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**THRUST COEFFICIENTS,  
THRUST DEFLECTION ANGLES, AND  
NONDIMENSIONAL MOMENTS  
FOR NOZZLES WITH OBLIQUE EXIT PLANES**

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→ Nozzles with oblique exit planes, scarfed nozzles, are encountered in aerospace applications such as reaction control and thrust reversal systems. This document provides thrust coefficient, thrust deflection angle, and nondimensional turning moment data for scarfed conical nozzles on machine-generated graphs. Based on one-dimensional isentropic flow of a perfect gas, the data cover specific heat ratios from 1.18 to 1.40, nozzle half-angles from 5 to 25 degrees, scarf angles from 10 to 60 degrees, area ratios at the upstream scarf point from 1.5 to 15, and ratios of chamber pressure to ambient pressure from 20 to infinity (vacuum).		

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THE BOEING COMPANY  
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## LIST OF GRAPHS

Graphs of thrust coefficient, deflection angle, and nondimensional moment are listed below.

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## PREFACE

Nozzles with oblique exit planes, scarfed nozzles, are encountered in aerospace applications such as reaction control and thrust reversal systems. This document provides thrust coefficient, thrust deflection angle, and nondimensional turning moment data for scarfed conical nozzles on machine-generated graphs. Based on one-dimensional isentropic flow of a perfect gas, the data cover specific heat ratios from 1.18 to 1.40, nozzle half-angles from 5 to 25 degrees, scarf angles from 10 to 60 degrees, area ratios at the upstream scarf point from 1.5 to 15, and ratios of chamber pressure to ambient pressure from 20 to infinity (vacuum).

The data presented herein were developed by the Rocket Propulsion Research Staff of the Missile and Information Systems Division of The Boeing Company. An original analysis by Robert Hopcroft was extended in scope and programmed for computation by Ross Fiedler and William Phillips. Mike Whitaker programmed the machine plotting. William Phillips wrote the text and coordinated printing.

## SYMBOLS

(See Figures A and B on Page vii)

$A_t$	Nozzle throat area
$C_{F_{sc}}$	Total thrust coefficient
$C_{F_o}$	Thrust coefficient for symmetrical section of nozzle (corrected for flow divergence)
$C_{T_x}$	Total thrust coefficient in x-direction
$C_{T_y}$	Total thrust coefficient in y-direction
$F_x$	Thrust produced by scarfed section of nozzle in x-direction
$F_y$	Thrust produced by scarfed section of nozzle in y-direction
$L$	Length of scarfed section of nozzle
$M_{z_{oND}}$	Nondimensional moment produced about z-axis at point o (positive in clockwise direction)
$P$	Pressure at any point inside scarfed section
$P_a$	Ambient pressure
$P_c$	Chamber pressure
$R$	Radius of nozzle at any point inside scarfed section
$R_o$	Radius of nozzle at upstream scarf point
$R_t$	Nozzle throat radius
$T$	Total thrust produced by the nozzle
$T_x$	Total thrust in x-direction
$T_y$	Total thrust in y-direction
$x$	Axial distance inside nozzle from point o
$y$	Distance inside nozzle perpendicular to axis
$\alpha$	Nozzle half-angle
$\beta$	Direction of radius vector R
$\gamma$	Specific heat ratio
$\theta$	Thrust deflection angle
$\phi$	Nozzle scarf angle

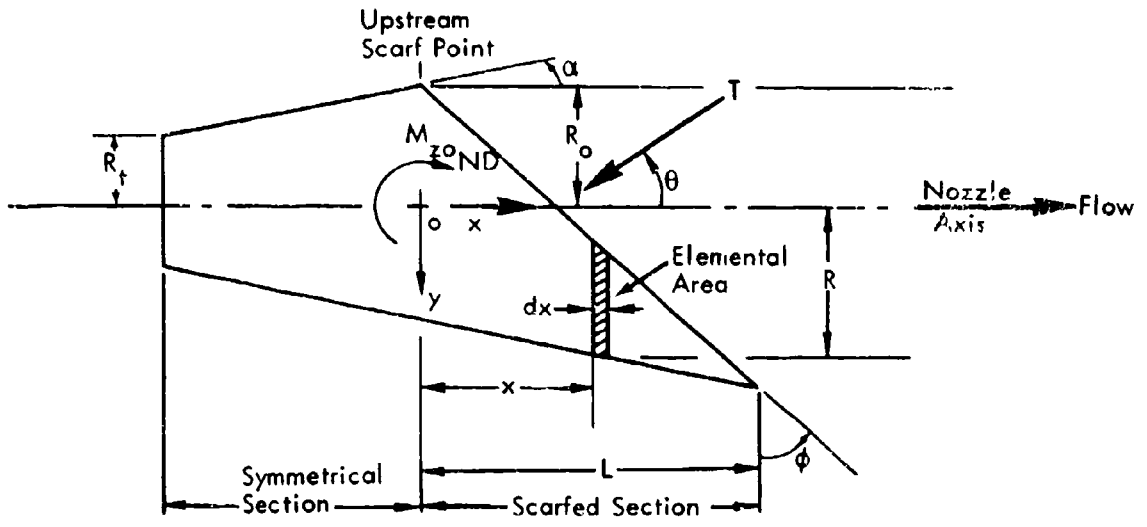


Figure A: SIDE VIEW OF SCARFED CONICAL NOZZLE

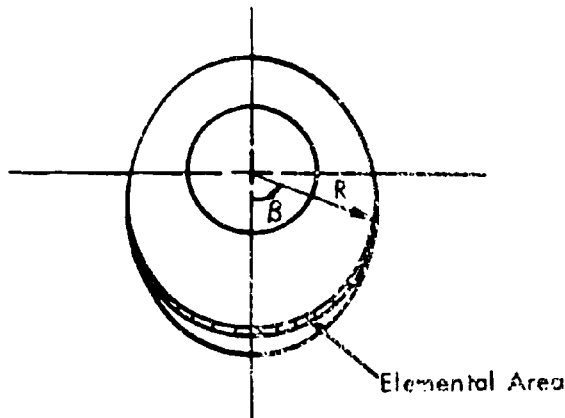


Figure B: END VIEW OF SCARFED CONICAL NOZZLE



## ANALYSIS

### ASSUMPTIONS AND LIMITATIONS

- 1) The flow is accelerated from stagnation conditions.
- 2) The gases obey the perfect gas laws.
- 3) The flow is one-dimensional, steady, and isentropic.
- 4) The momentum term of the thrust equation is corrected for divergence of the gas flow.
- 5) The data provided exclude those cases where:
  - a) Expansion fans originating from the upstream scarf point would intersect the opposite wall of the nozzle;
  - b) Flow separation would occur inside the nozzle.

### EQUATIONS

The scarfed nozzle thrust coefficient, deflection angle, and nondimensional moment are defined as follows:

$$C_{F_{sc}} = \frac{T}{P_c A_t}$$
$$\theta = \tan^{-1} \left( \frac{T_y}{T_x} \right)$$
$$M_{z_{0ND}} = \frac{\int_0^L x \, dF_y + \int_0^L y \, dF_x}{P_c R_t^3}$$

The thrust coefficient and deflection angle are calculated from:

$$C_{F_{sc}} = \sqrt{C_{T_x}^2 + C_{T_y}^2}$$
$$\theta = \tan^{-1} \left( \frac{C_{T_y}}{C_{T_x}} \right)$$

where,

$$C_{T_x} = \frac{2 \tan \alpha}{\pi} \int_0^{L/R_t} \left( \frac{P}{P_c} - \frac{P_a}{P_c} \right) \frac{R}{R_t} \sin \beta d\left(\frac{x}{R_t}\right) + C_{F_0}$$

$$C_{T_y} = \frac{2}{\pi} \int_0^{L/R_t} \left( \frac{P}{P_c} - \frac{P_a}{P_c} \right) \frac{R}{R_t} \sin \beta d\left(\frac{x}{R_t}\right)$$

The nondimensional moment is calculated from:

$$M_{z_{0ND}} = 2 \tan \alpha \int_0^{L/R_t} \left( \frac{P}{P_c} - \frac{P_a}{P_c} \right) \left( \frac{R}{R_t} \right)^2 \sin \beta d\left(\frac{x}{R_t}\right) \\ + 2 \int_0^{L/R_t} \left( \frac{P}{P_c} - \frac{P_a}{P_c} \right) \left( \frac{R}{R_t} \right) \sin \beta \frac{x}{R_t} d\left(\frac{x}{R_t}\right)$$

The moment axis is perpendicular to the nozzle plane of symmetry at a point on the nozzle axis opposite the upstream scarf point (point o in the diagram on Page vii). The pressure ratio,  $P/P_c$ , is determined from one-dimensional isentropic flow theory. The parameters  $R/R_t$ ,  $L/R_t$ , and  $\beta$  are expressed in terms of the nozzle half-angle, scarf angle, and initial area ratio.

#### COMPUTATIONAL ACCURACY

The implicit relationship between pressure ratio and area ratio requires that an iterative computation be carried out to determine the pressure ratio at the upstream scarf point and the pressure profile in the scarfed section of the nozzle, which is required for numerical integration of the forces. The number of increments in the integration procedure has been selected to ensure an accuracy of 0.006% in the calculations.

## EXPLANATION OF GRAPHS

## USE OF GRAPHS

The plots of the performance parameters as functions of the ratio of chamber pressure to ambient pressure are discontinued at the maximum *calculated* value of initial expansion ratio (less than 15.0) for which separation does not occur downstream in the scarfed section. The performance parameters were calculated for each half-unit of expansion ratio from 1.5 to 15. Separation criteria from the accumulation of data presented\* are employed to provide limits to the calculated data for initial expansion ratios of less than 15.

With initial expansion ratios equal to or greater than 1.5, the minimum for which data are calculated, expansion waves originating from the upstream scarf point will not intersect the opposite wall (thus influencing the pressure distribution on the nozzle wall), provided the scarf angle is not greater than 60 degrees for nozzle half-angles of 5 degrees or more. Any extrapolation of the curves below a scarf-point area ratio of 1.5 must be checked for this condition.

Linear interpolation may be used to obtain values of the performance parameters for low intermediate values of scarf angle and nozzle half-angle without incurring errors greater than 1%. For values of scarf angle greater than 40 degrees and nozzle half-angle greater than 20 degrees, errors of up to 10% may be incurred.

## PLOTTING ACCURACY

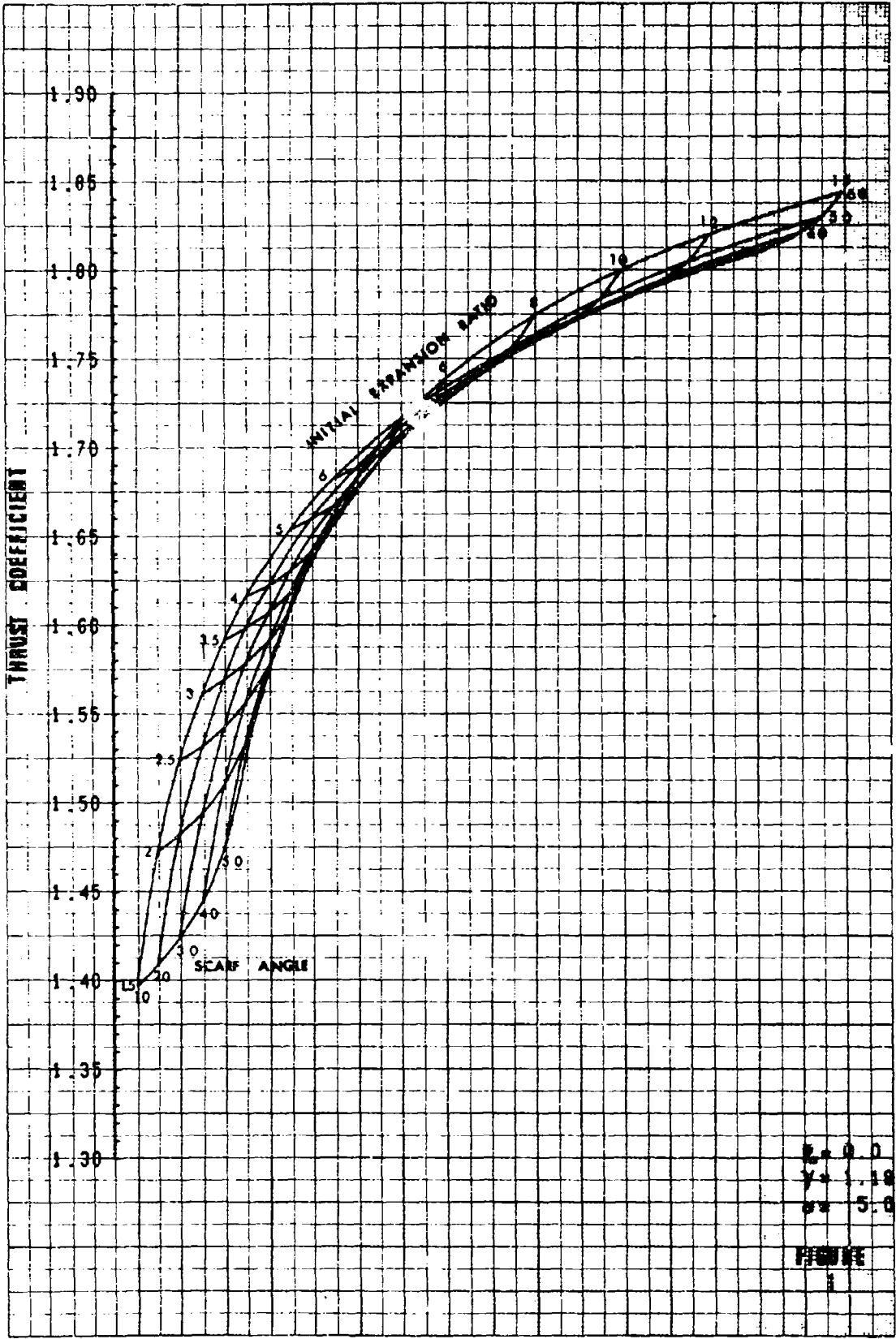
These graphs were machine-plotted with an accuracy of 0.5% compared to the computed data.

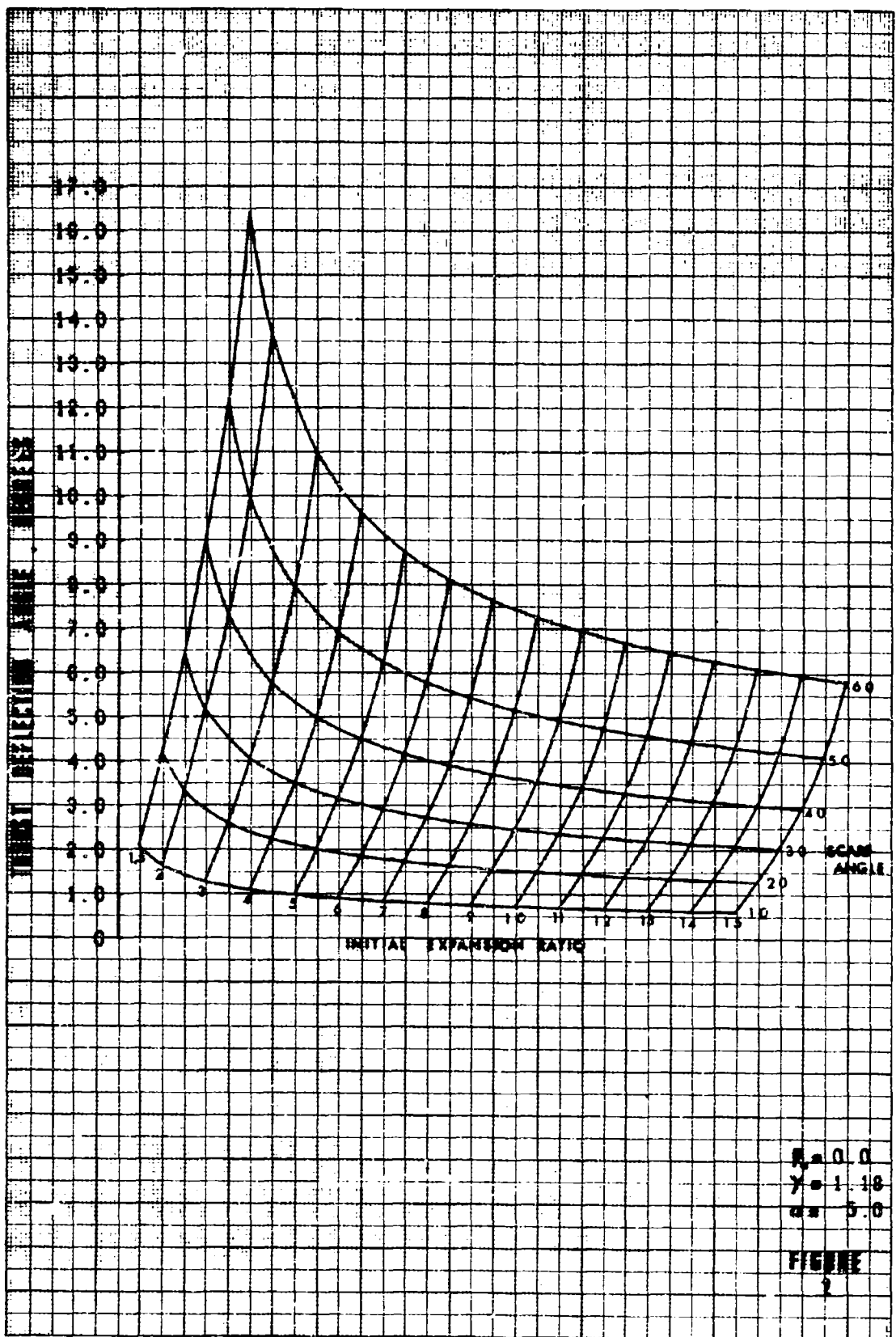
## SEQUENCE OF GRAPHS

The graphs are divided into four sections, one for each value of specific heat ratio of 1.18, 1.20, 1.22, and 1.40. For each specific heat ratio there are five values of nozzle half-angle: 5, 10, 15, 20, and 25 degrees. For each nozzle half-angle there are 27 graphs, of which the first three are carpet plots of each of the performance parameters as functions of initial area ratio and scarf angle for vacuum conditions. On the following 24 pages, the graphs of thrust coefficient, deflection angle, and moment as functions of initial area ratio and ambient pressure are arranged together for each value of scarf angle: 10, 20, 30, 40, 45, 50, 55, and 60 degrees.

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\* Arens, M., and E. Spiegler, "Shock-Induced Boundary Layer Separation in Overexpanded Conical Exhaust Nozzles," *AIAA Journal*, March 1963.





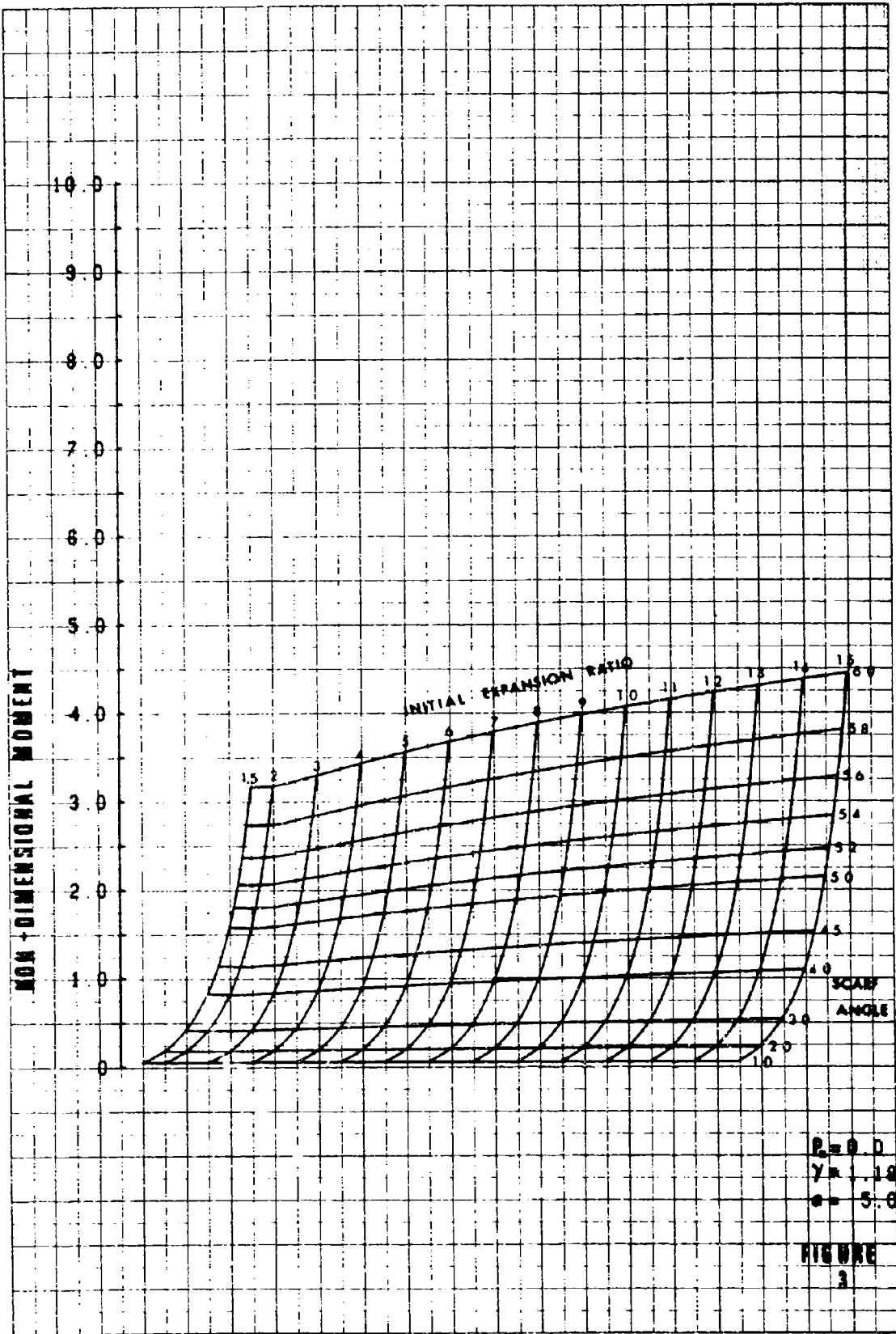


FIGURE 3

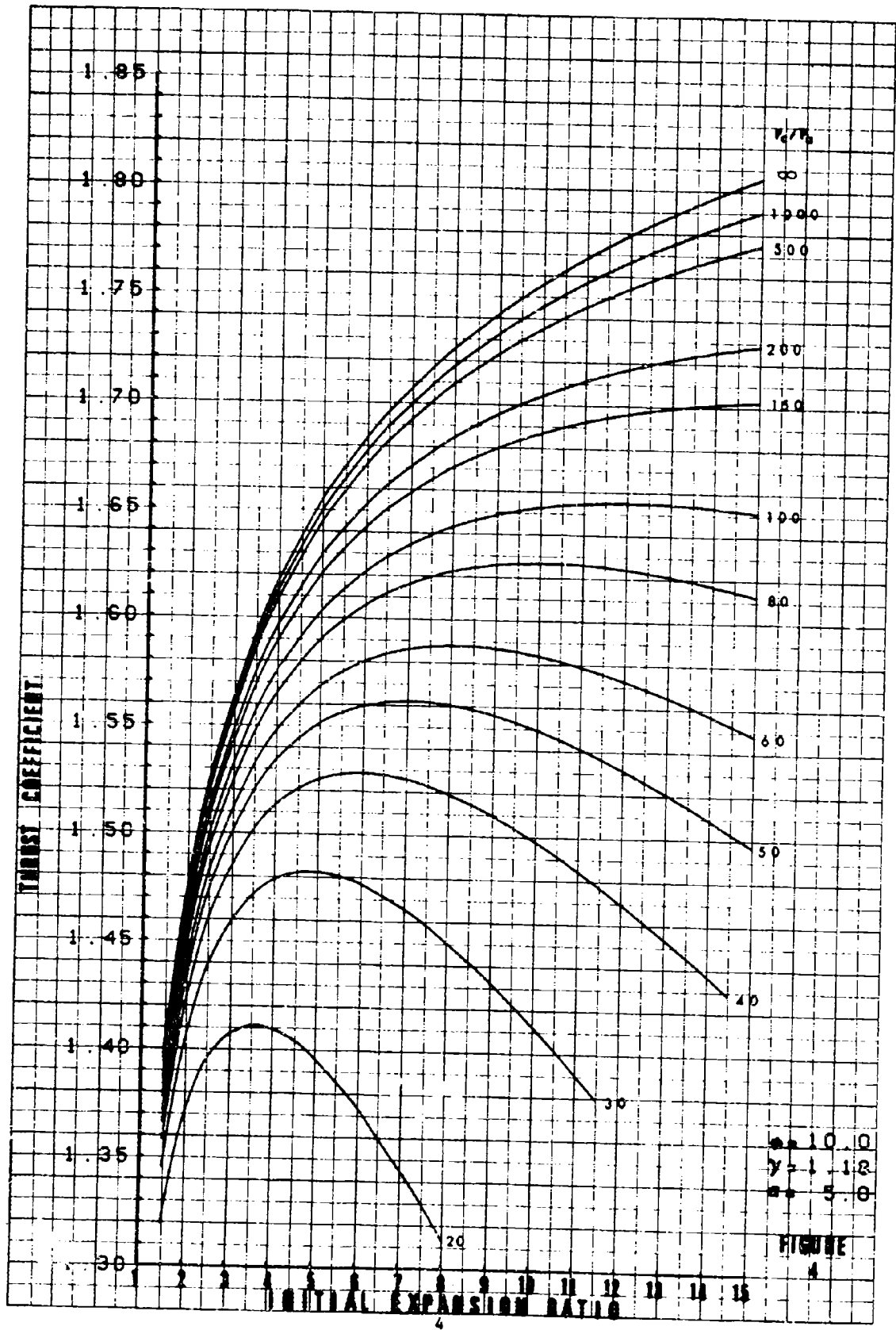
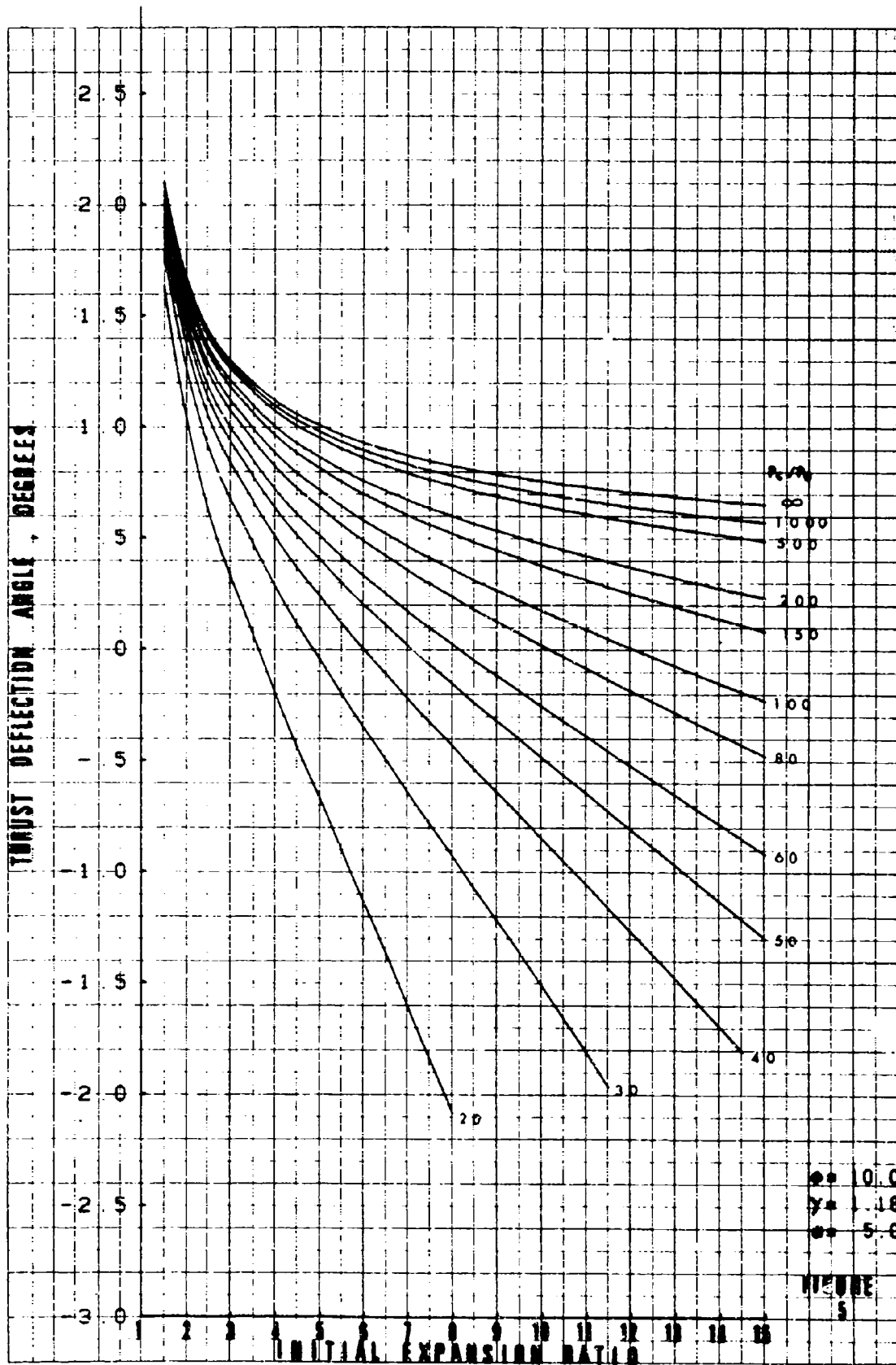


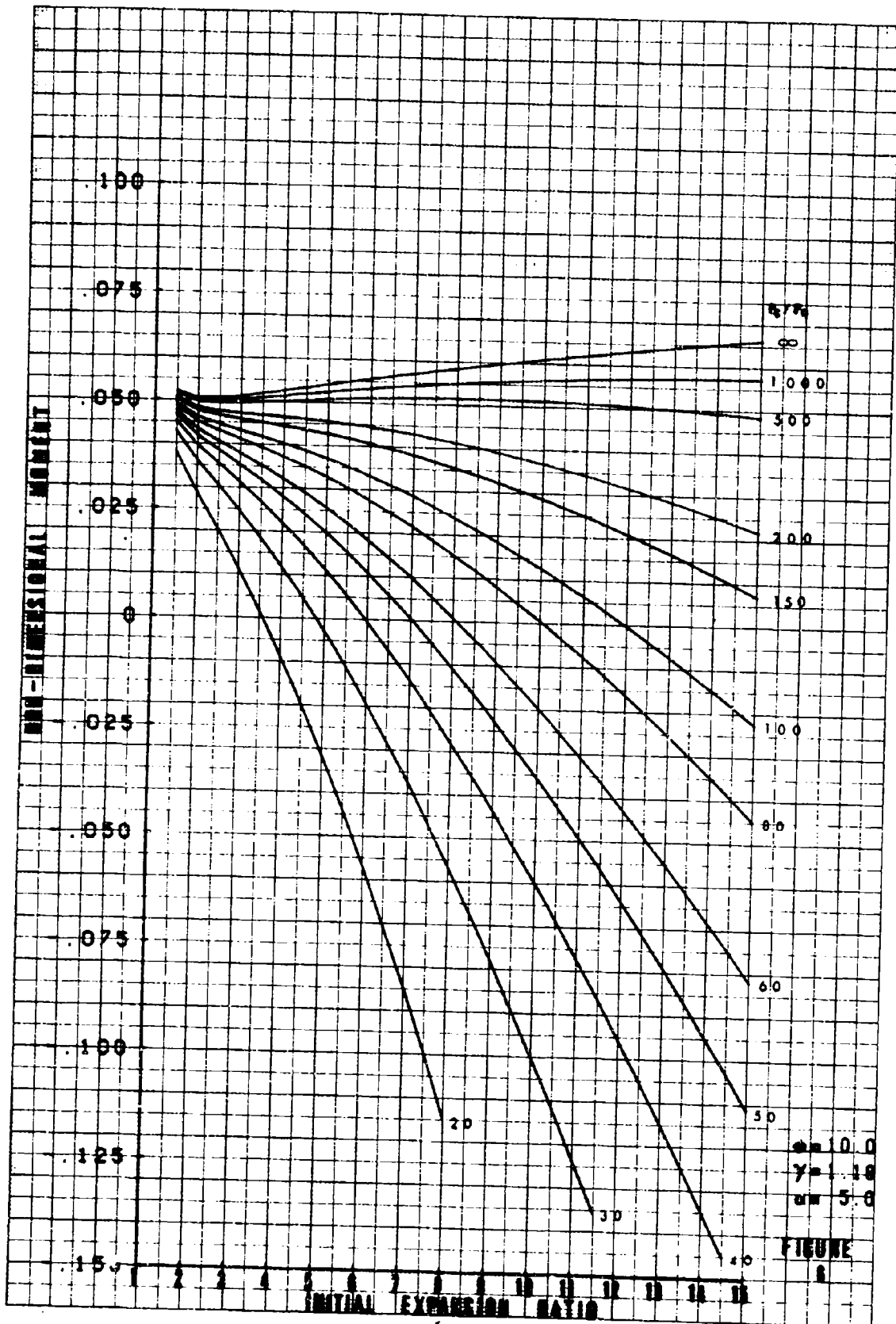
FIGURE 4

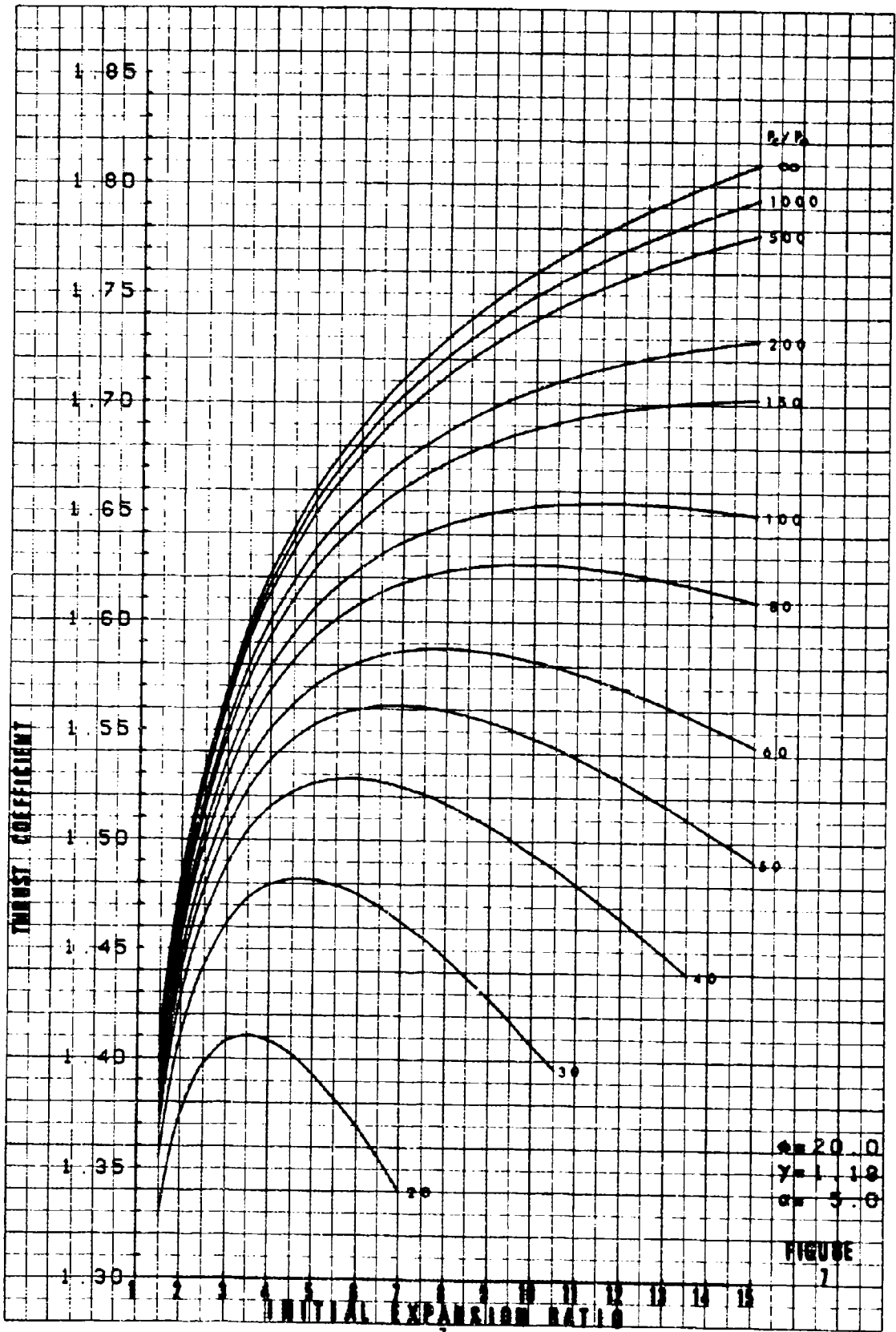


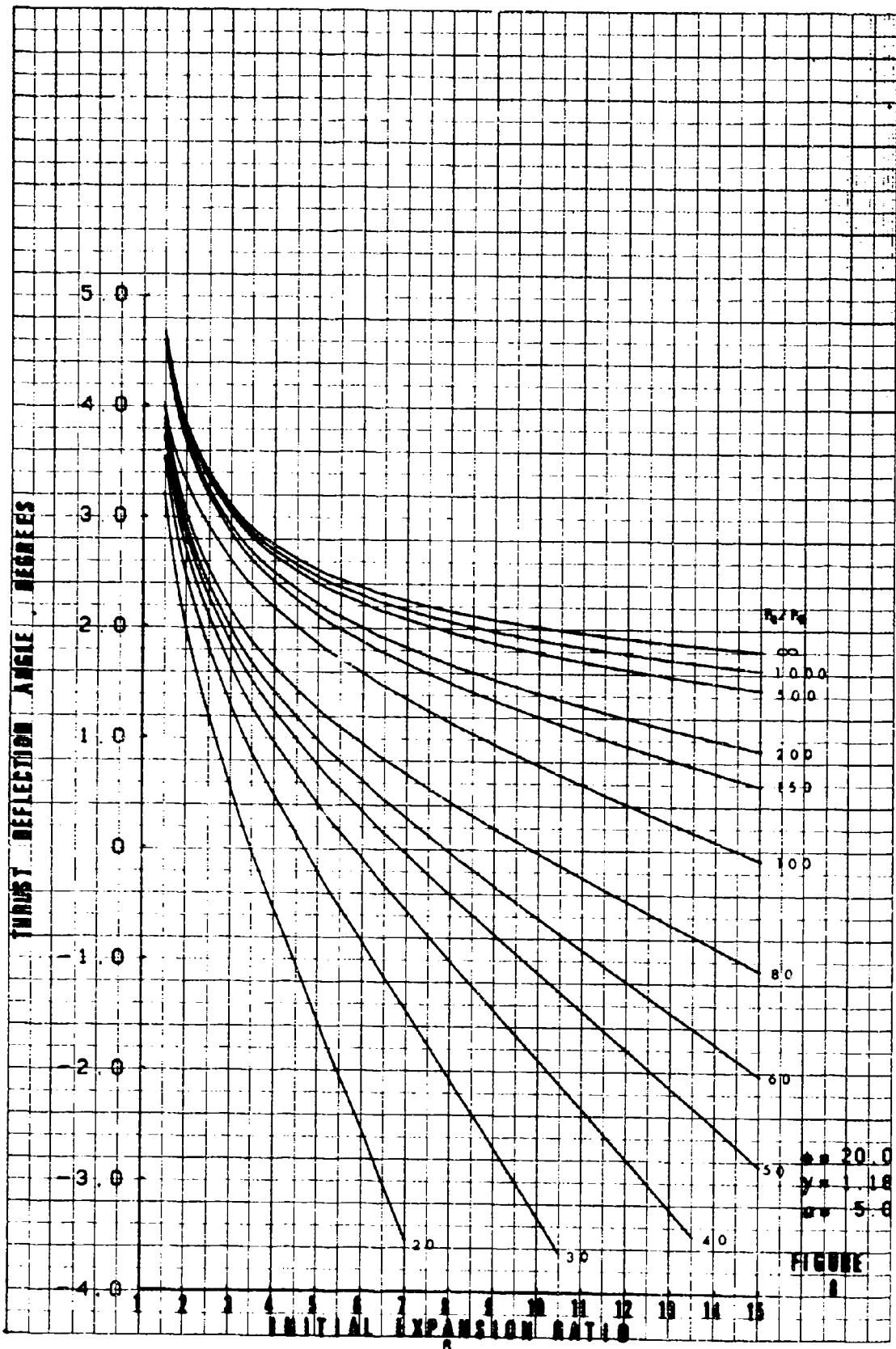
•• 10.0  
 •• 1.18  
 •• 5.8

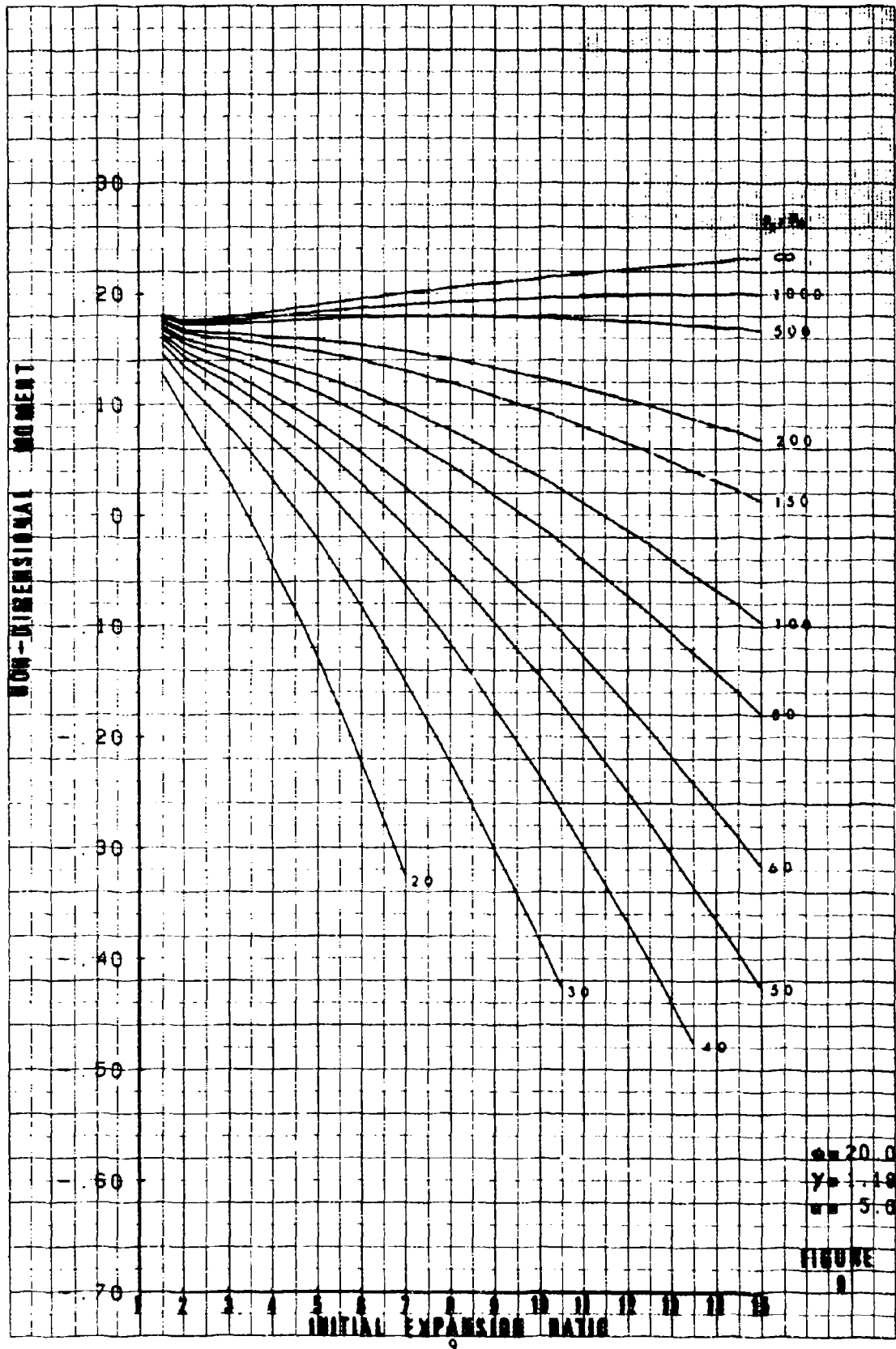
FIGURE 5











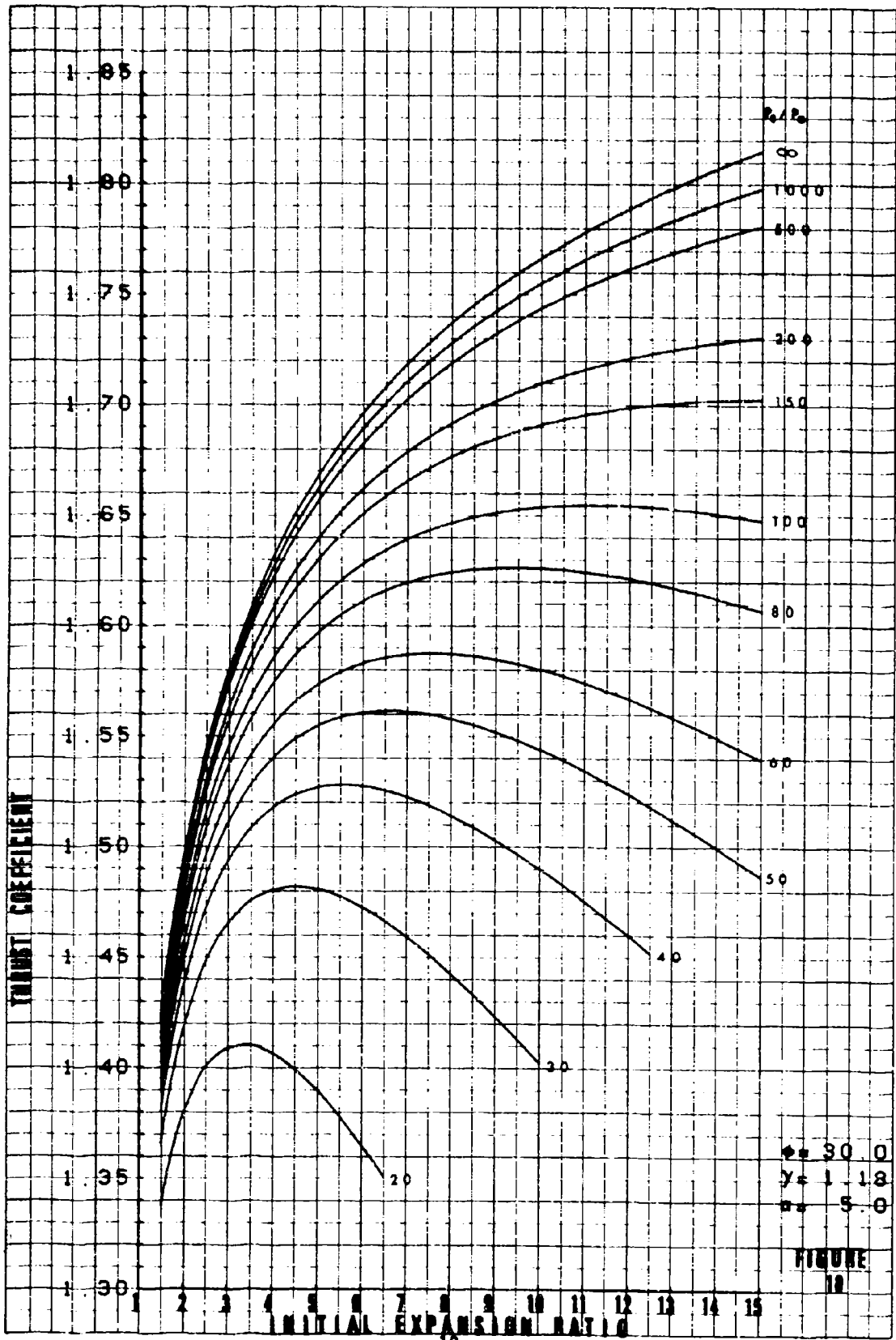


FIGURE 10

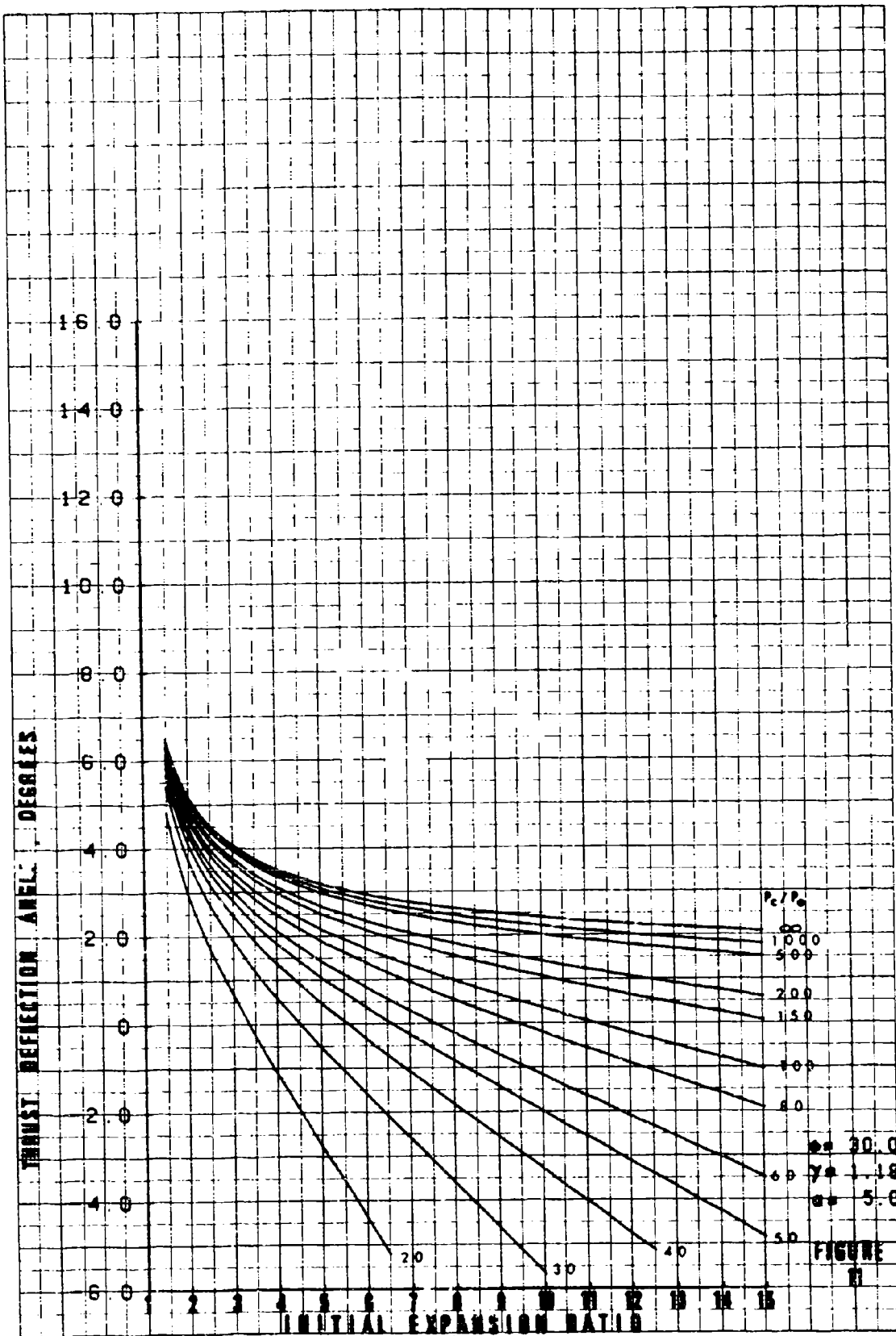


FIGURE 11

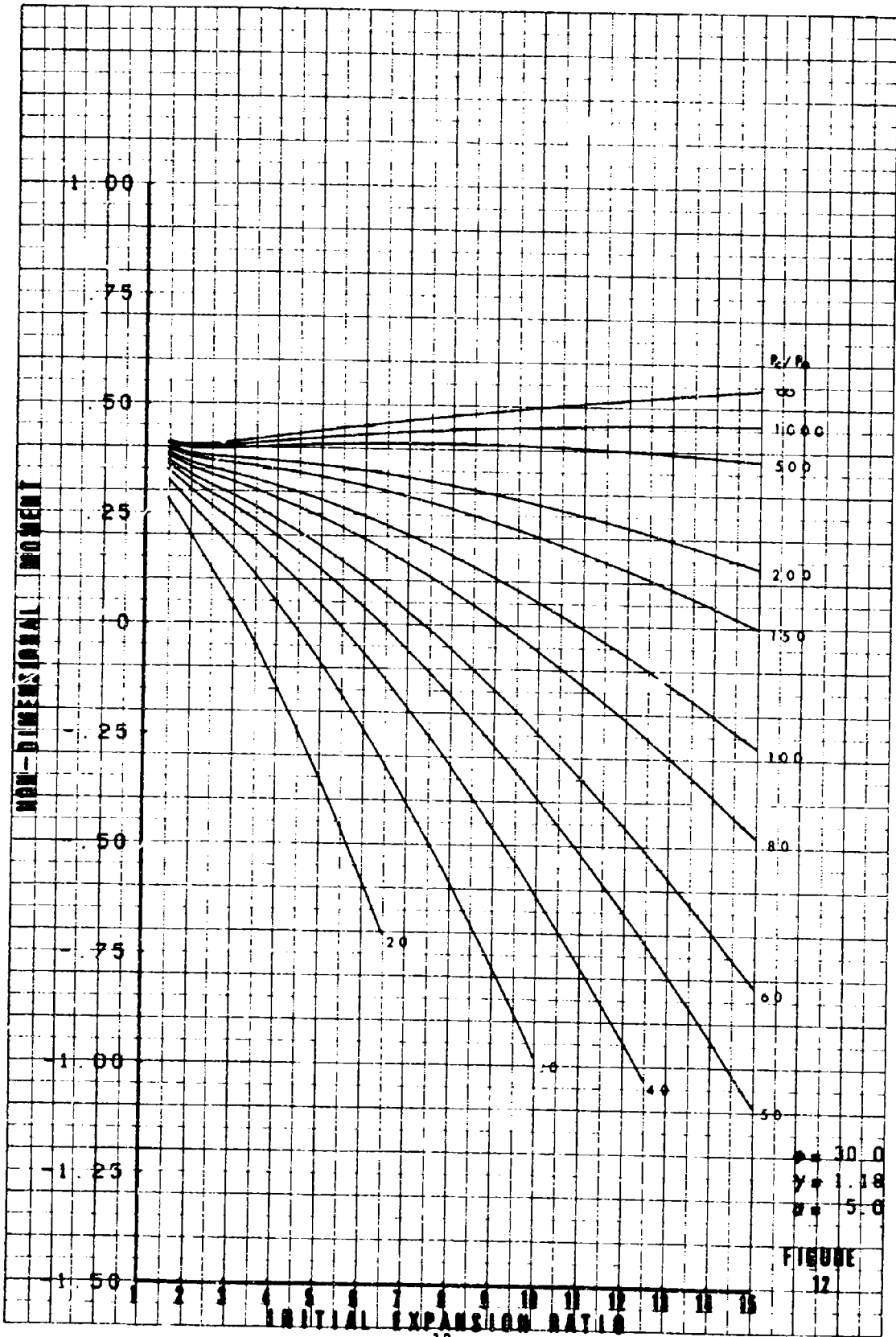


FIGURE 12

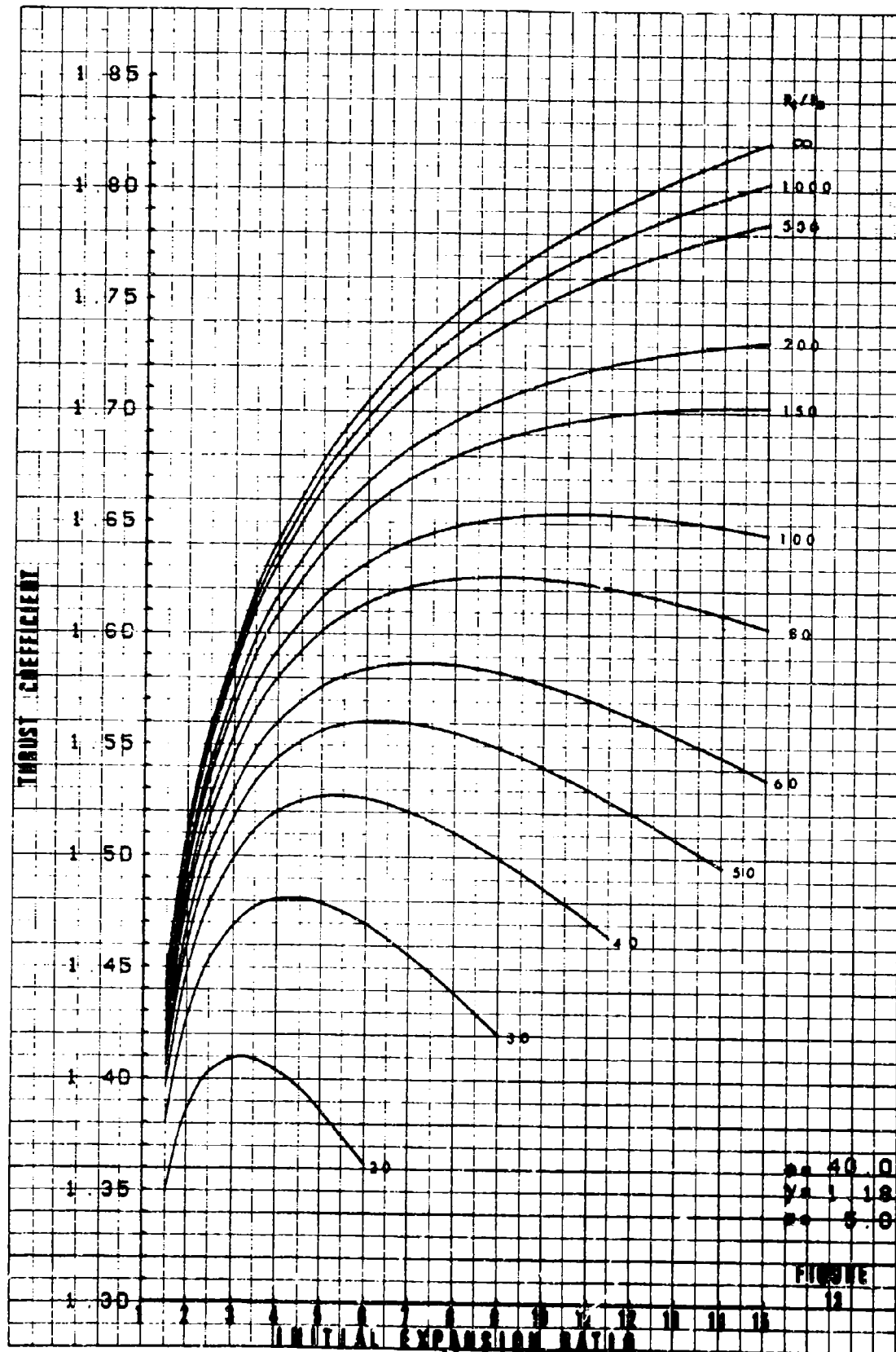


FIGURE 12



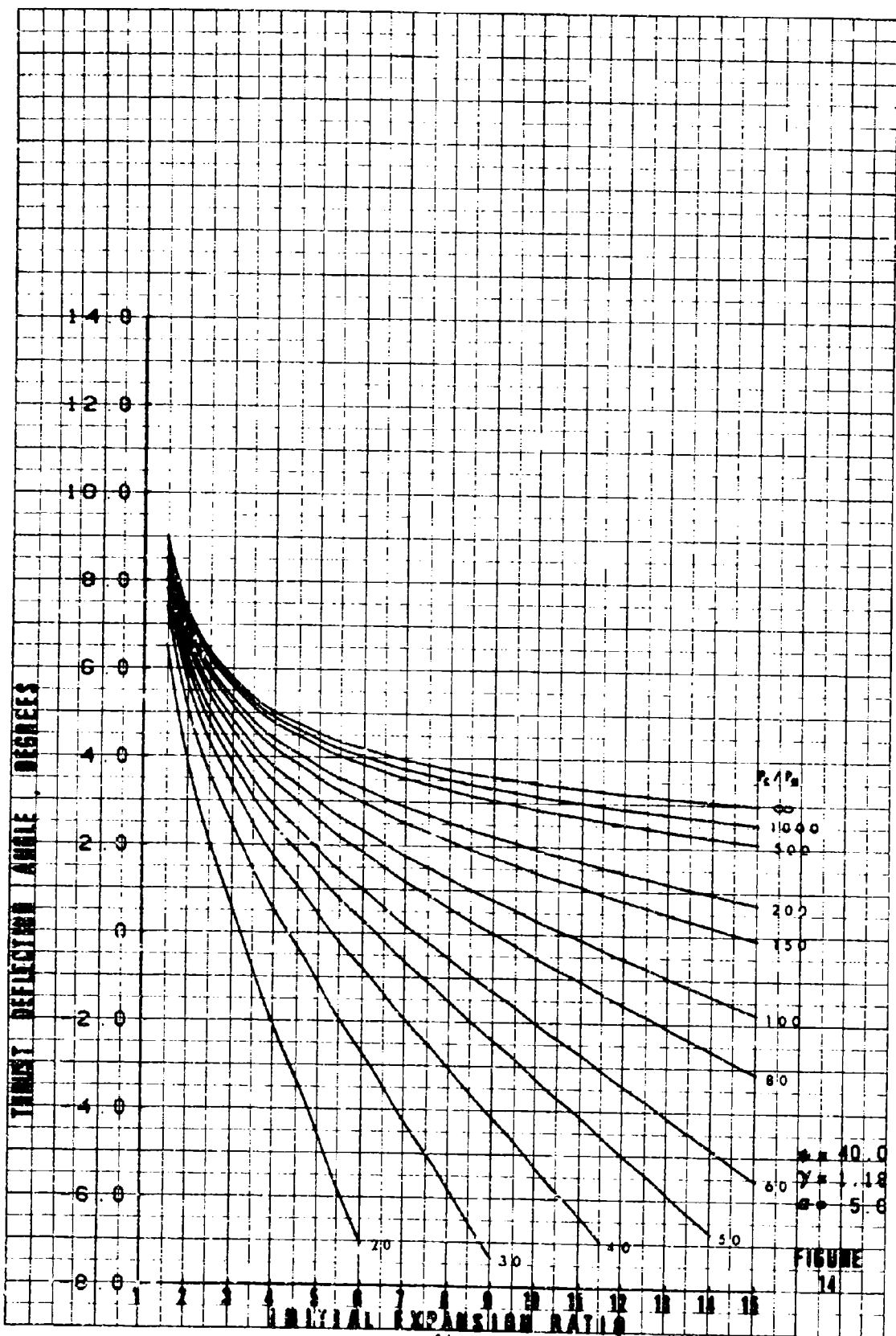


FIGURE 14

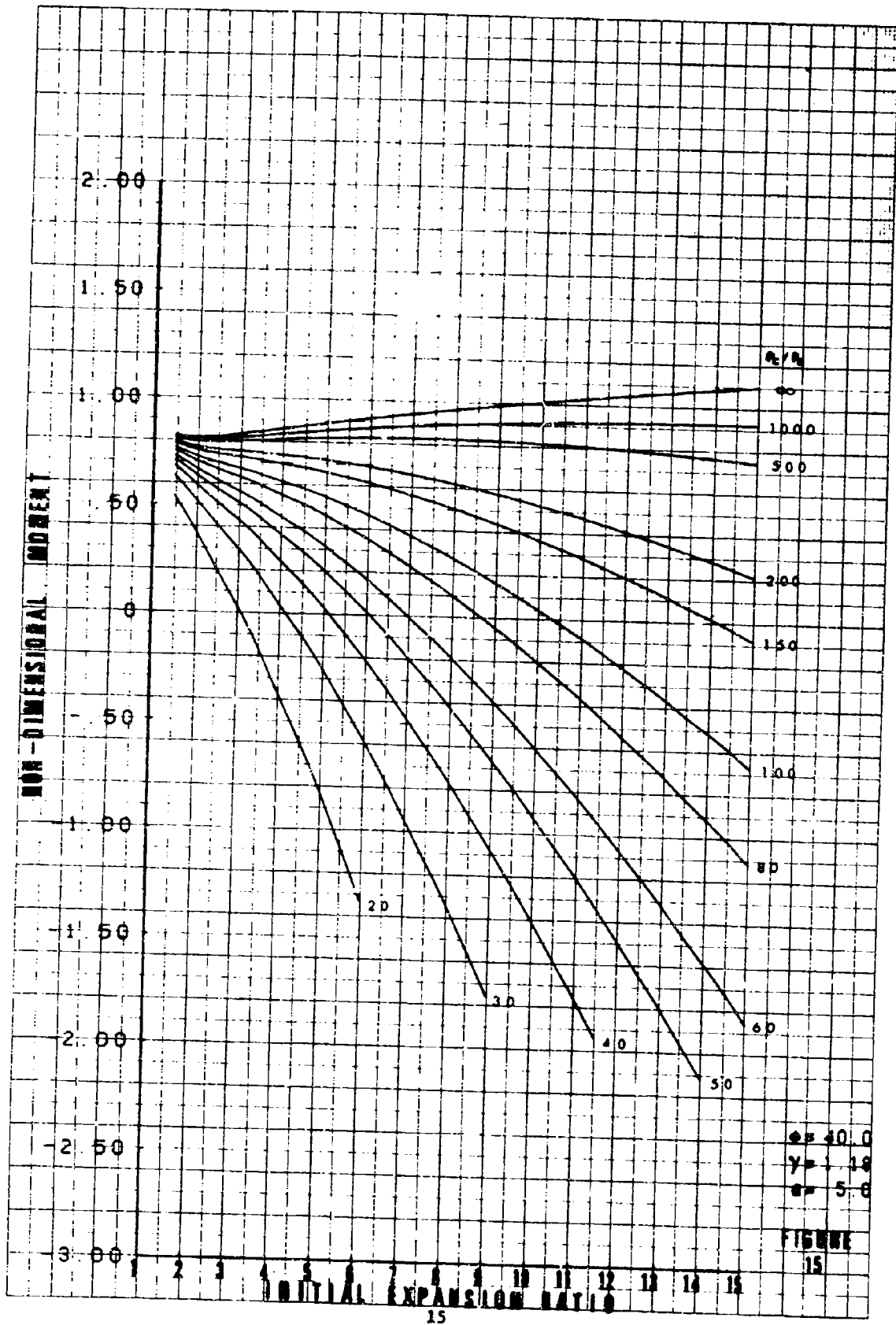
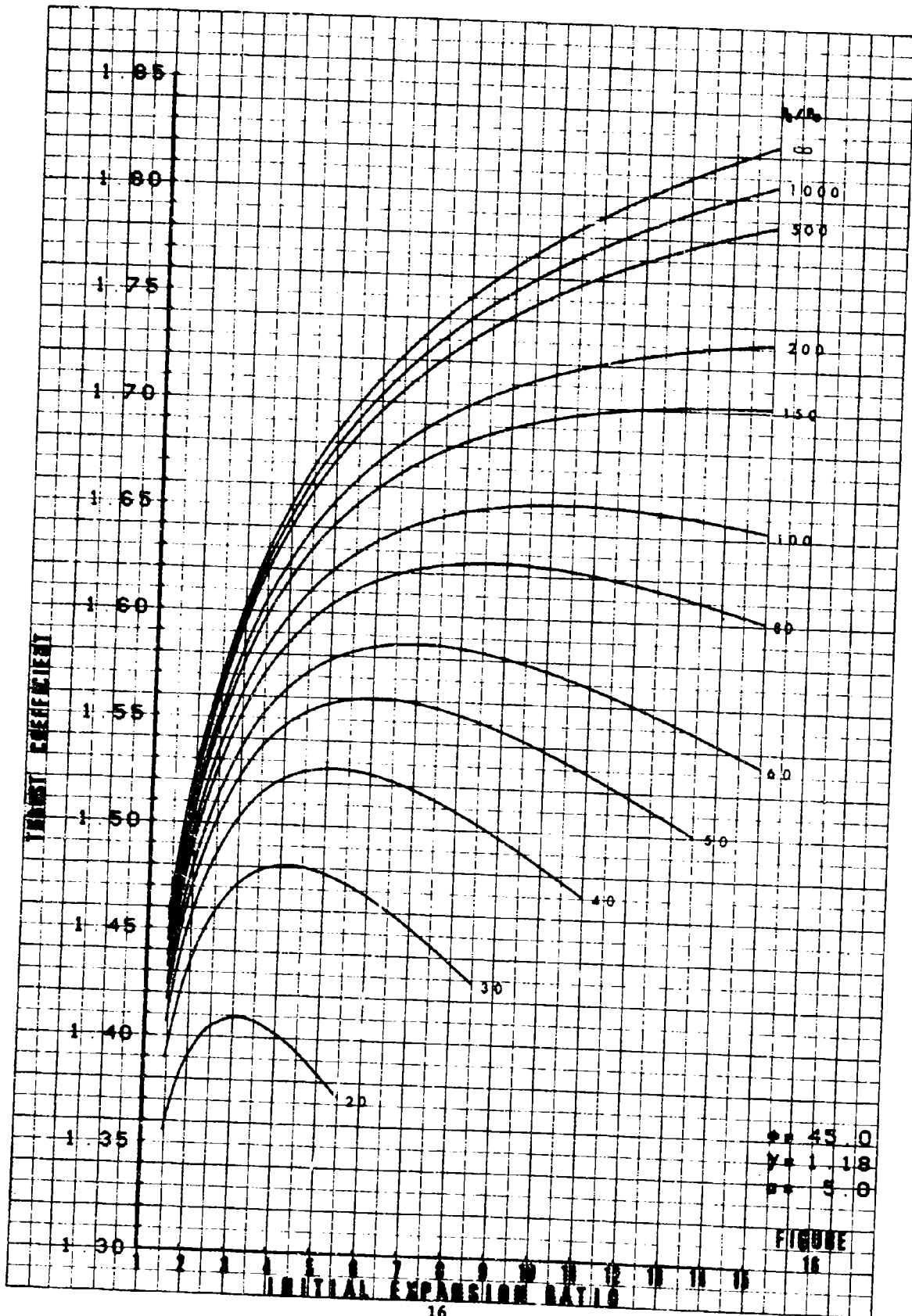
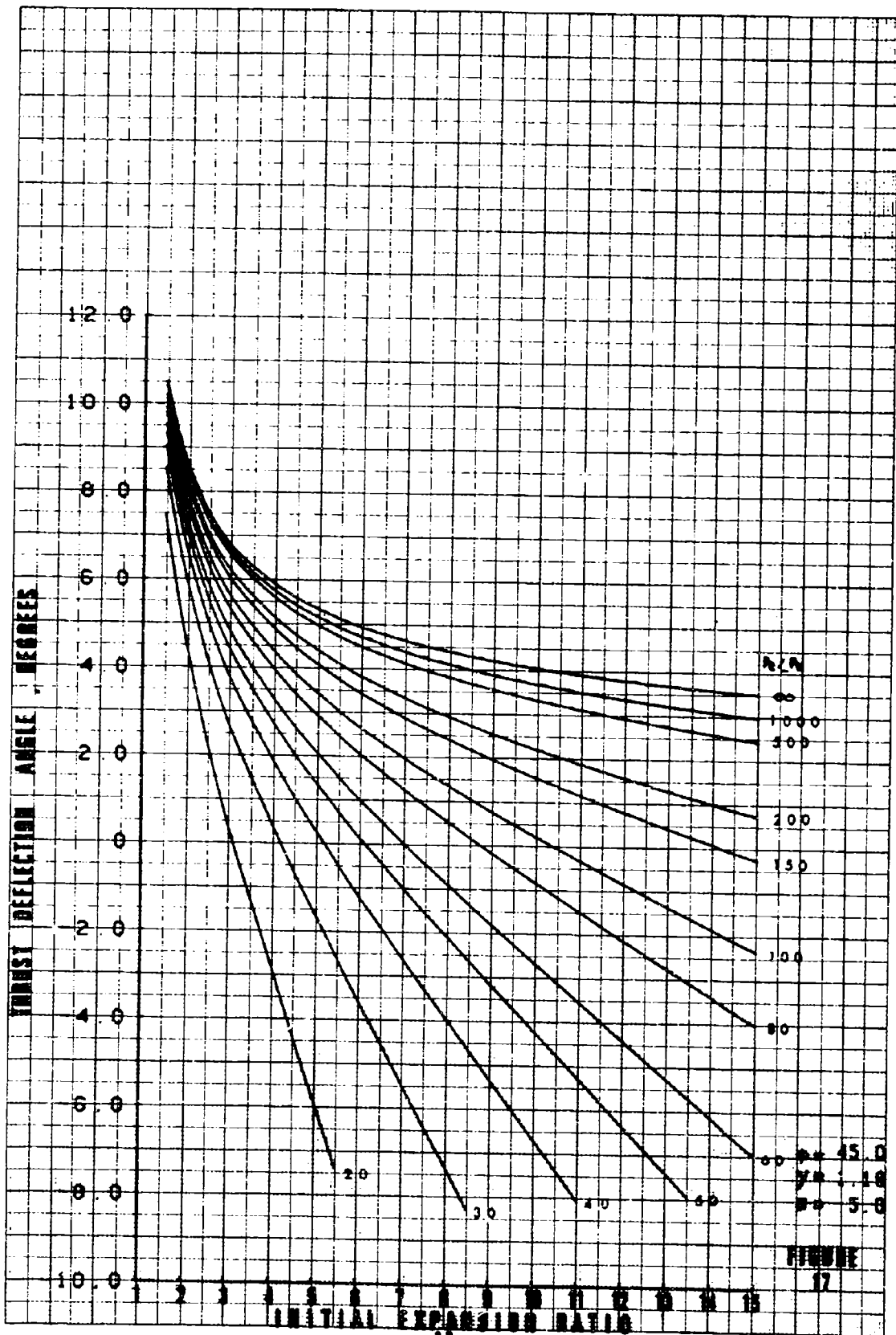
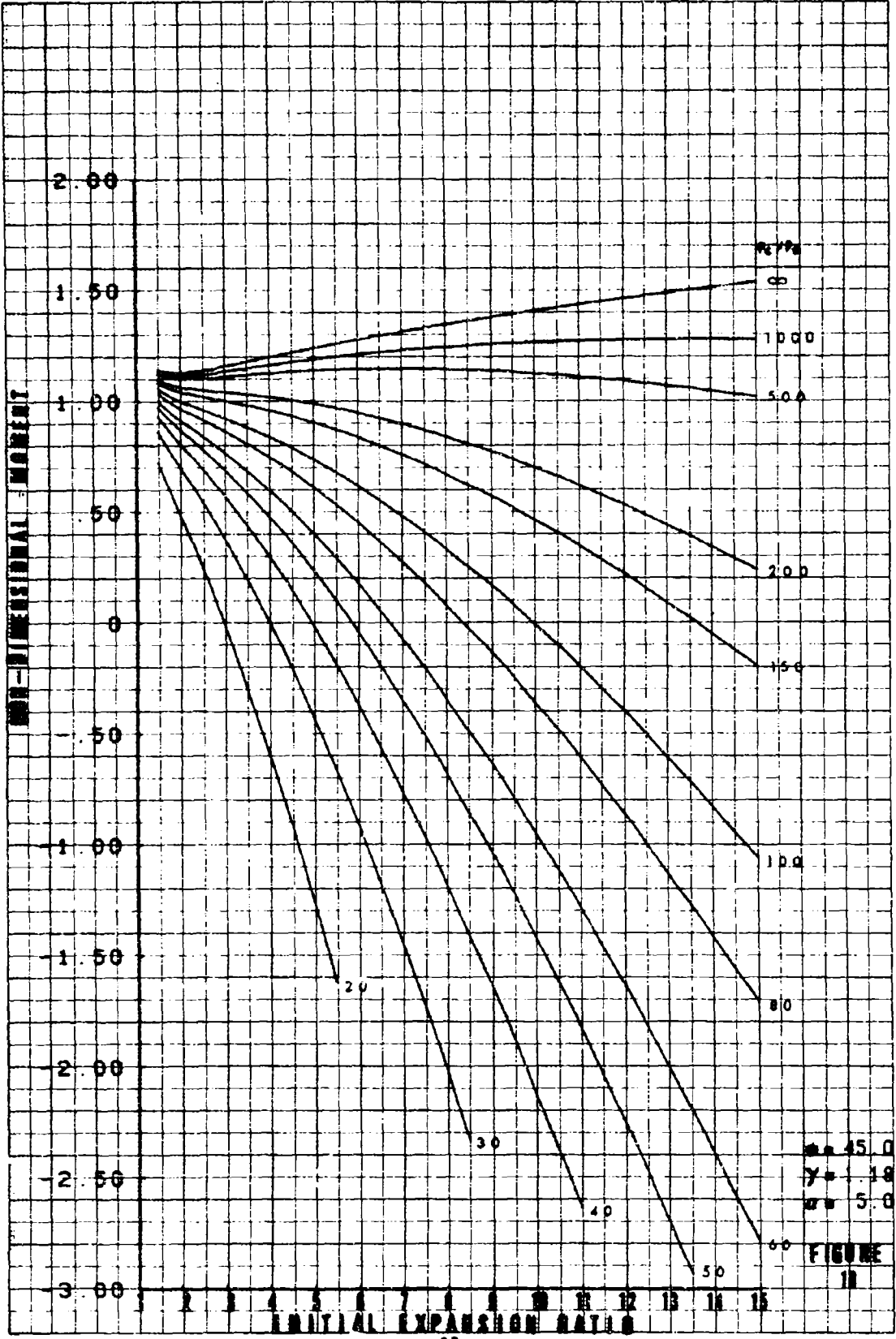


FIGURE 15







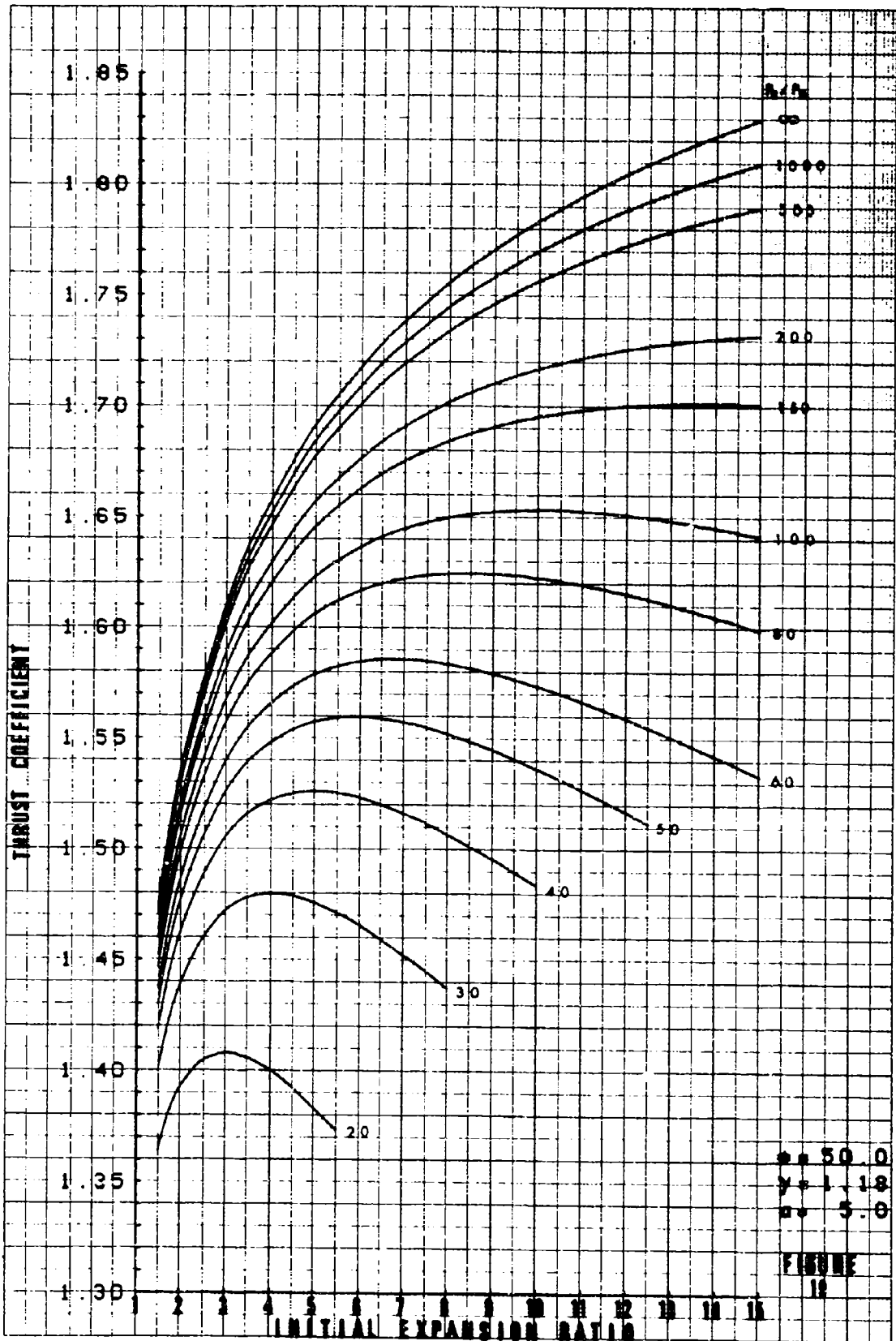
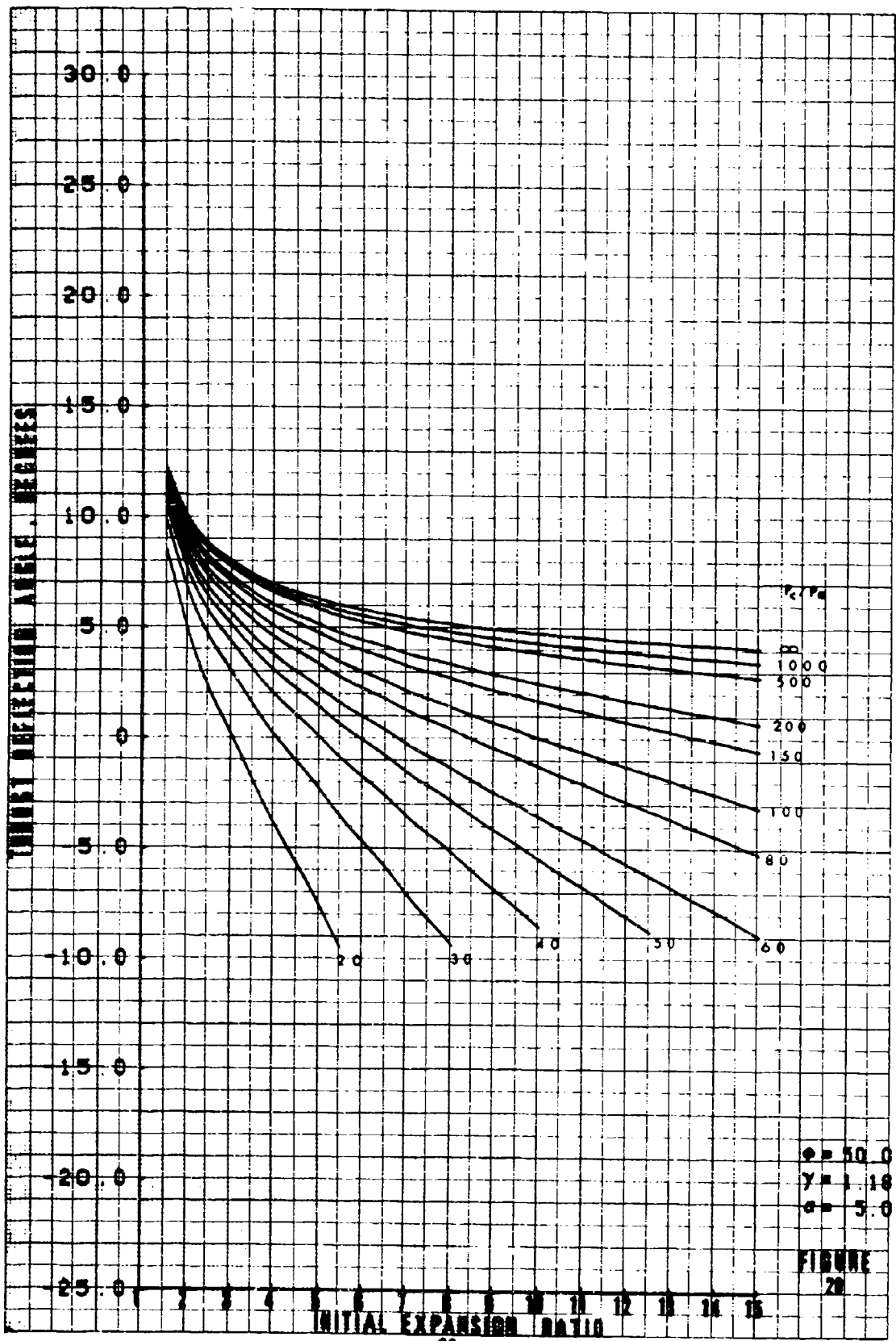


FIGURE 19



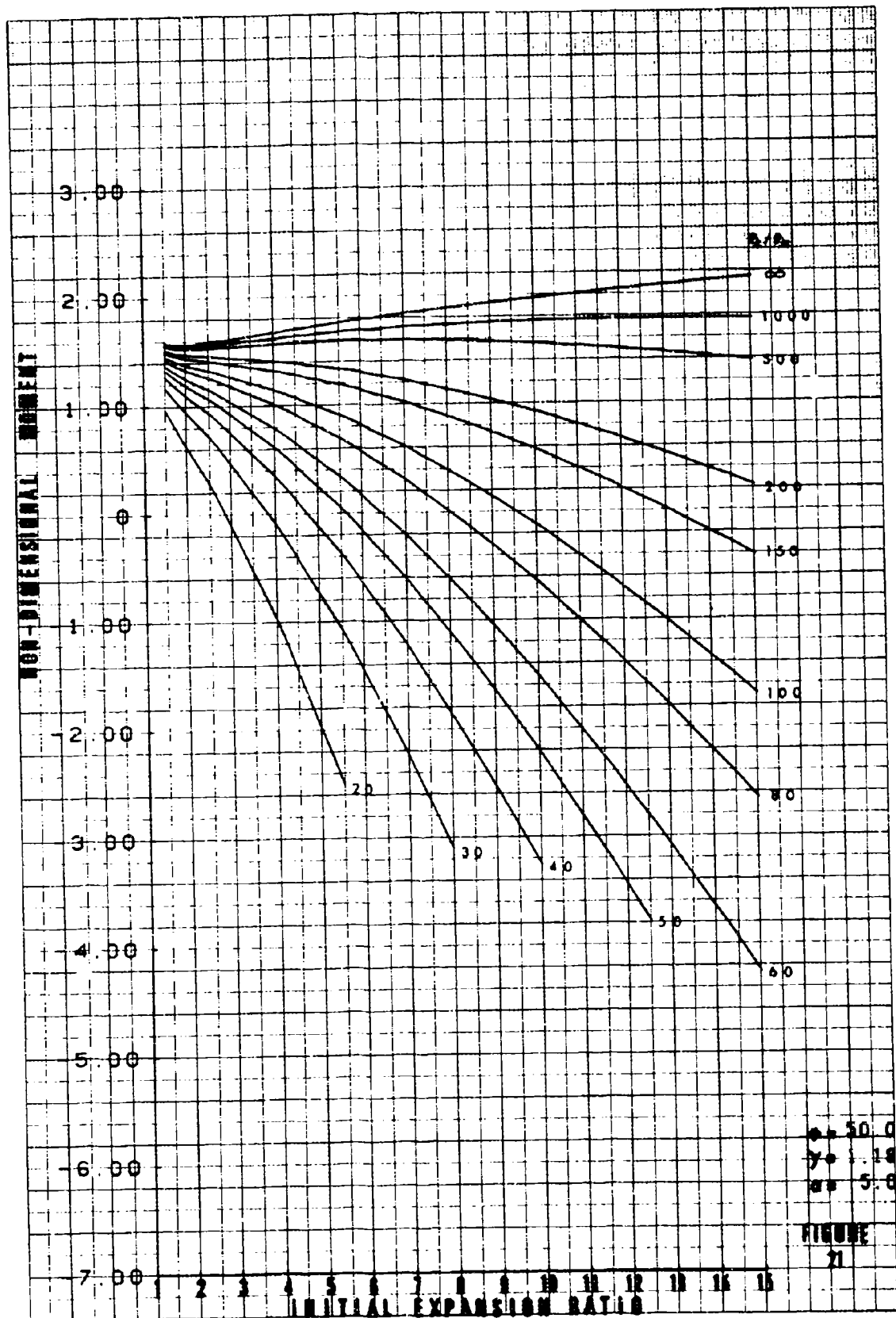
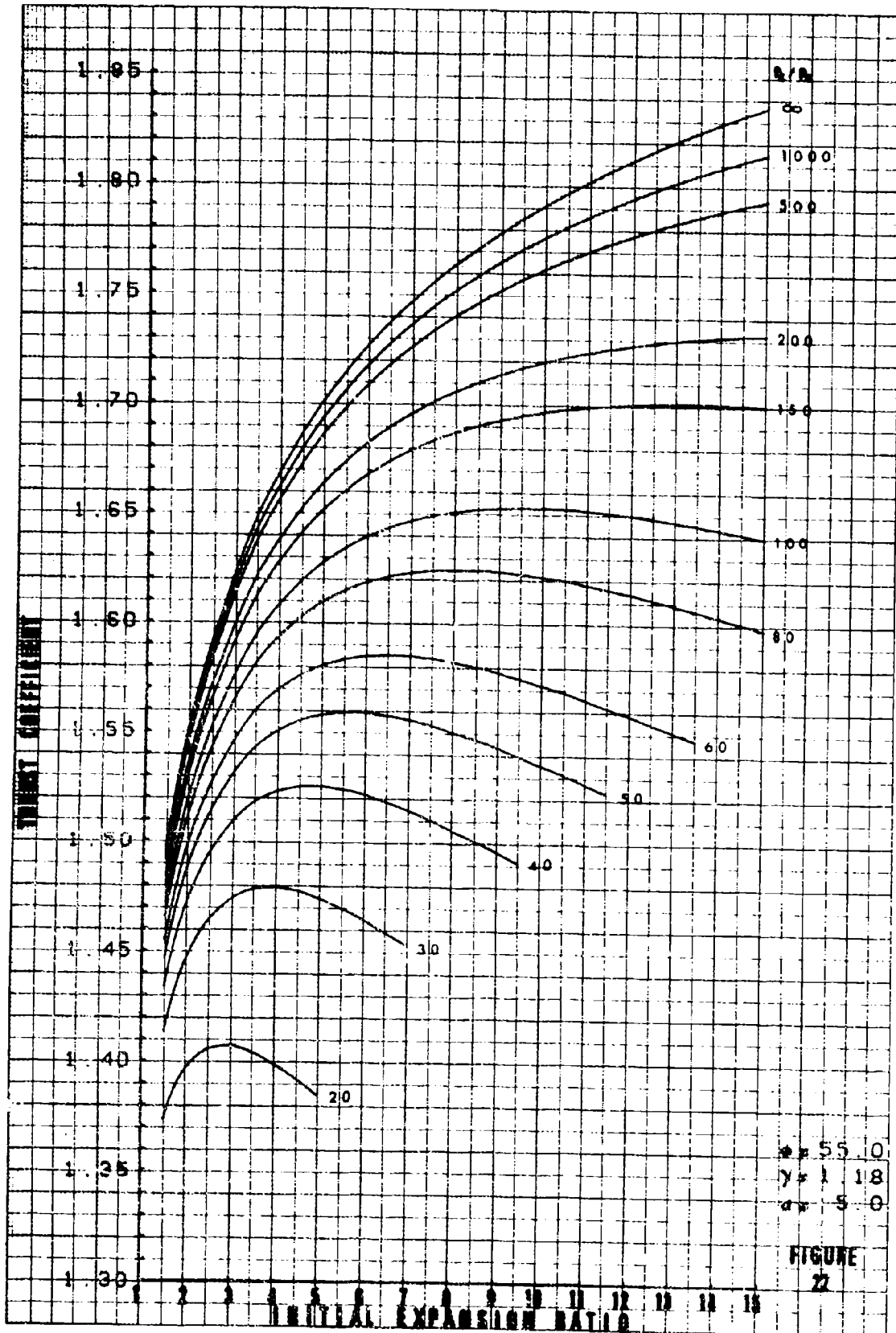


FIGURE 21





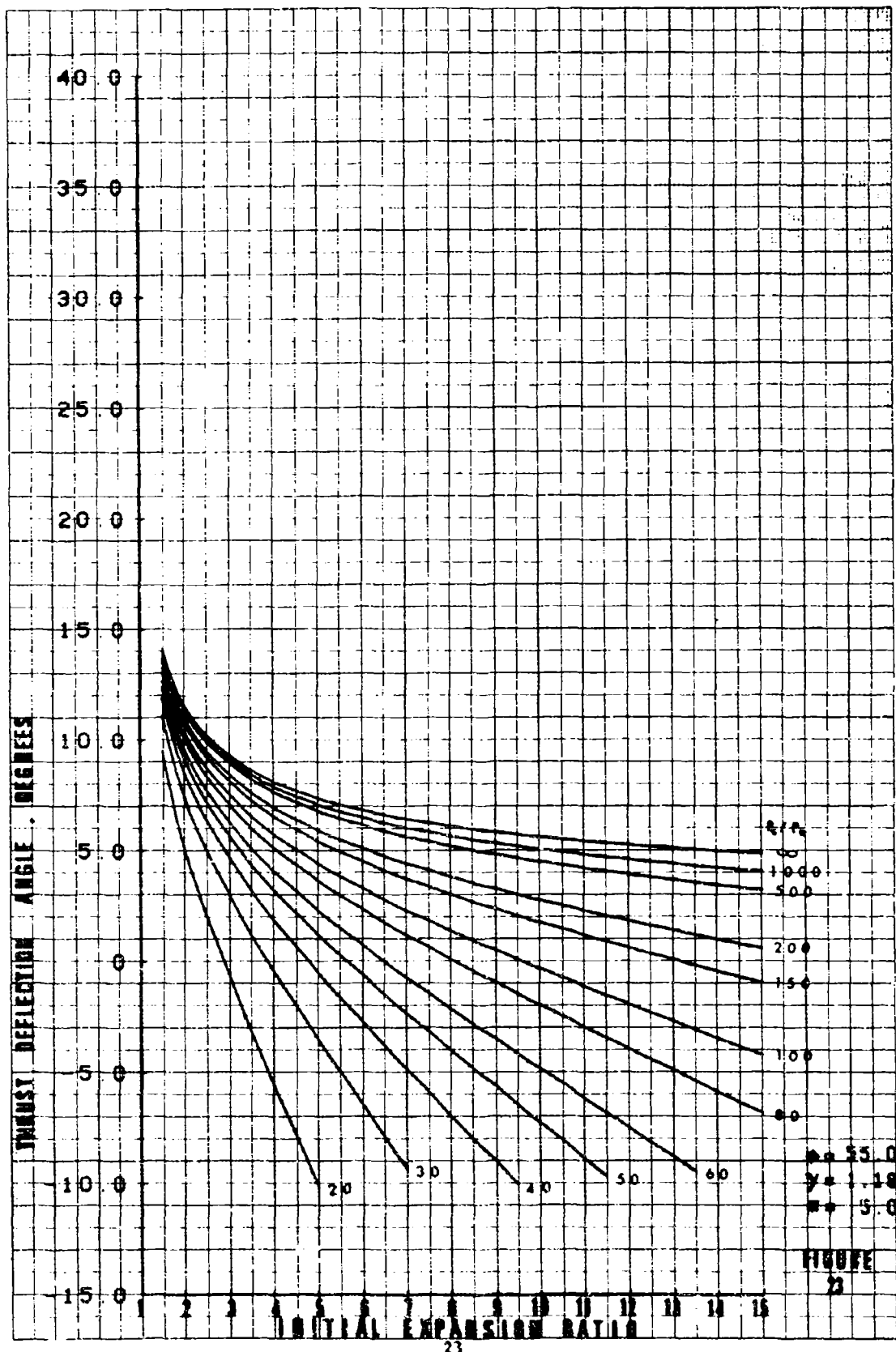


FIGURE 23

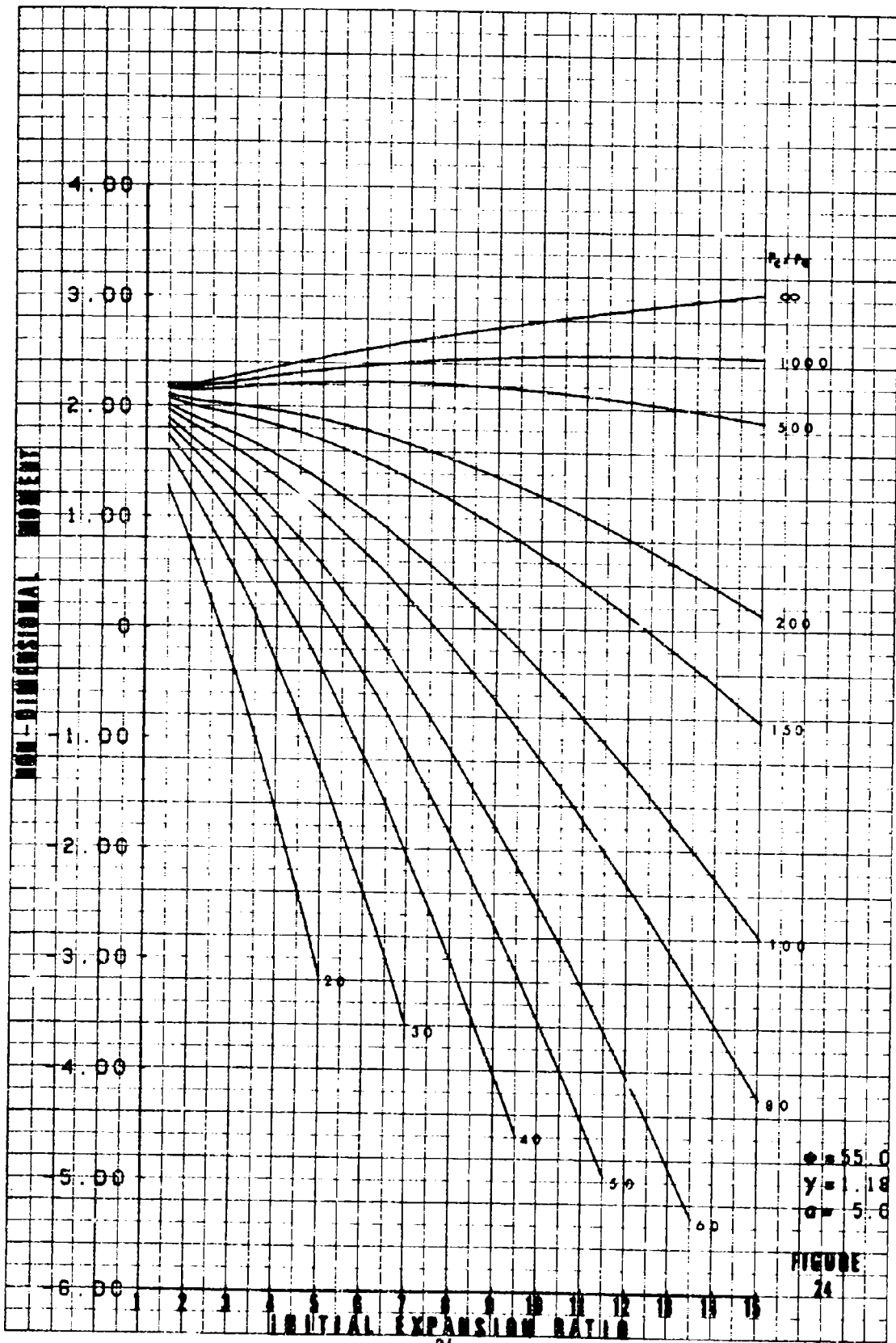
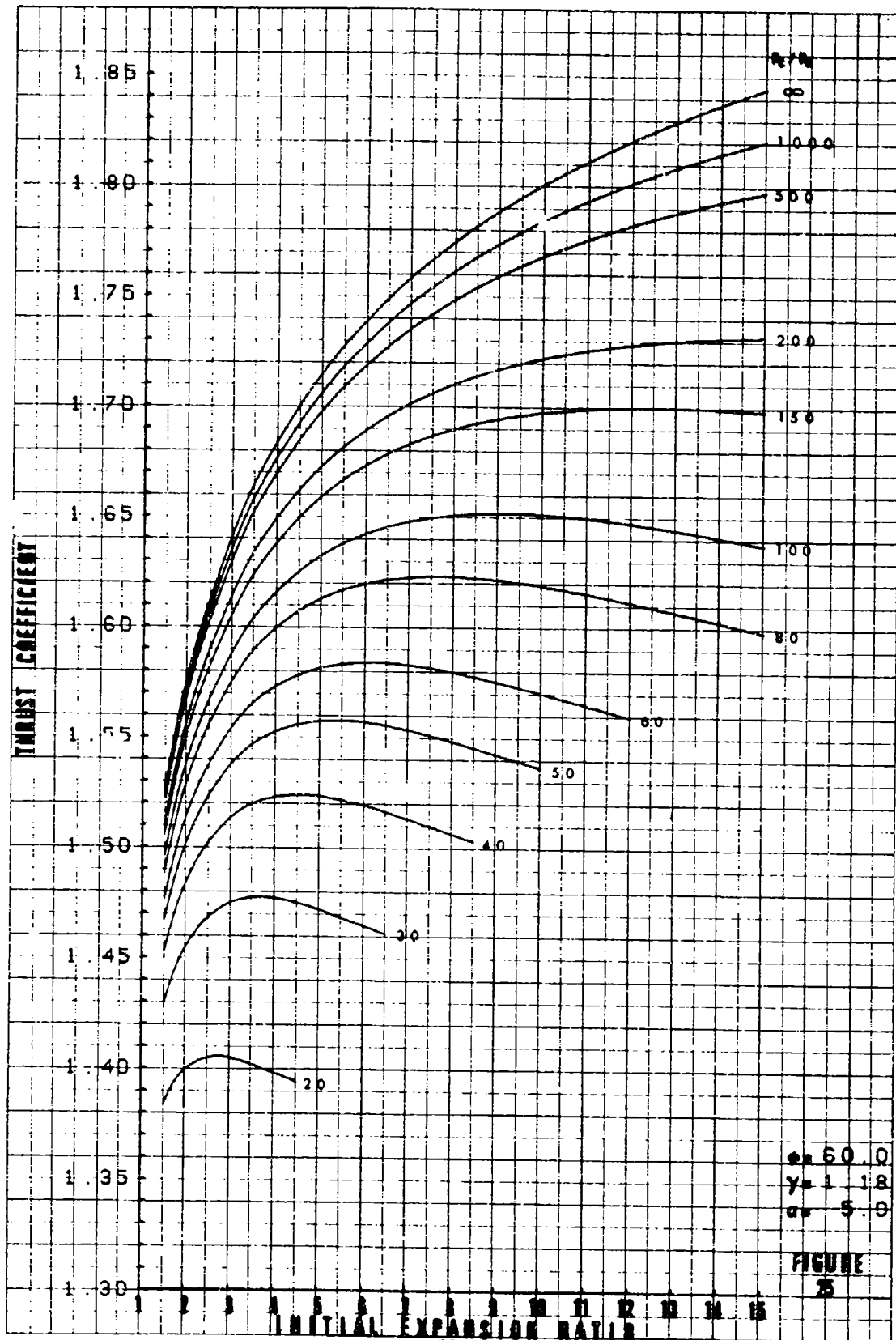
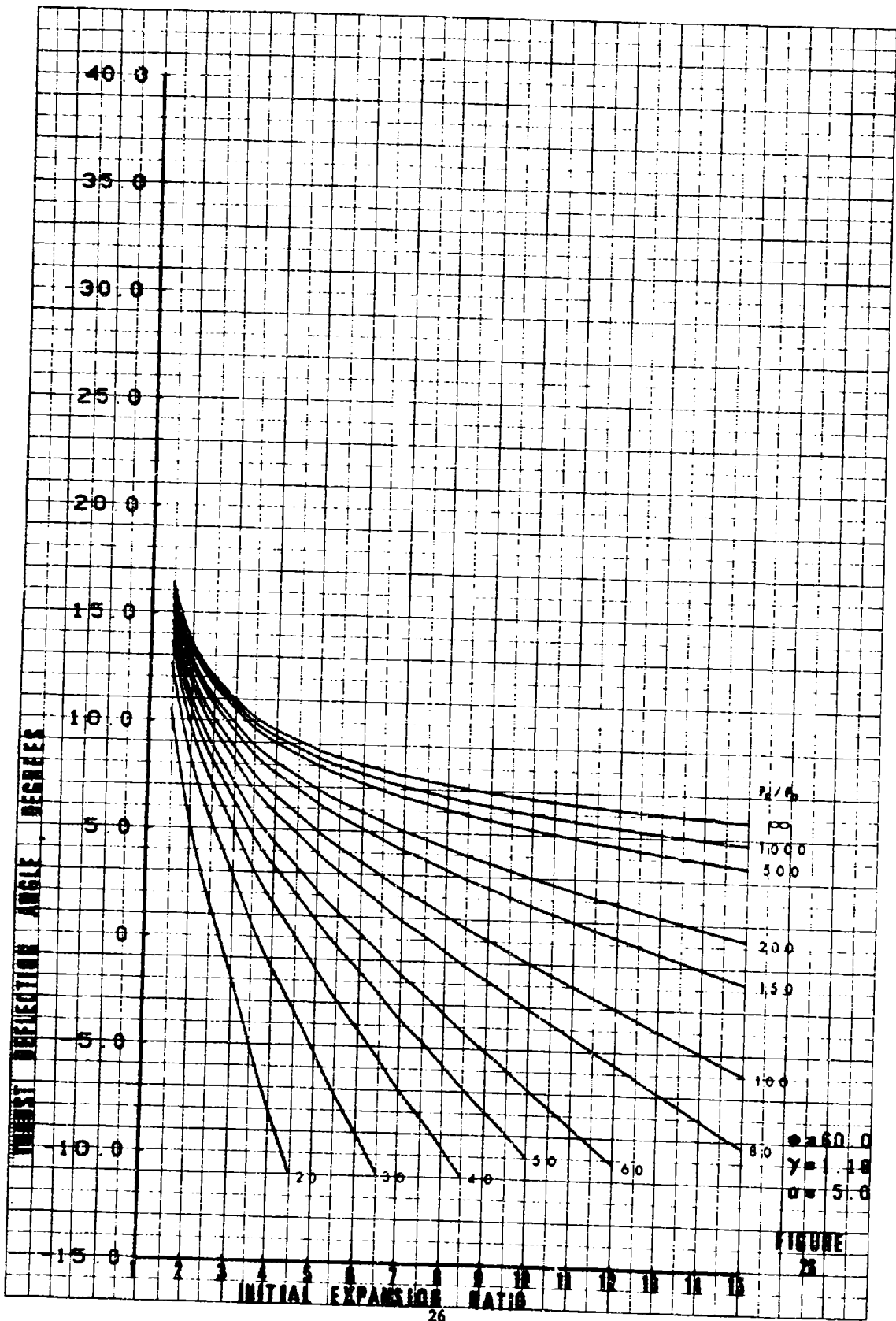


