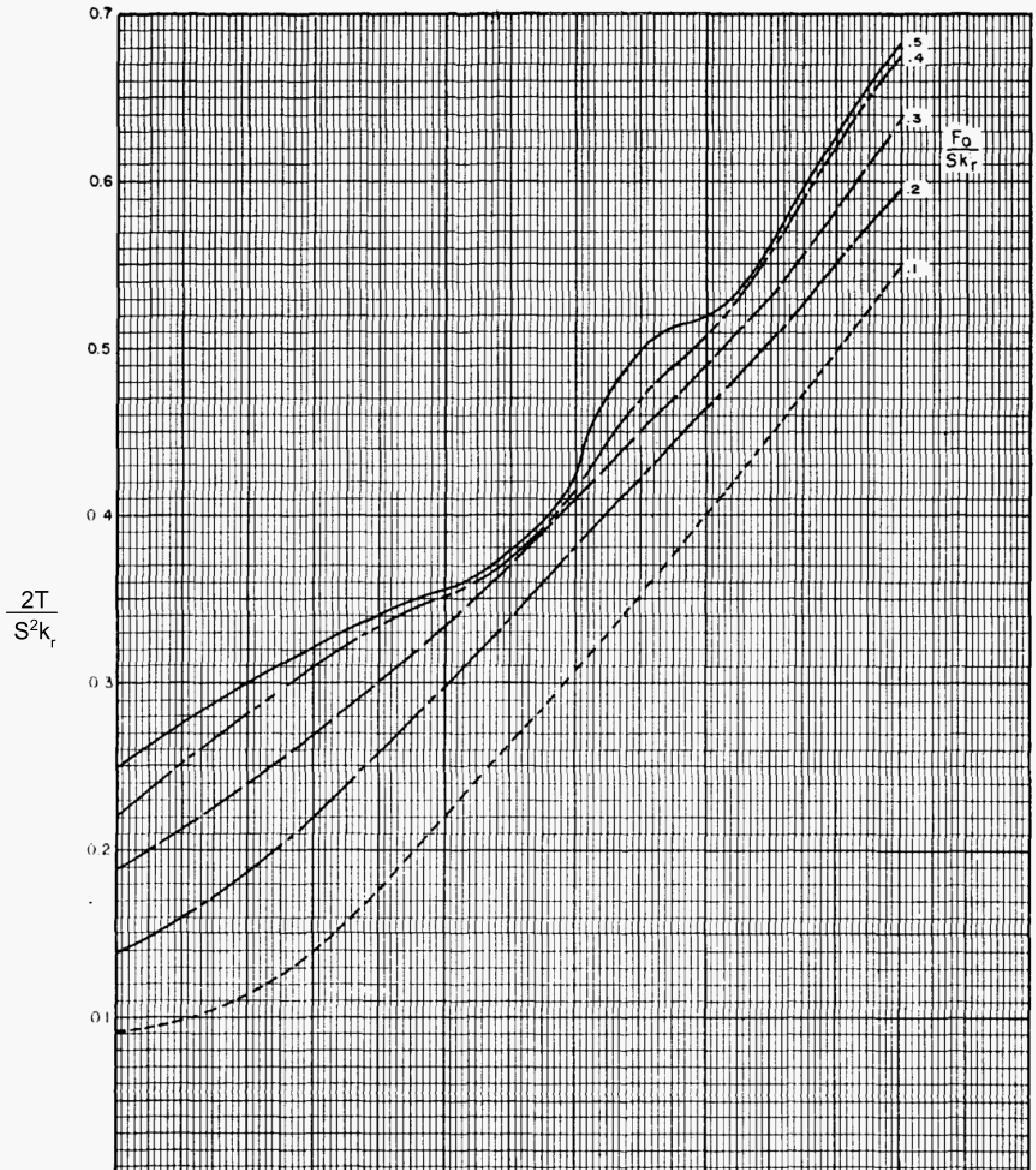

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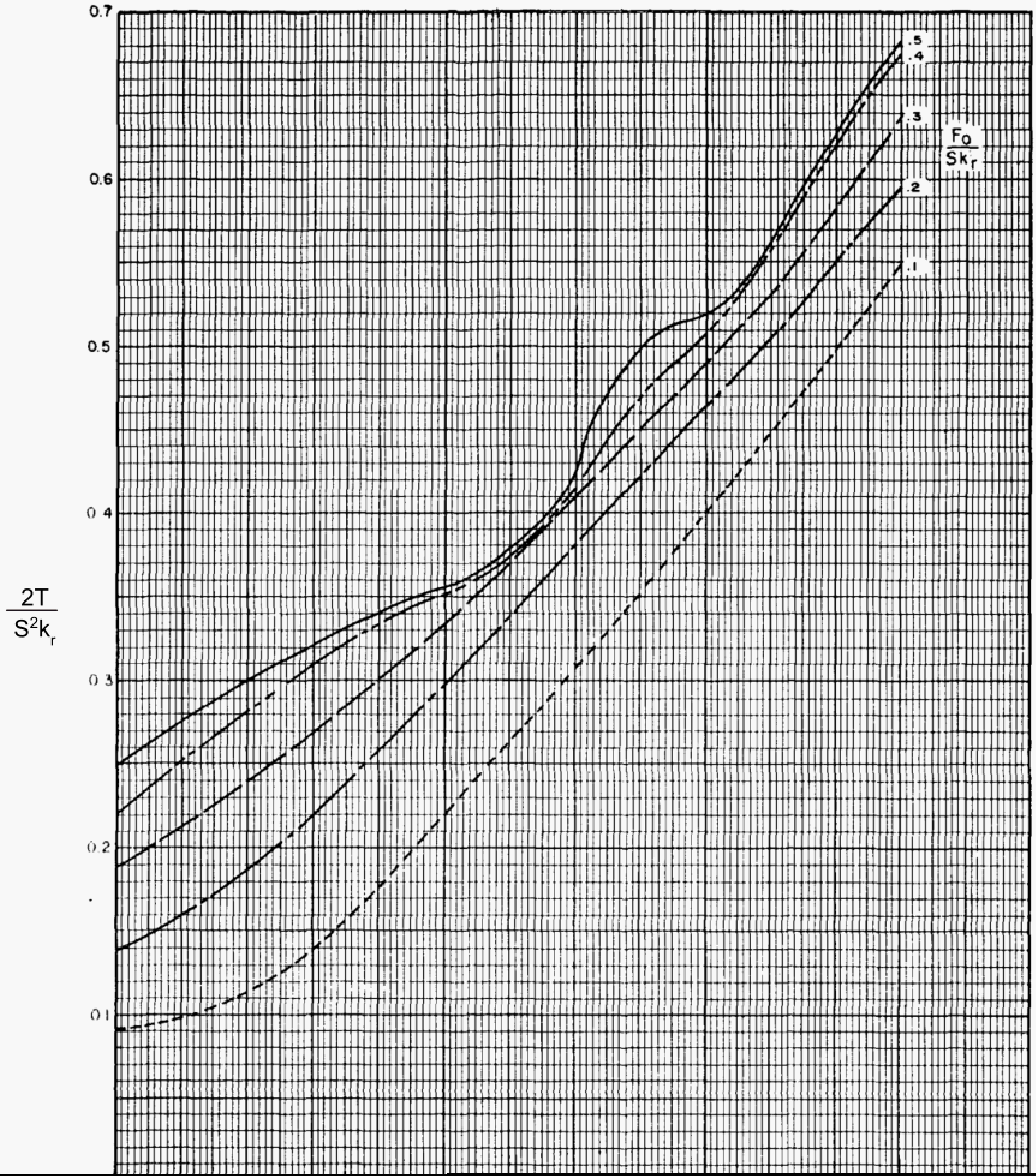