FIGURE 24





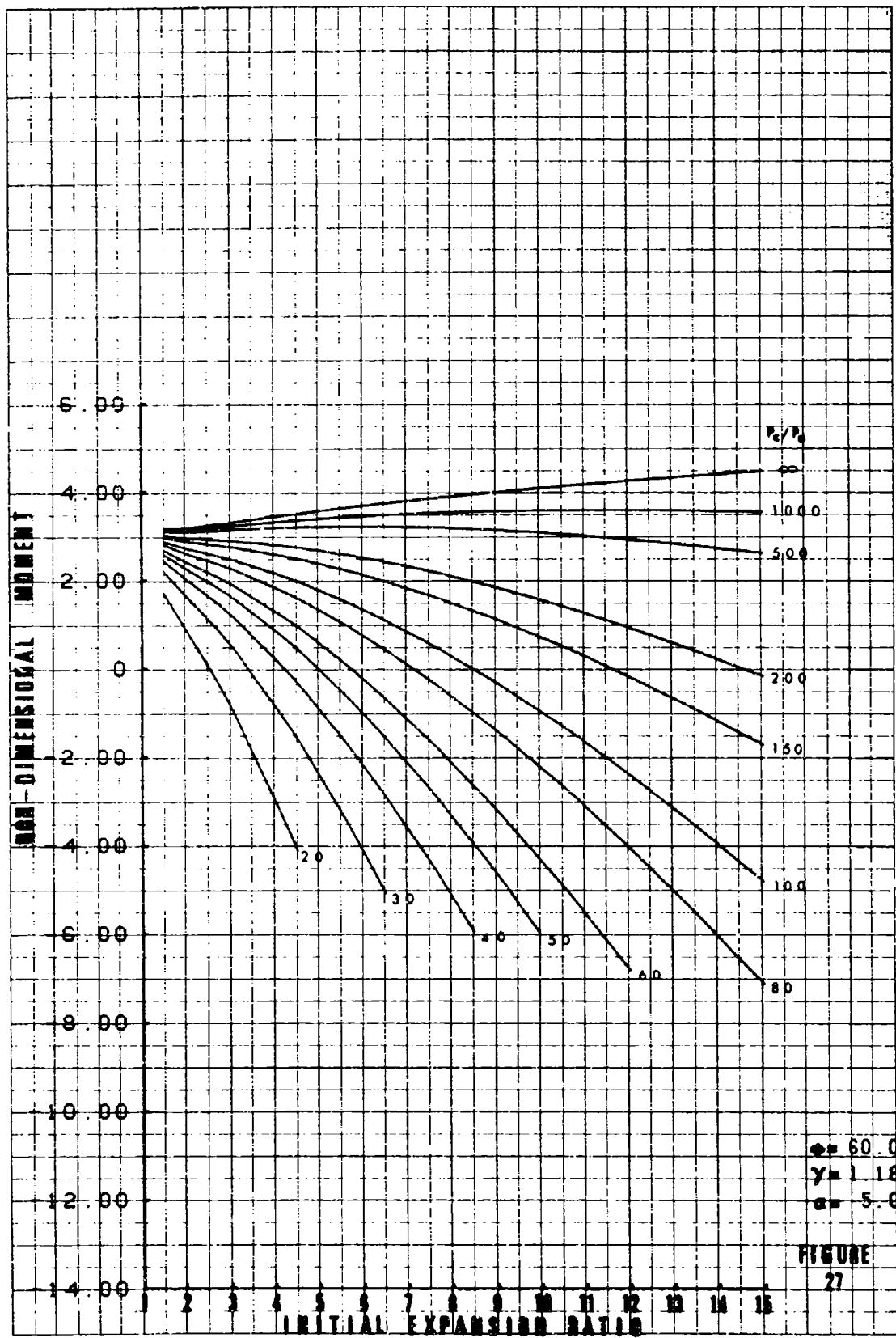
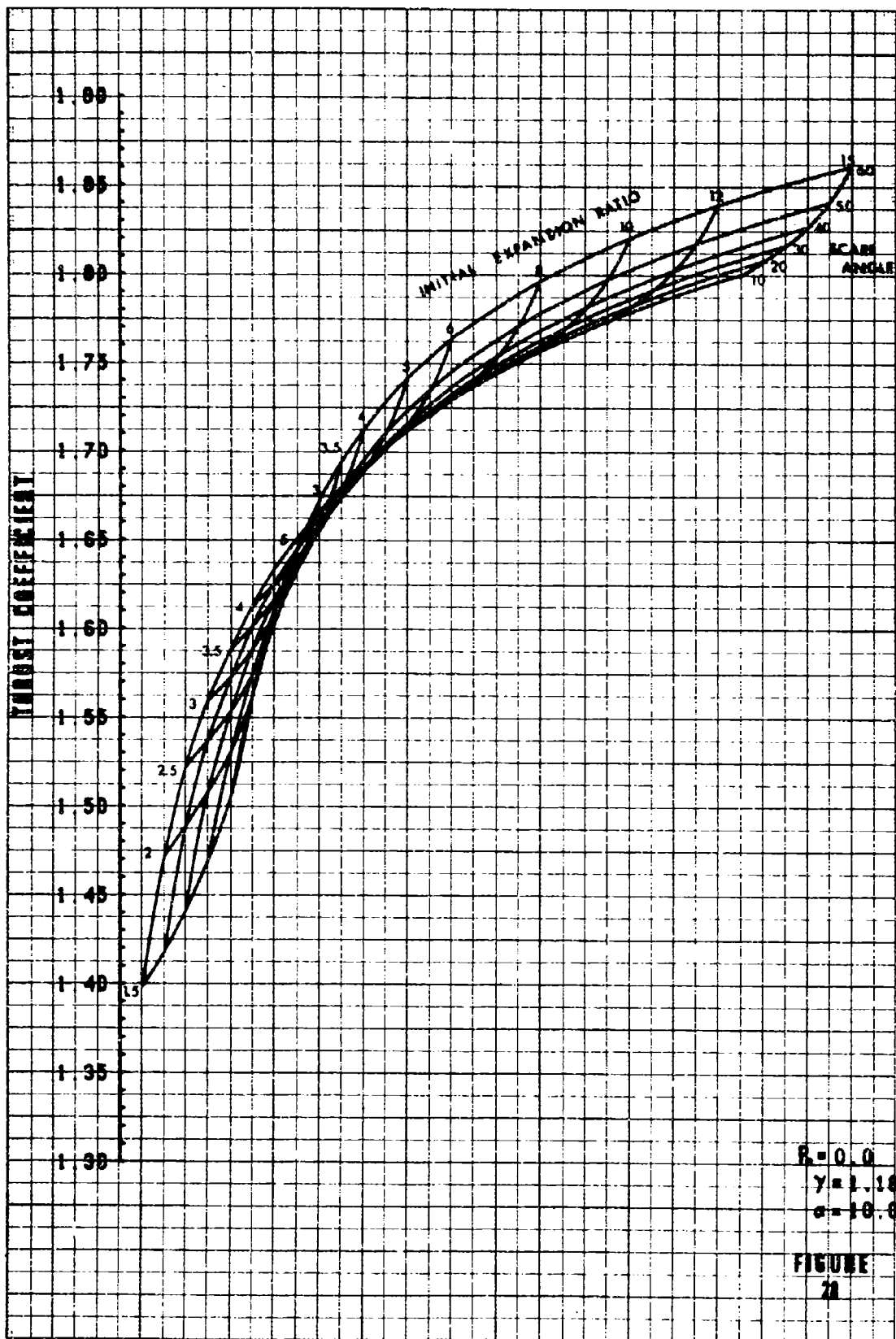
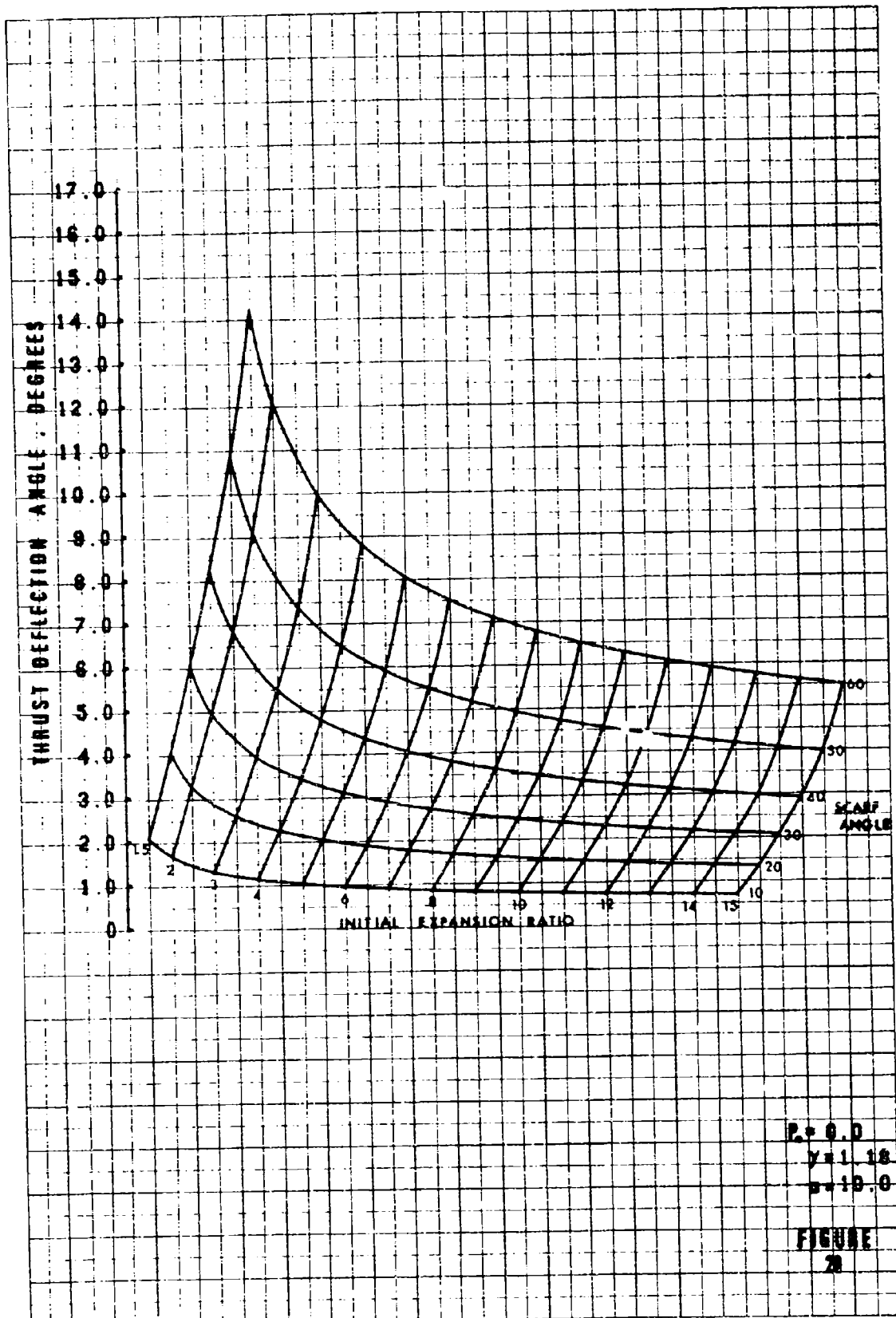
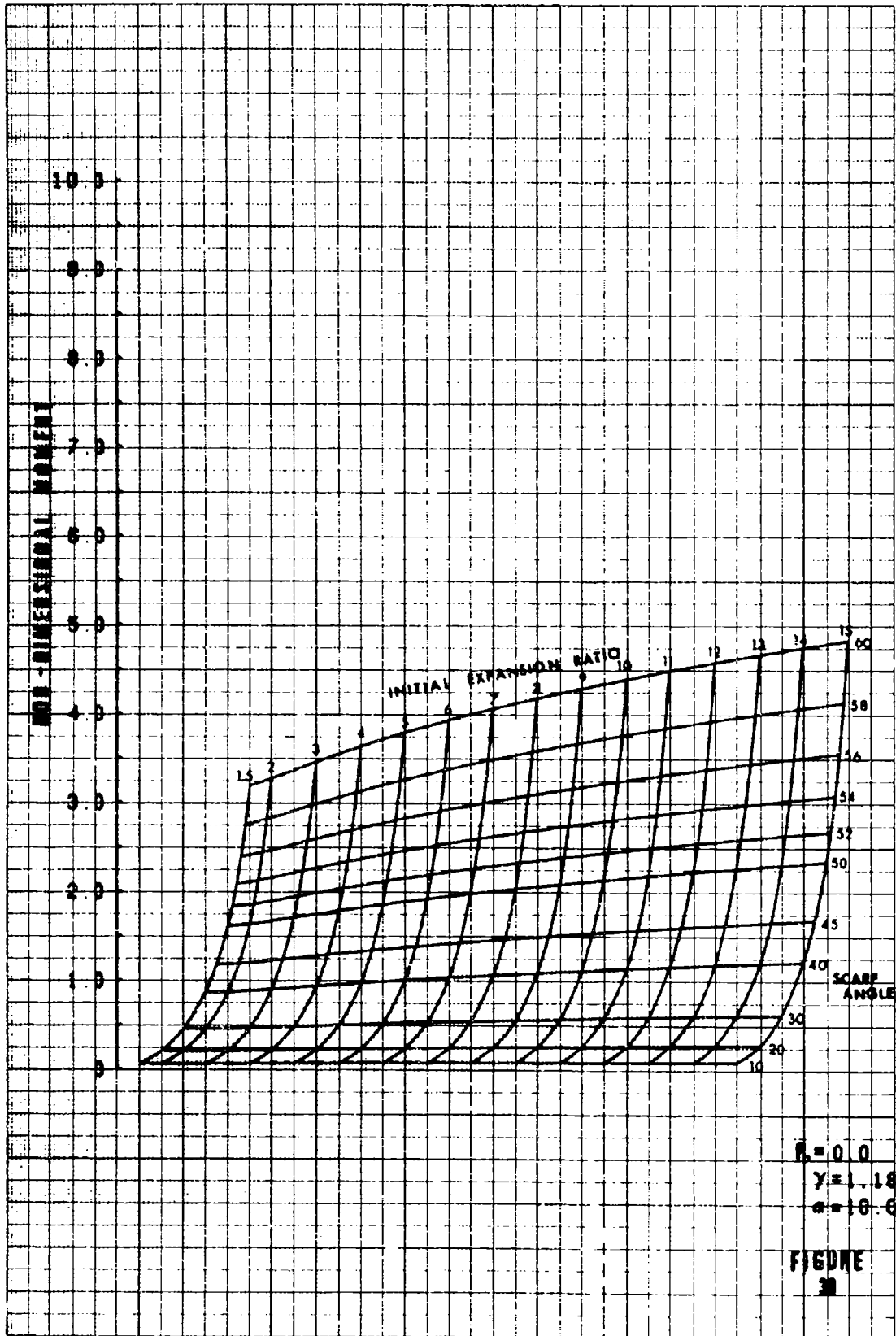


FIGURE 27









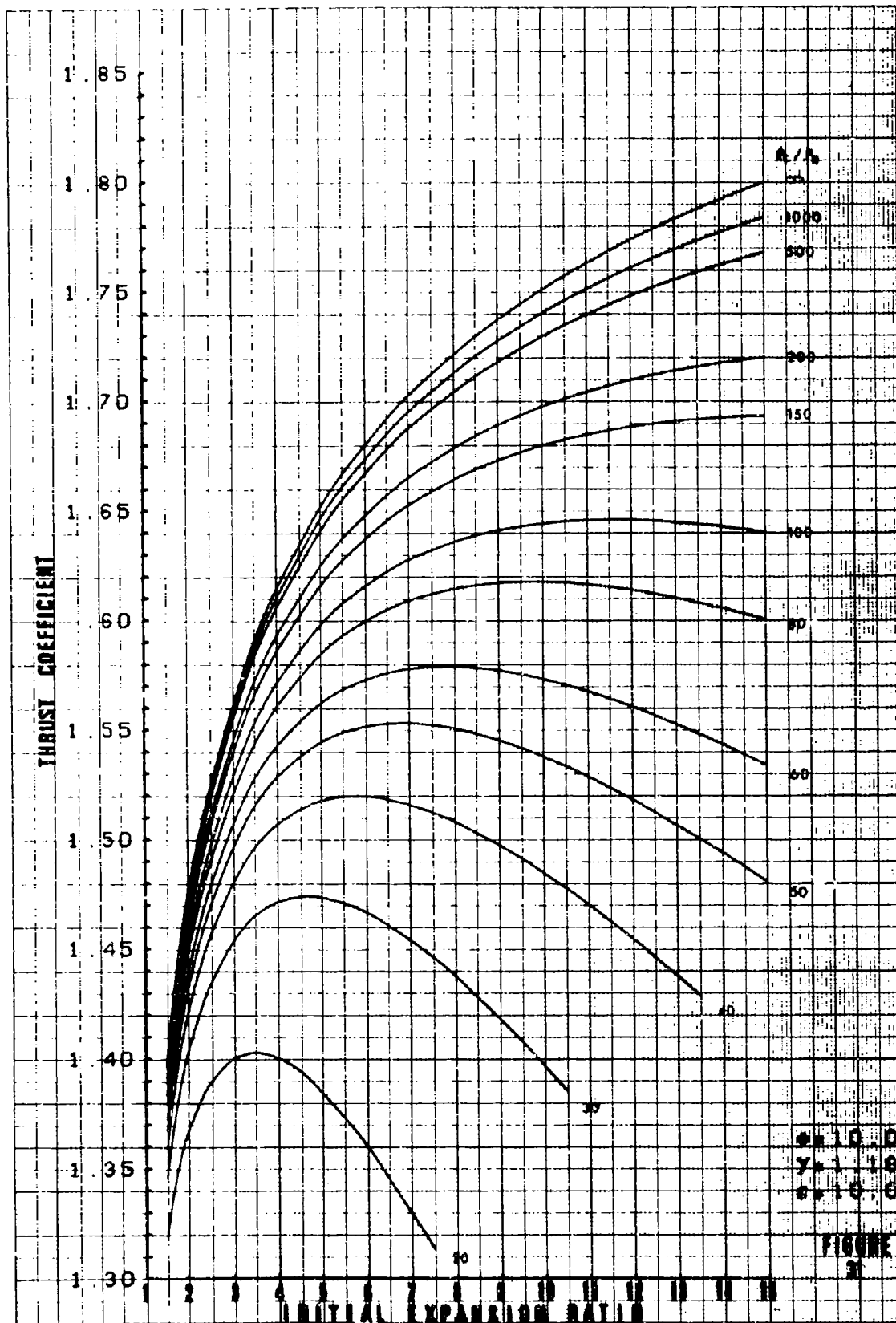
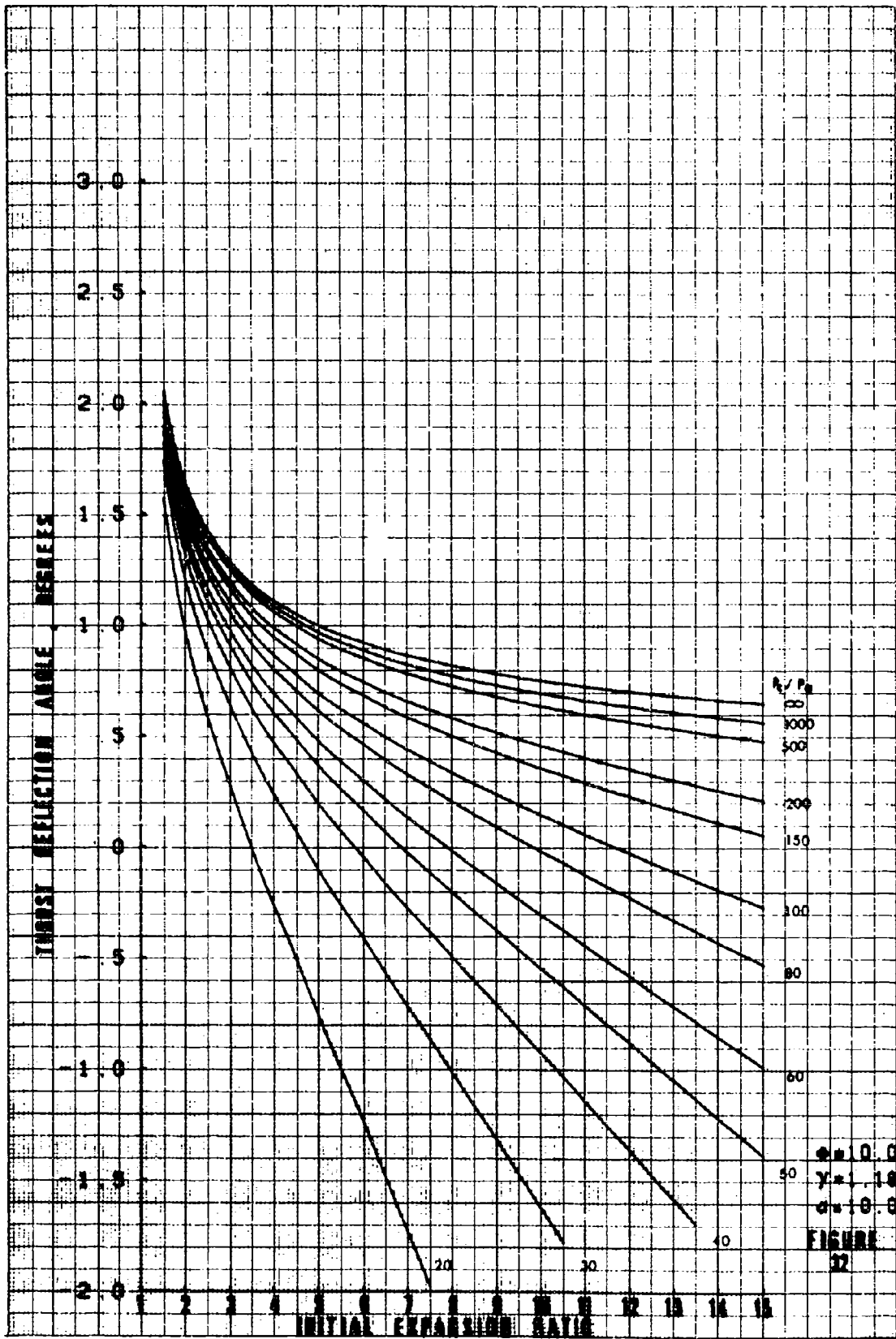
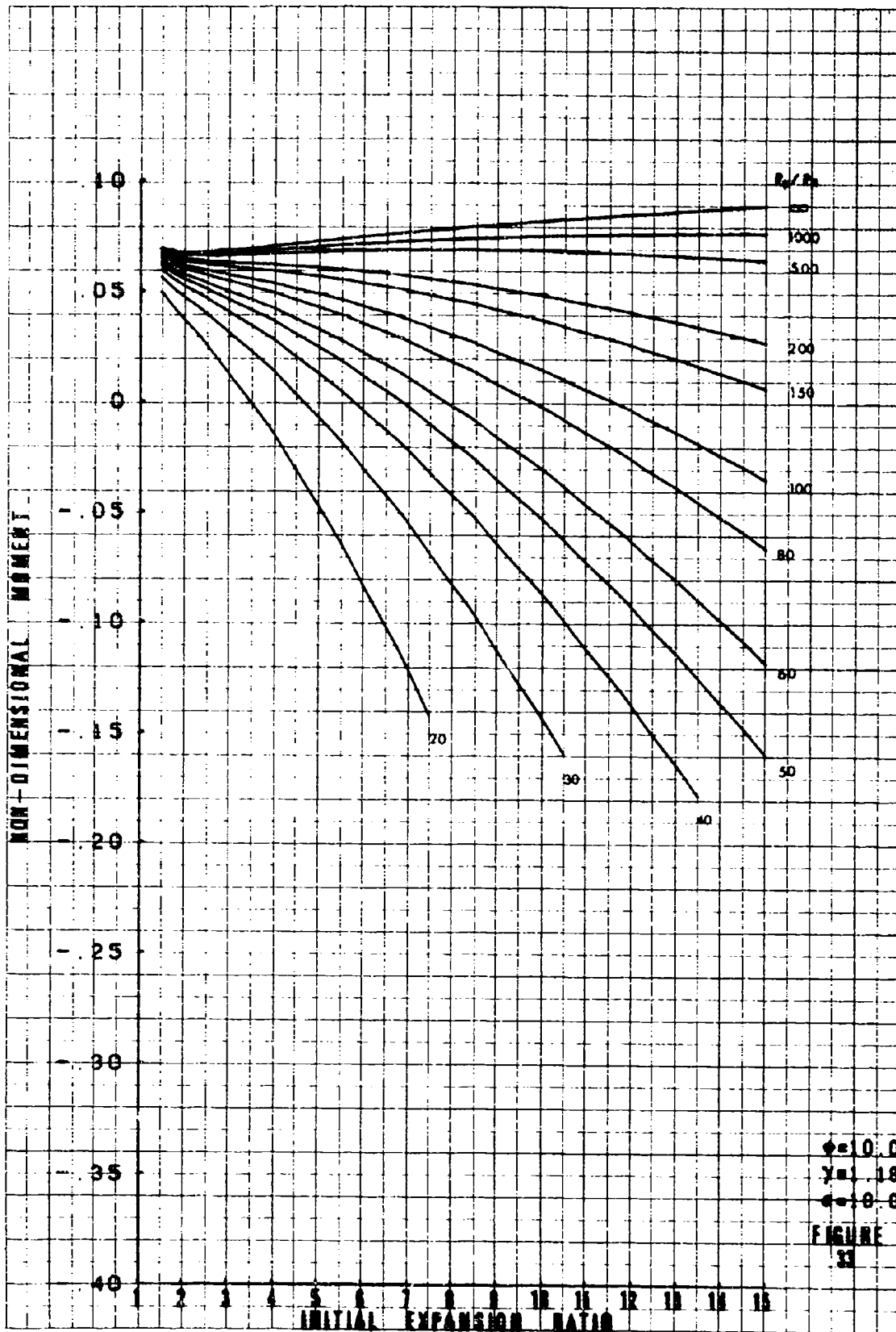
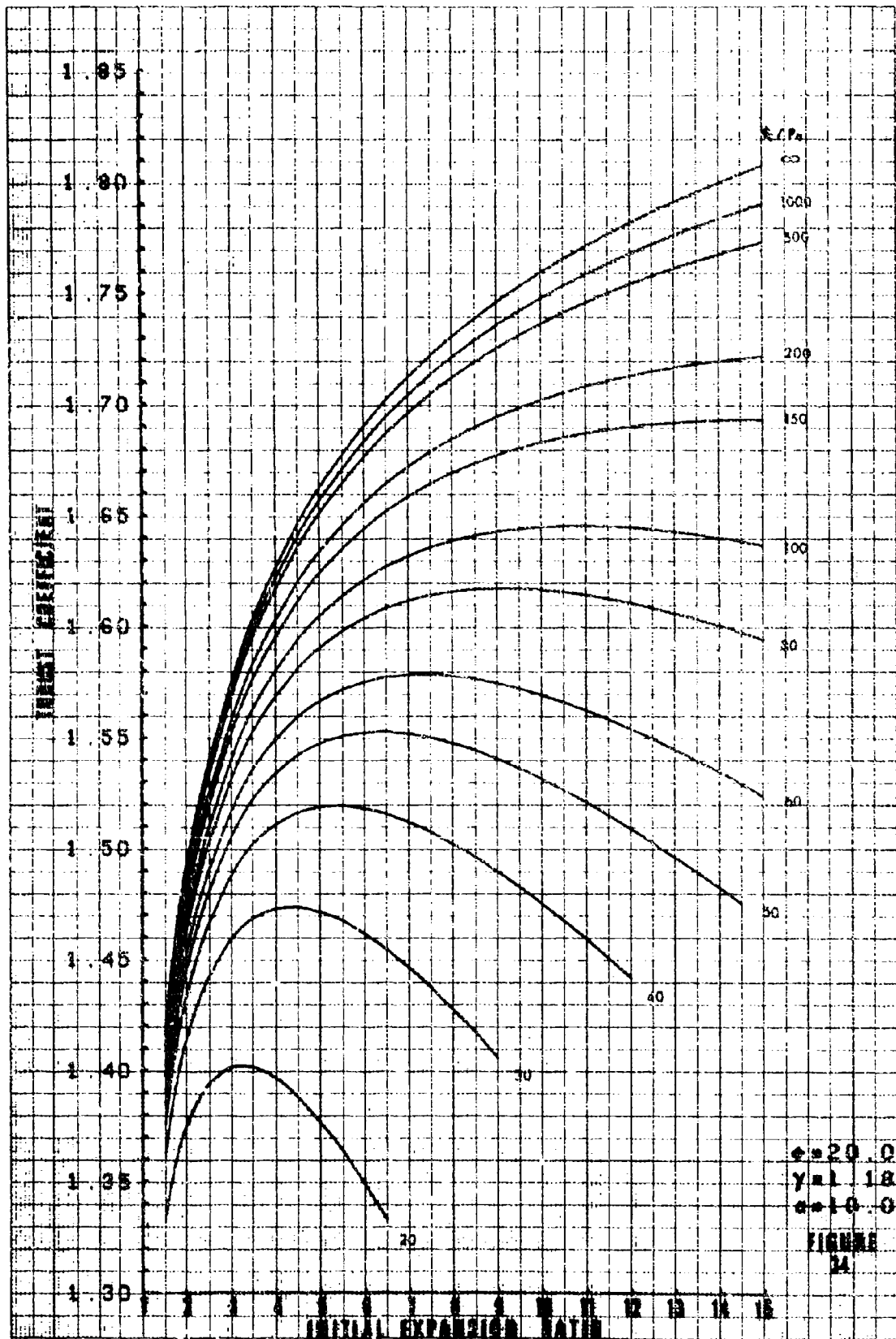


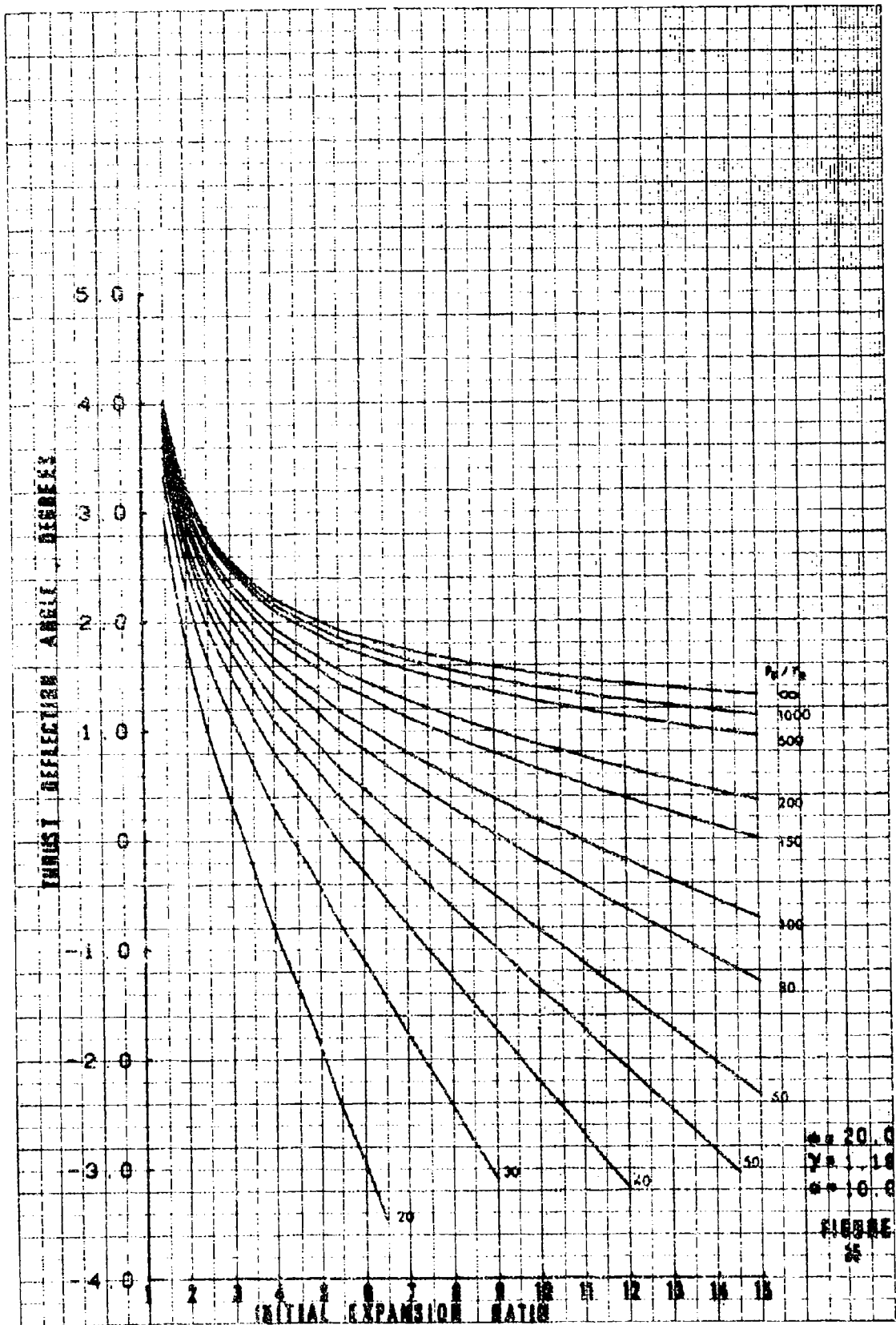
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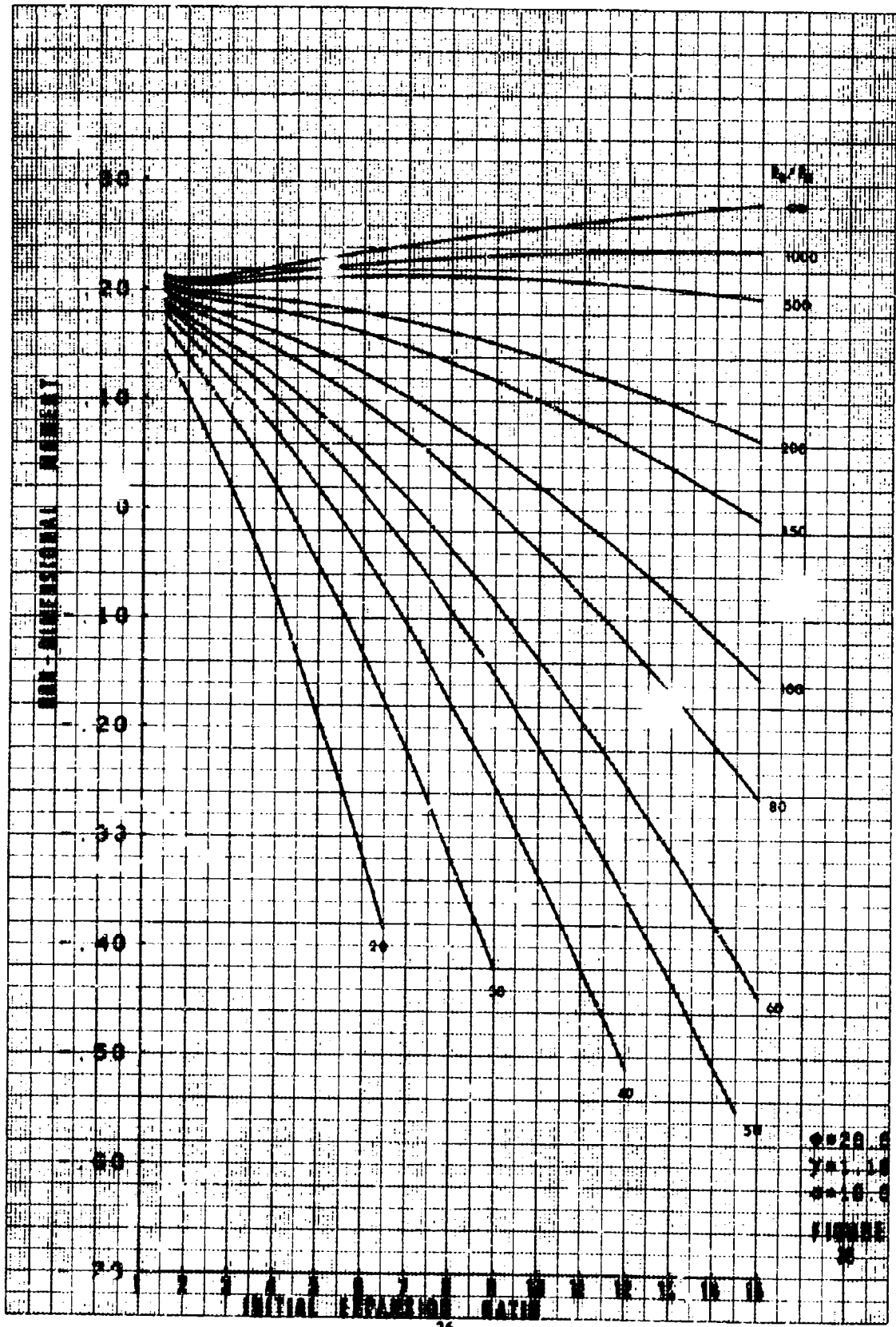


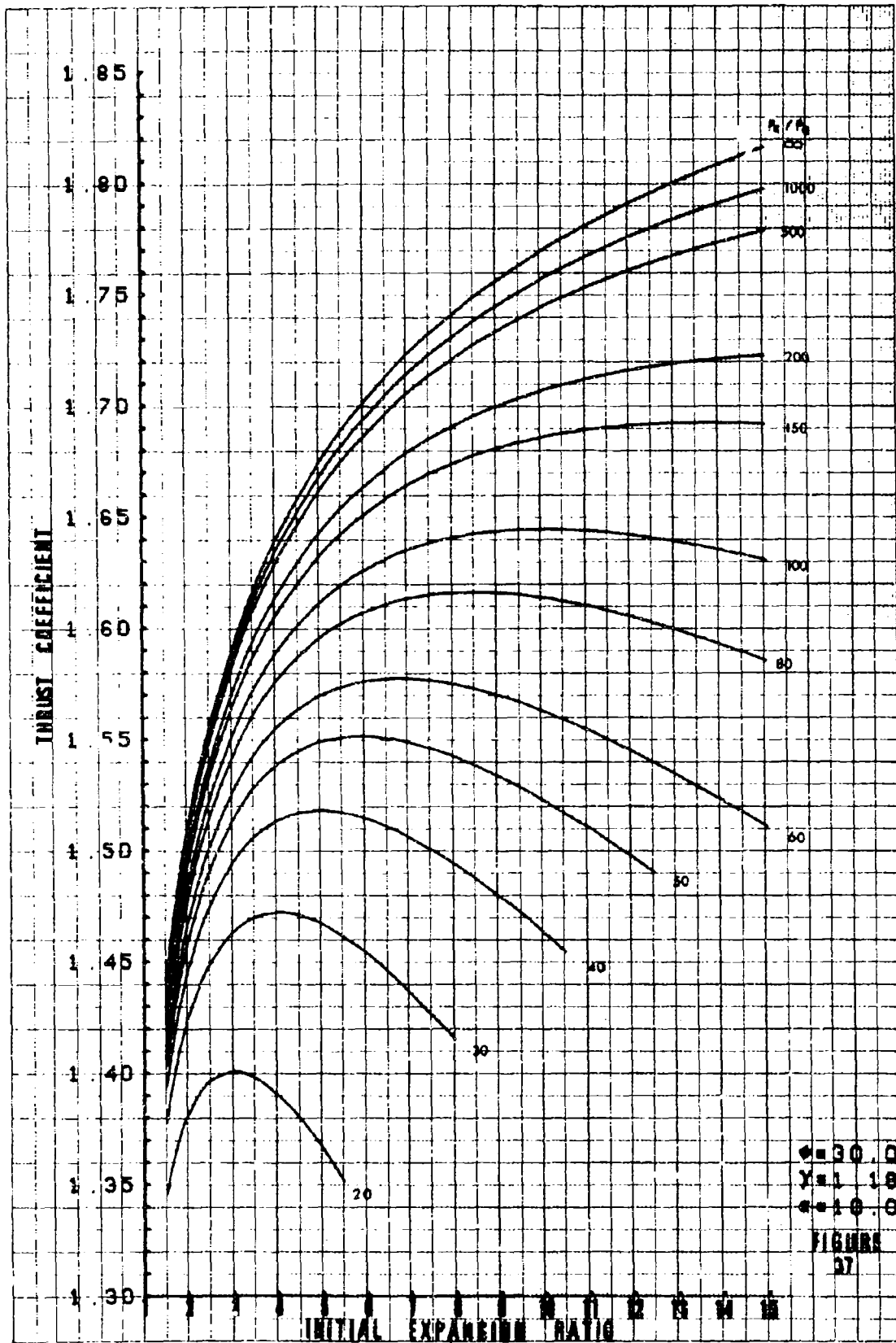
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 $\alpha = 18.8^\circ$   
**FIGURE 32**













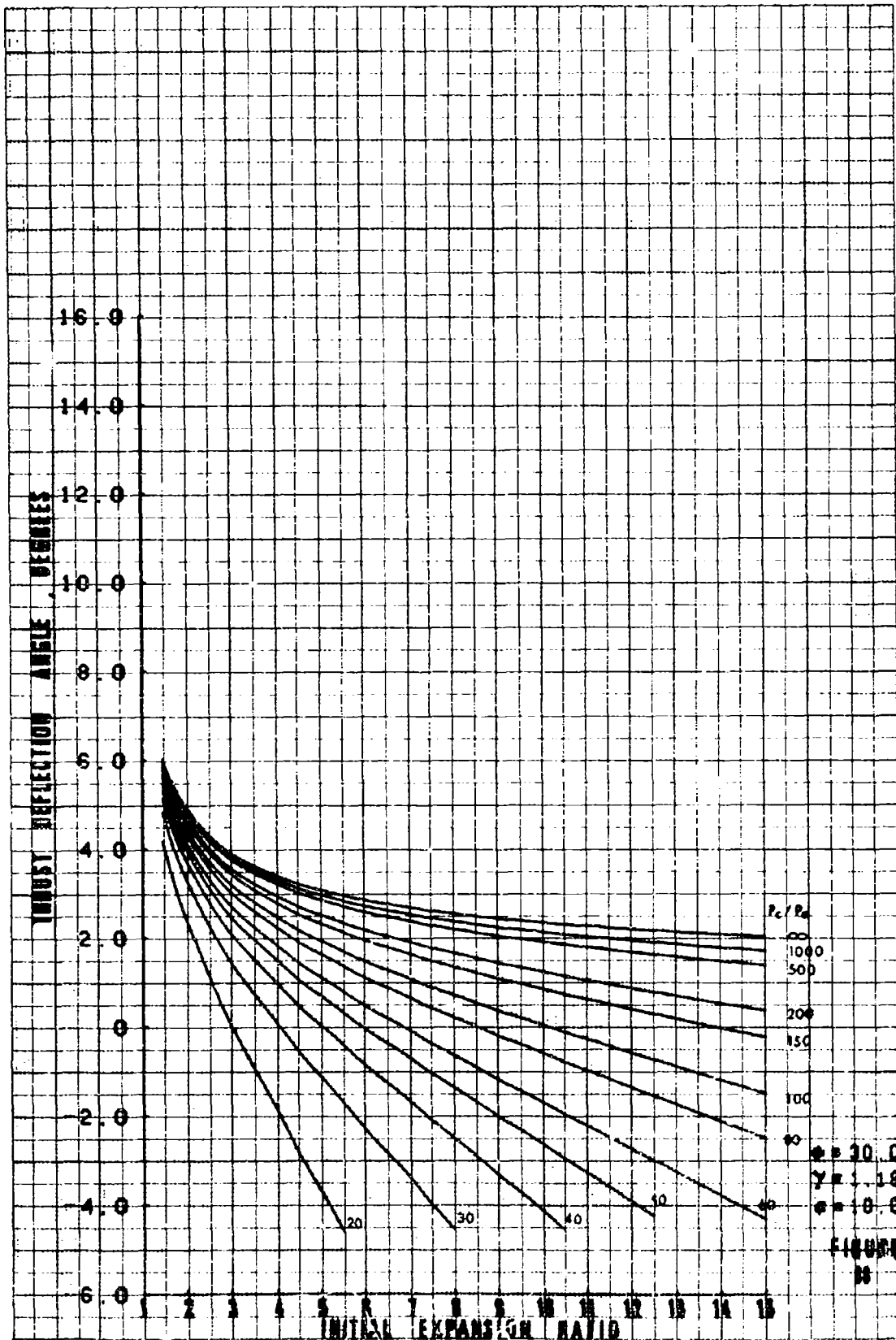
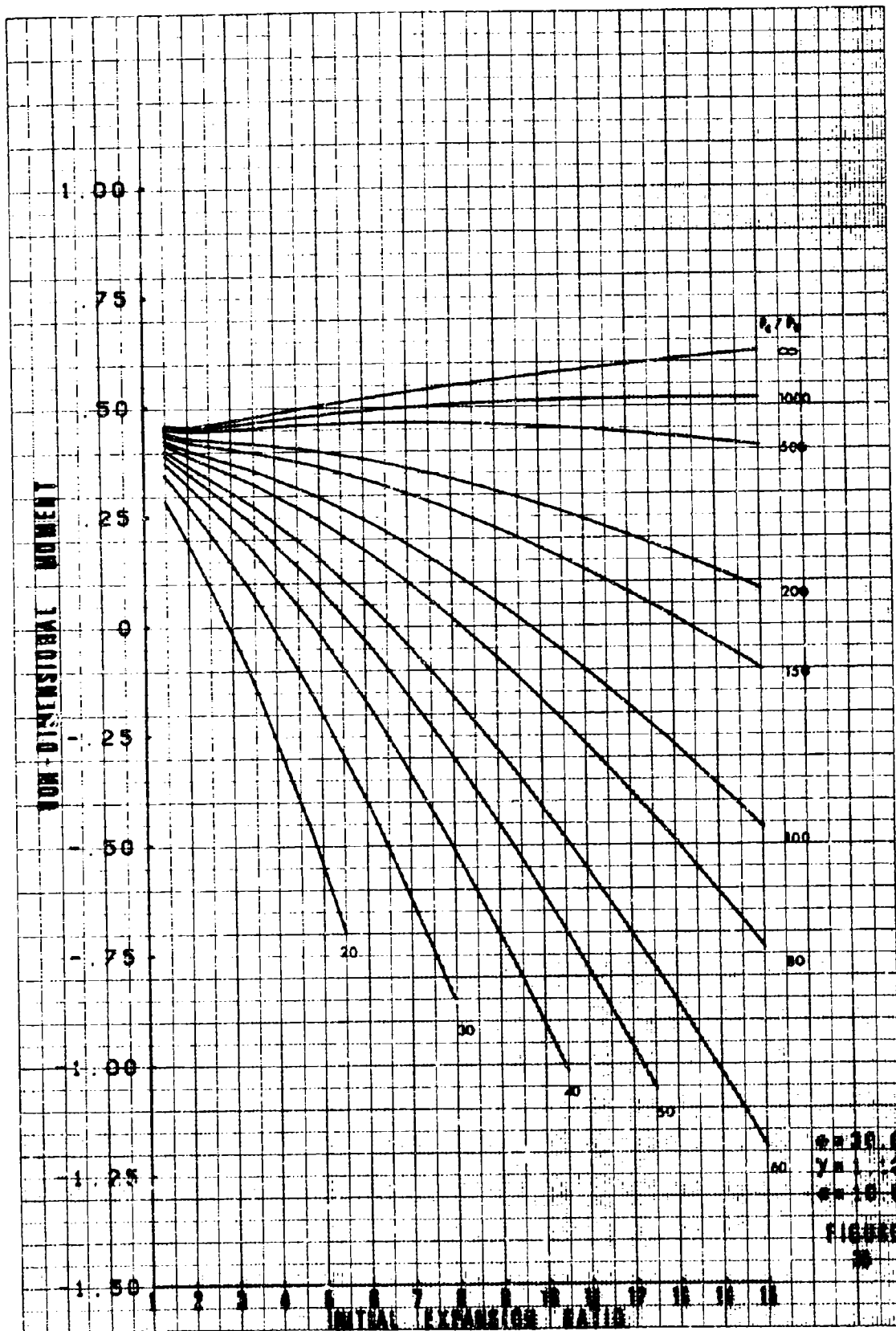
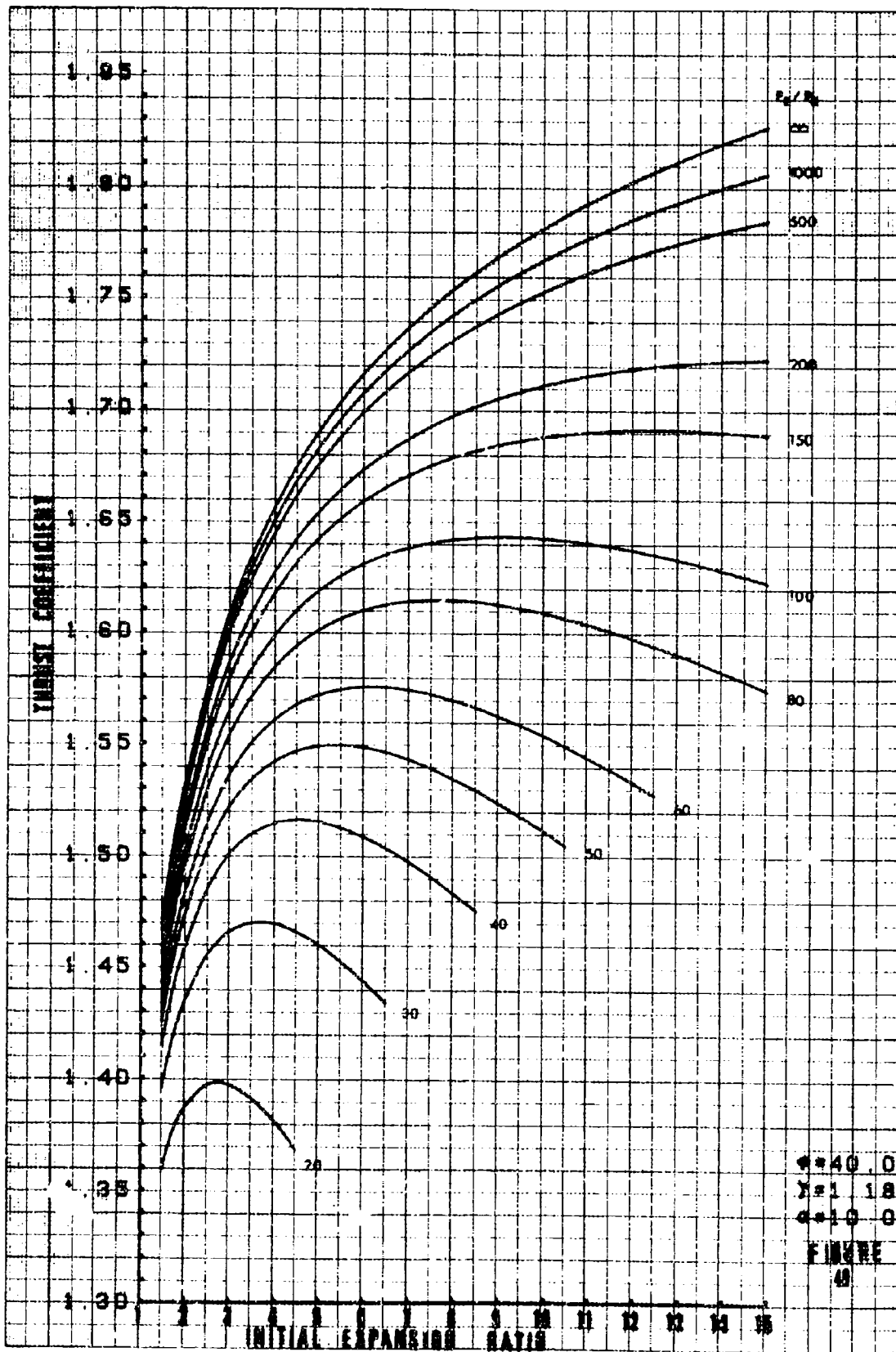


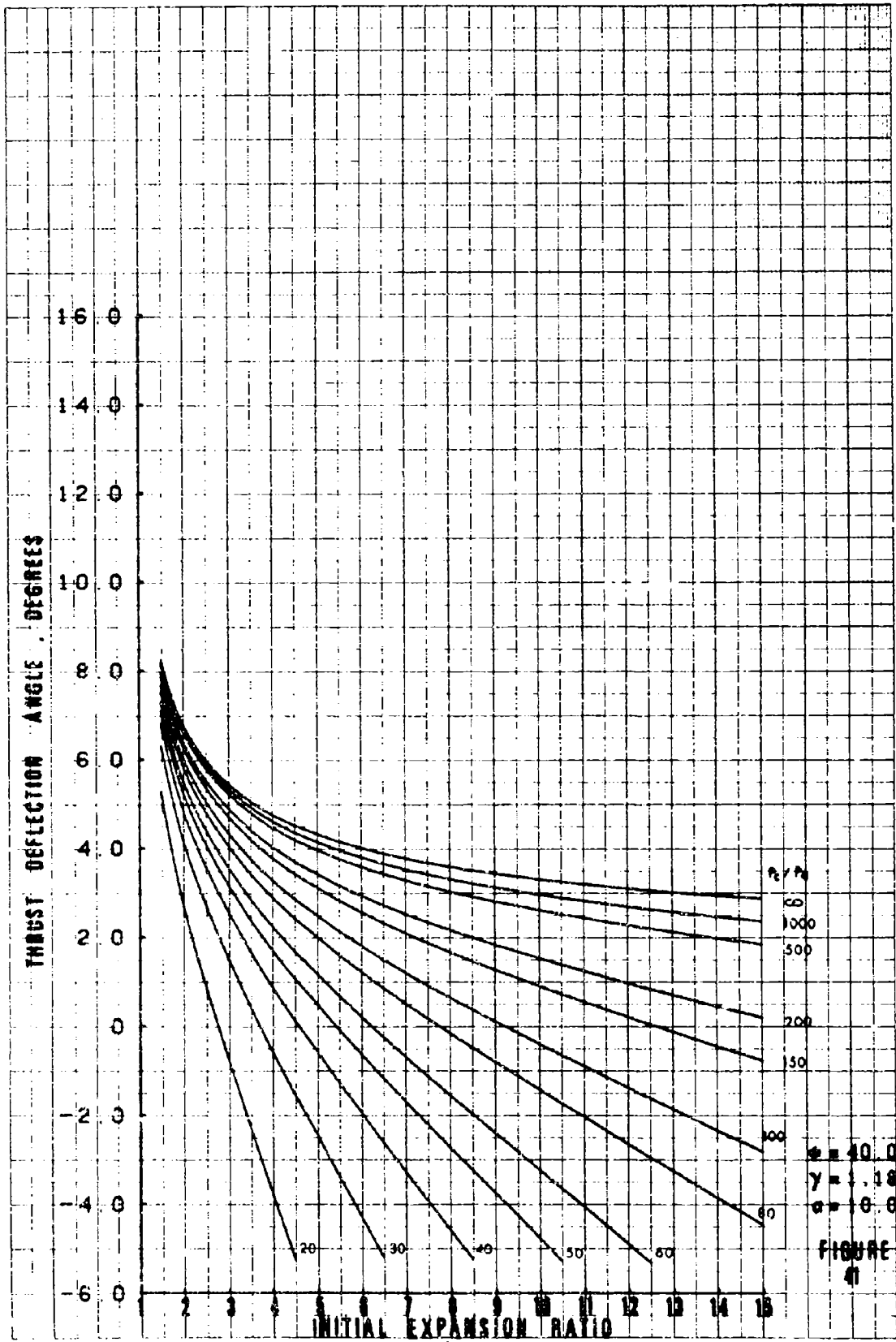
FIGURE 38





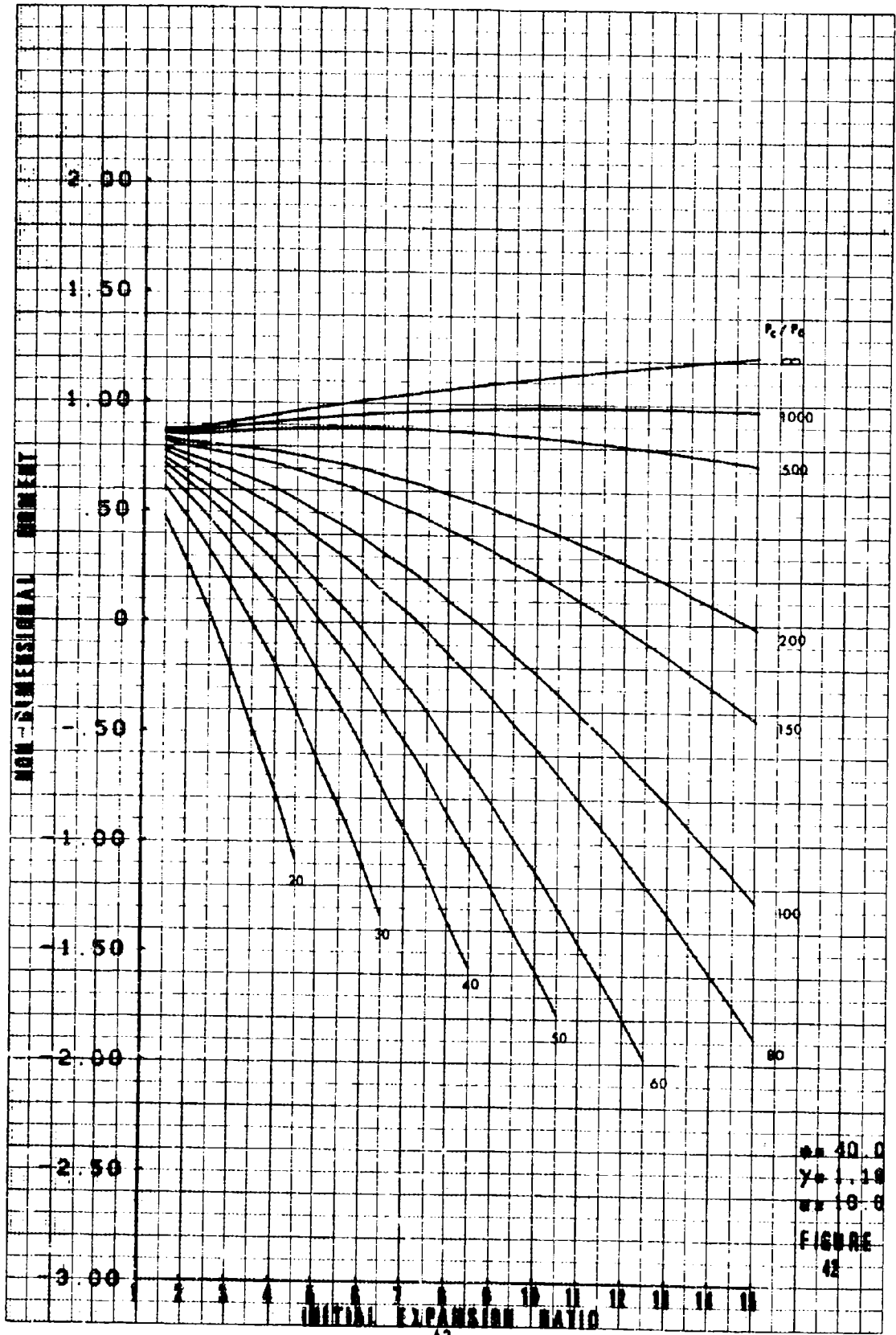
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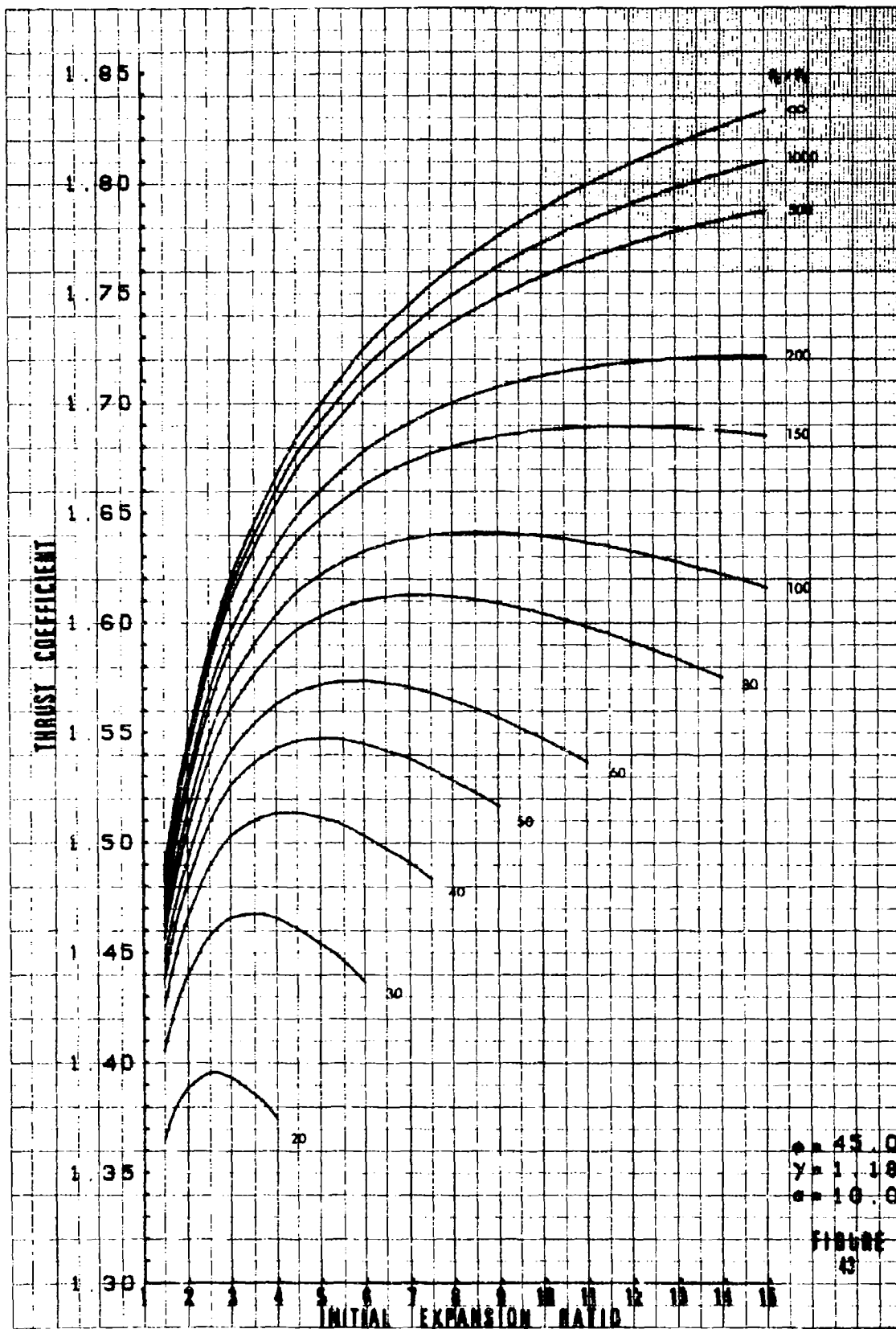
FIGURE 49

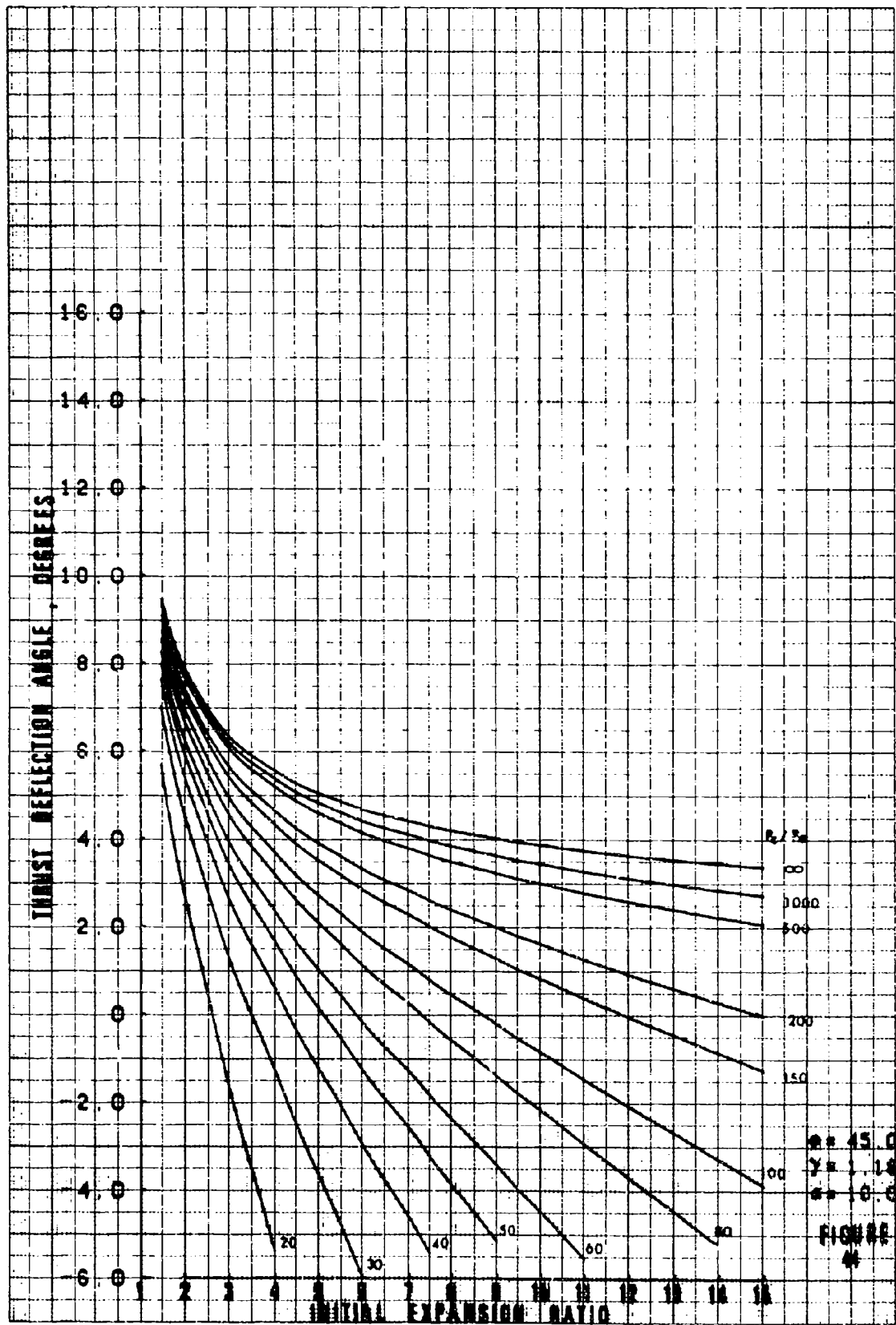


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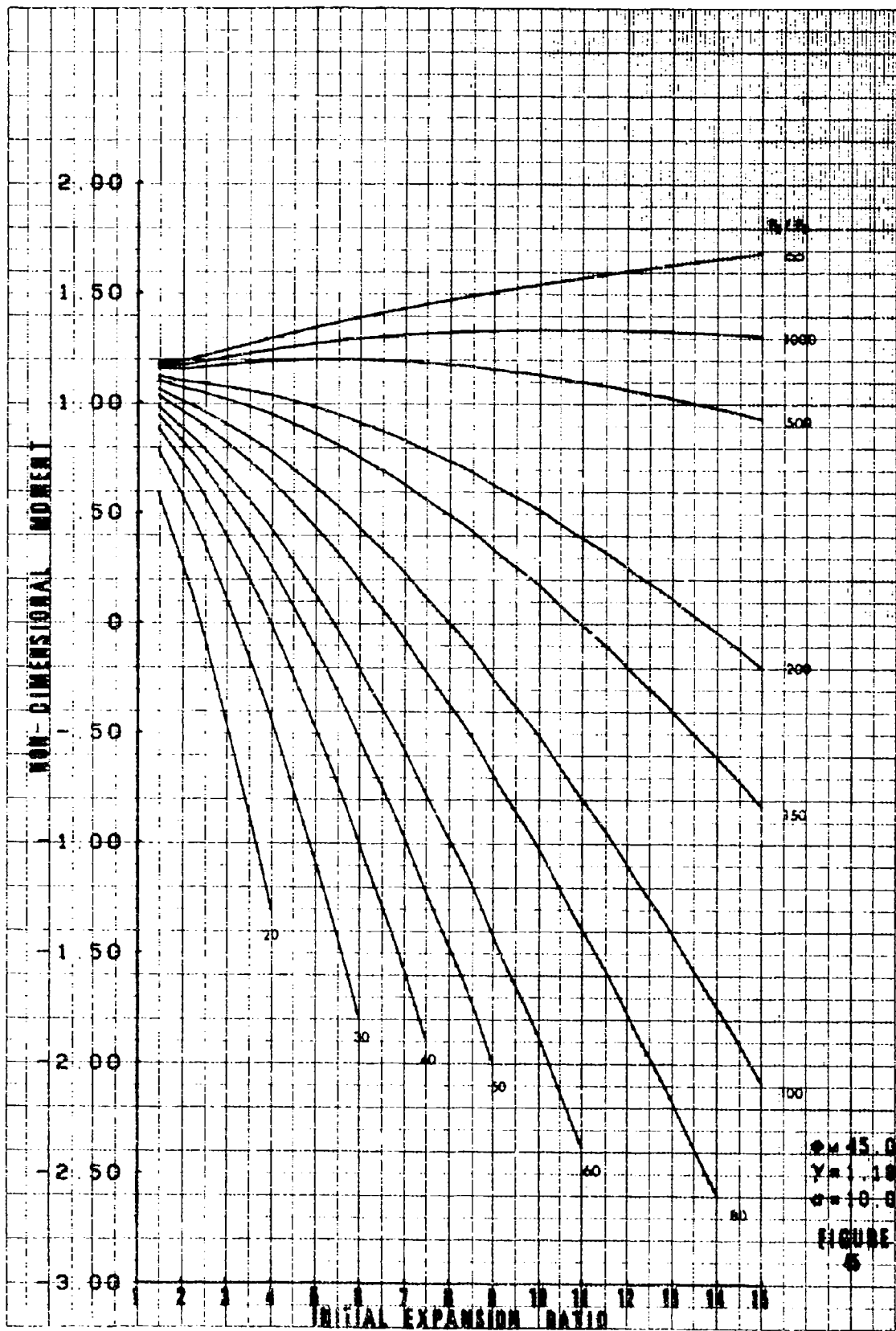
FIGURE 41



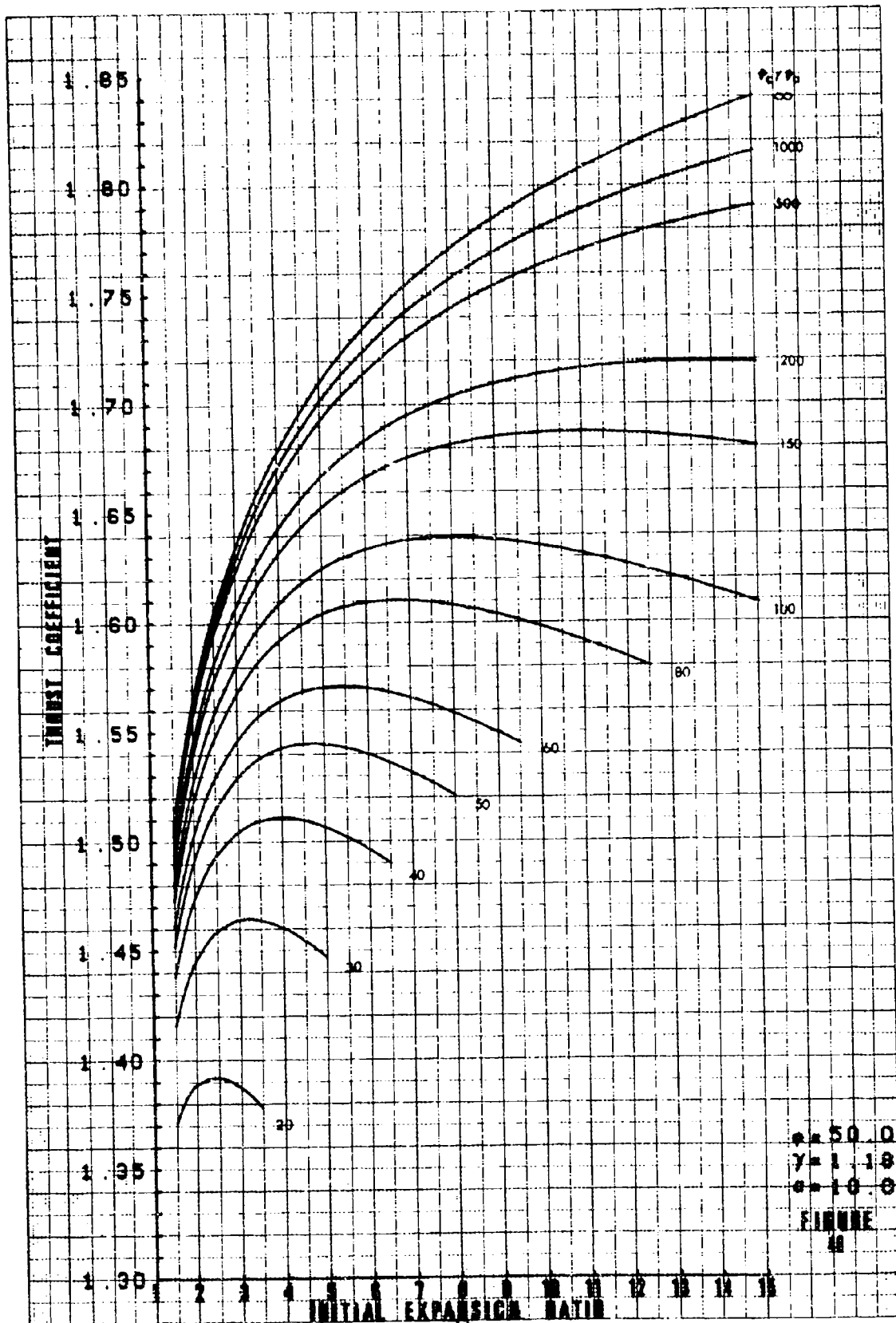


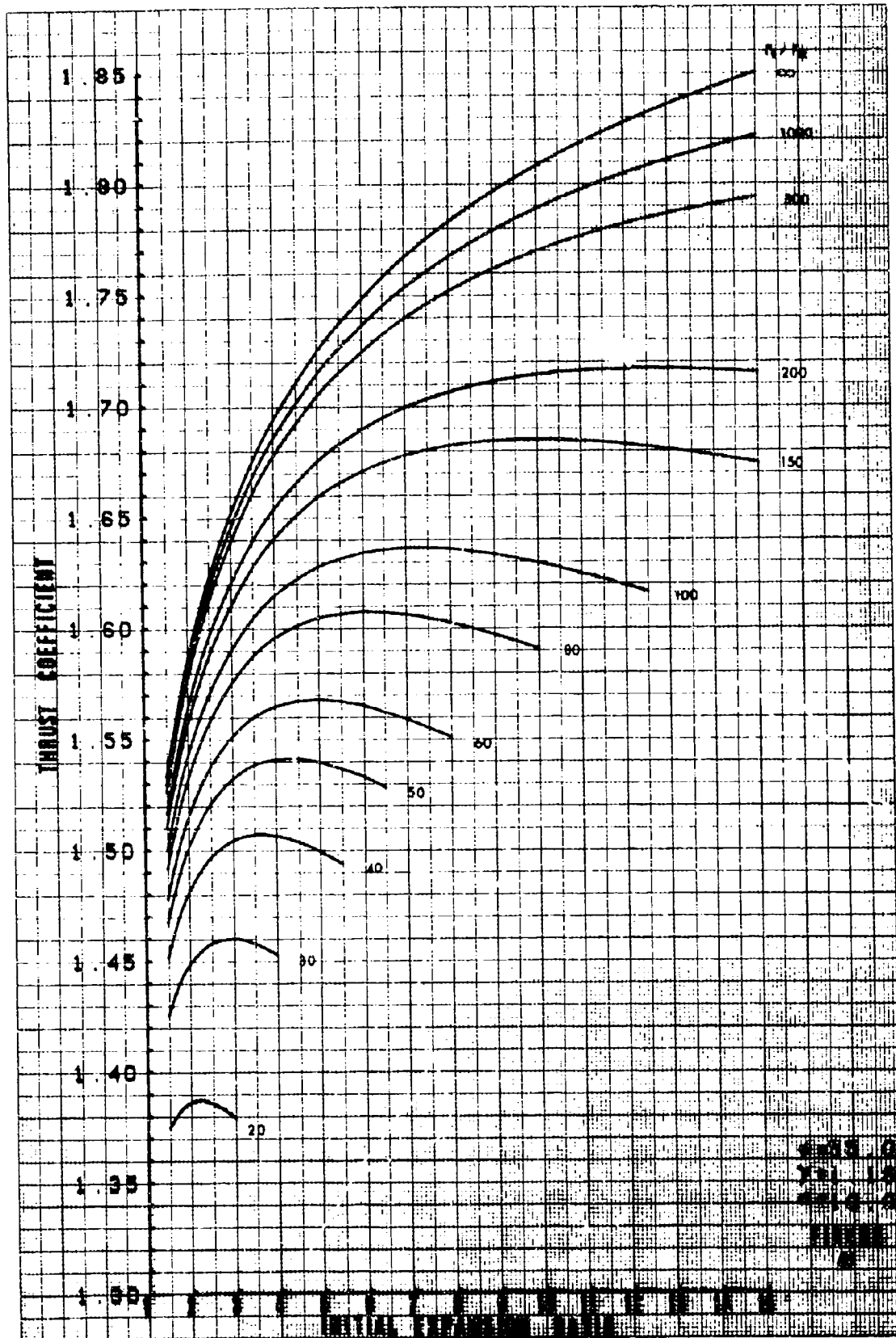


$\theta = 45.0$   
 $\gamma = 1.4$   
 $\alpha = 10.0$   
**FIGURE 4**









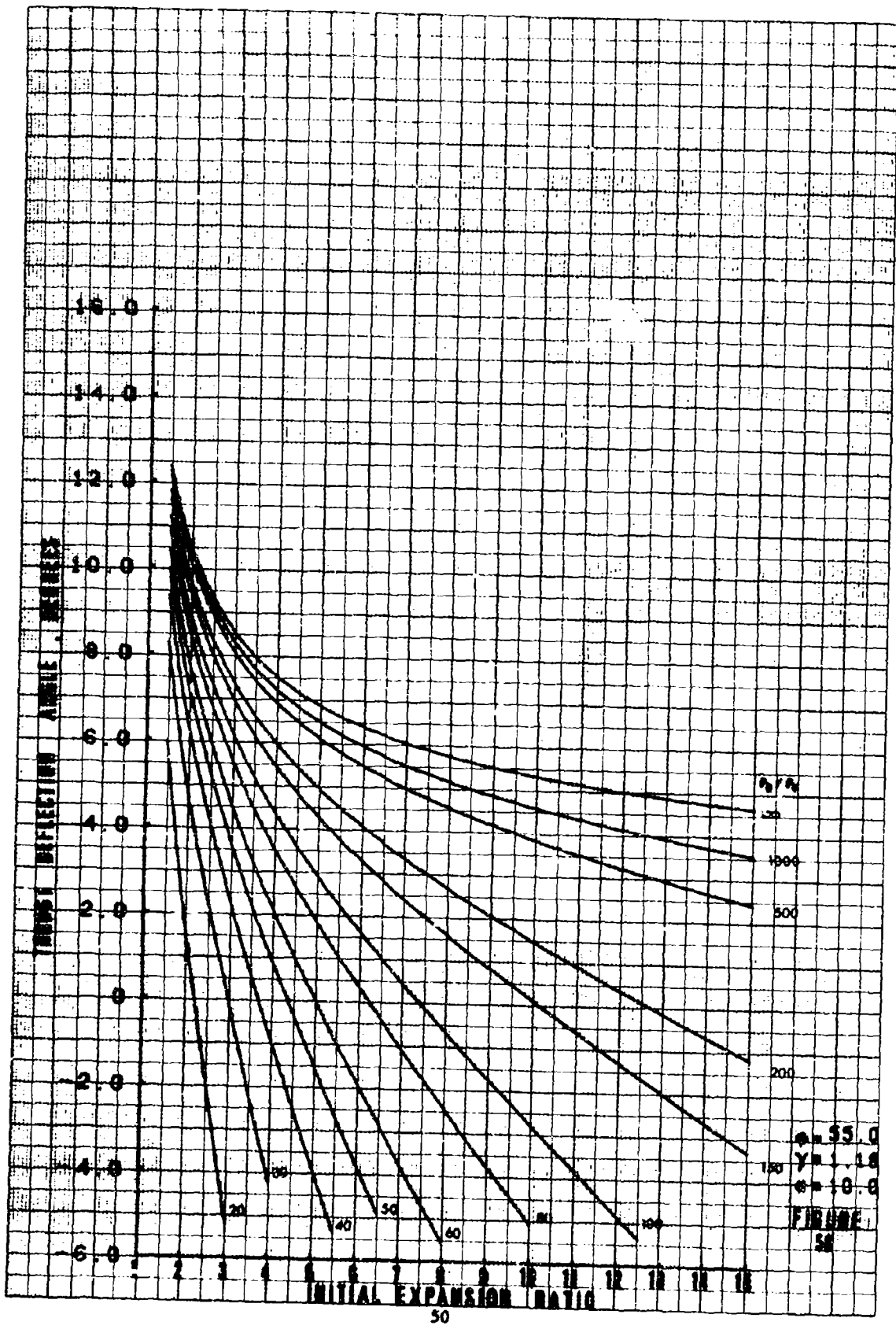
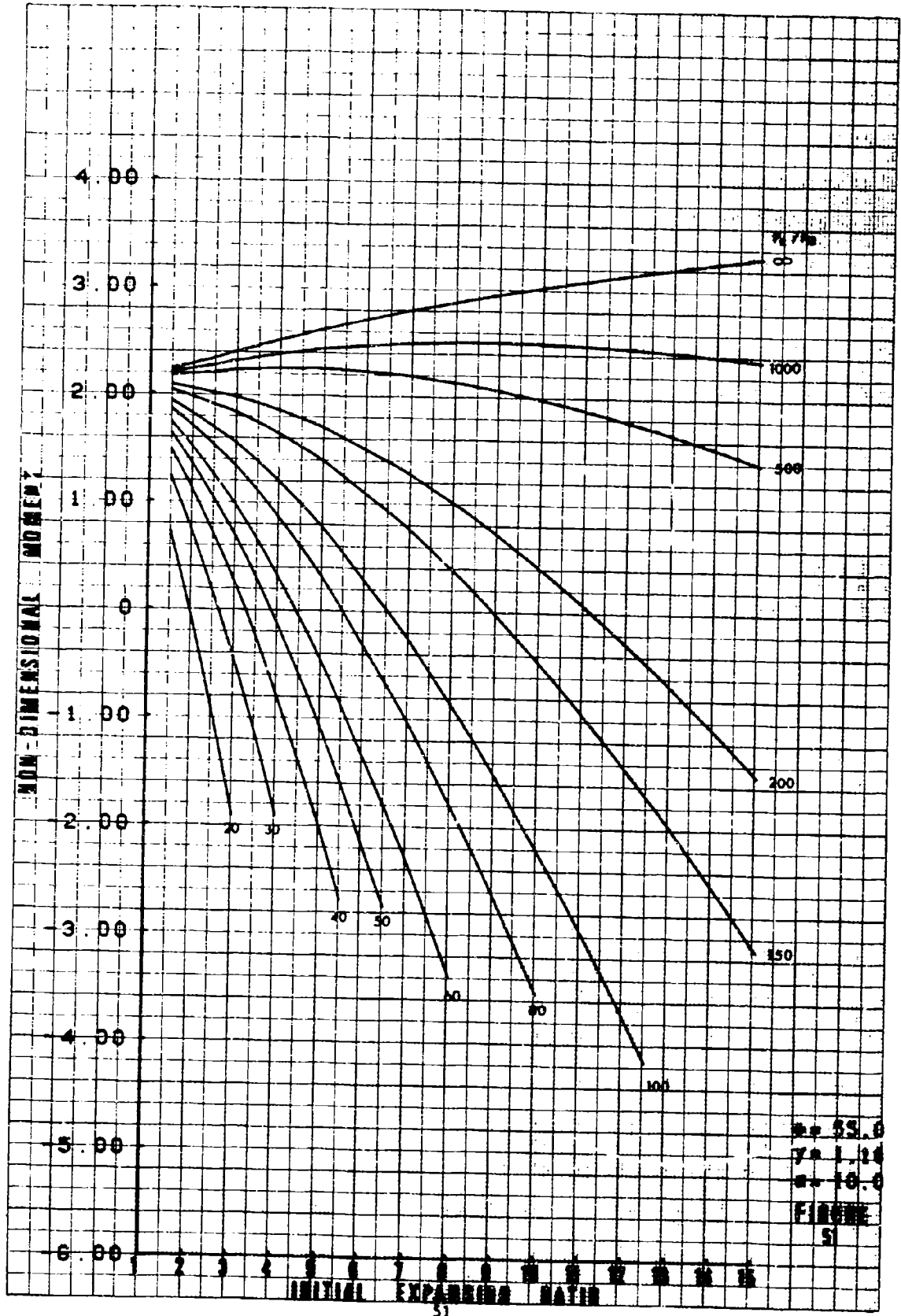
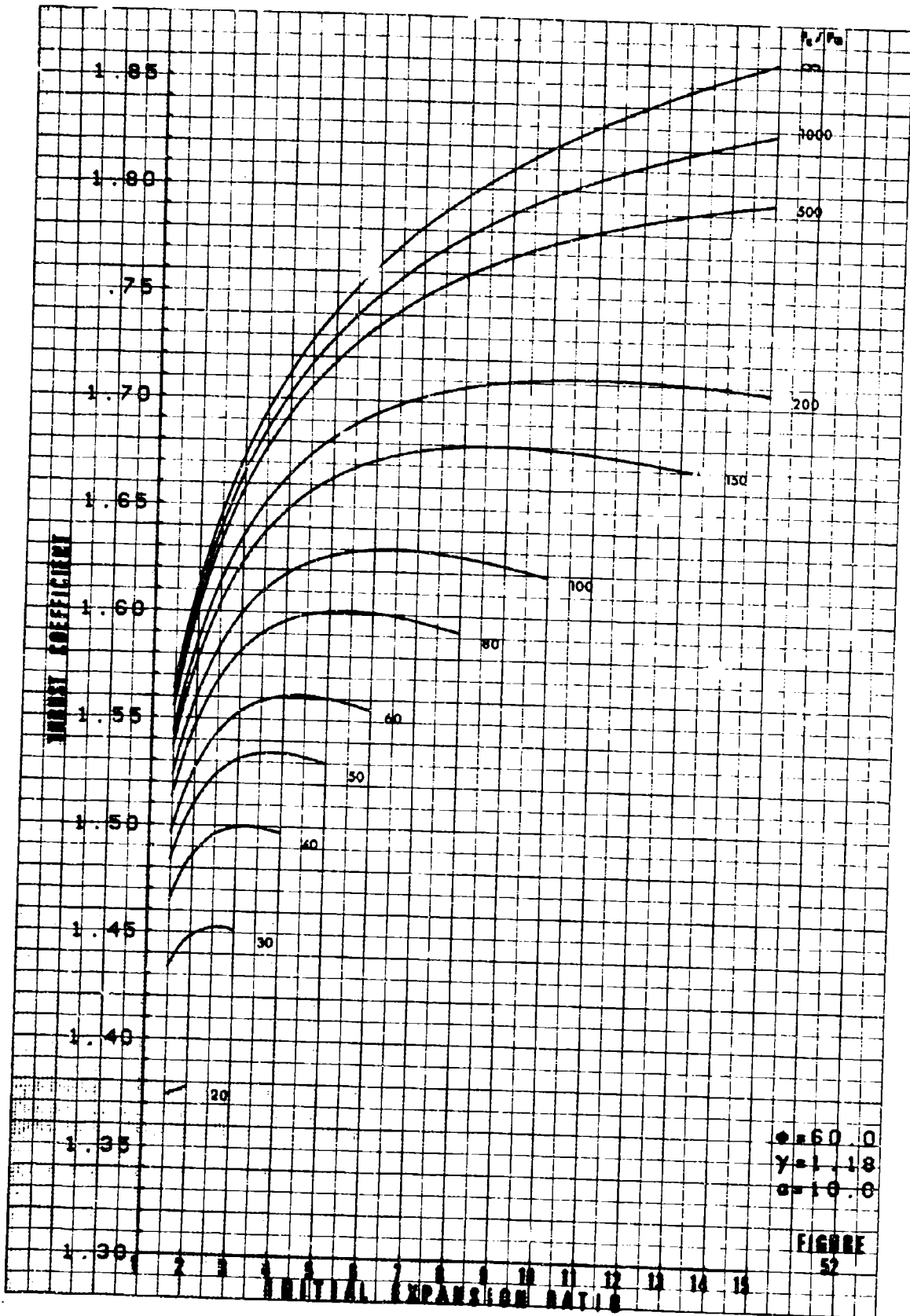
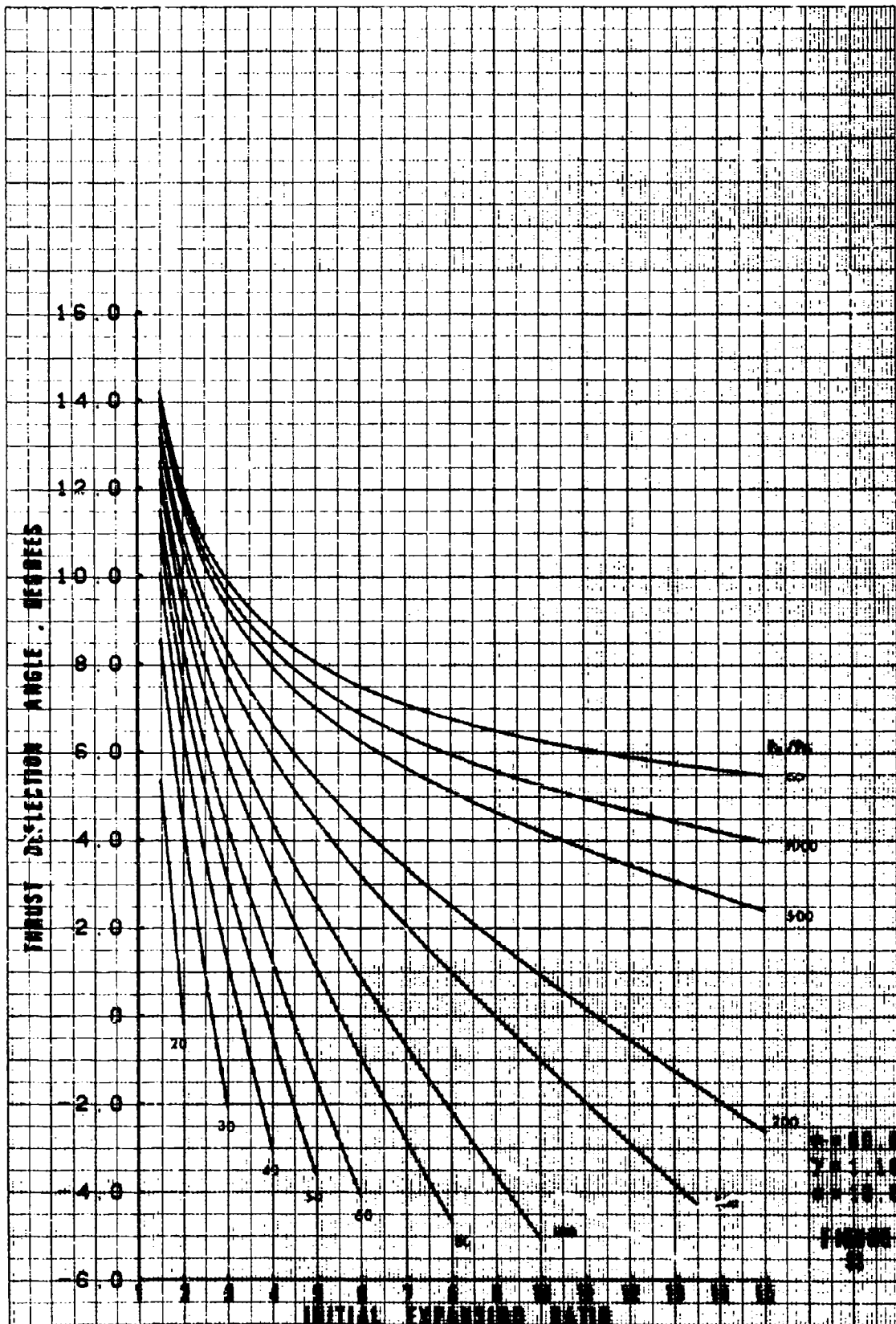
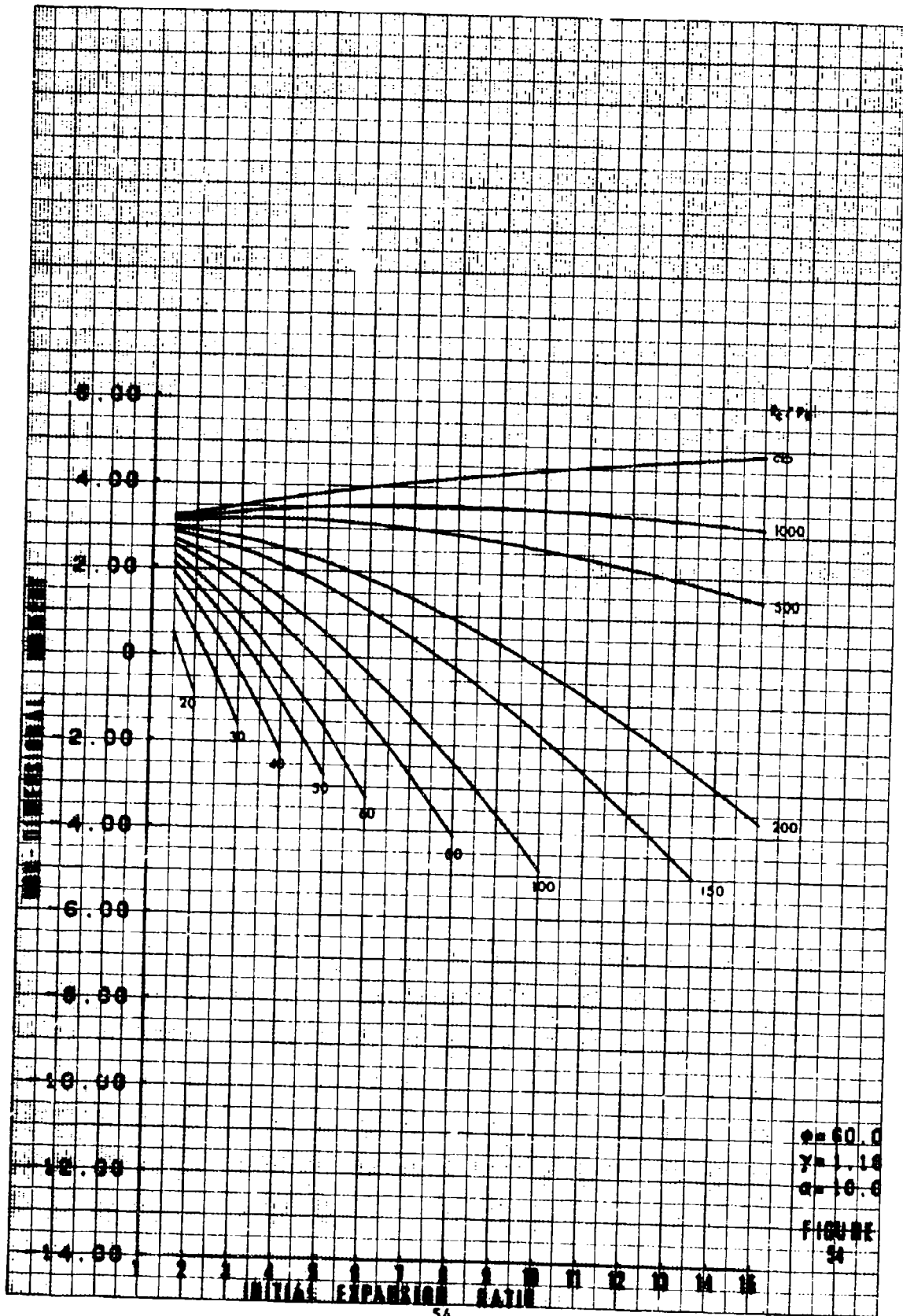


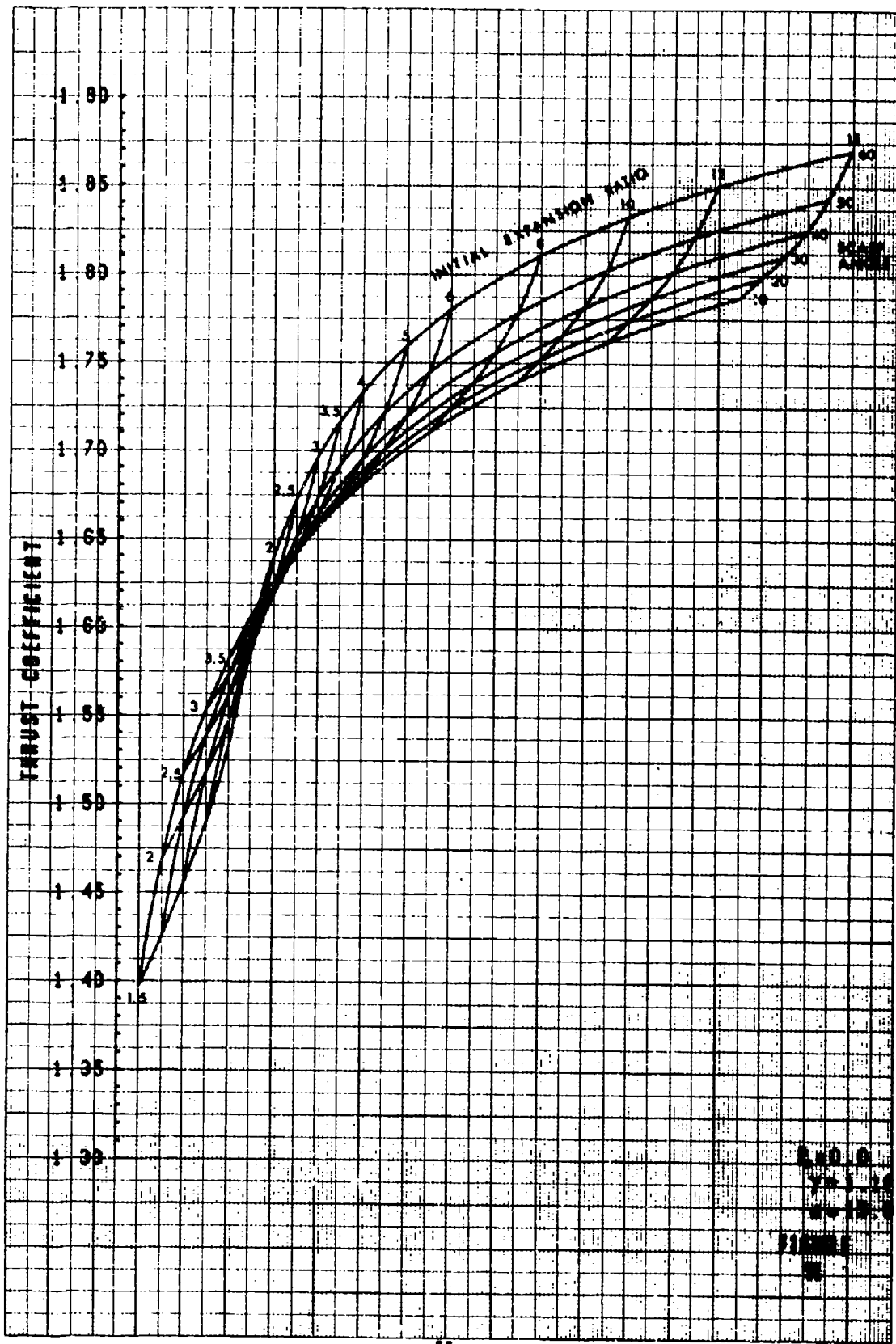
FIGURE 58



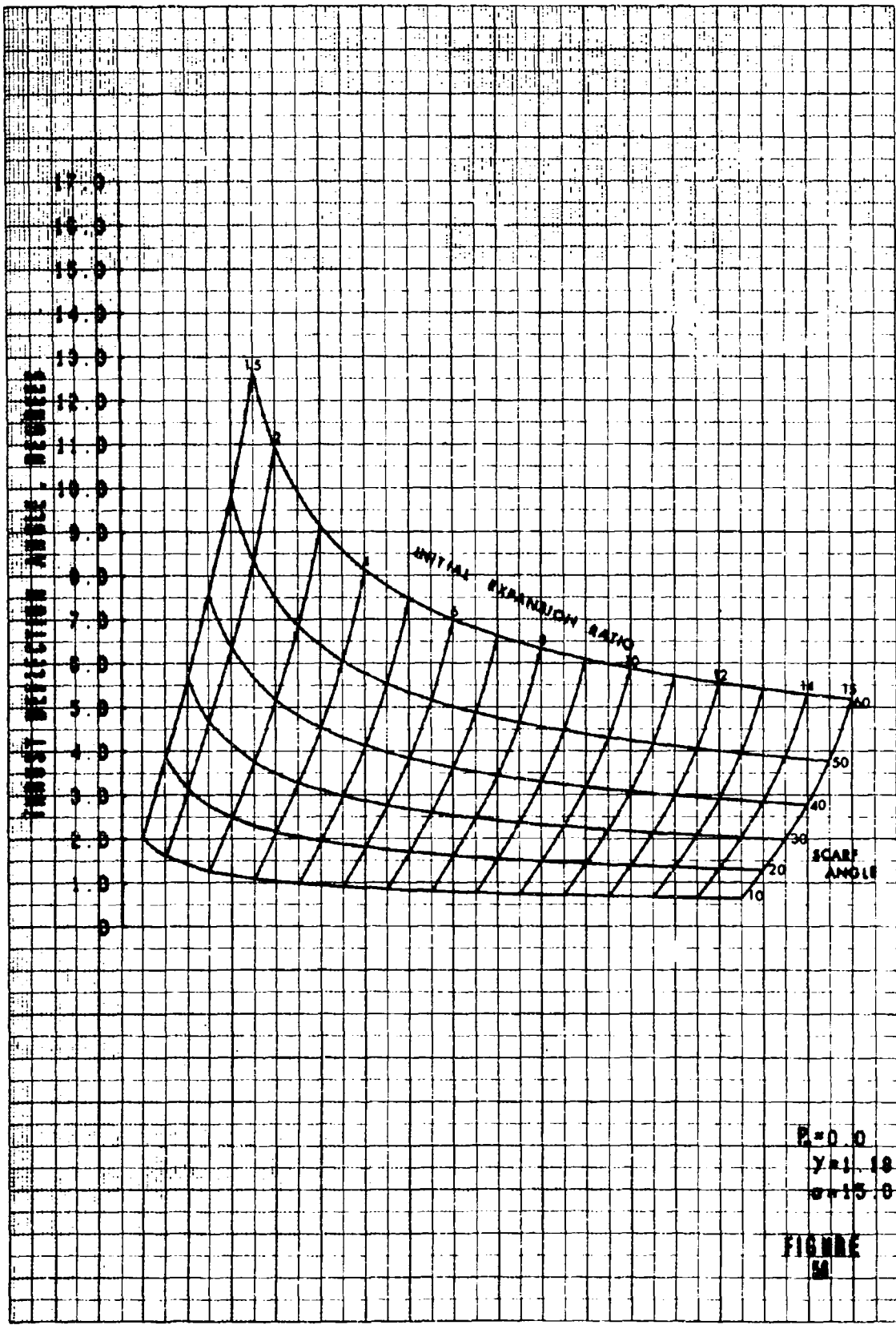


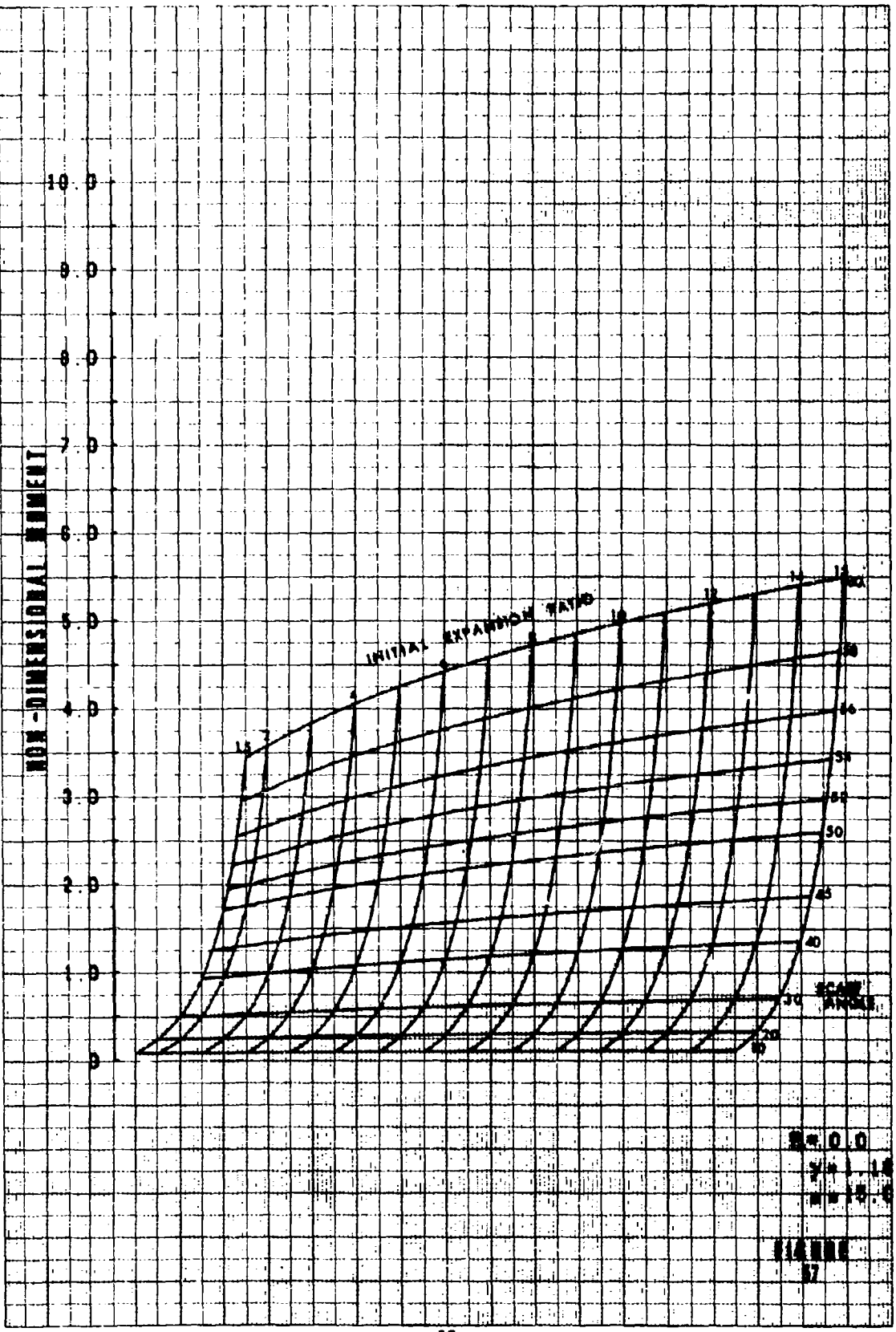




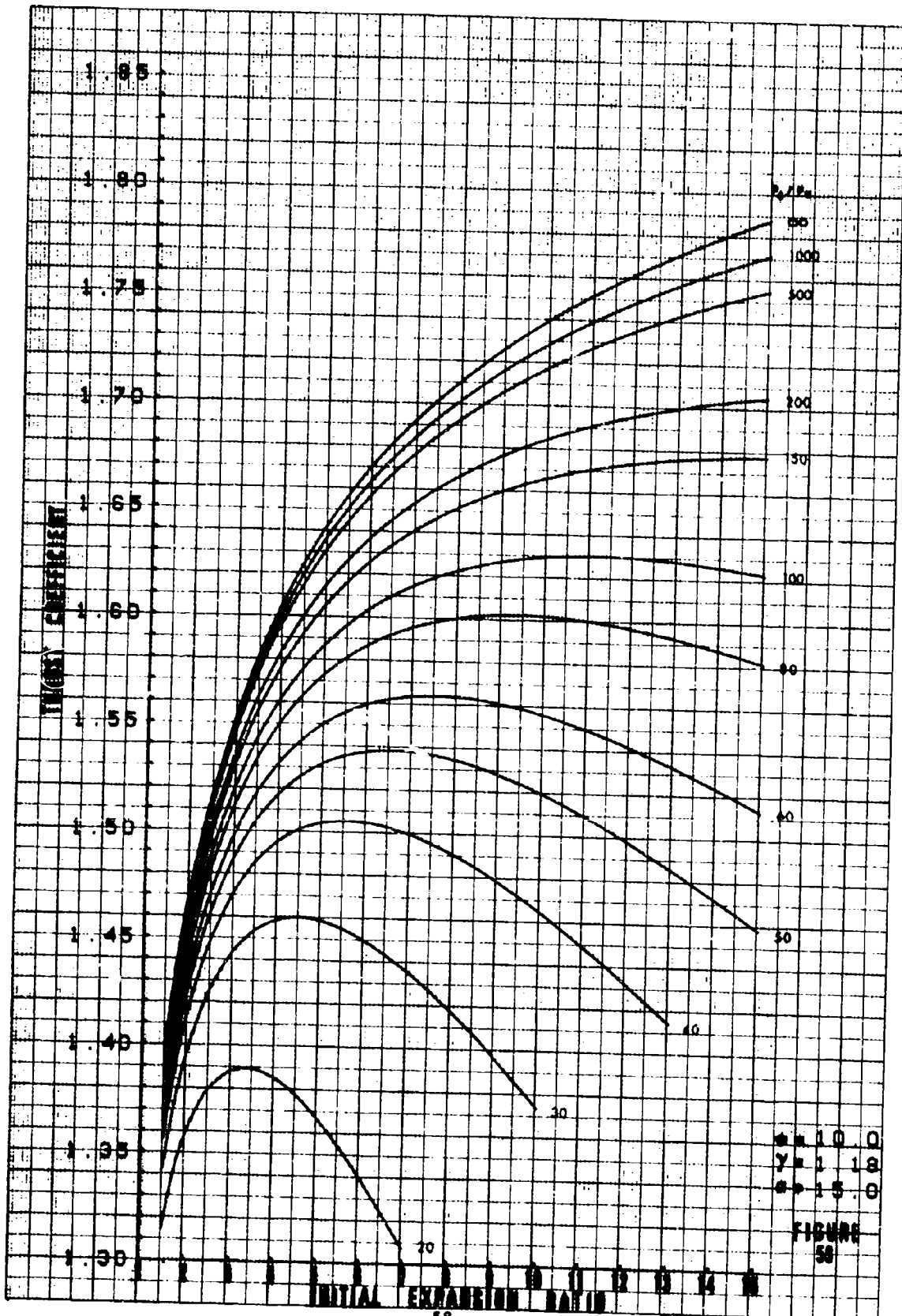






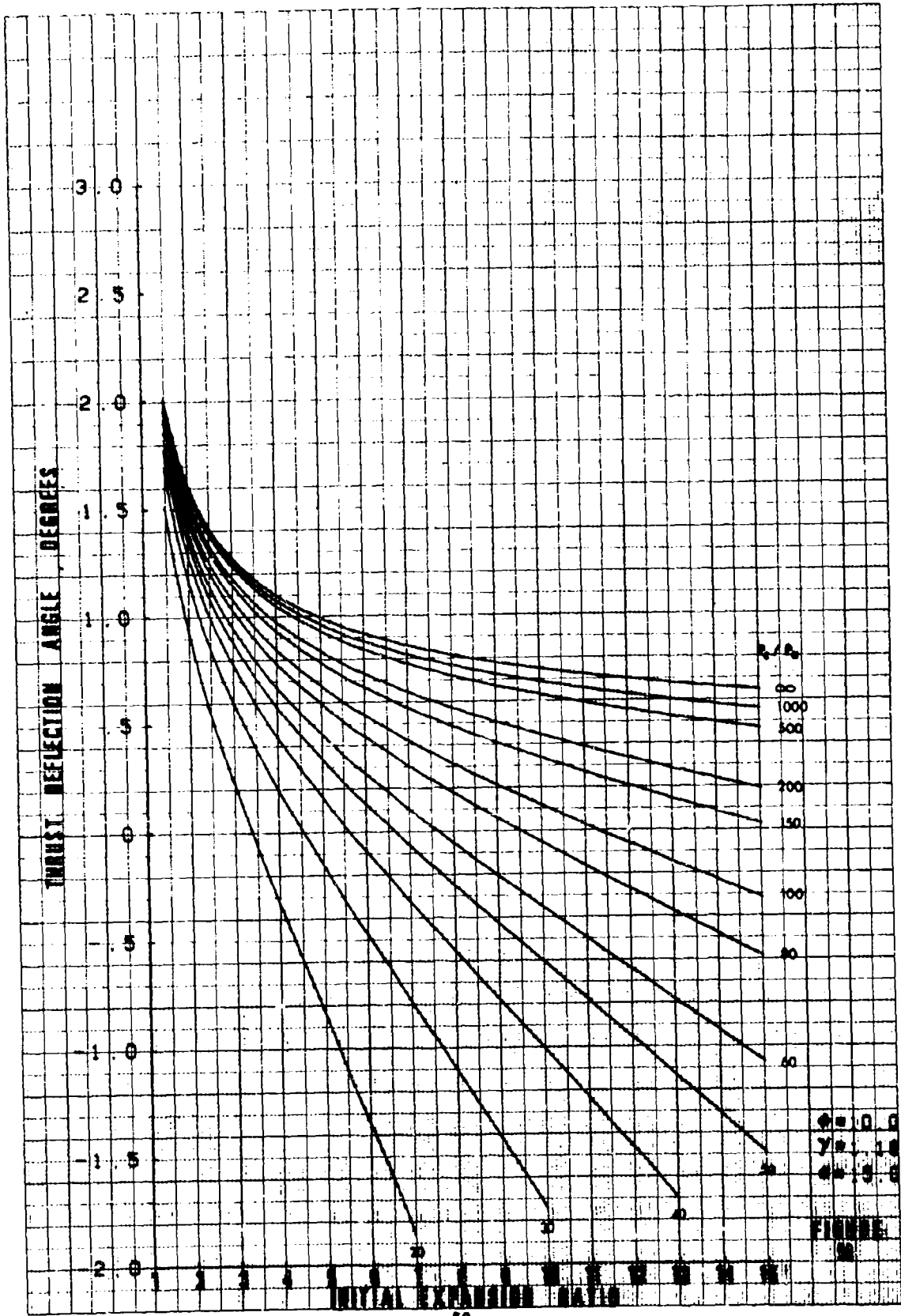


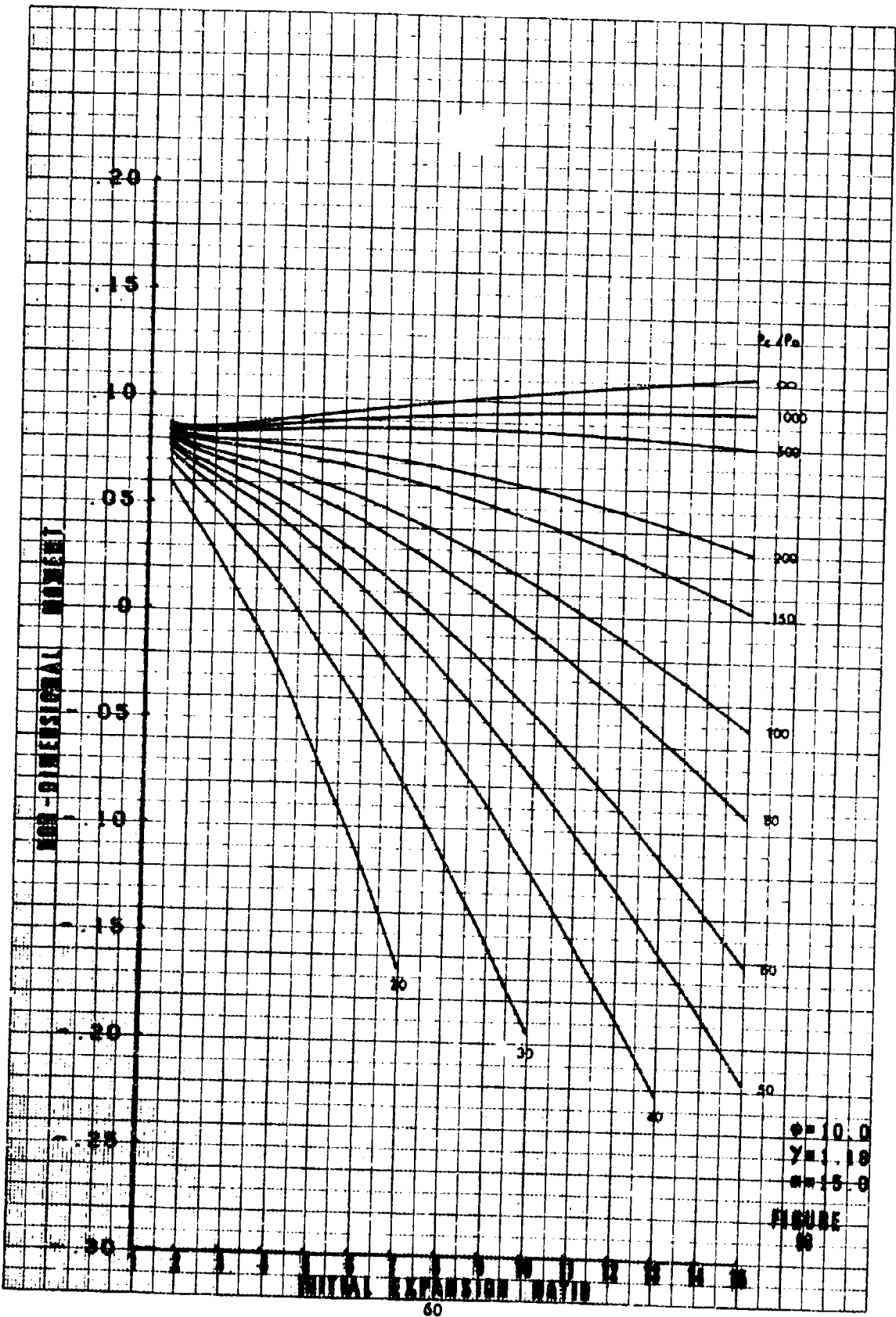
S = 0.0  
 Y = 1.0  
 M = 0.0  
 FIGURE  
 17



$\bullet$  10.0  
 $\blacktriangleright$  15.0  
 $\blacktriangleleft$  15.0

FIGURE 58





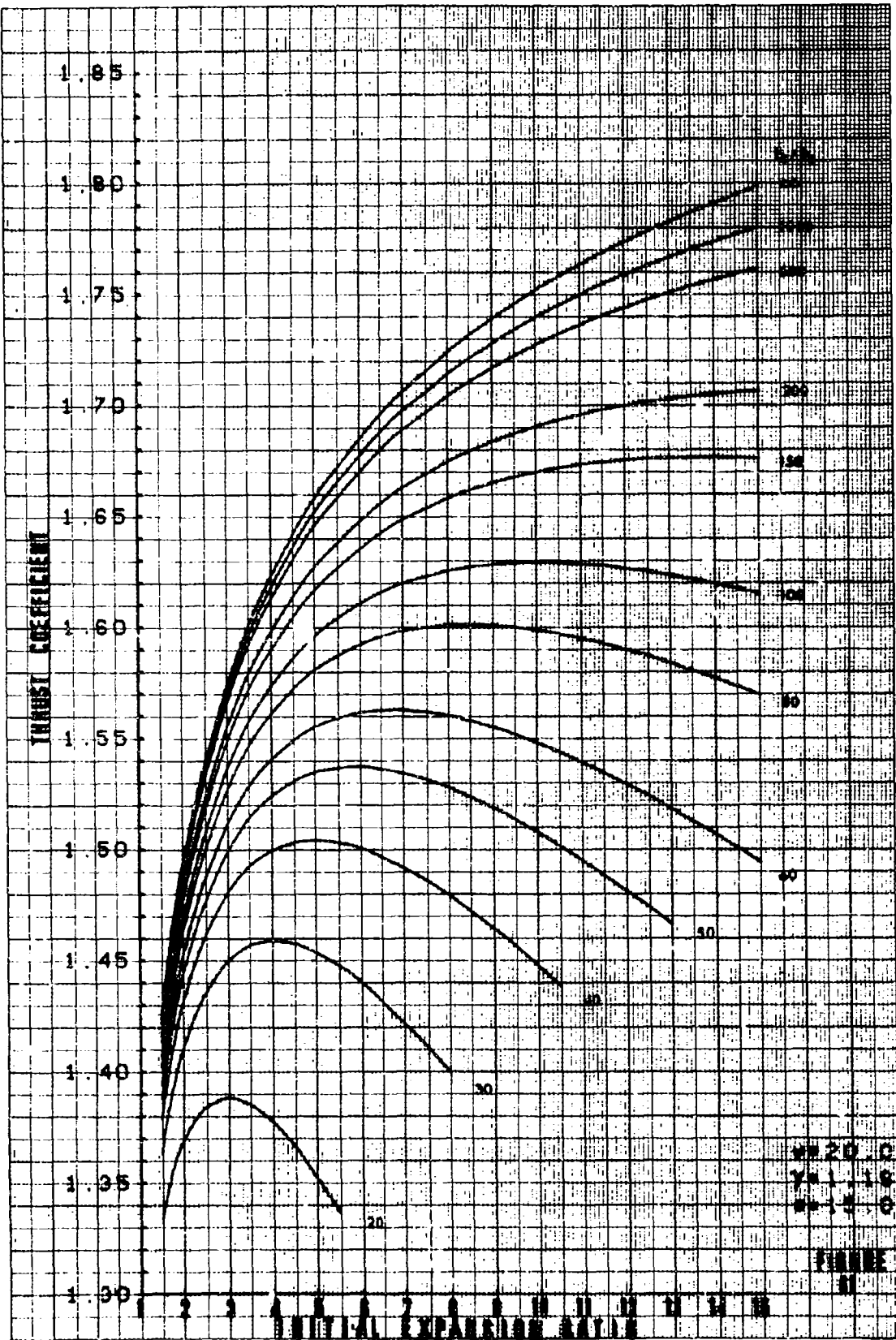


FIGURE 11

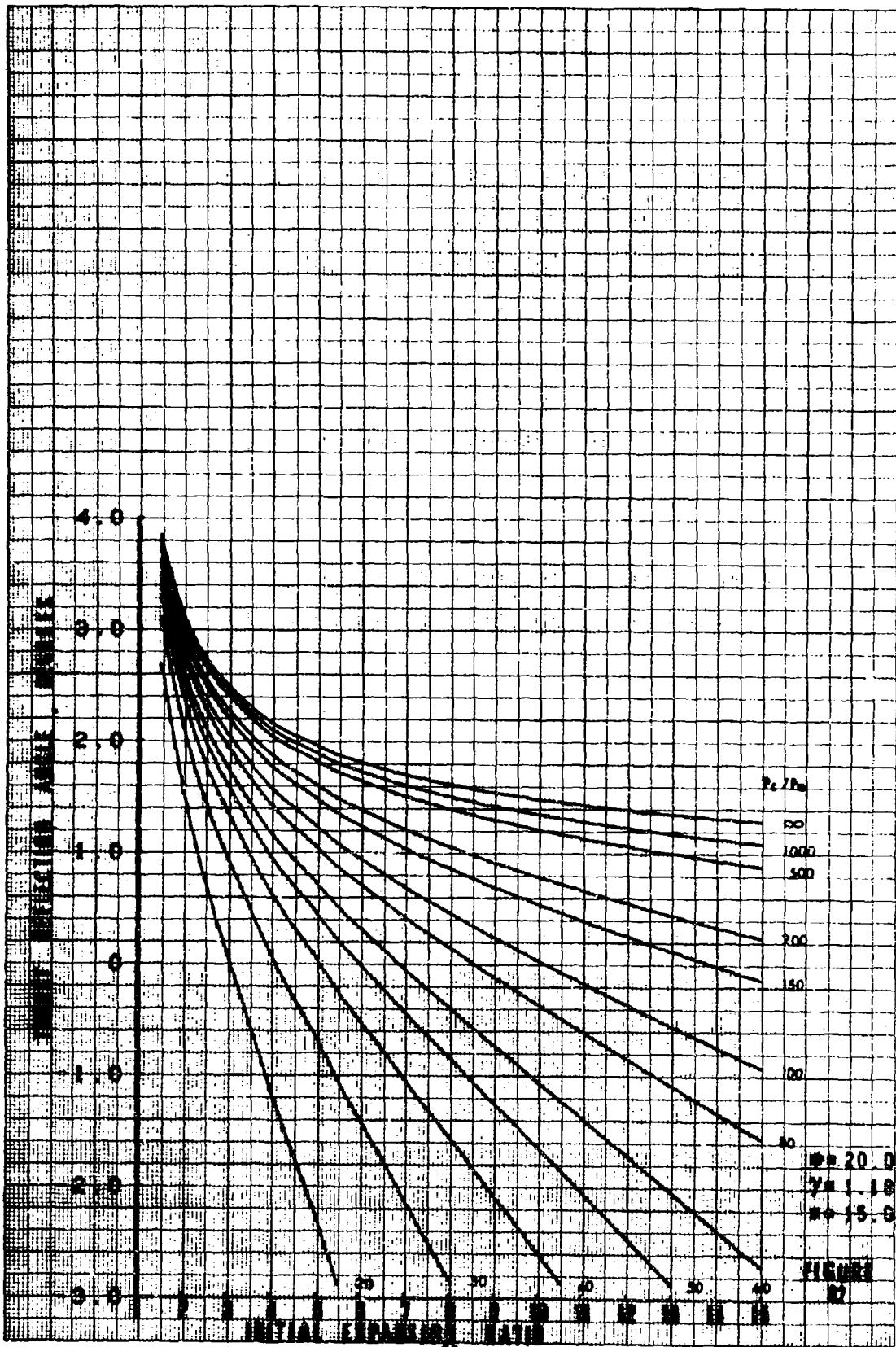
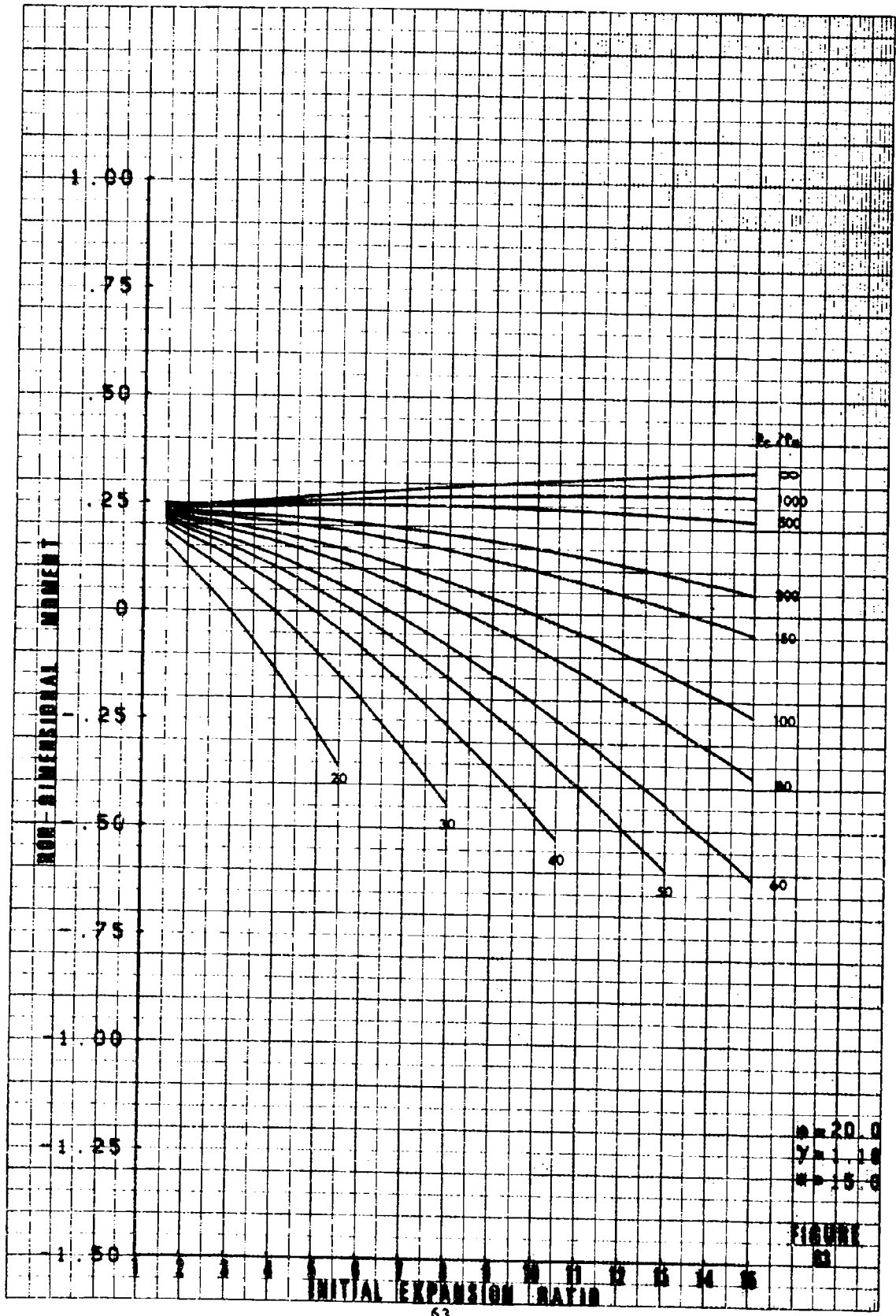
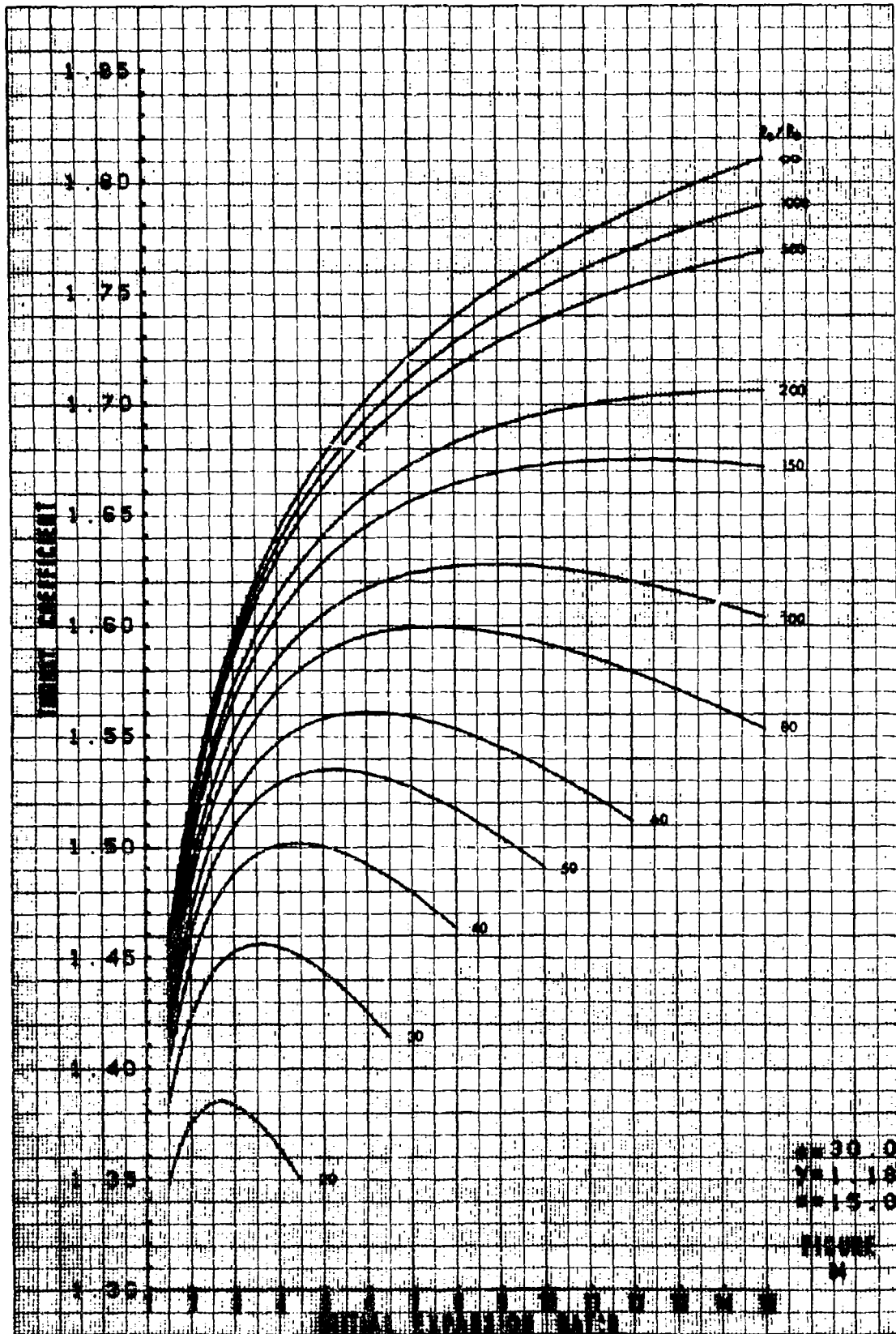
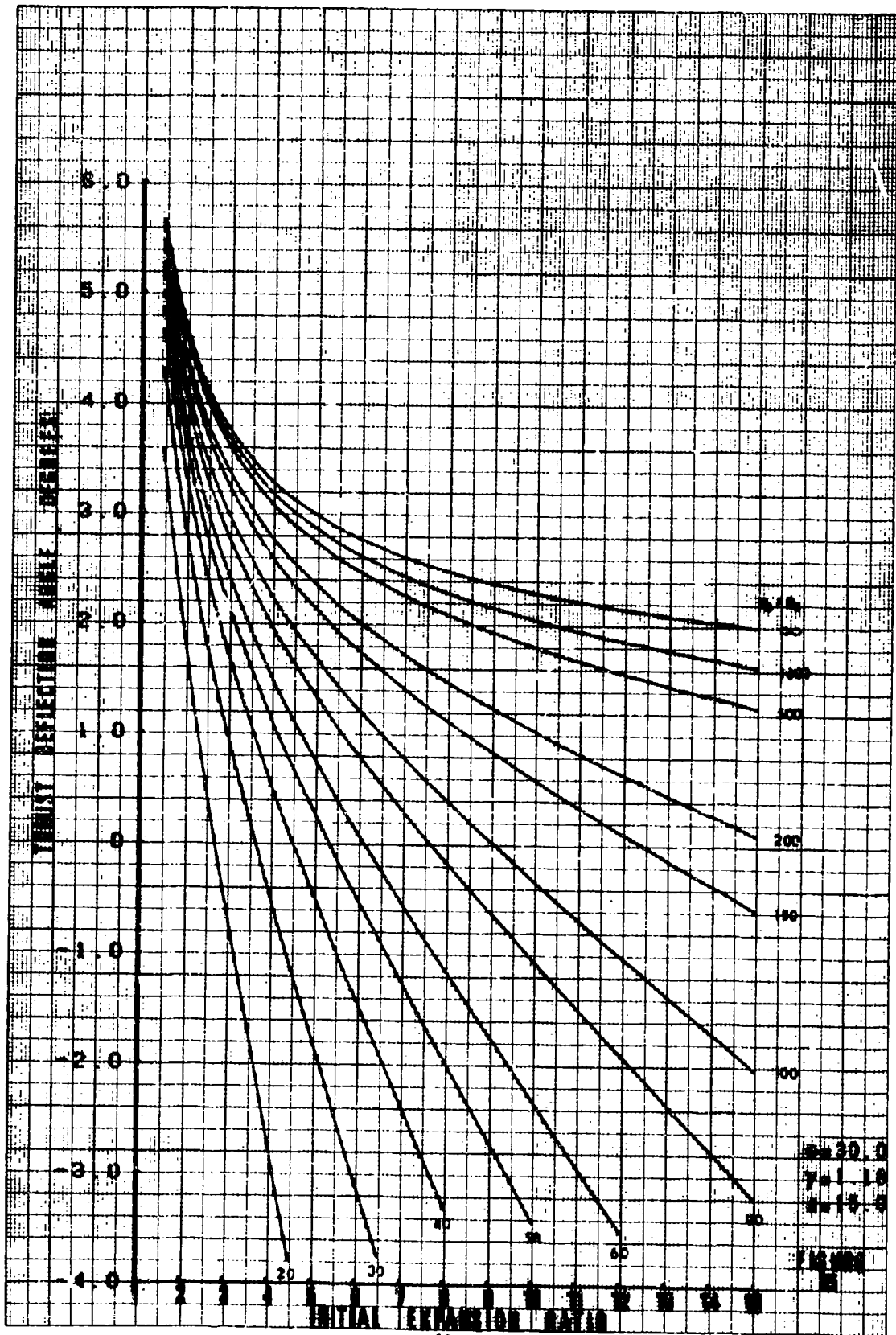


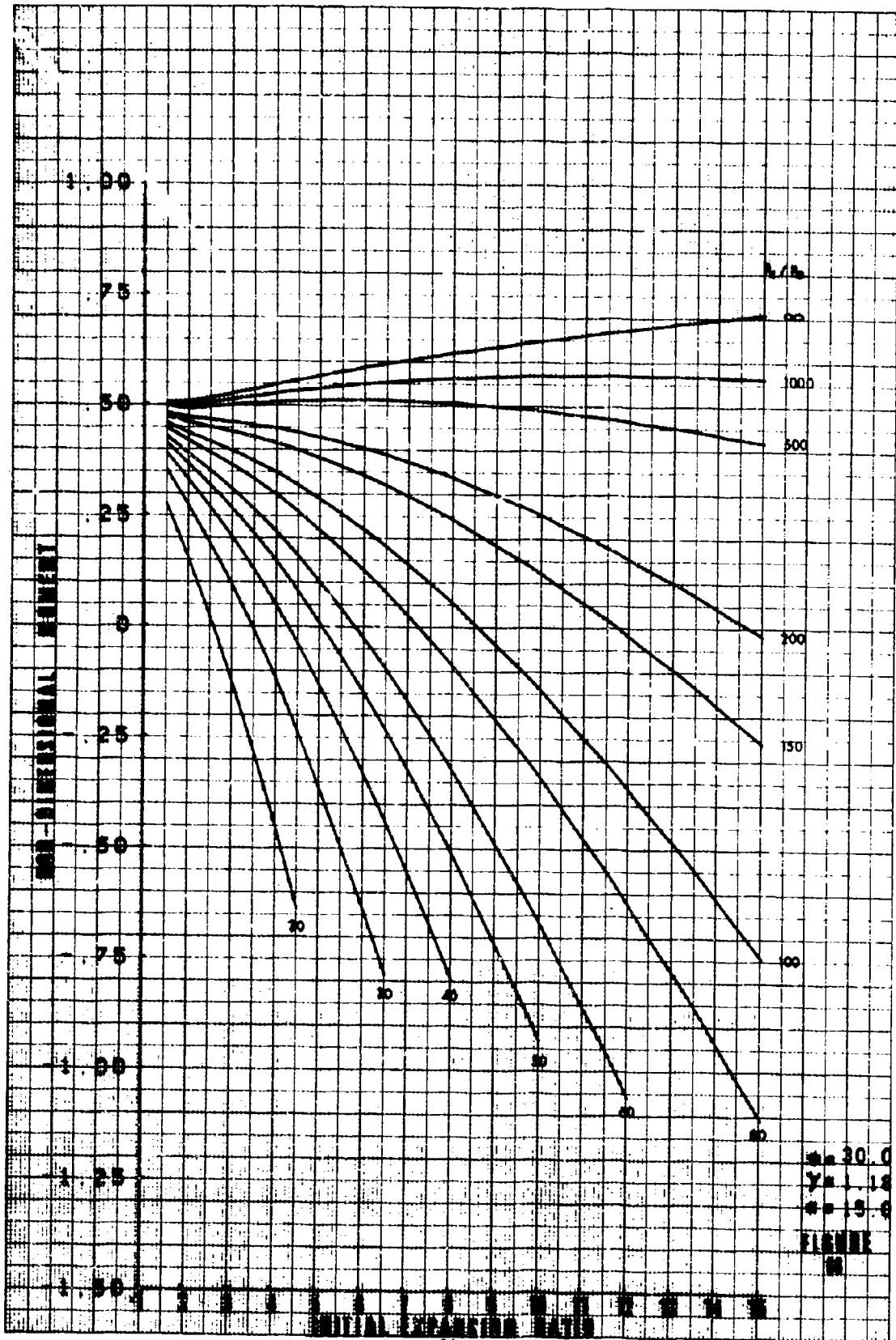
FIGURE 82

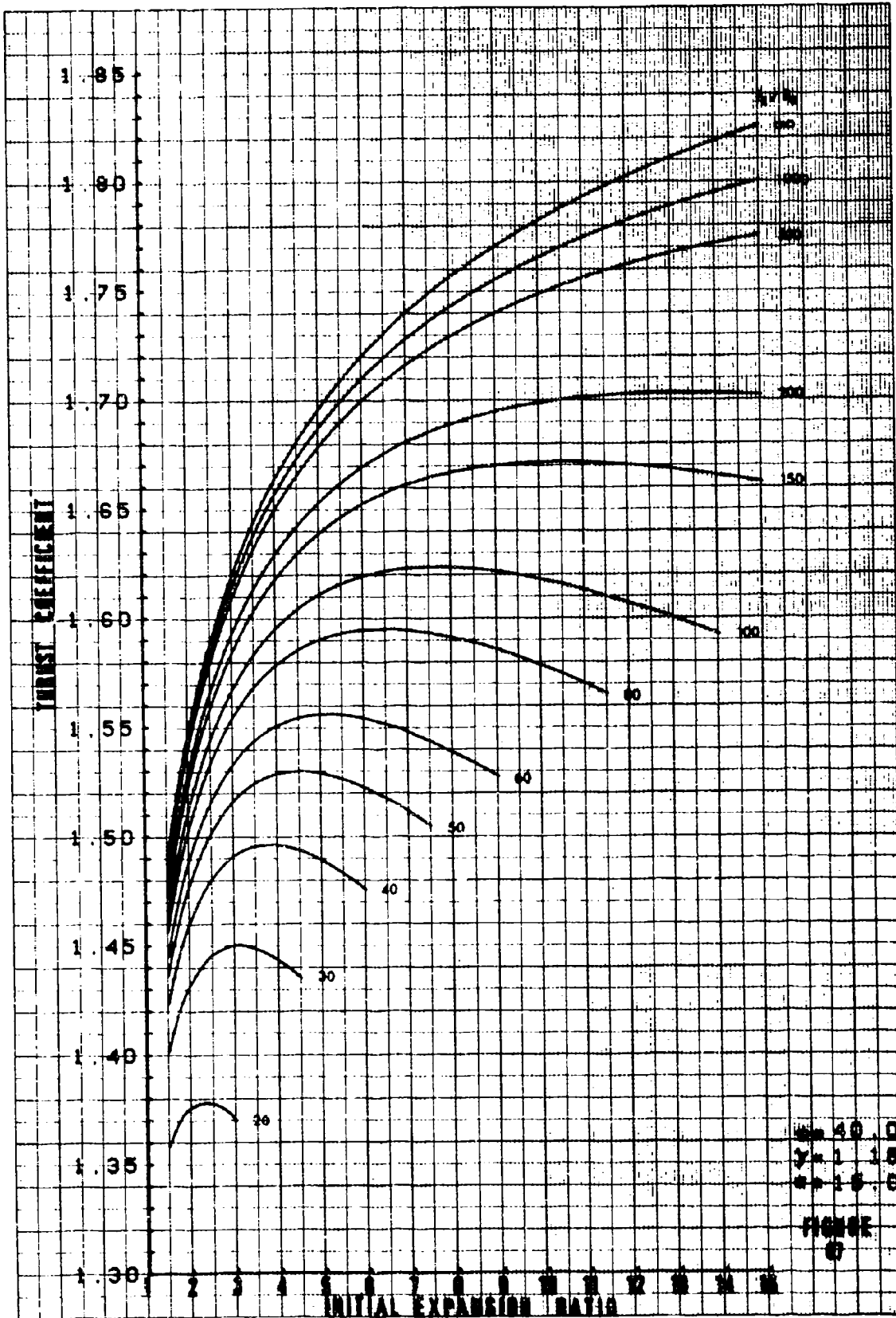




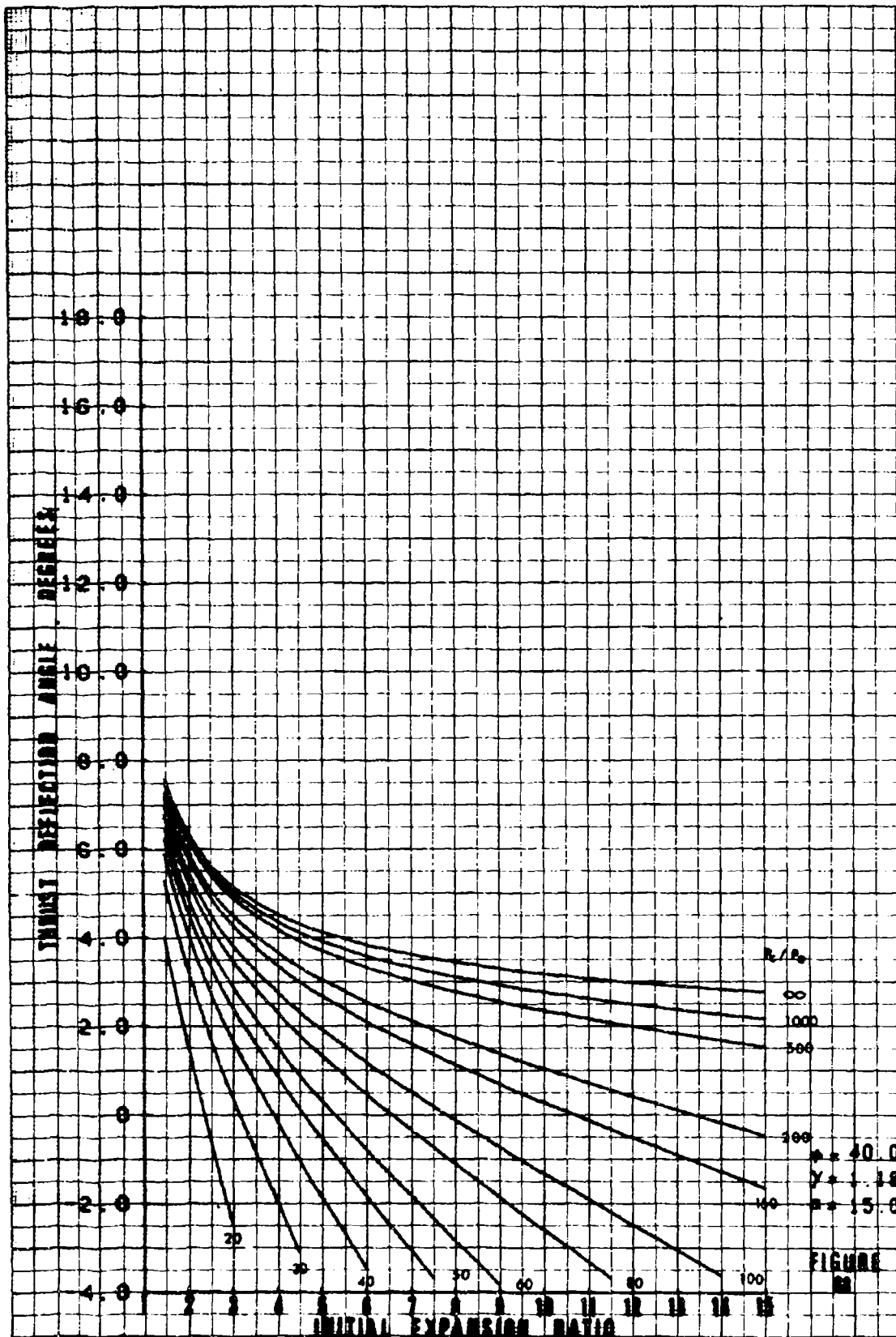


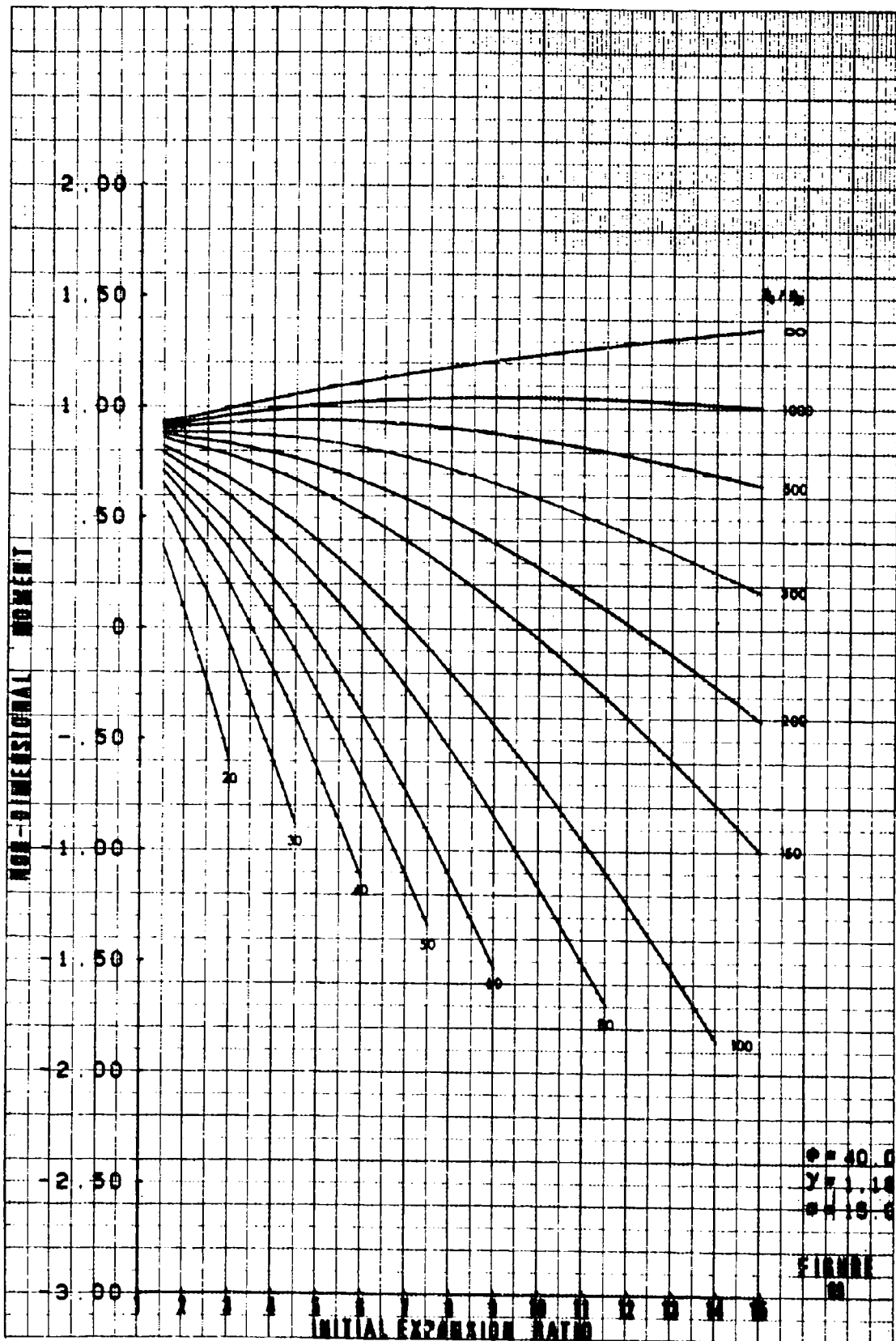


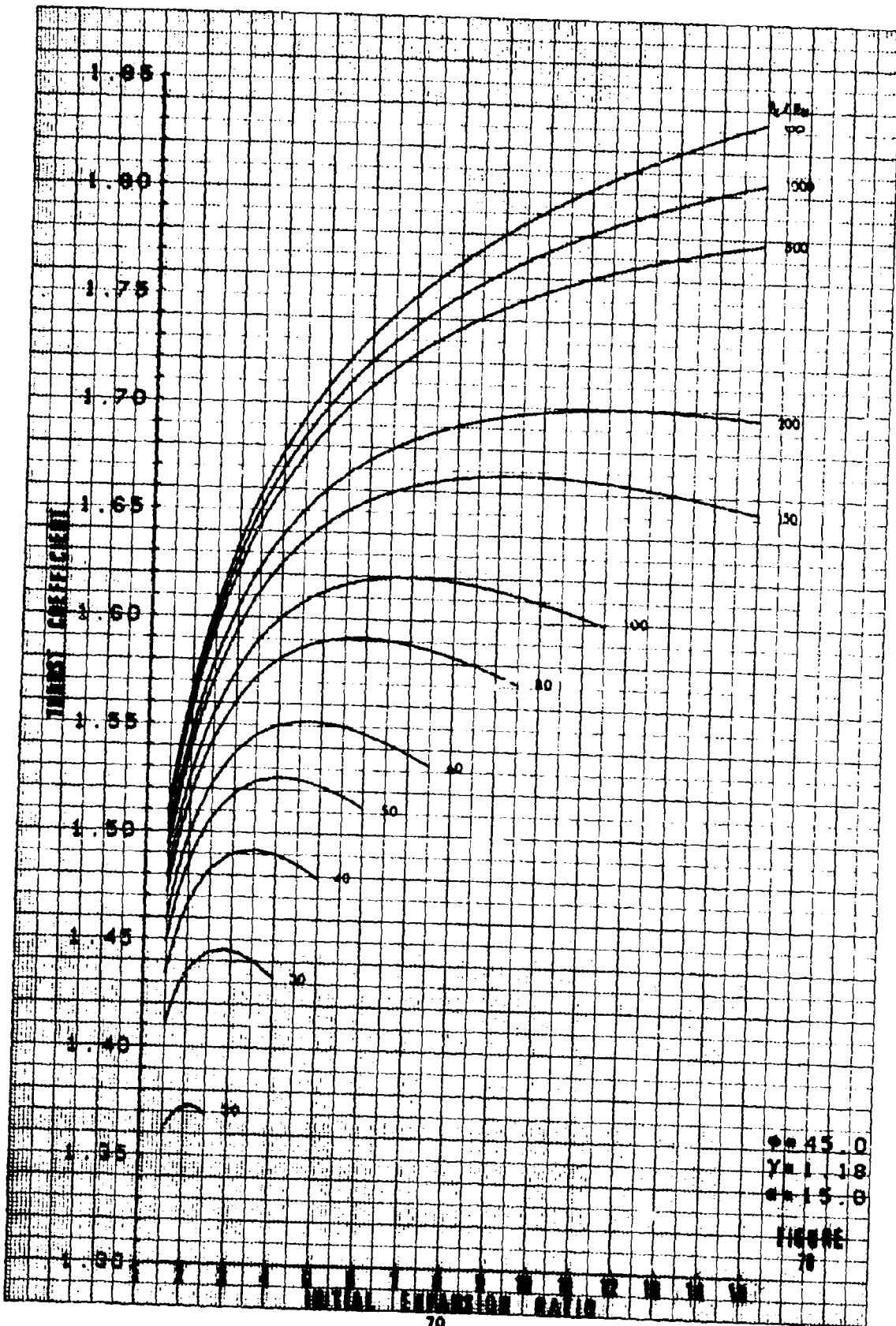




$\gamma = 1.4$   
 $\gamma = 1.67$   
 $\gamma = 1.3$   
 FIGURE 6







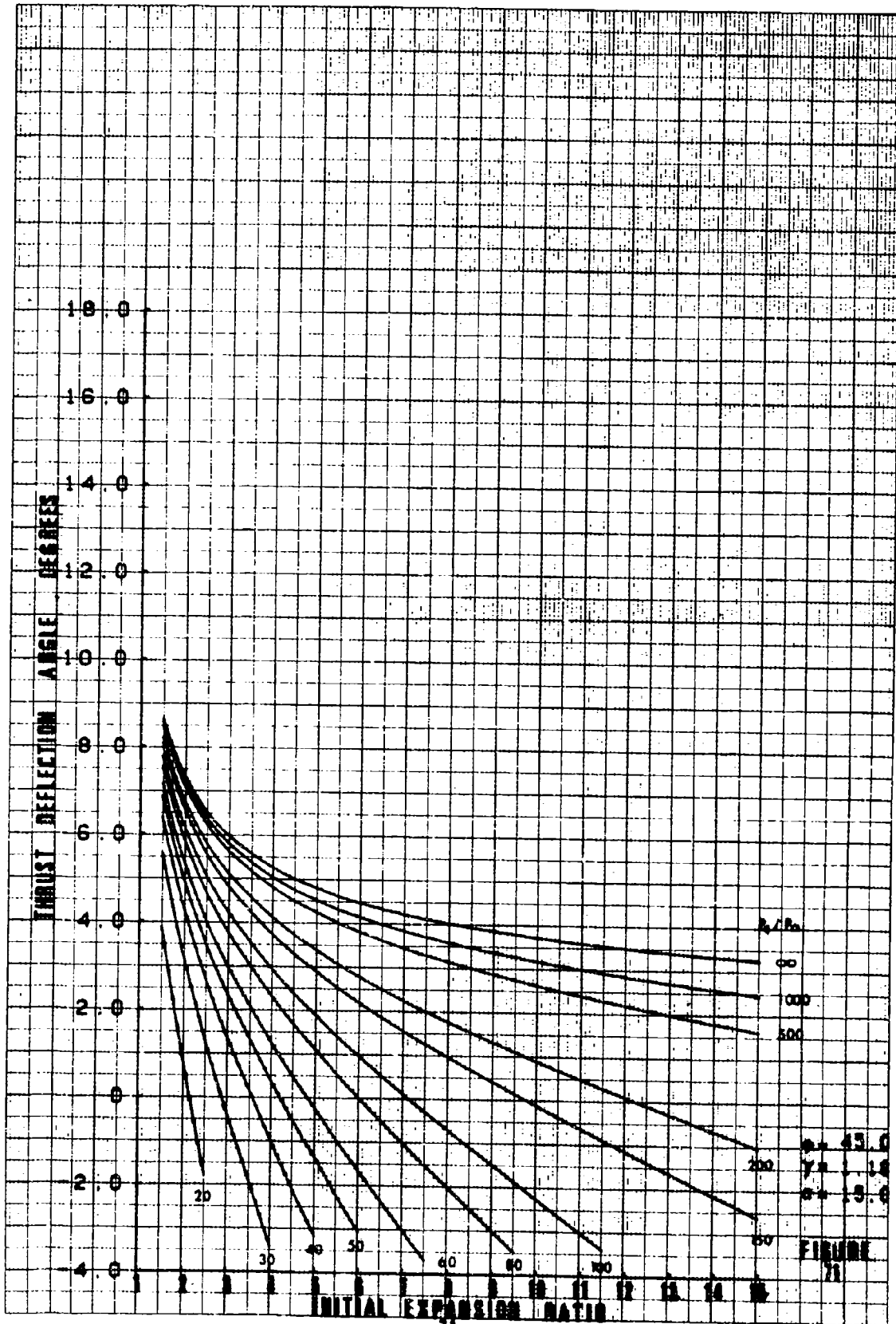
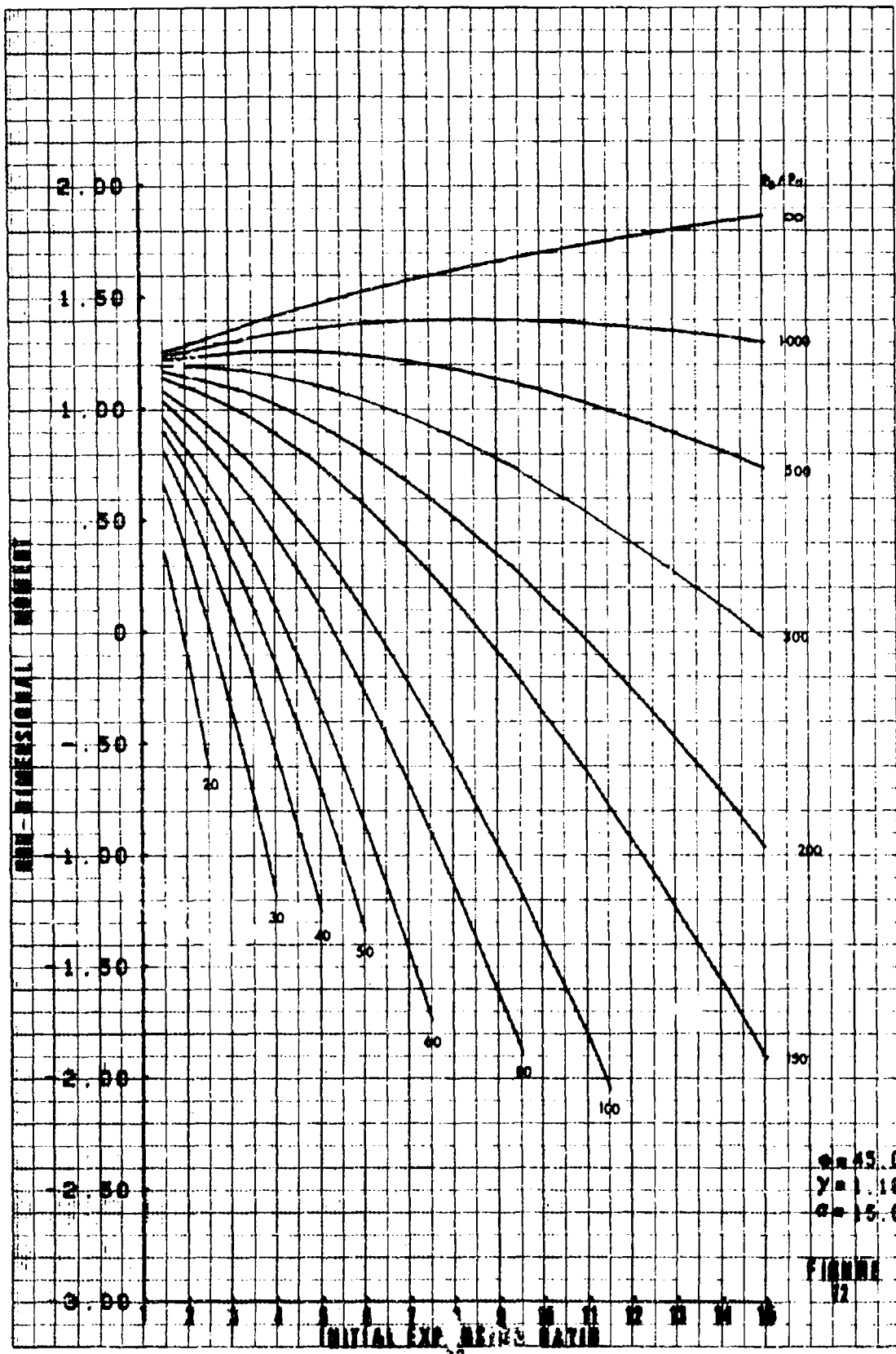
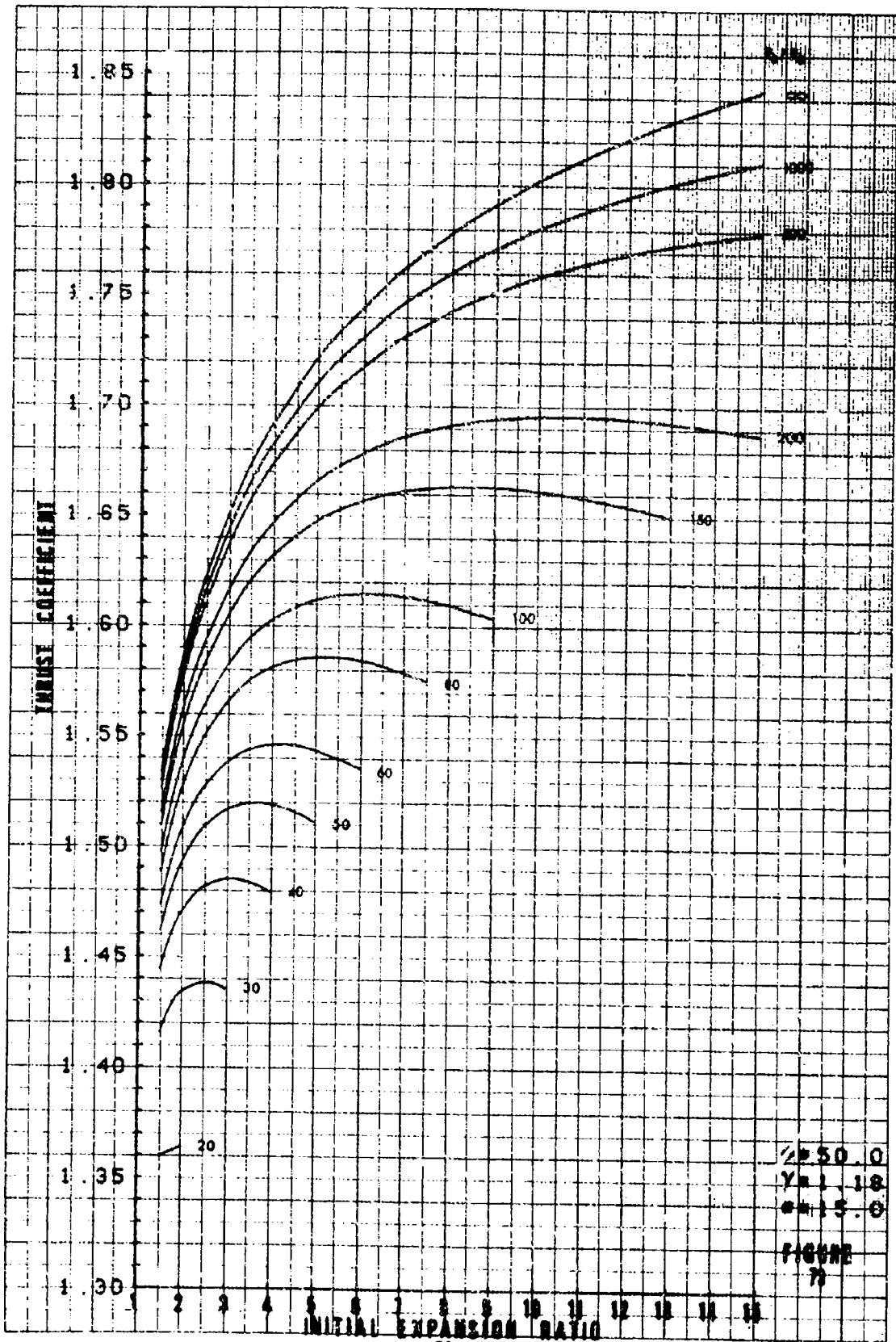


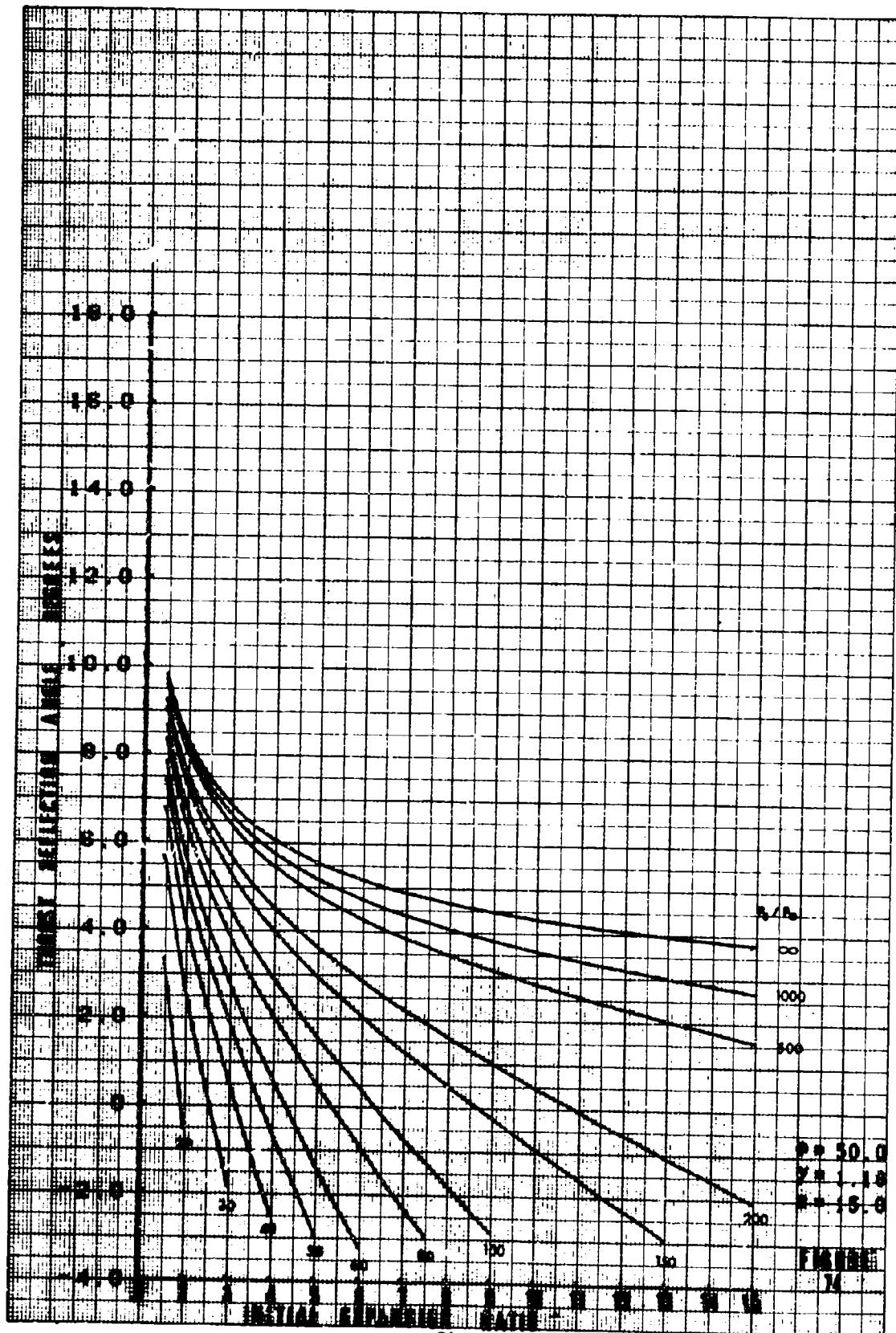
FIGURE 71

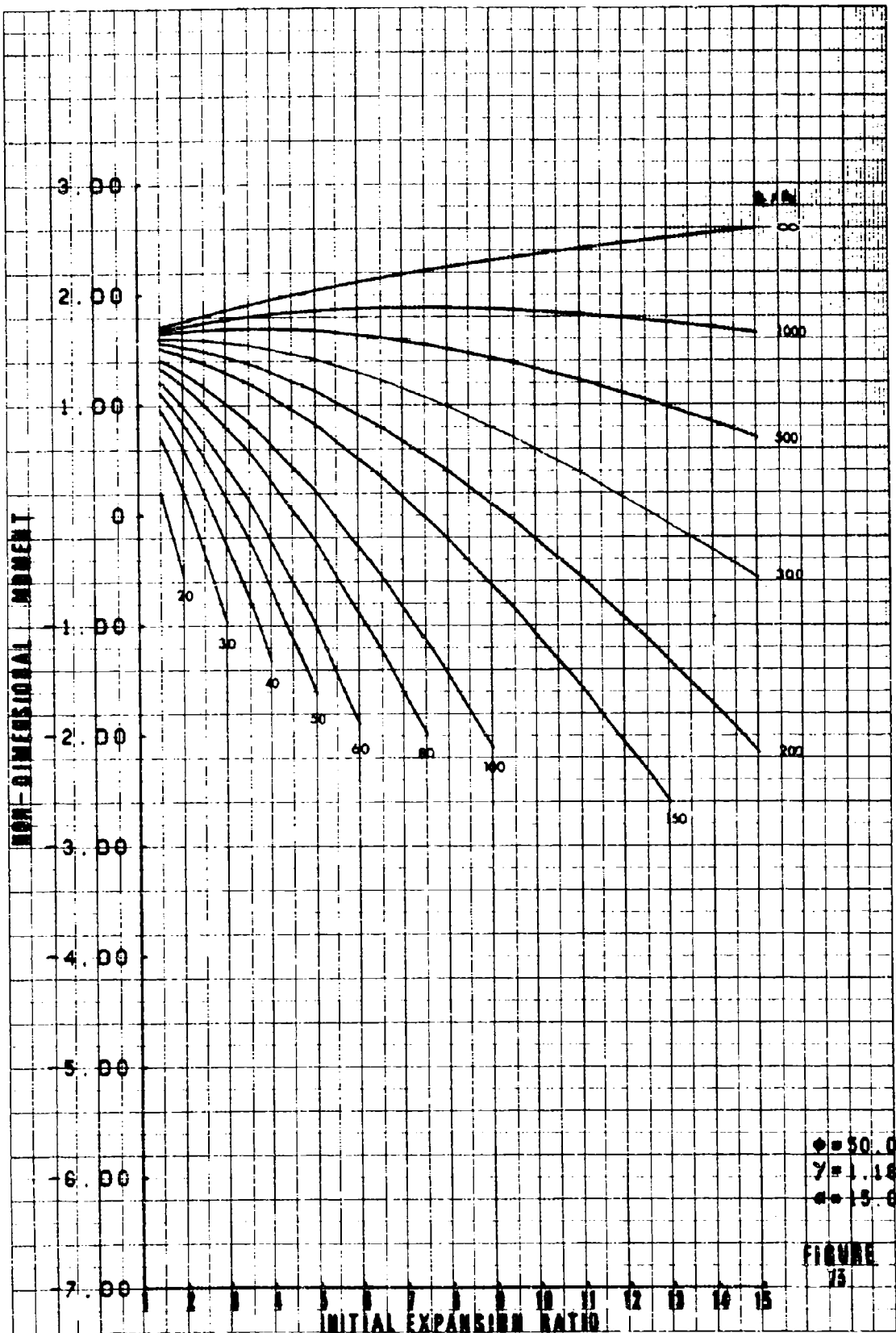


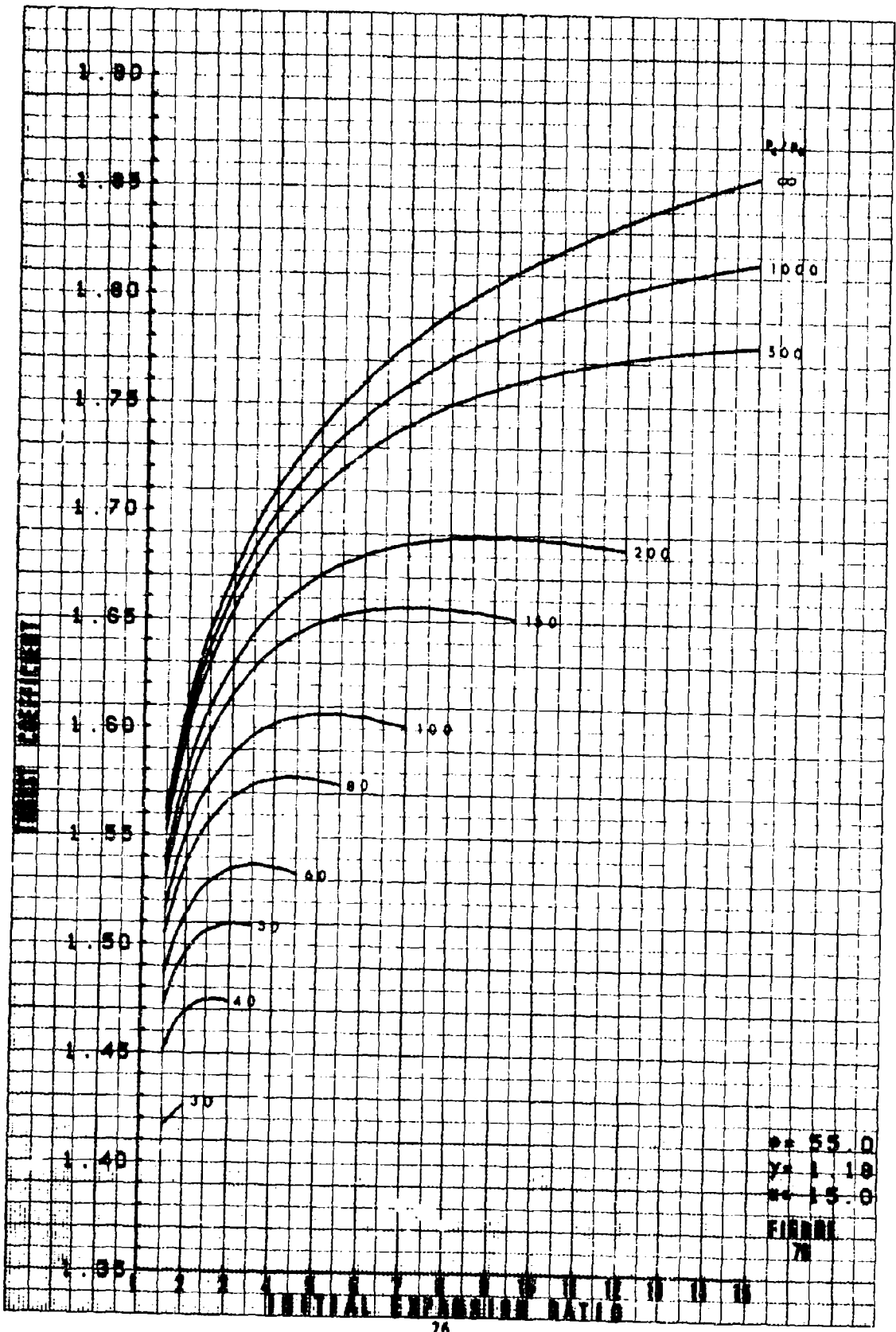




$\gamma = 1.4$   
 $M = 50.0$   
 $Y = 1.18$   
 $z = 15.0$   
**FIGURE 73**







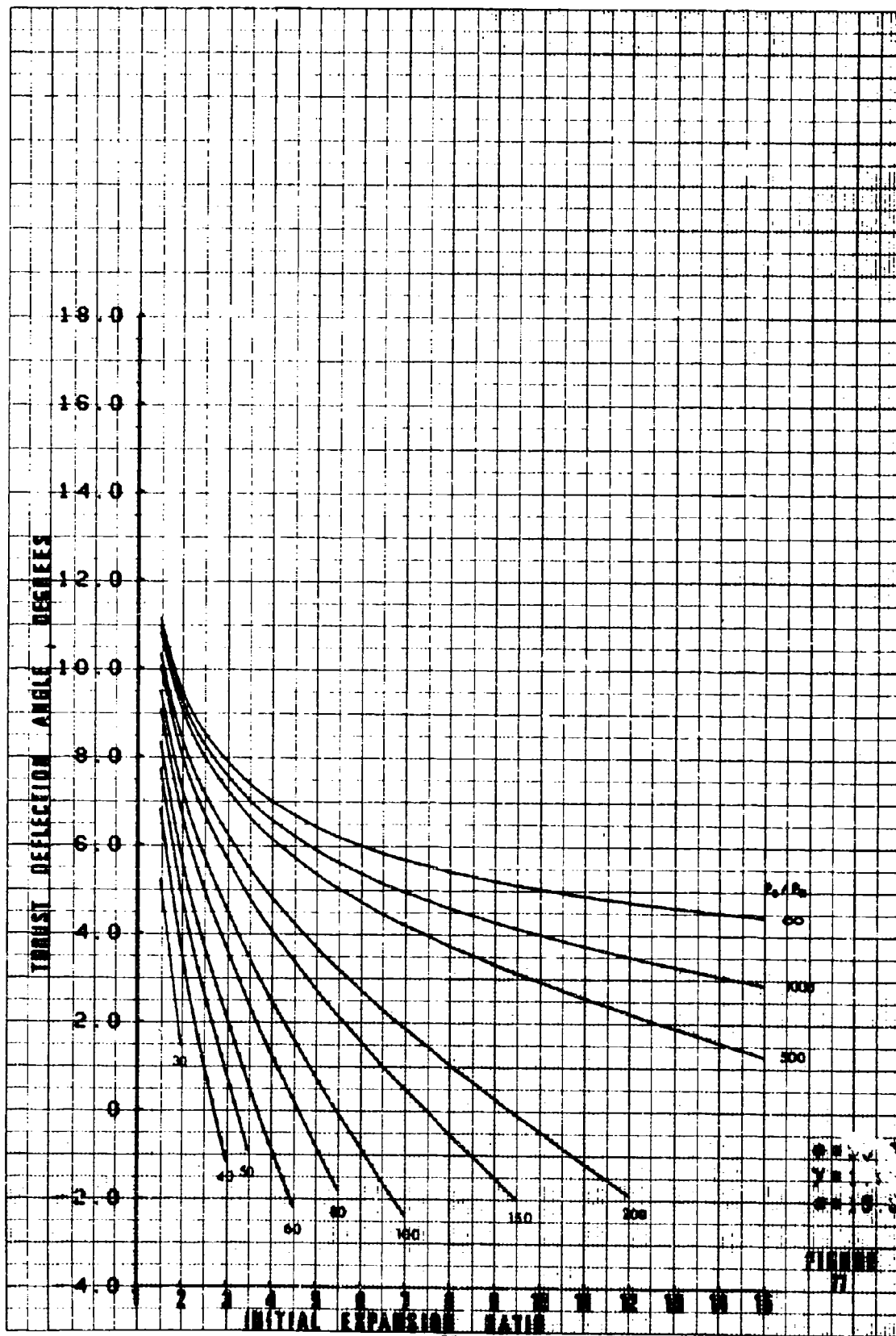
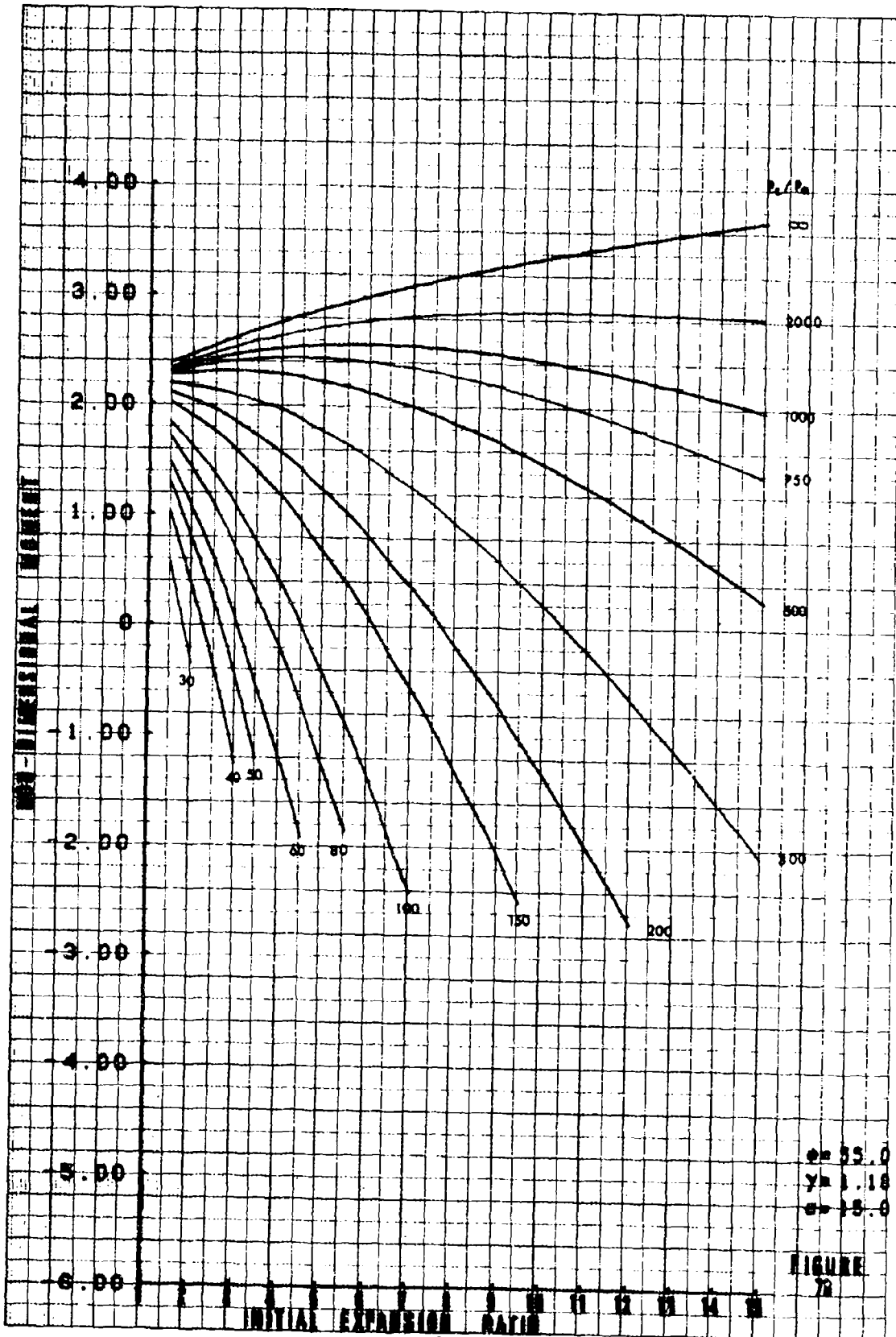
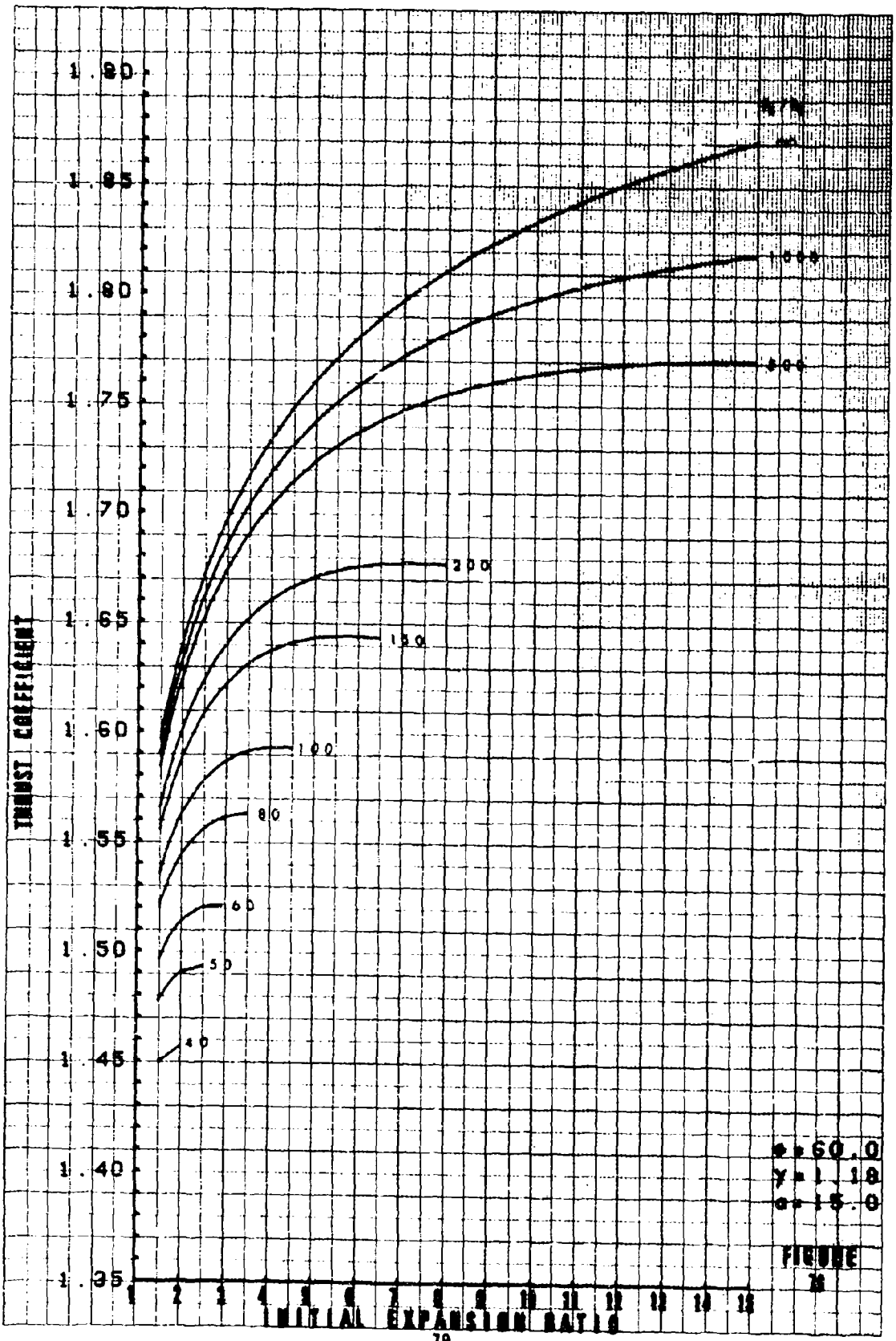


FIGURE 77







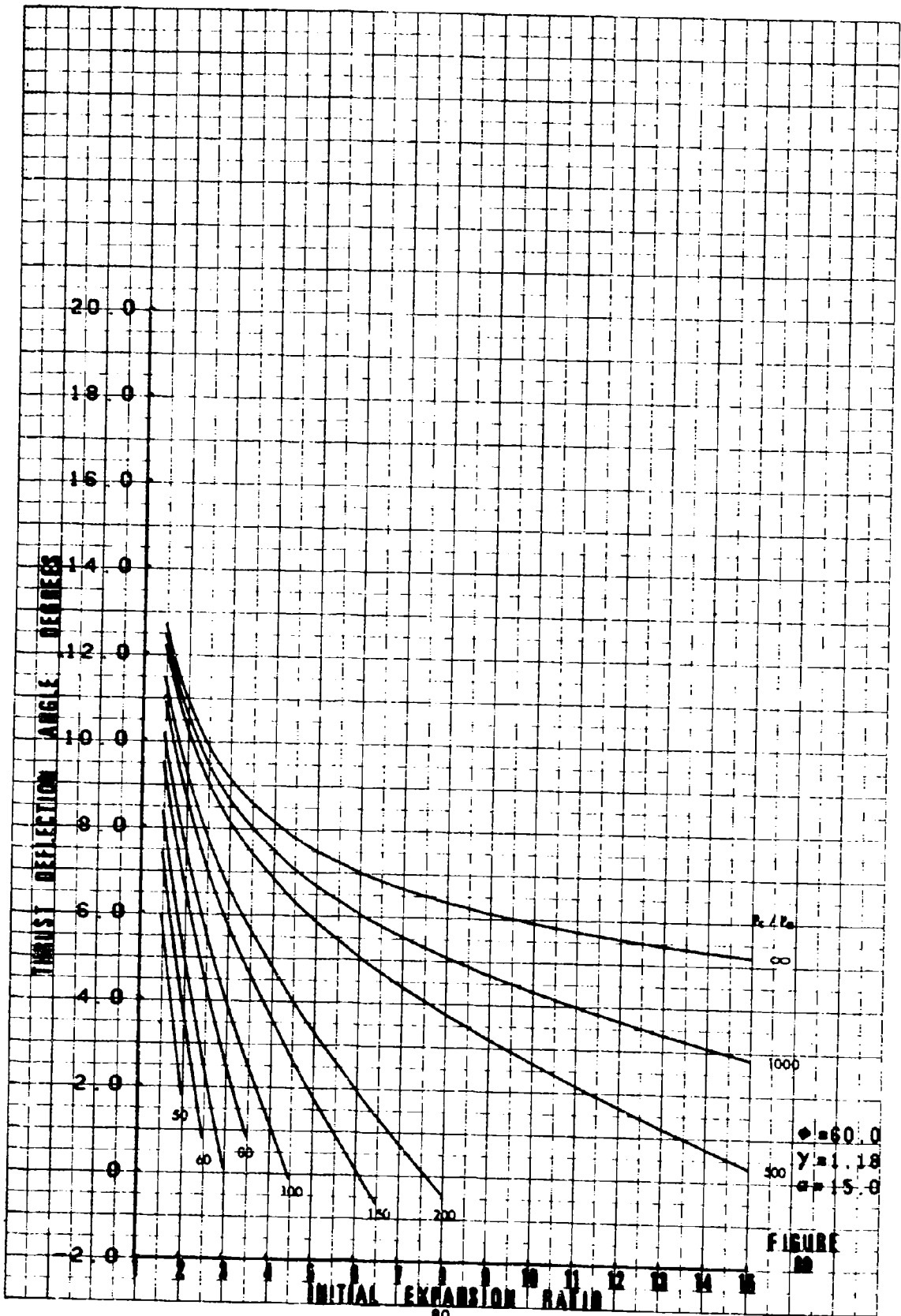
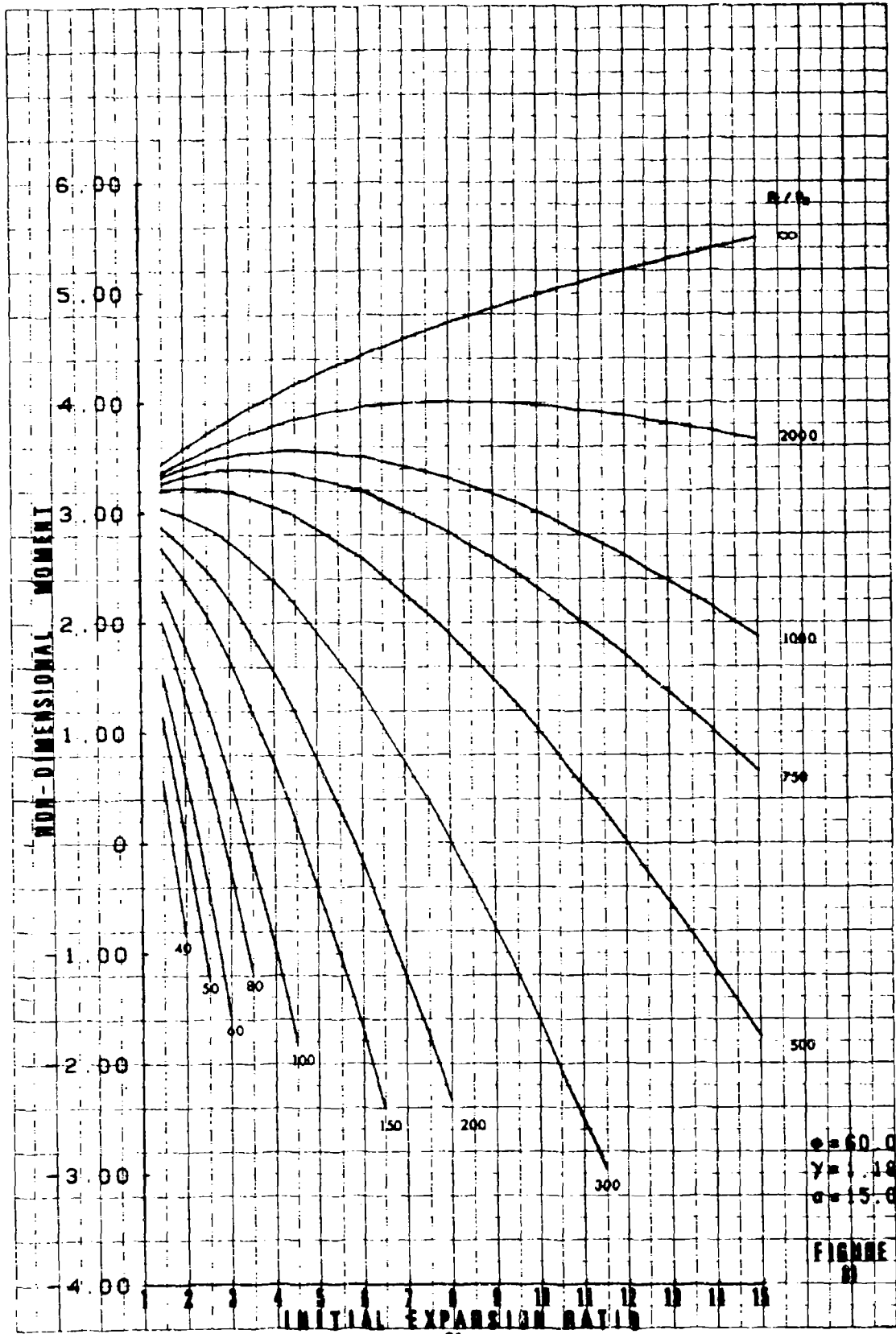
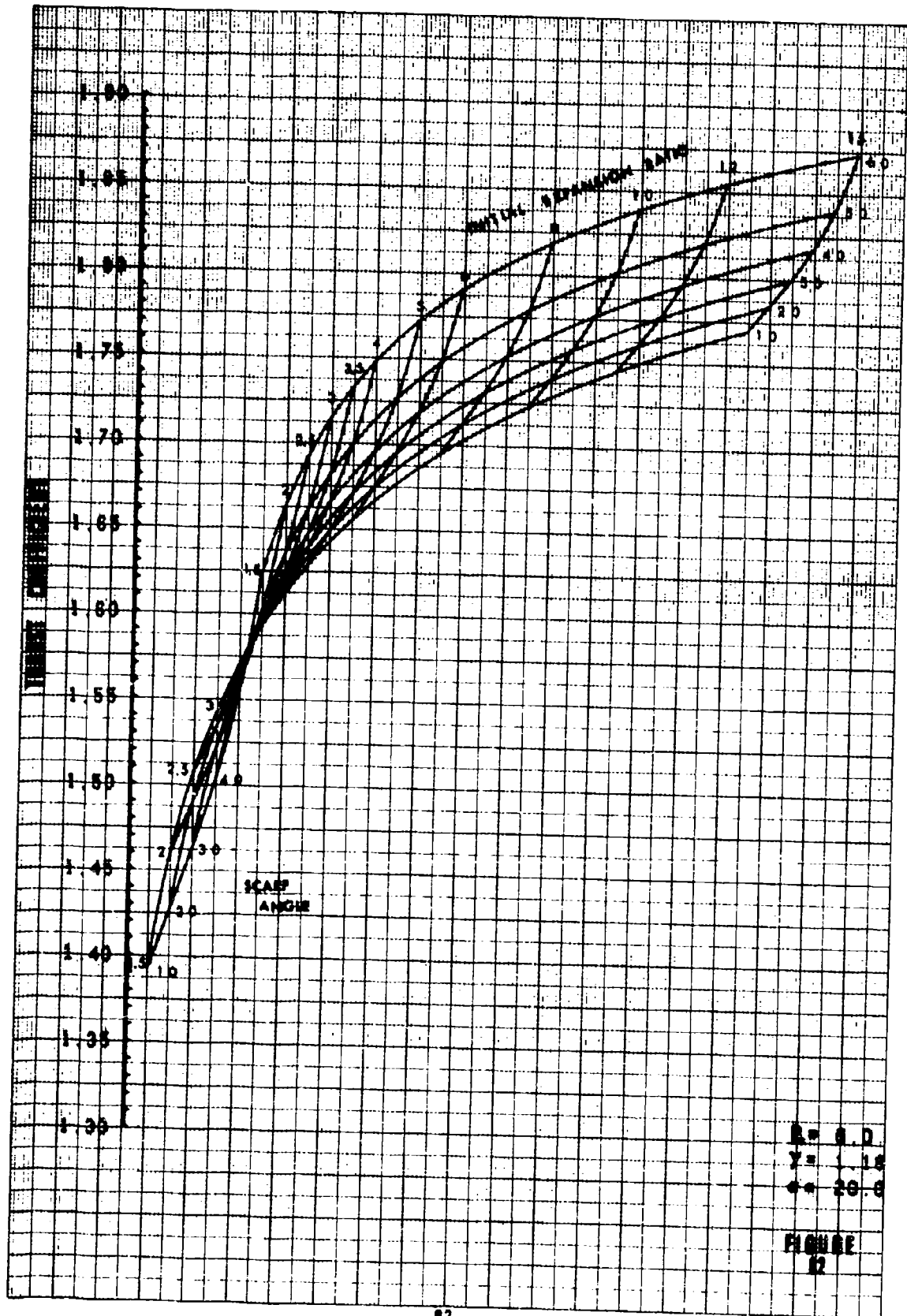