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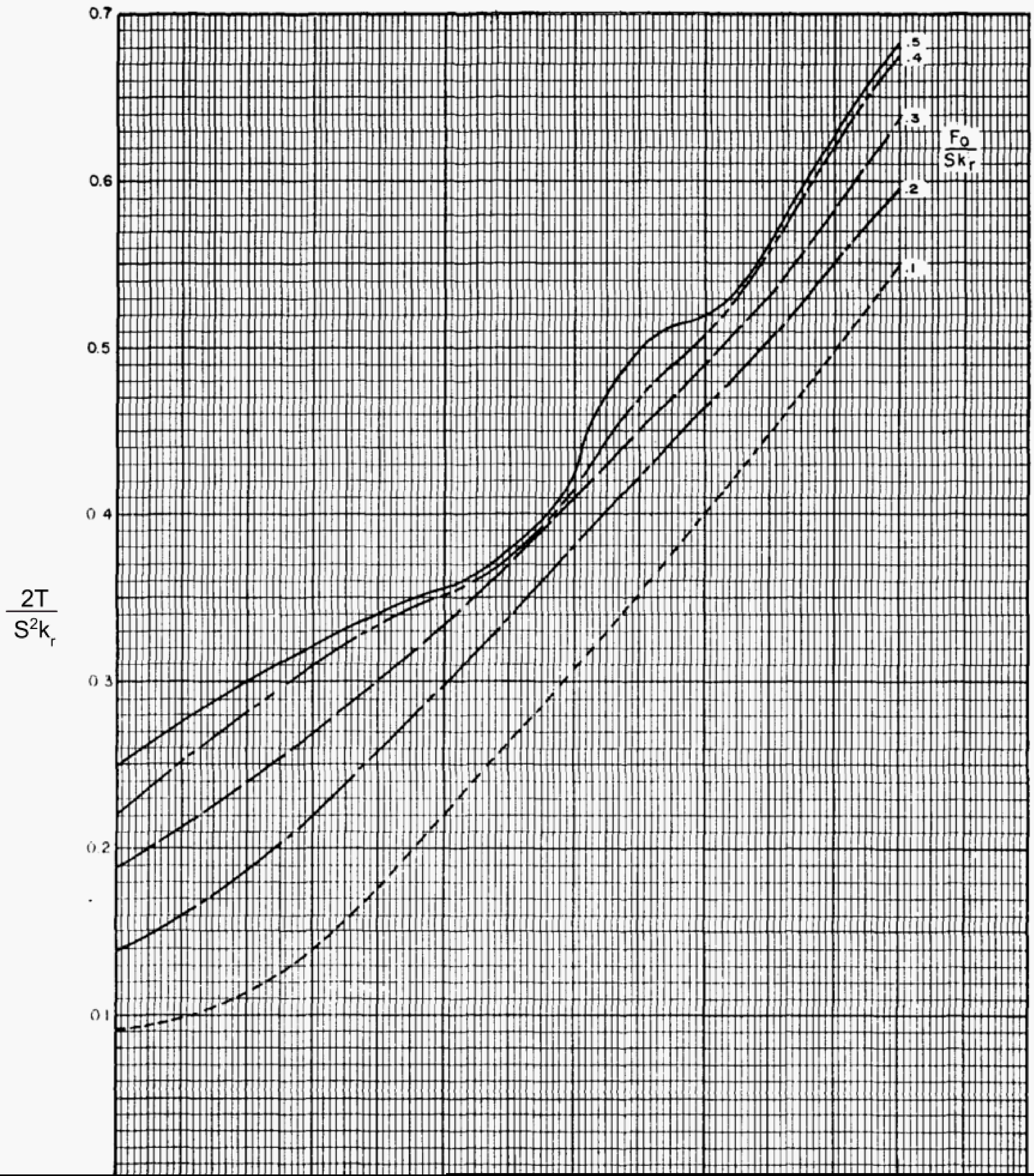

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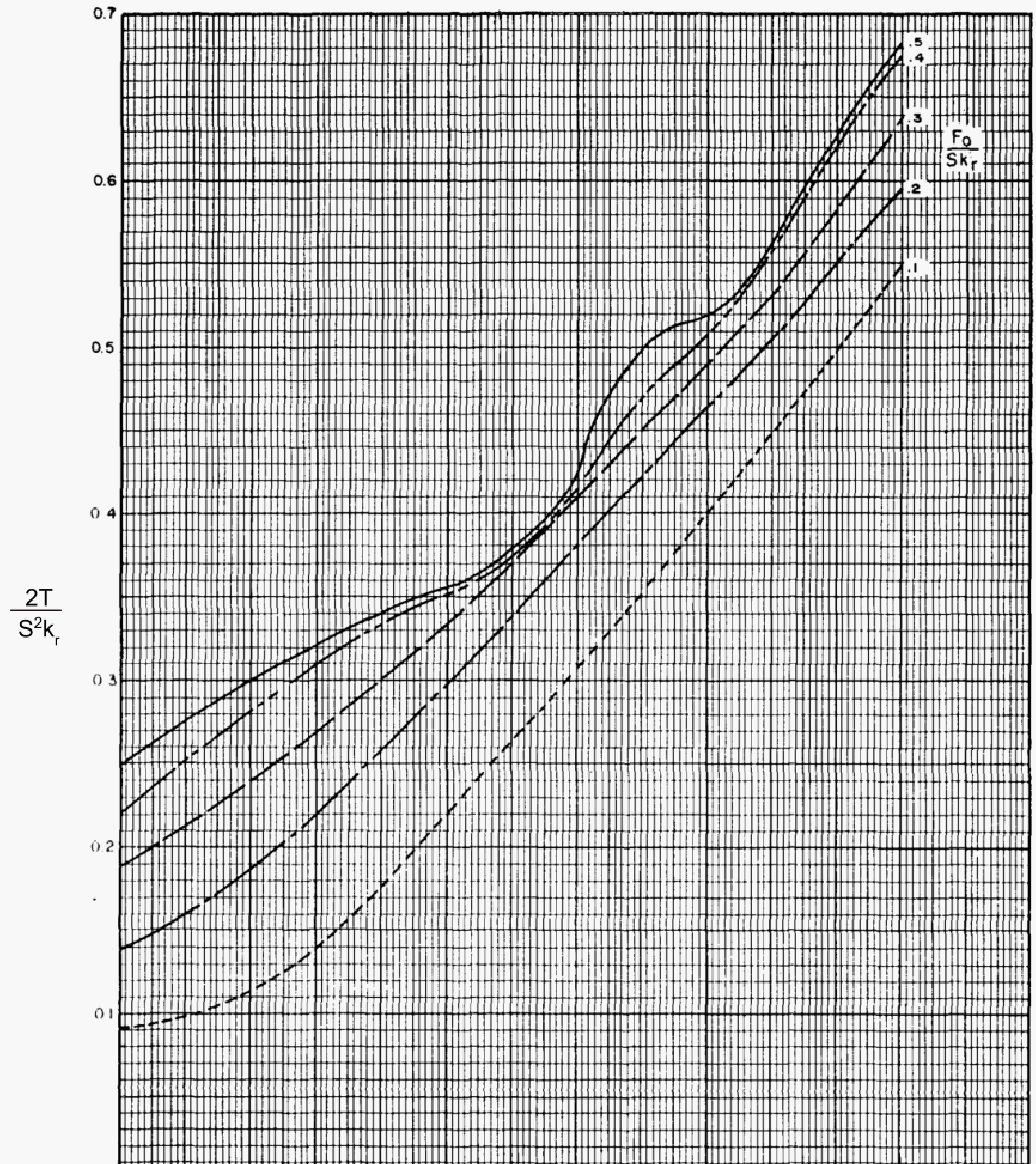

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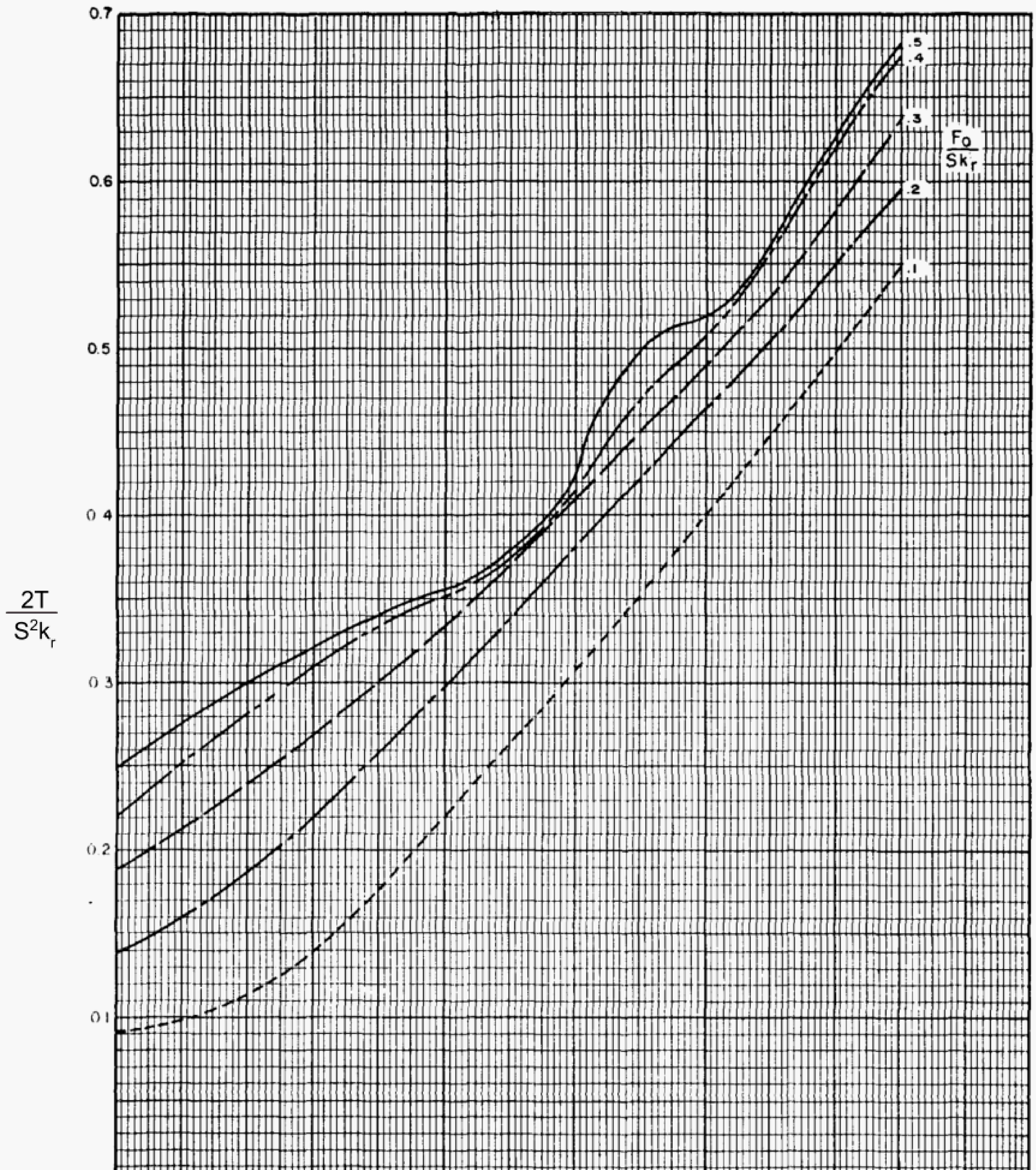

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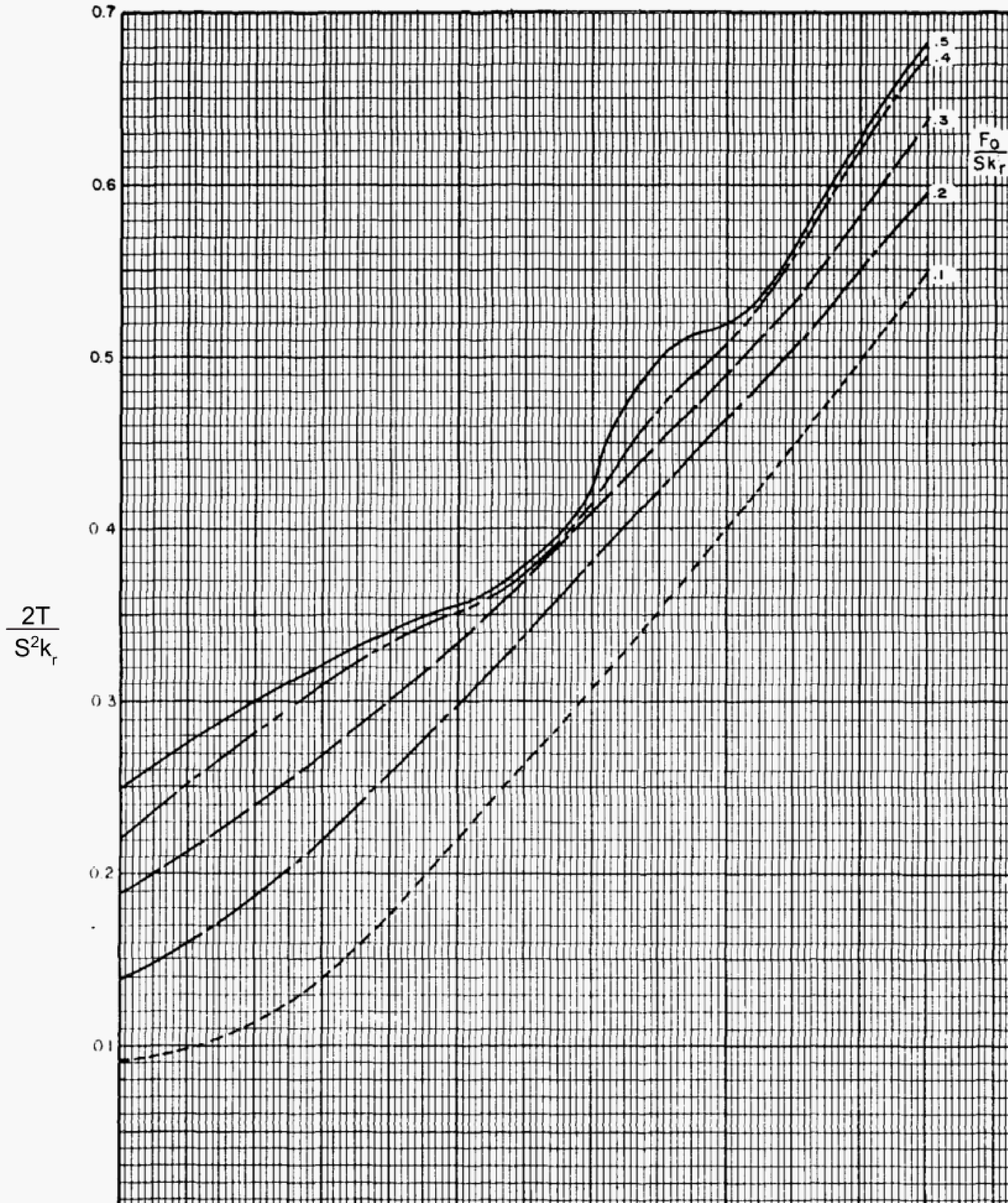