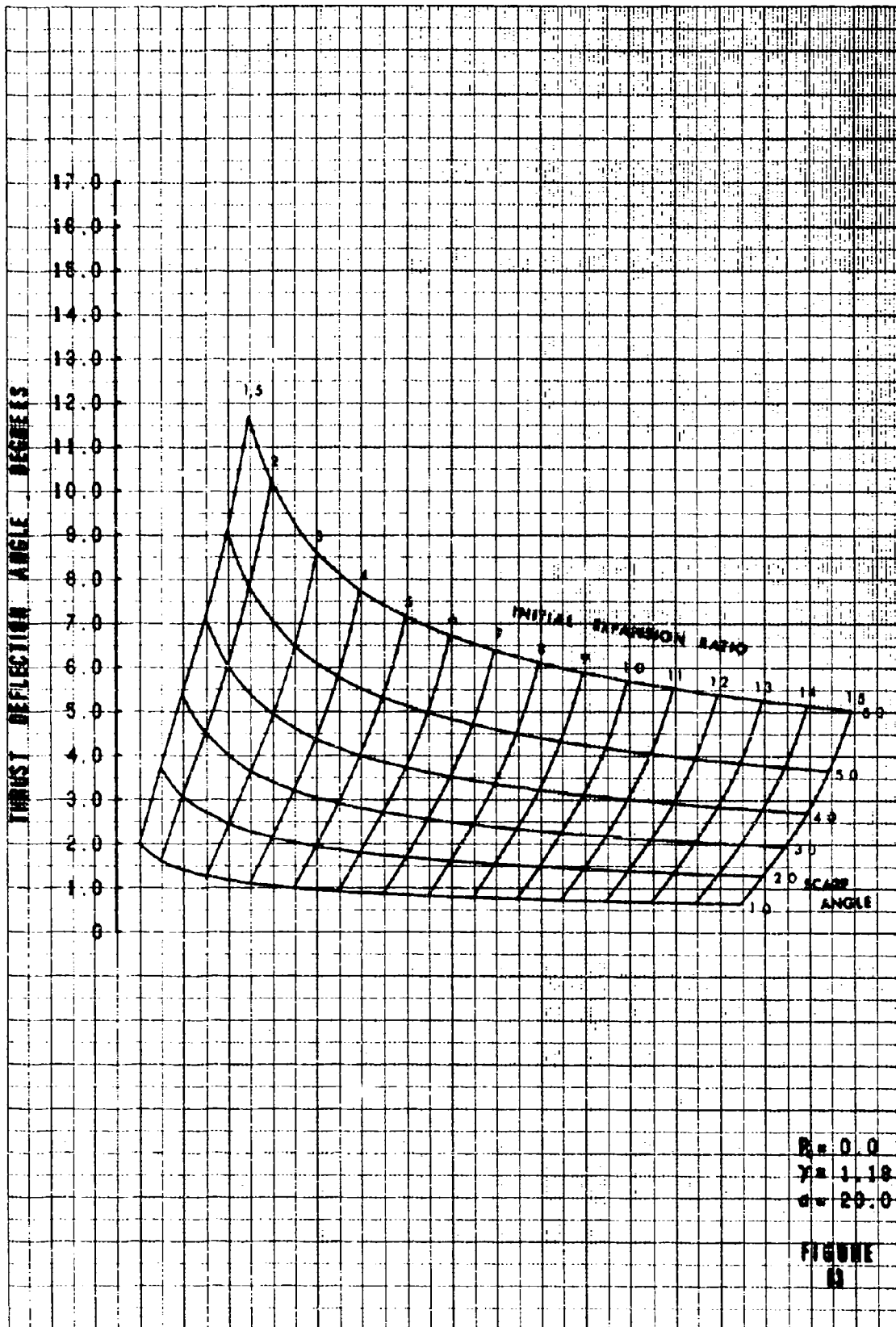
FIGURE 80

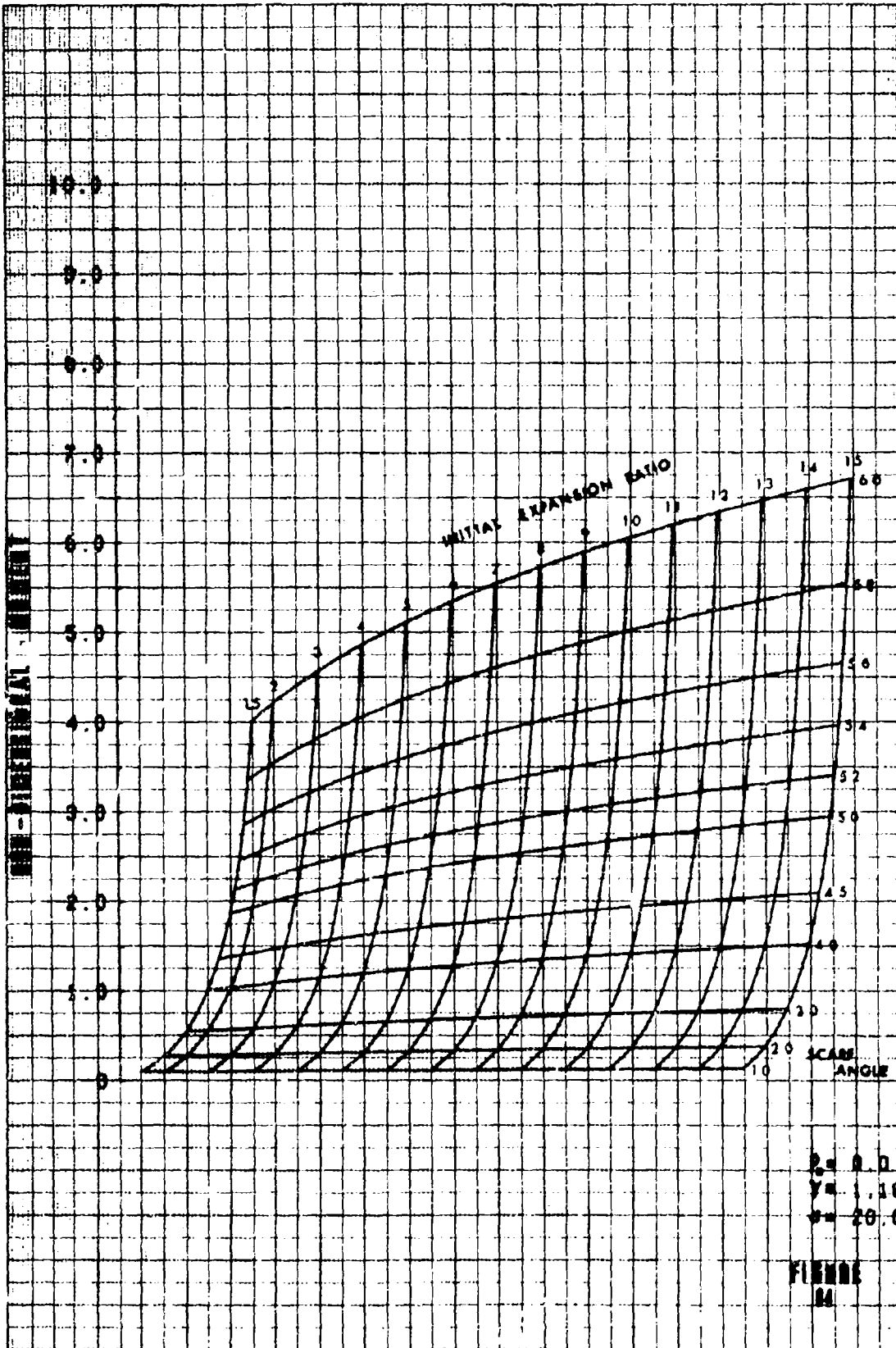


$\phi = 60.0$   
 $\gamma = 1.18$   
 $\alpha = 15.0$

FIGURE 8







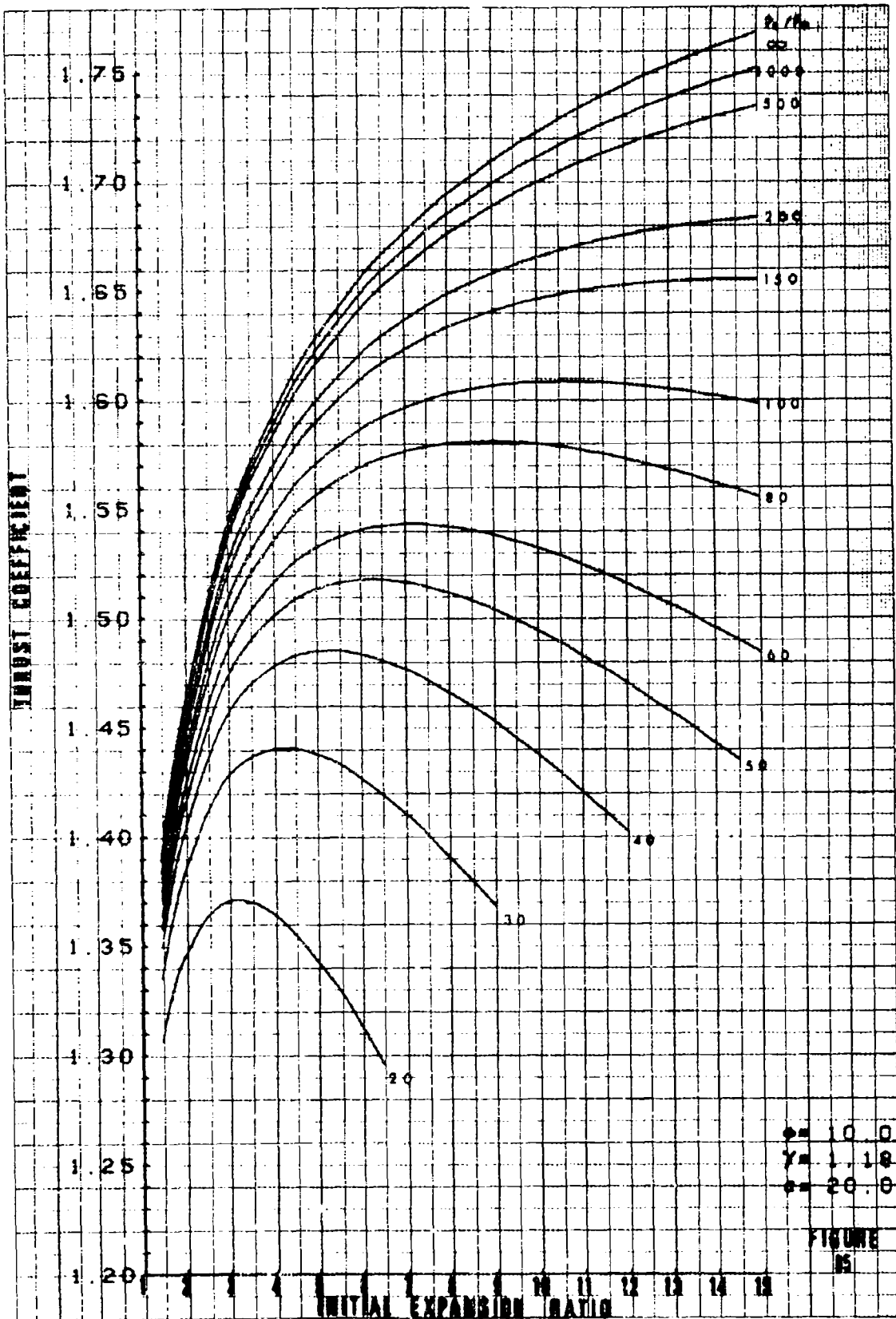
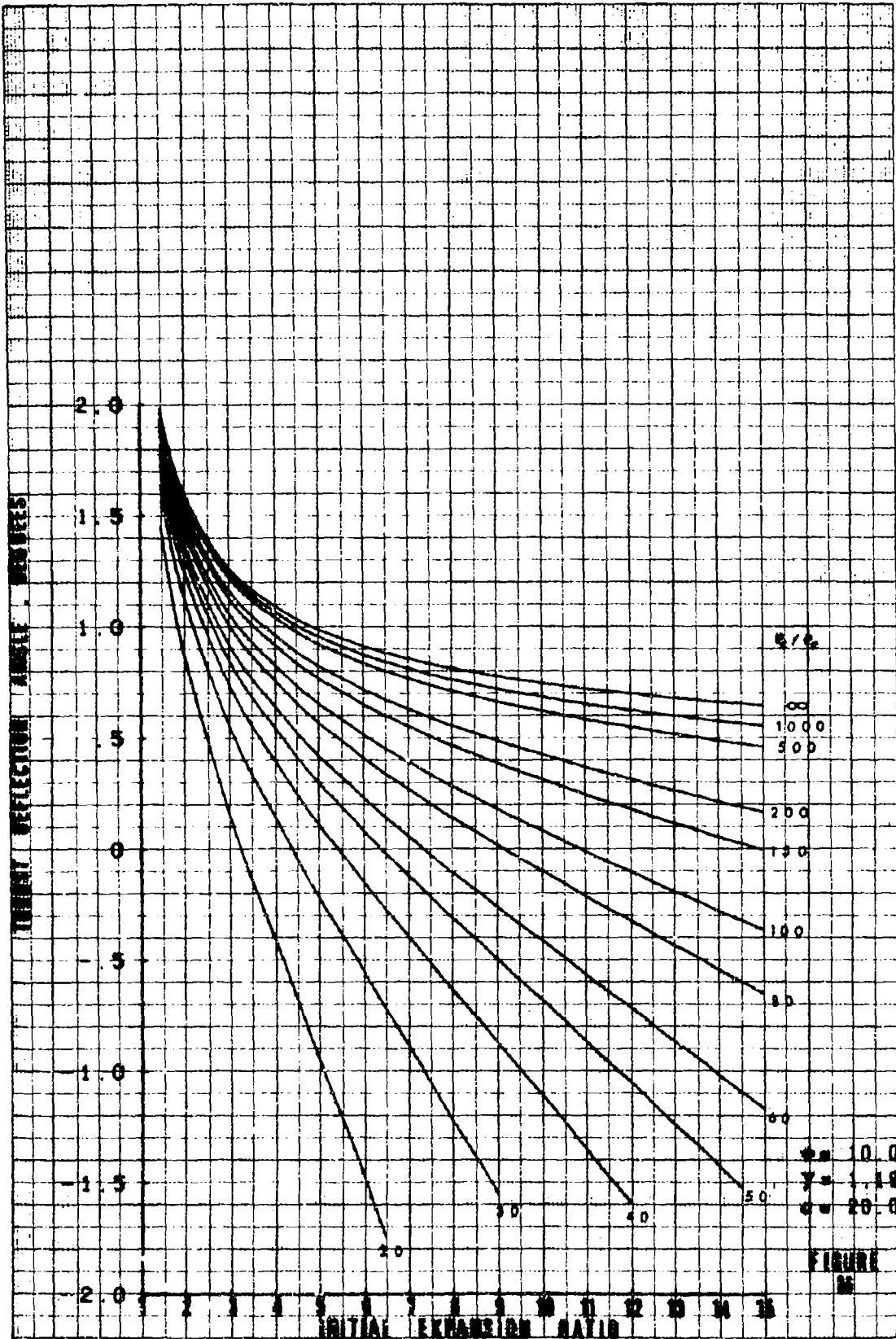
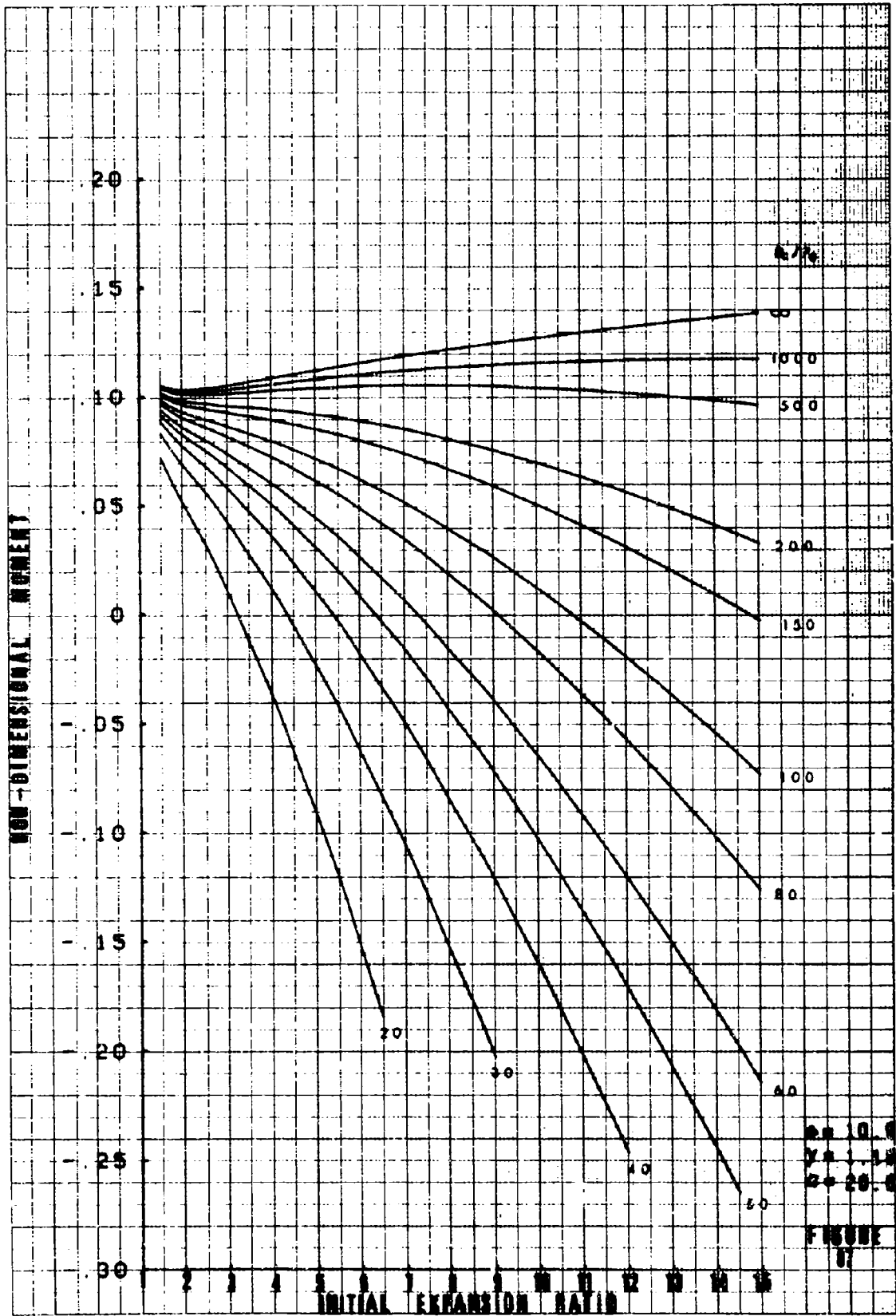
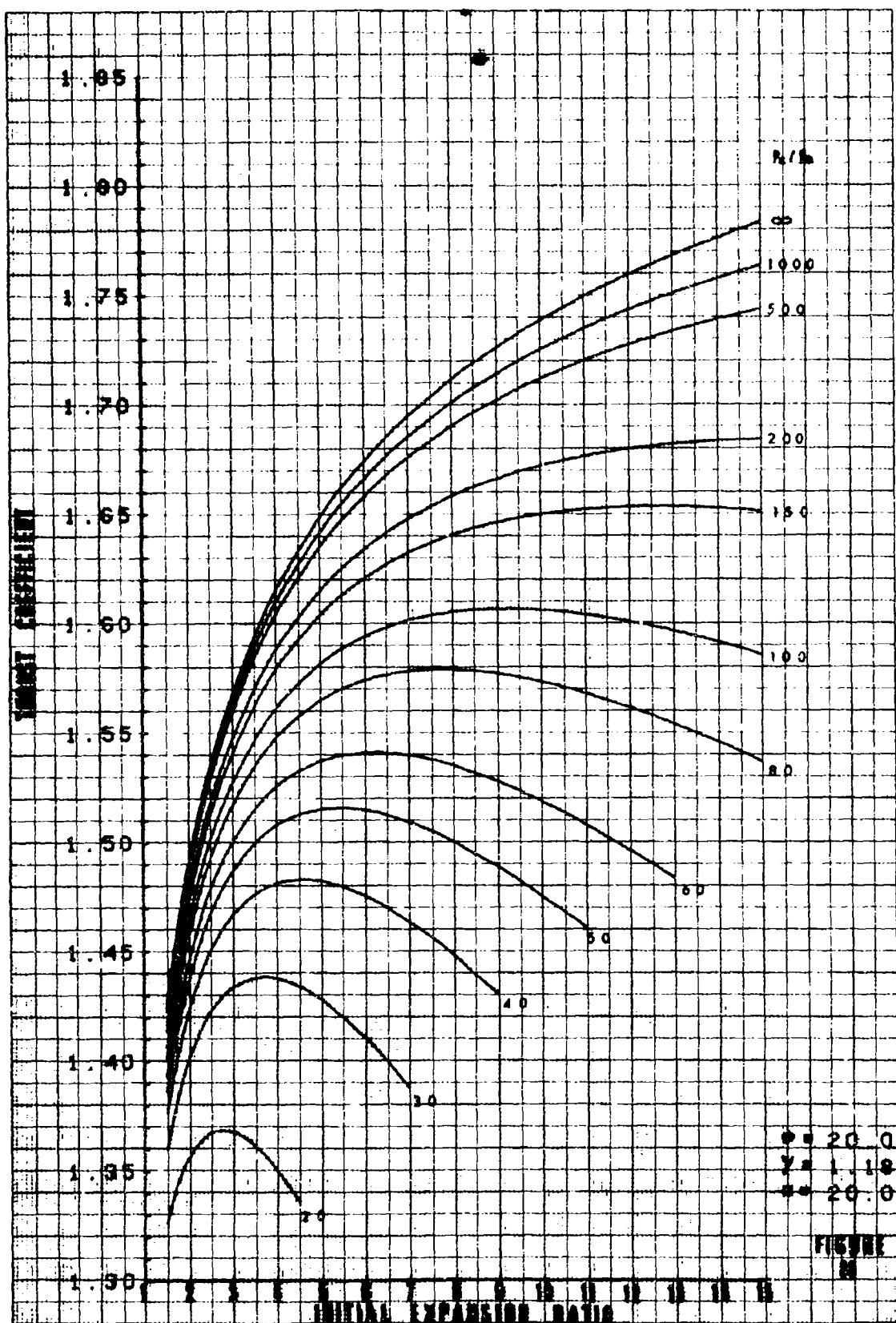


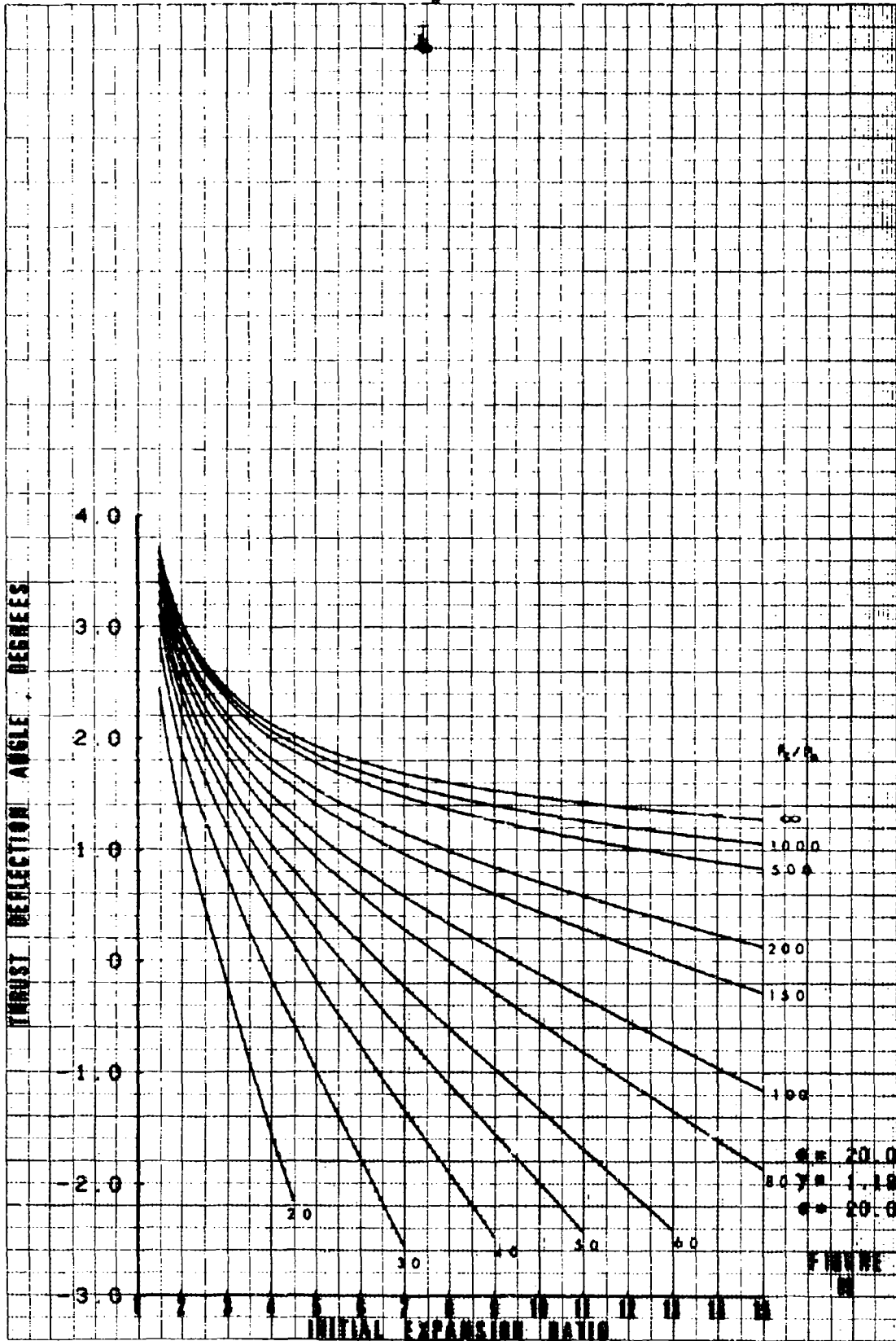
FIGURE 15

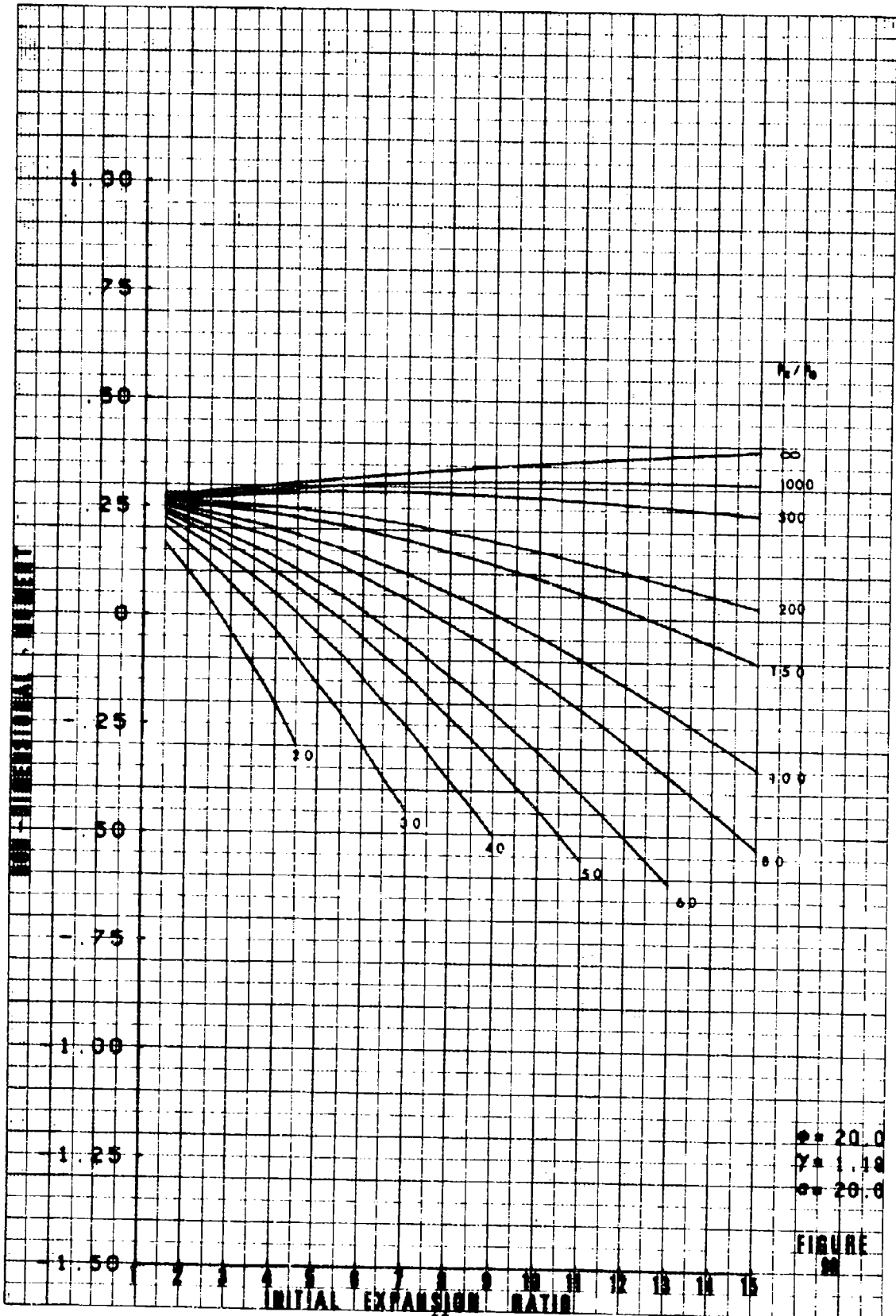












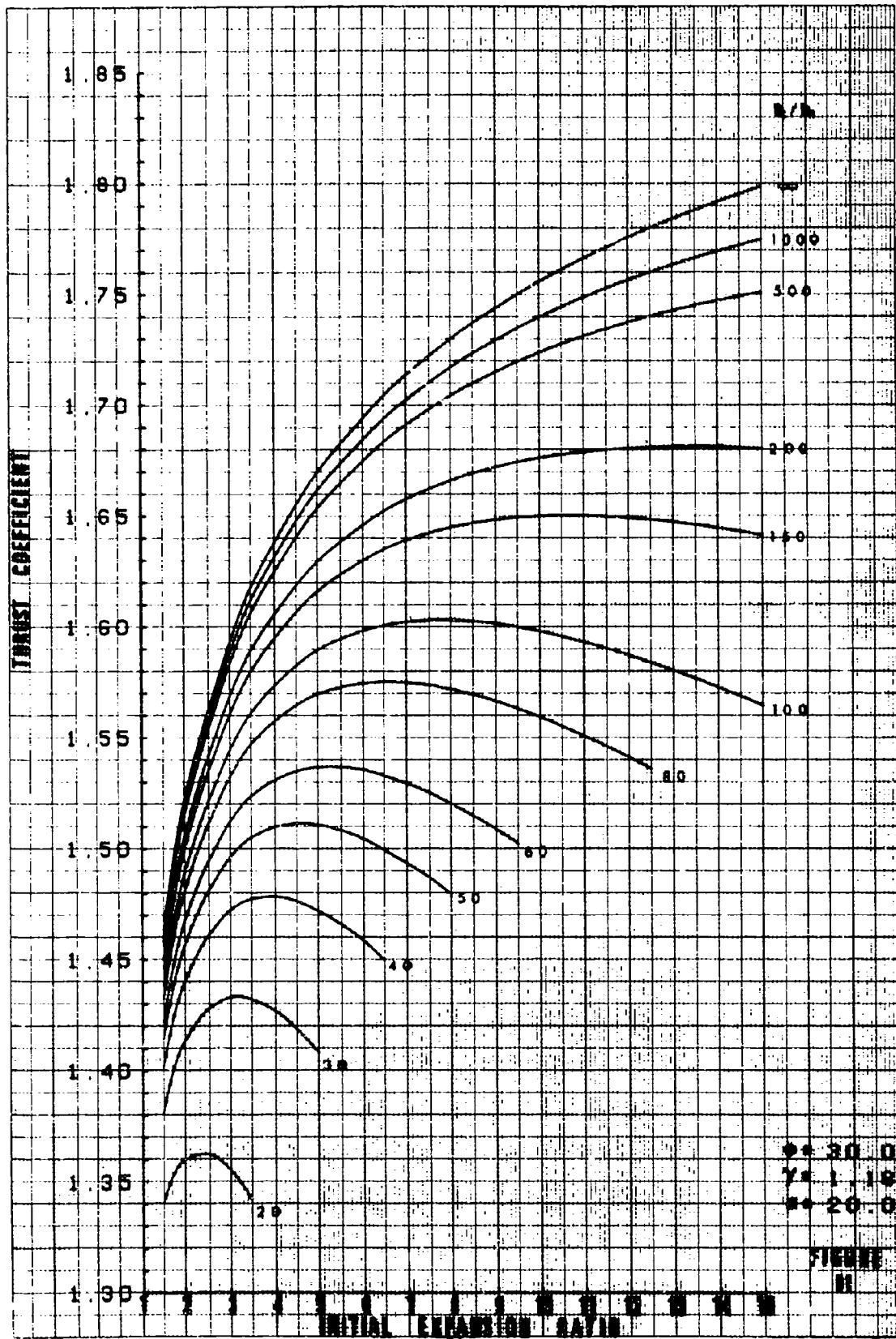
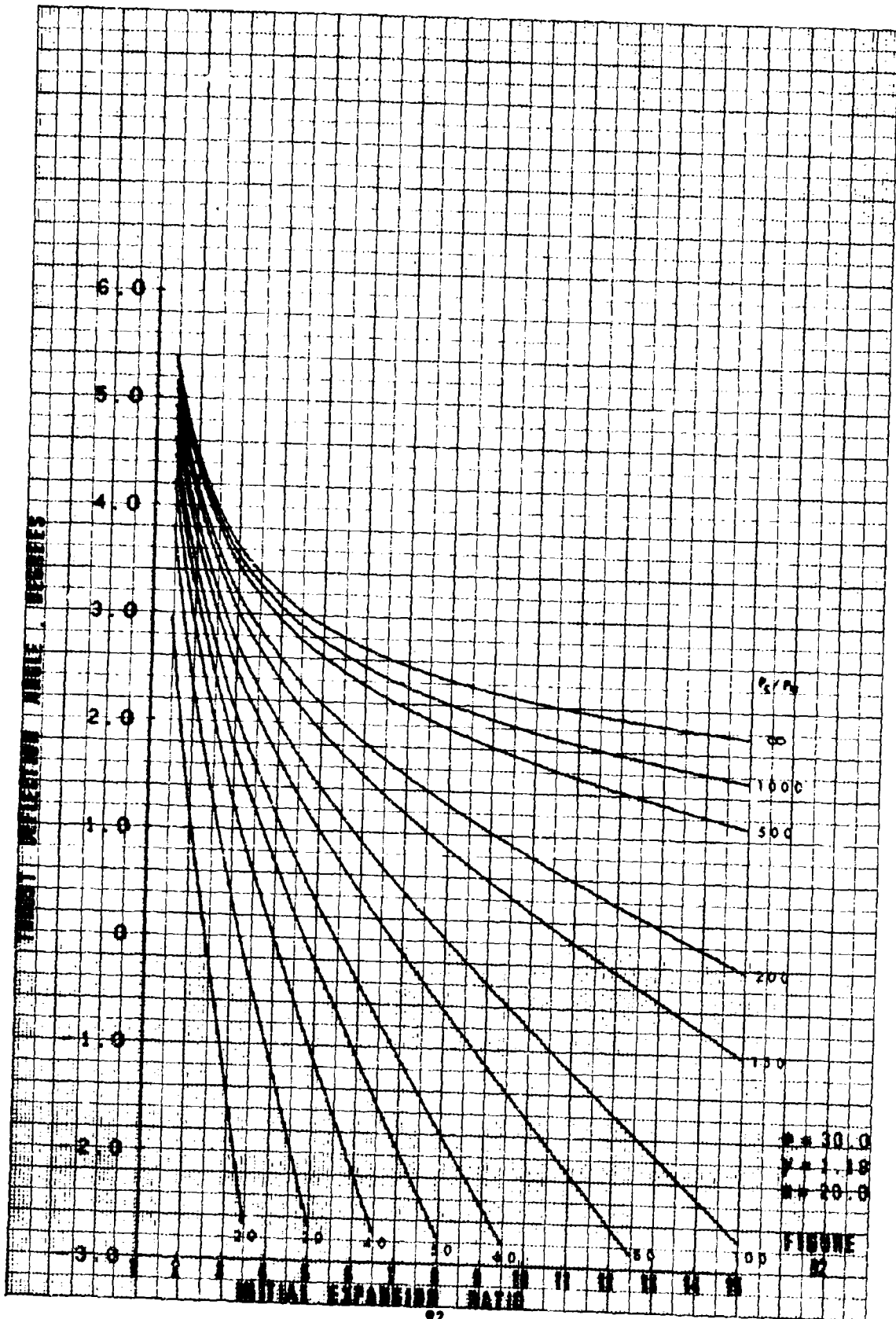
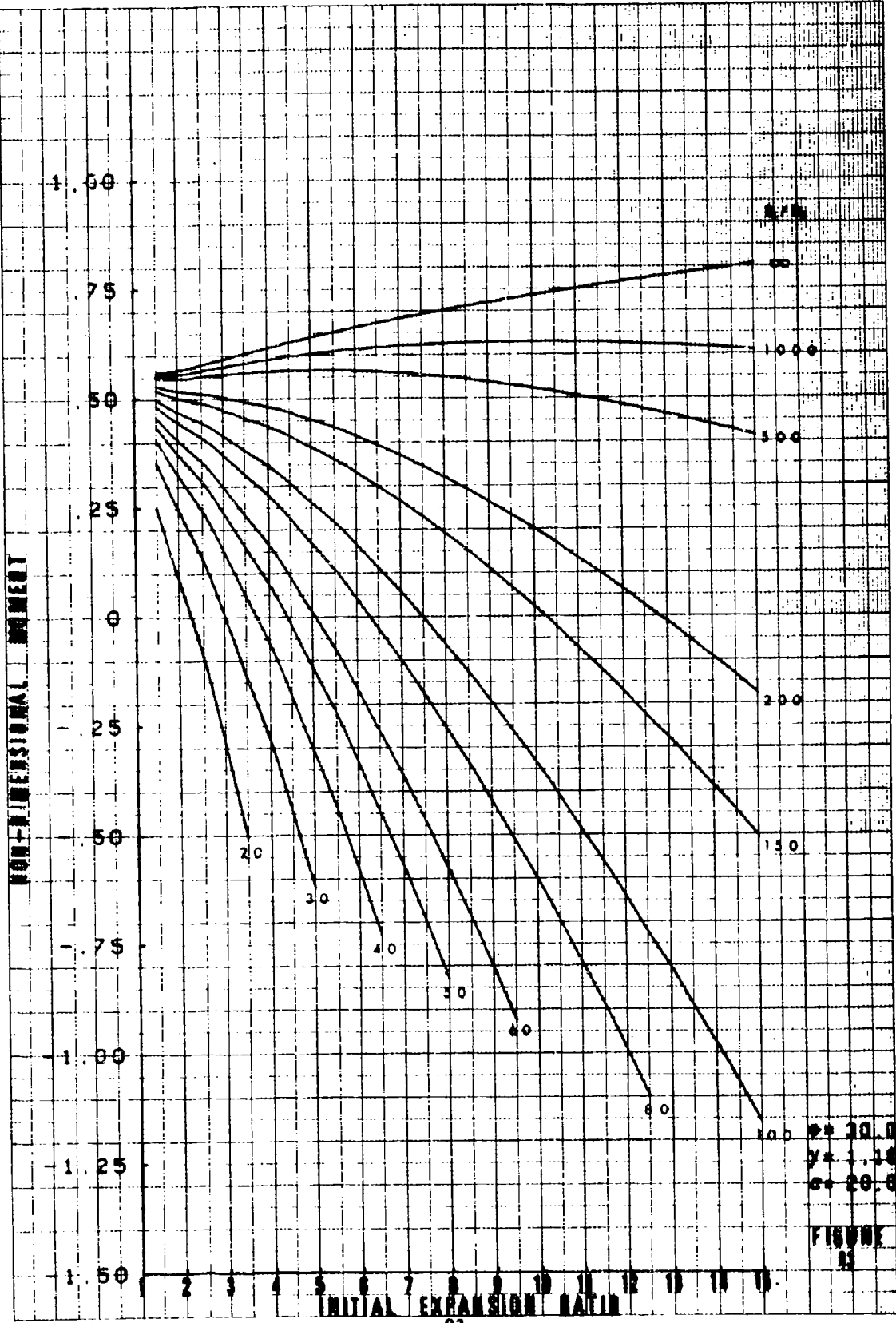
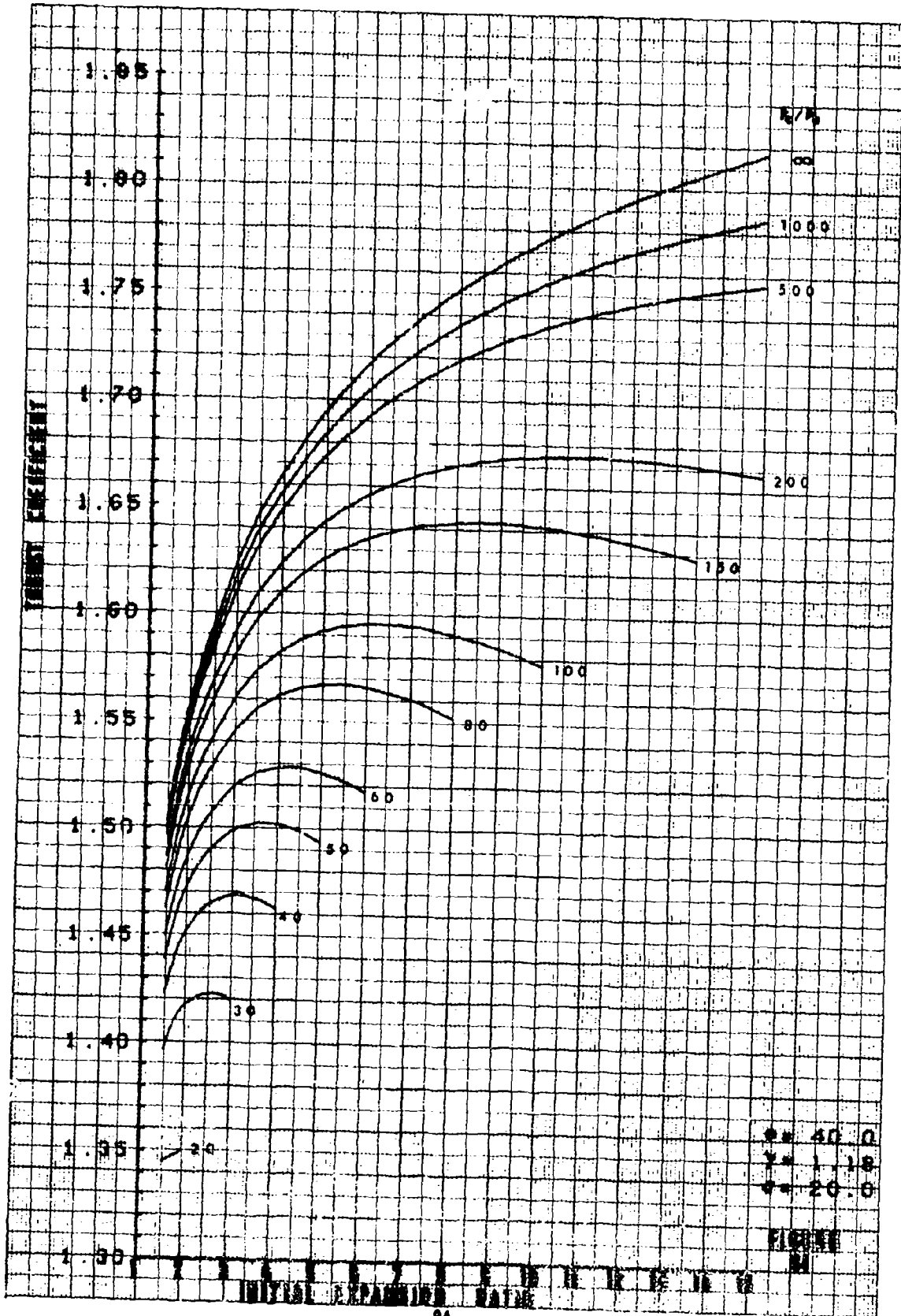
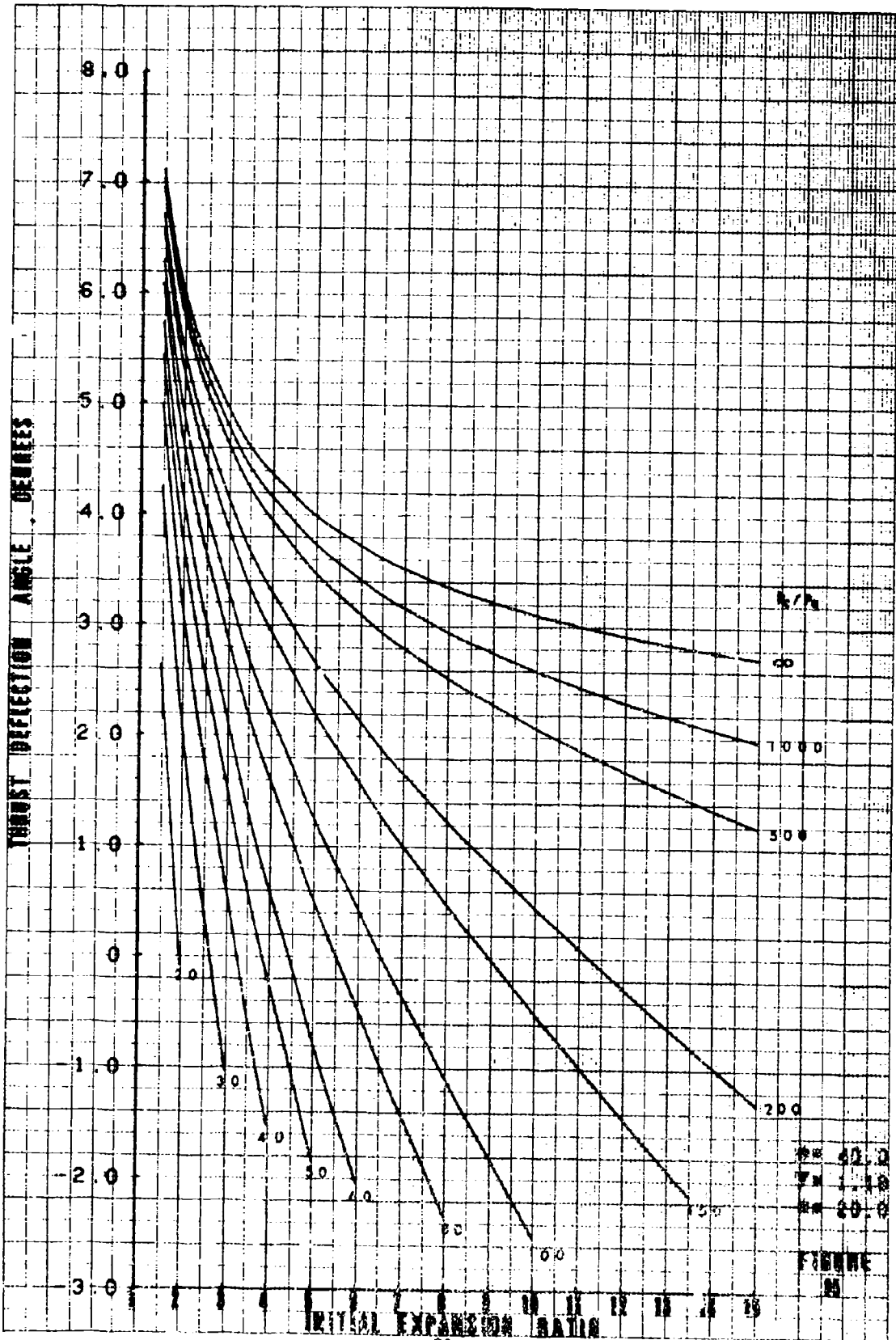


FIGURE 11





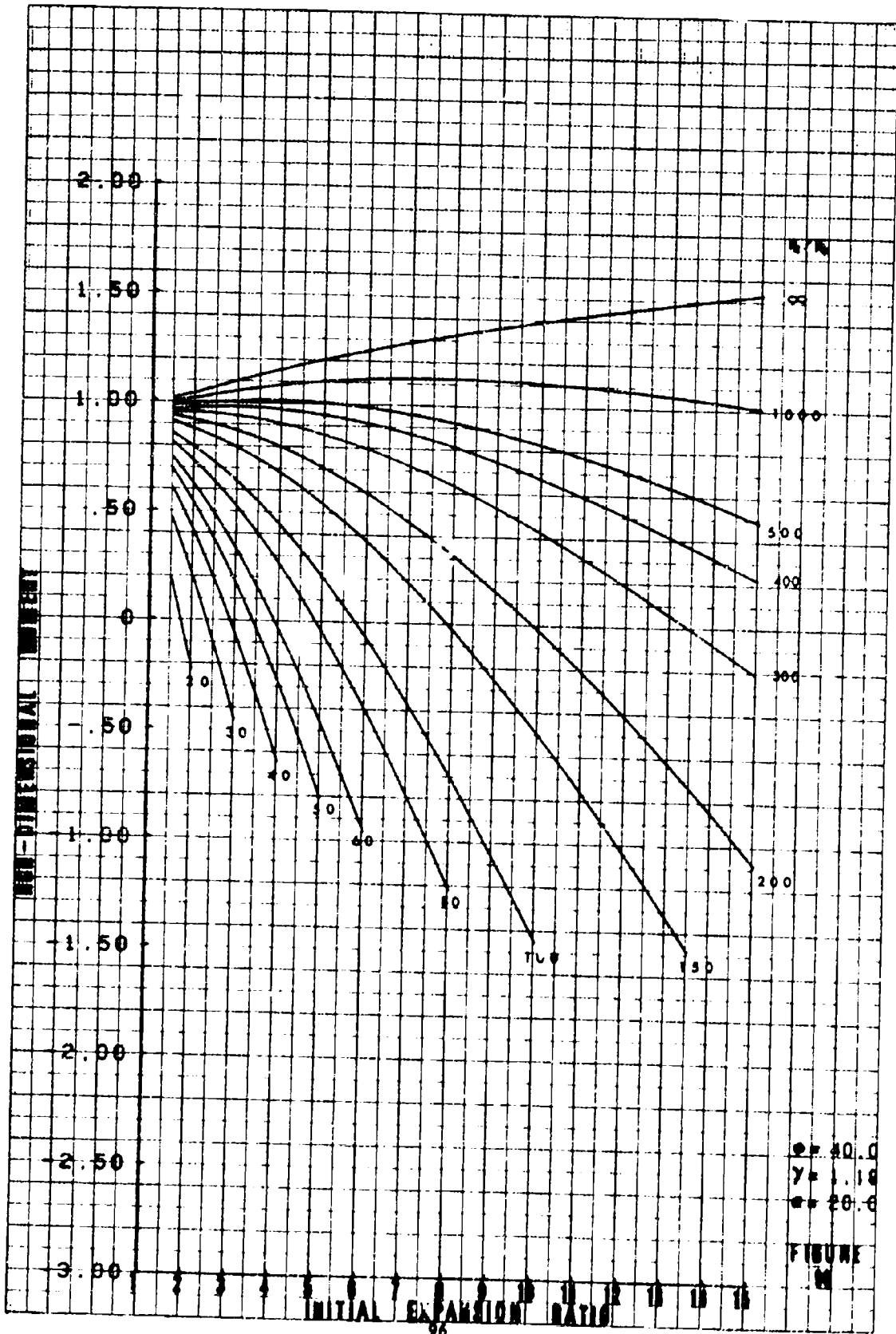




$\gamma = 1.4$   
 $M = 20.0$

FIGURE 20

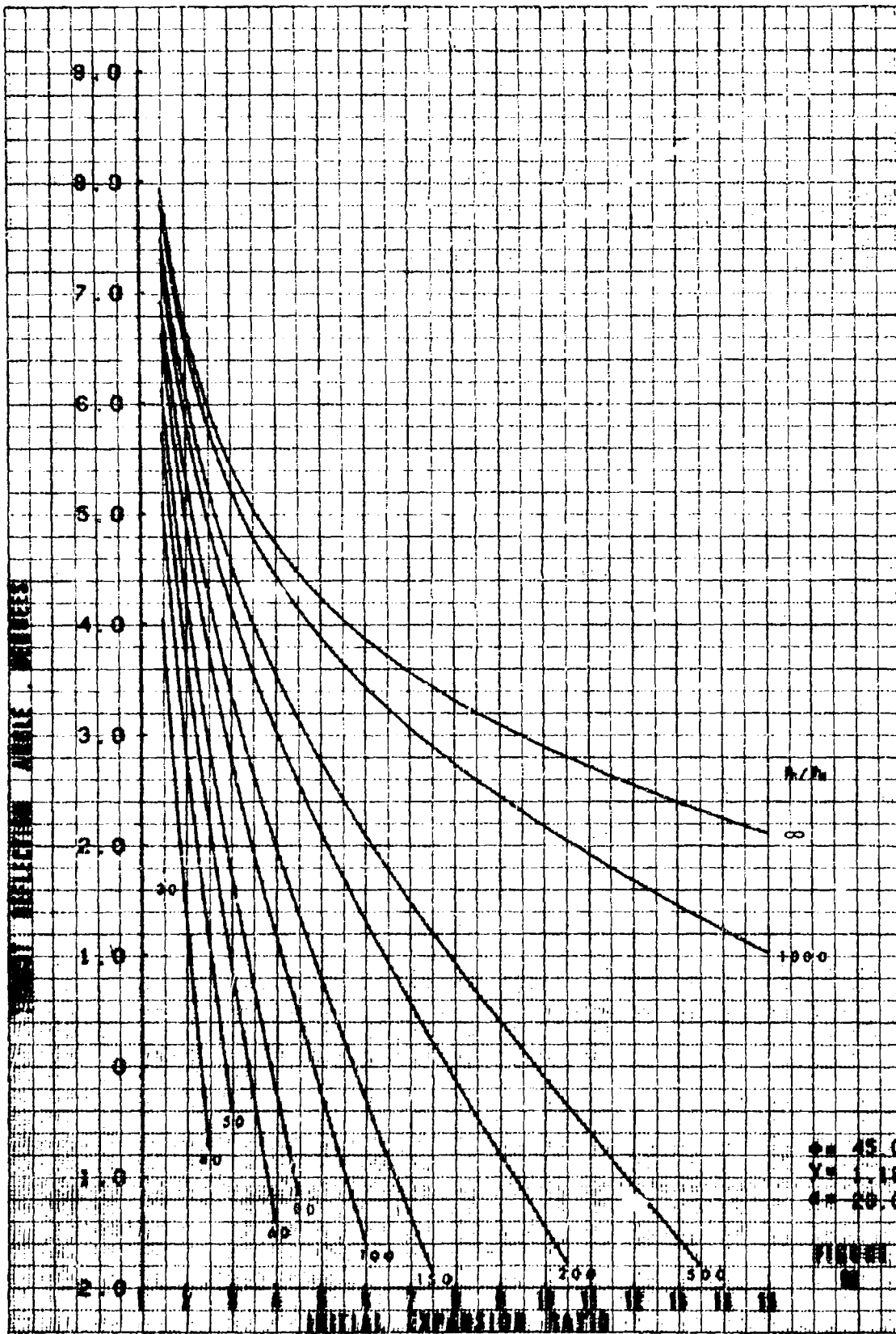




$\alpha = 40.0$   
 $\gamma = 1.18$   
 $\beta = 20.6$

FIGURE 2





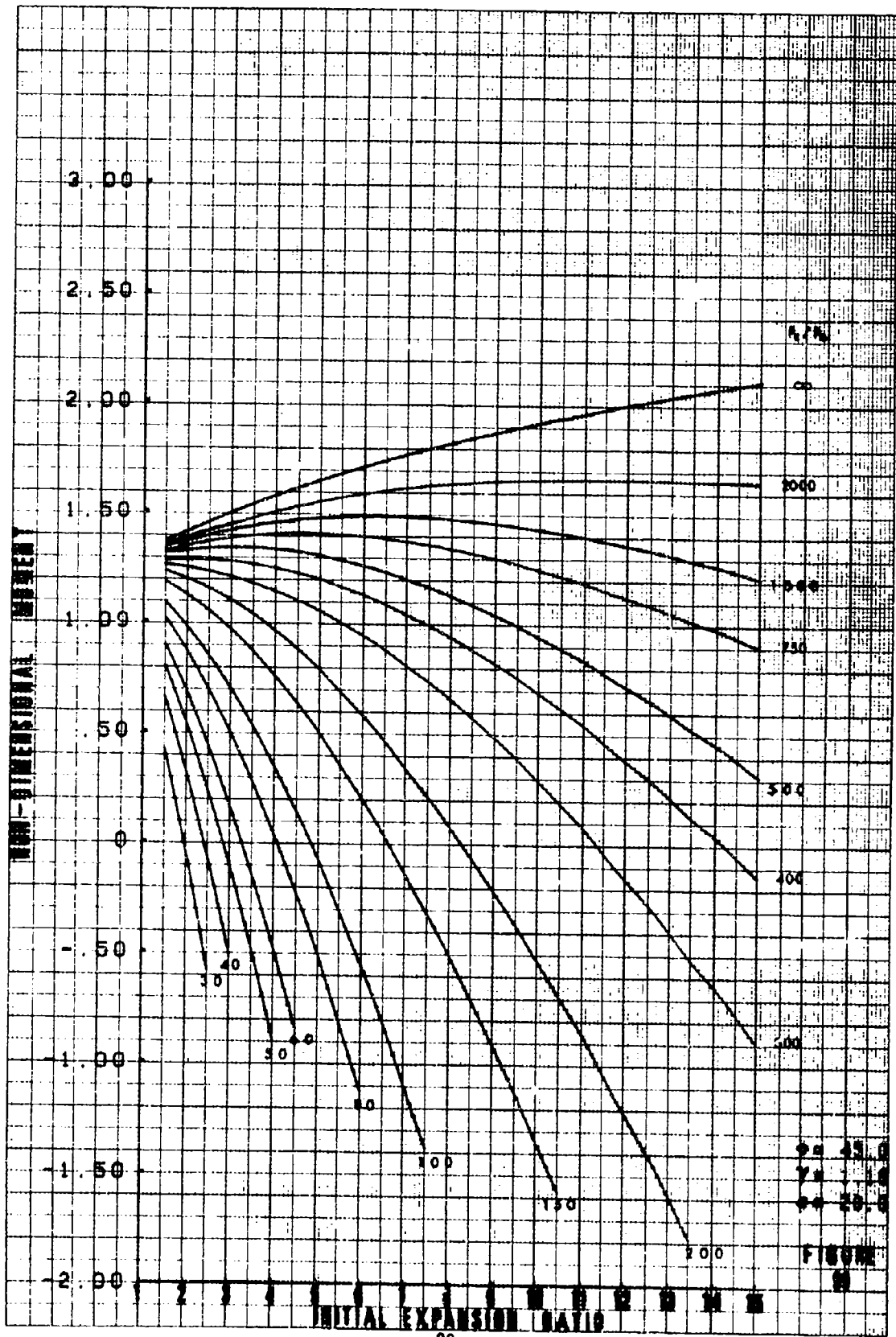
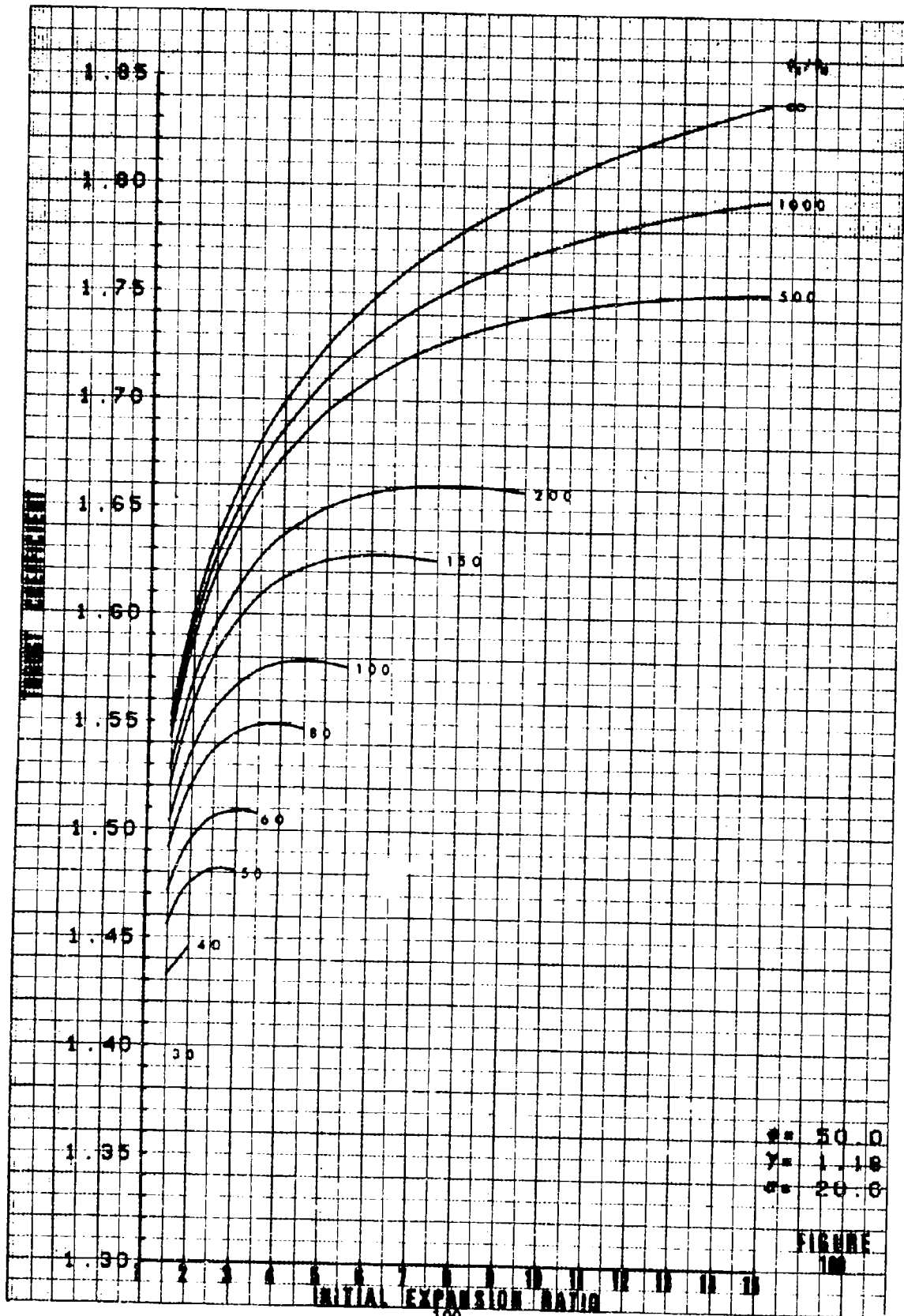


FIGURE 9



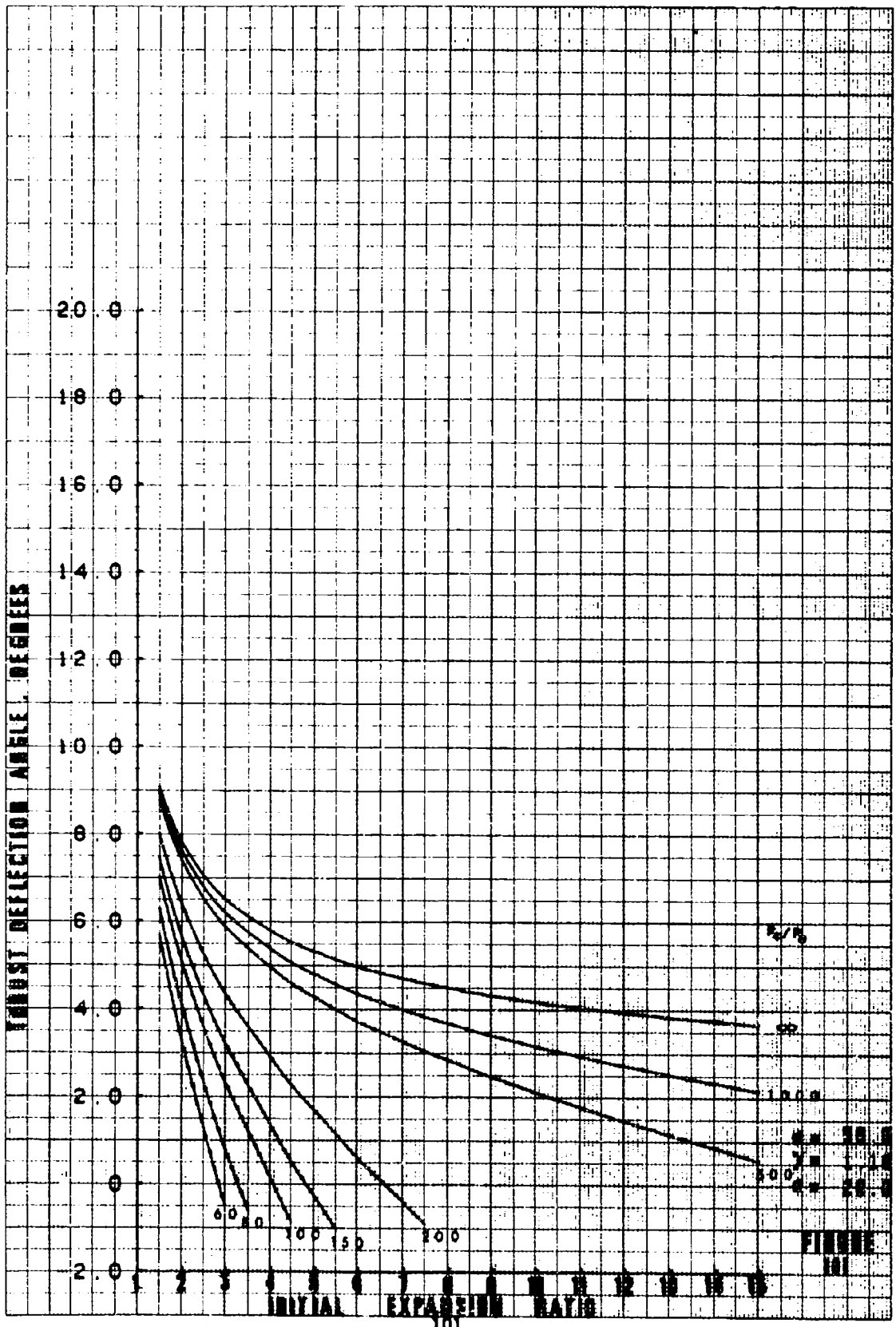
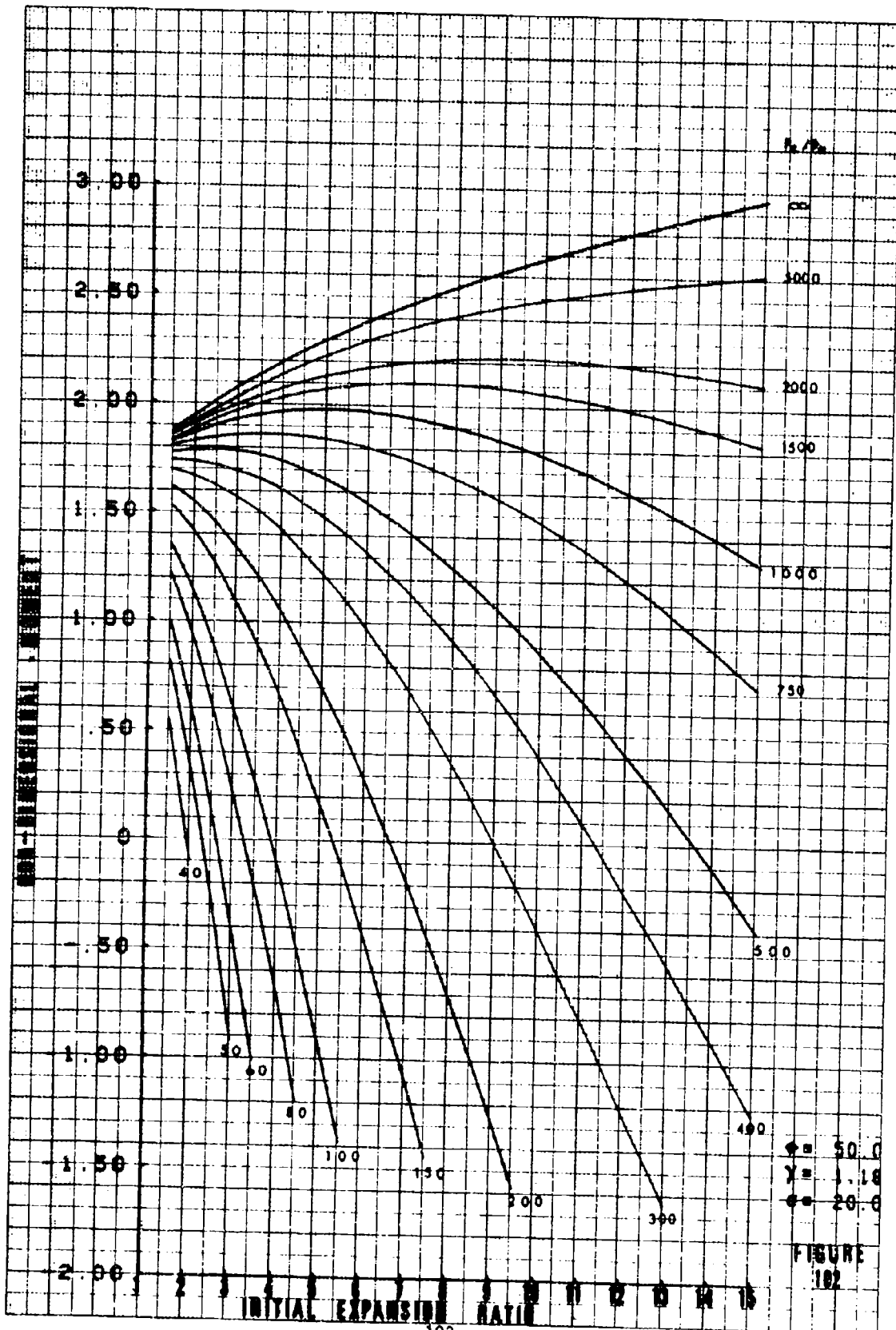
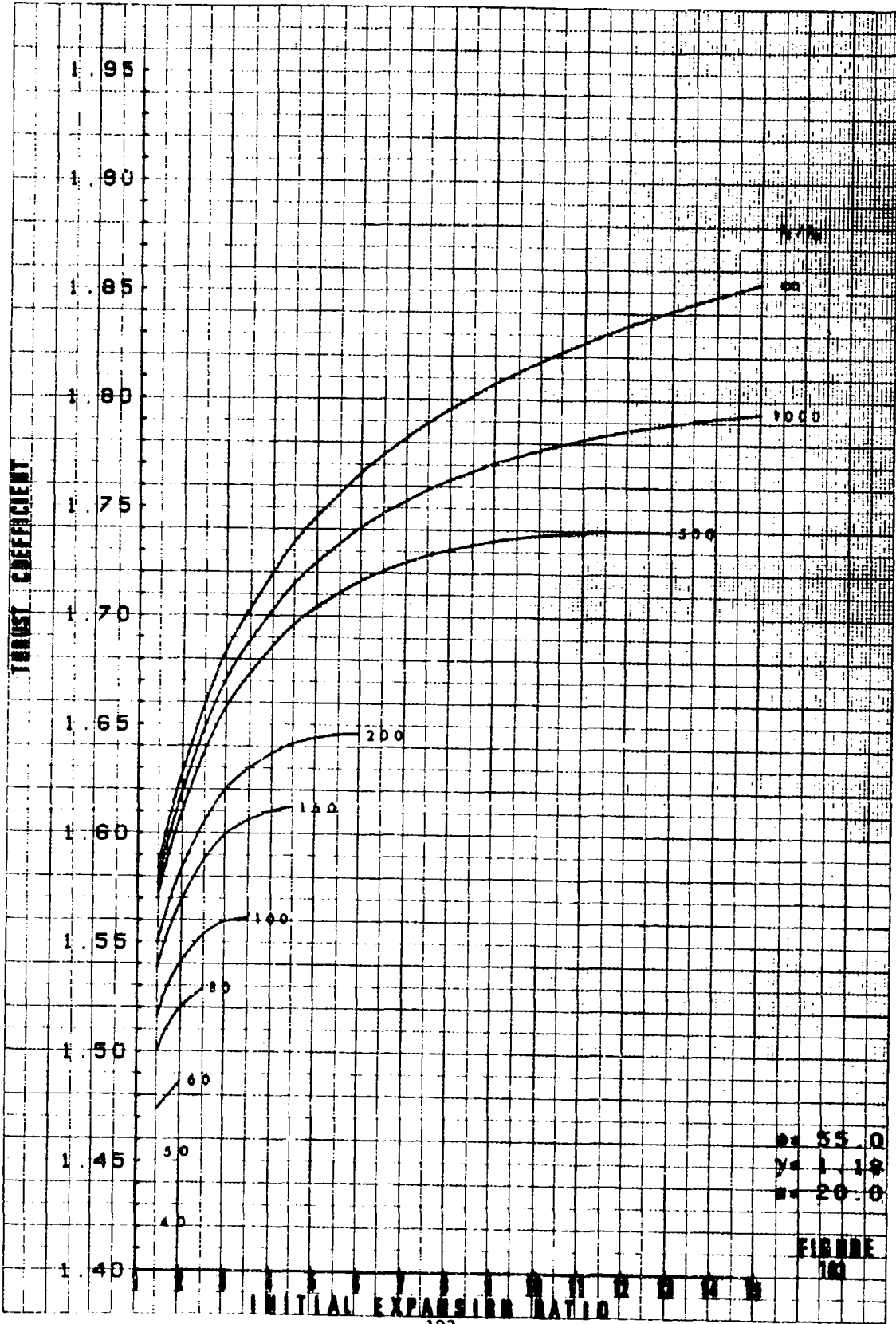


FIGURE 101







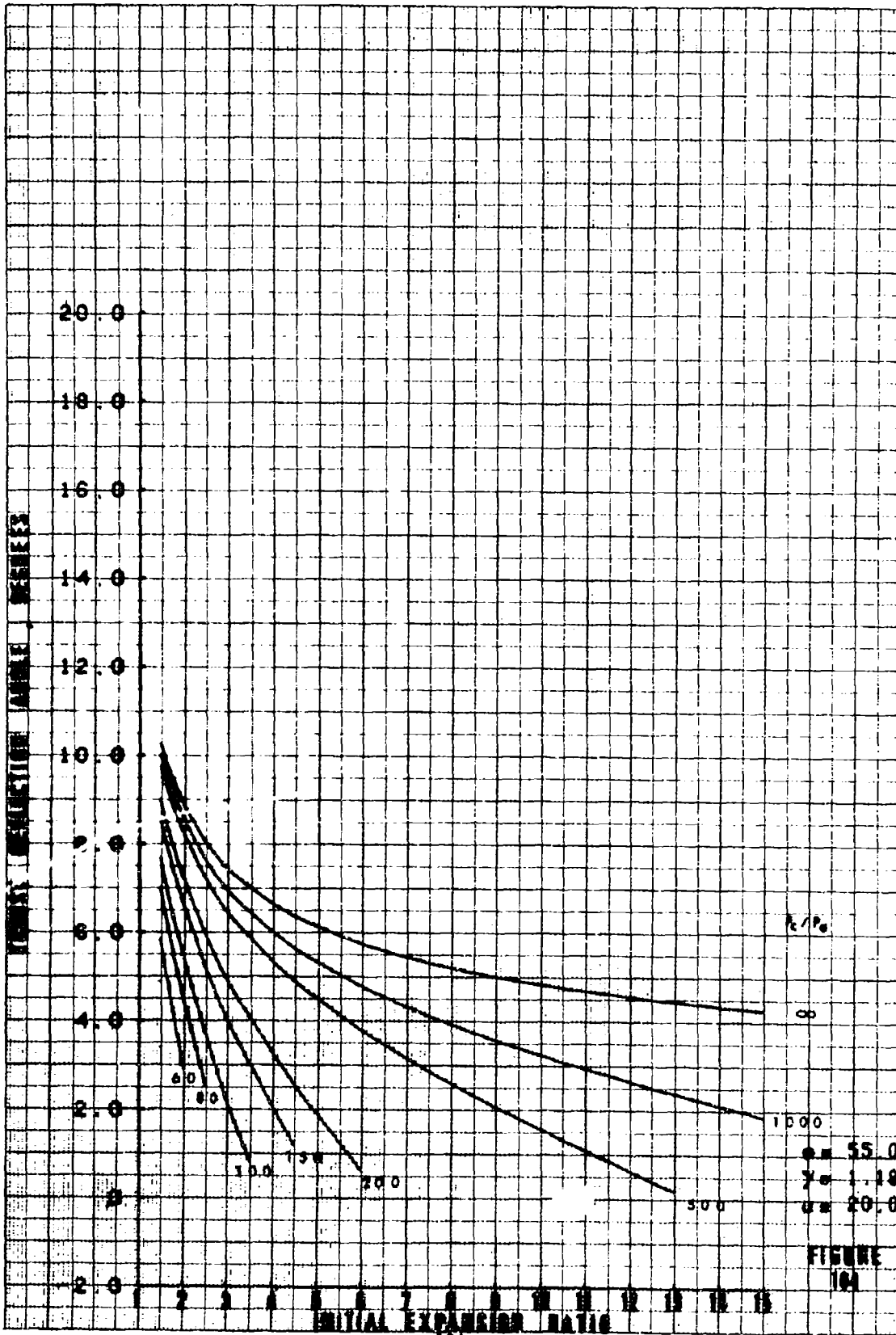
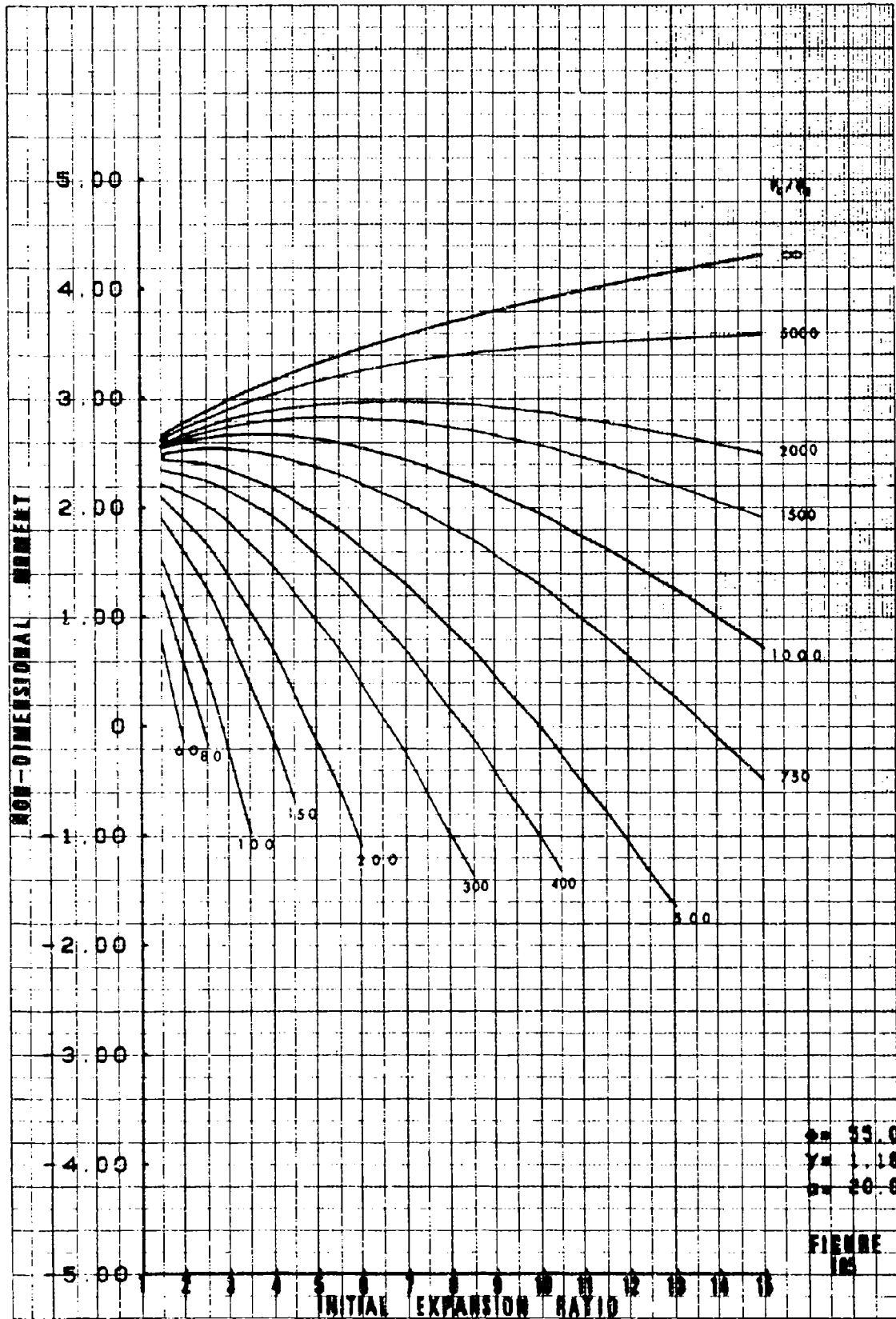


FIGURE 104



$\phi = 25.0$   
 $\gamma = 1.18$   
 $\rho = 20.0$

FIGURE 105

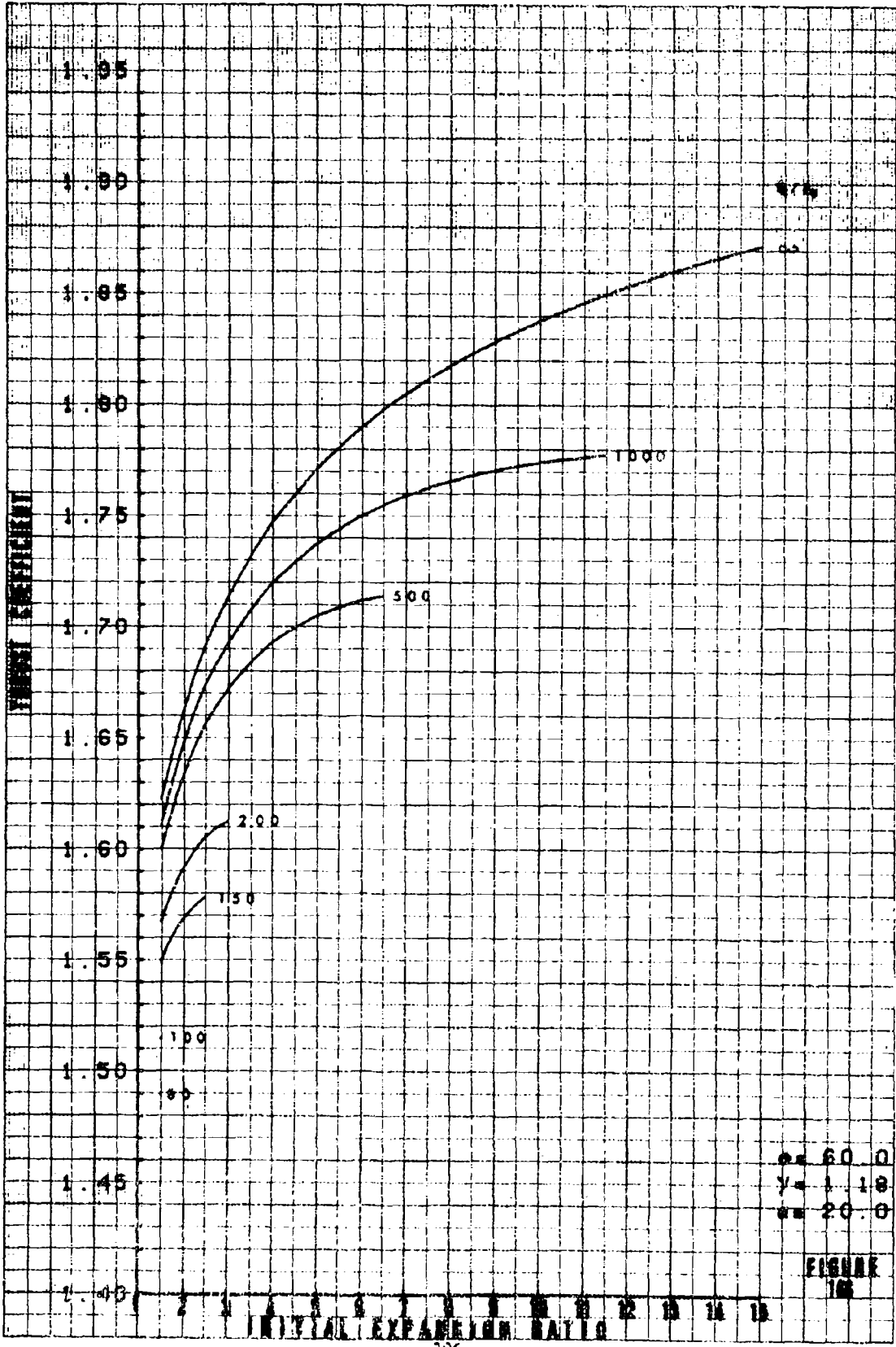
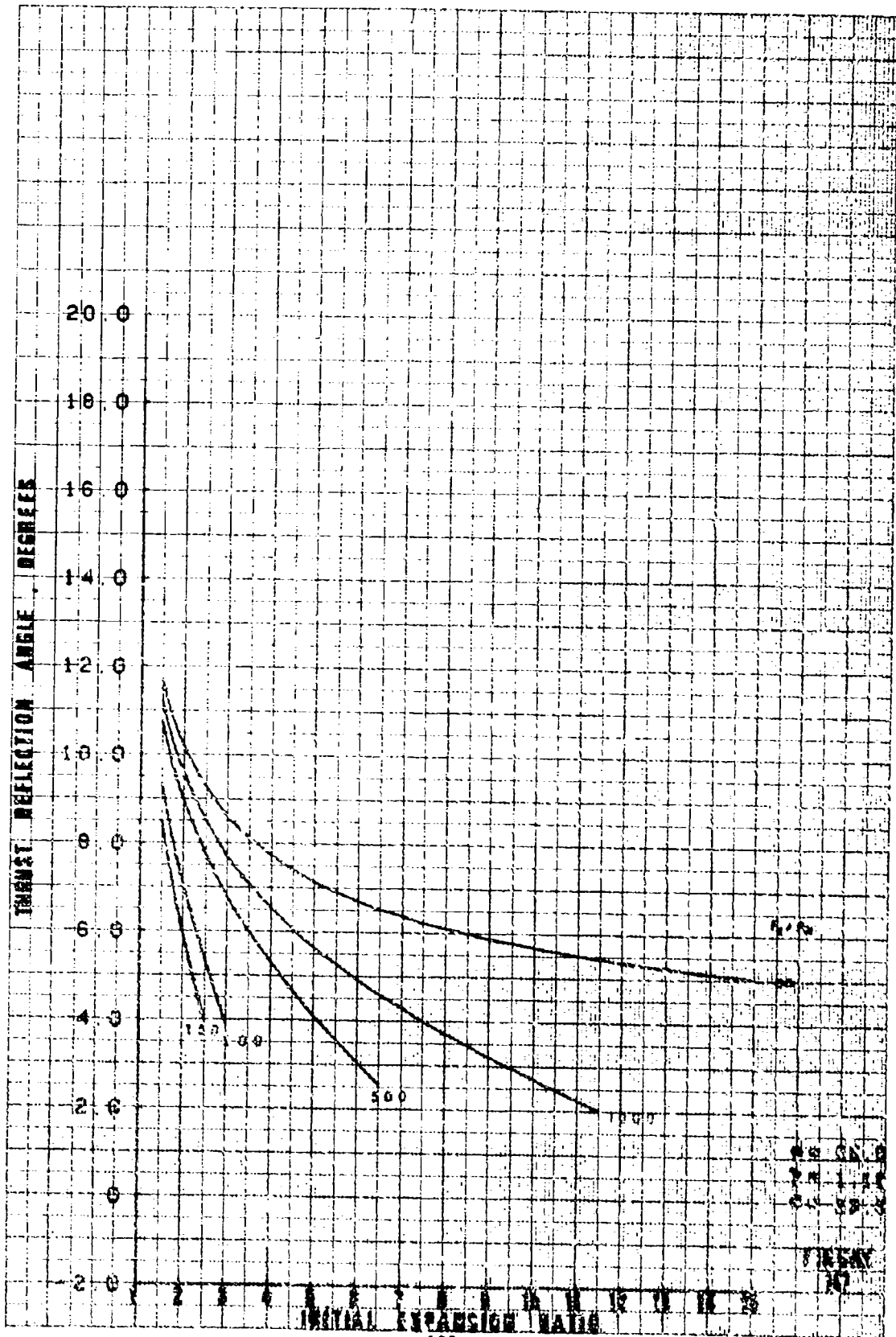
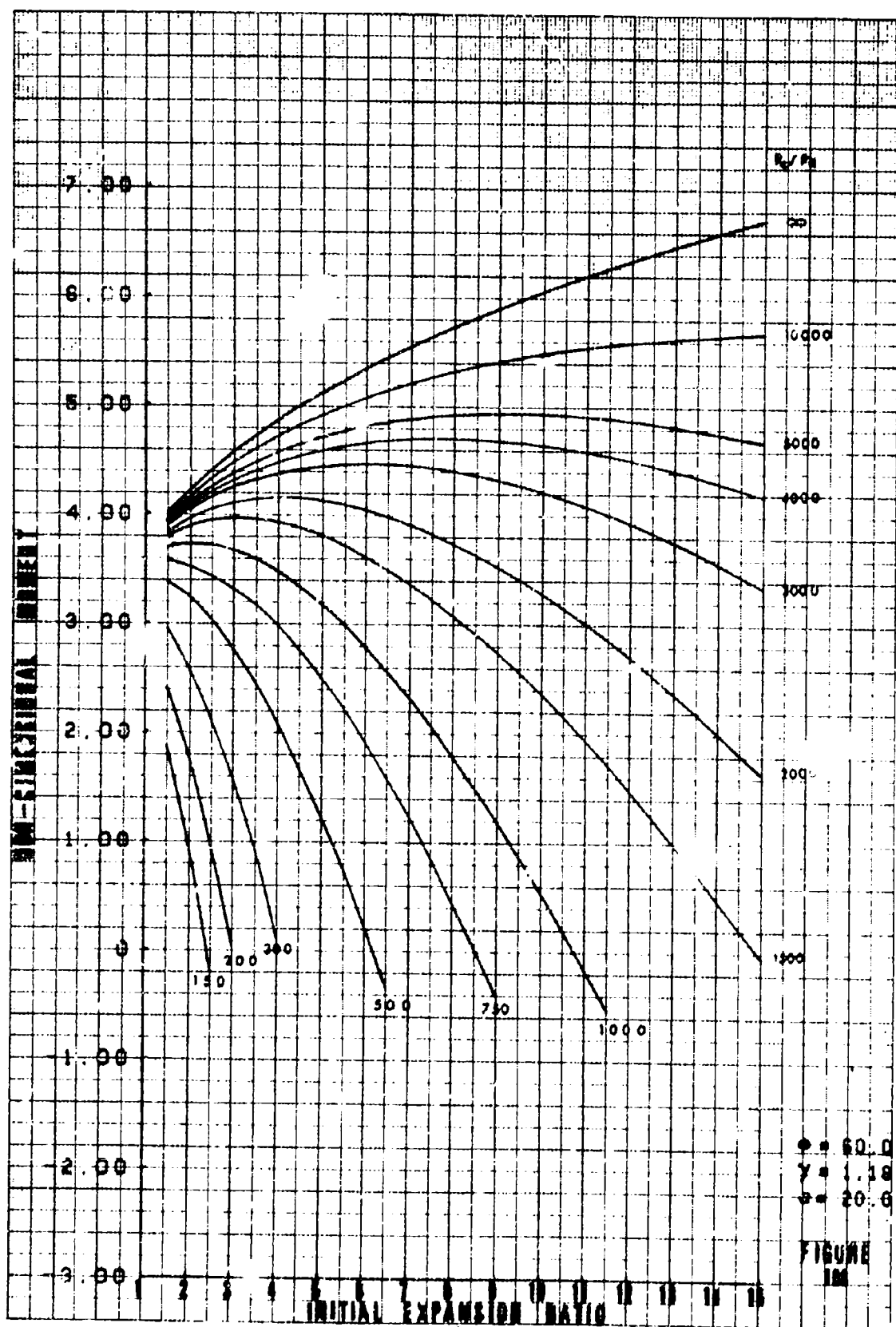
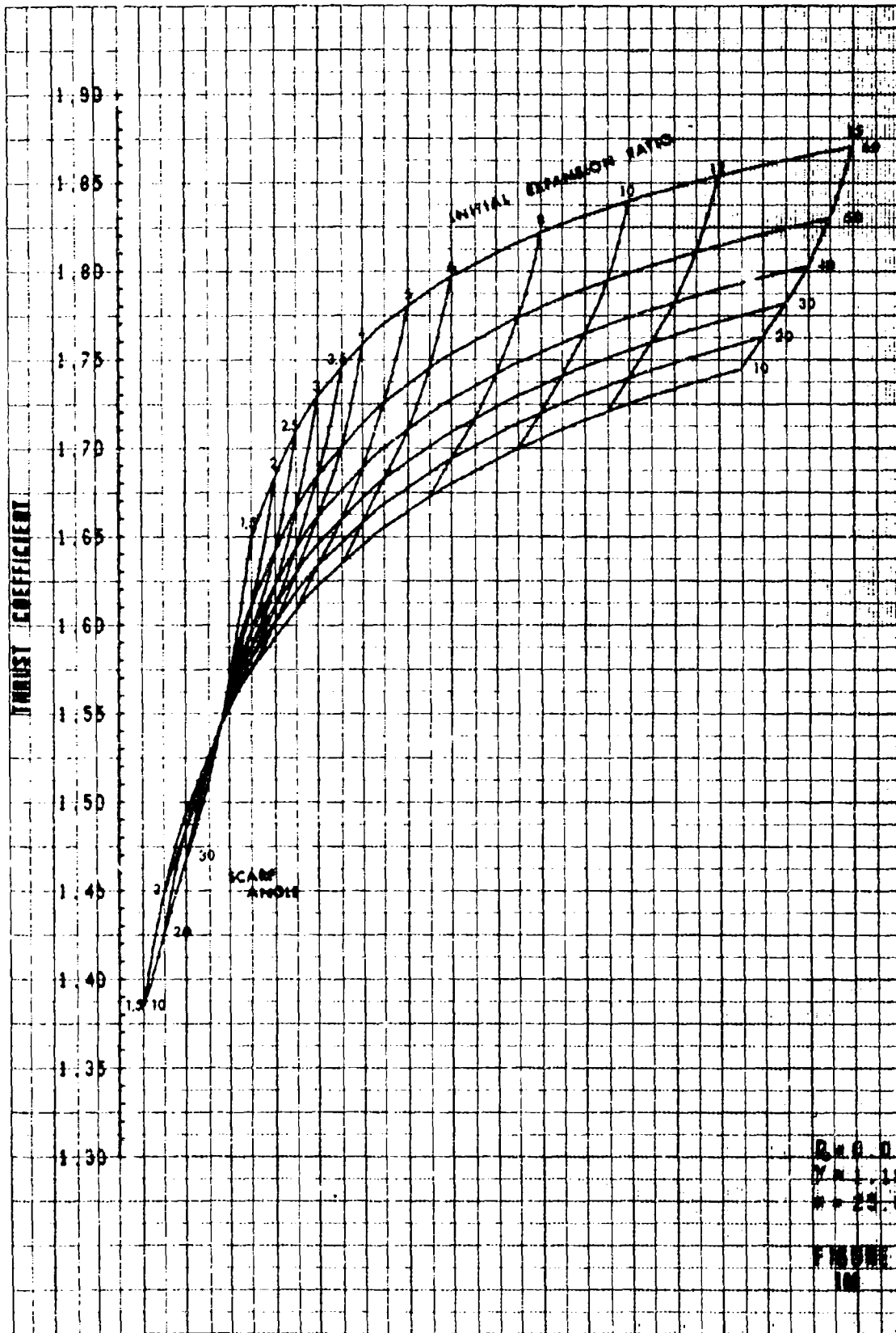
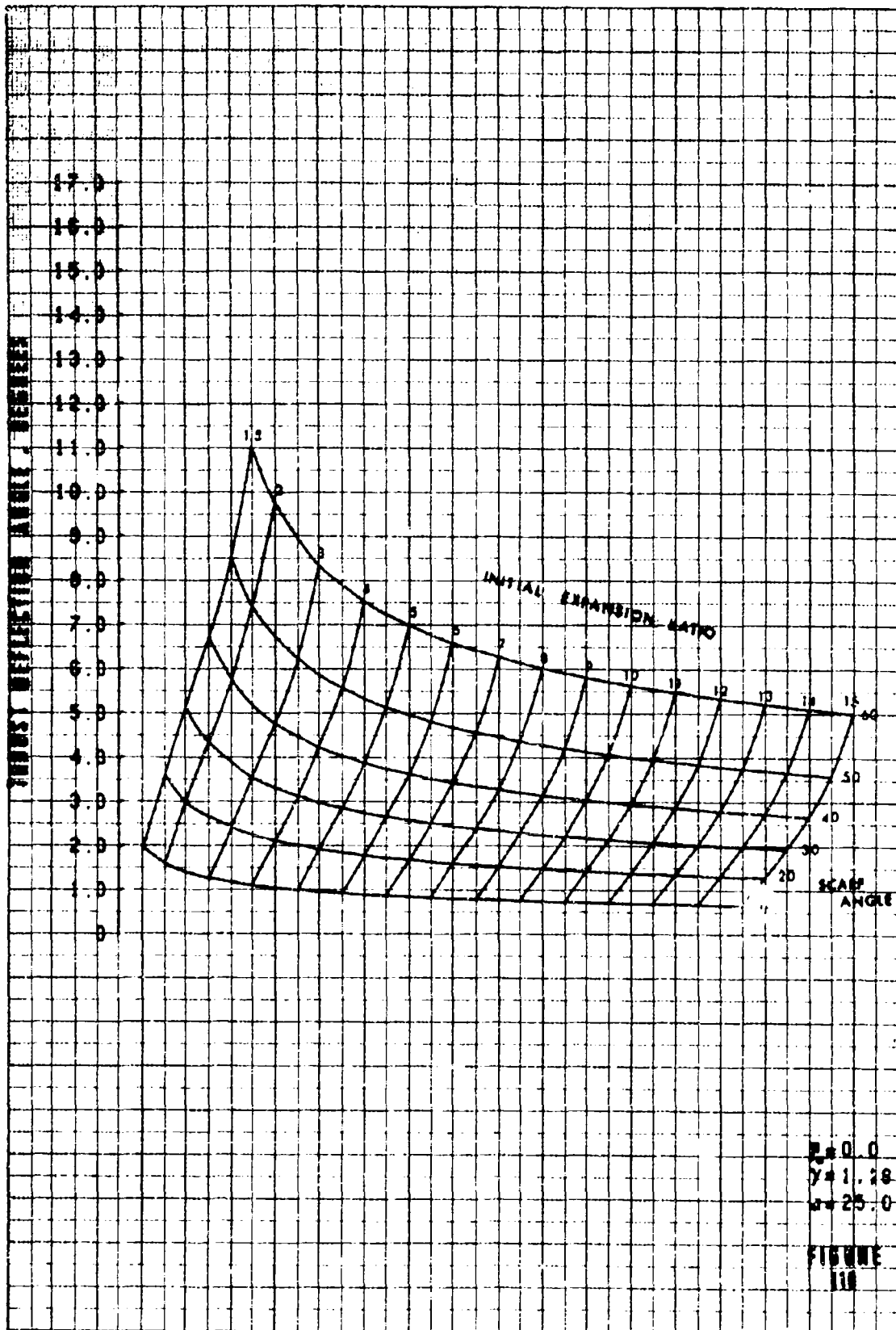