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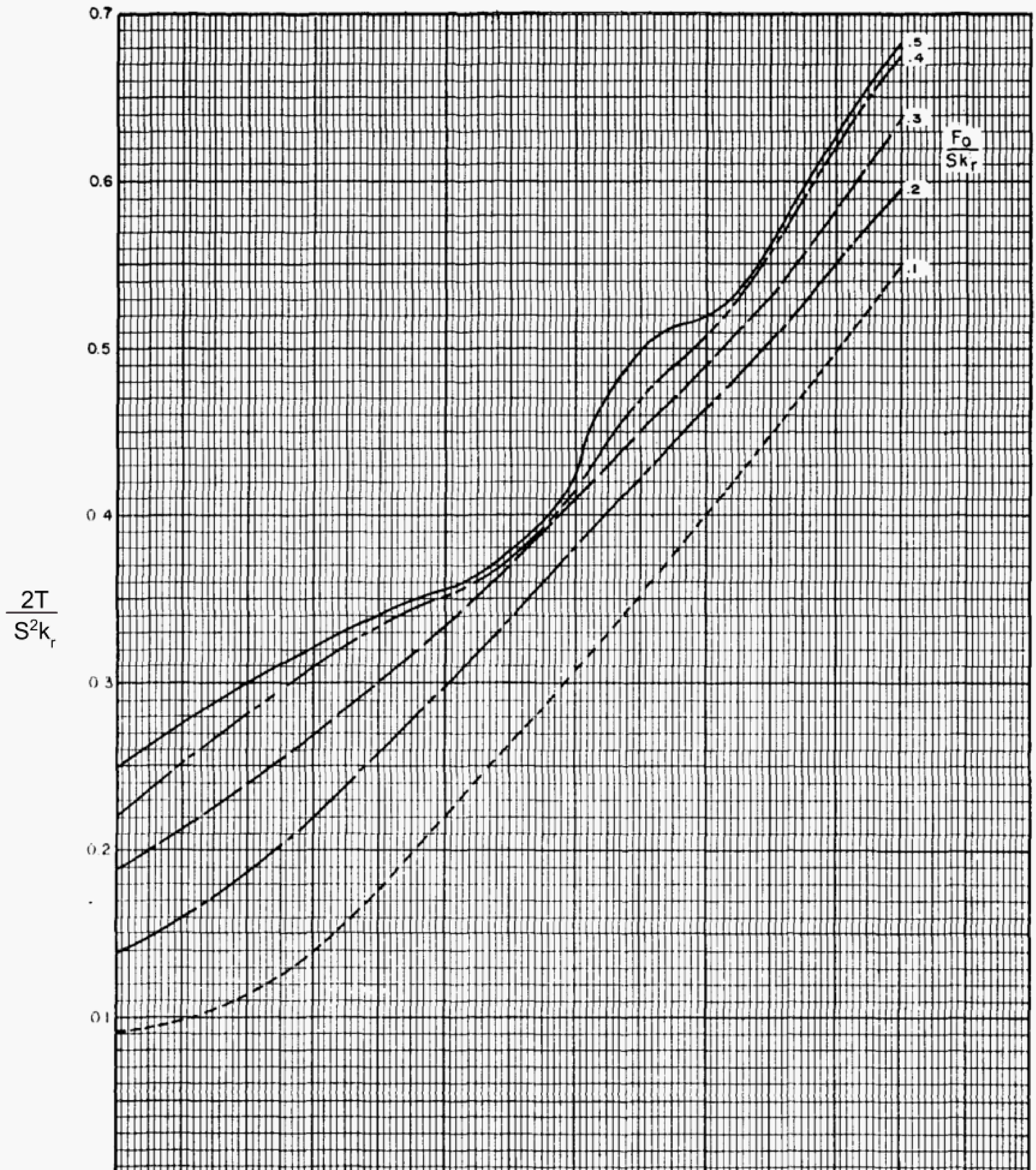

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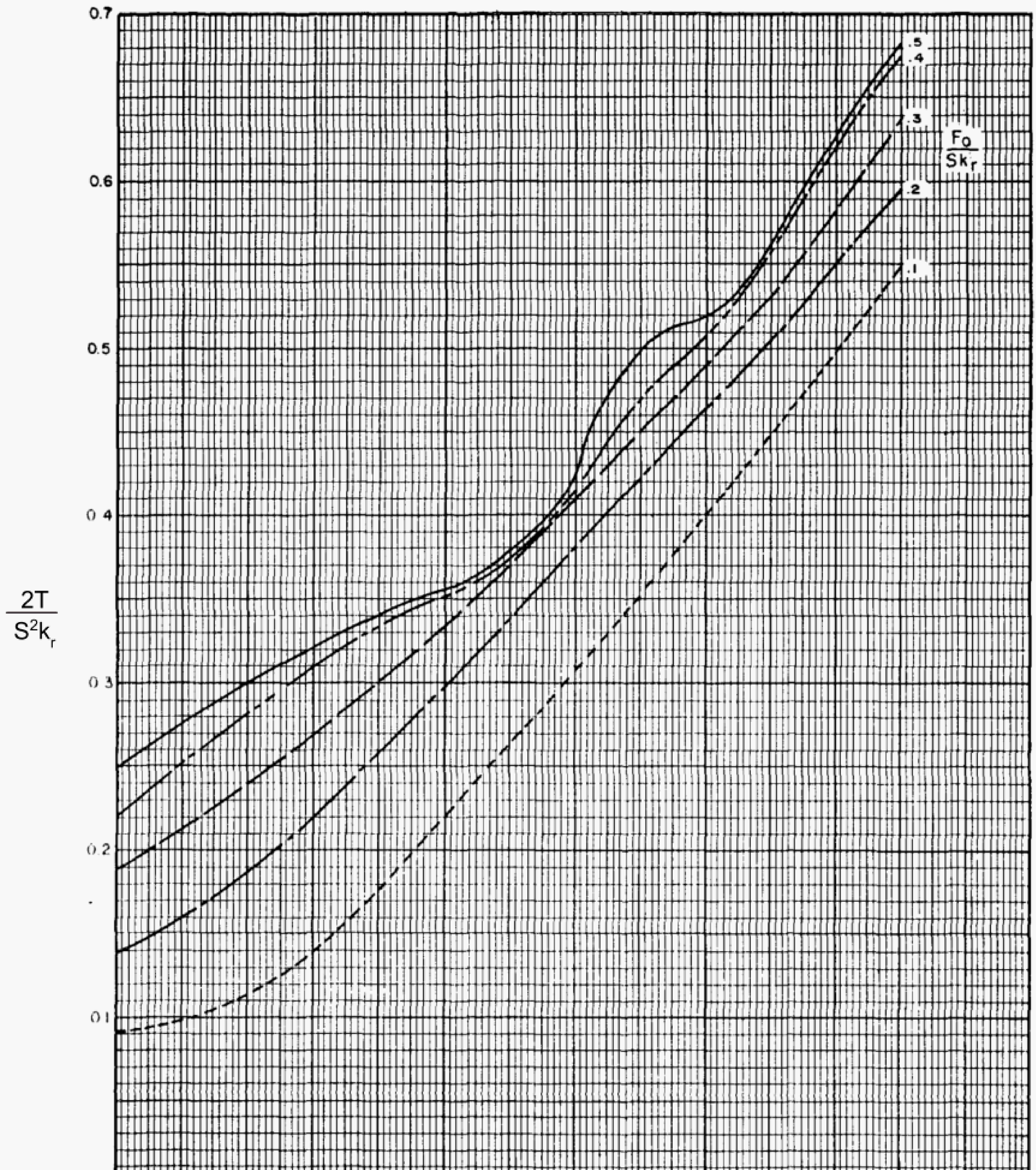