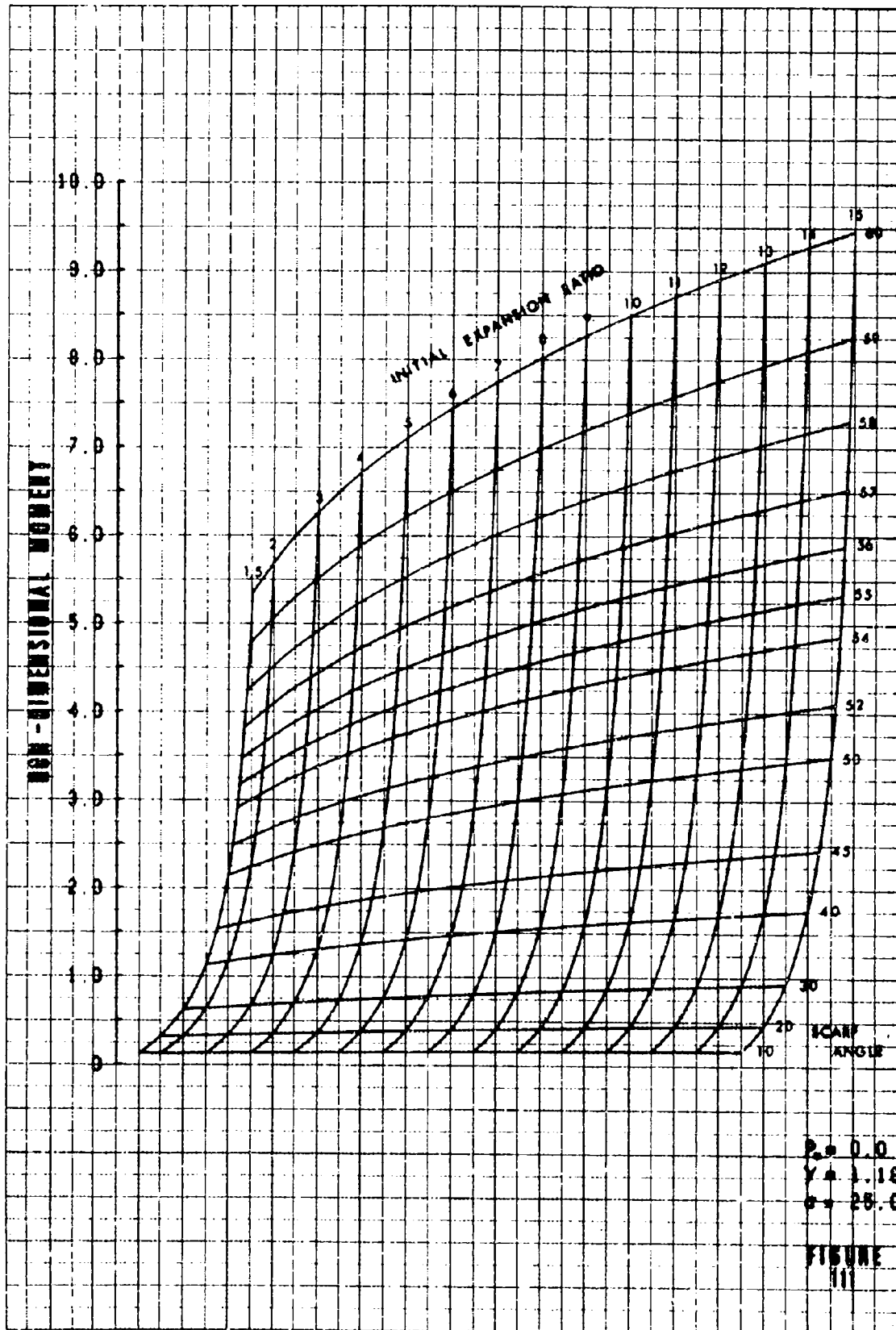
FIGURE 106



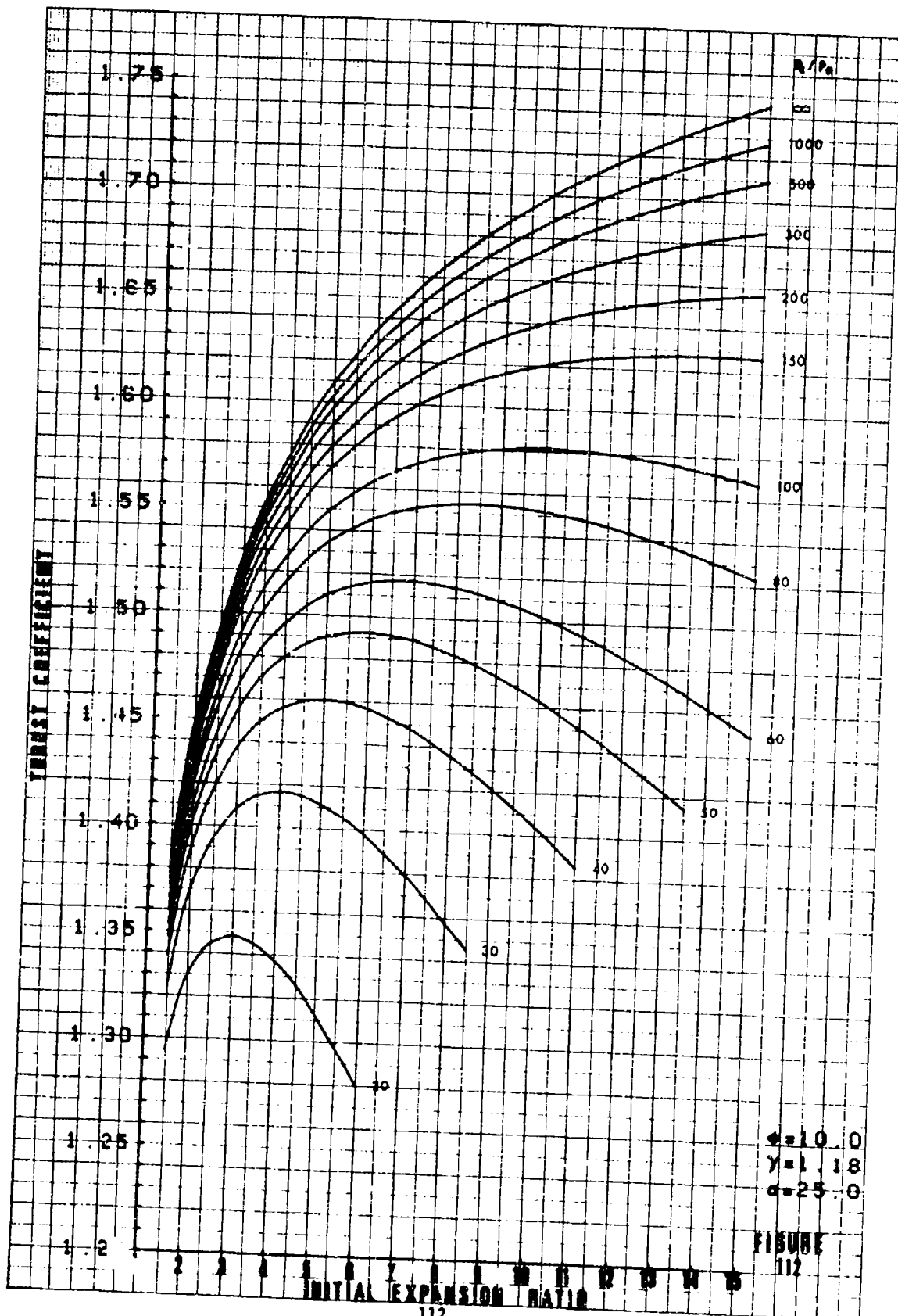


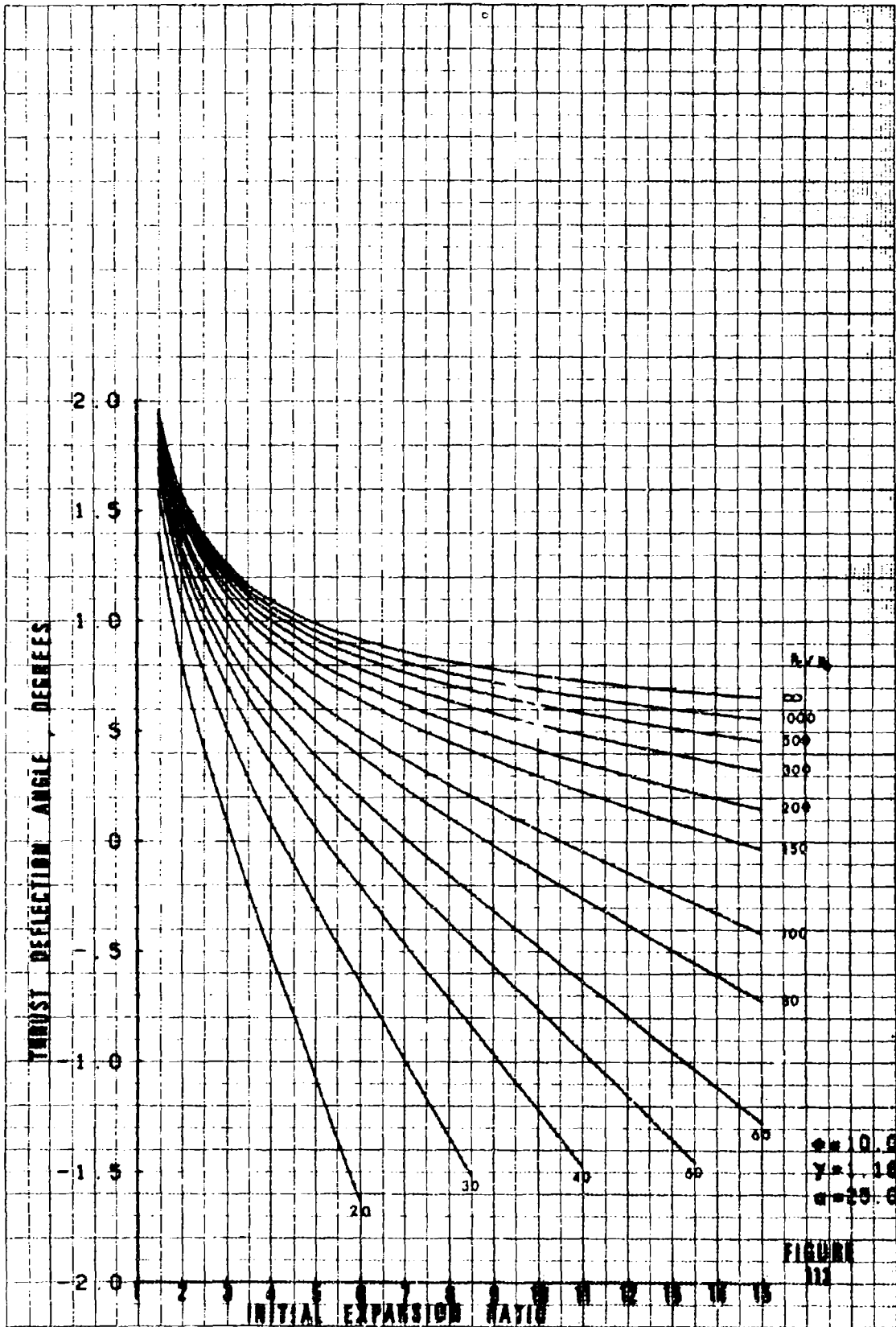


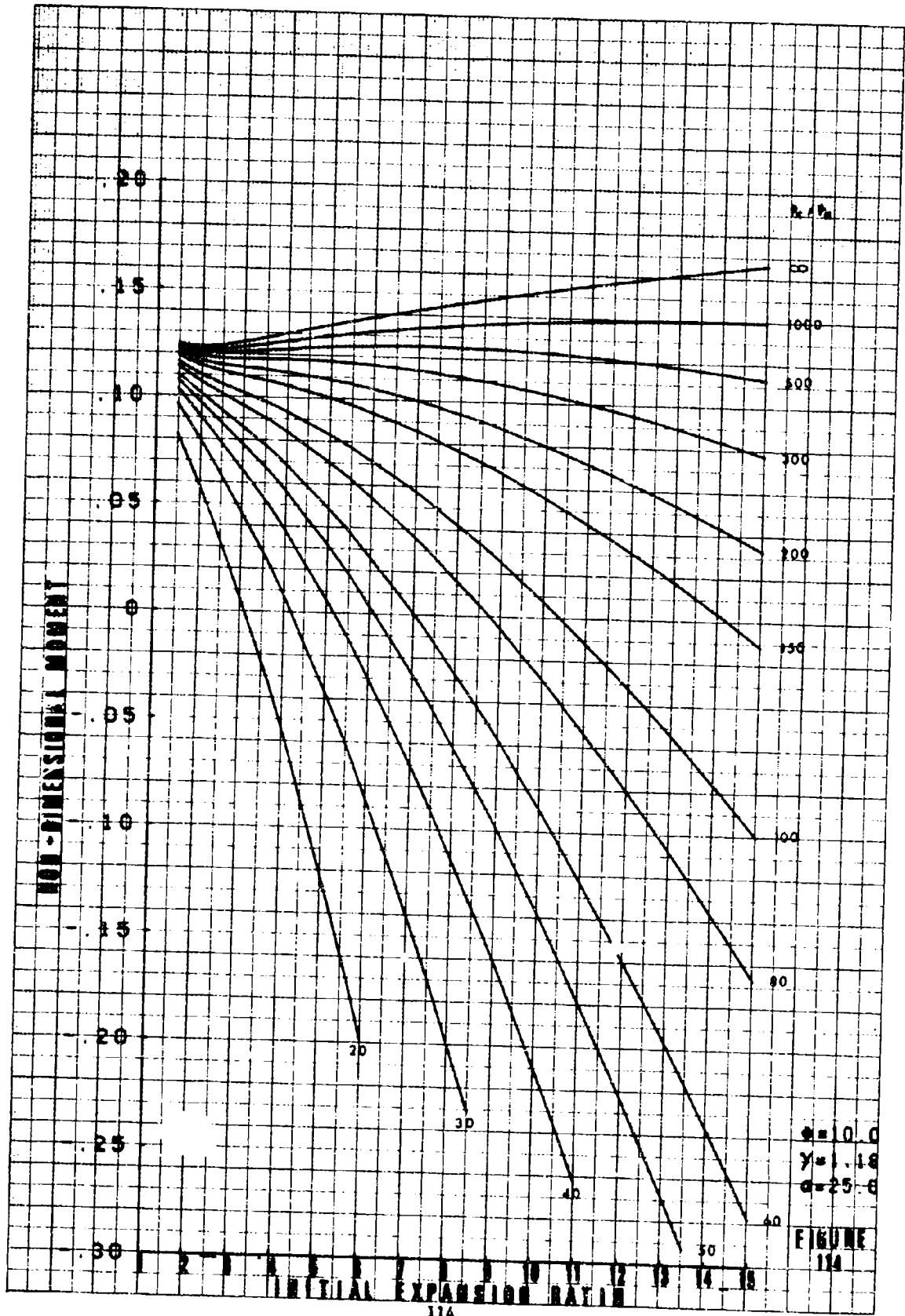






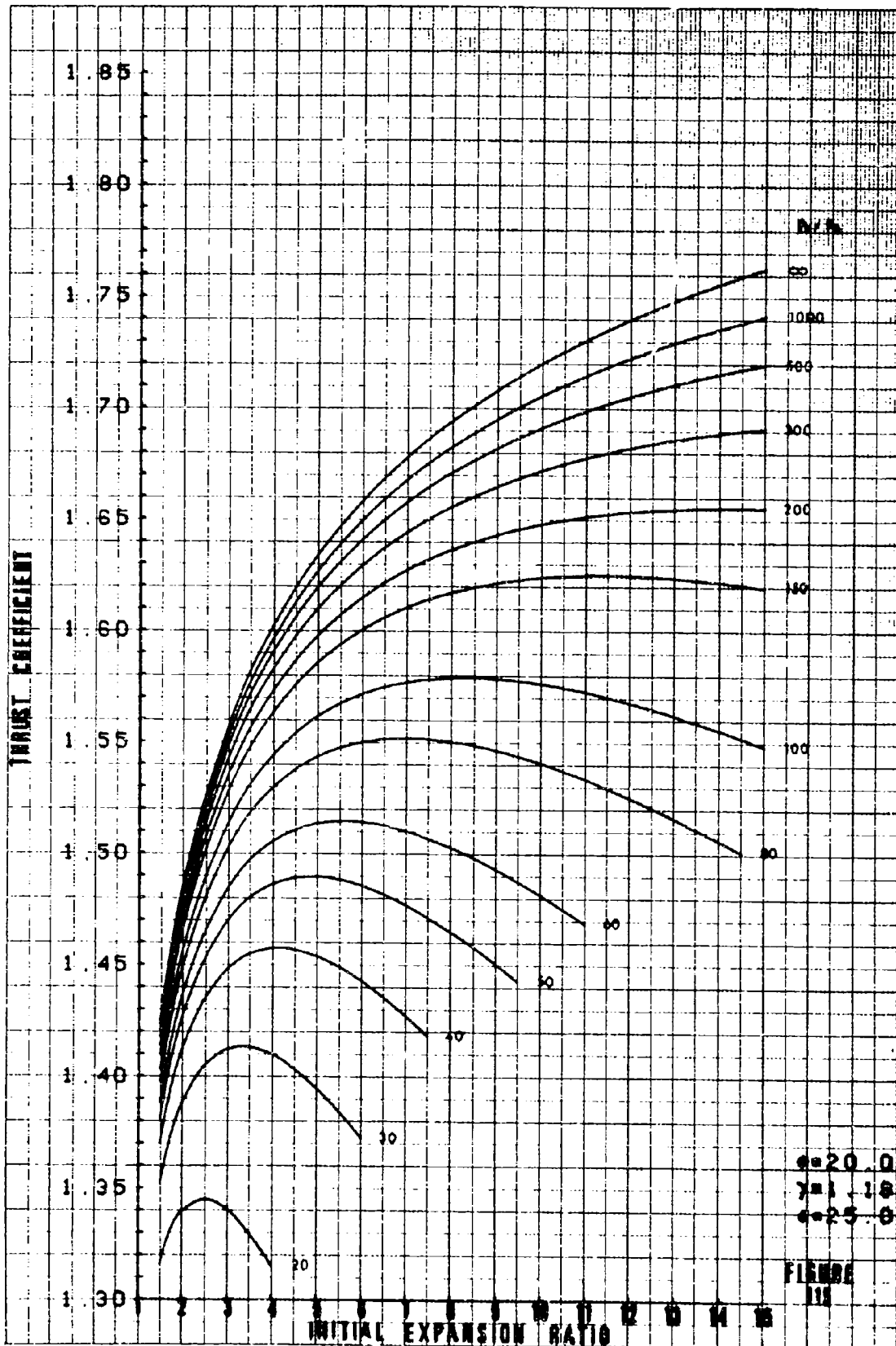


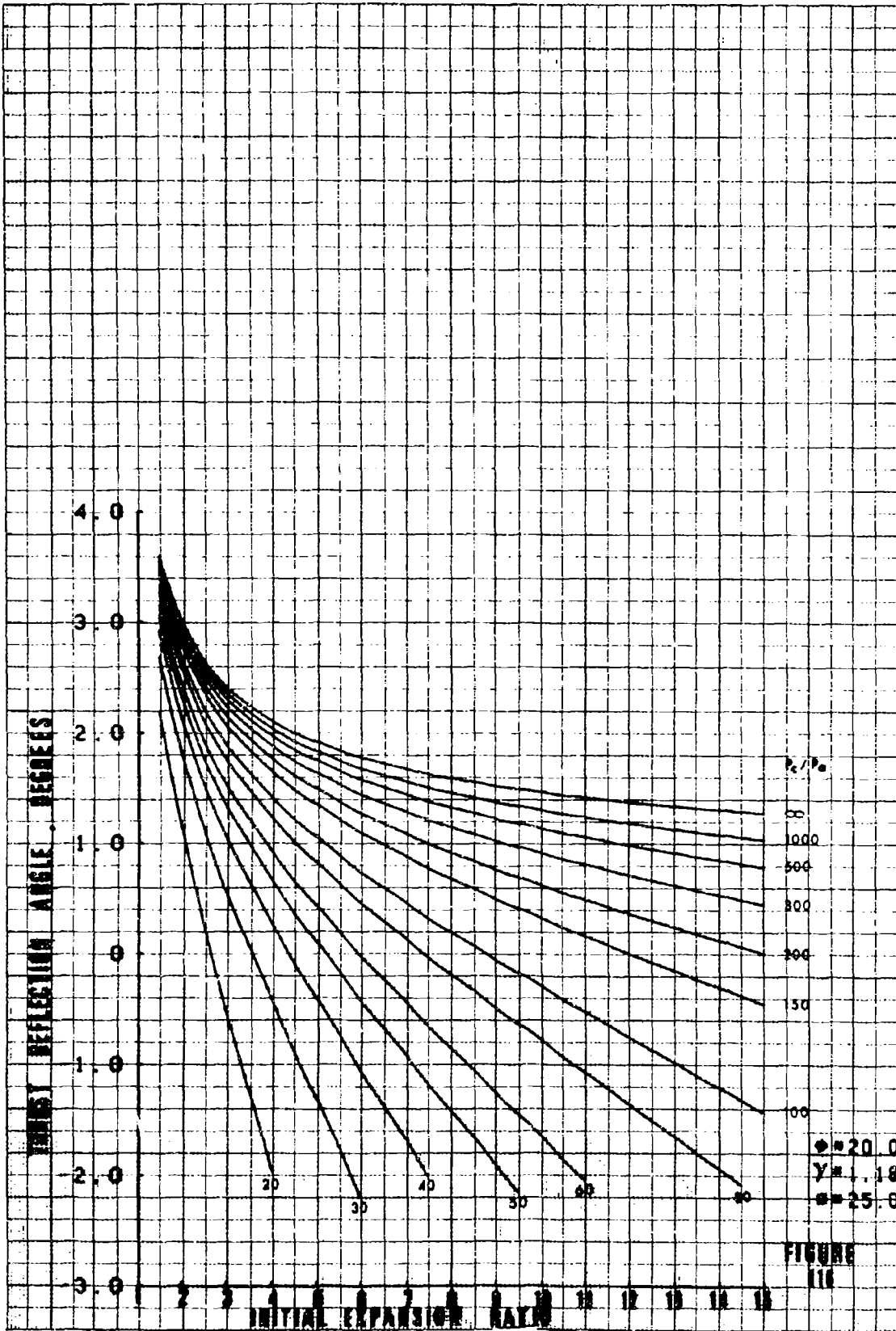




$\alpha = 10.0$   
 $\gamma = 1.18$   
 $\sigma = 25.6$

FIGURE  
114





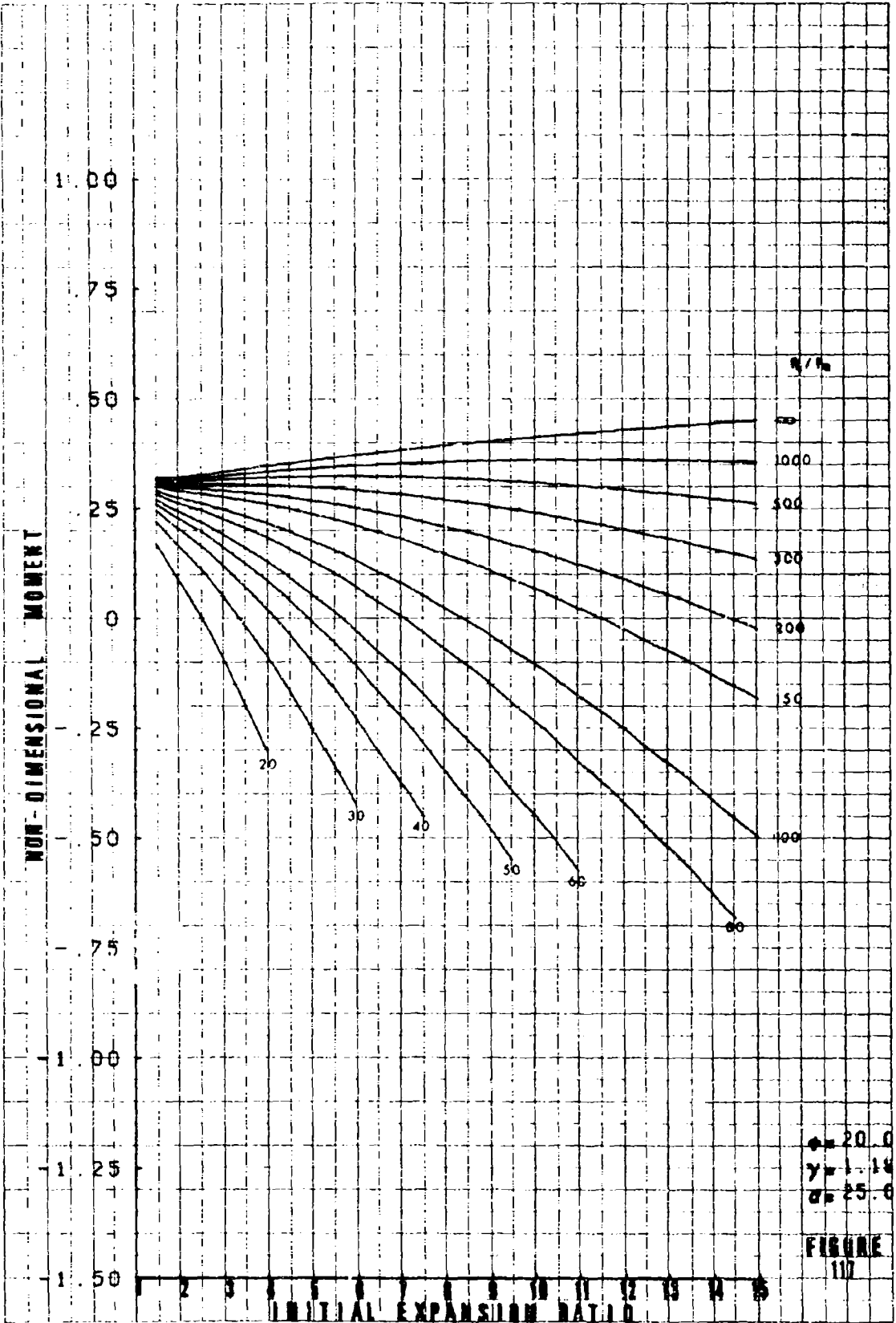


FIGURE 117

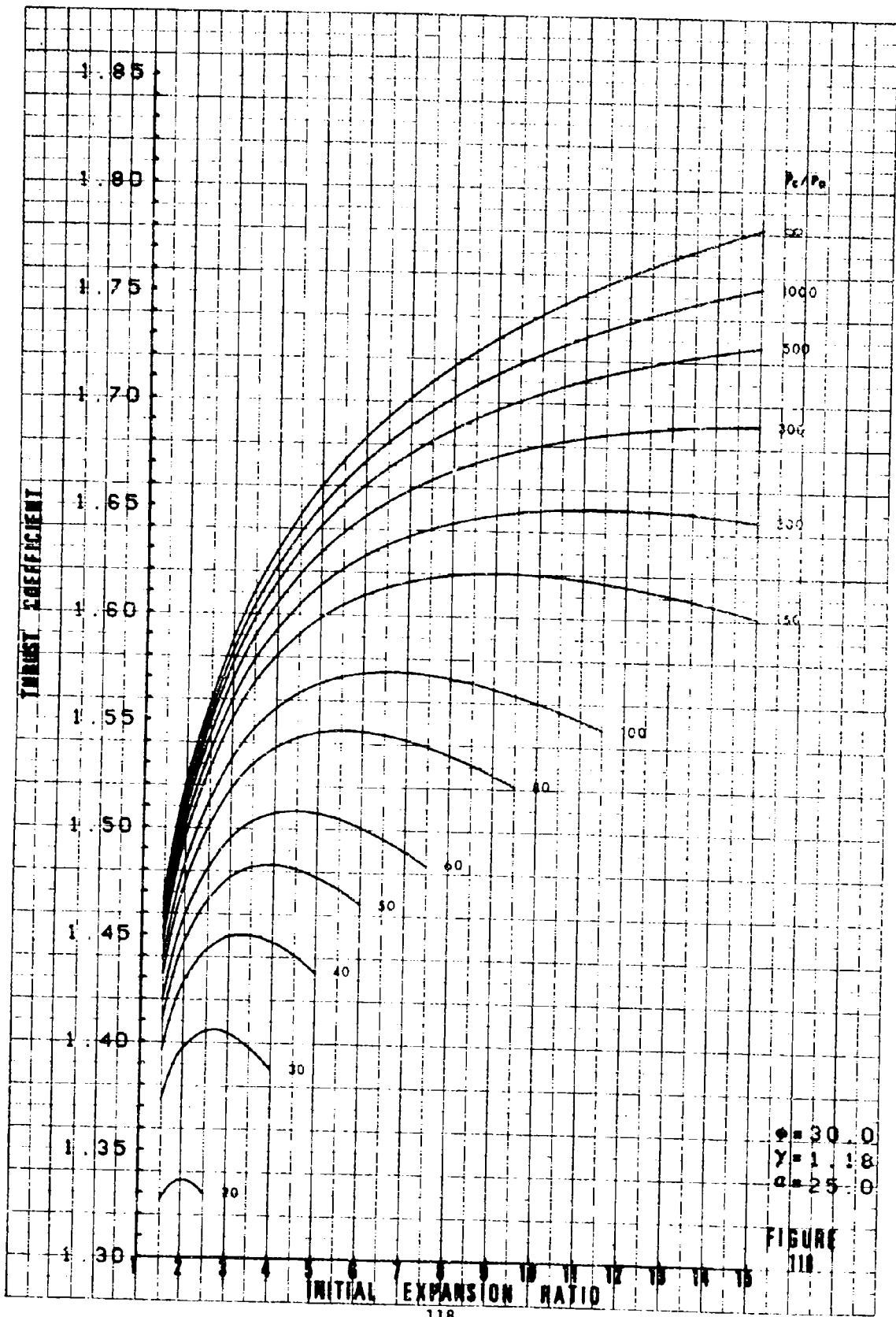
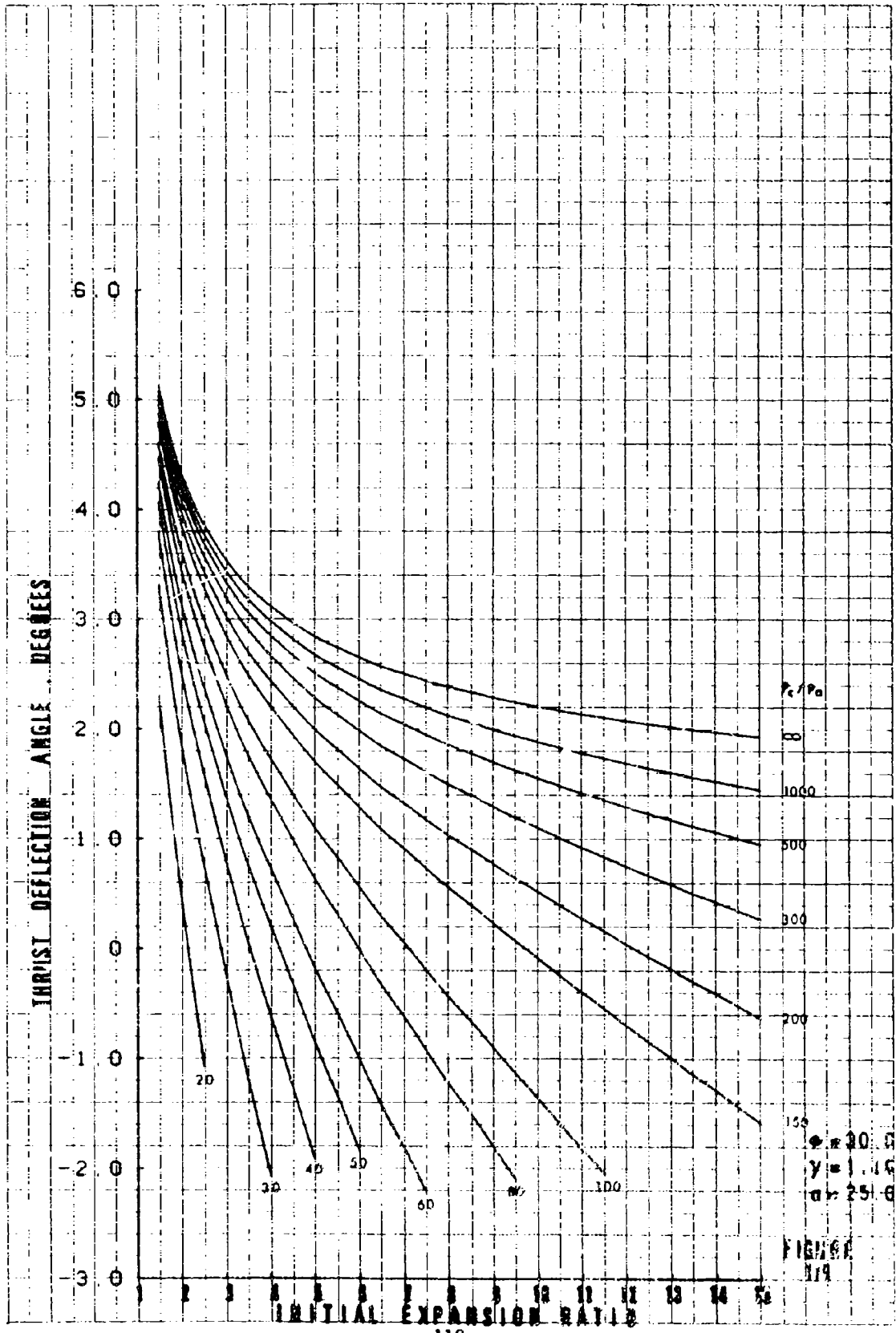
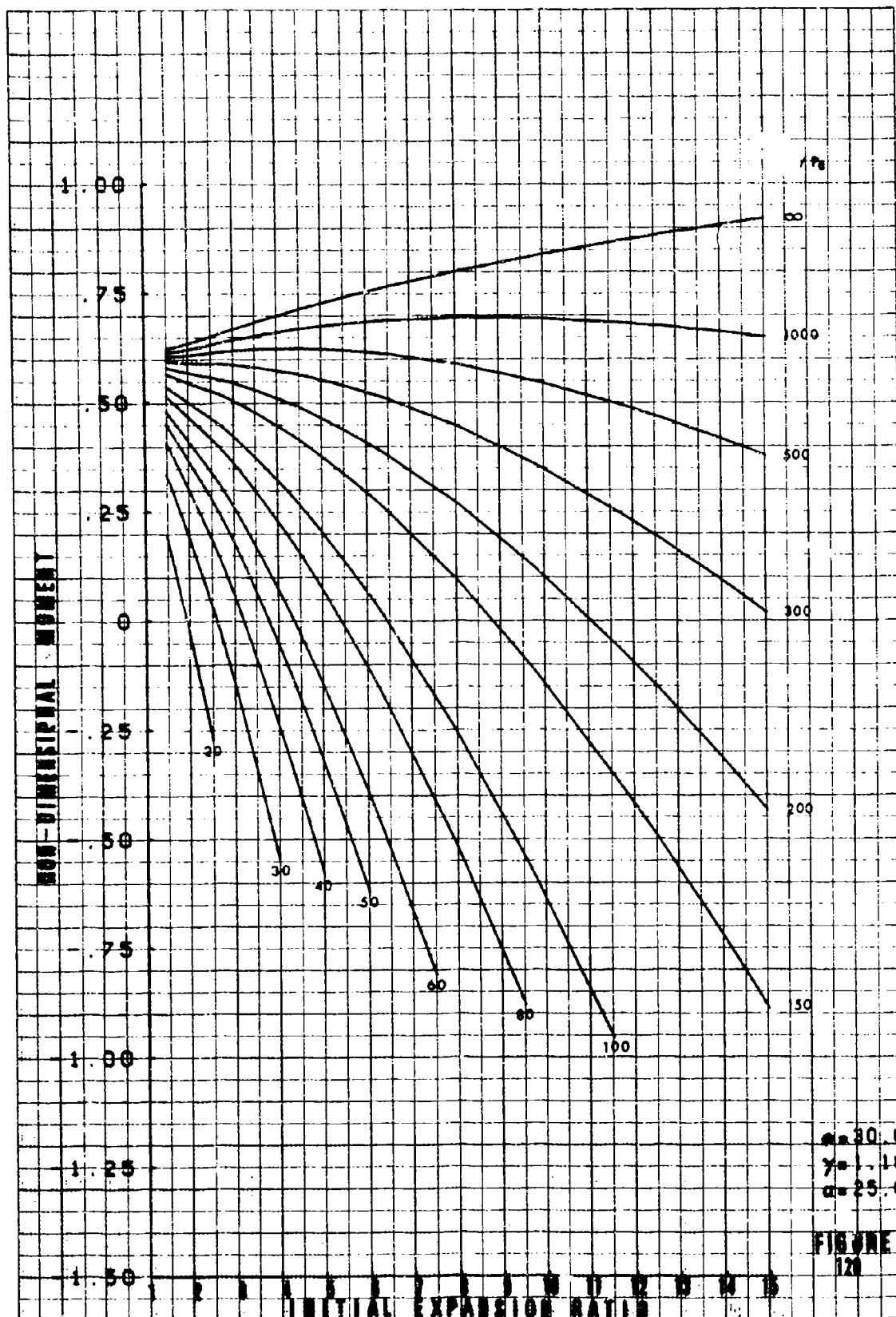
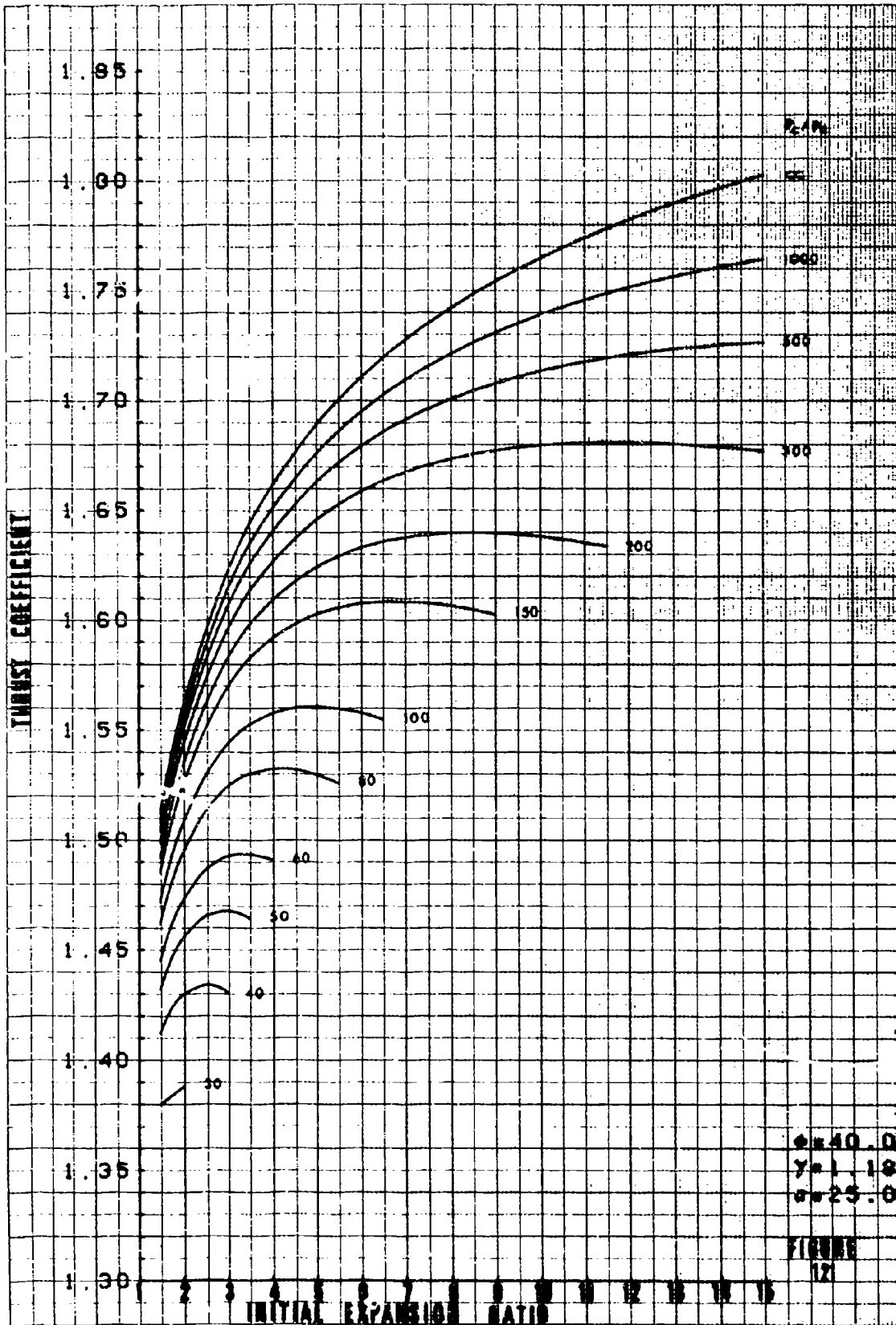


FIGURE 118









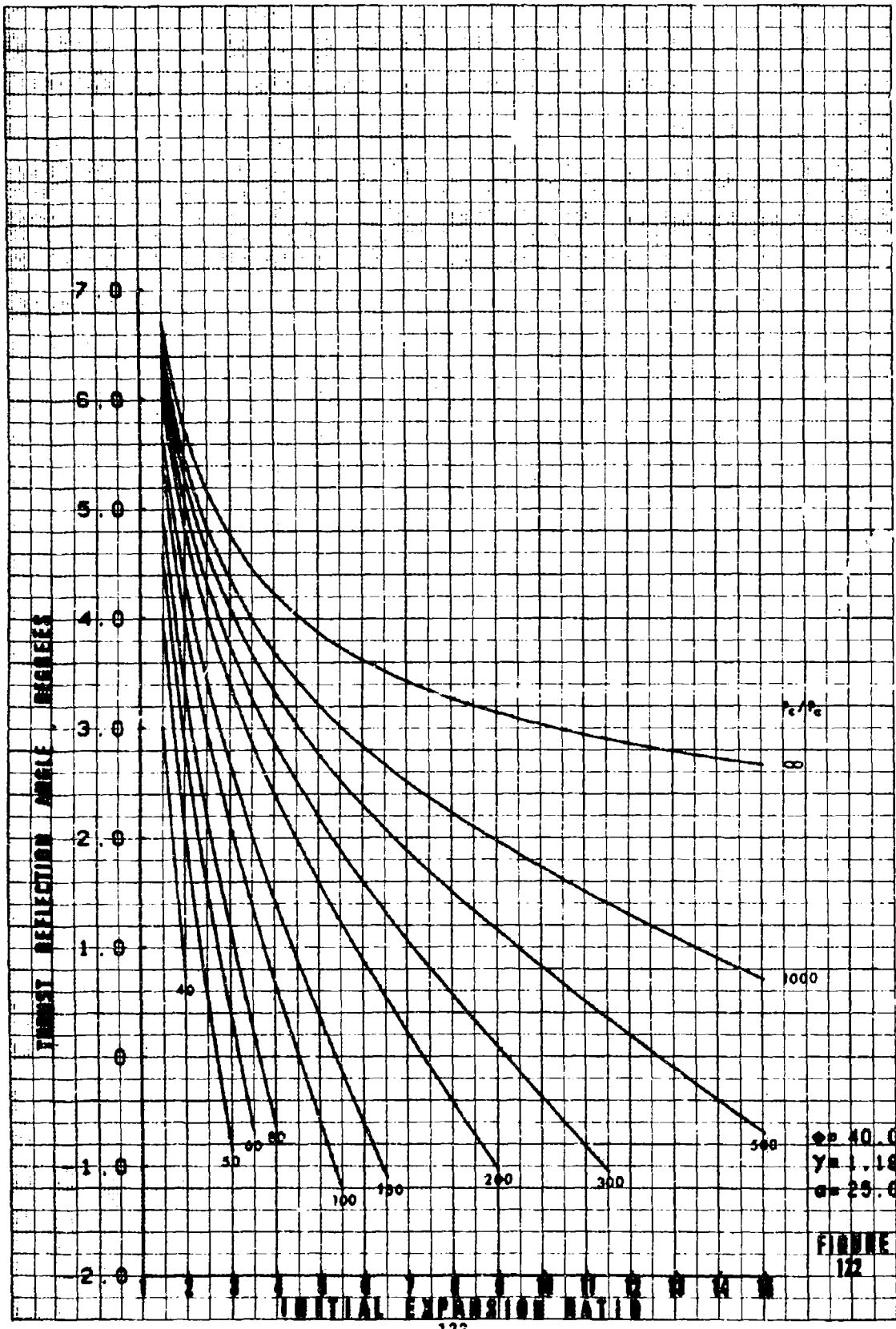
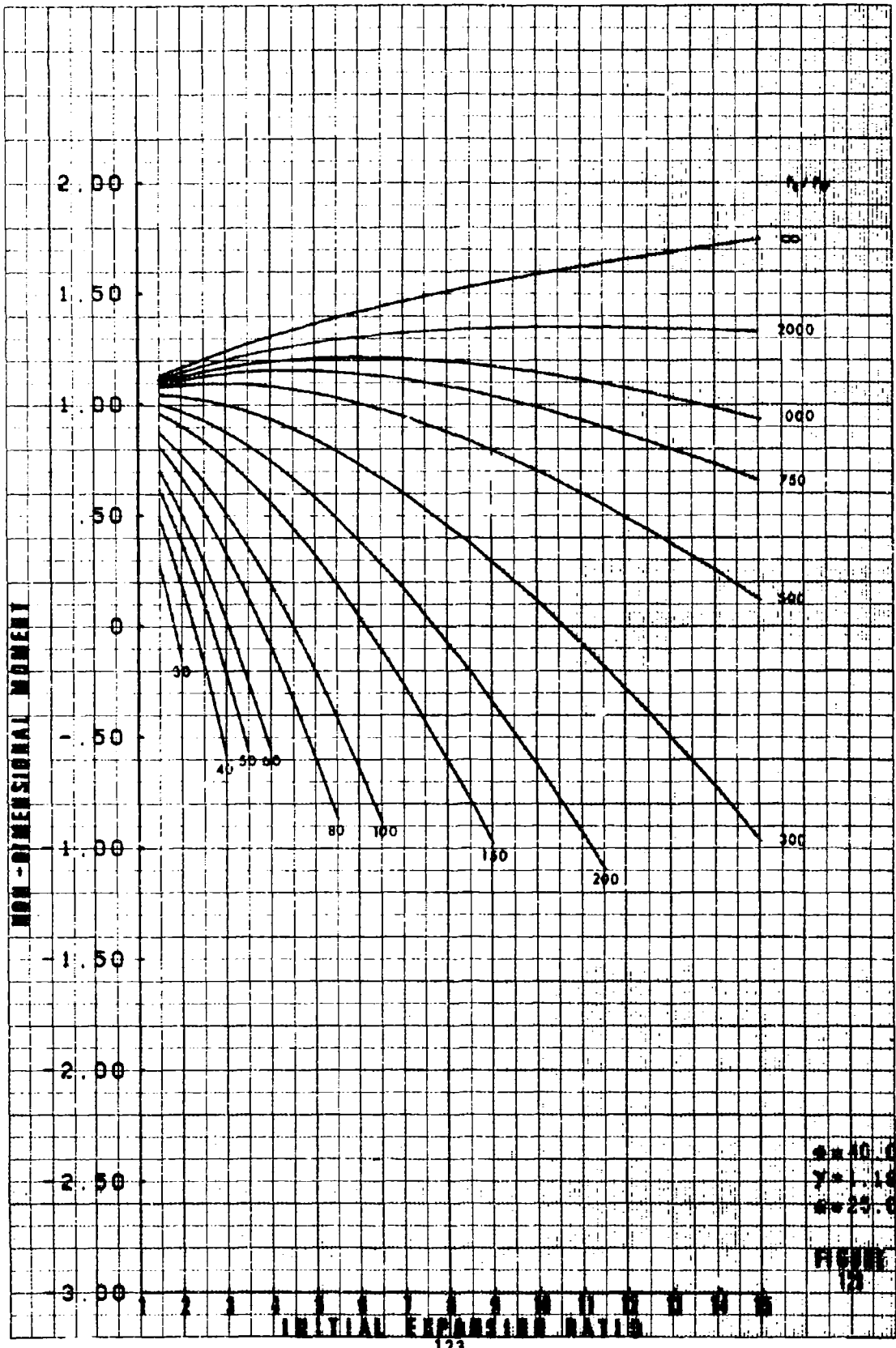
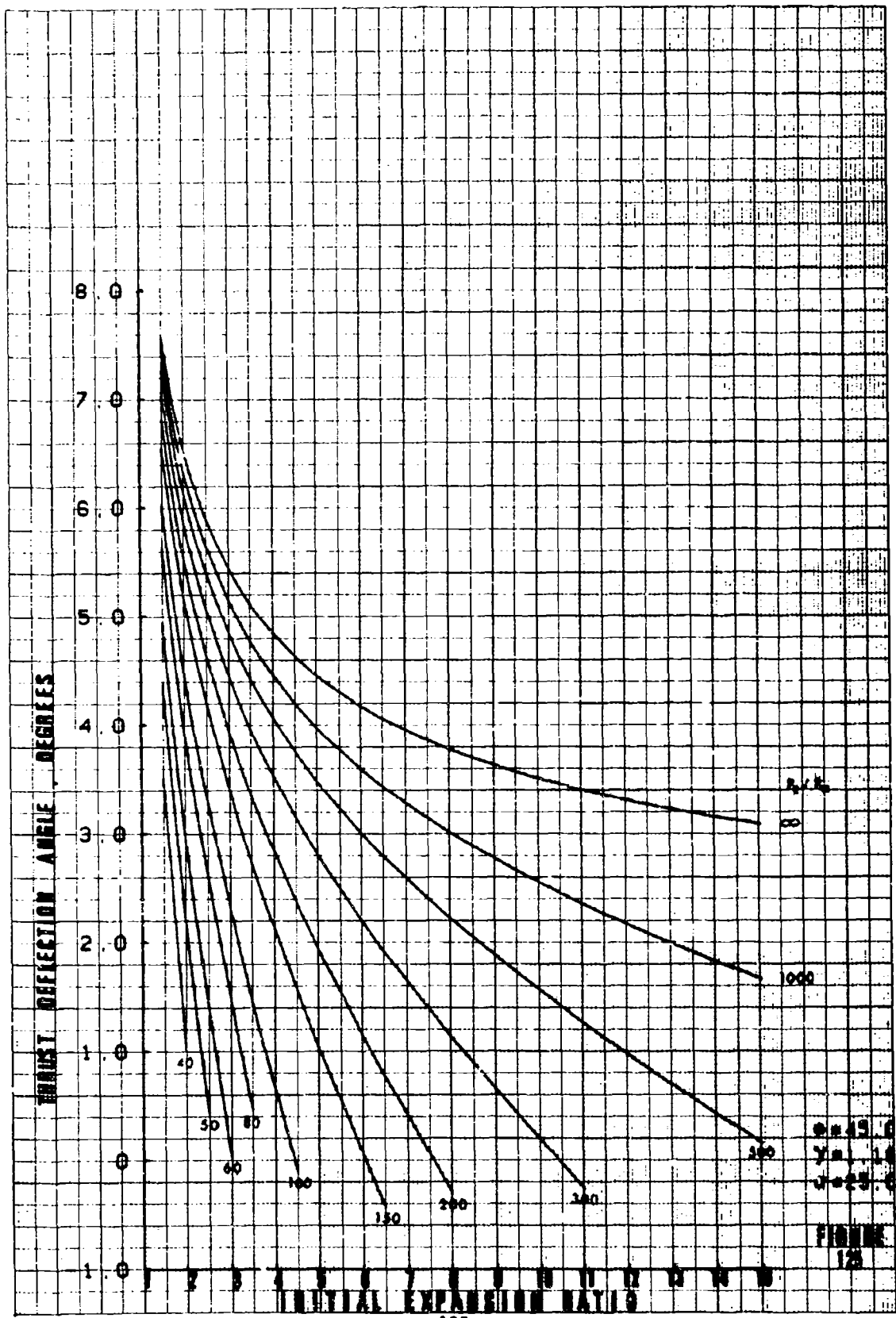


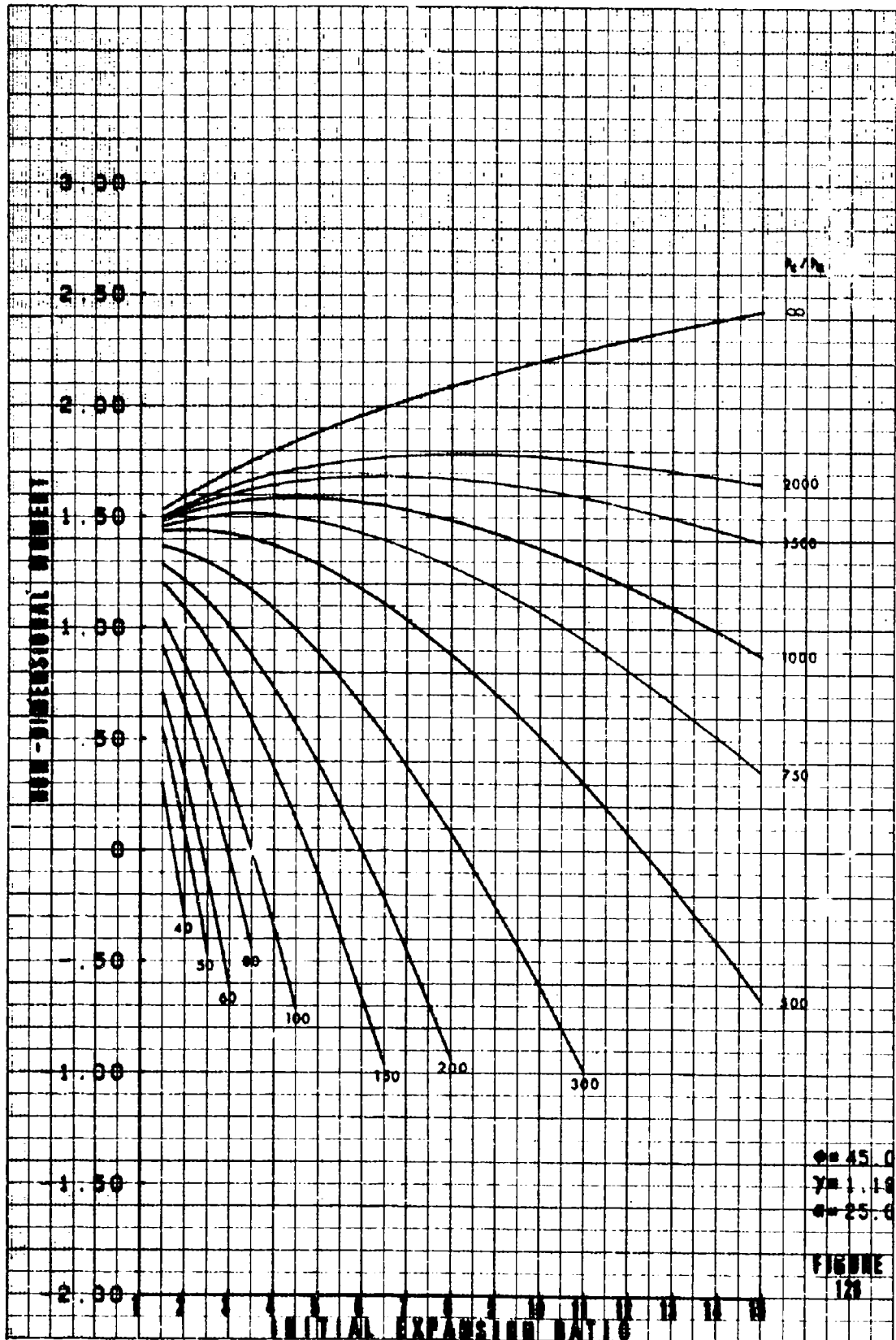
FIGURE 122

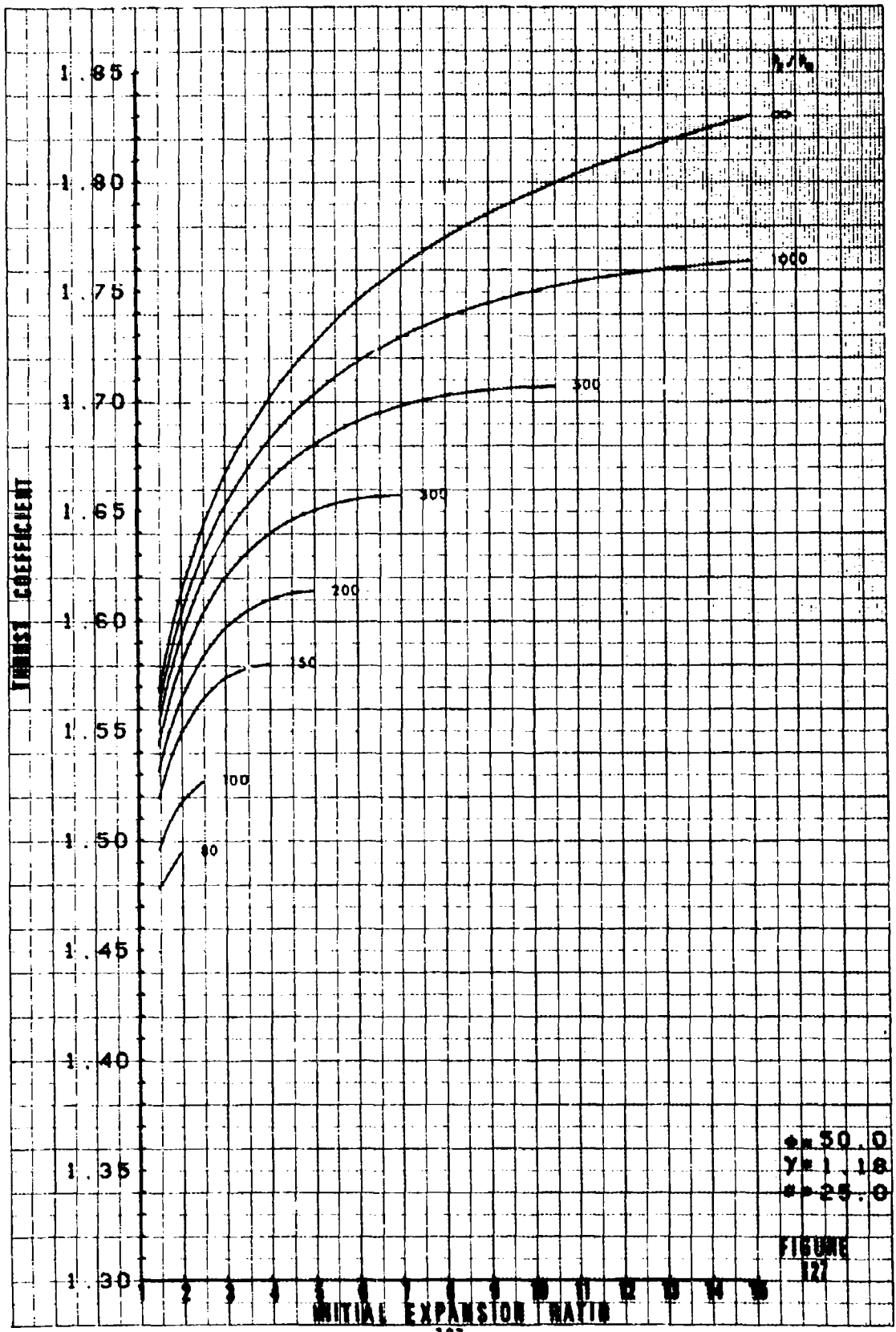


$\mu = 40.0$   
 $\gamma = 1.0$   
 $\delta = 25.0$   
 FIGURE 12





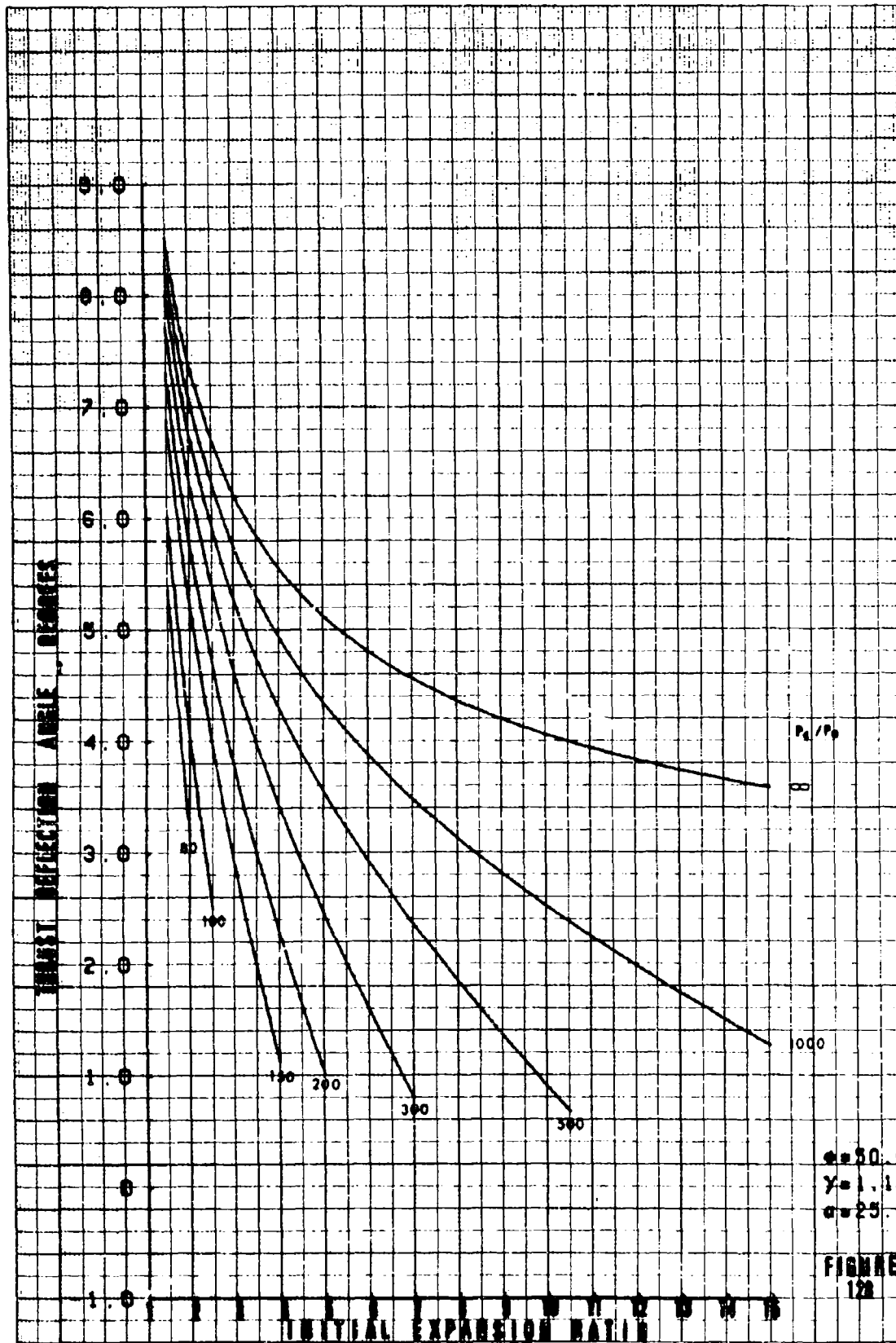


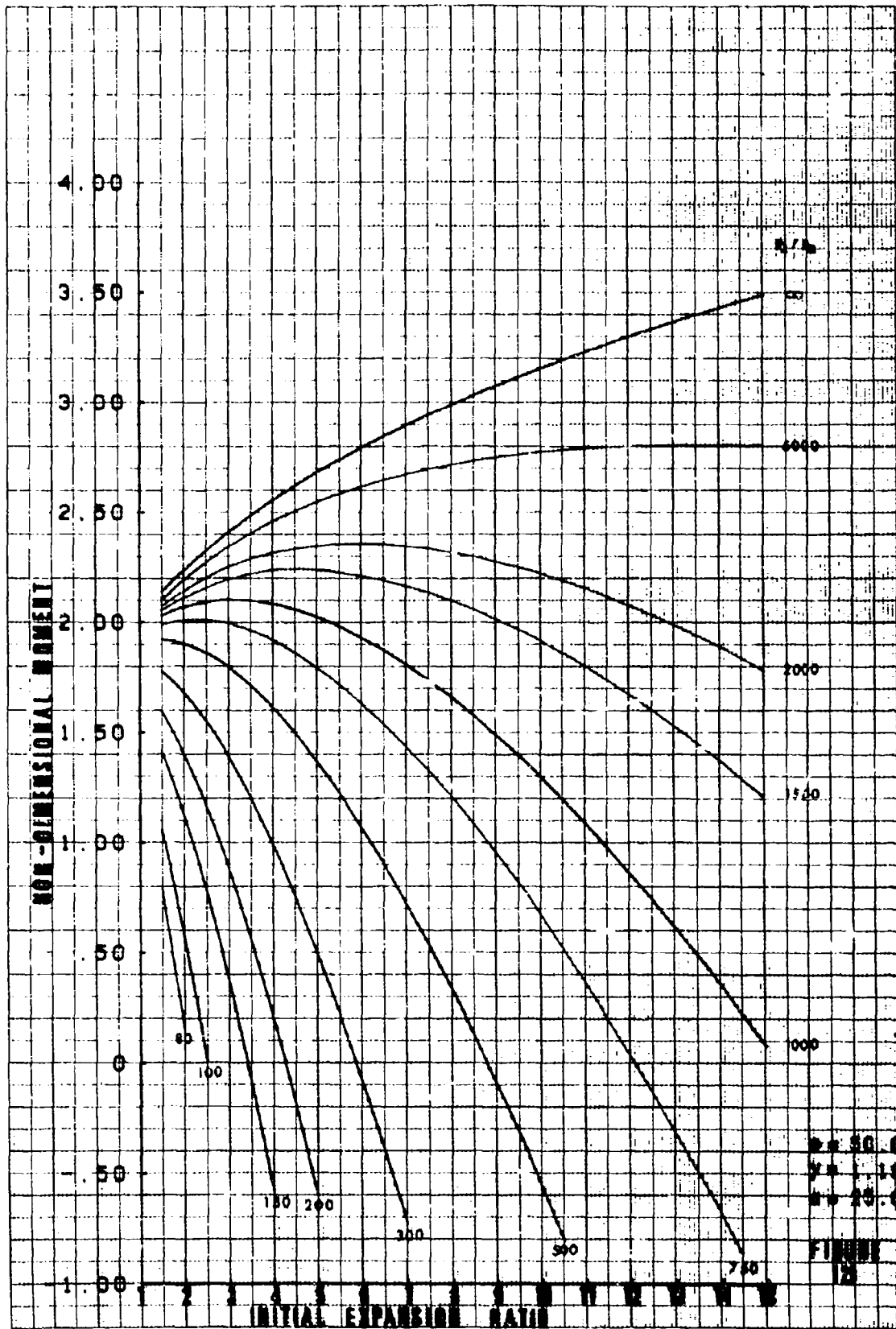


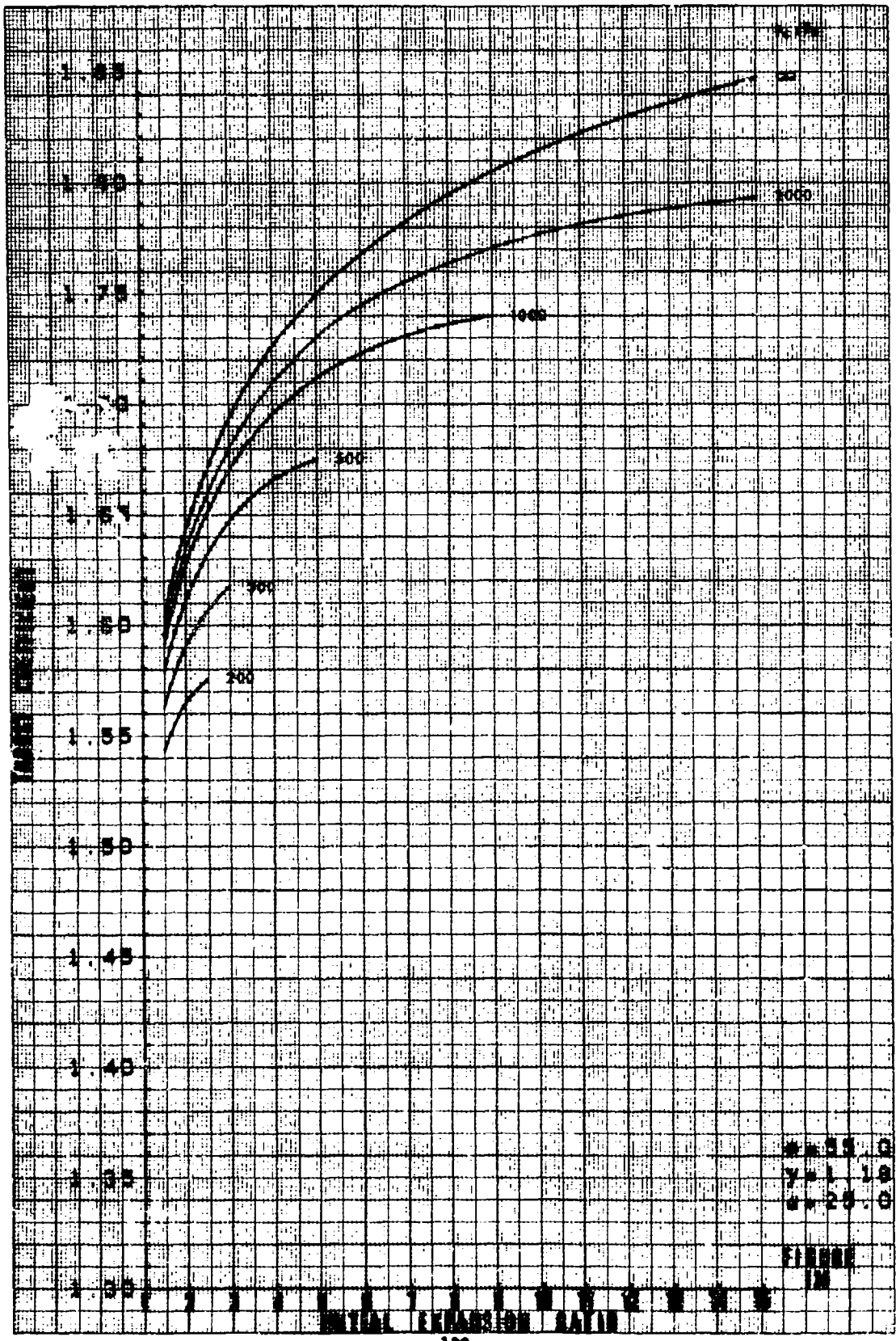
\* 50.0  
 γ = 1.18  
 \* 25.0

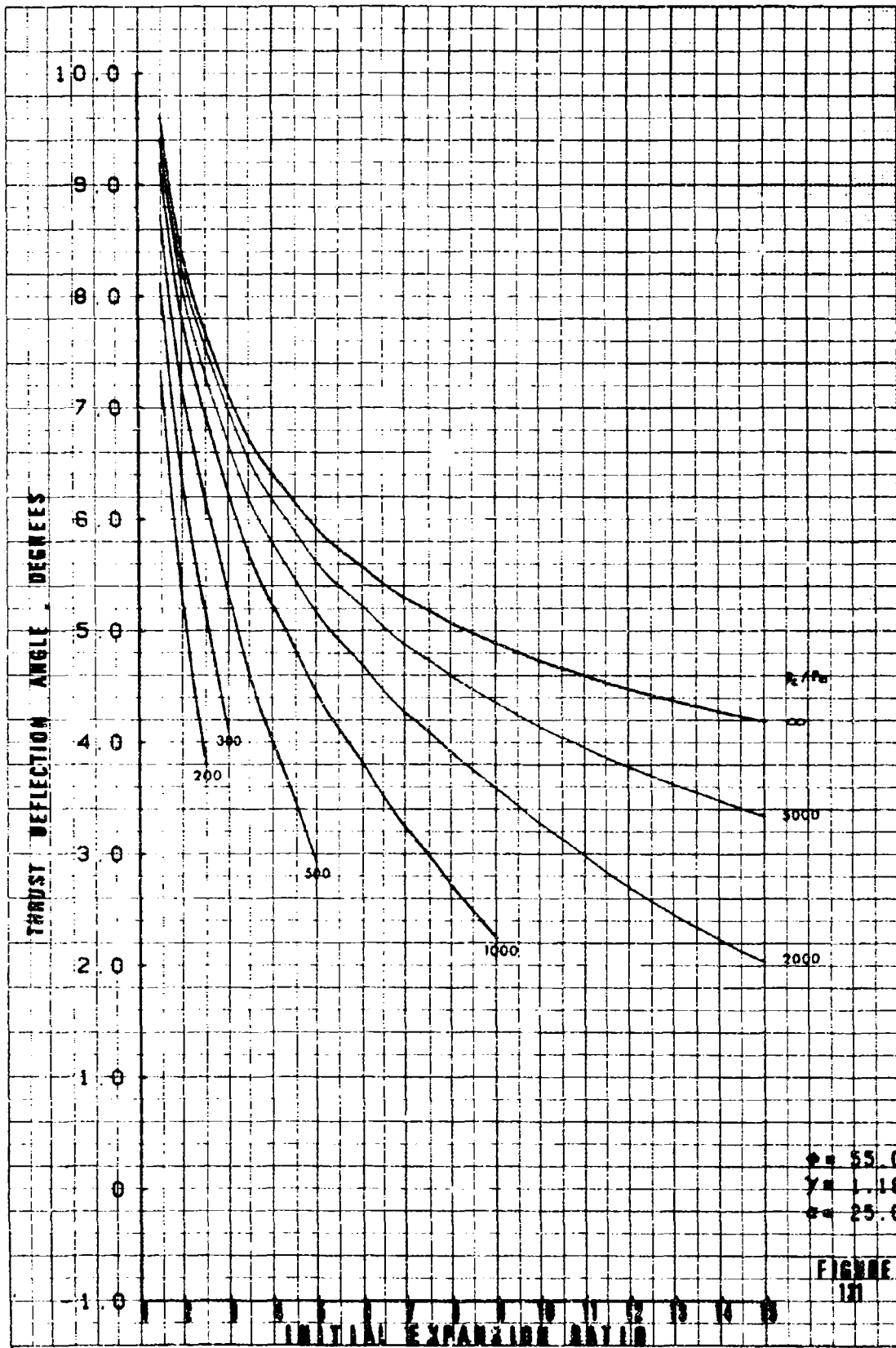
FIGURE 127

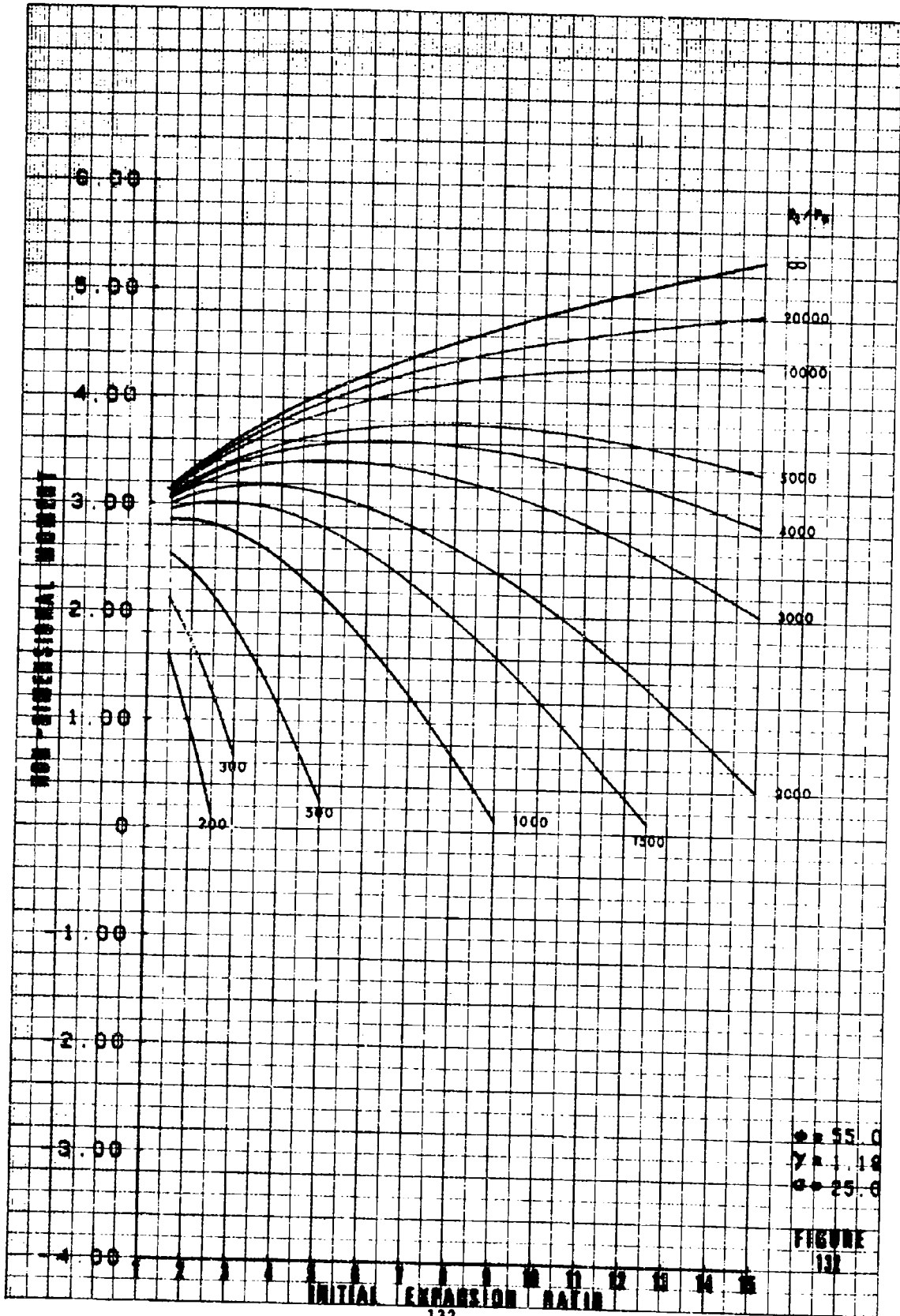


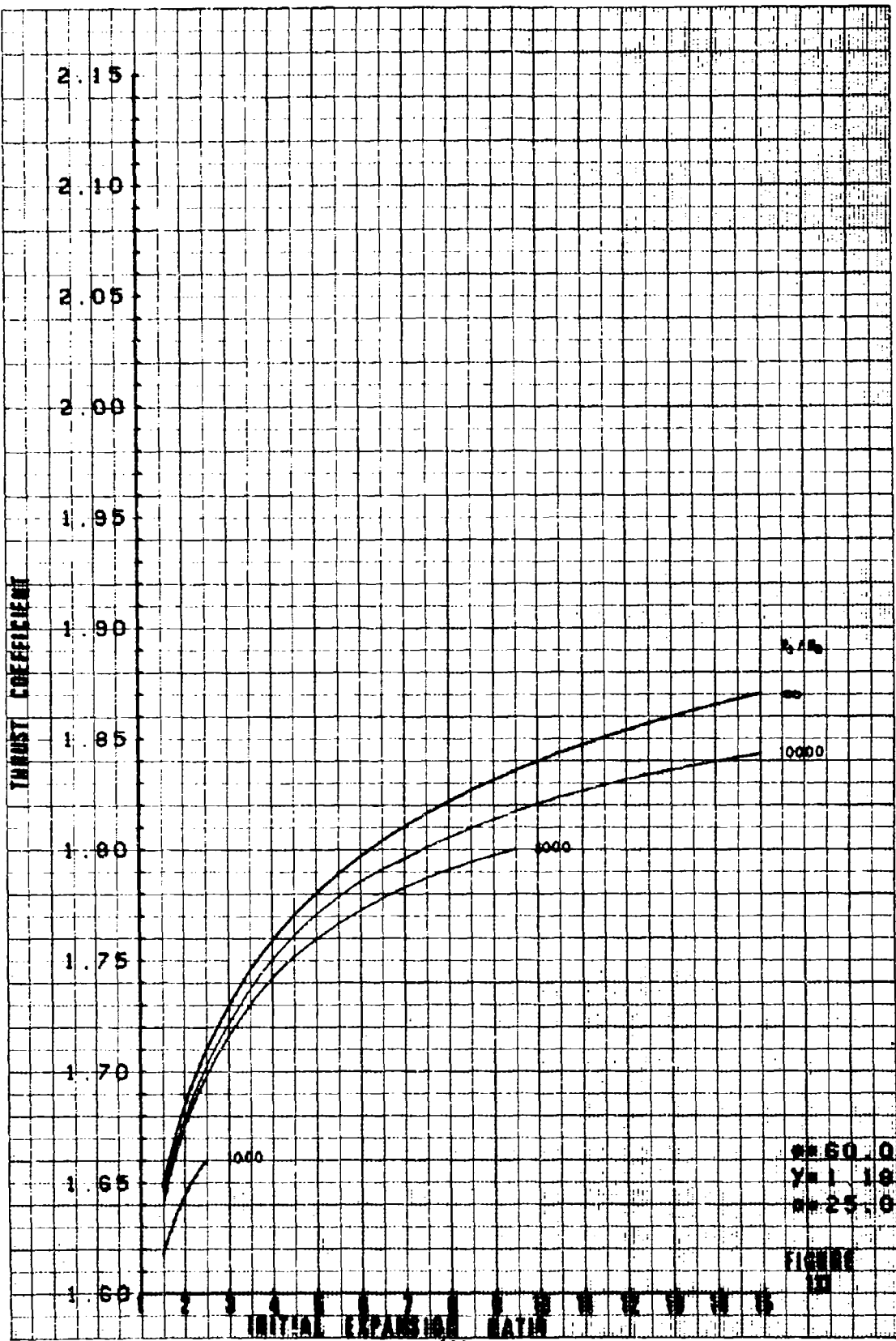






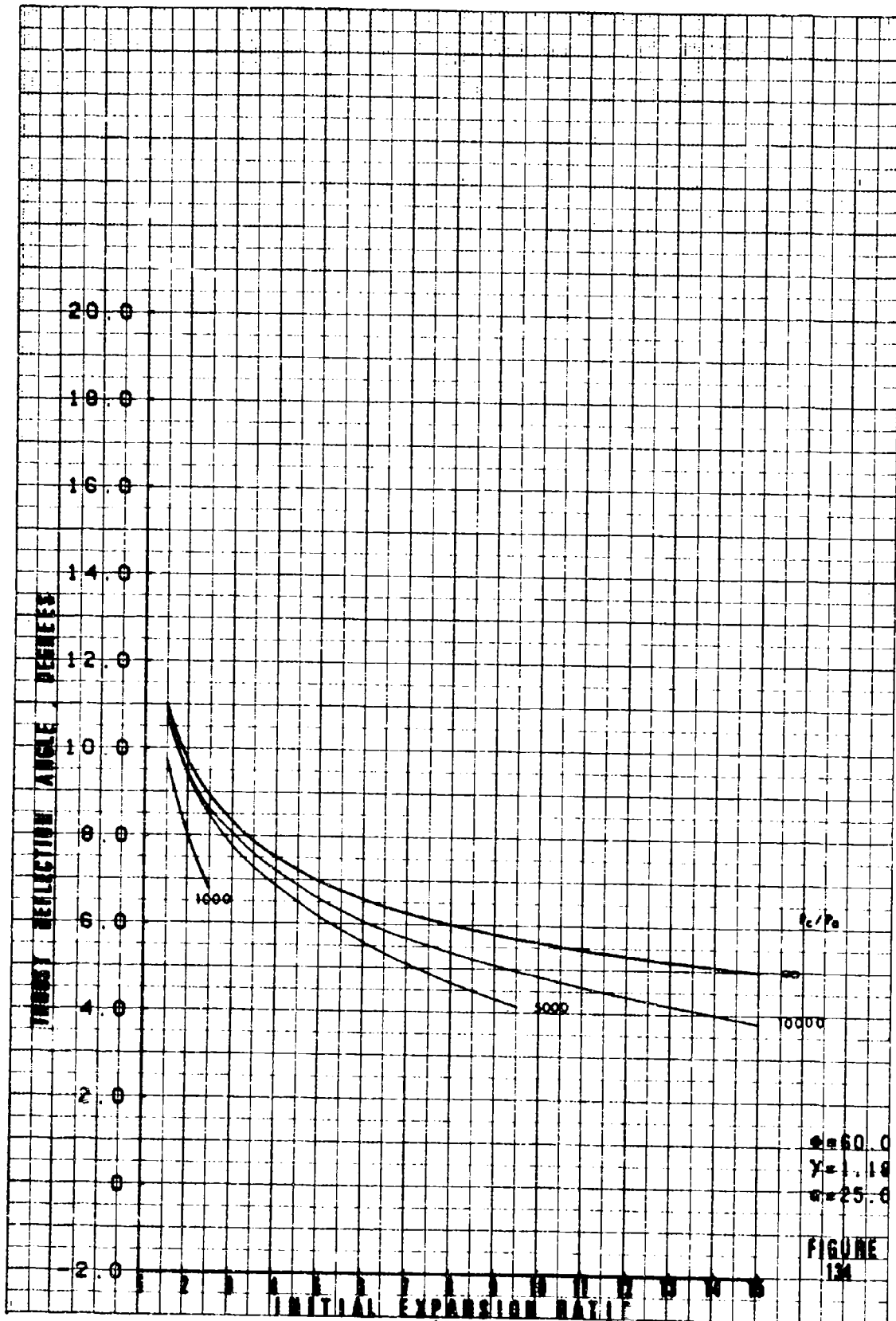


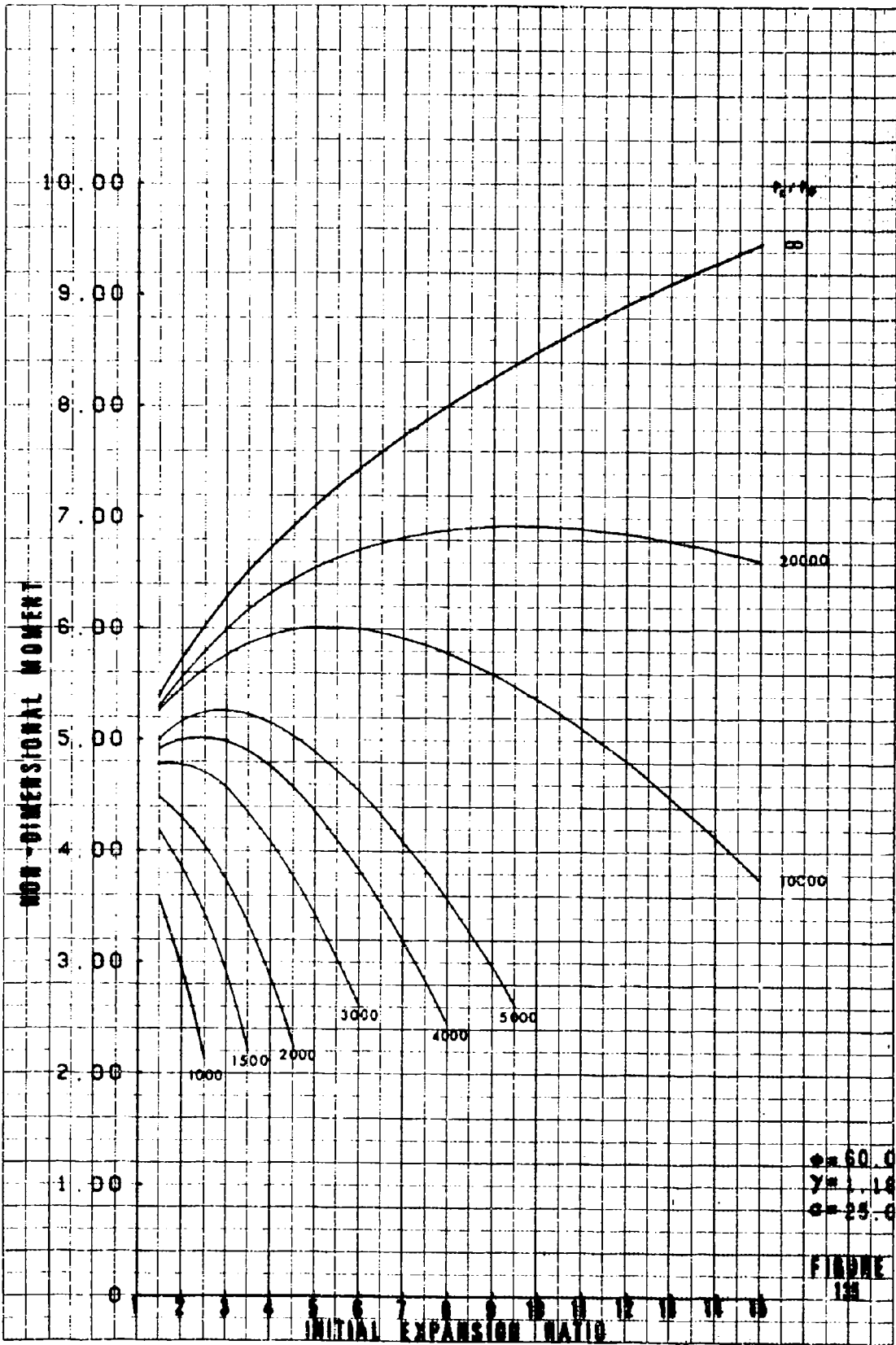




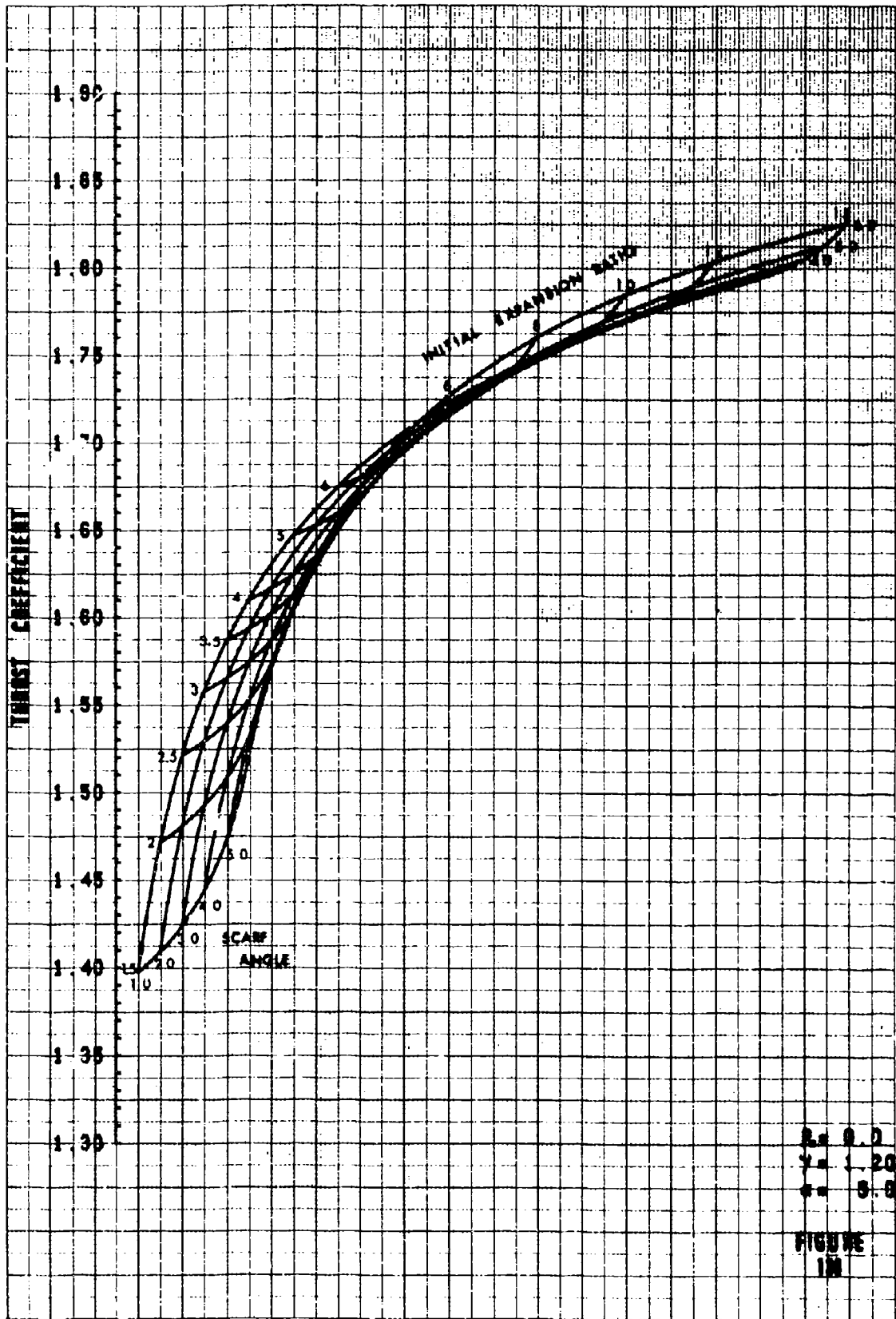
M=60.0  
 Y=1.18  
 M=25.0

FIGURE 13



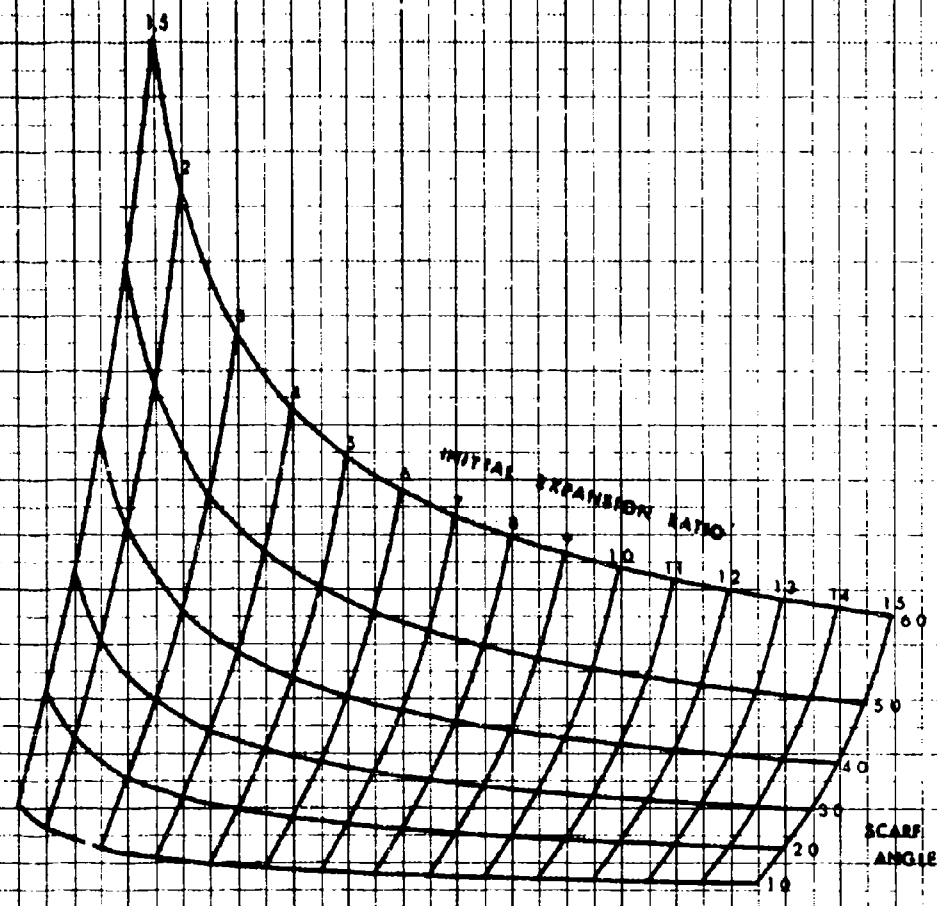




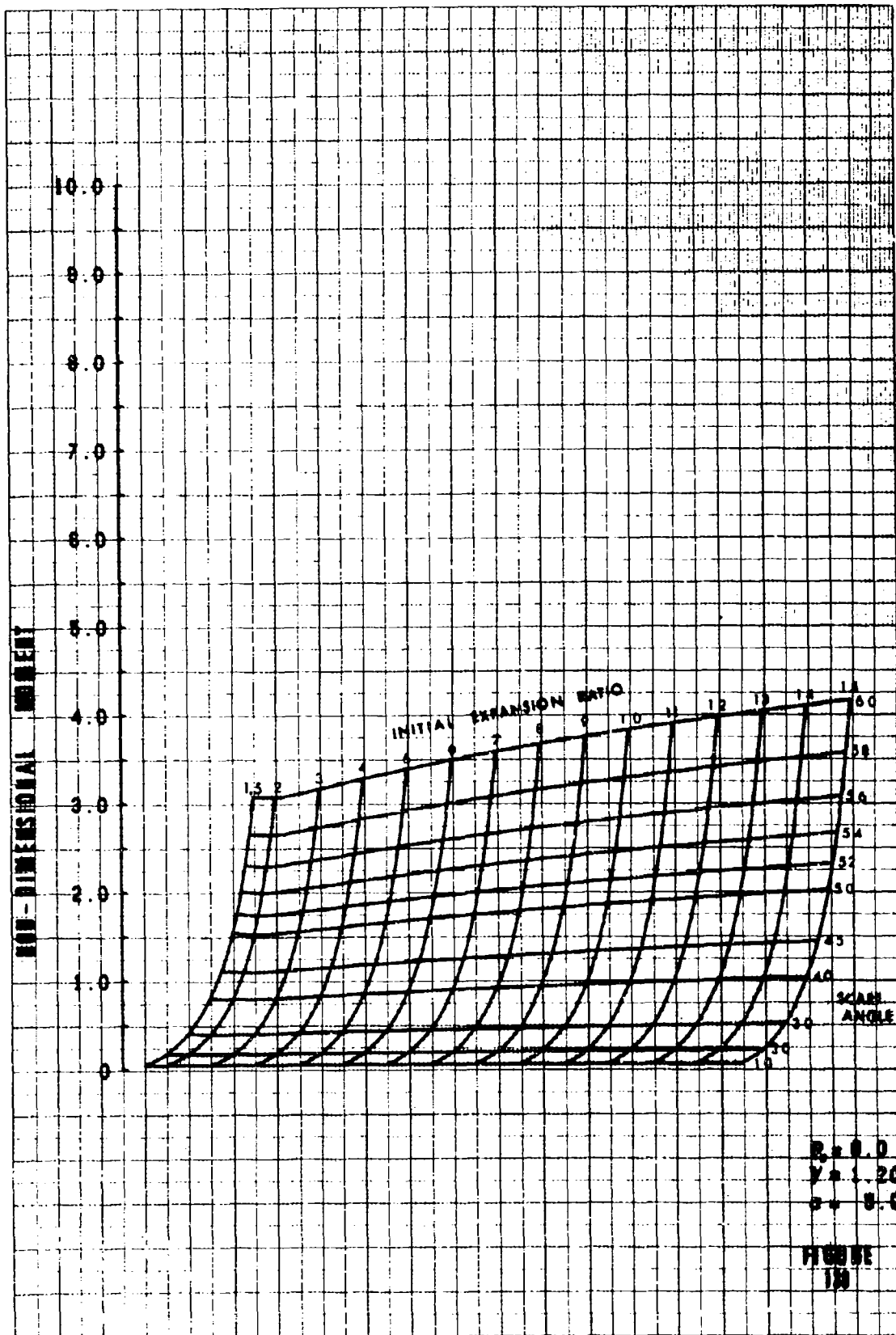


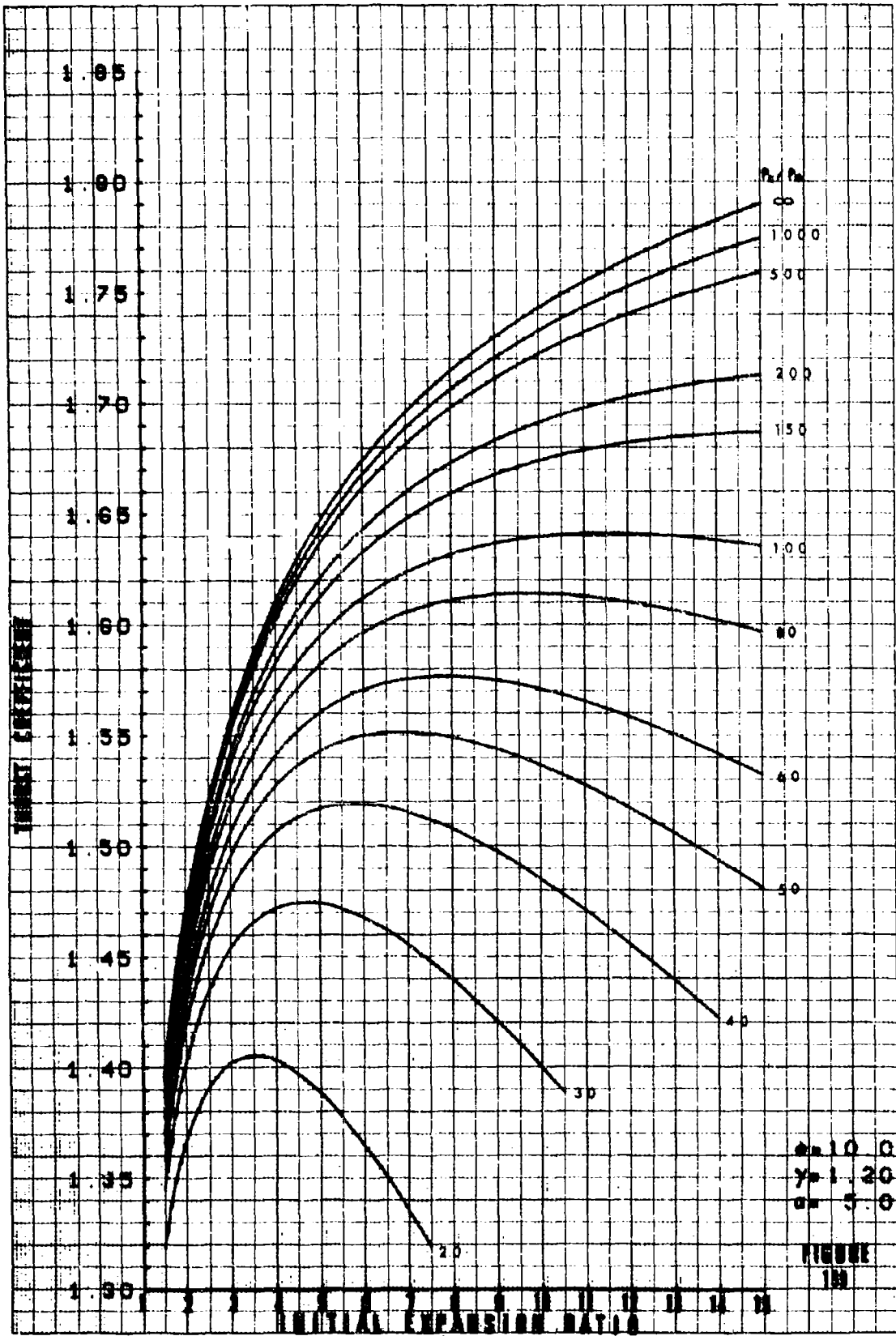
INITIAL EXPANSION RATIO

17.0  
16.0  
15.0  
14.0  
13.0  
12.0  
11.0  
10.0  
9.0  
8.0  
7.0  
6.0  
5.0  
4.0  
3.0  
2.0  
1.0  
0