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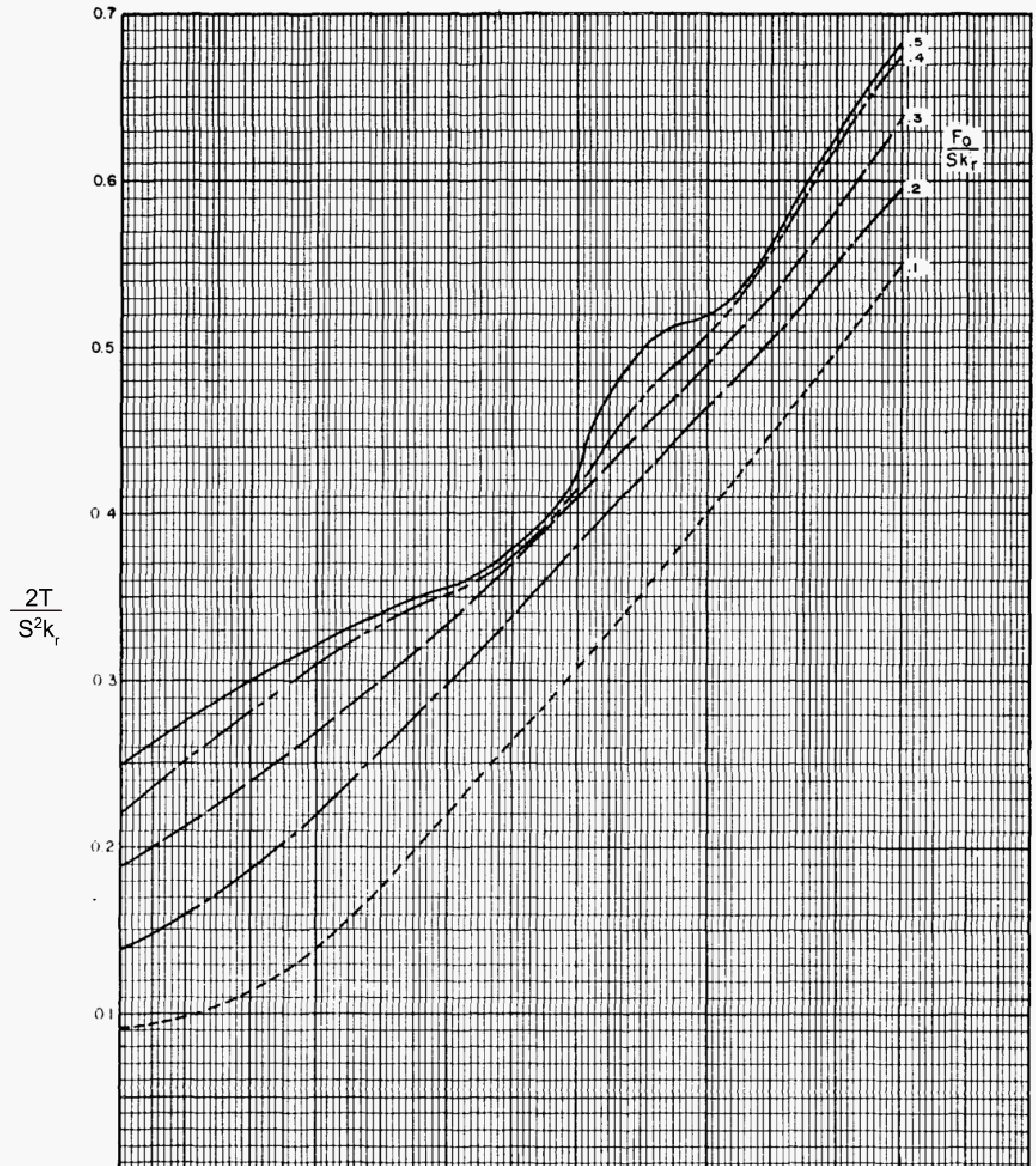