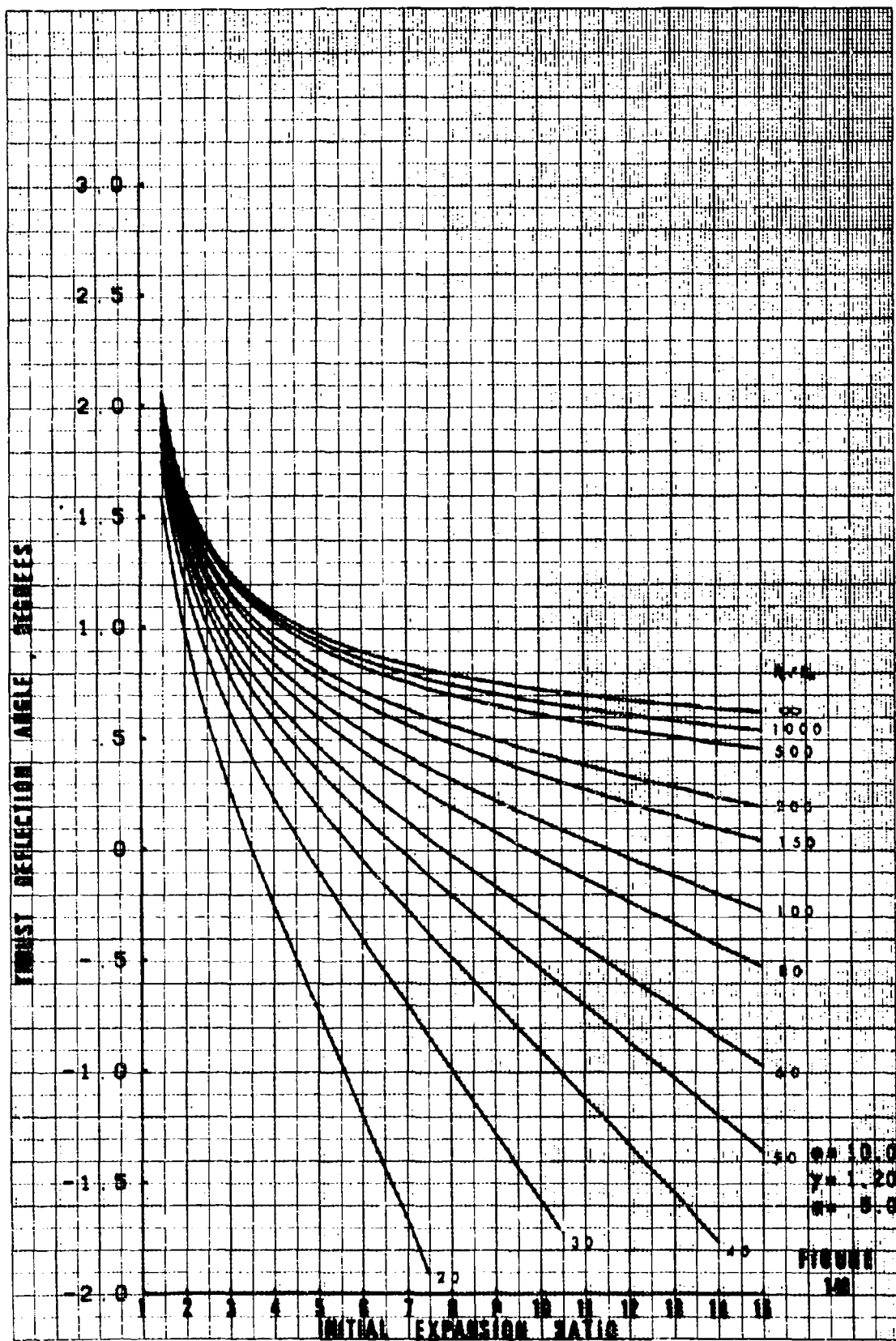
$R = 0.8$   
 $\gamma = 1.20$   
 $\mu = 0.6$   
FIGURE 11





$\gamma = 1.20$   
 $\sigma = 5.0$

FIGURE 100



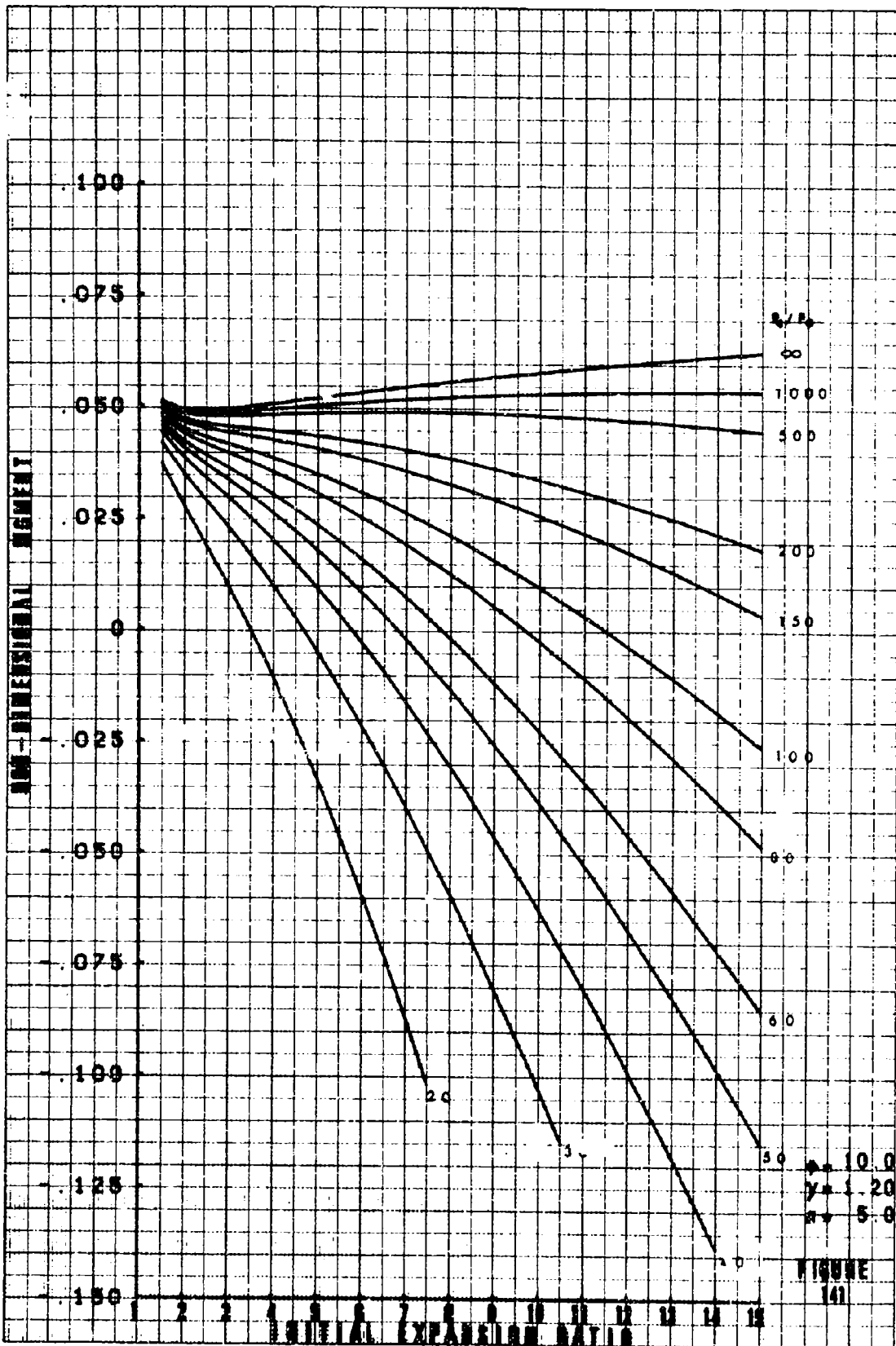


FIGURE 141

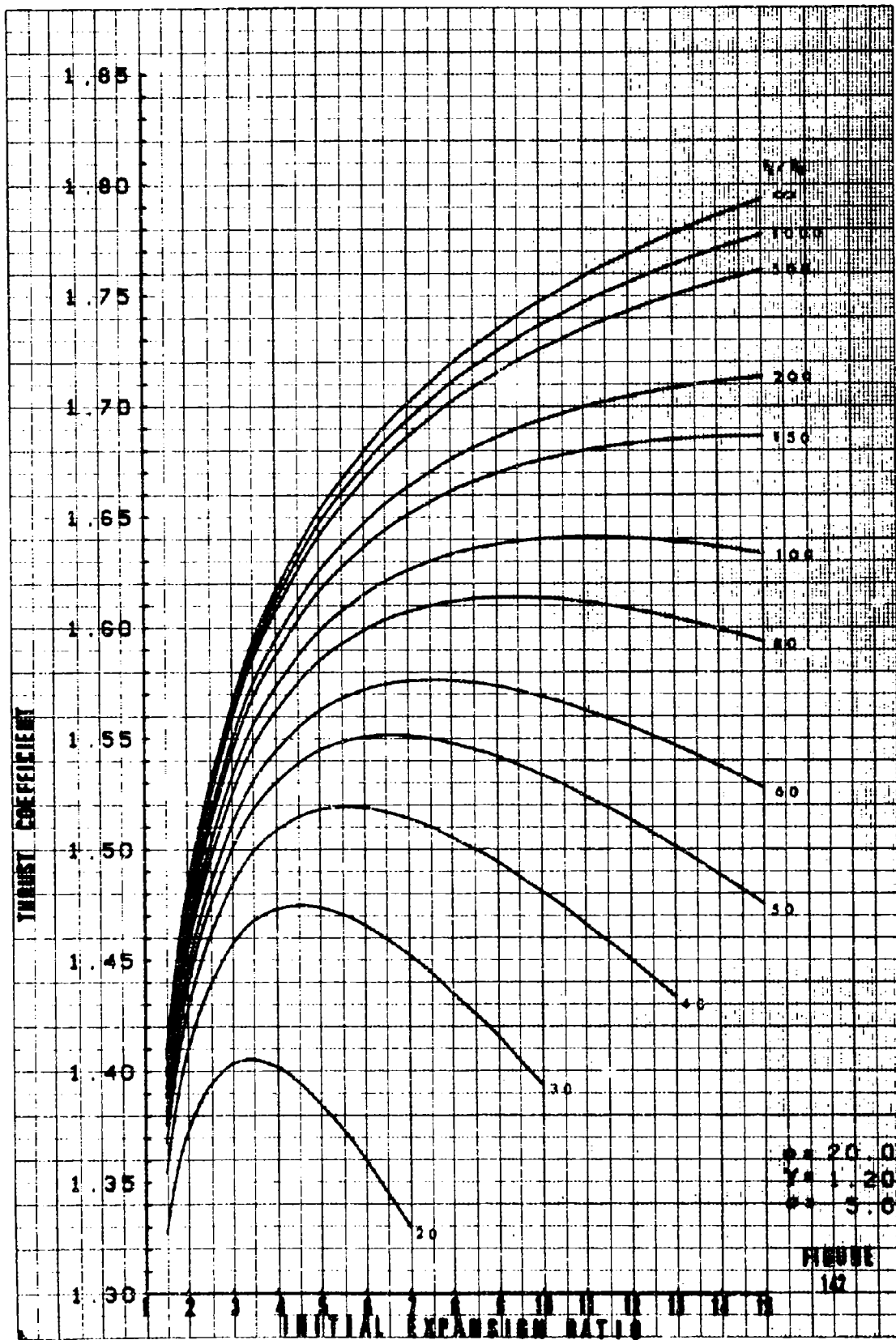
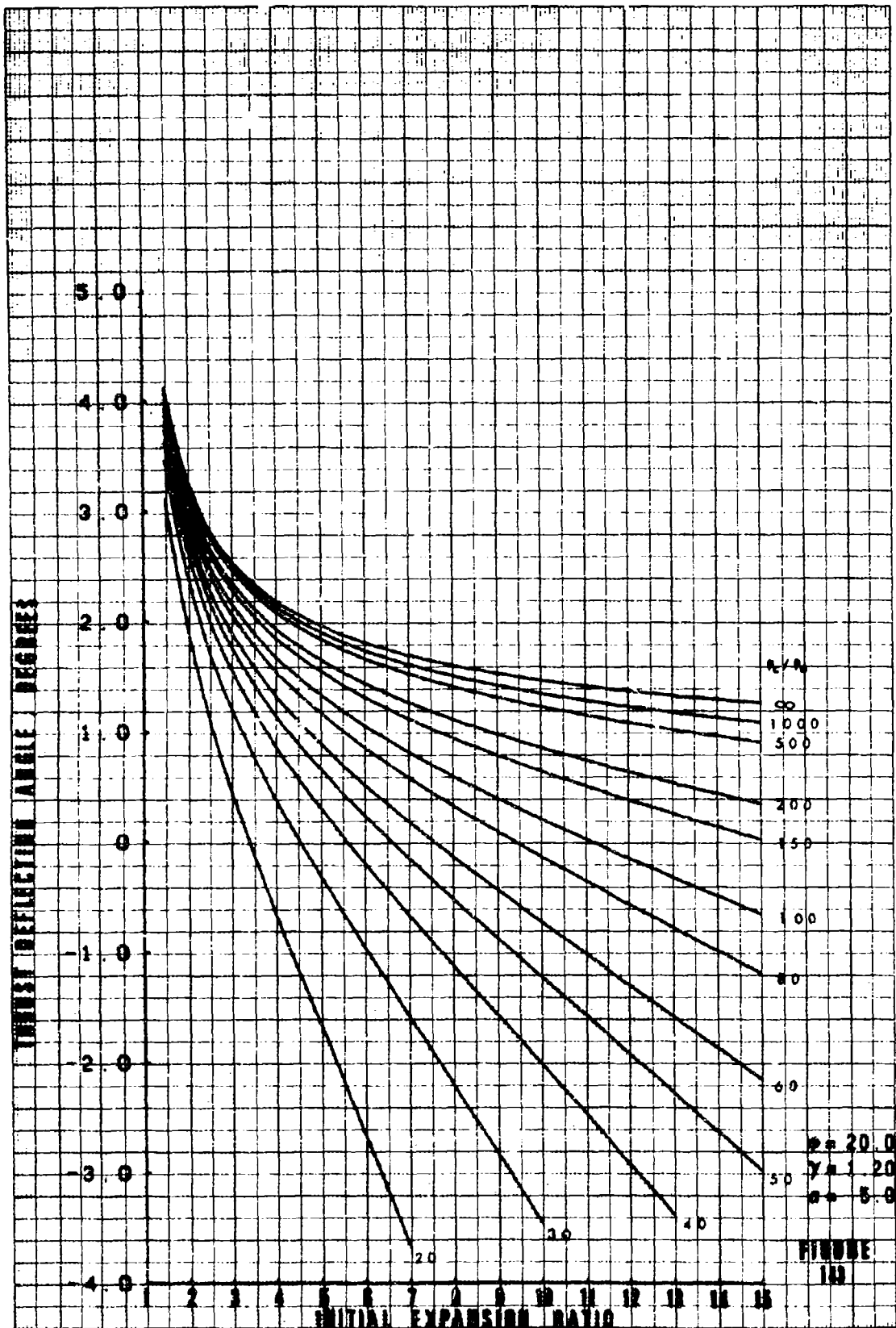
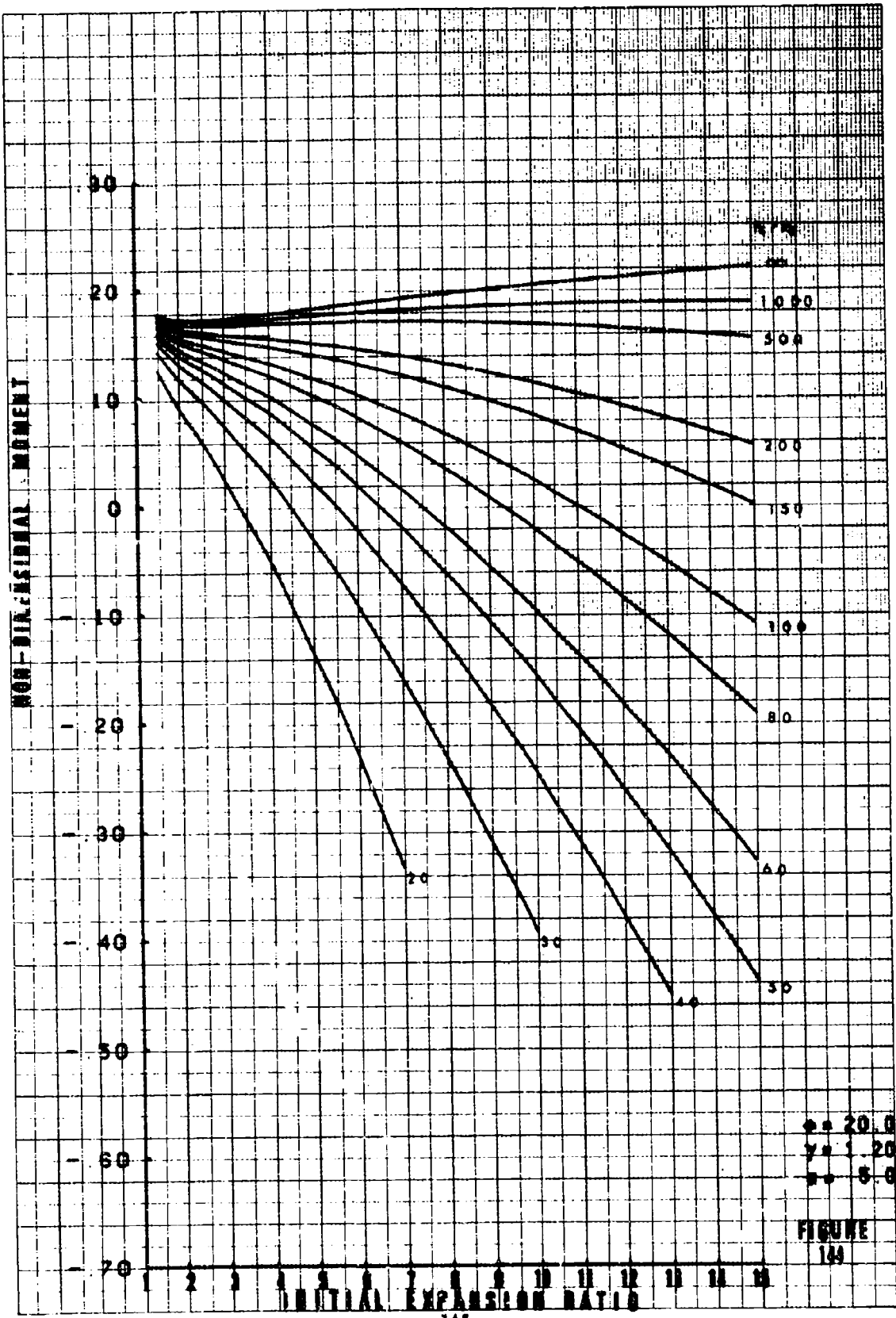
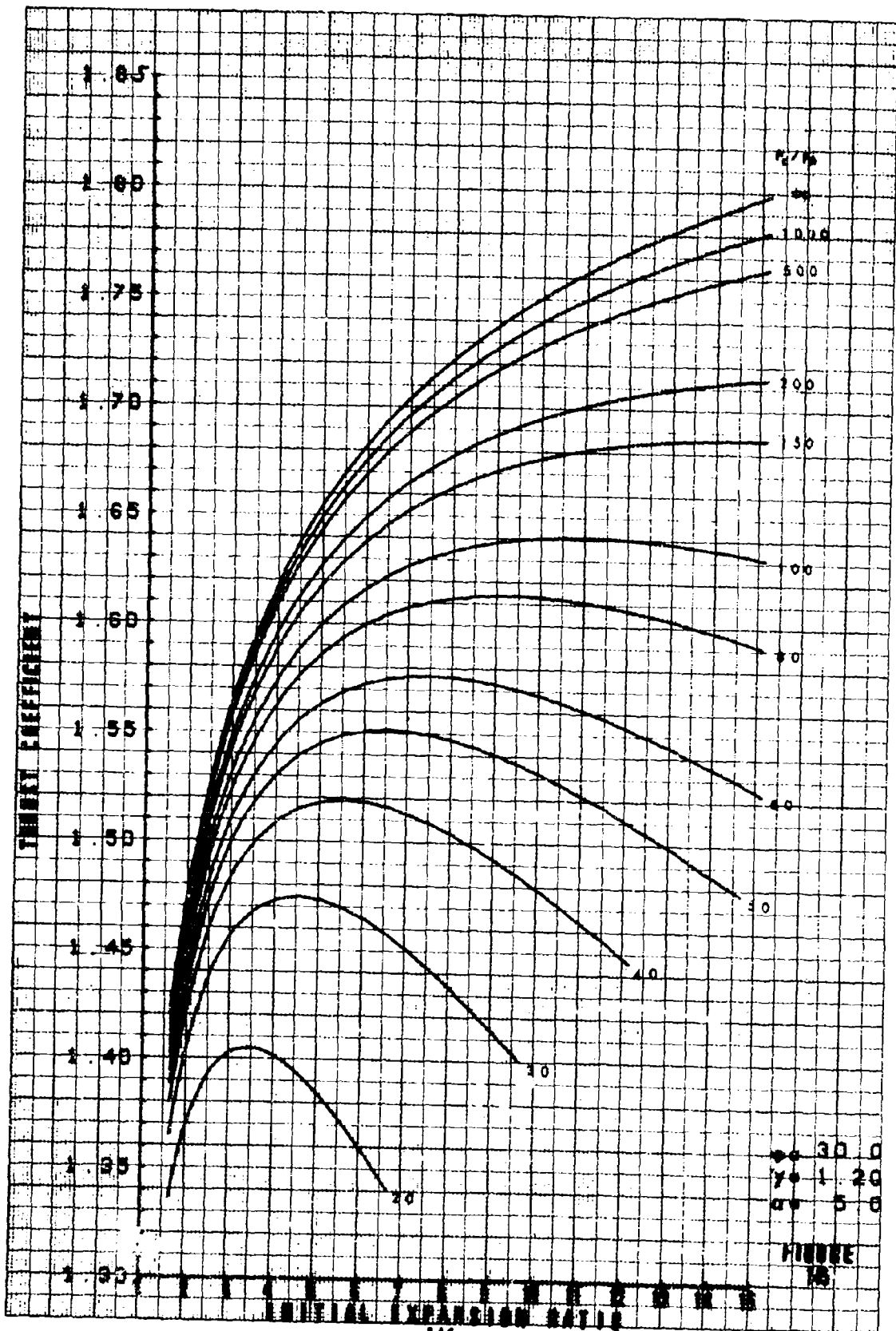


FIGURE 142



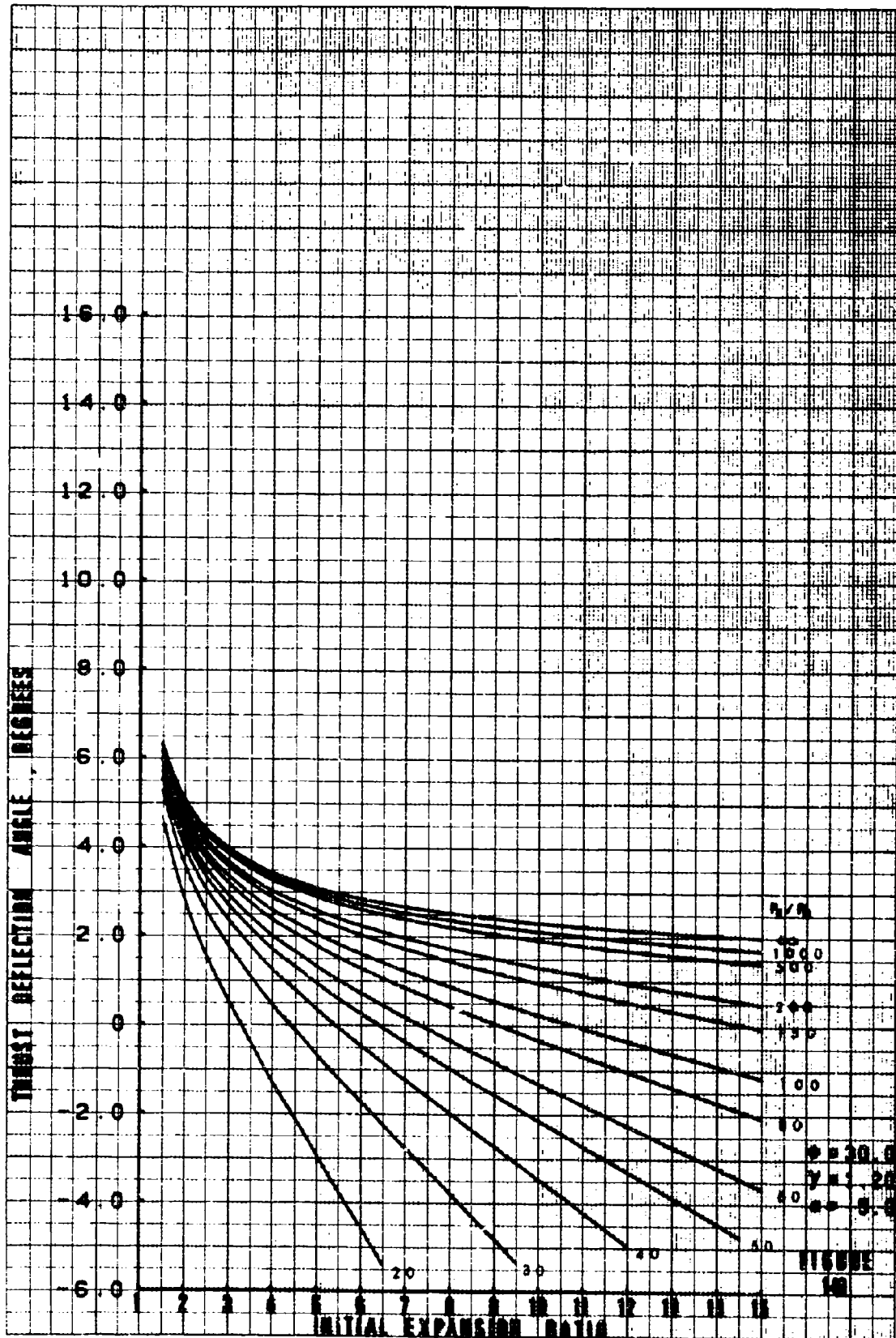






$P_2/P_1 = 30.0$   
 $P_2/P_1 = 1.20$   
 $P_2/P_1 = 5.0$

FIGURE 76



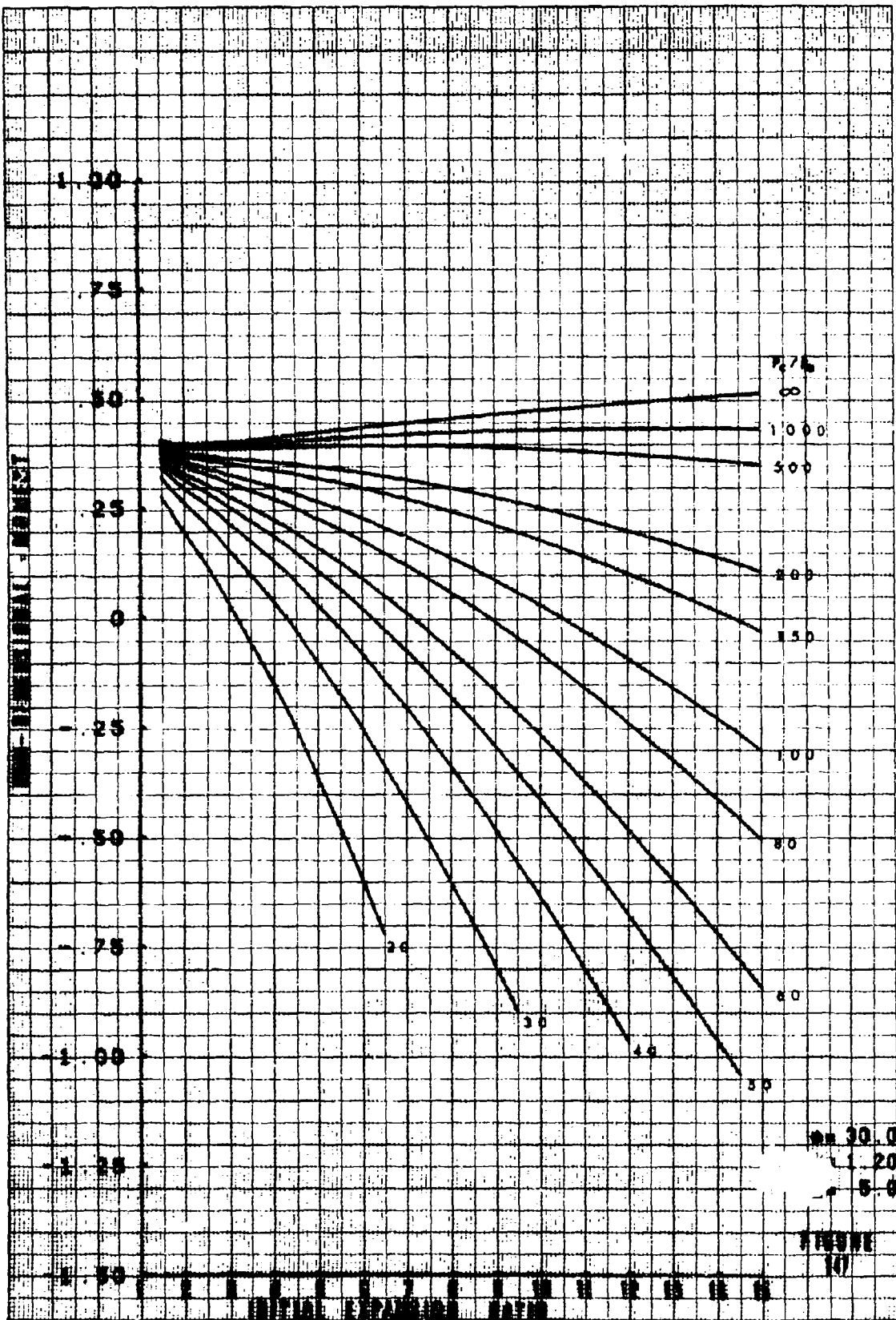
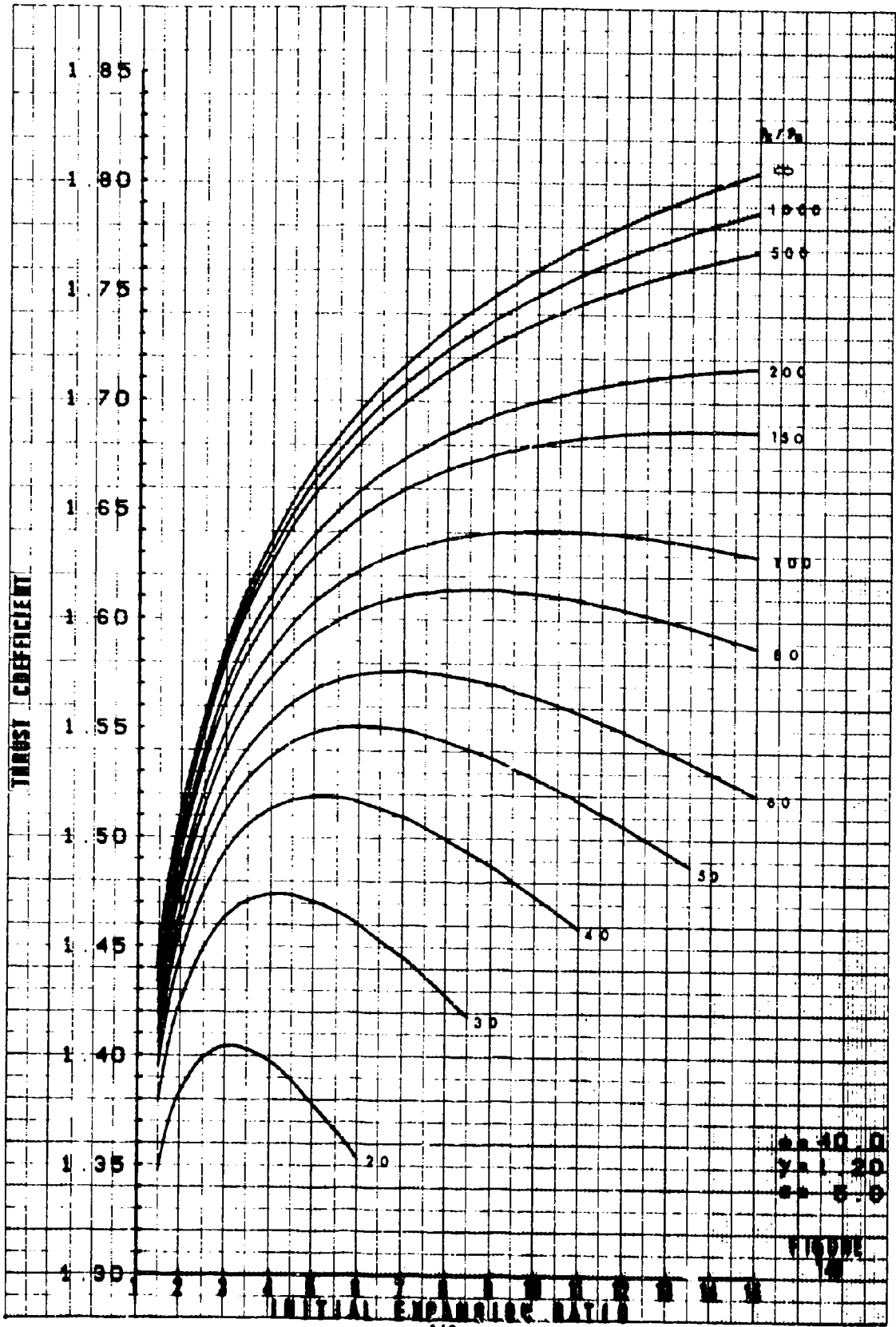
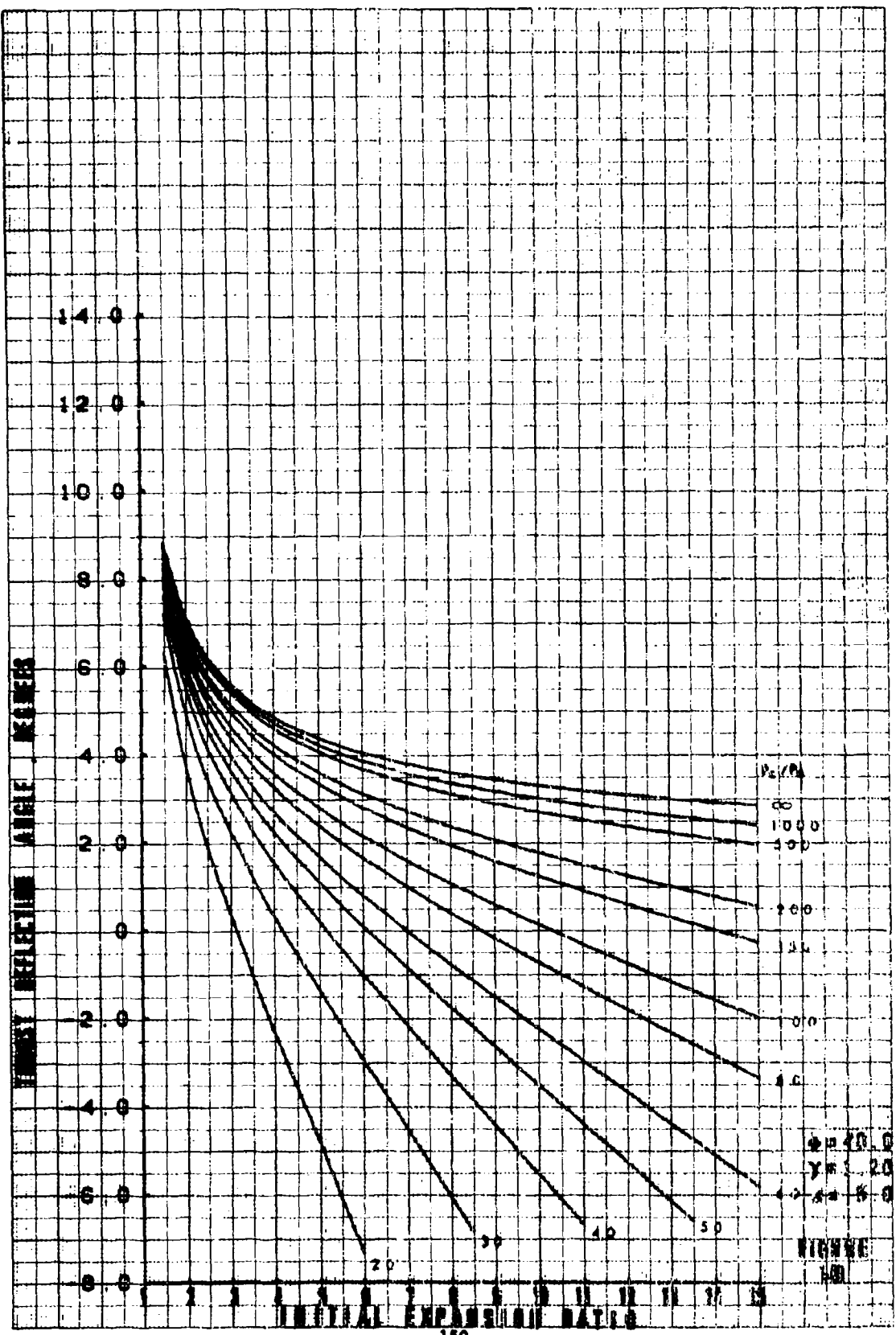
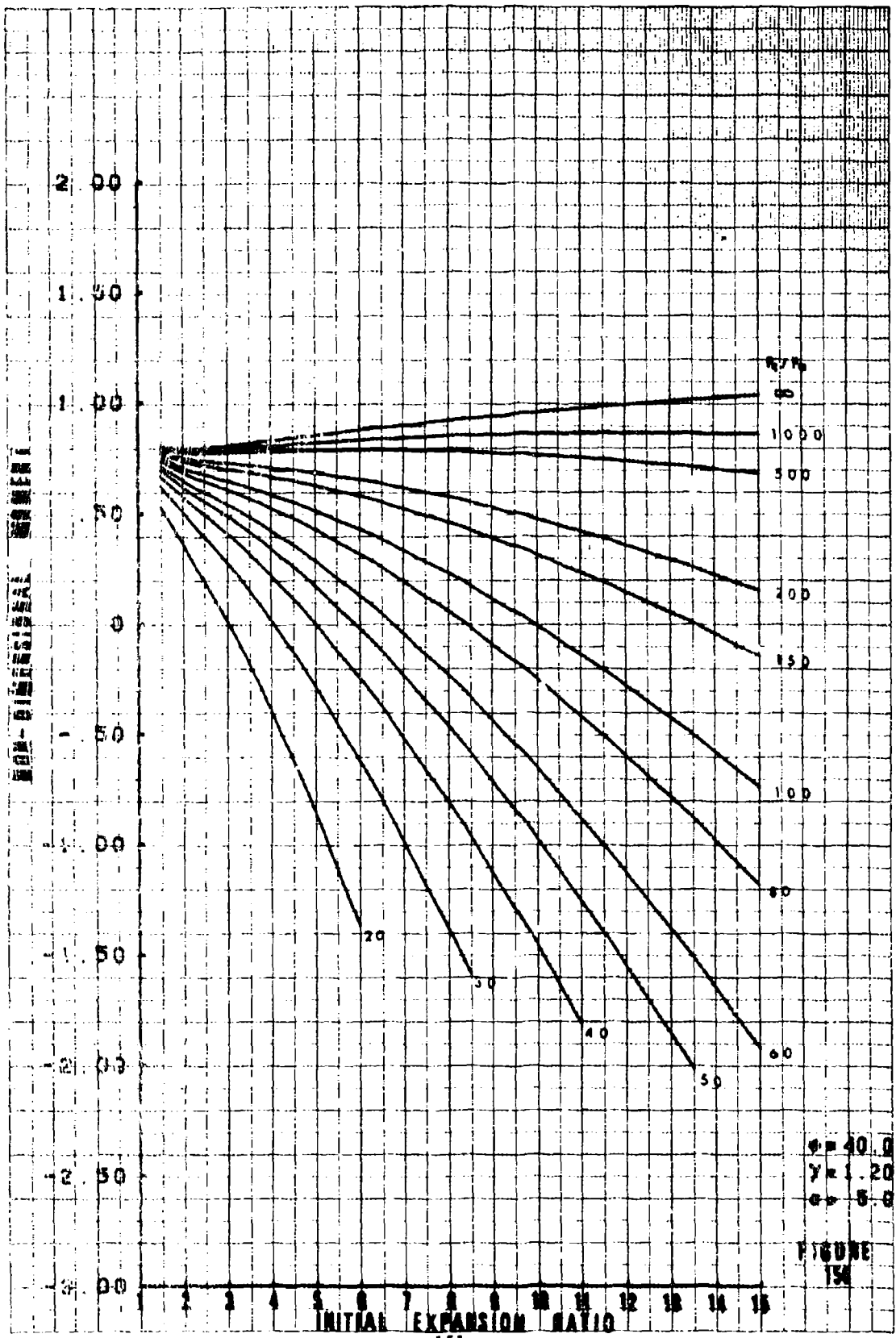
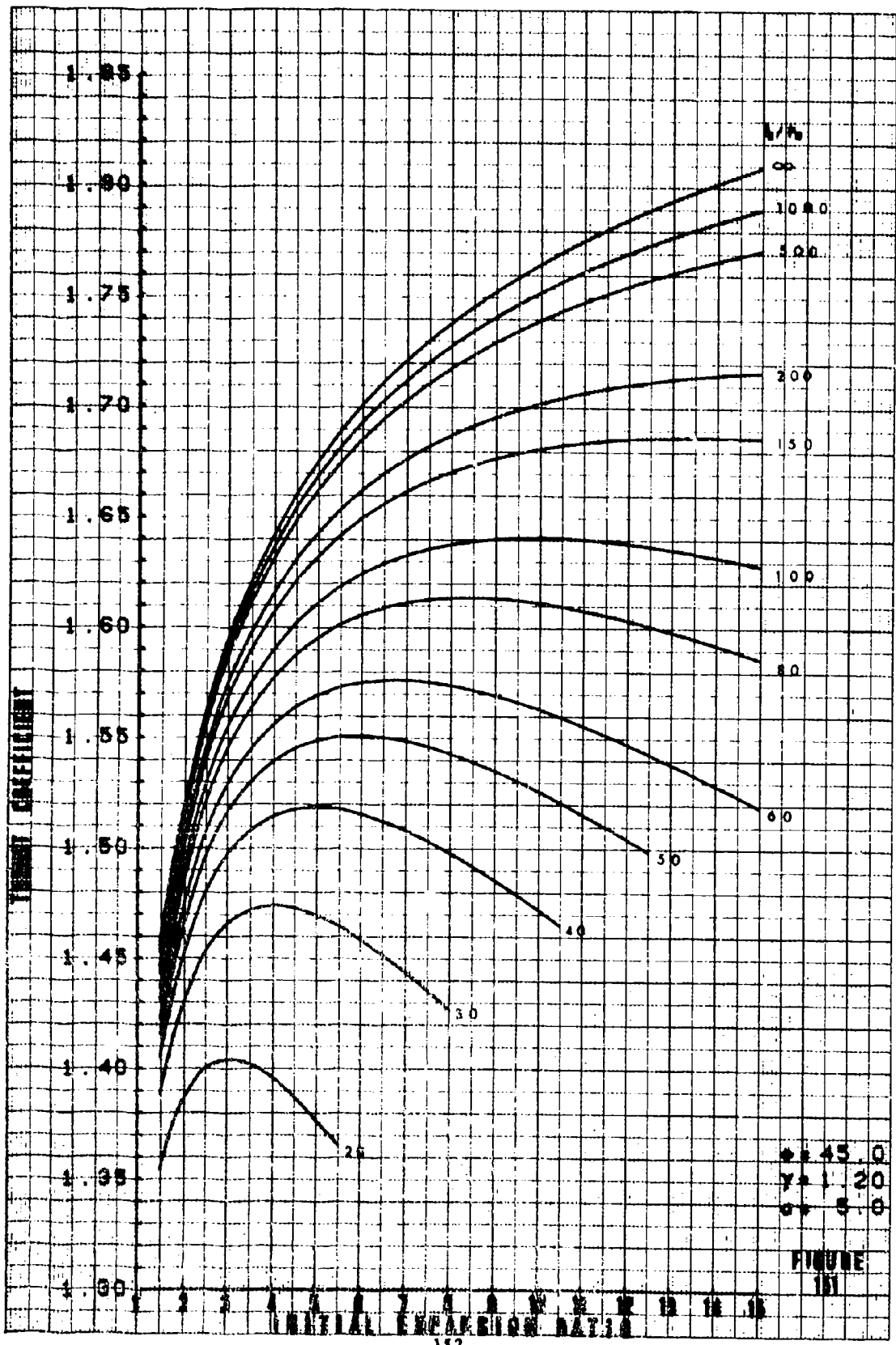


FIGURE 10

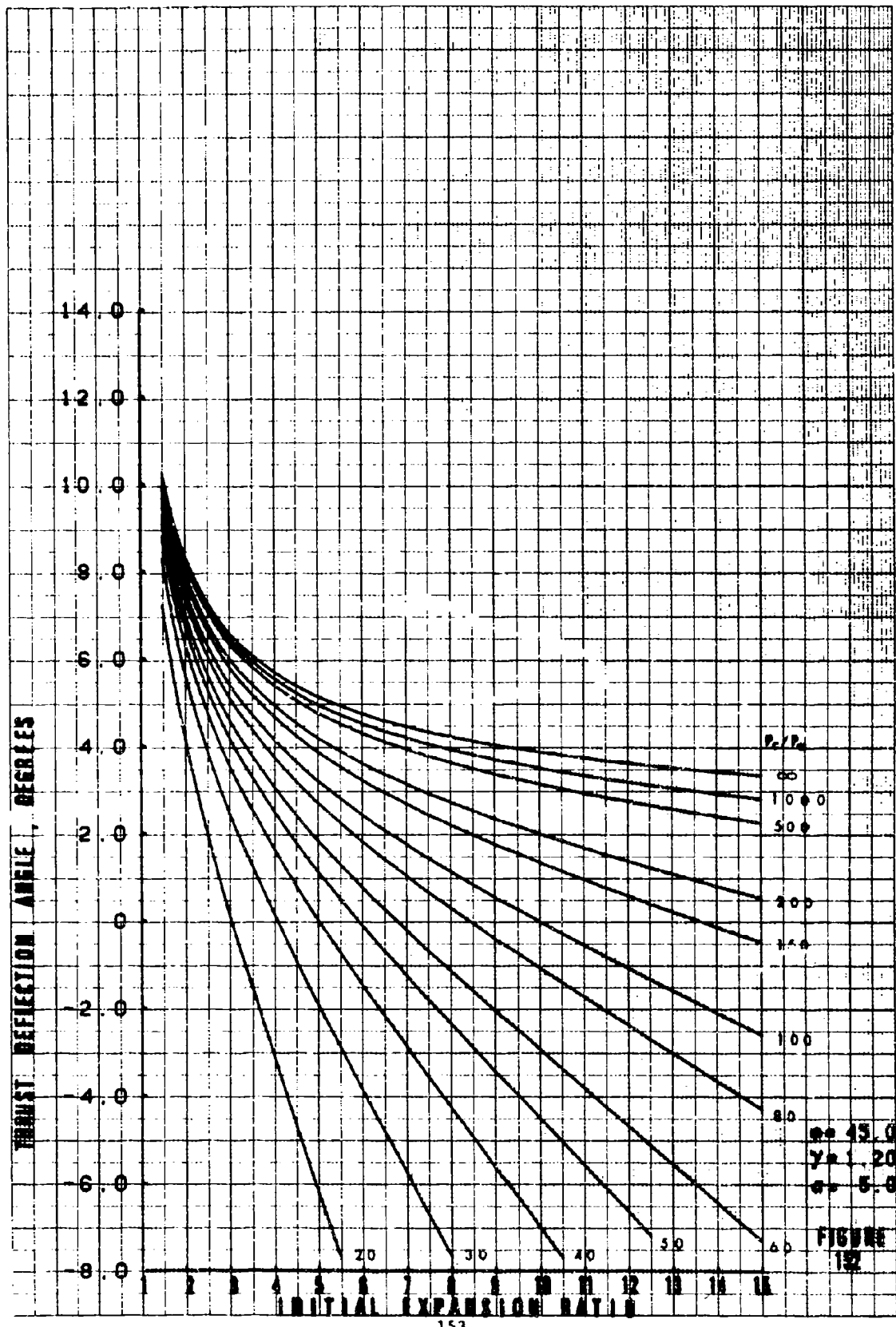


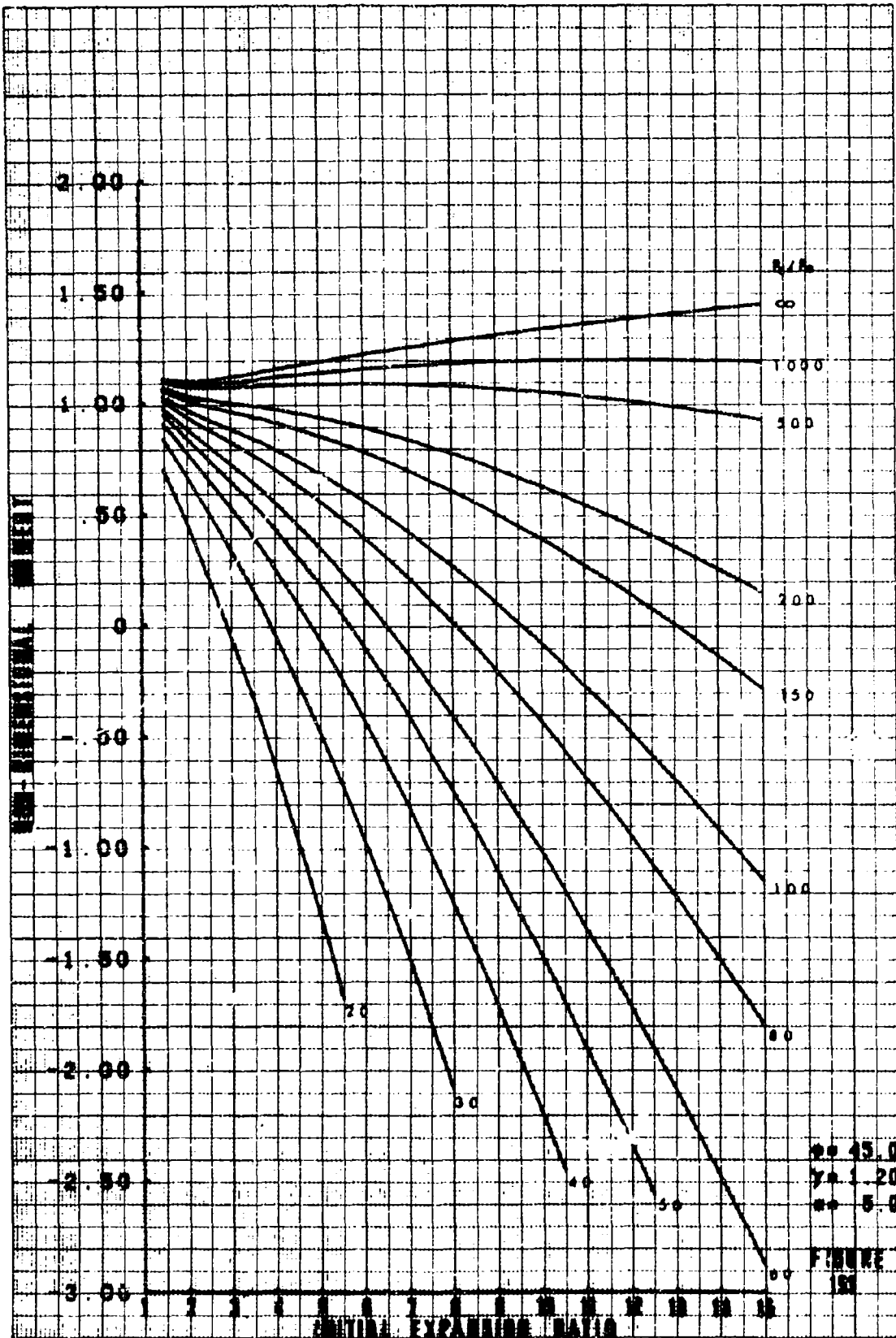




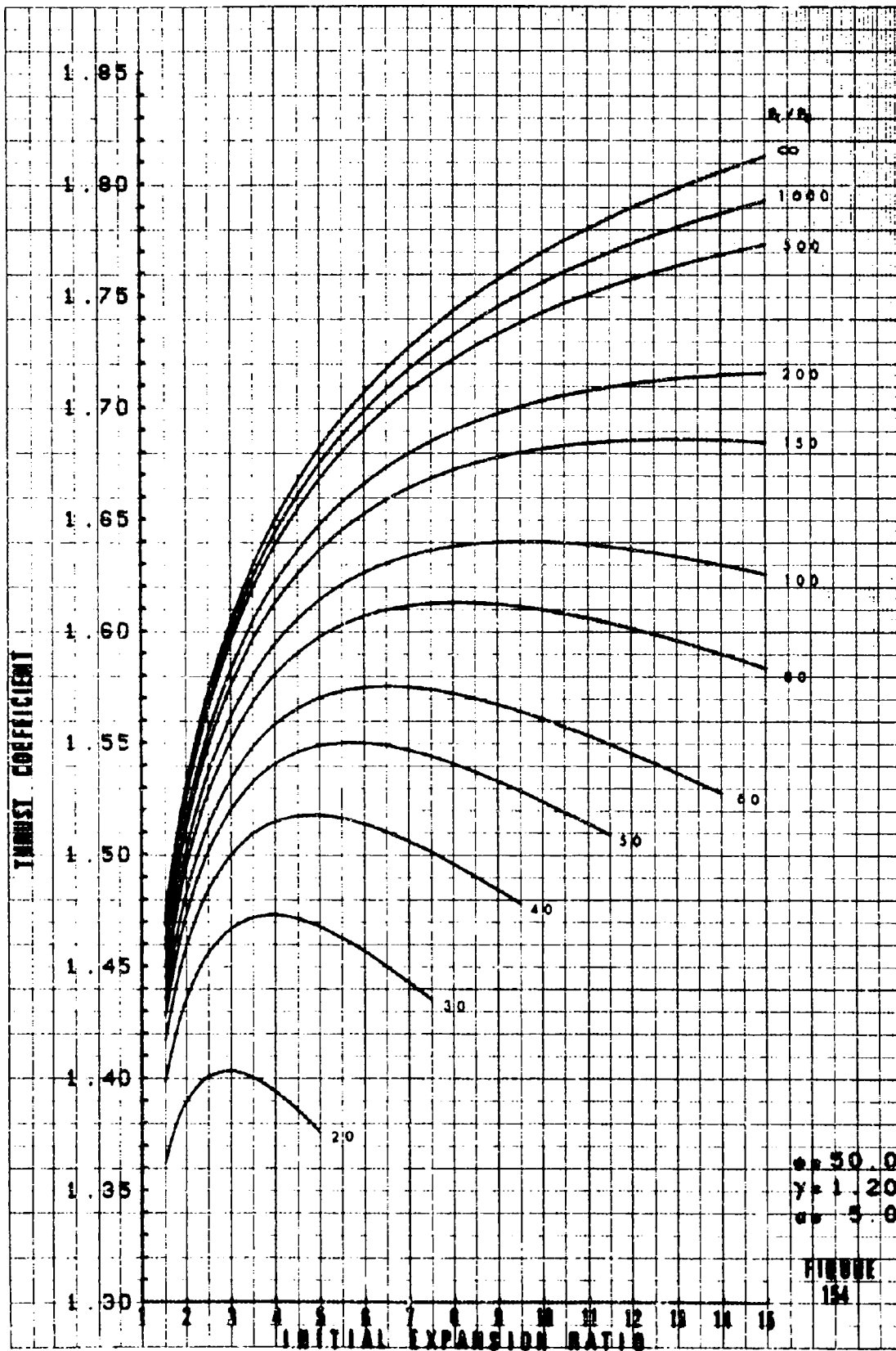


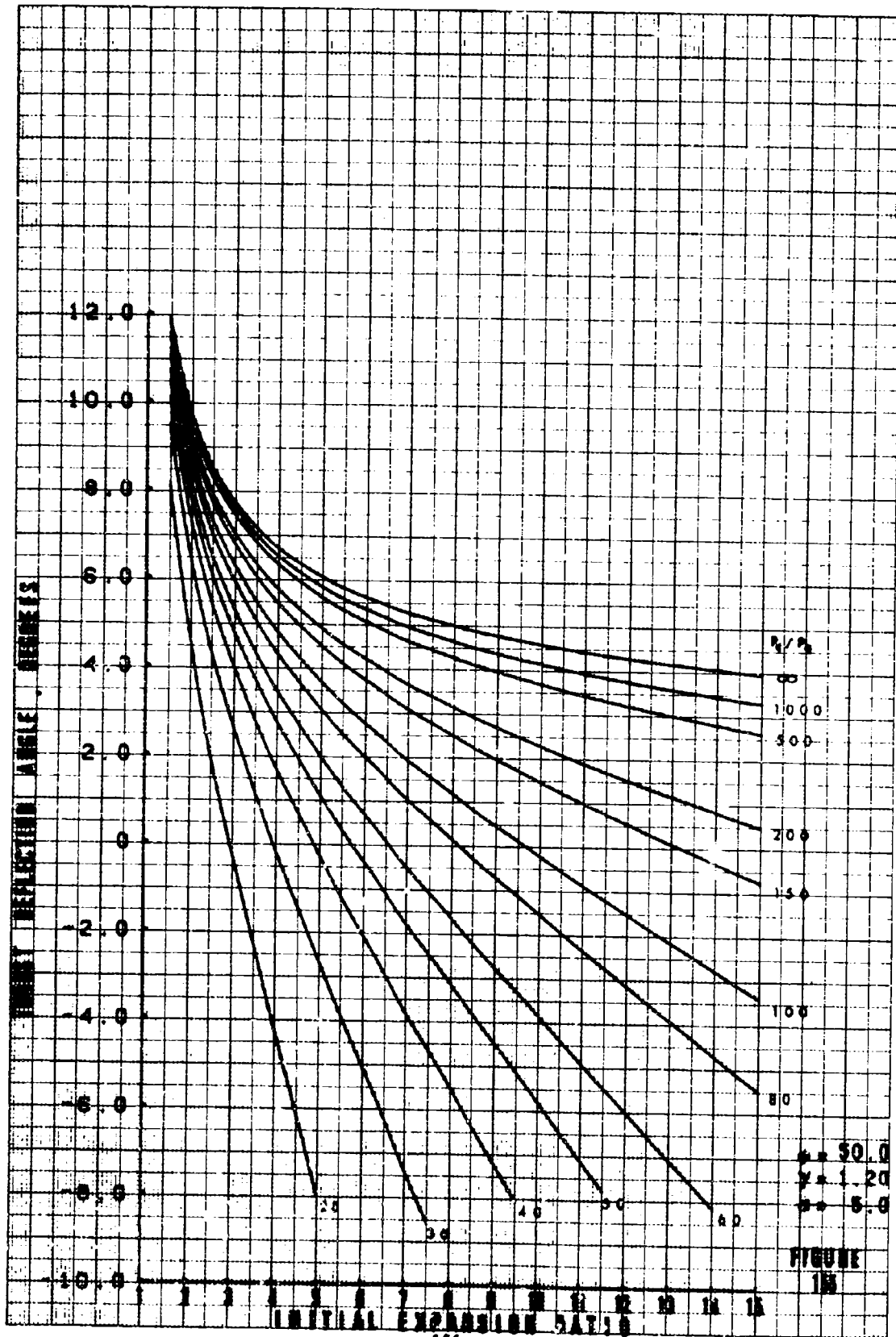


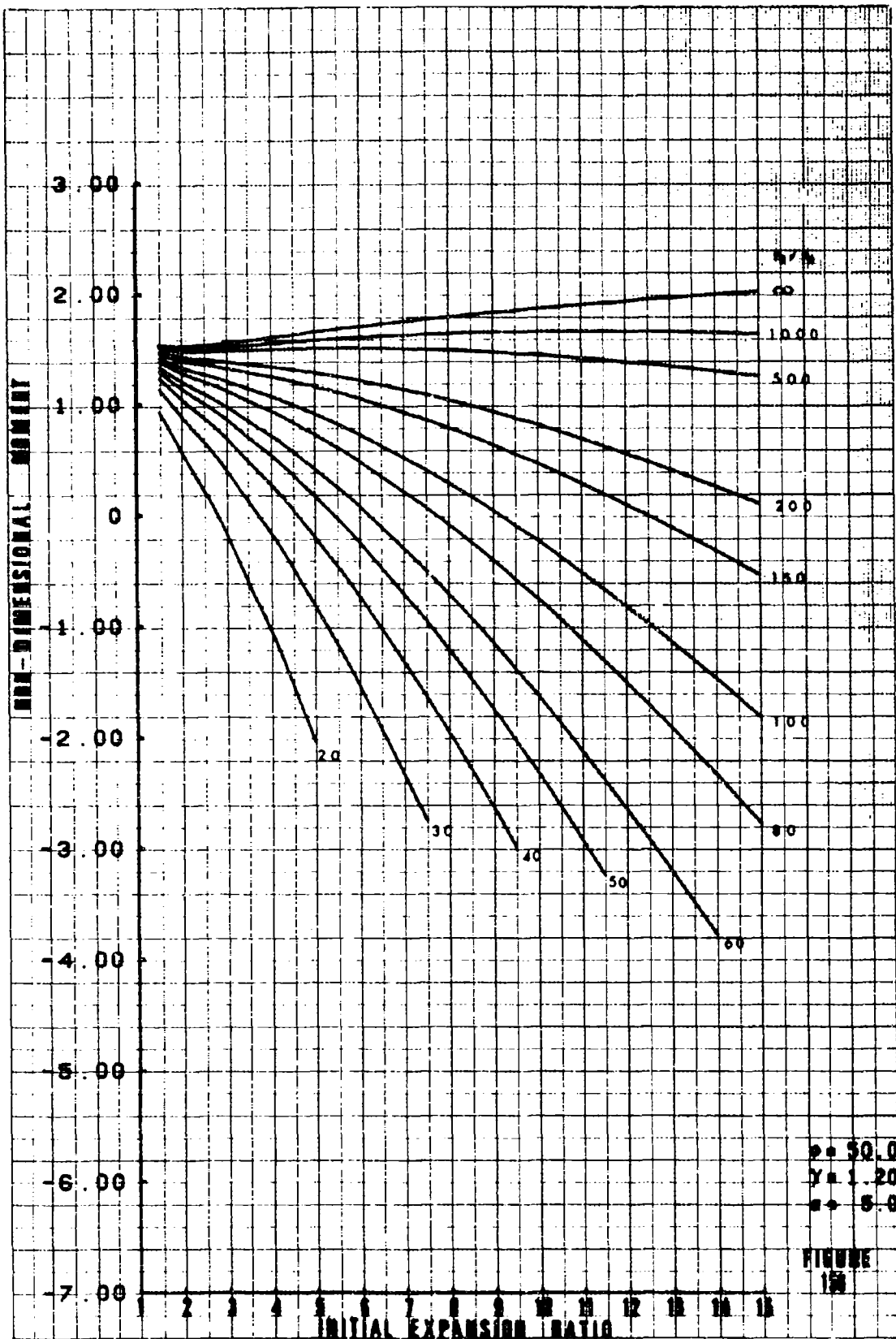


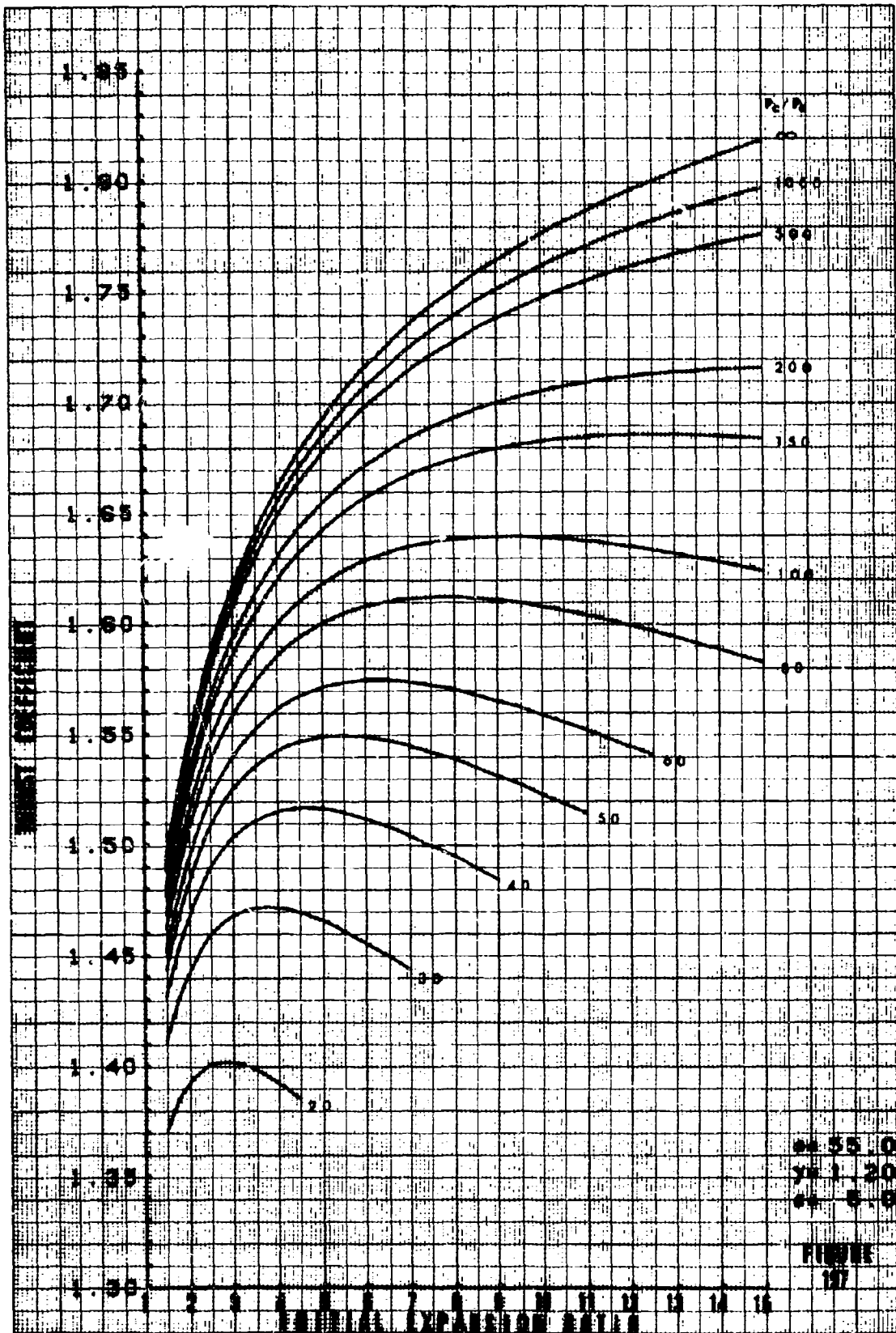


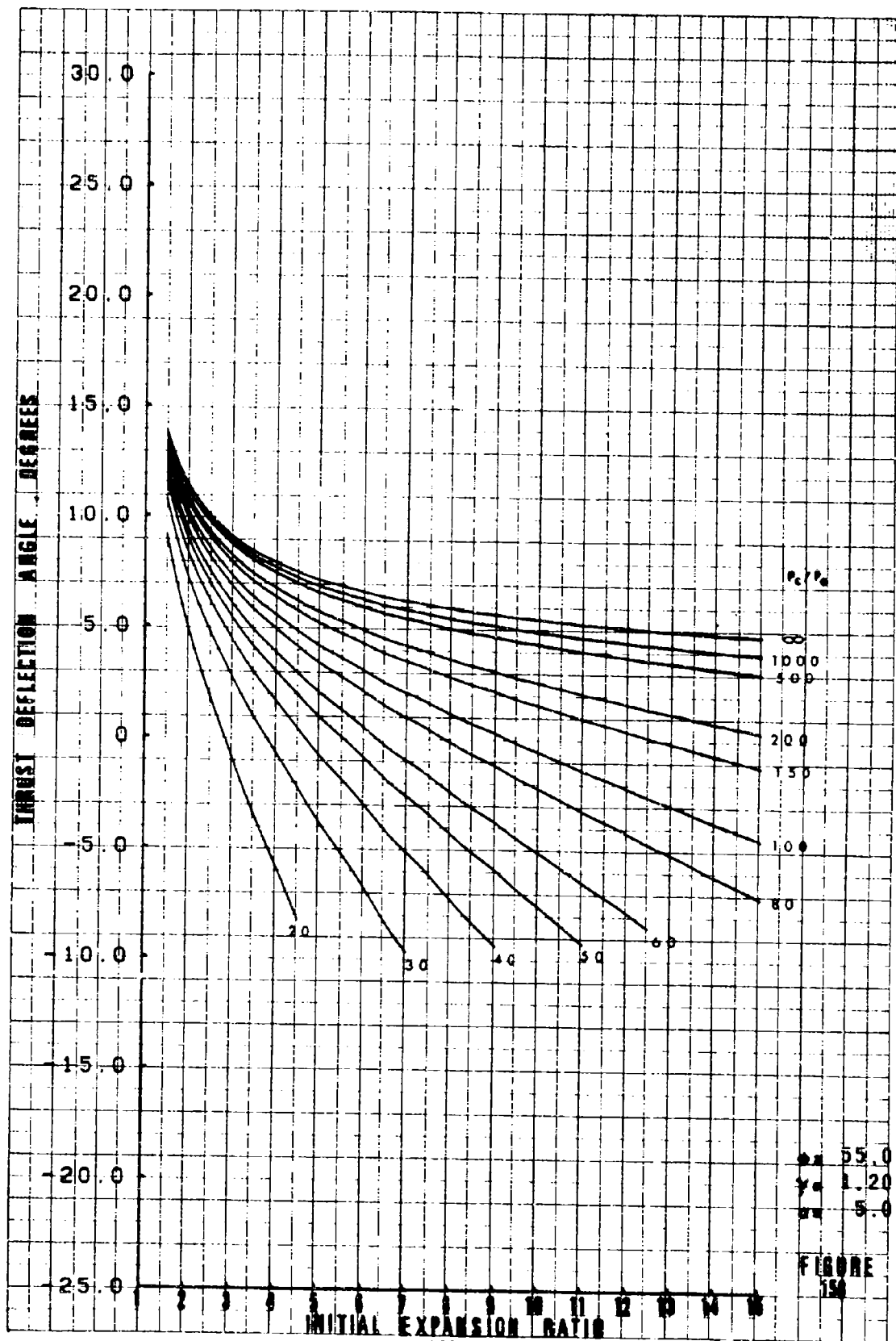
$R/L = 45.0$   
 $R/L = 1.20$   
 $R/L = 5.0$   
**FIGURE 150**