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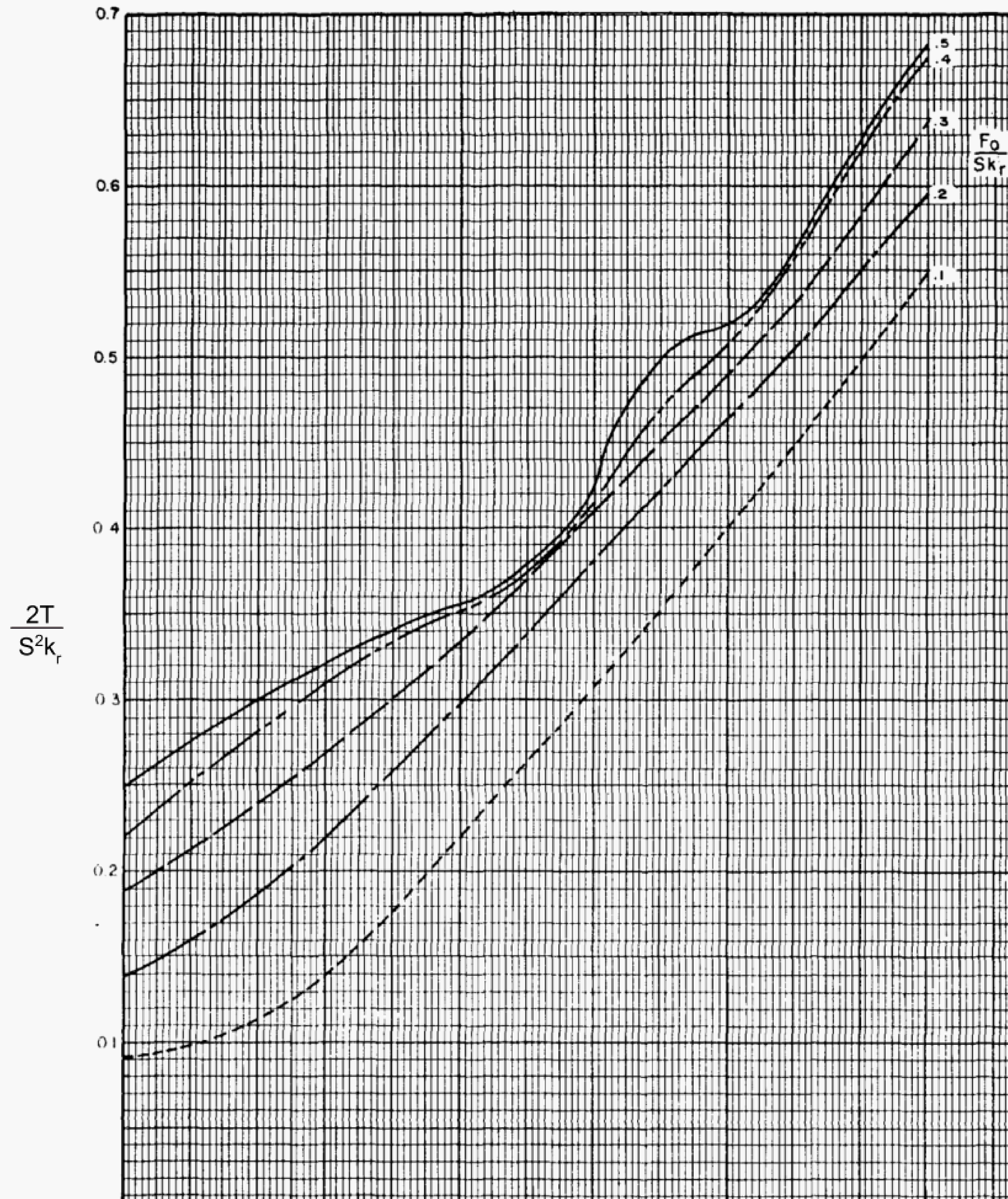

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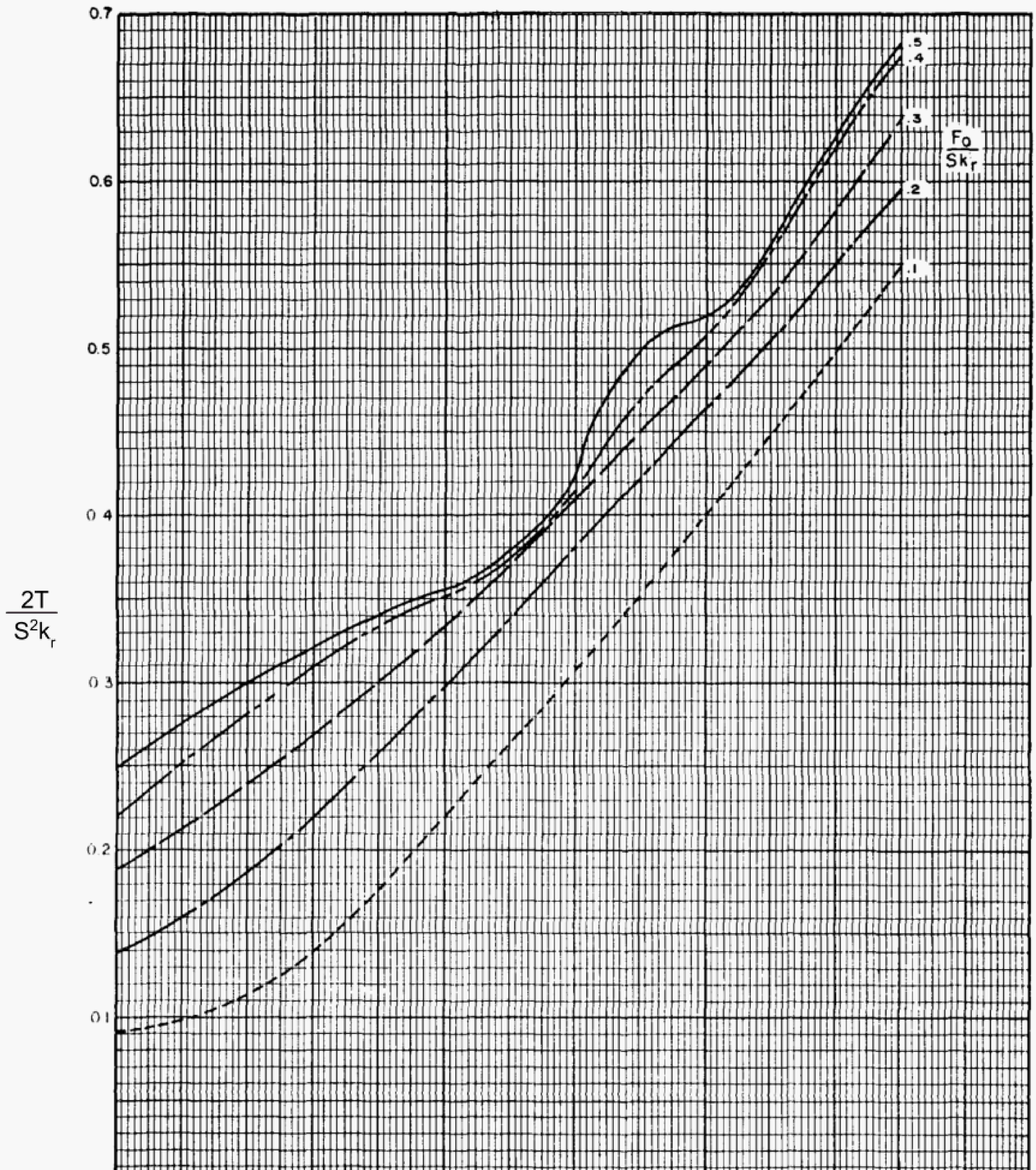