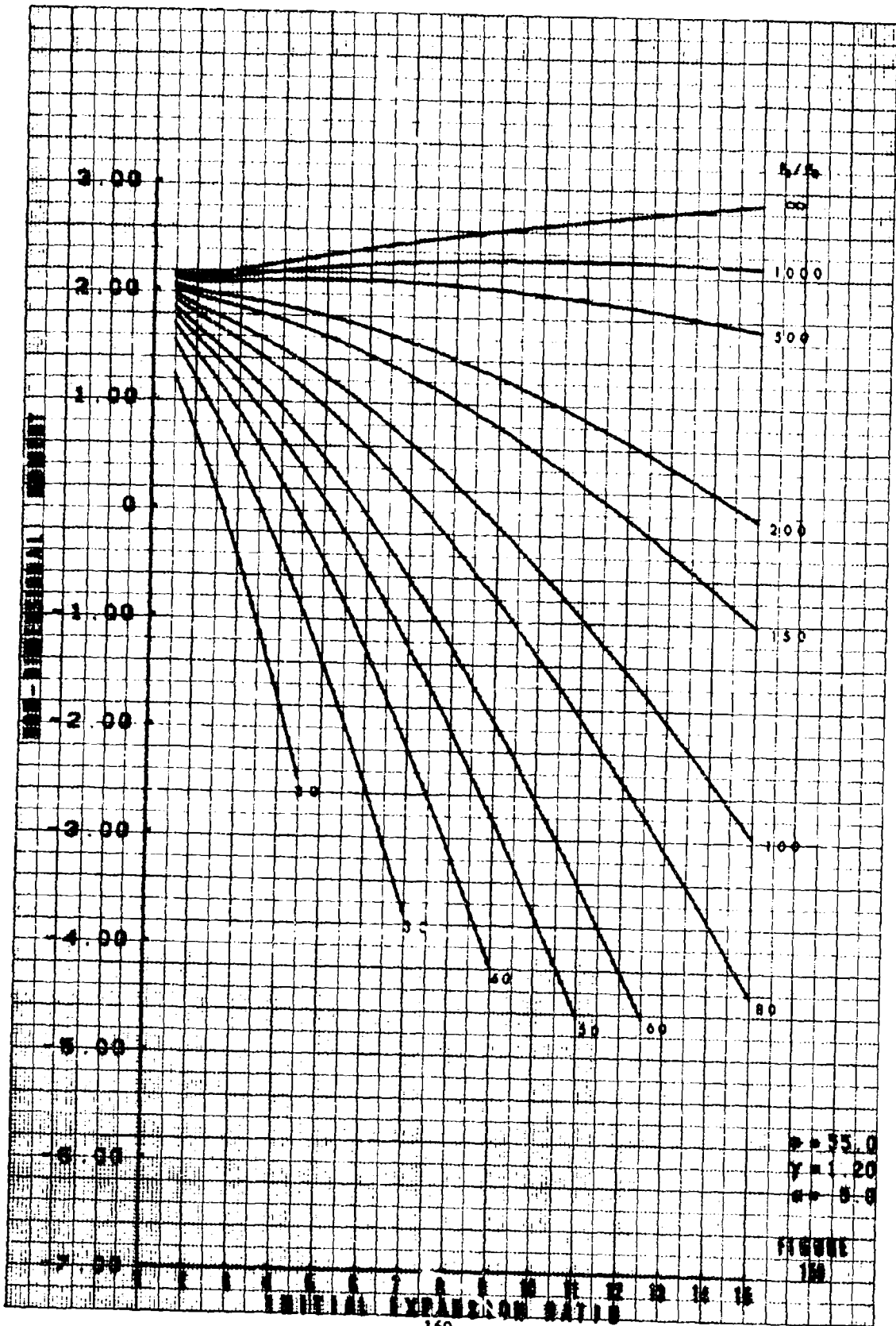




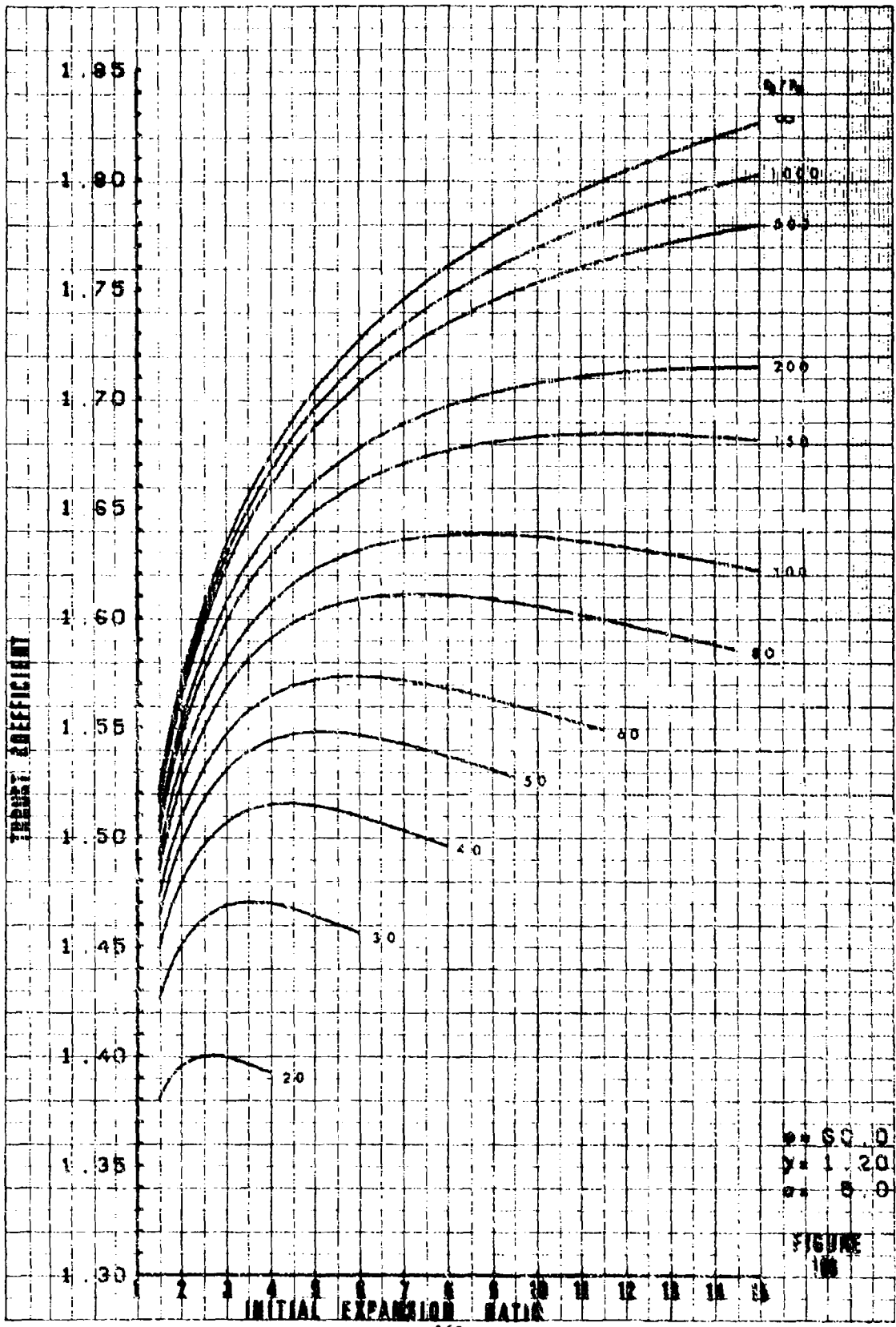


$\alpha = 55.0$   
 $\gamma = 1.20$   
 $u = 5.0$

FIGURE 150

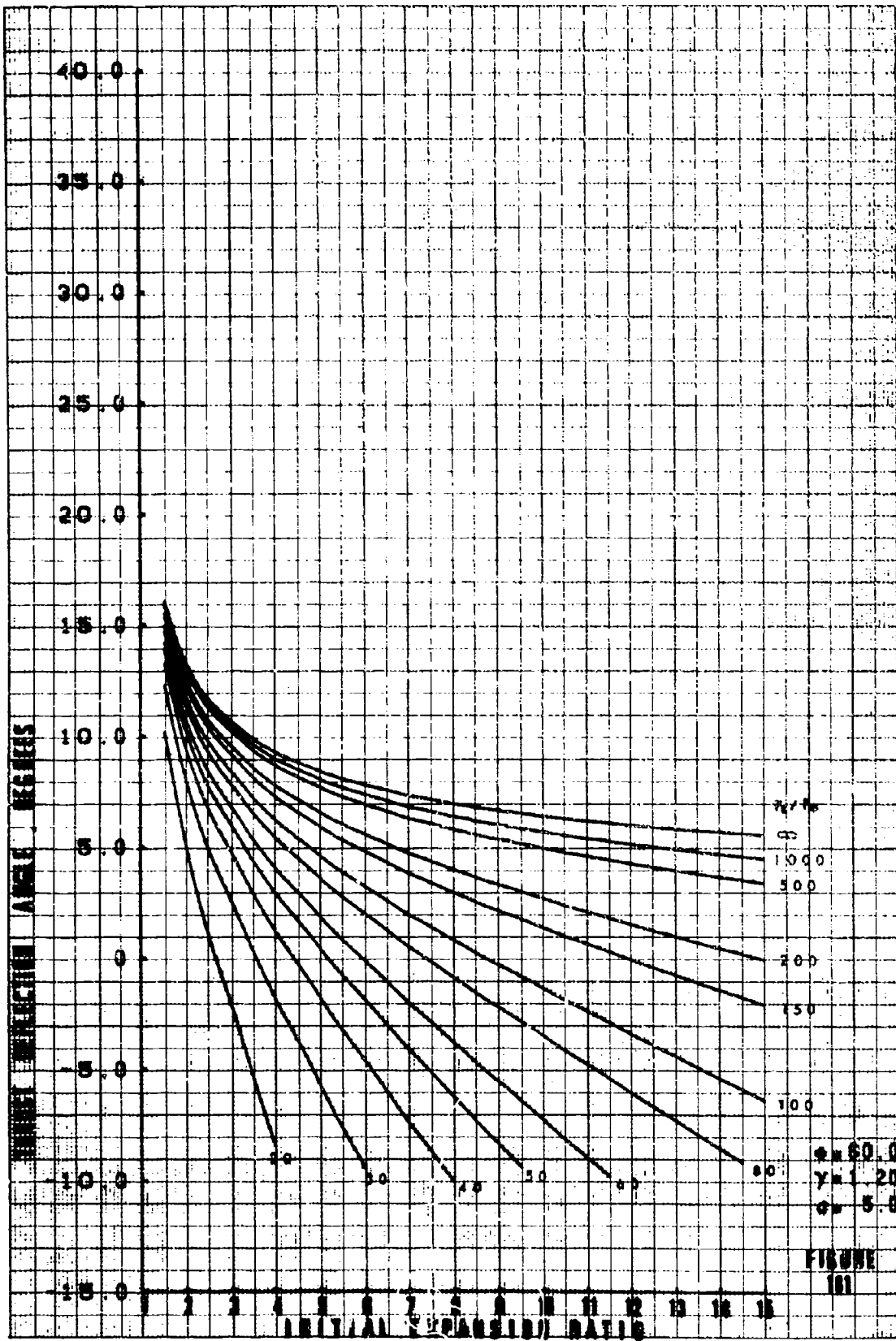


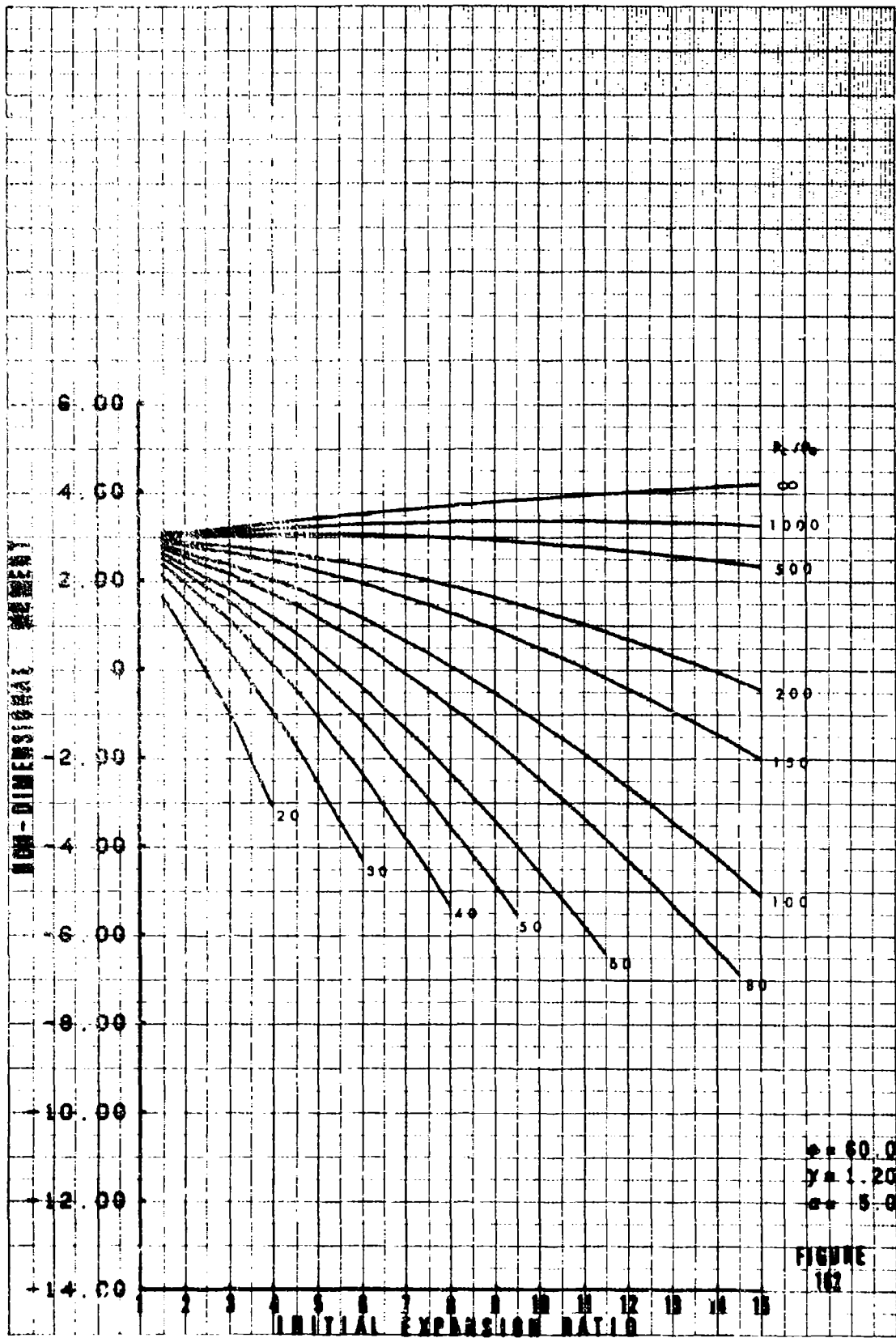


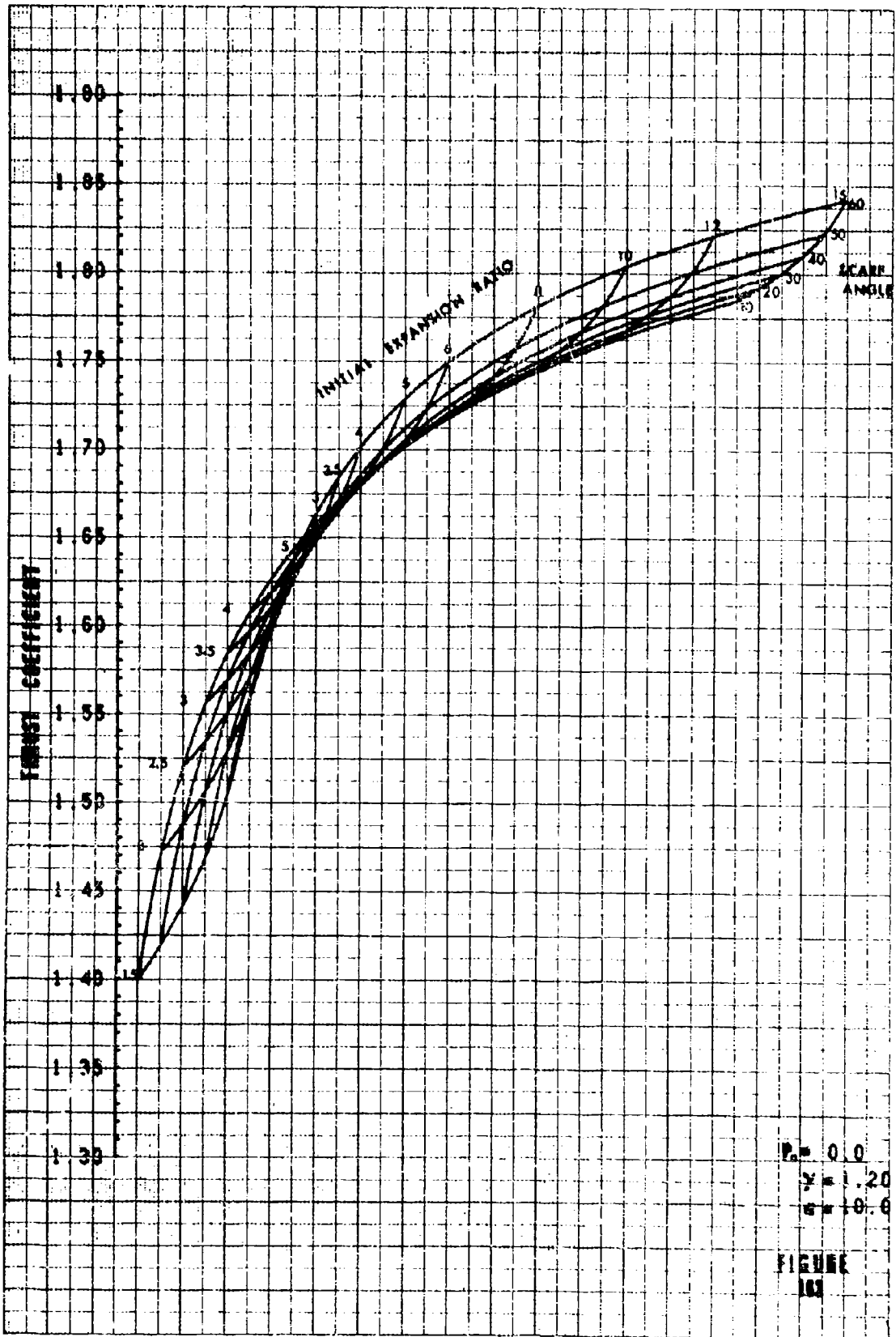


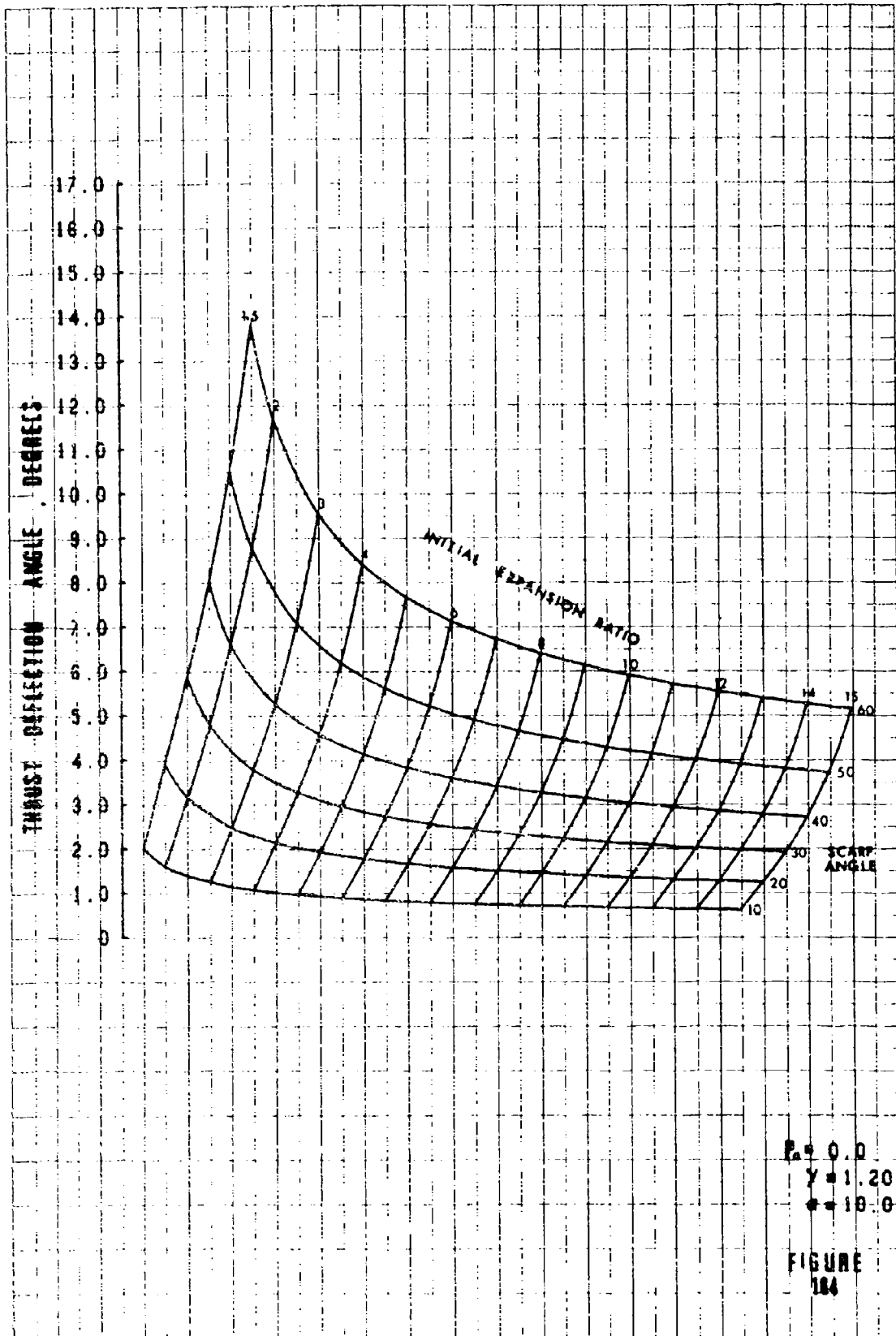
$\gamma = 1.20$   
 $\sigma = 0.0$

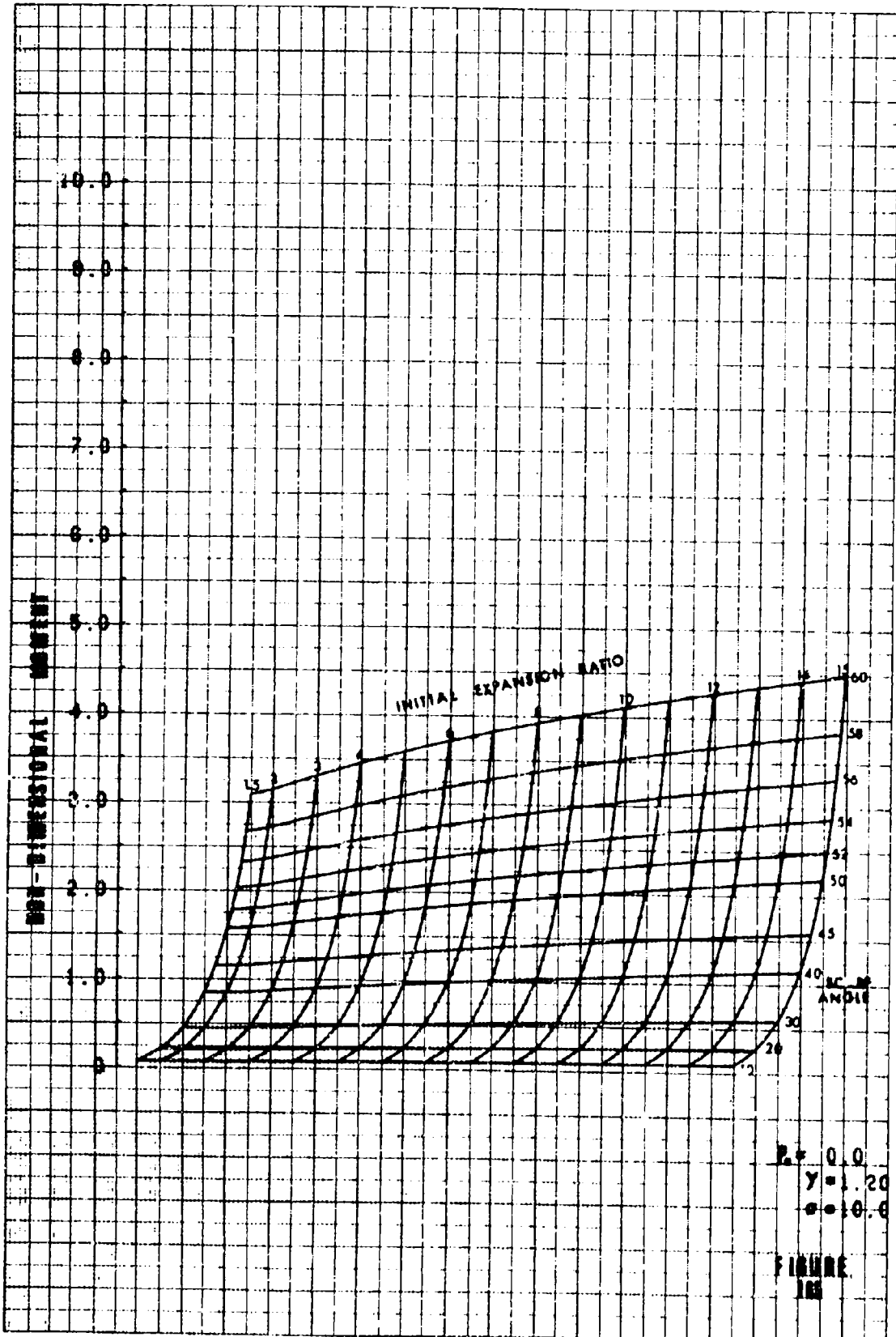
FIGURE 10

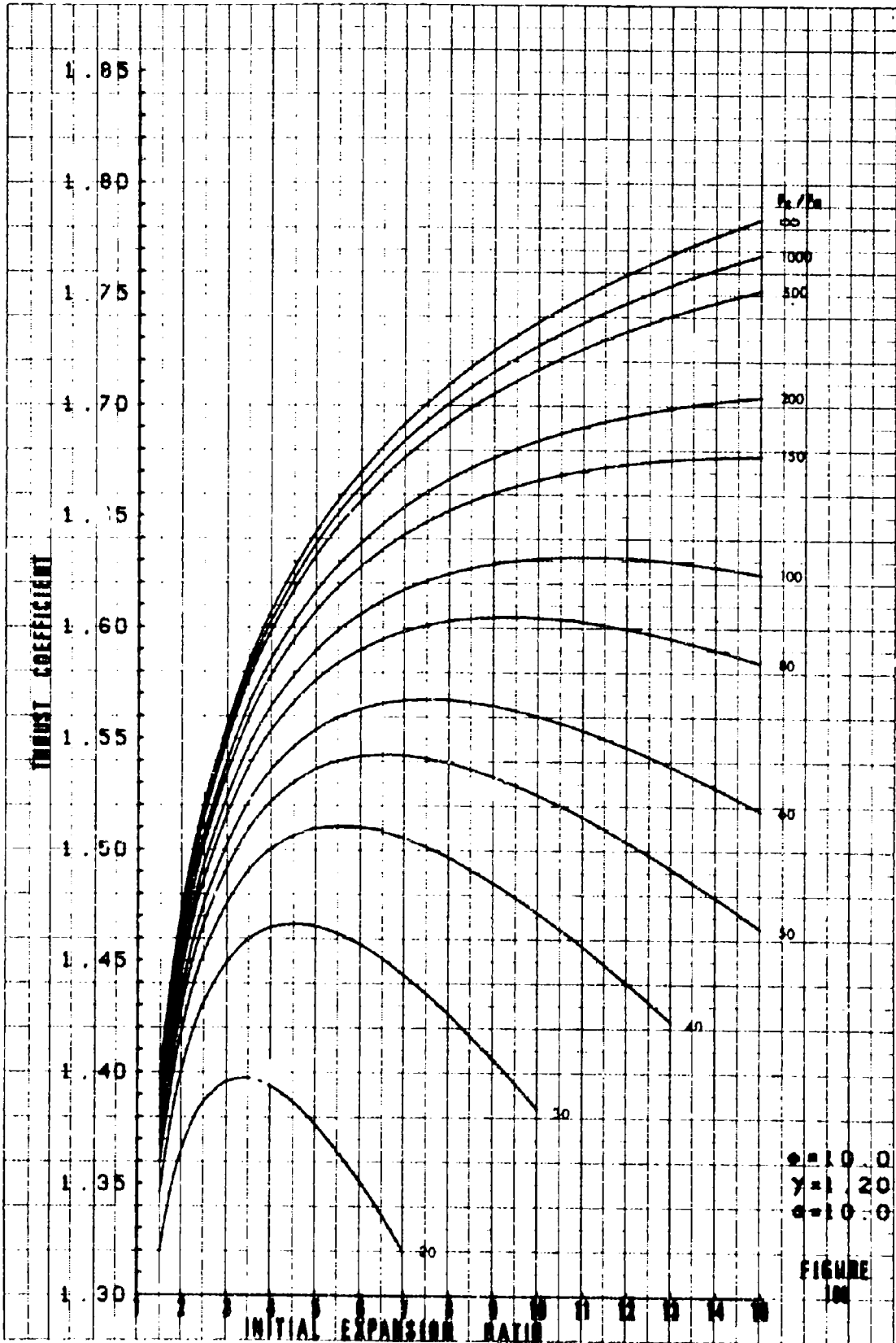


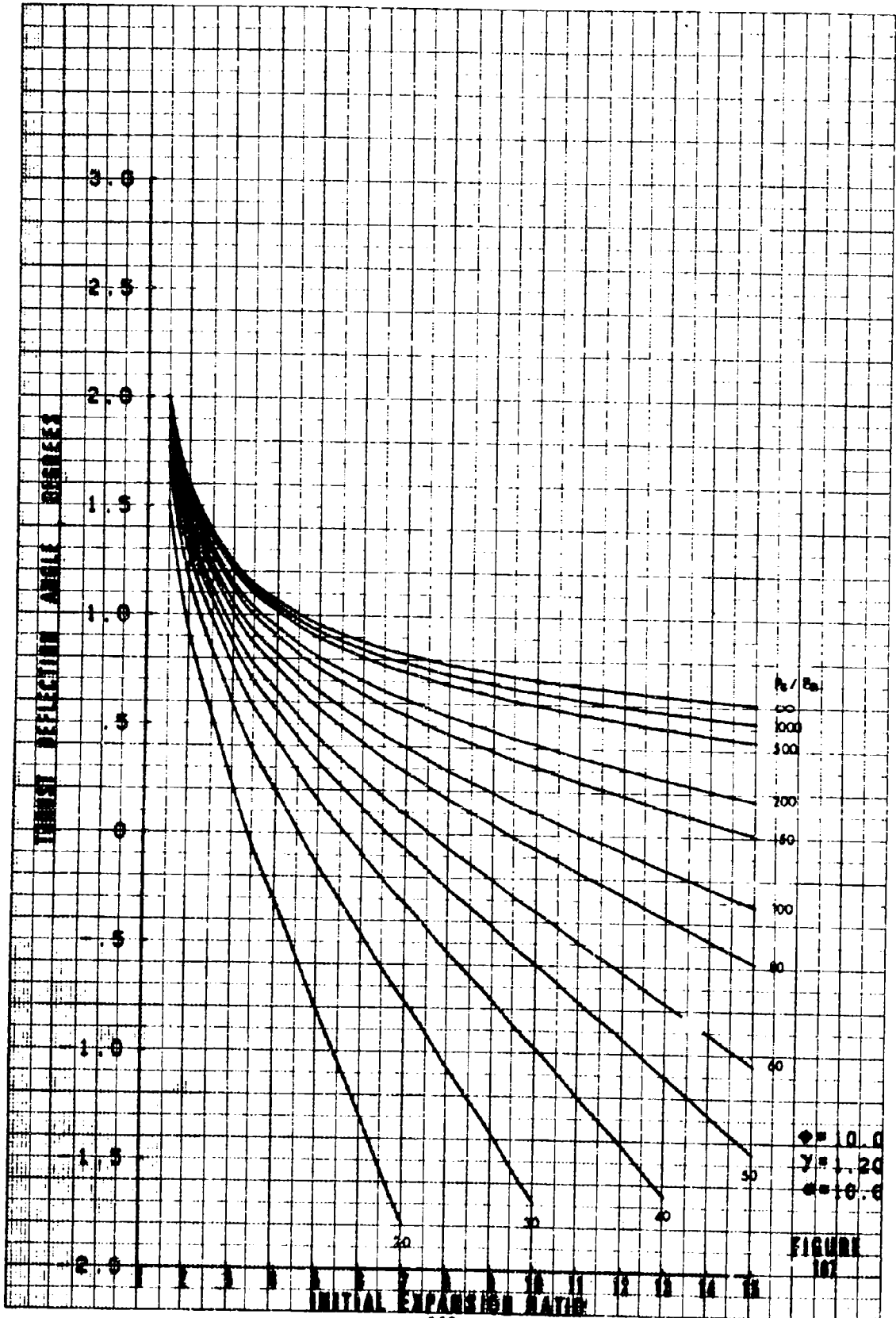




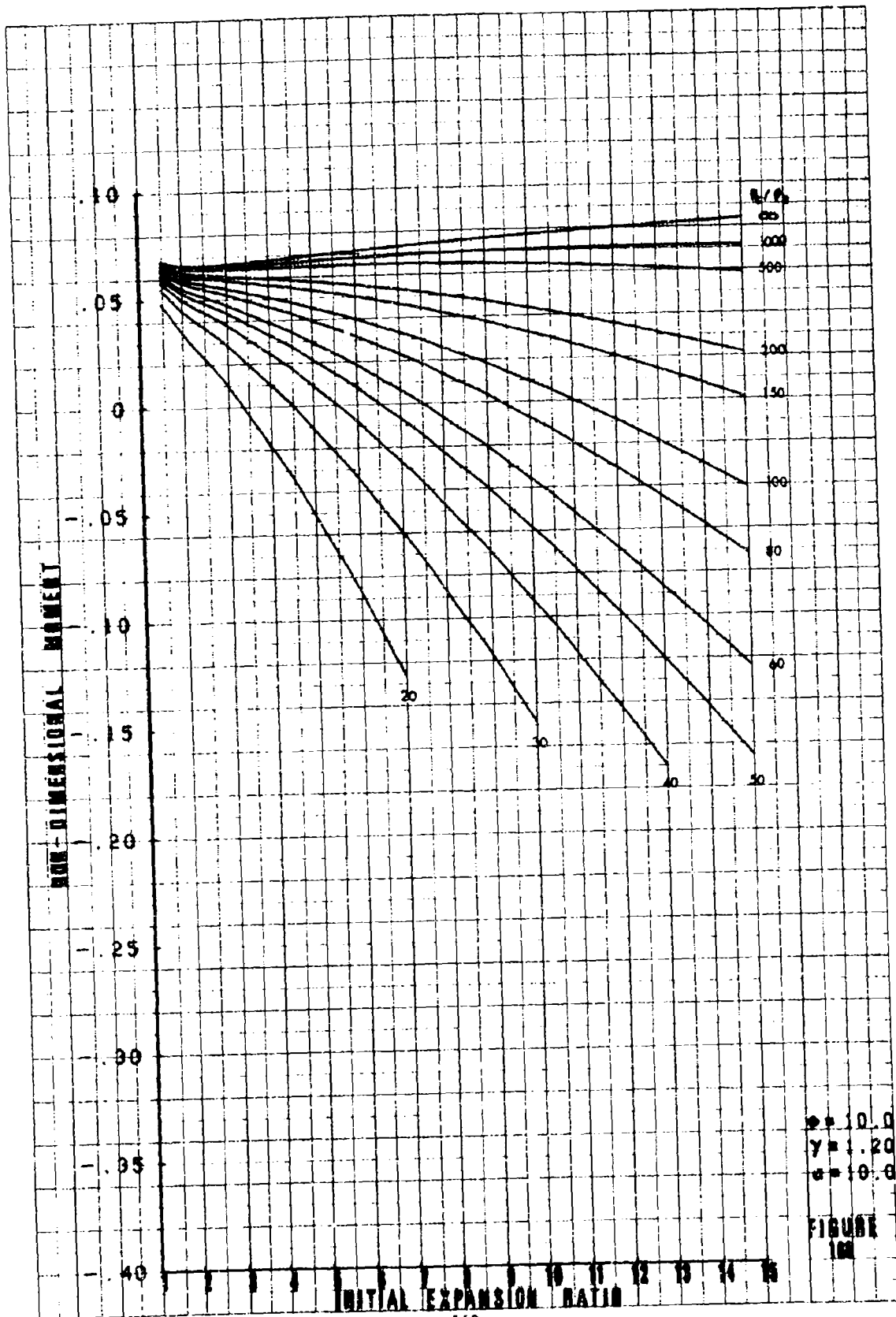


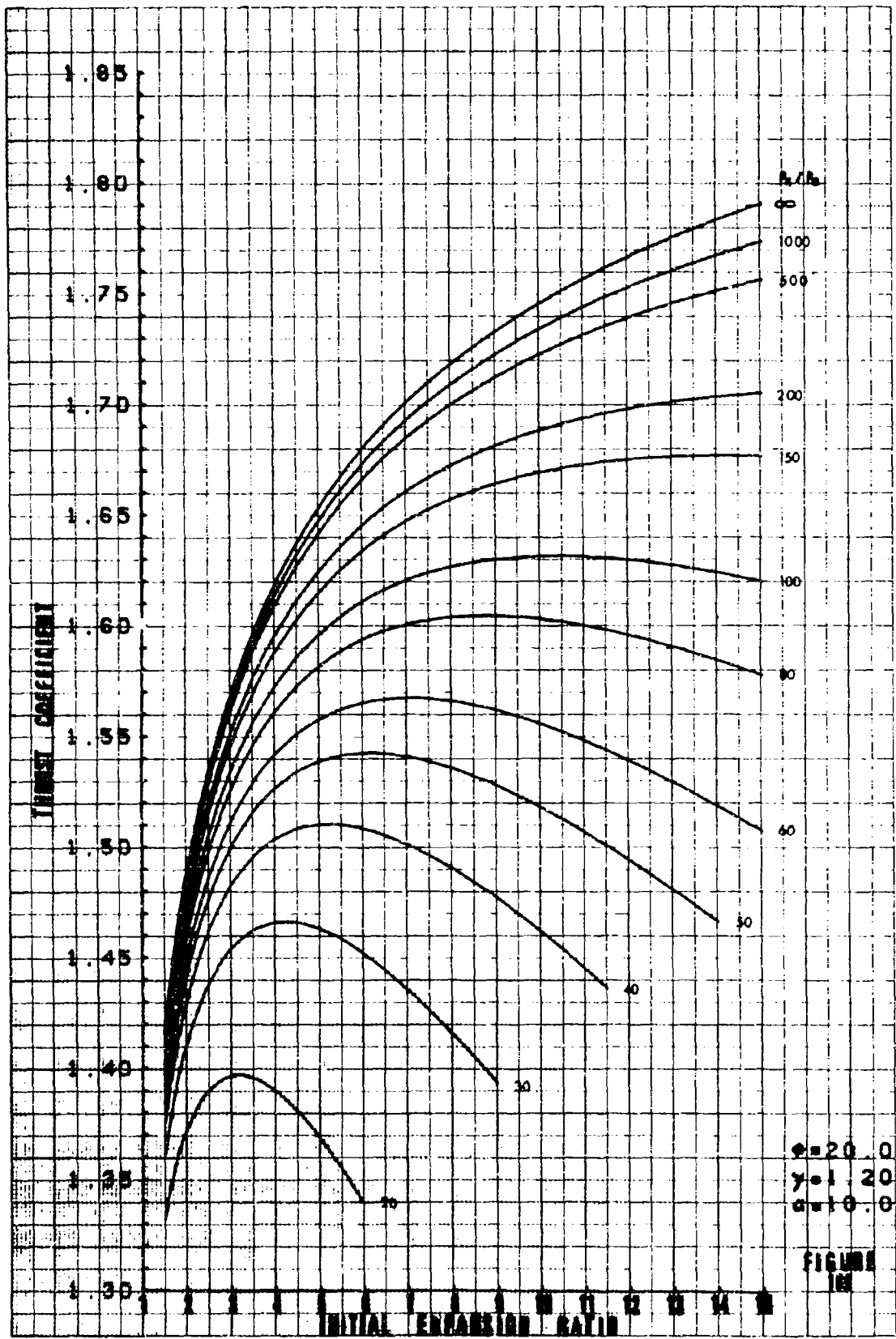












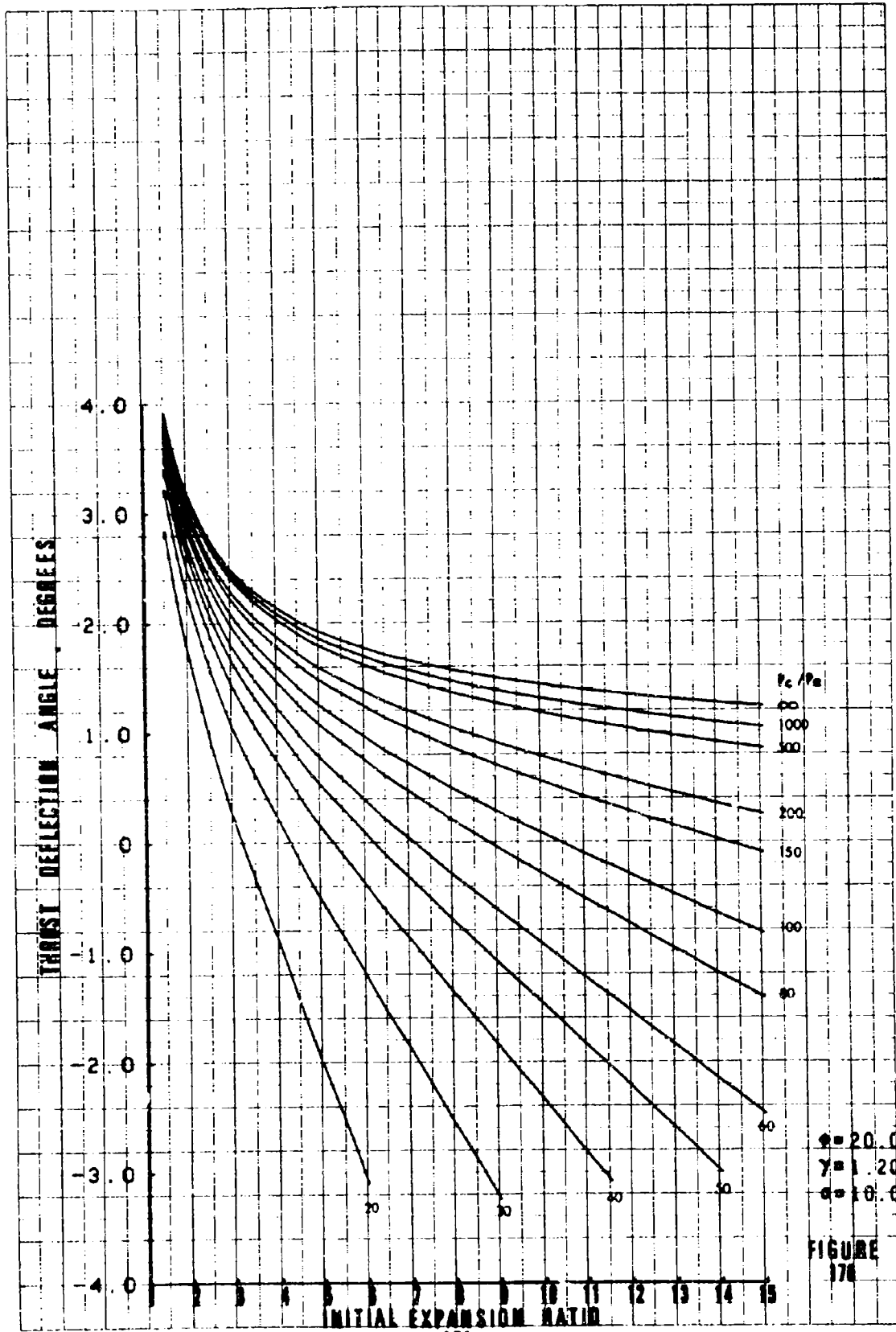
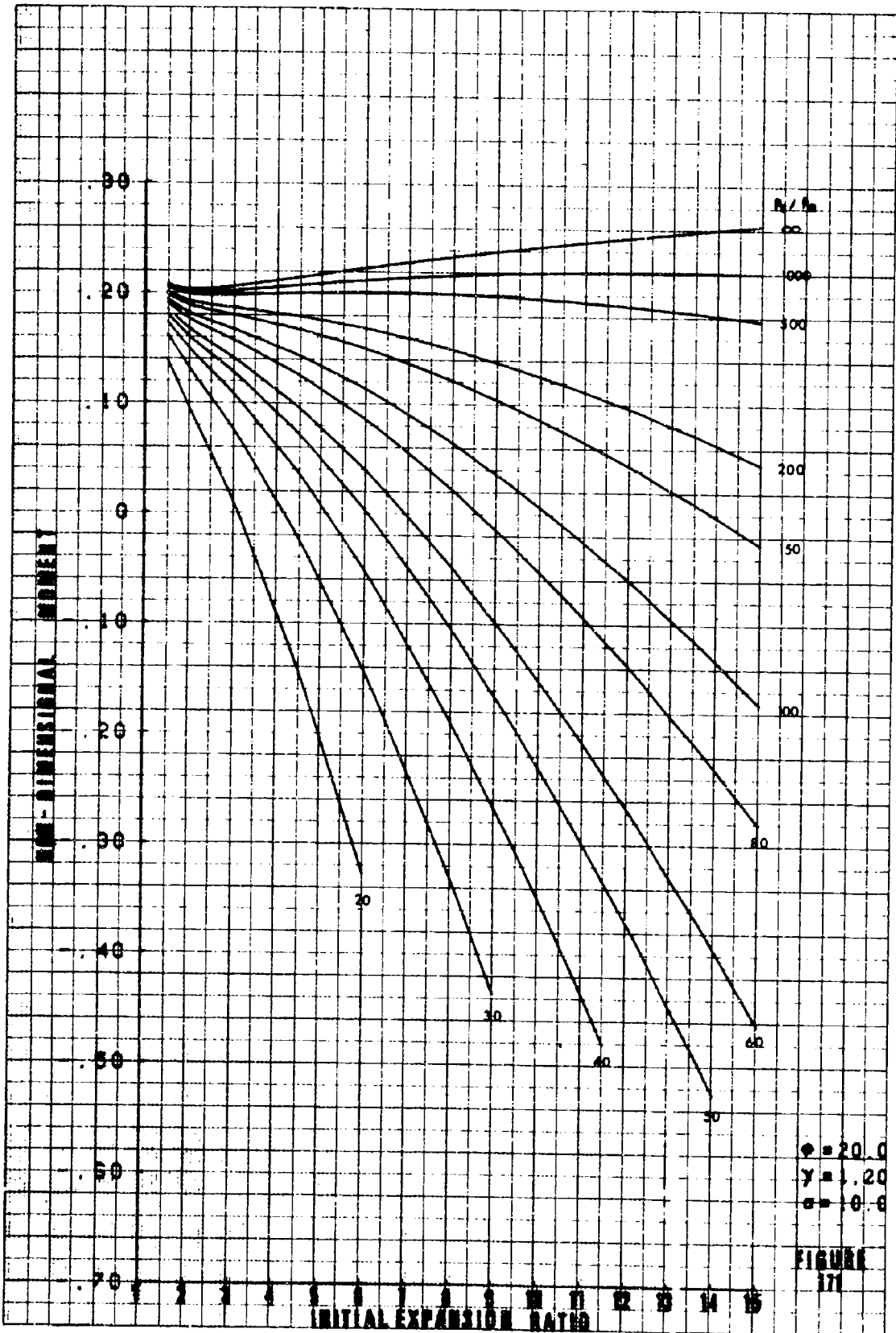
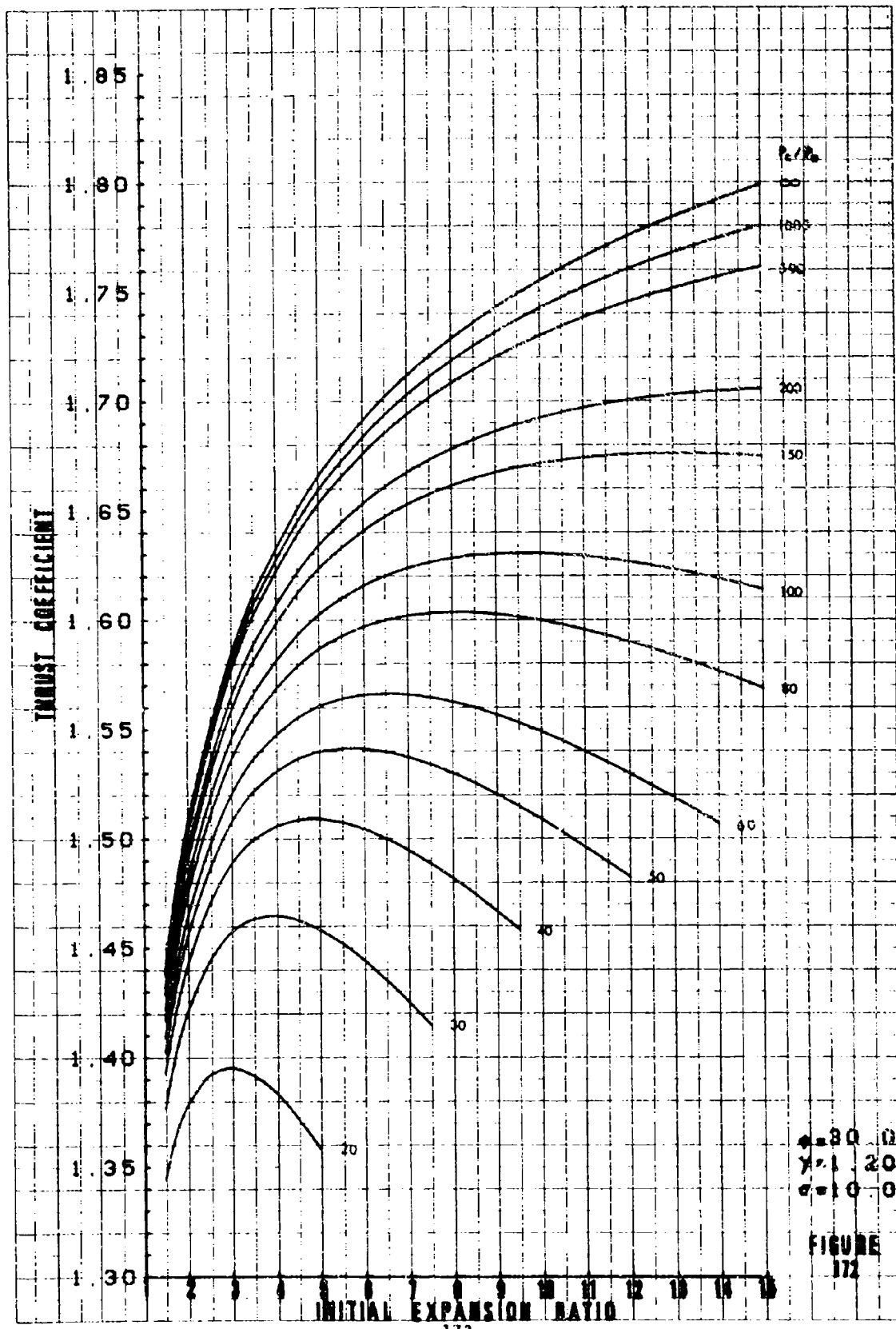


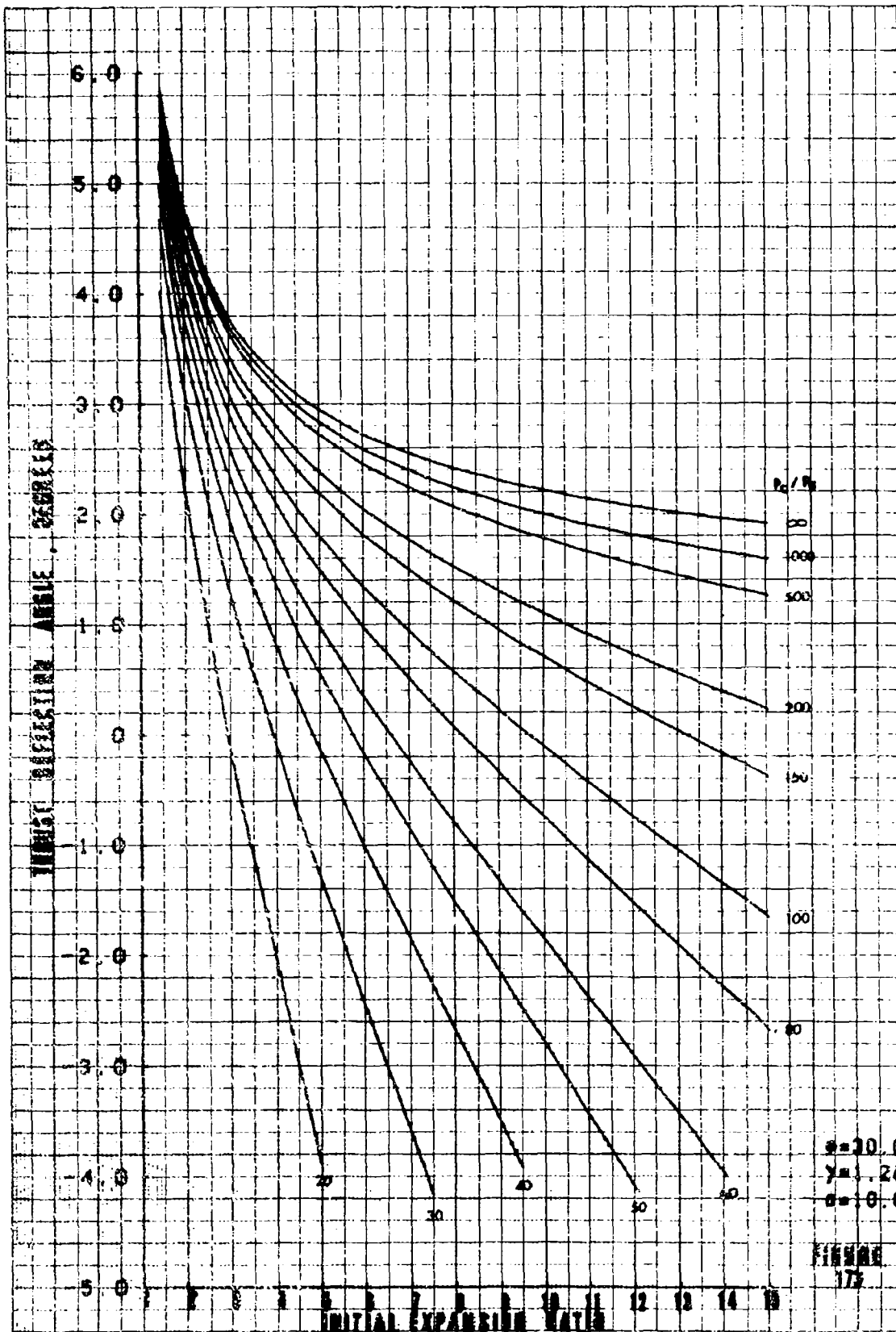
FIGURE 178

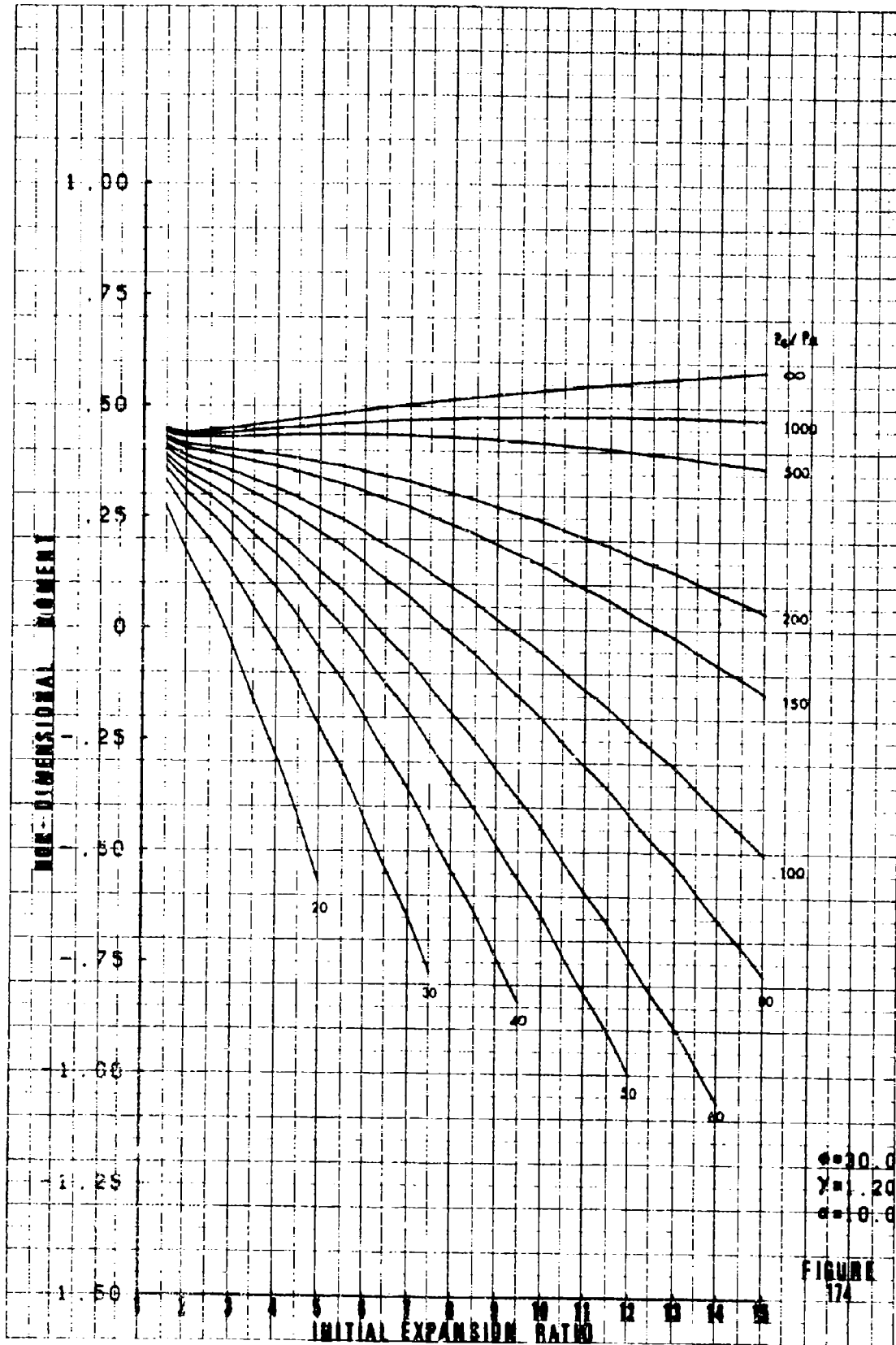


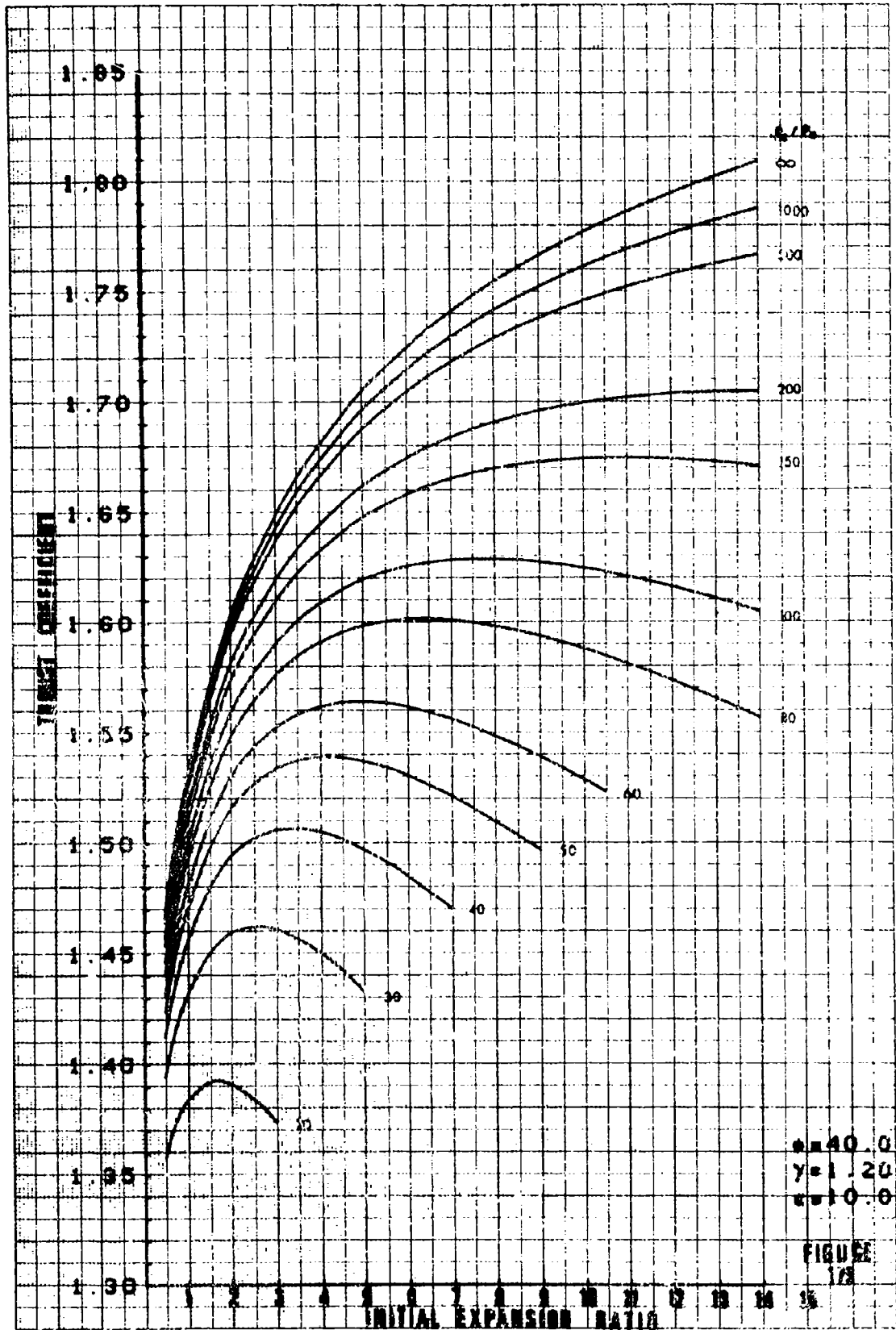


$\gamma = 1.4$   
 $\beta = 1.0$   
 $\alpha = 1.0$

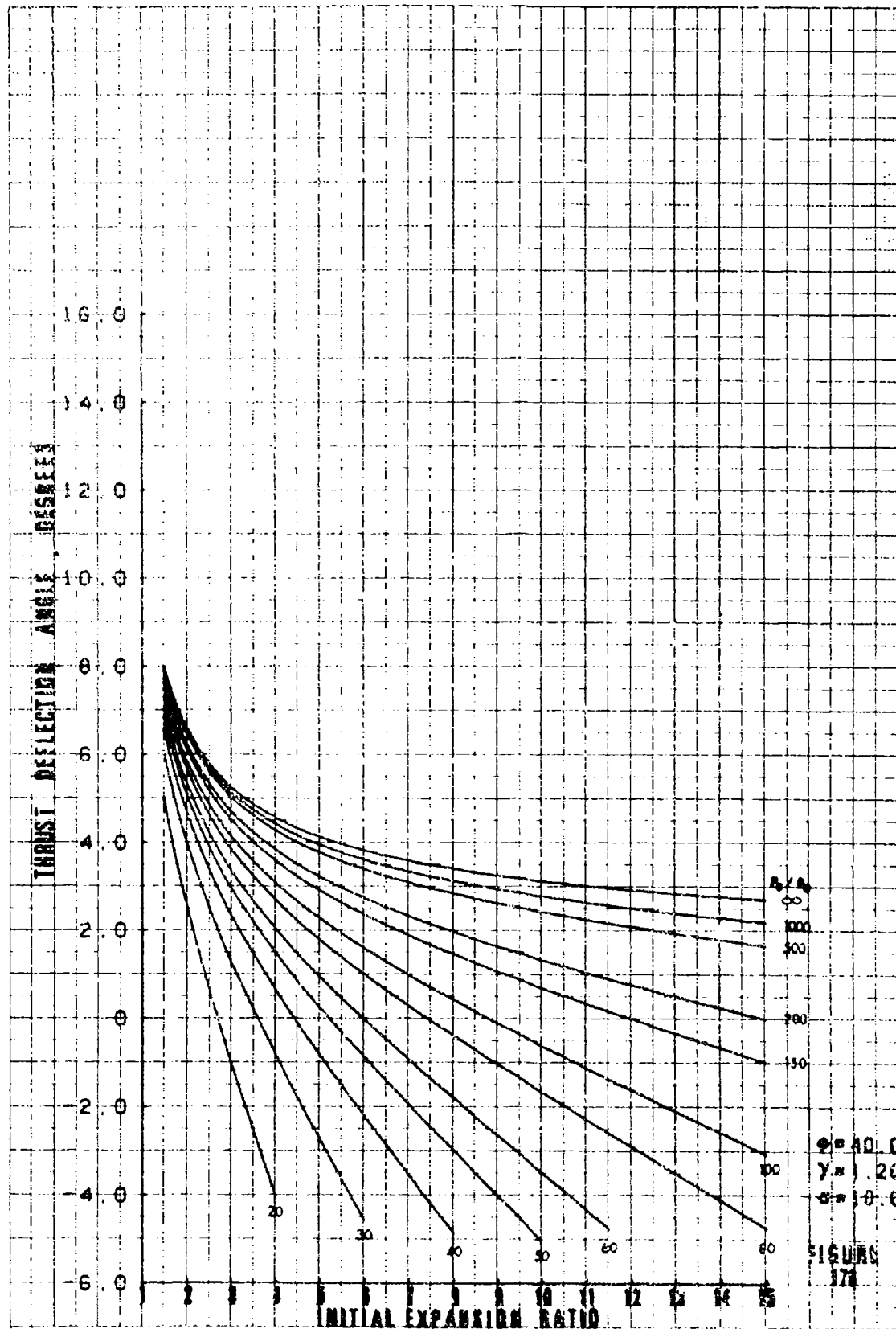
FIGURE 172

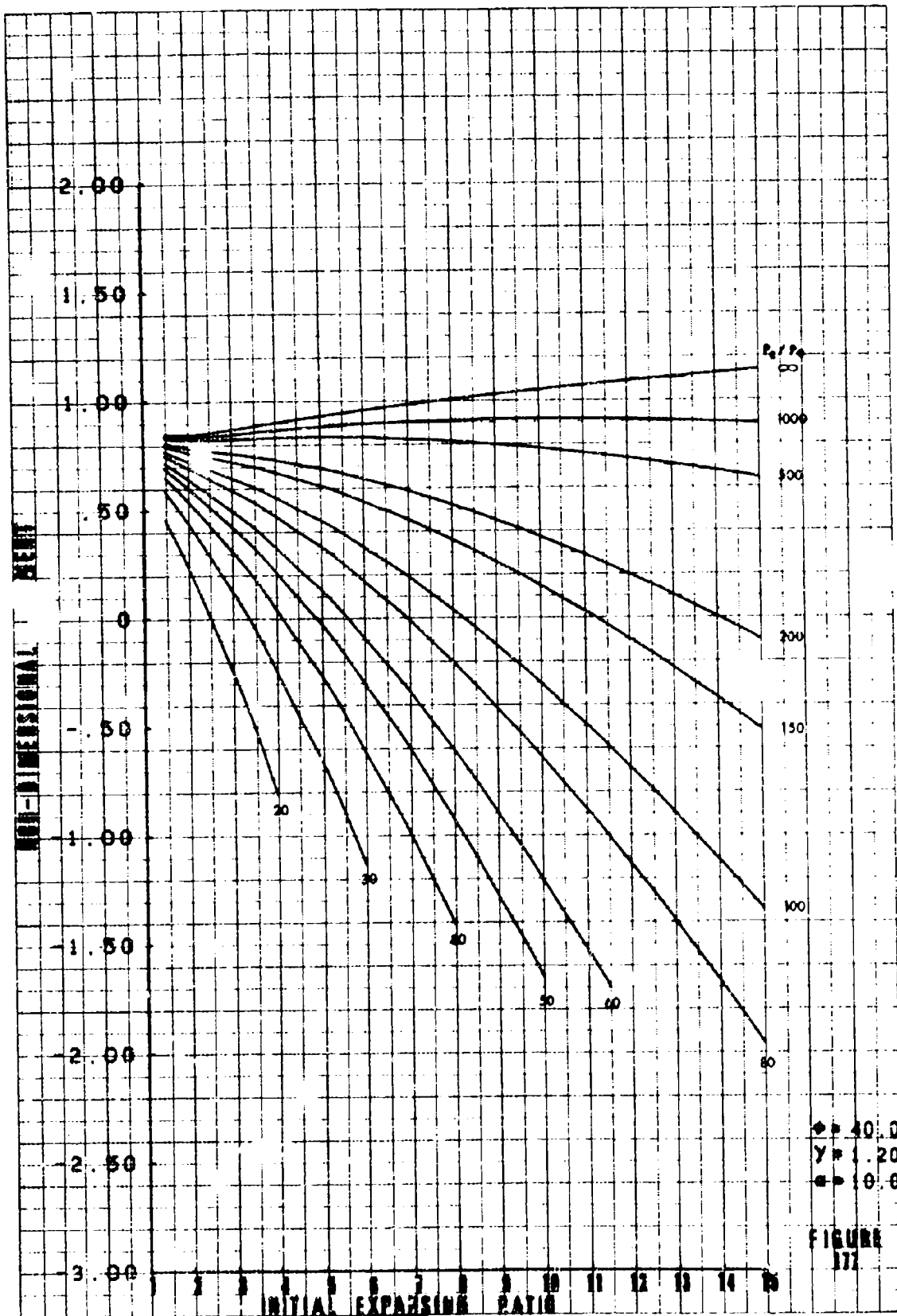












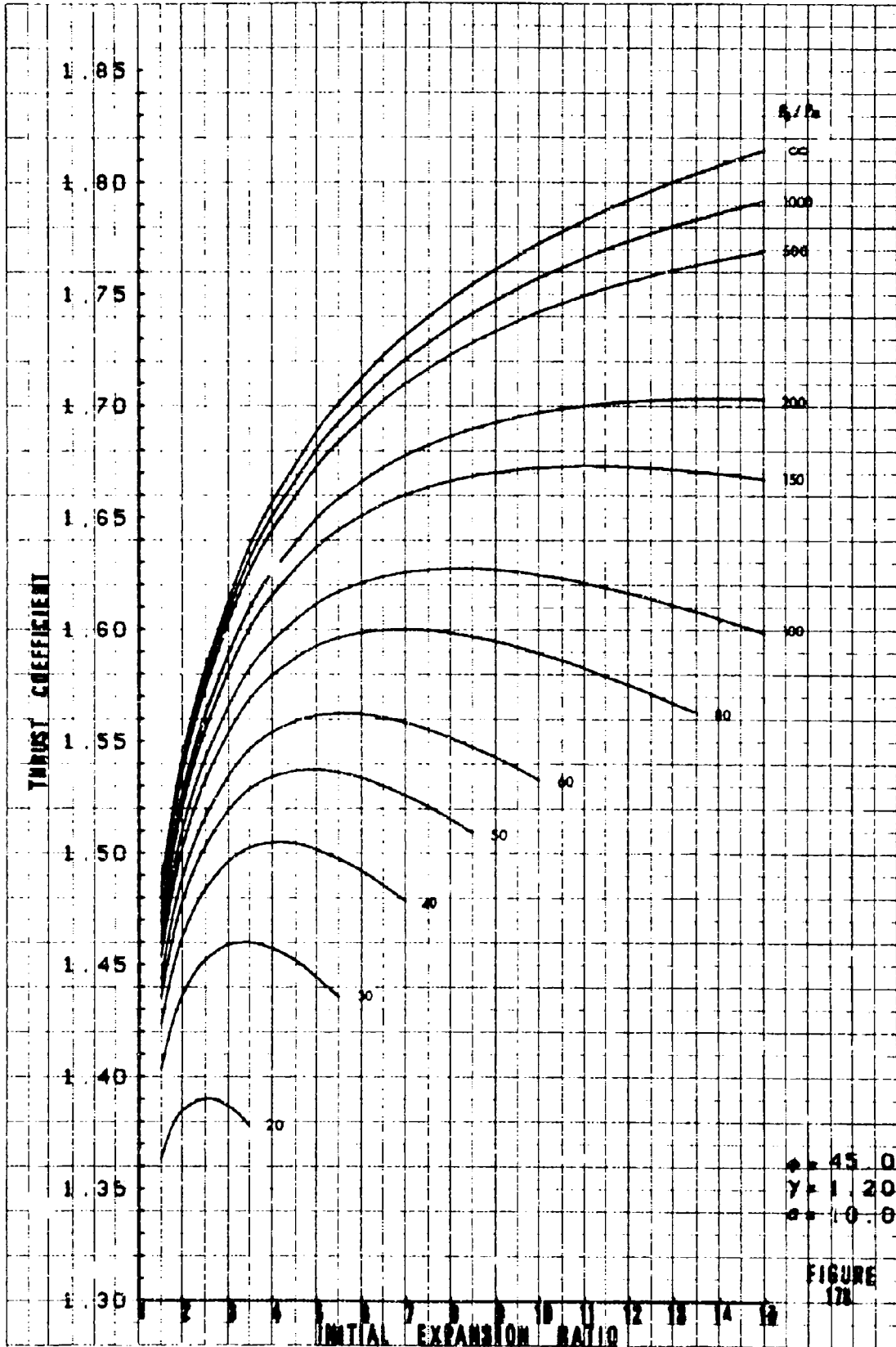
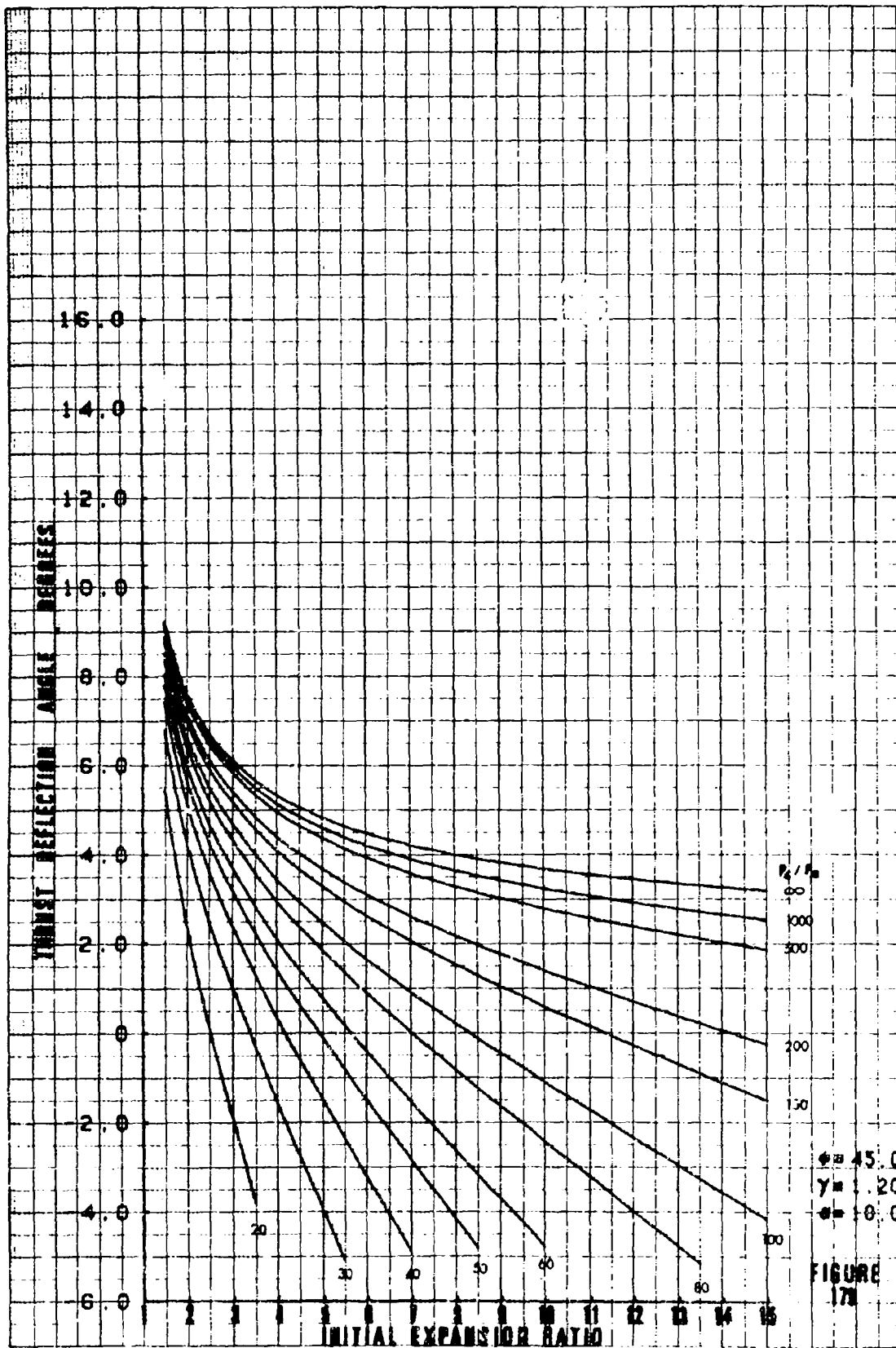
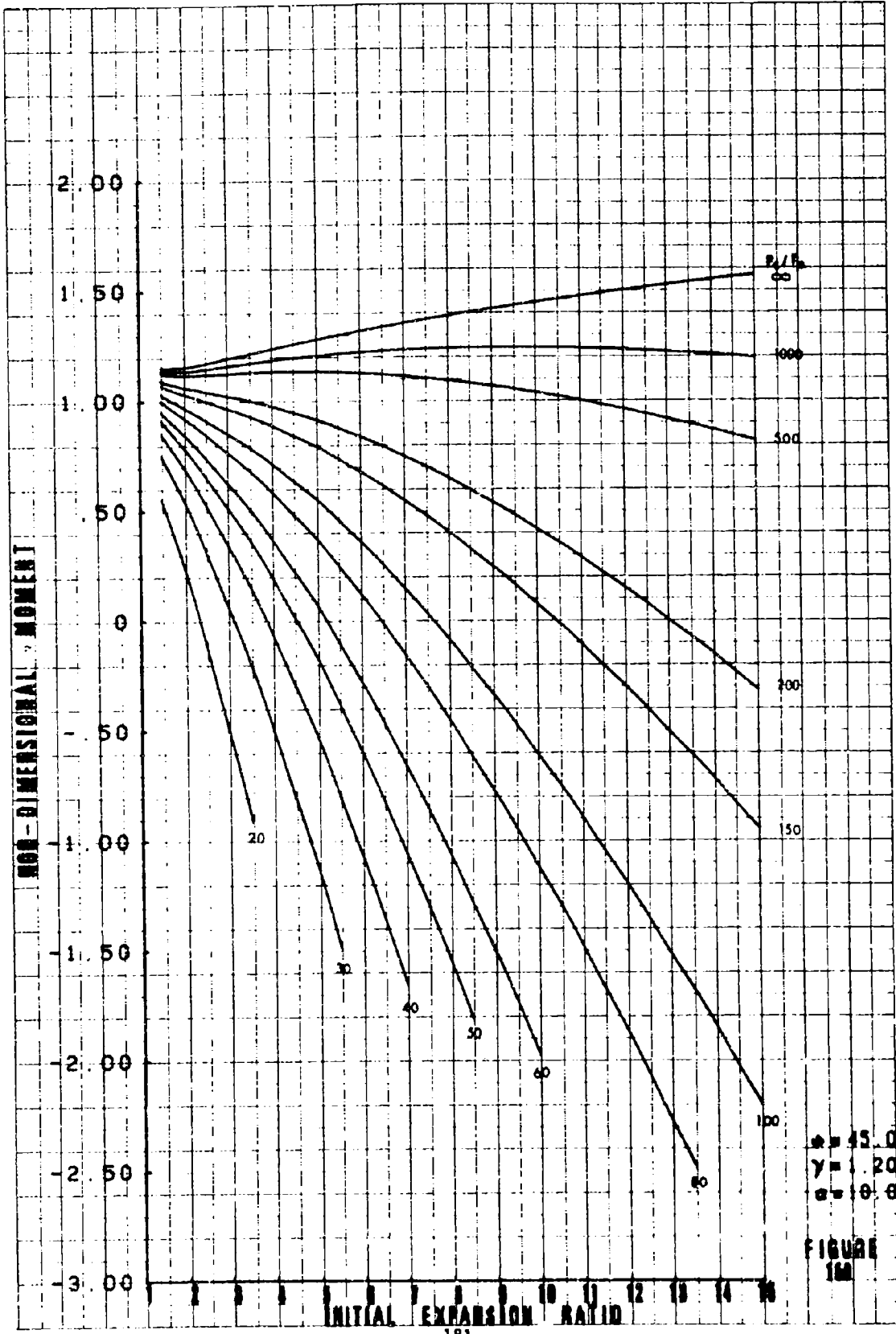
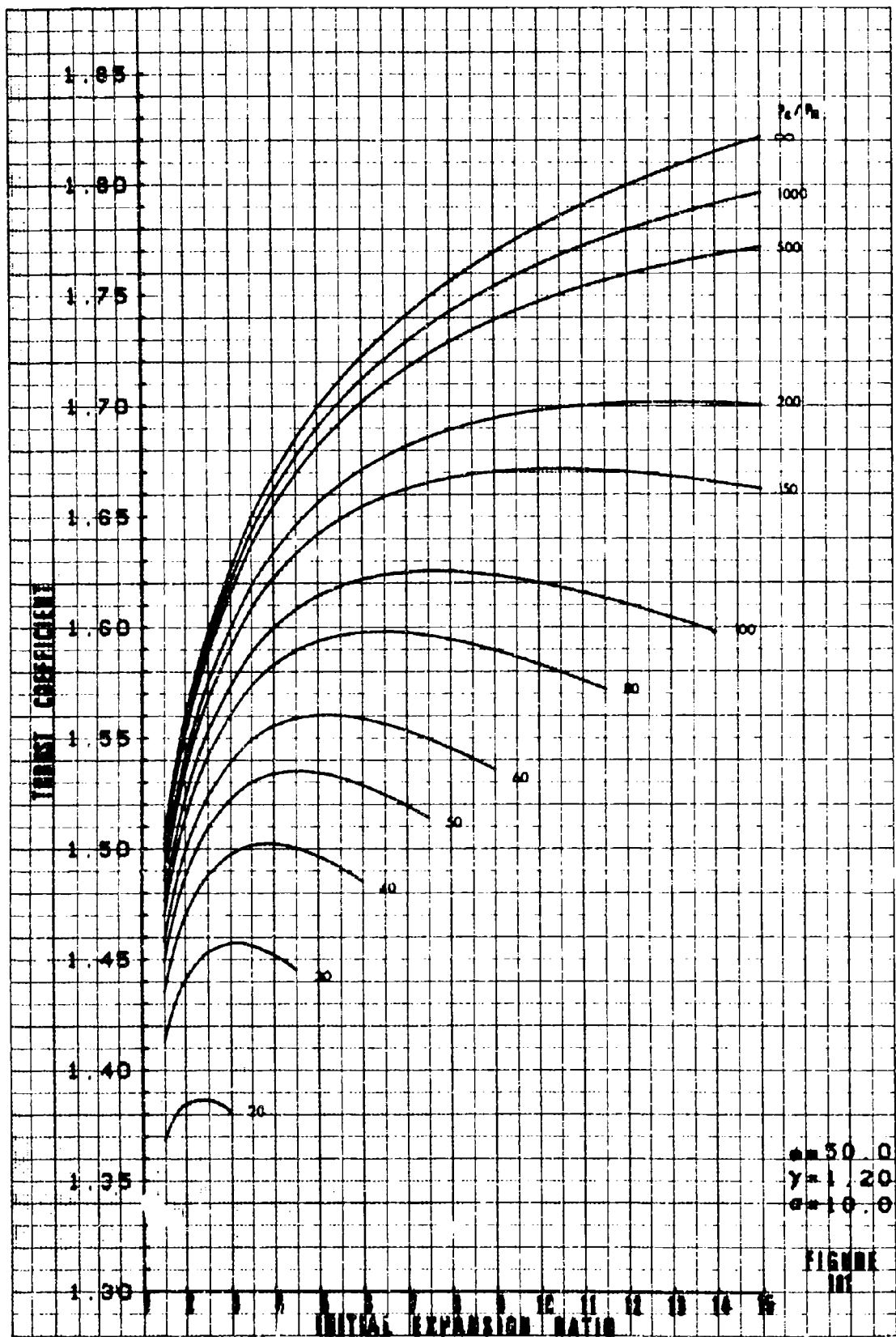


FIGURE 178







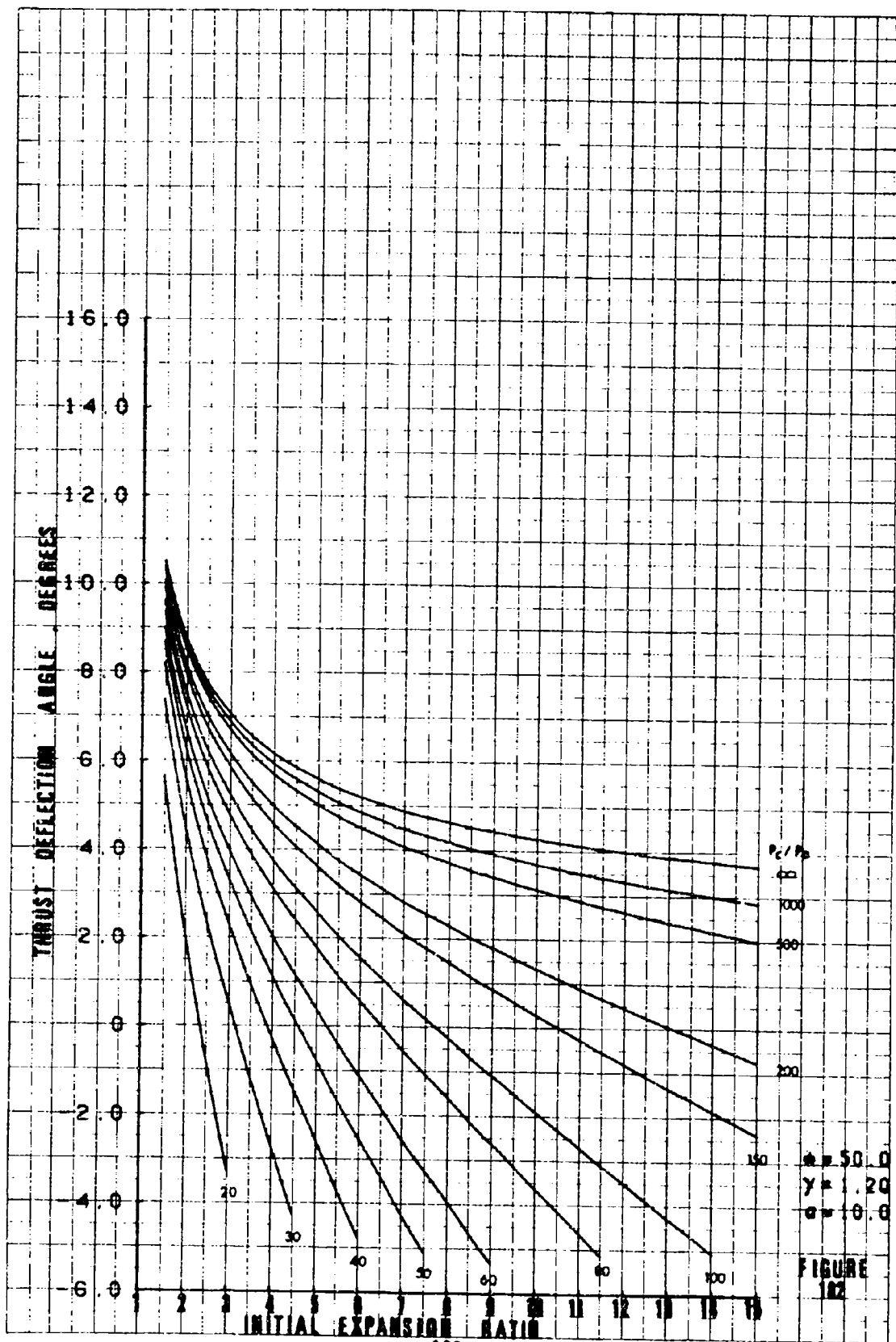
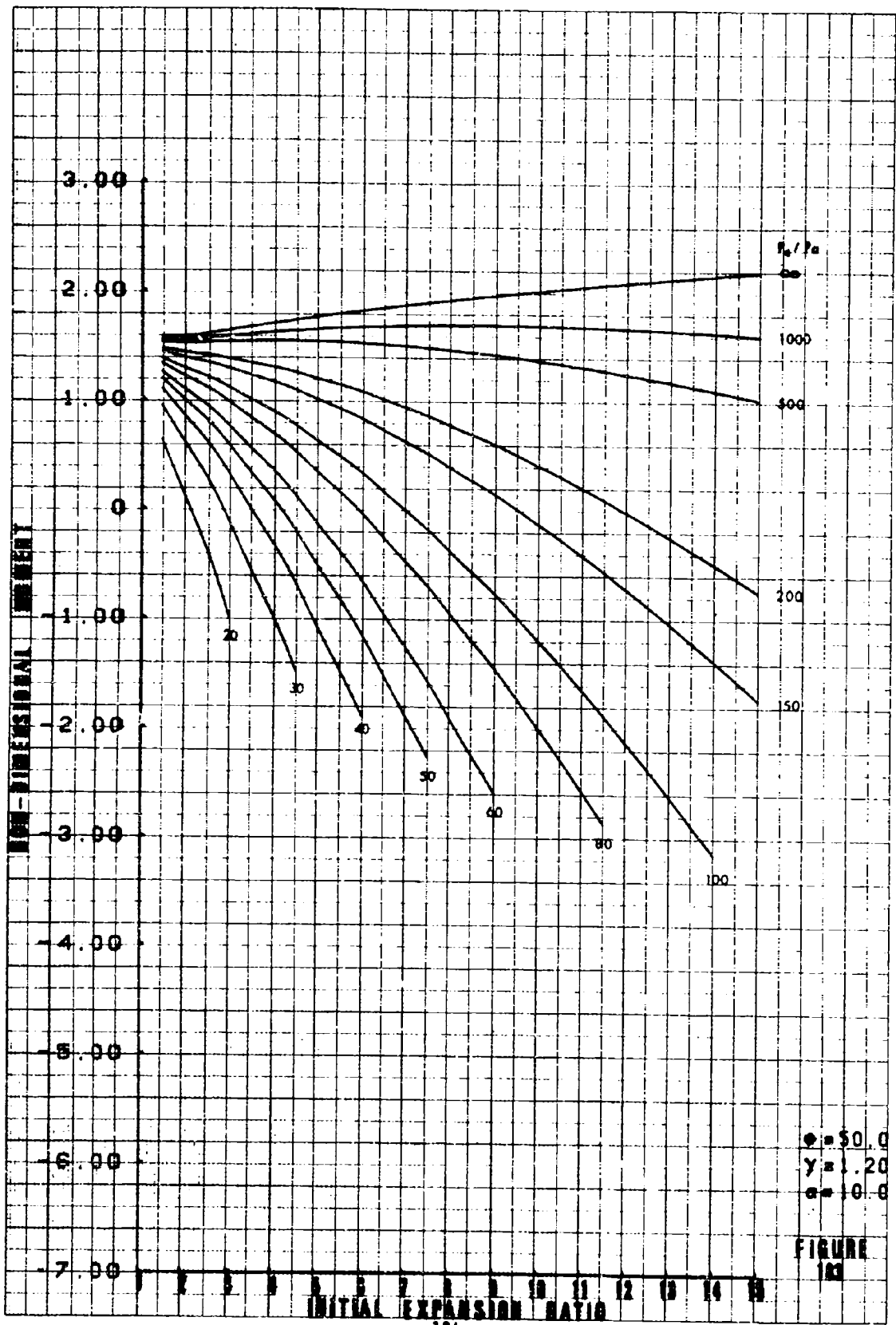
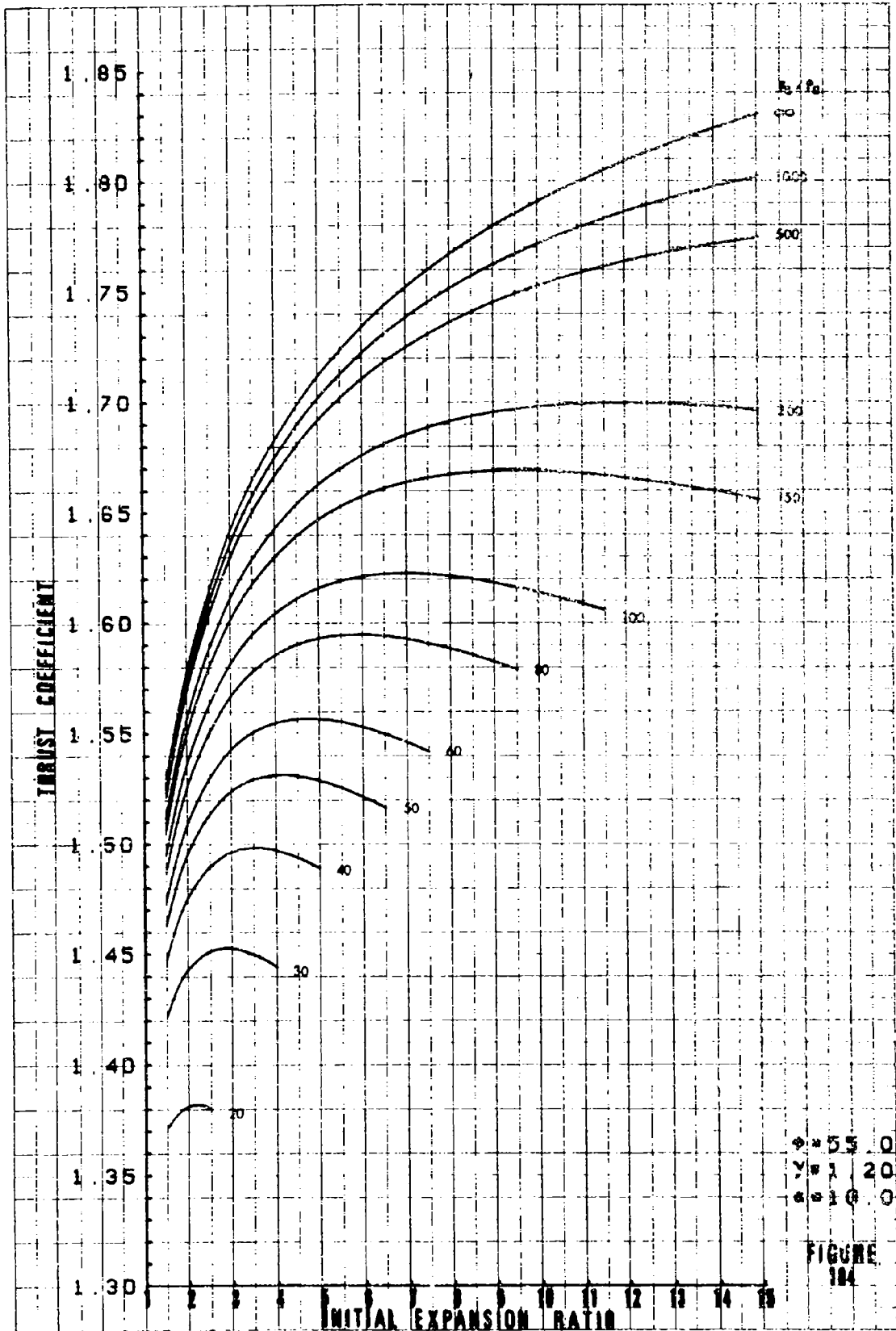


FIGURE 102

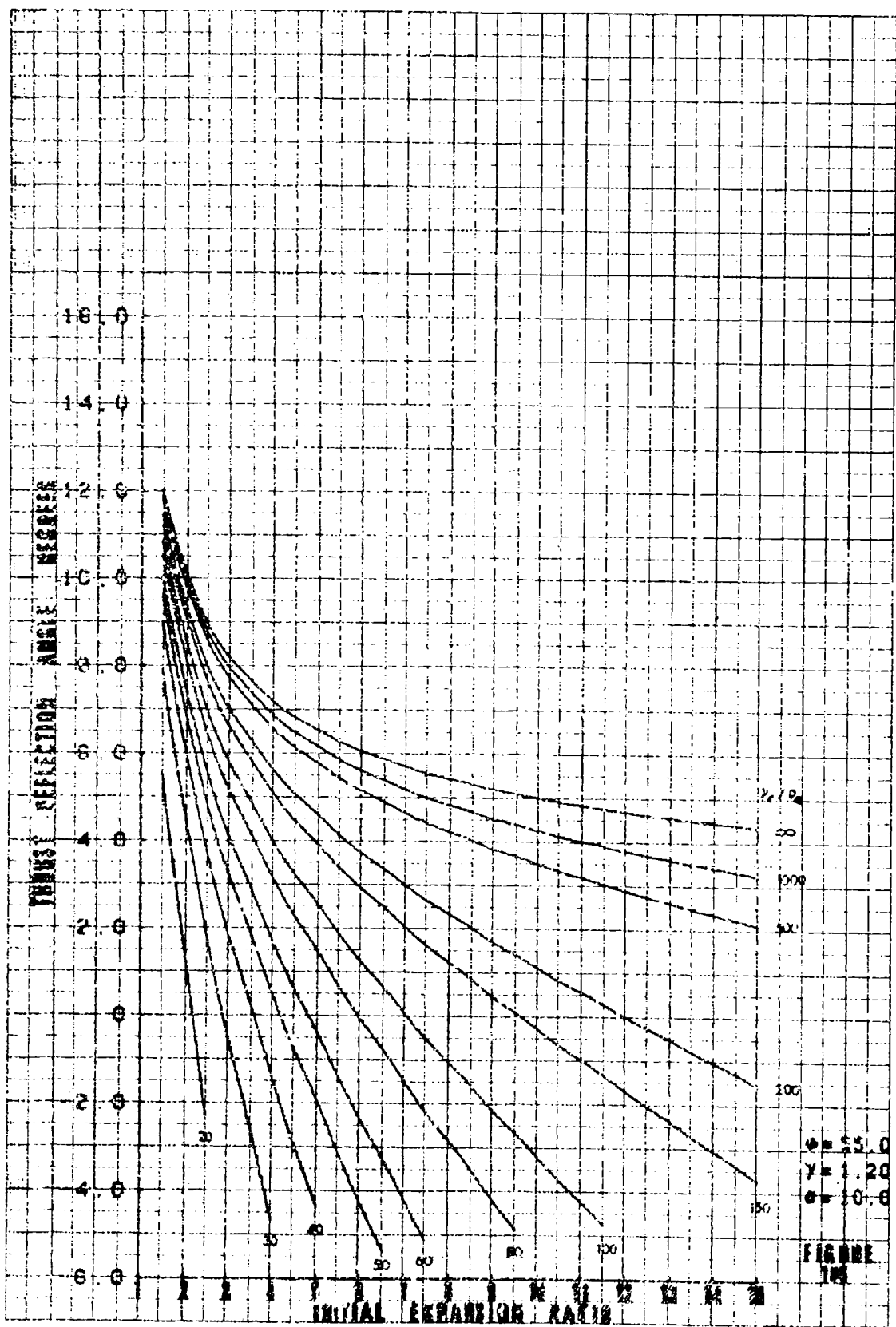


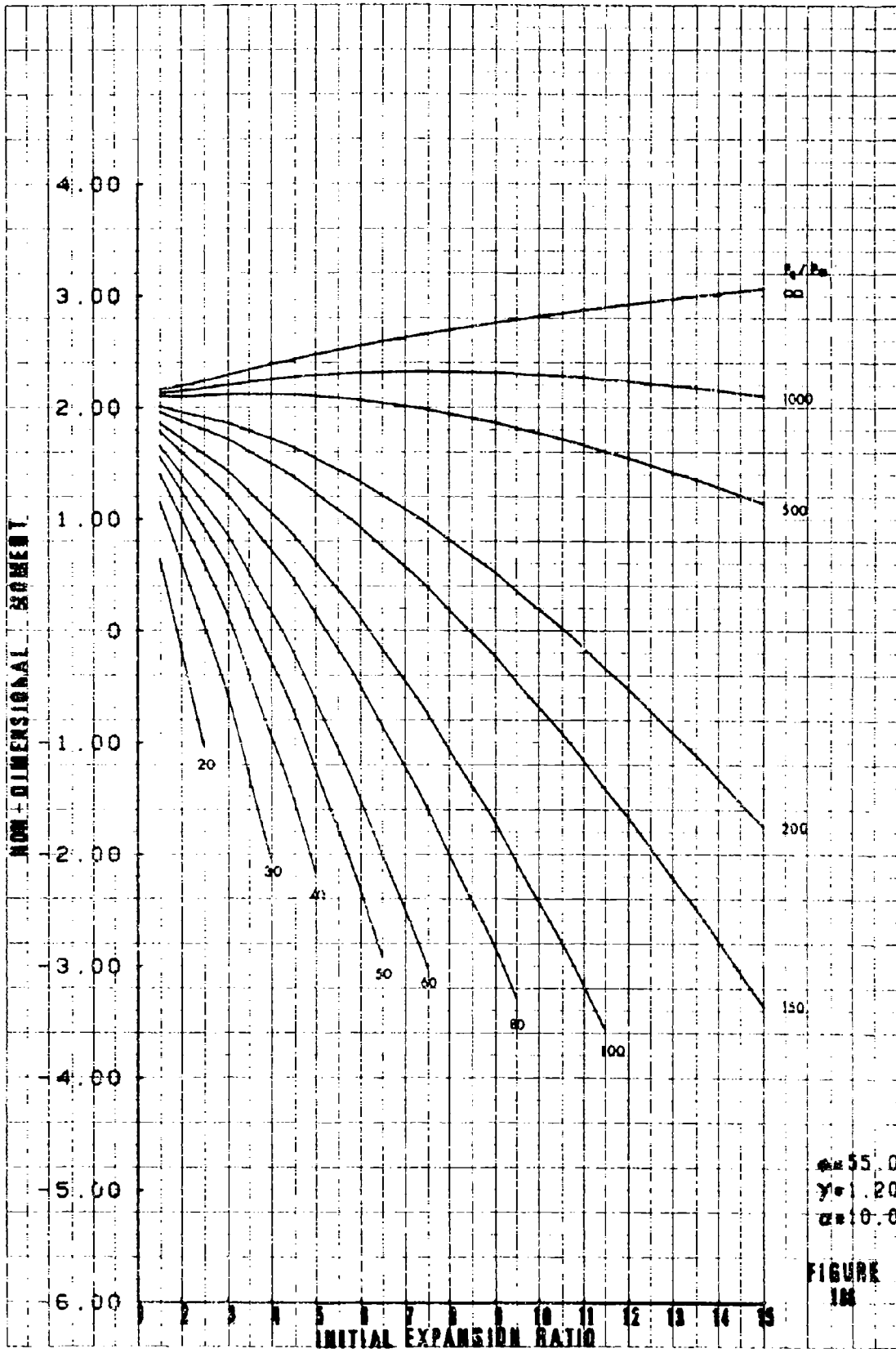


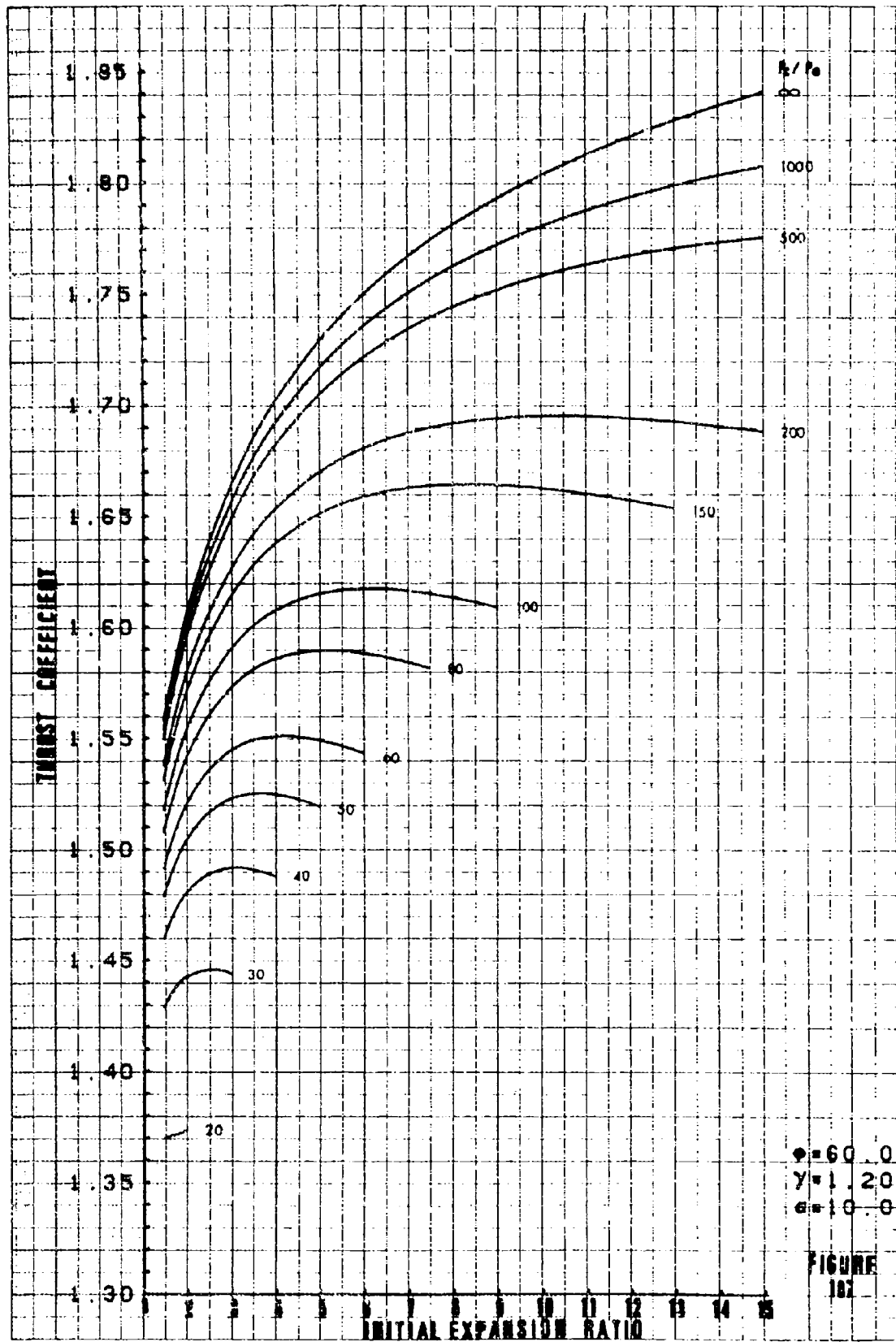


0 0 0  
 20 20 20  
 0 0 0

FIGURE 104







$\phi = 60.0$   
 $\gamma = 1.20$   
 $\epsilon = 10.0$

FIGURE 182

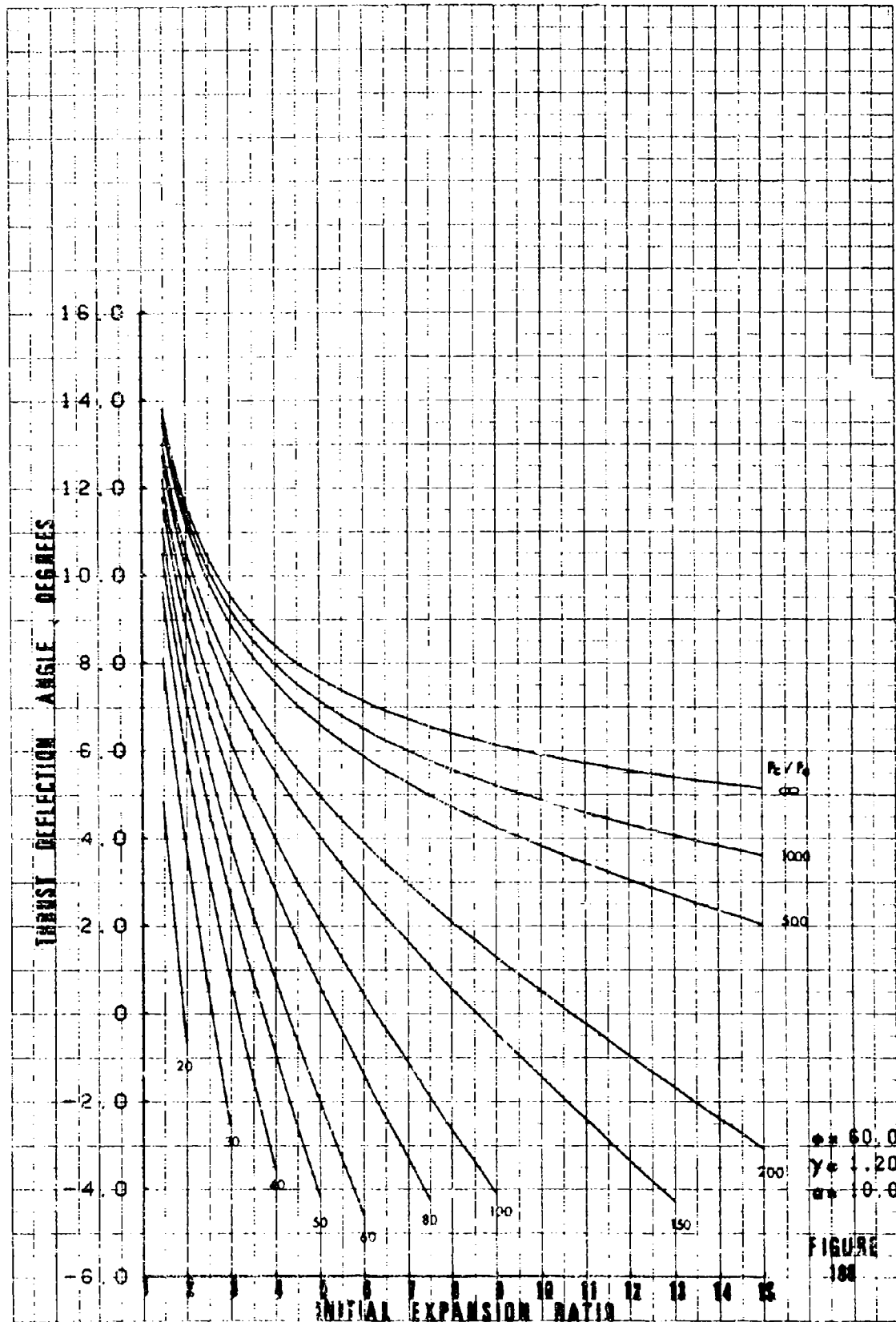
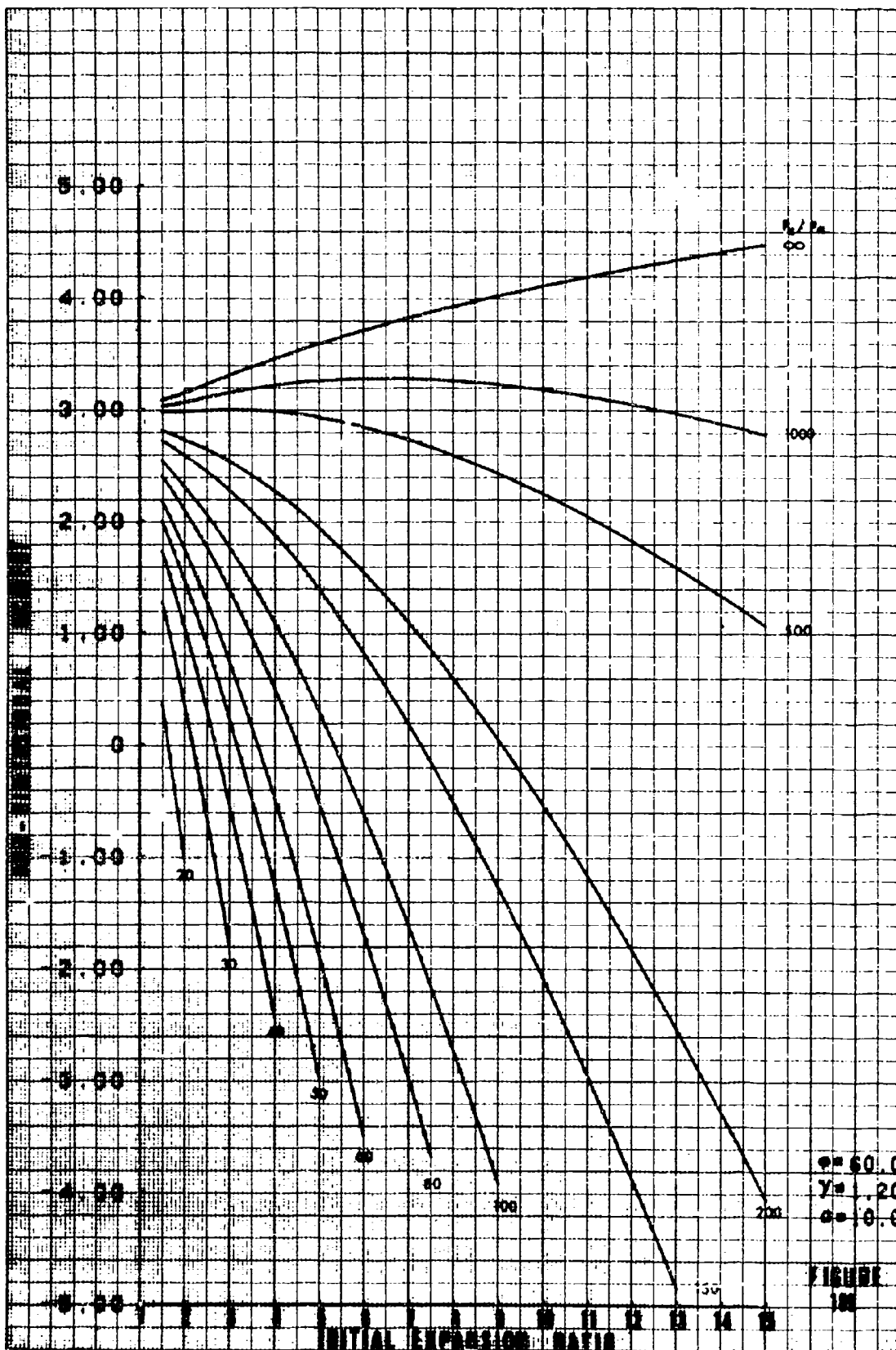
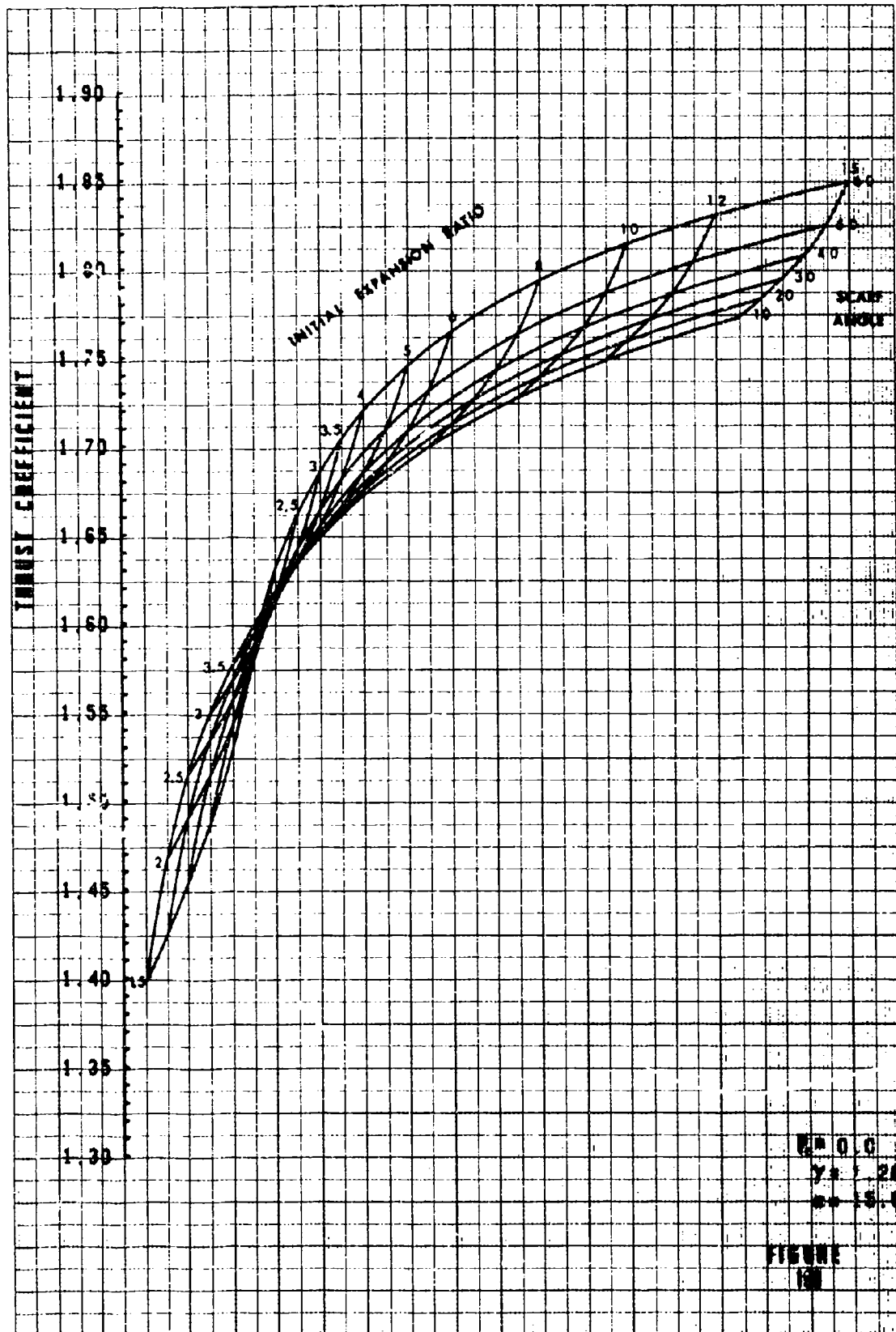
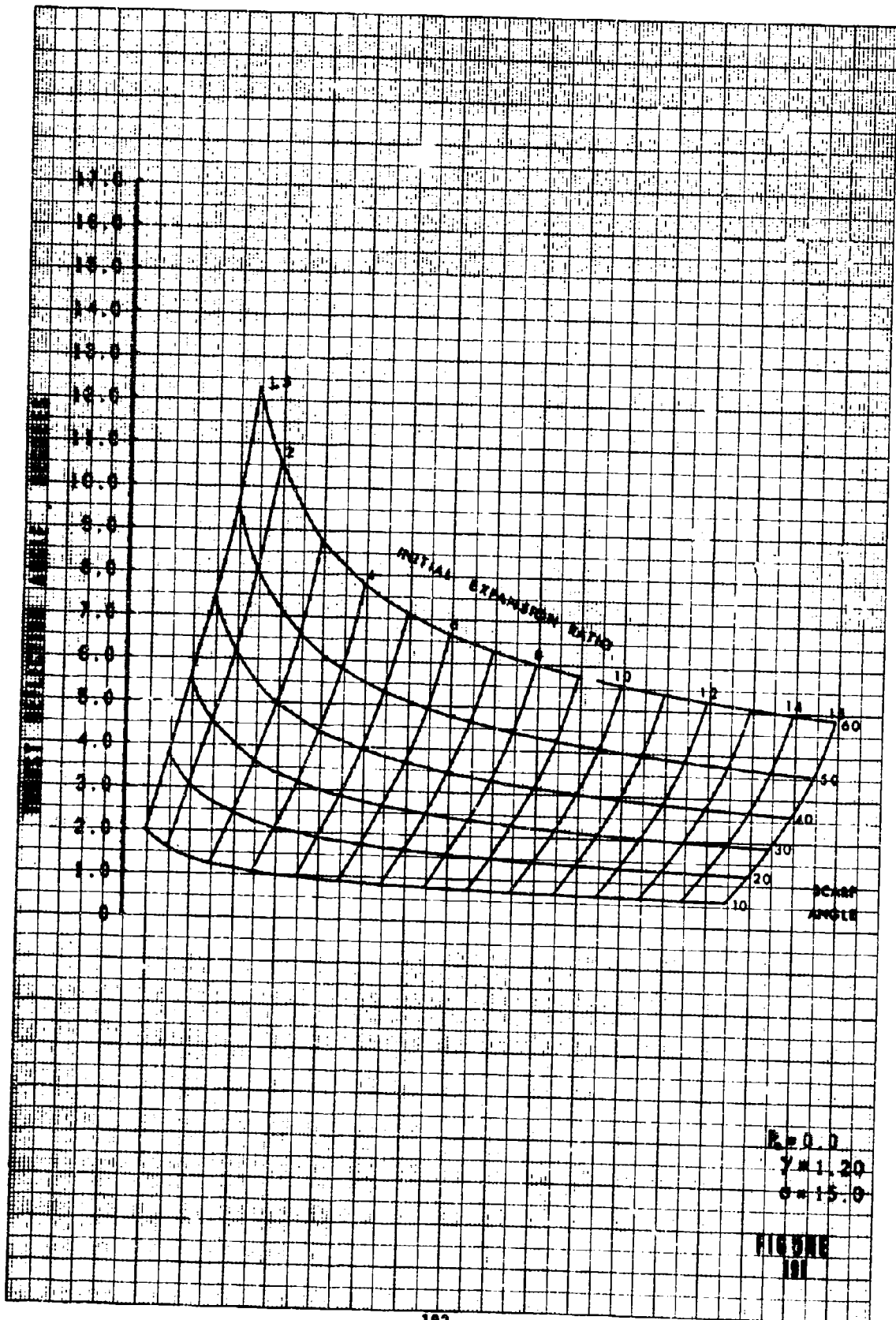


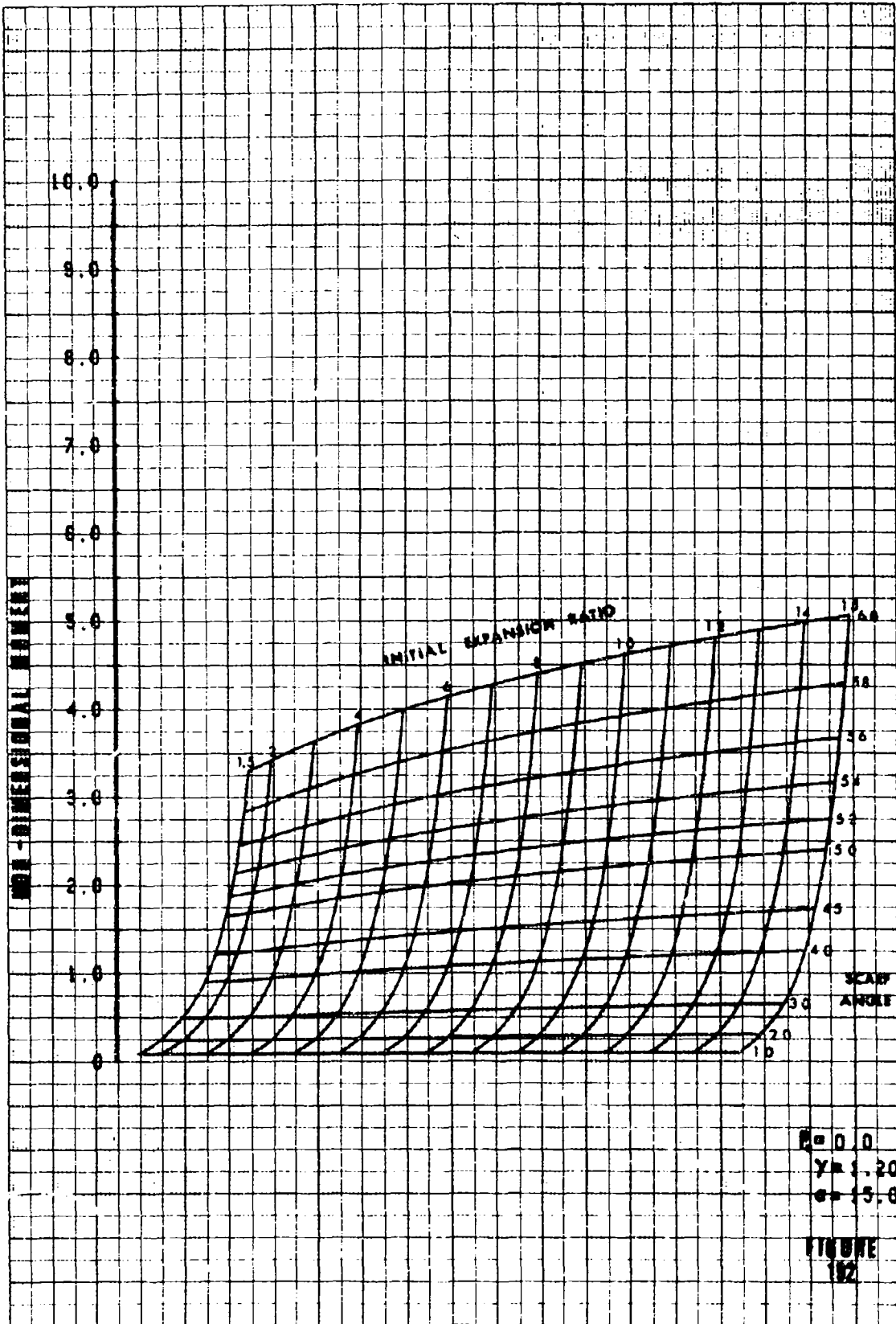
FIGURE 189











$\mu = 0.0$   
 $\gamma = 1.20$   
 $\sigma = 15.0$

FIGURE  
192

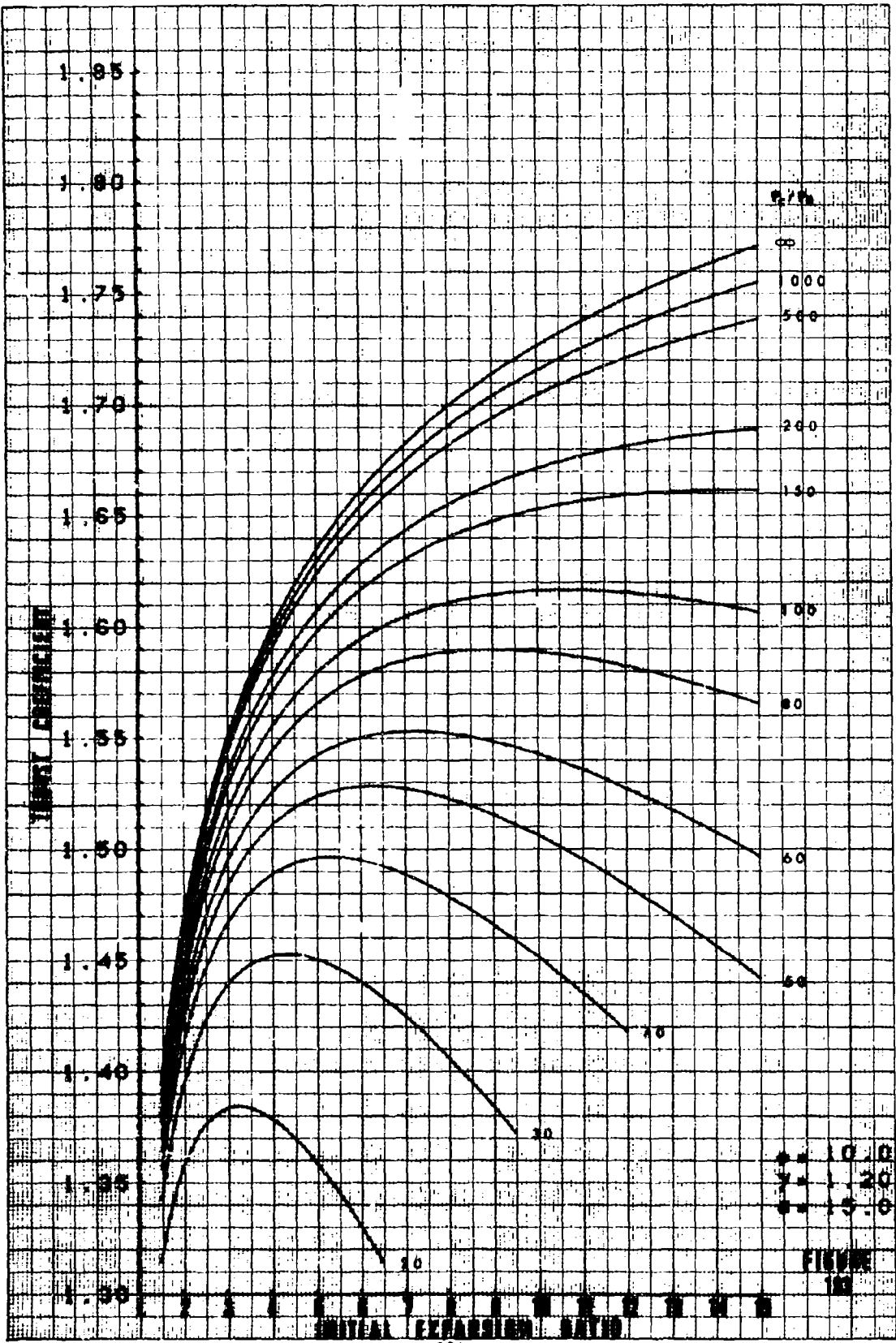
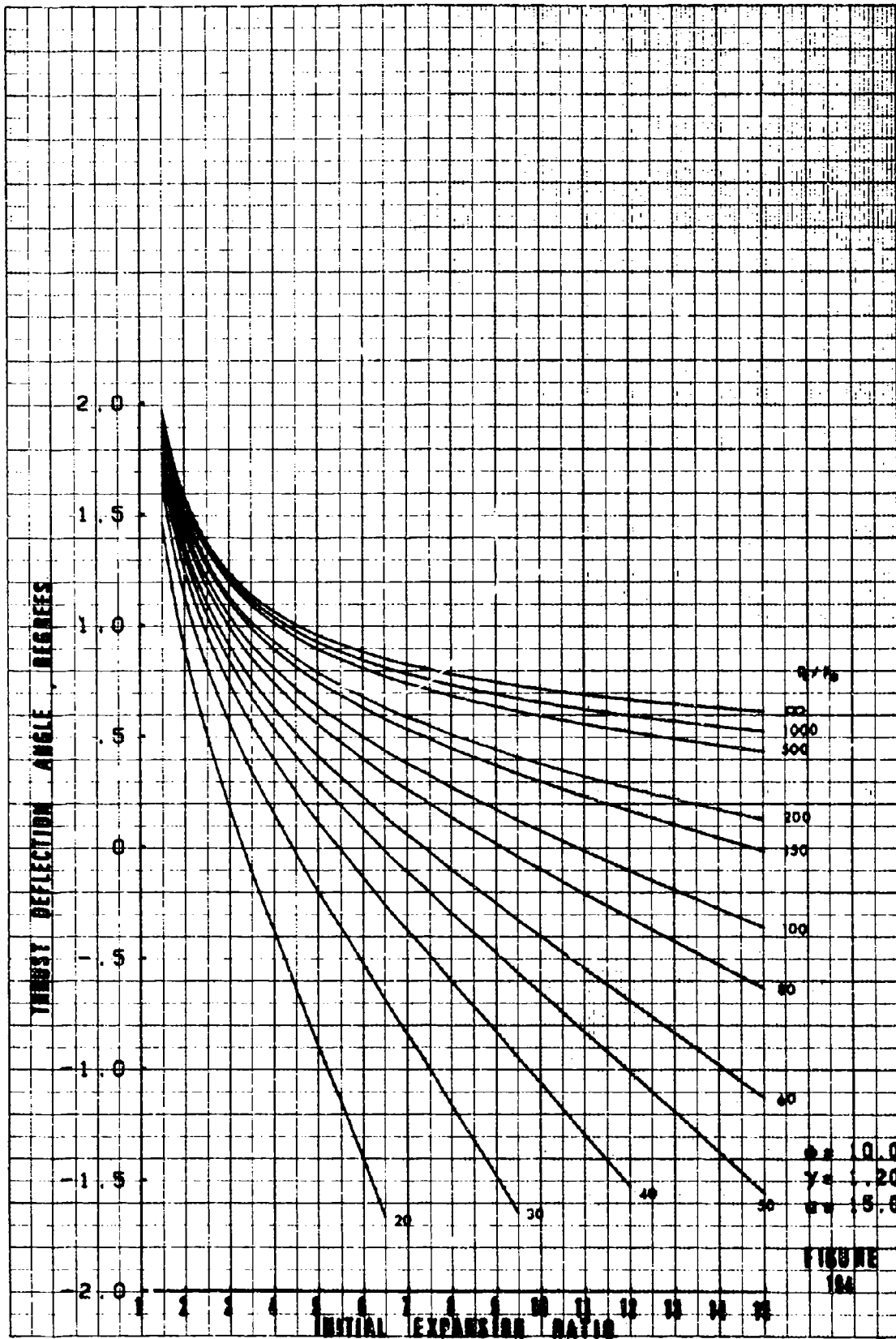
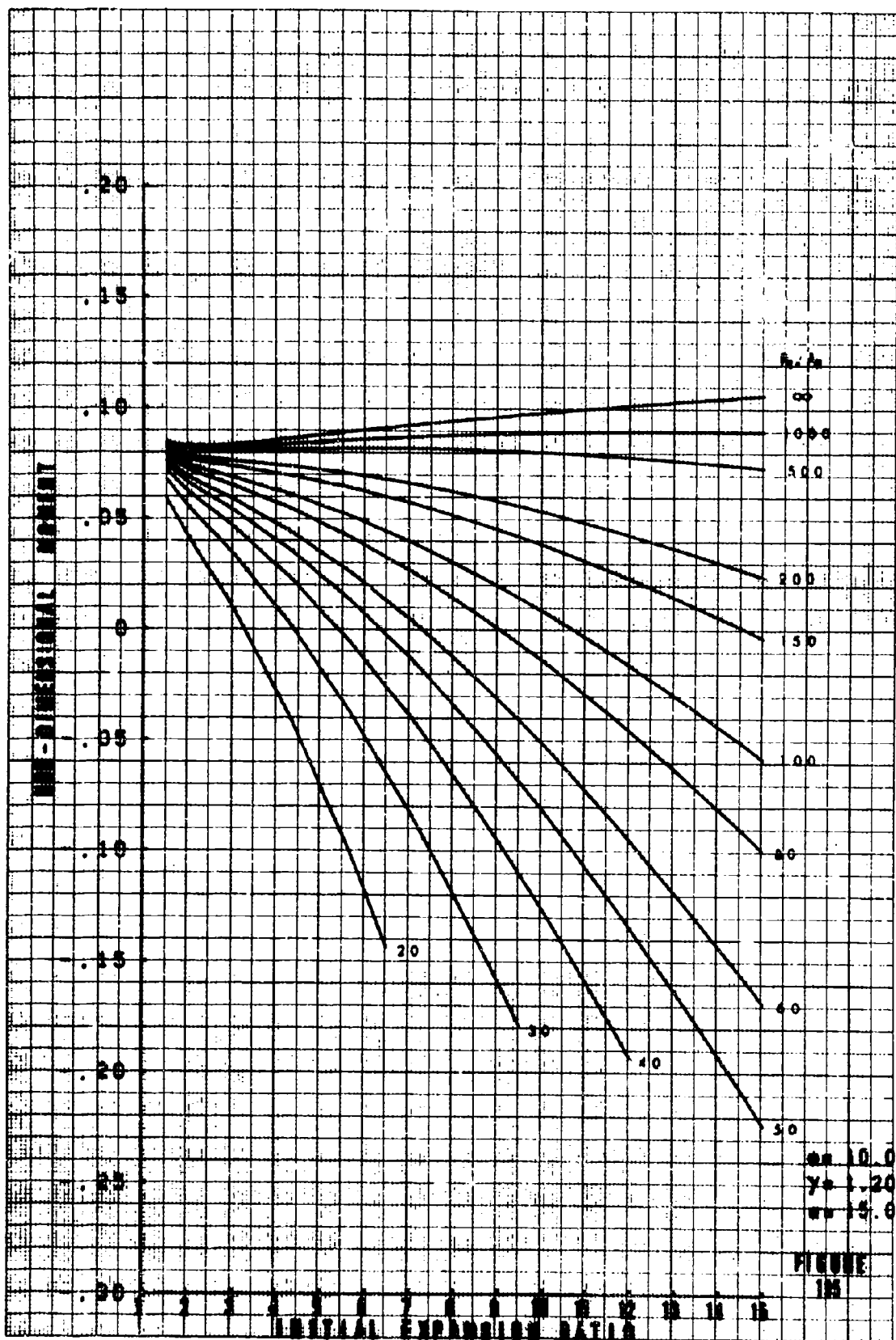
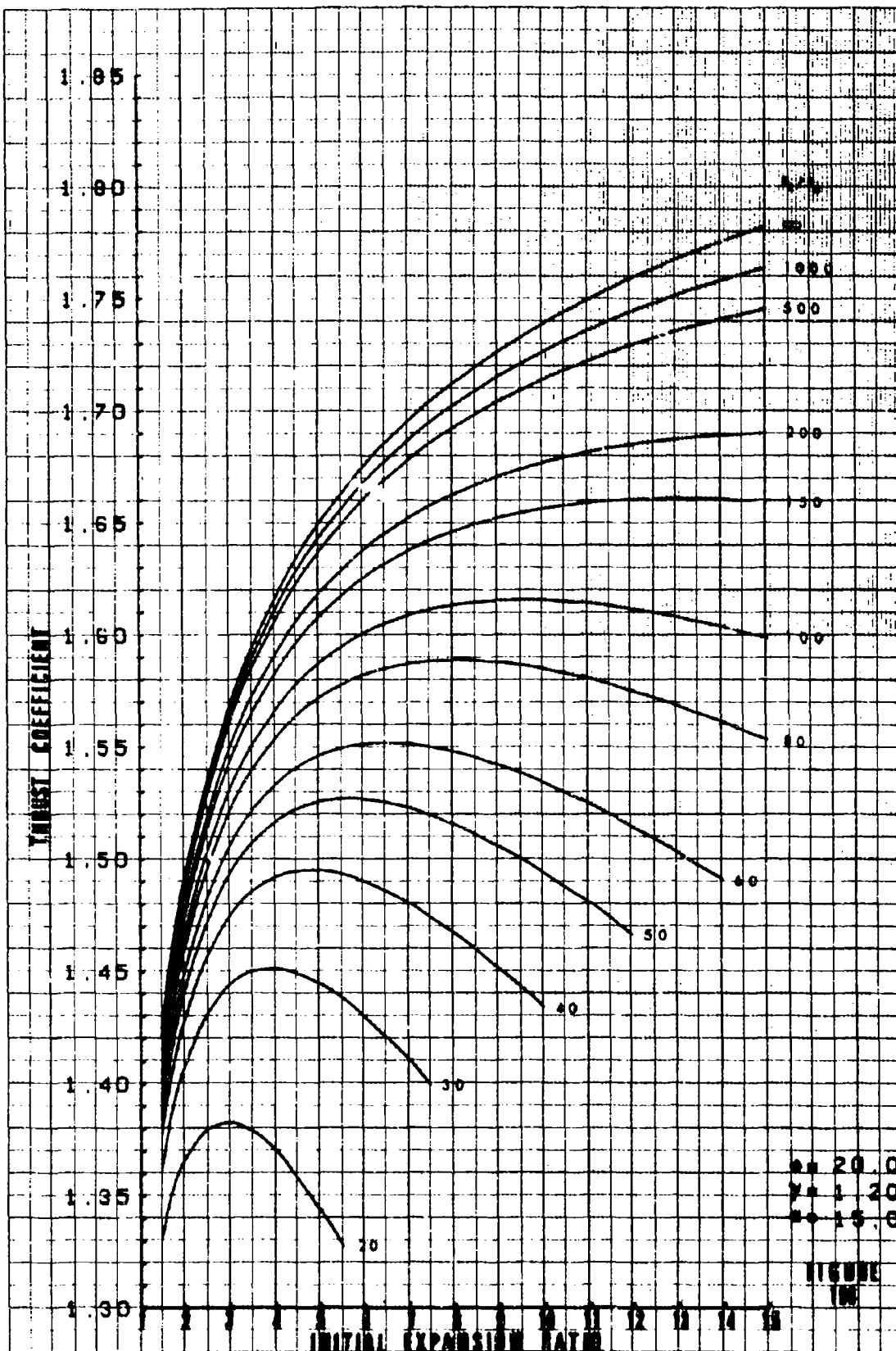