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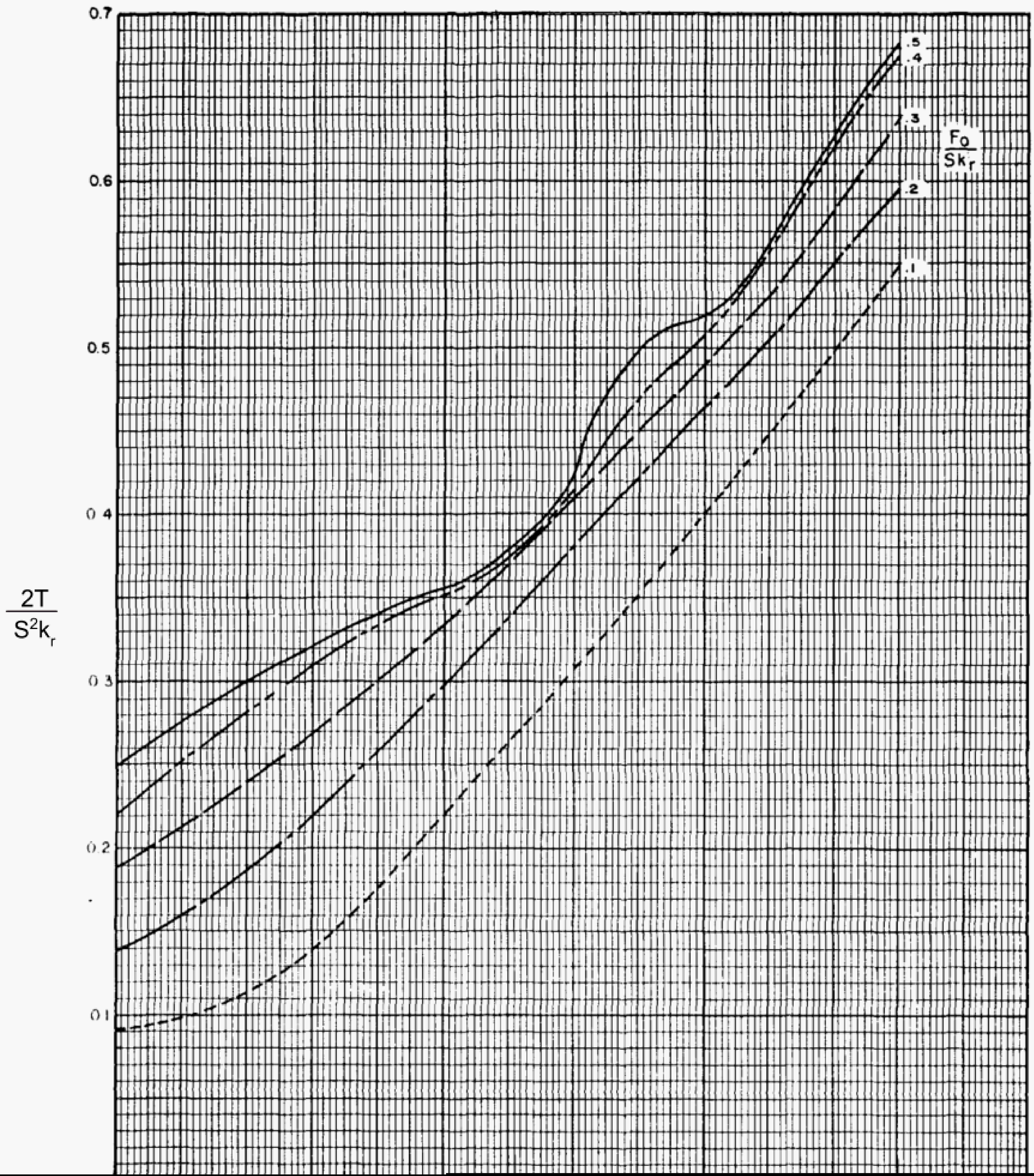

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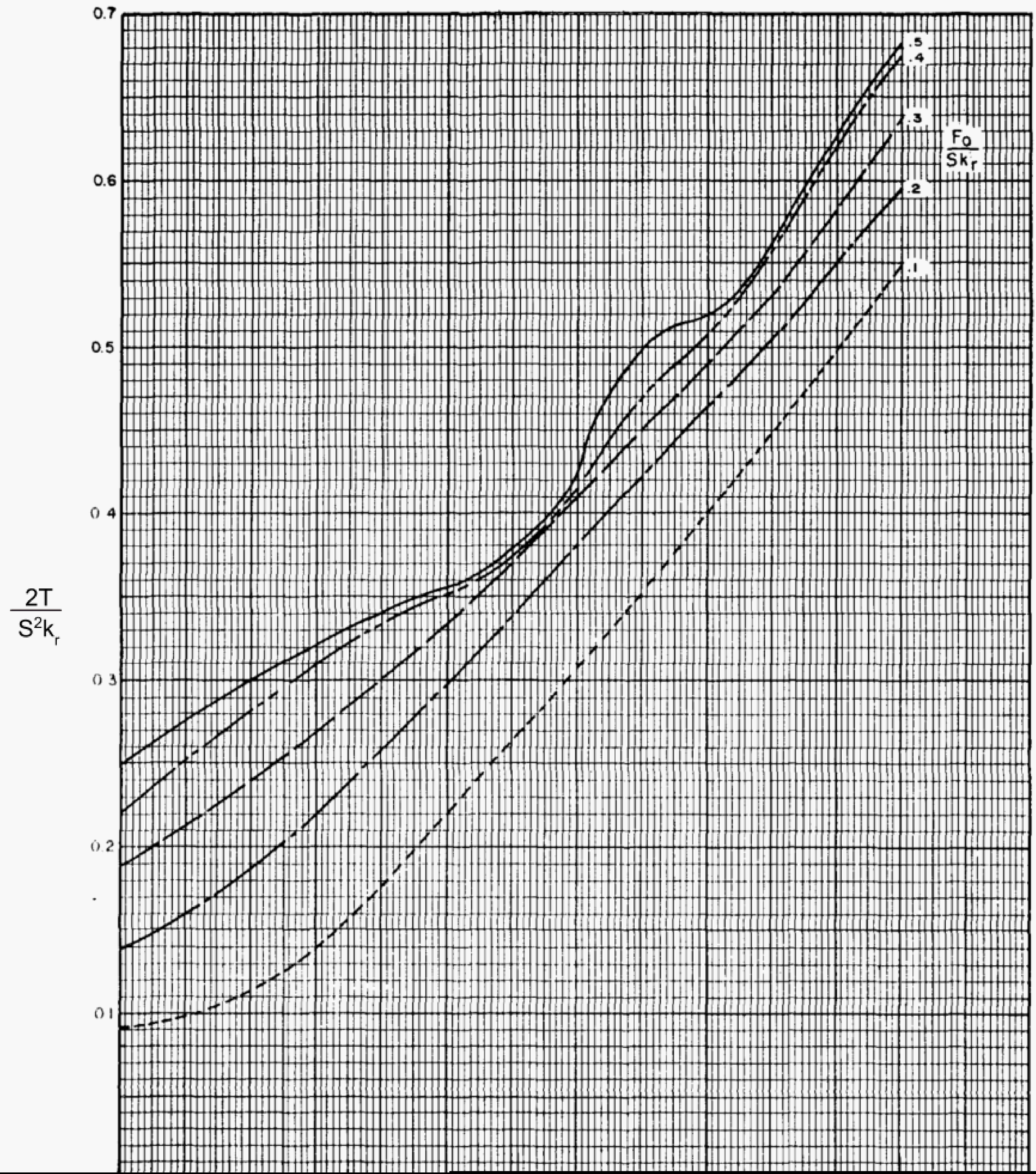

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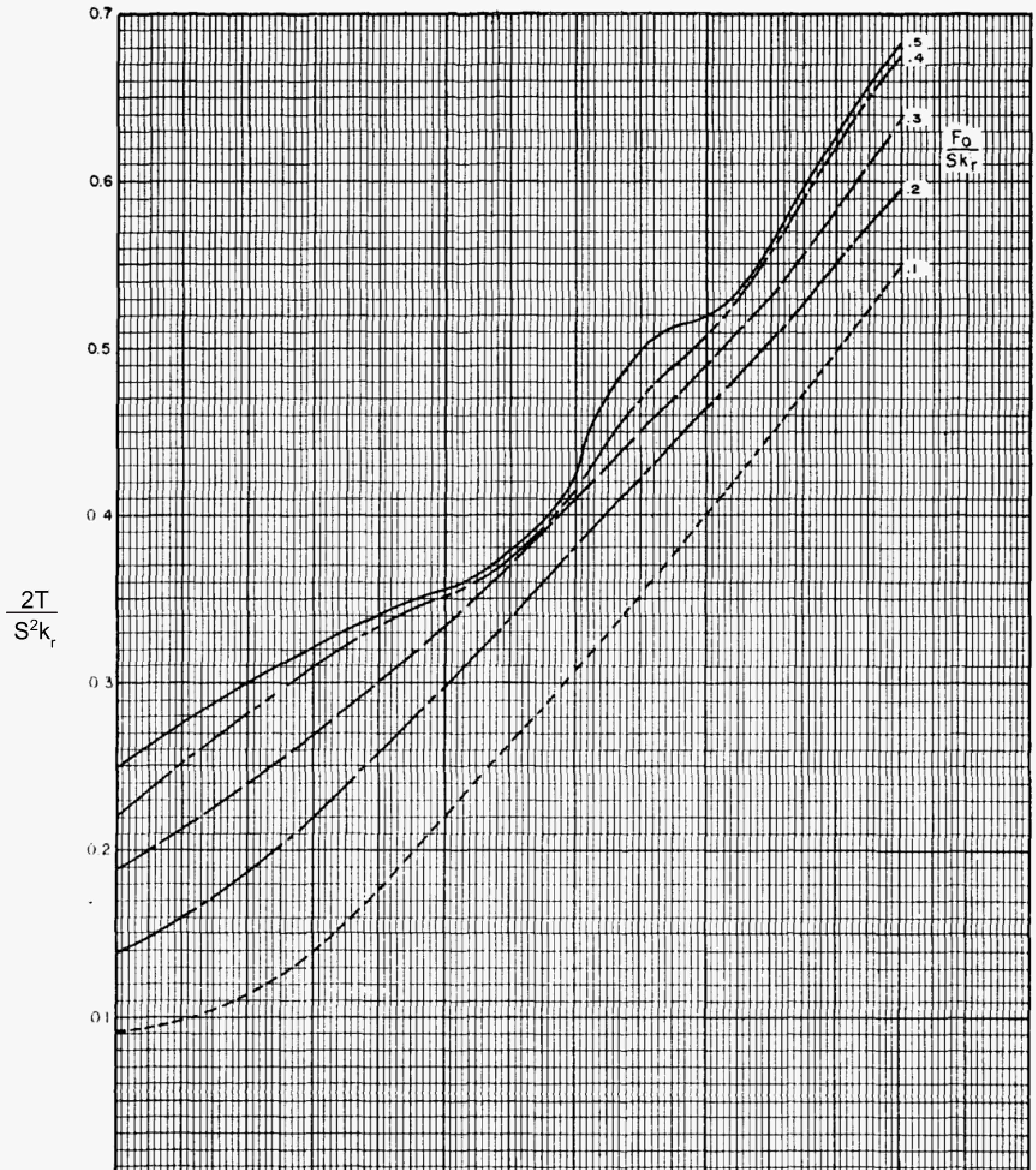

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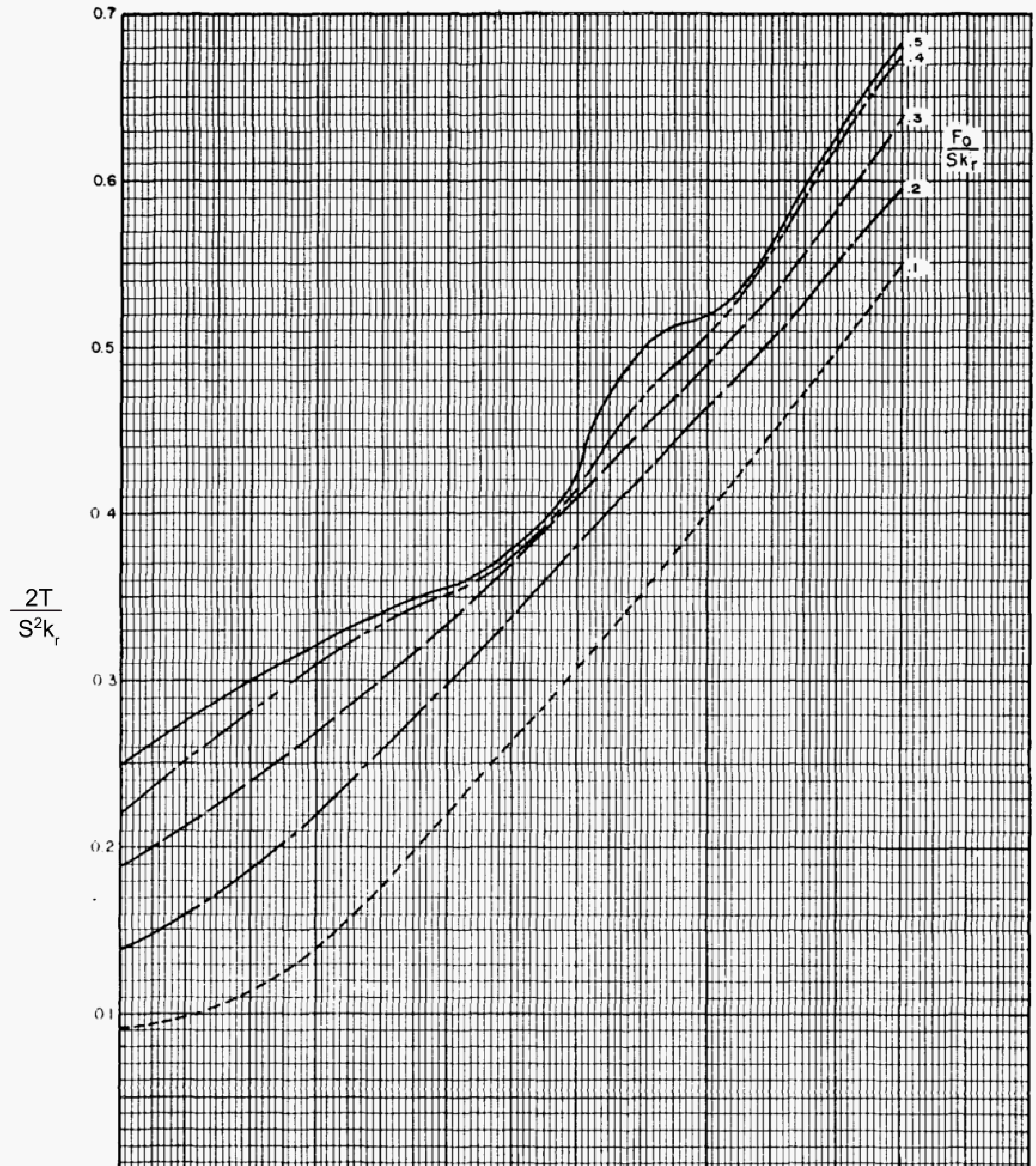

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