FIGURE 10

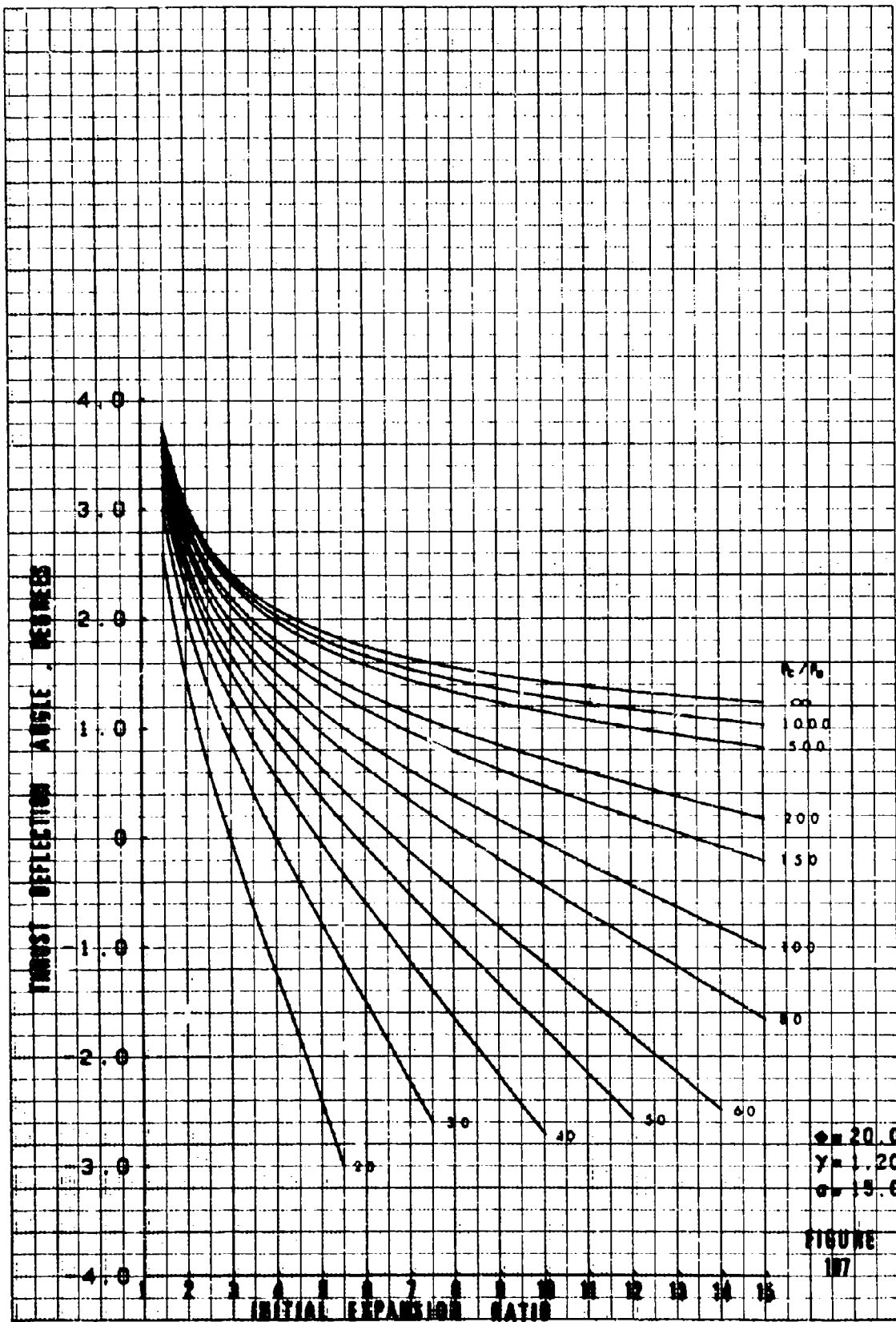


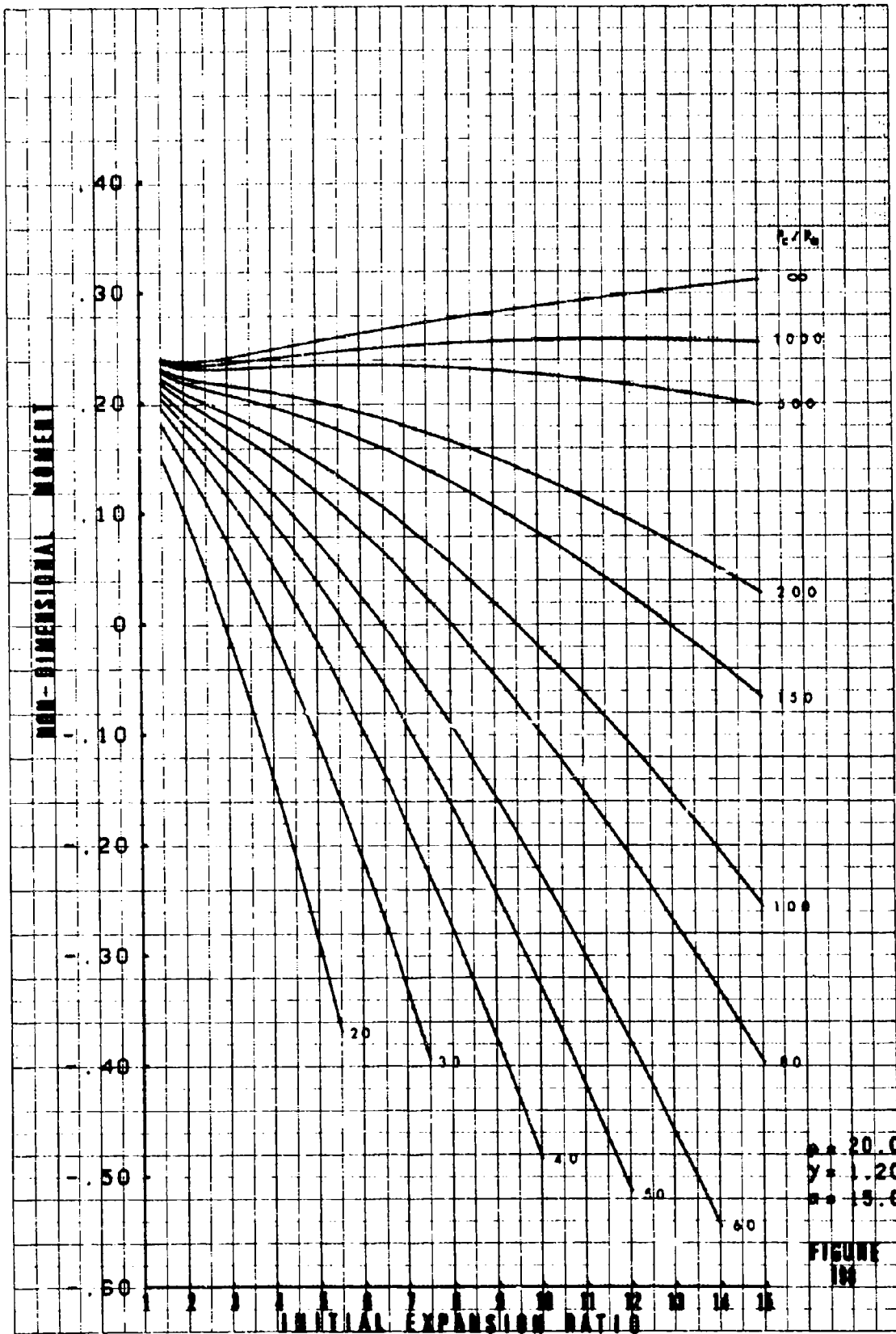




● 20.0  
 ○ 1.20  
 ■ 15.0

FIGURE 100





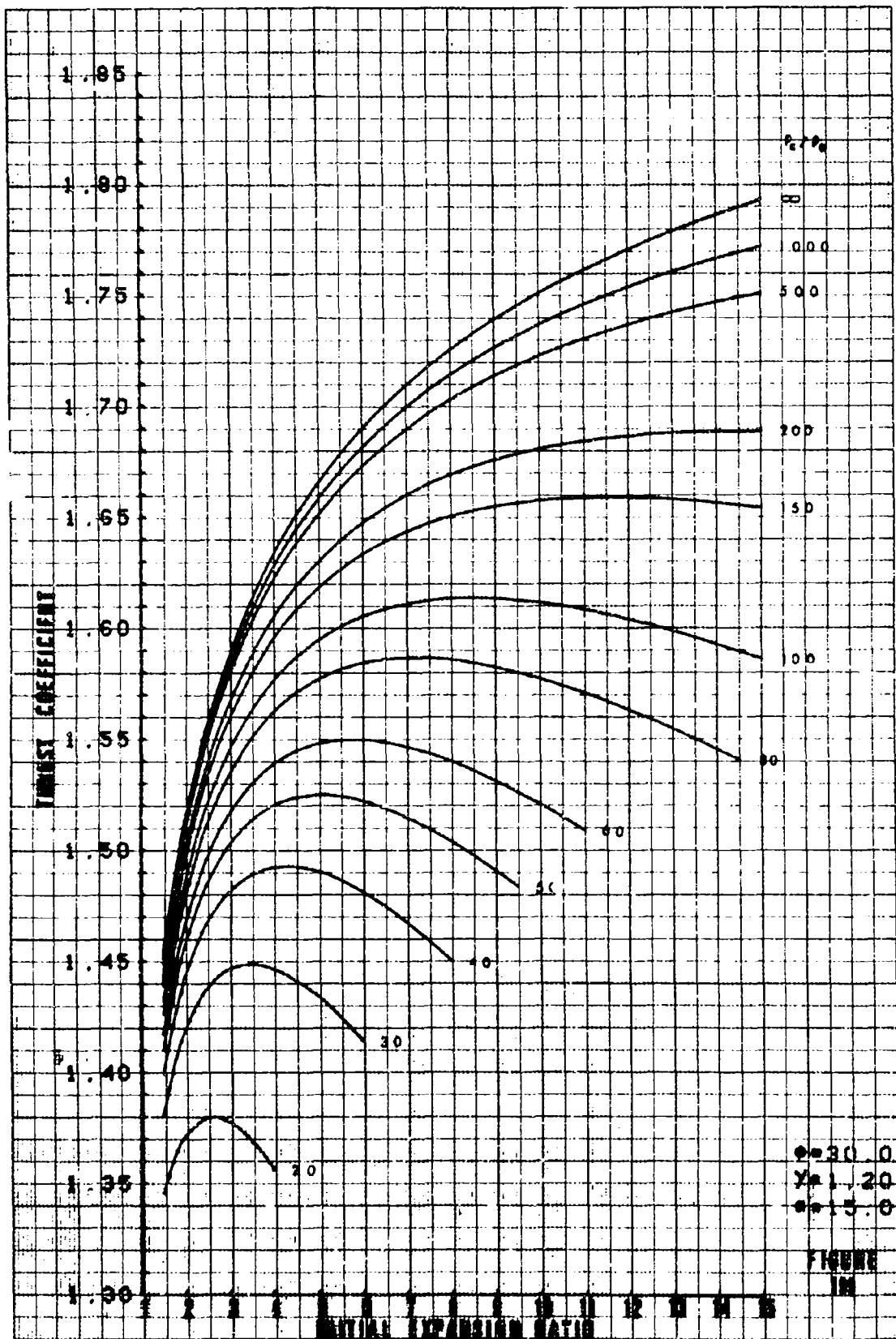


FIGURE 1M



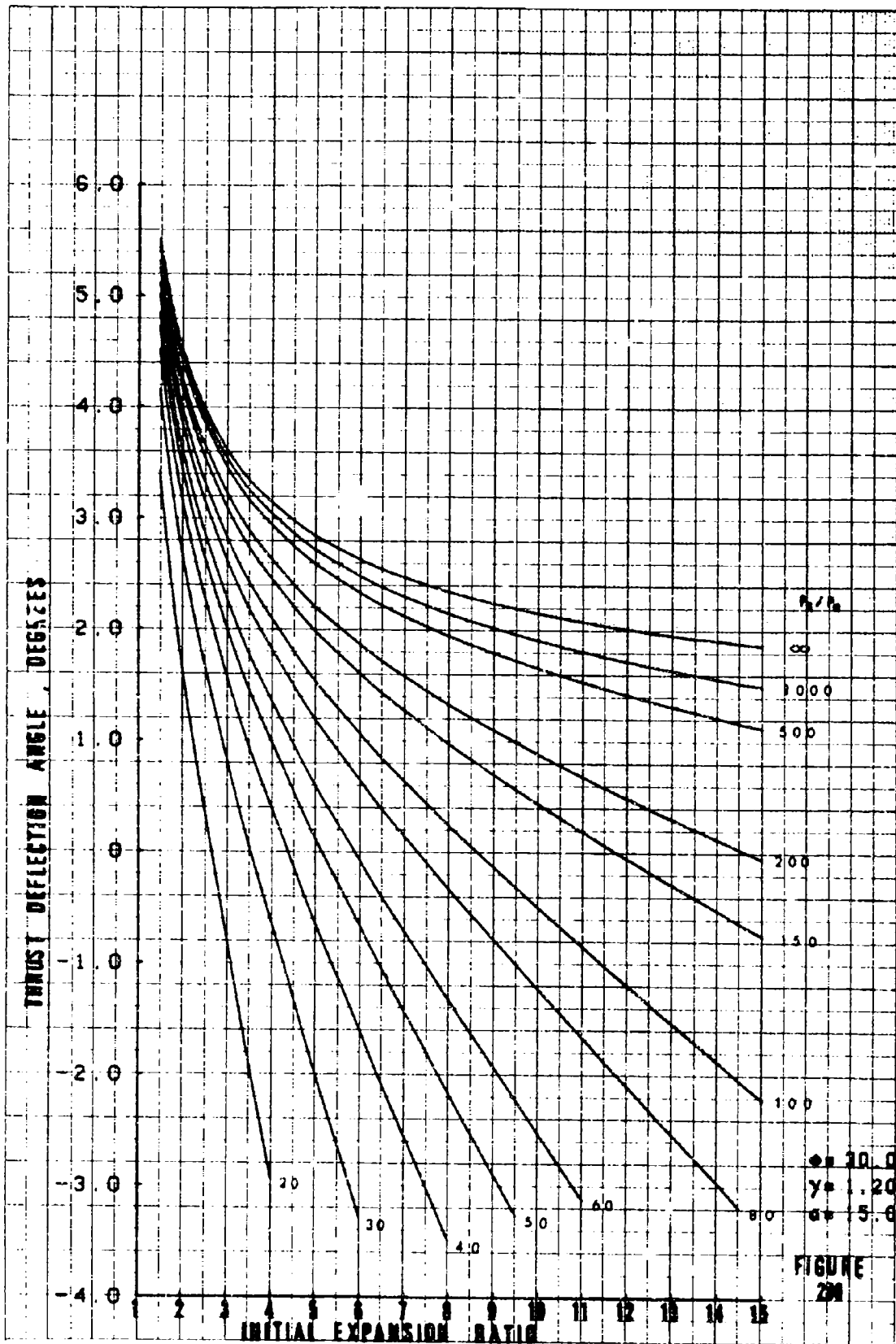


FIGURE 201

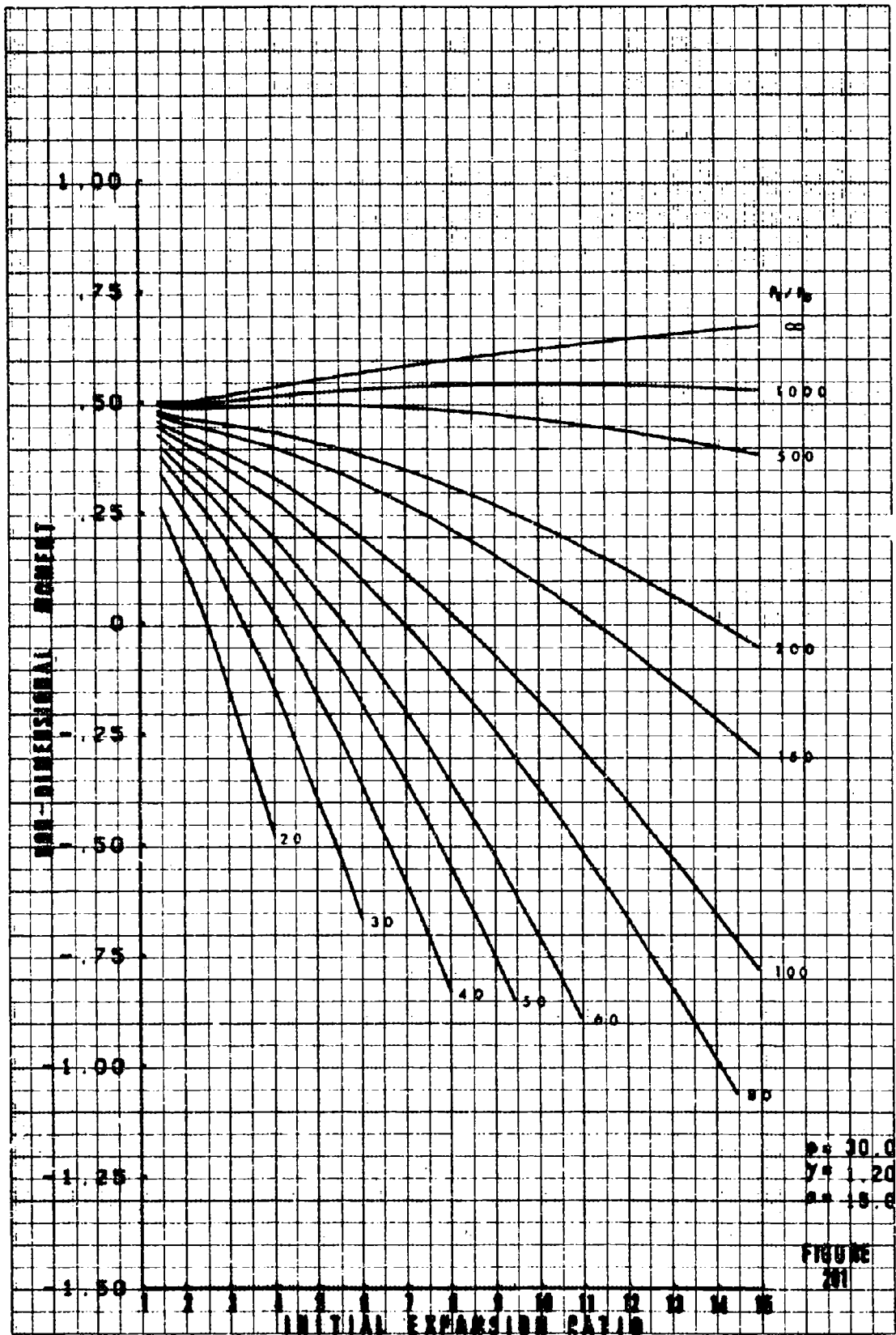
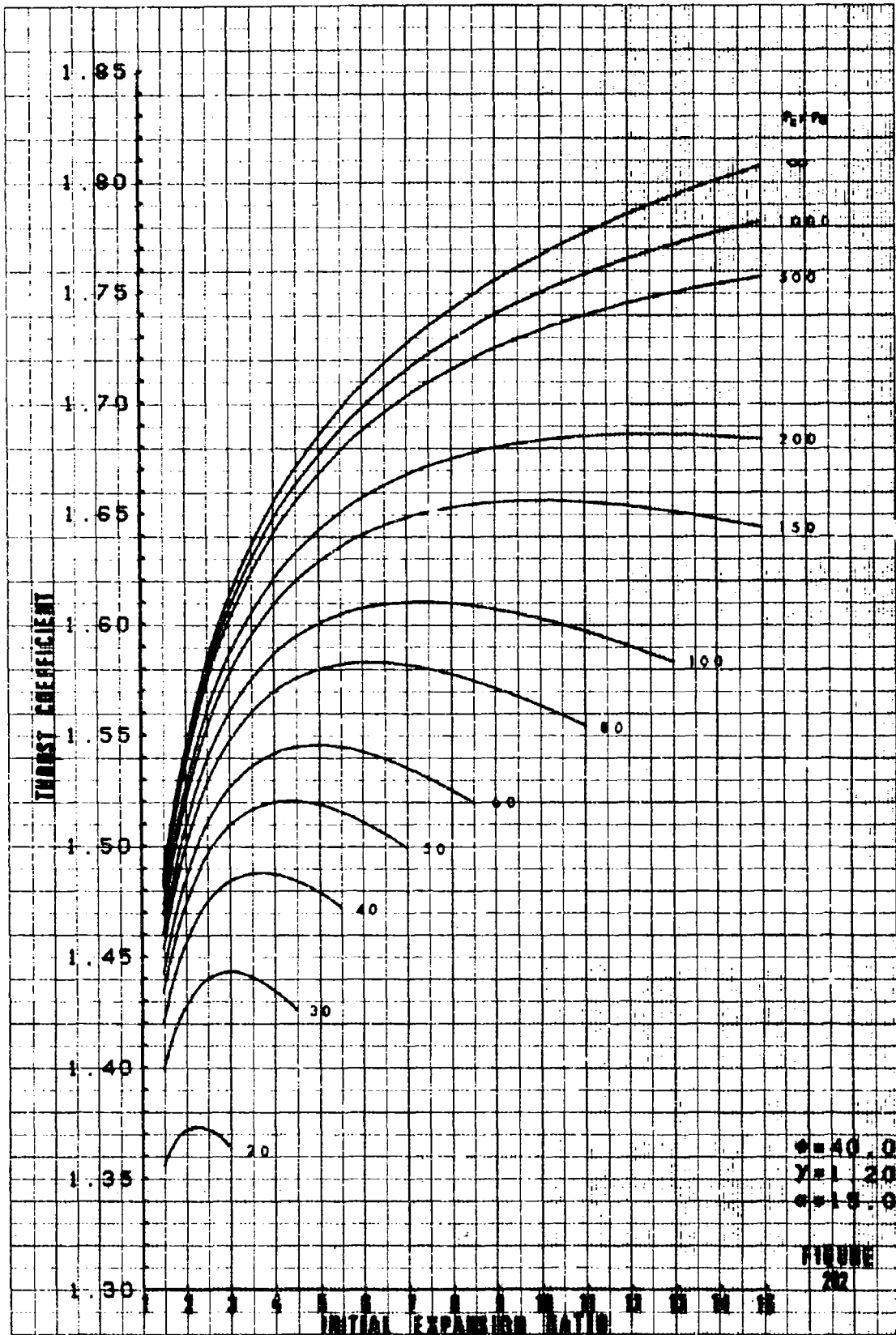


FIGURE 201



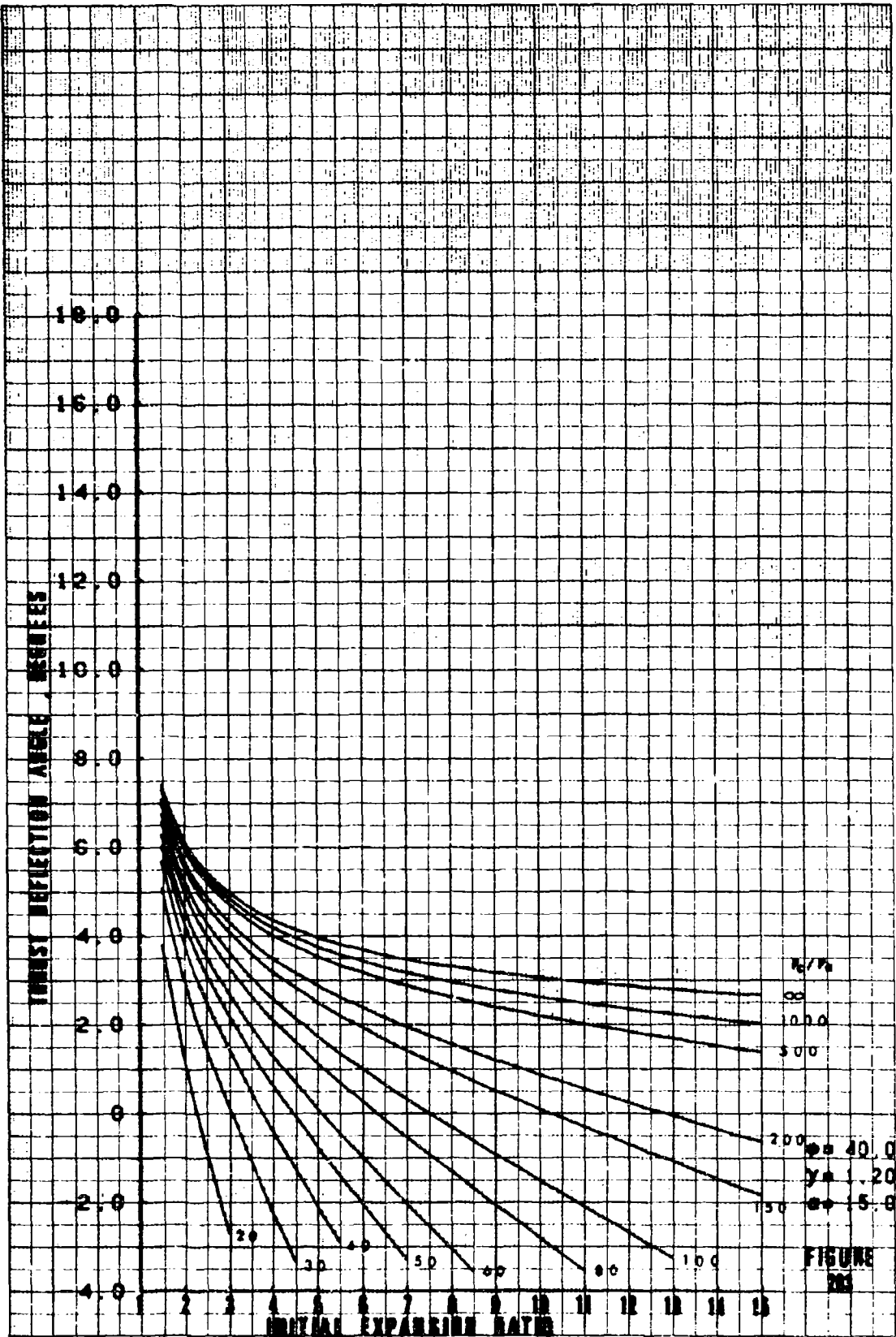
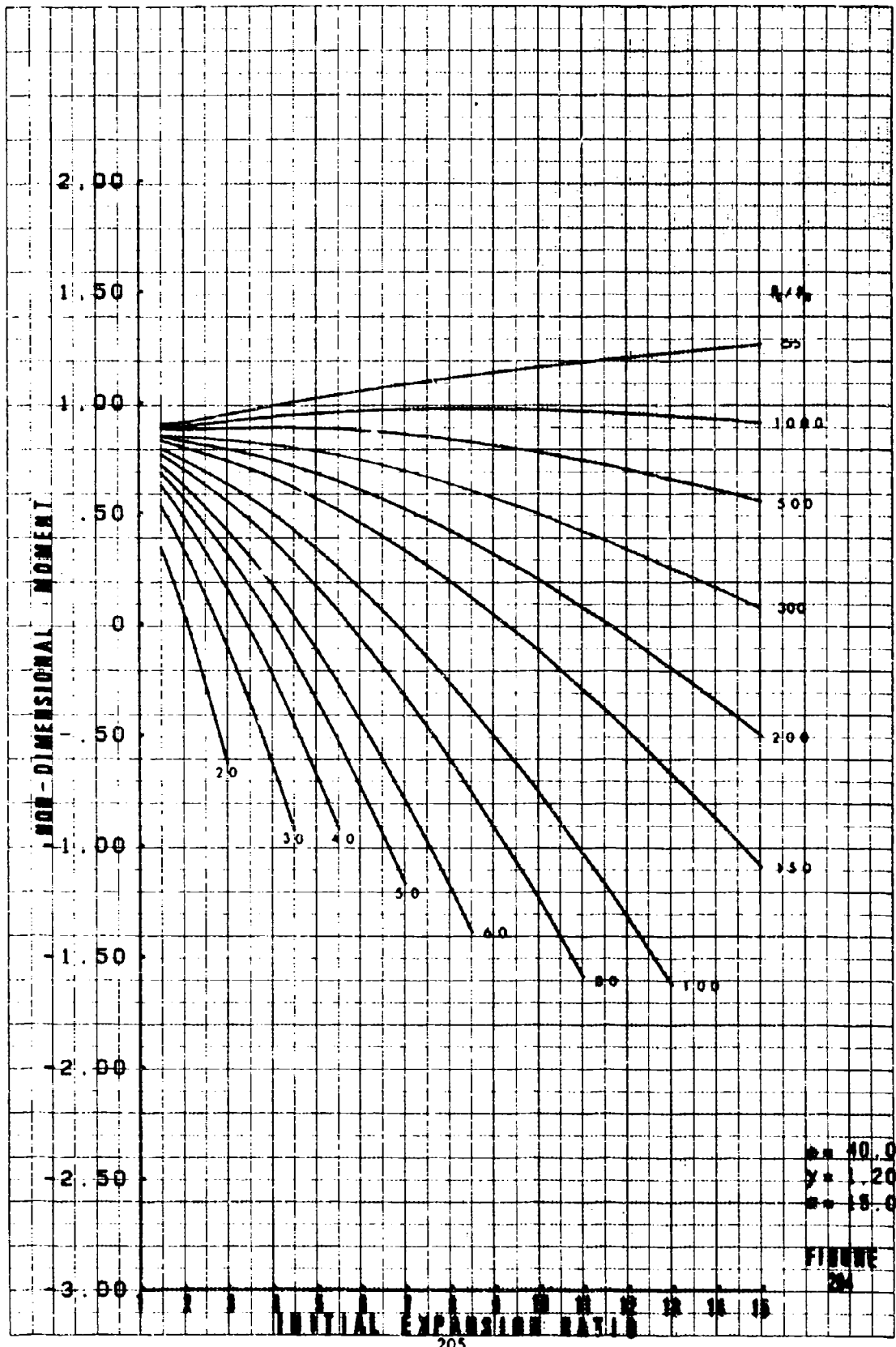
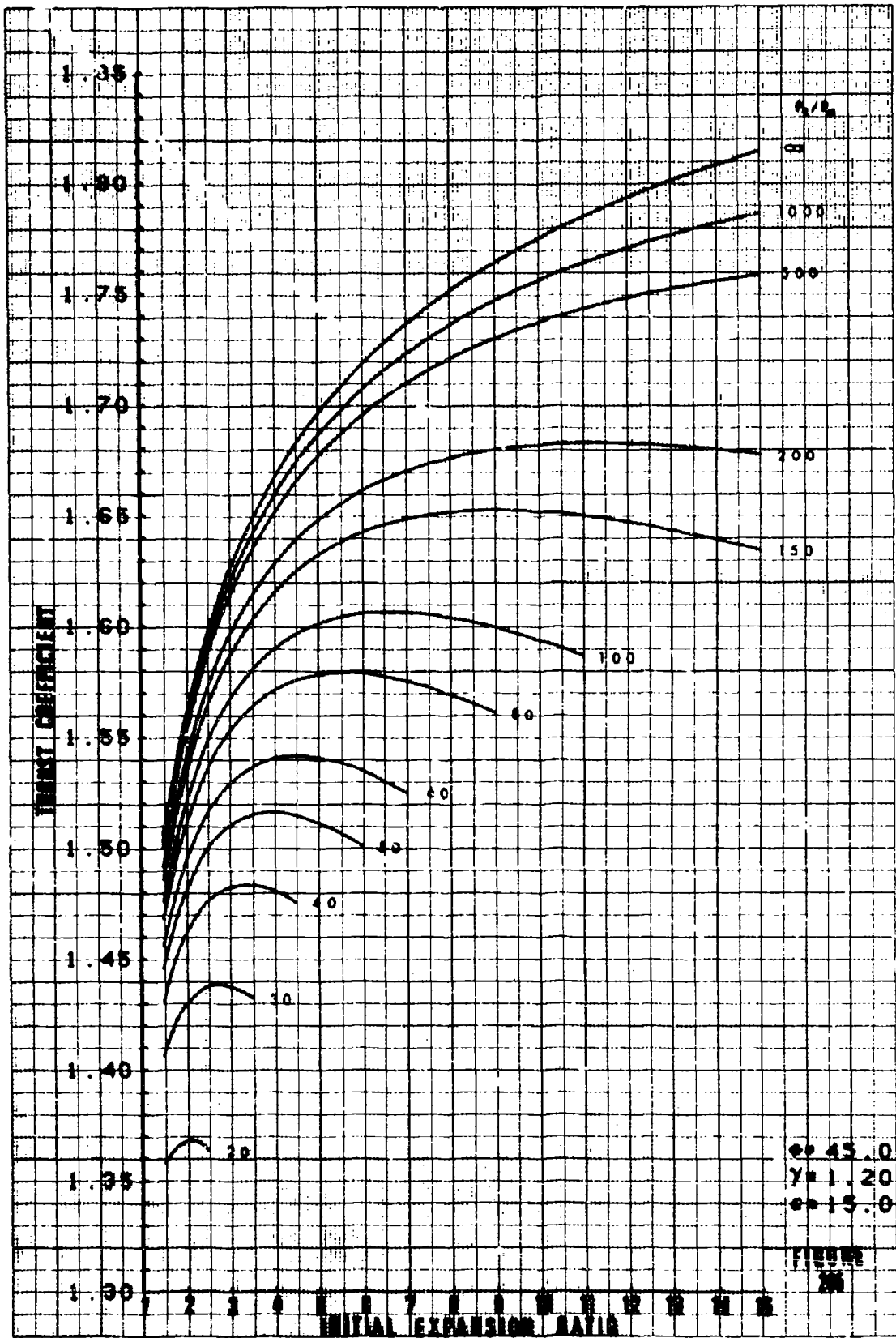
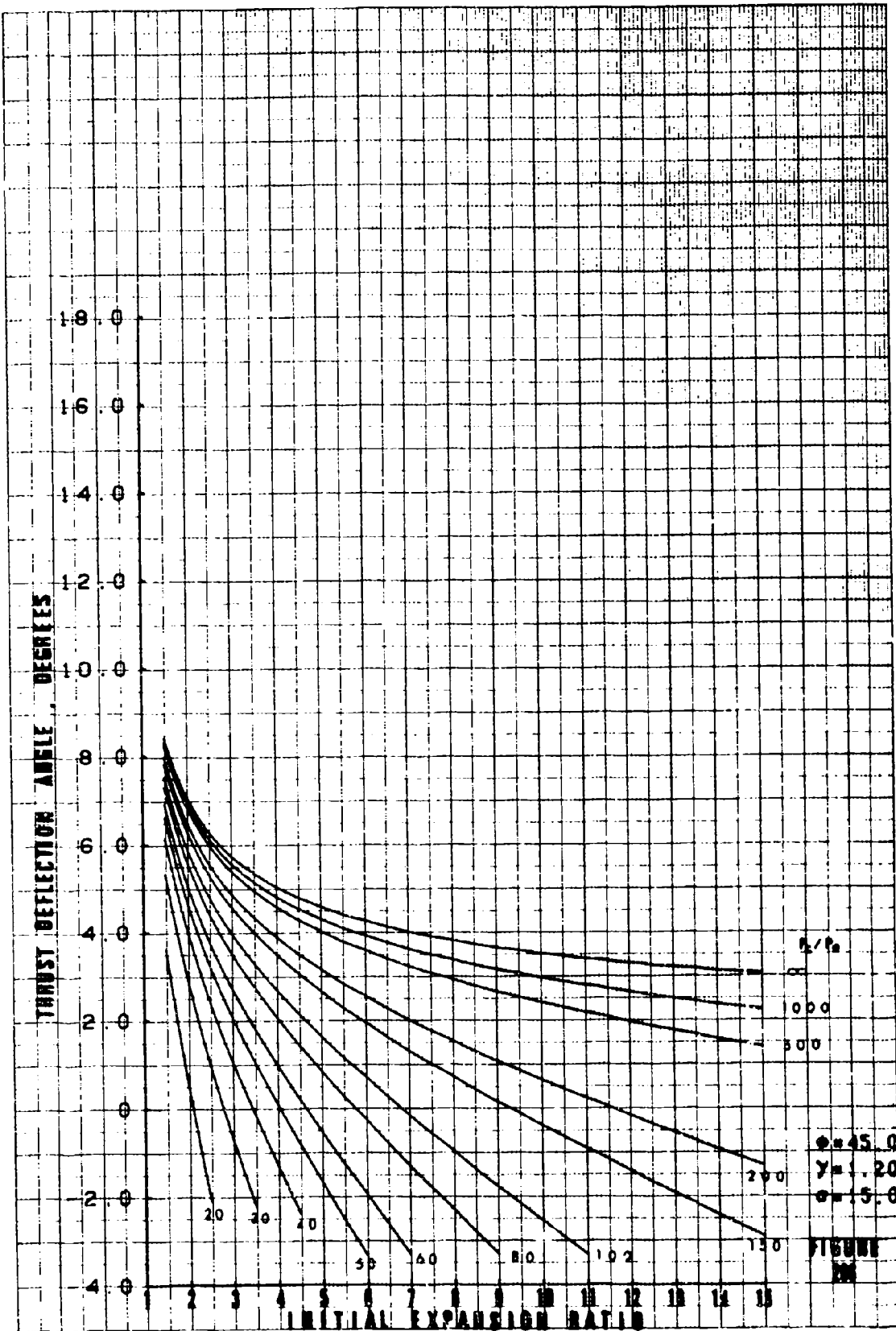
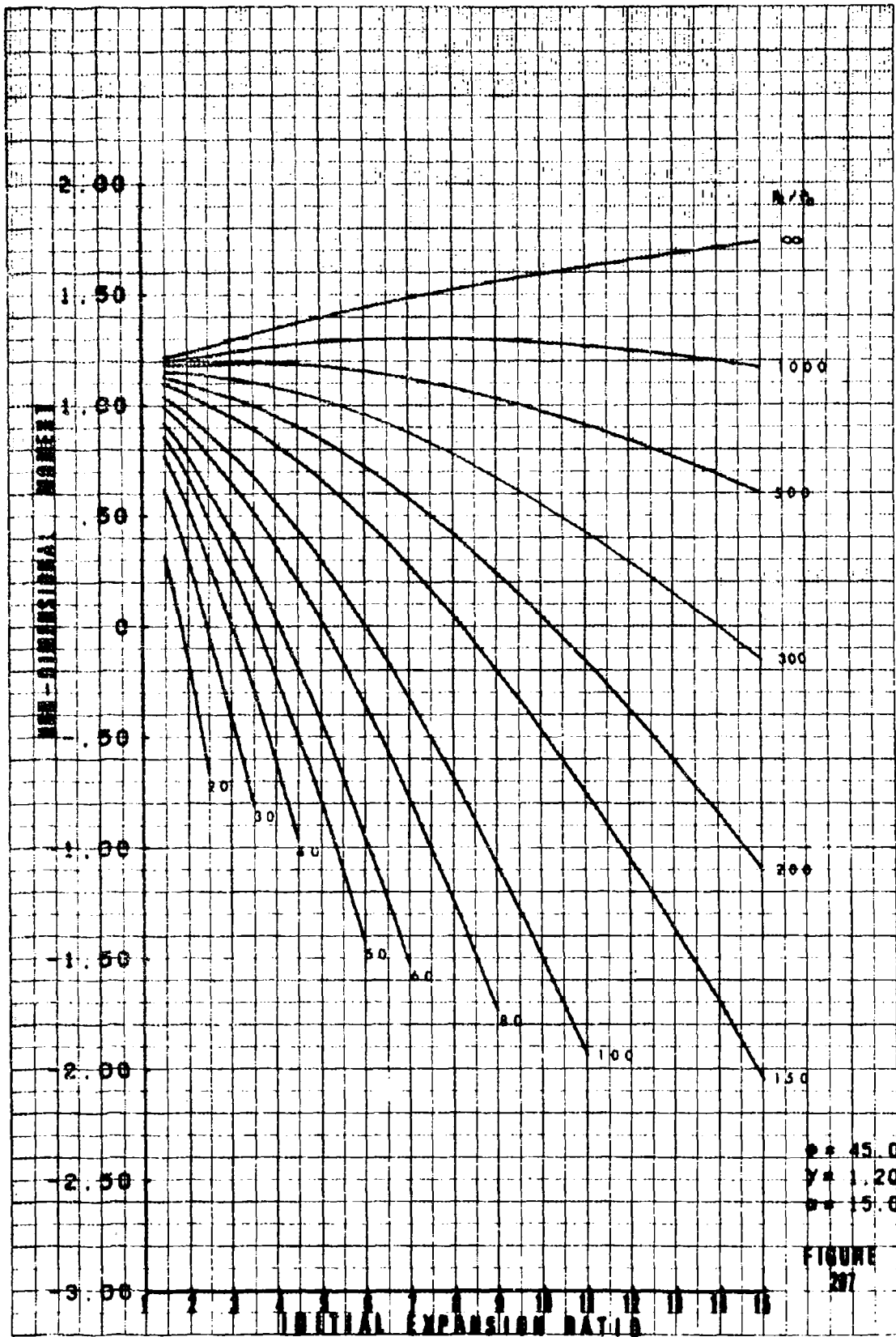


FIGURE 203

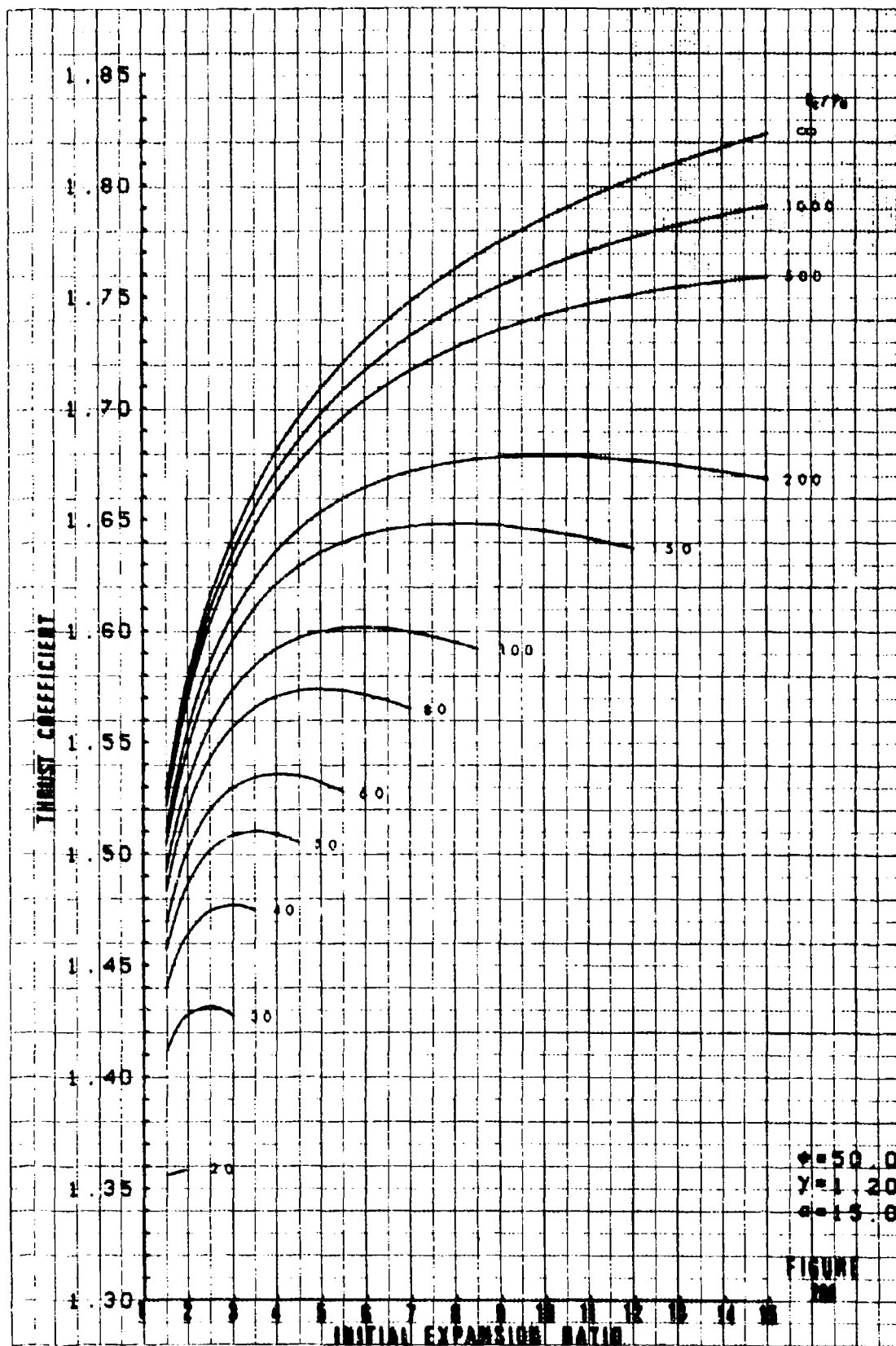


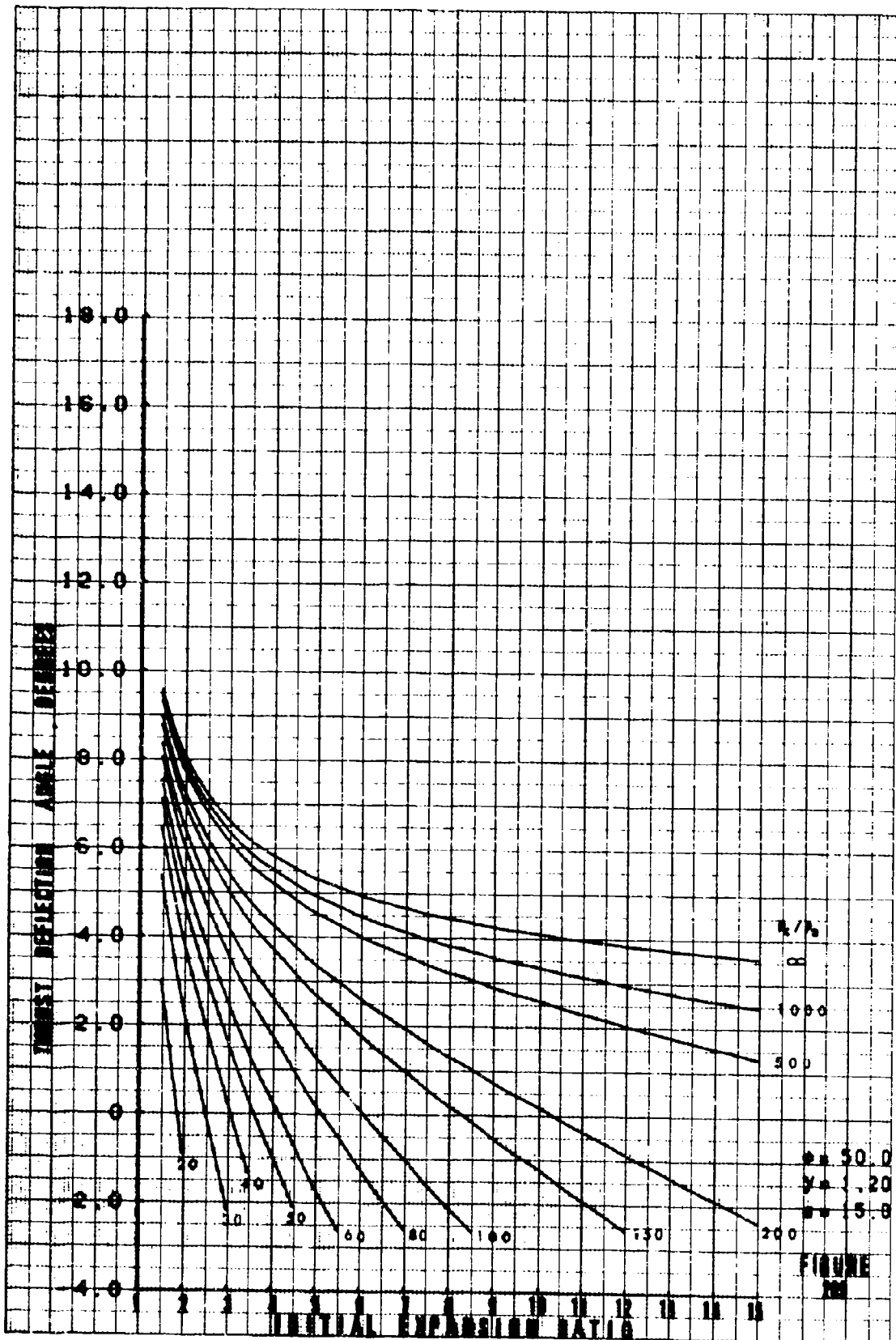


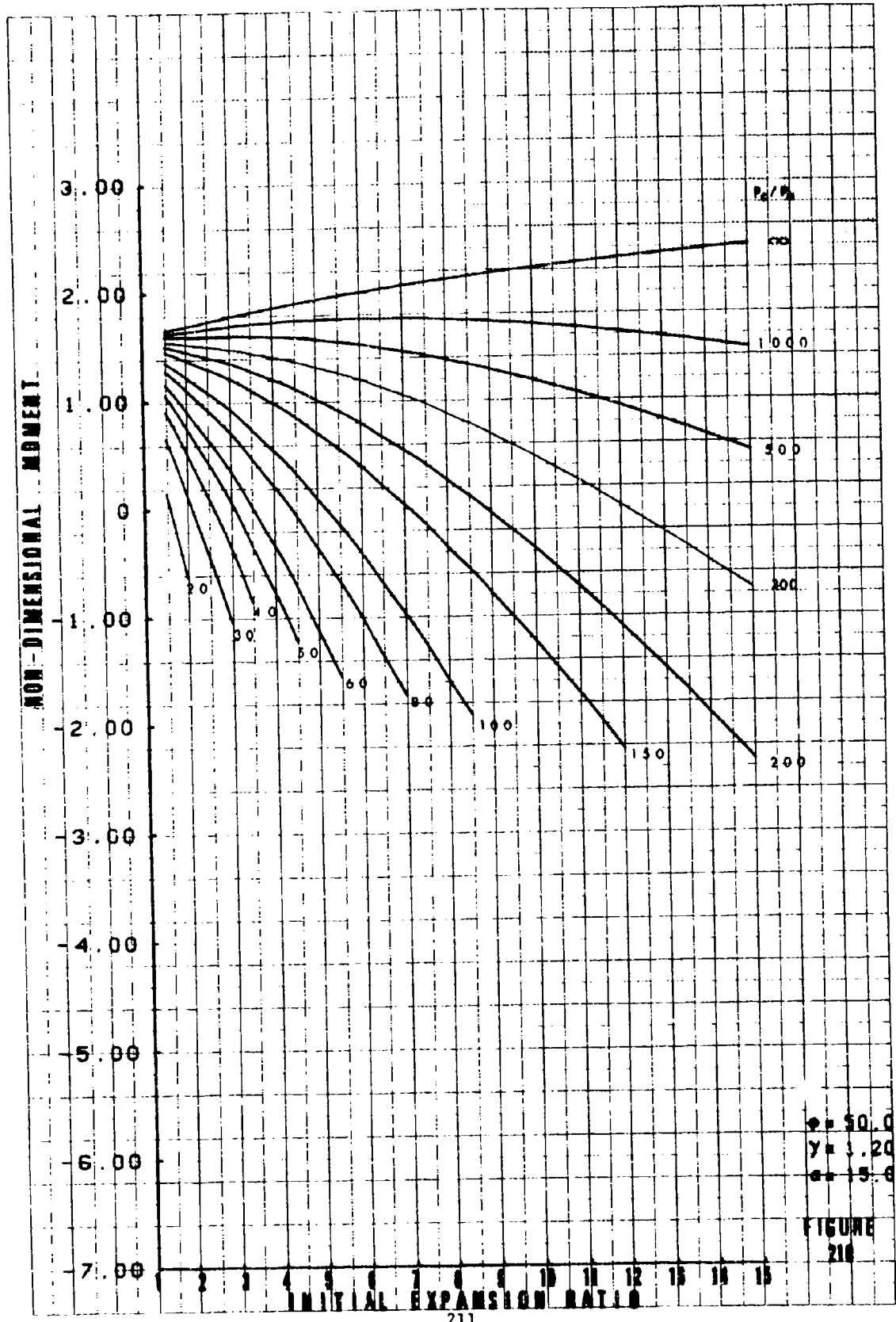


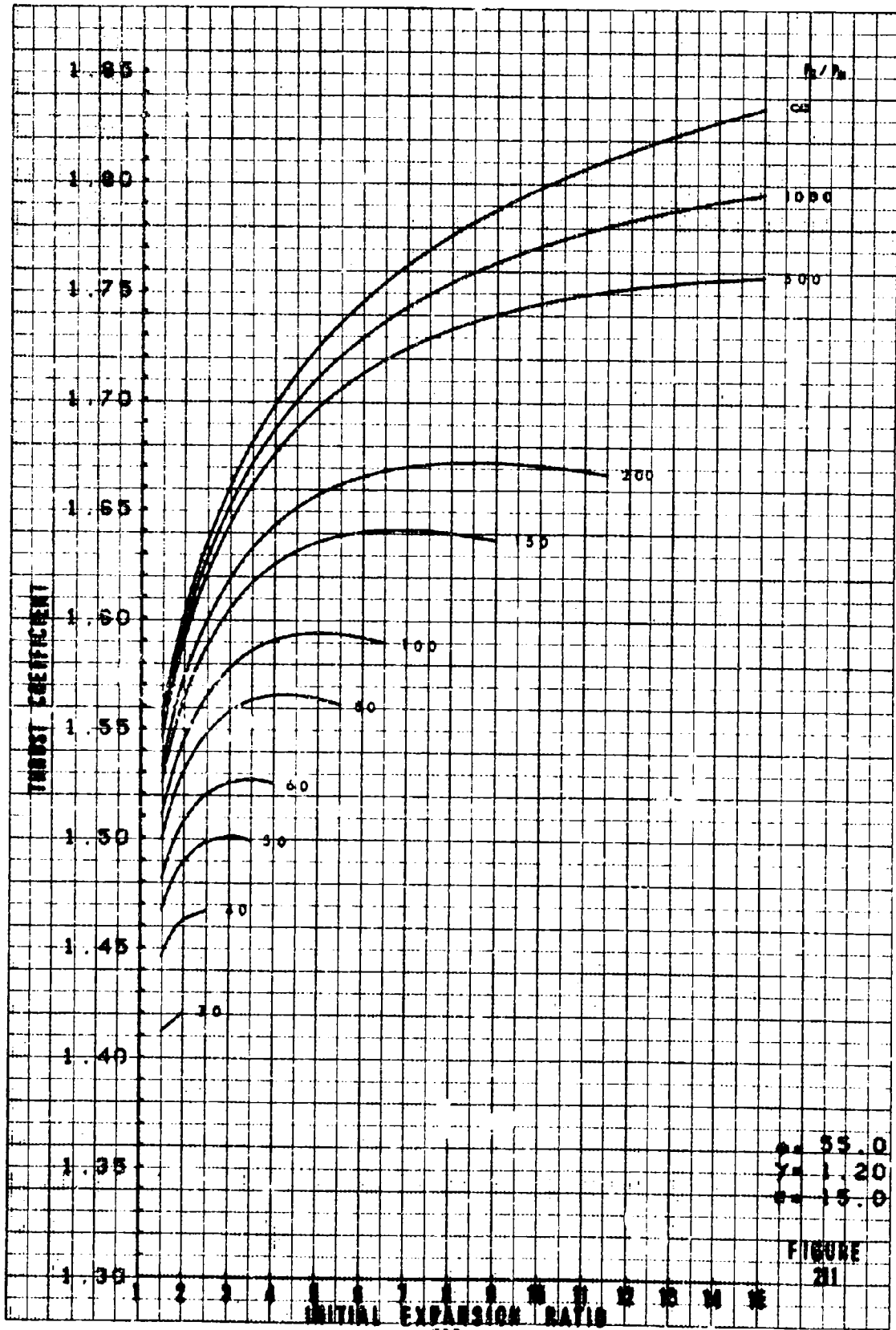












$\phi = 55.0$   
 $\gamma = 1.20$   
 $\epsilon = 15.0$

FIGURE 21

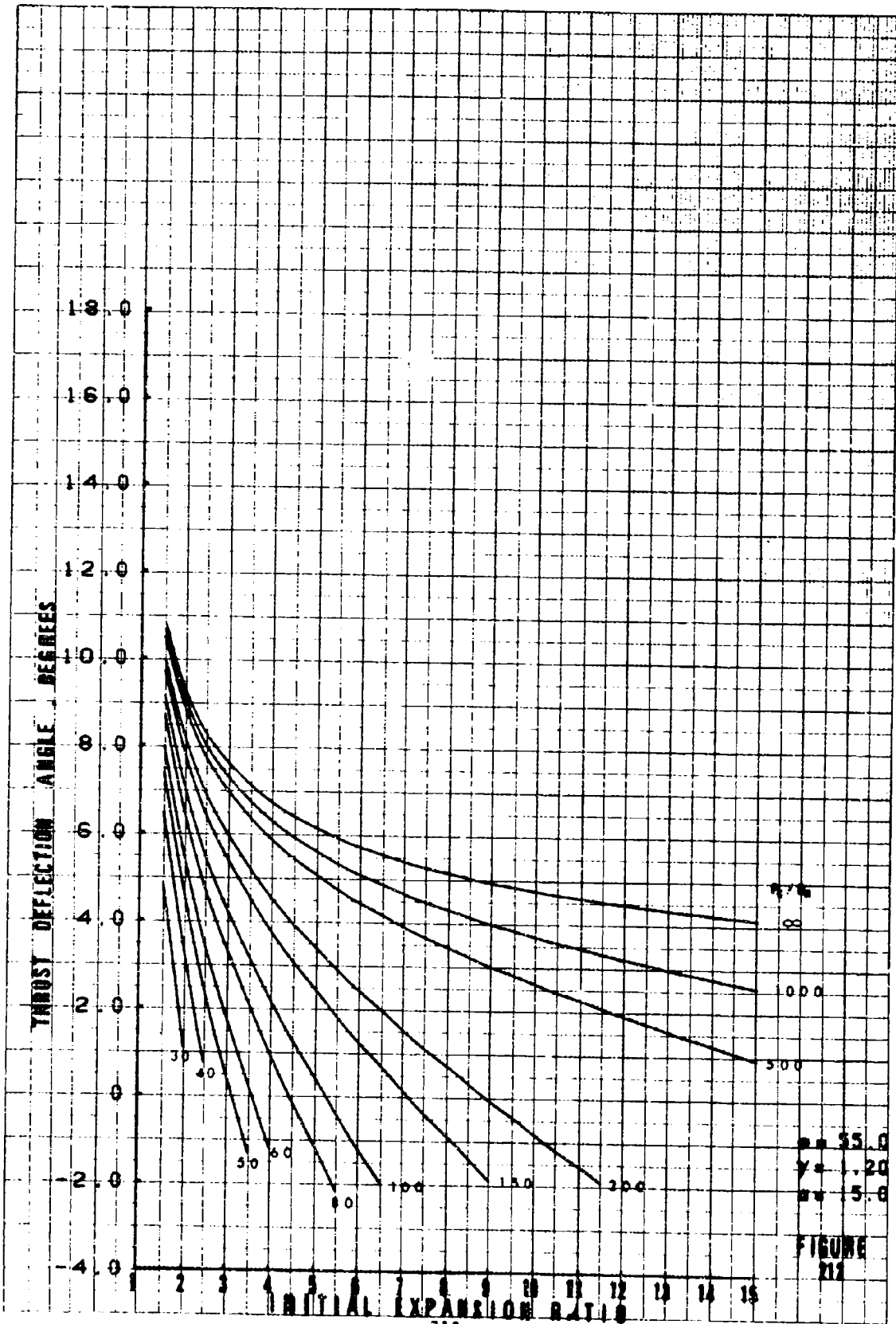
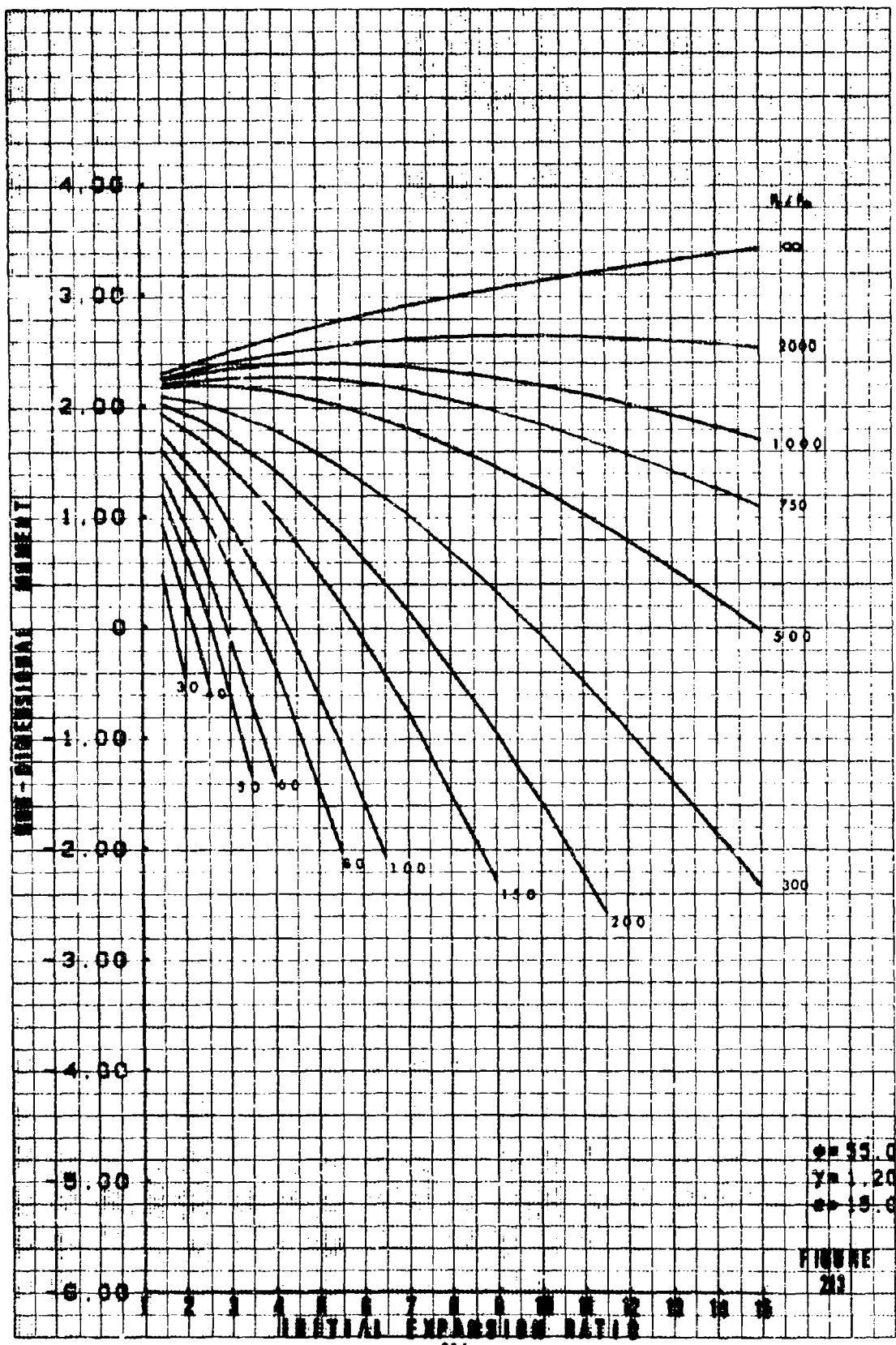


FIGURE 212



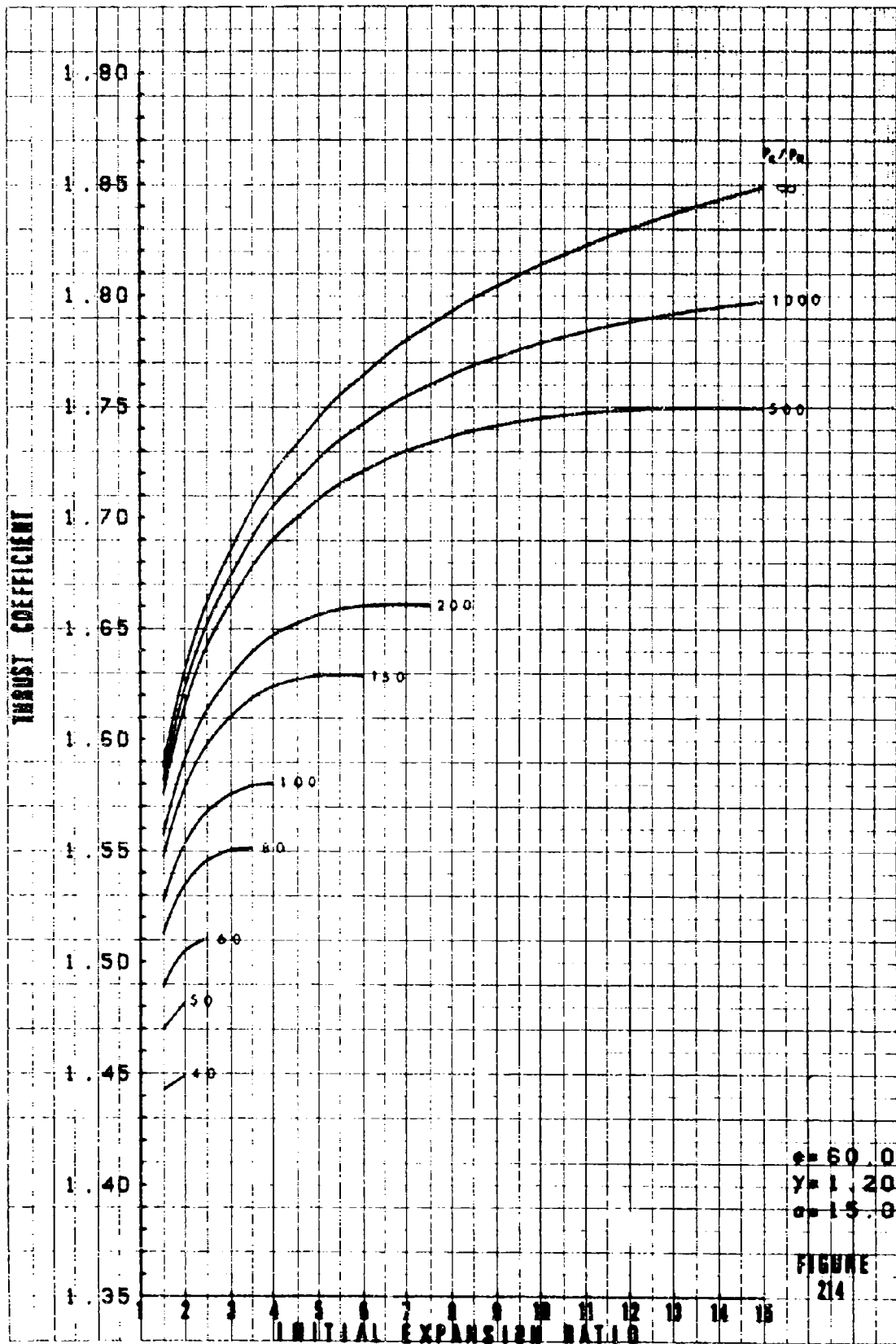
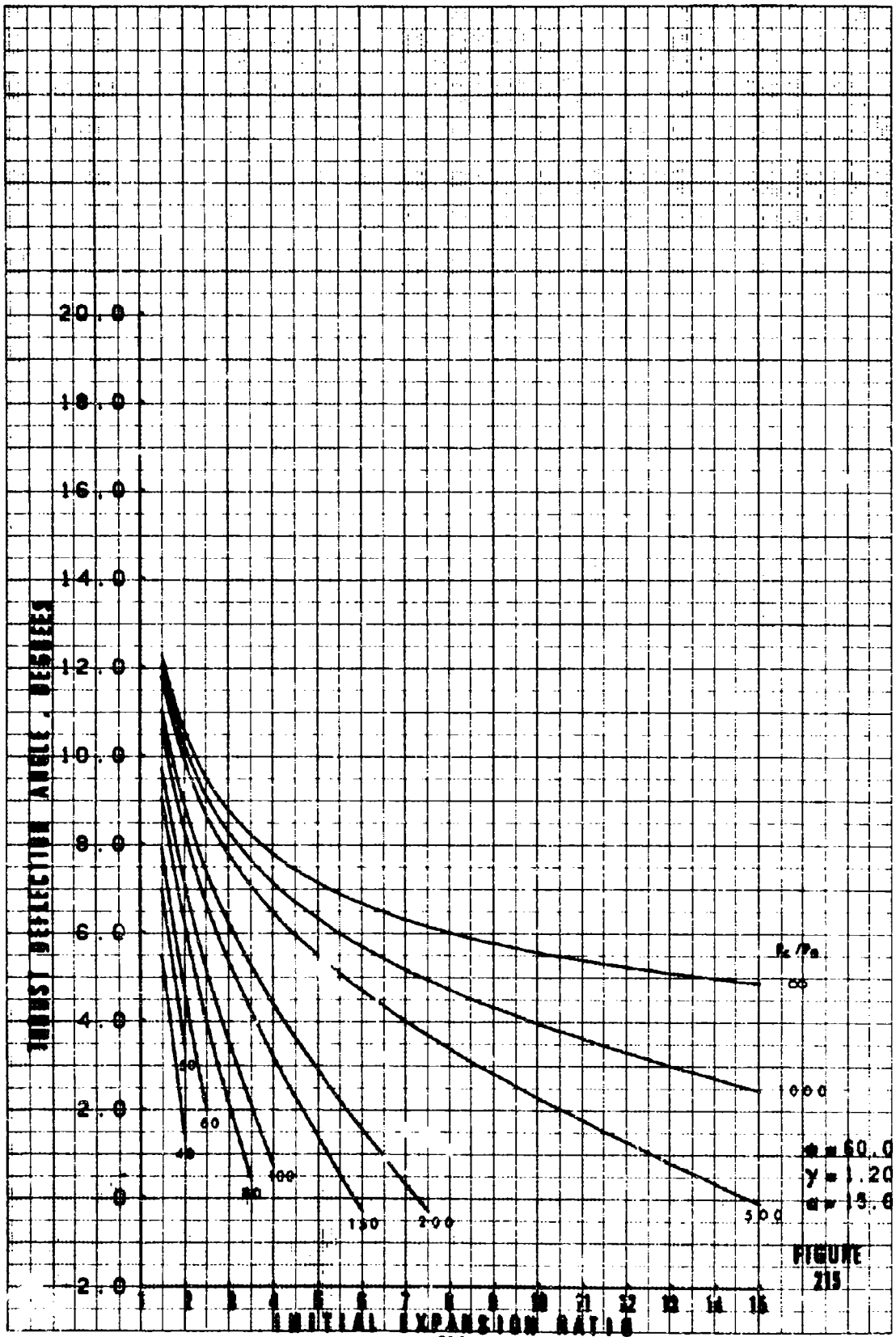


FIGURE 214





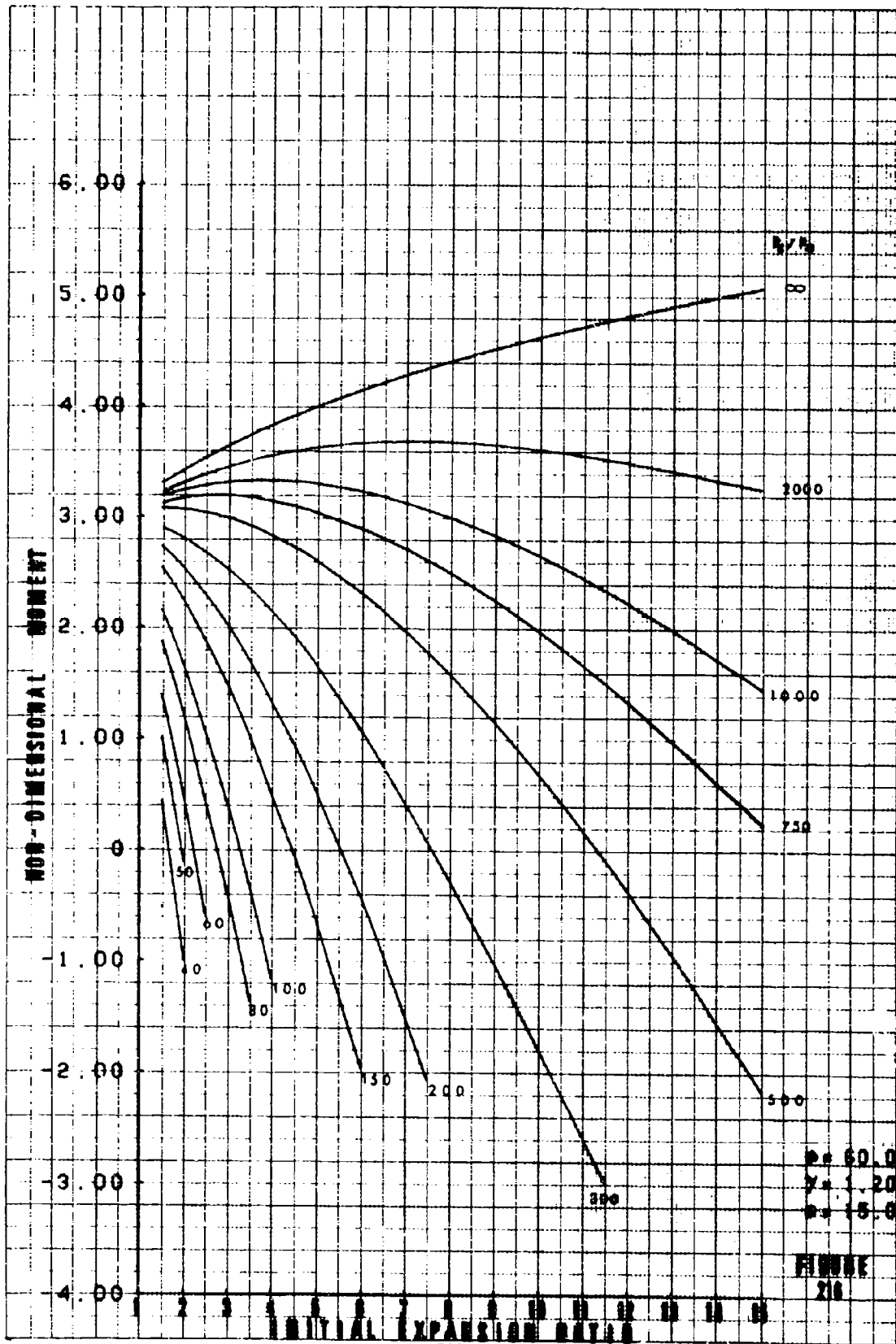
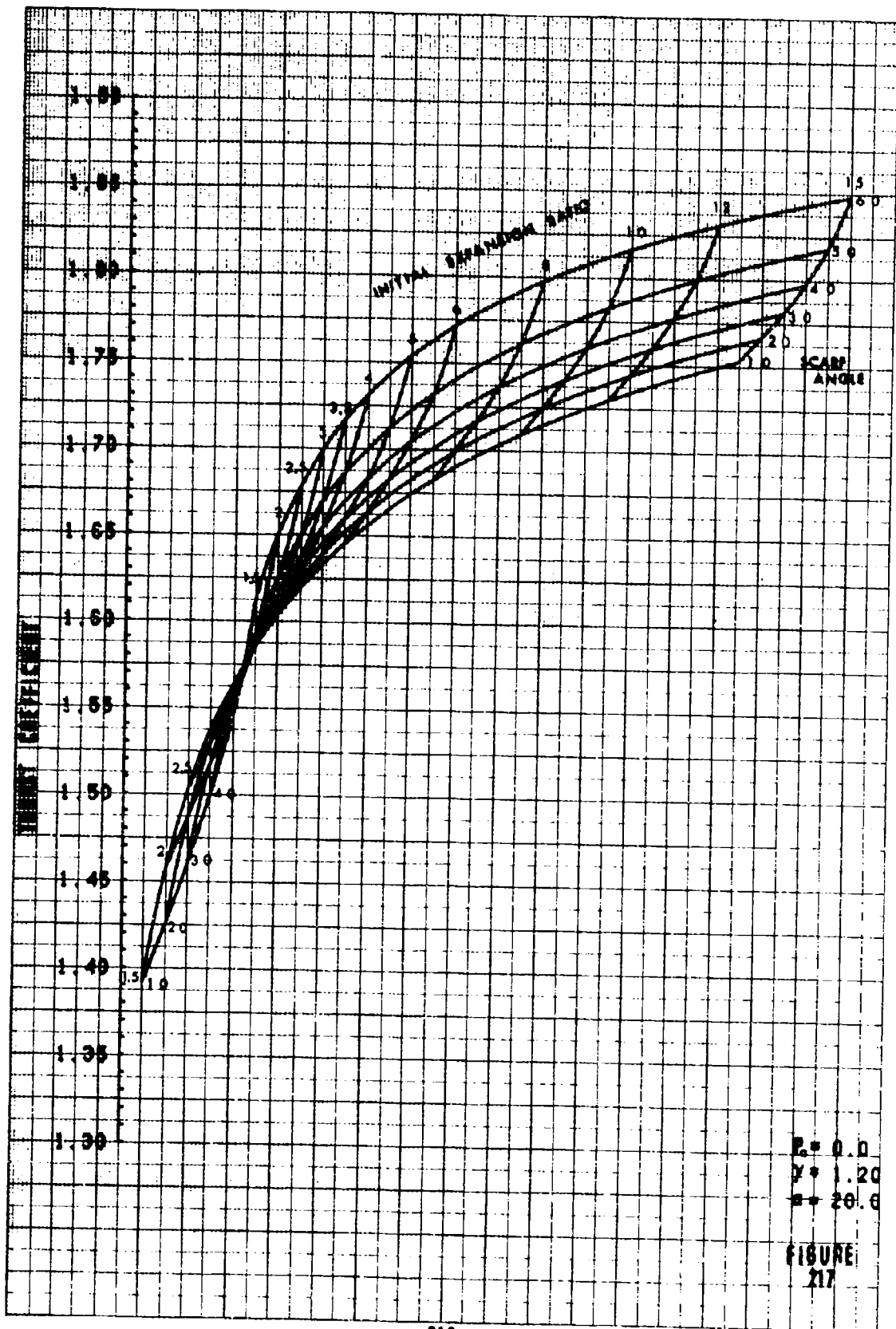
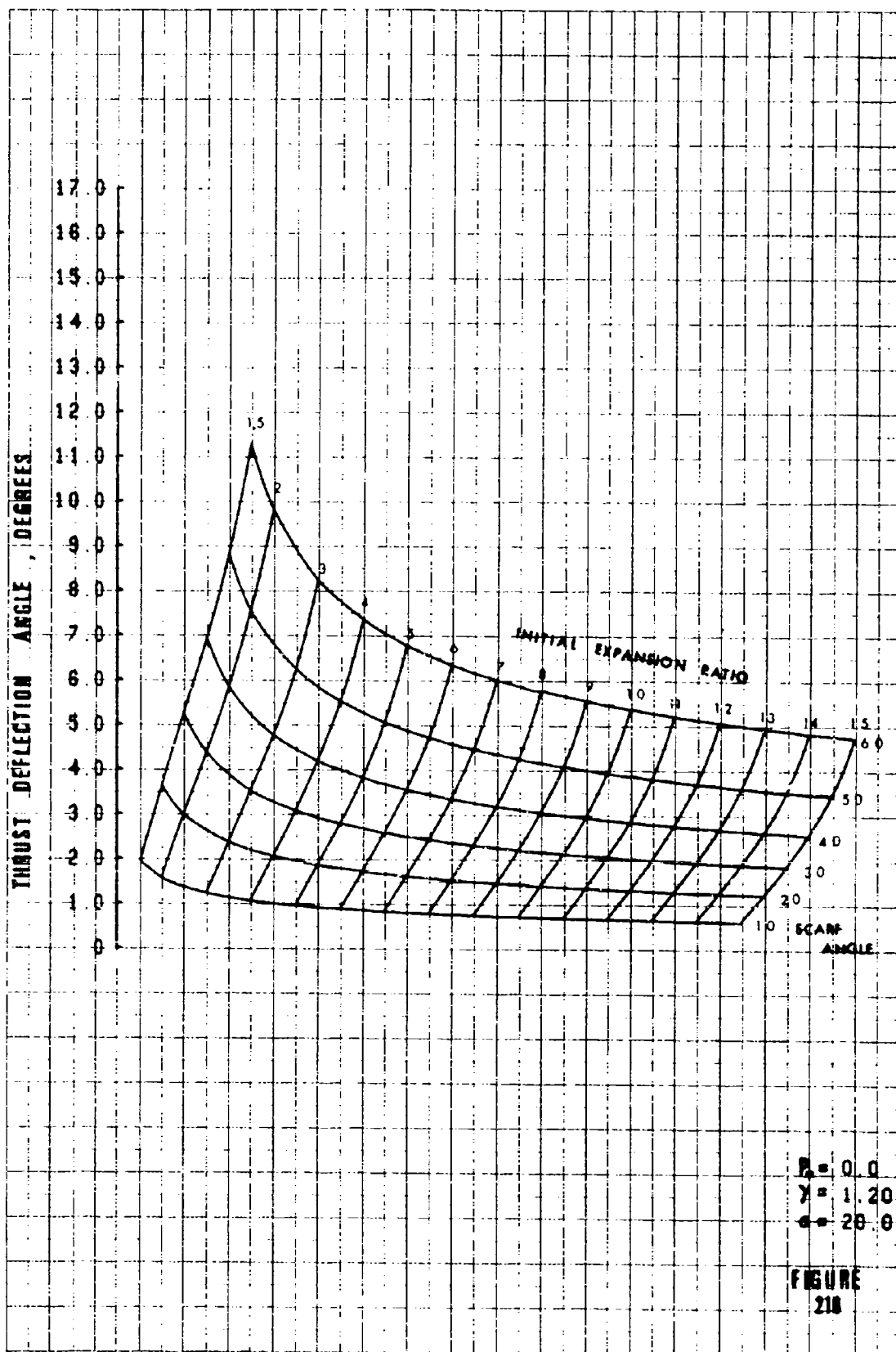
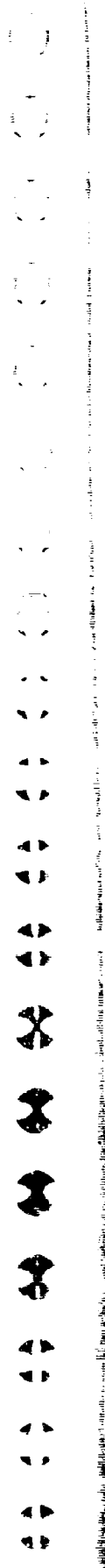
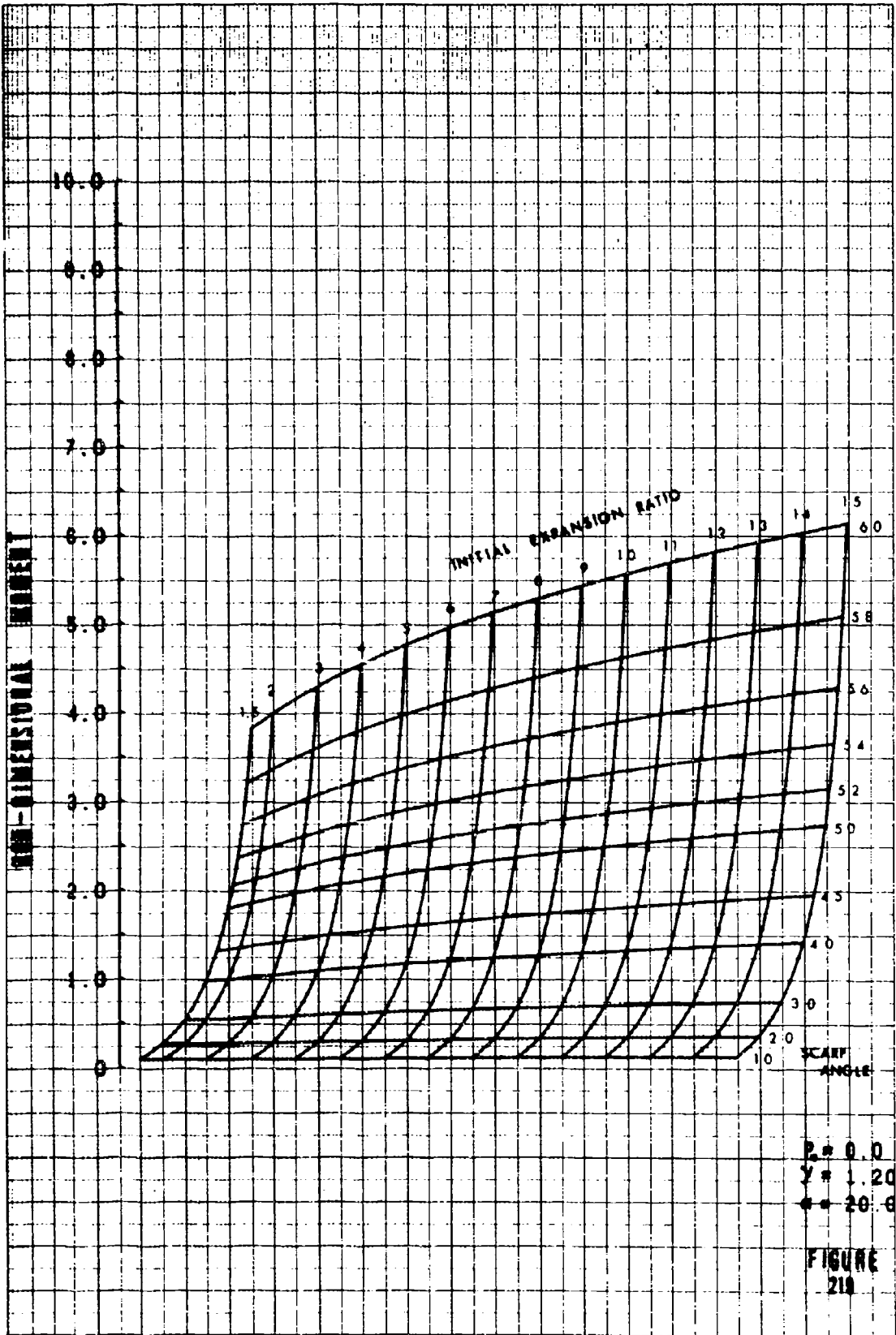
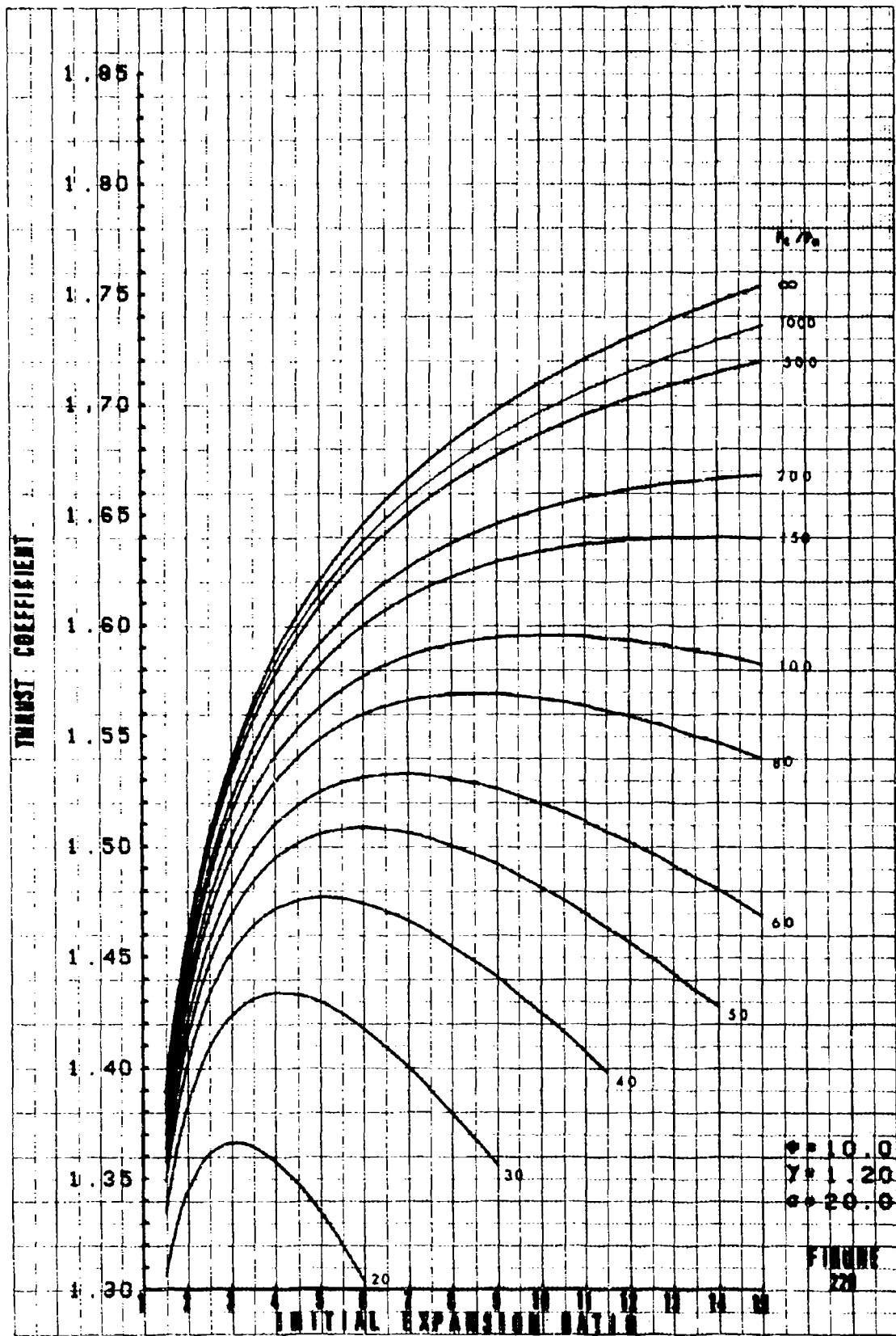


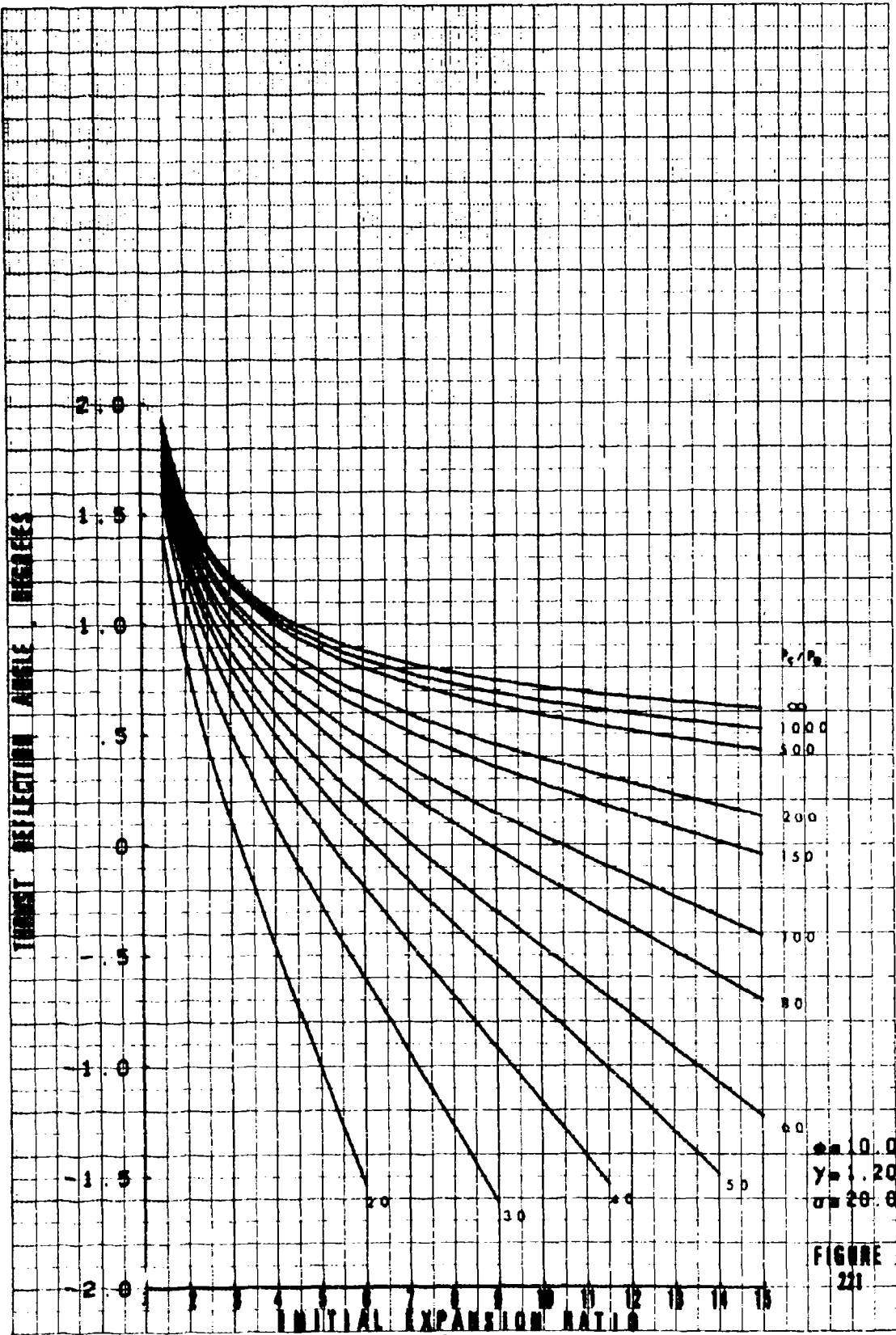
FIGURE 216

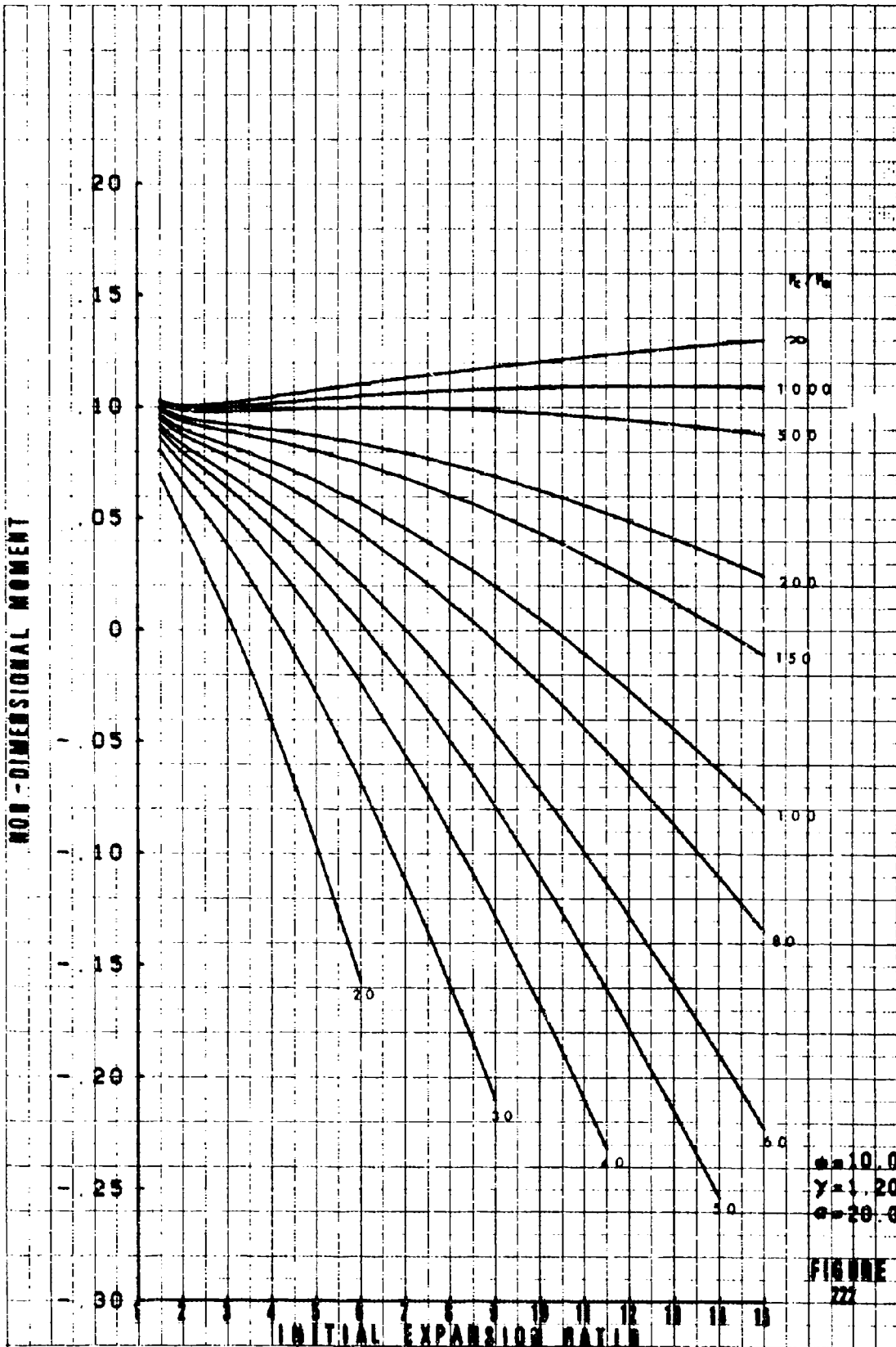


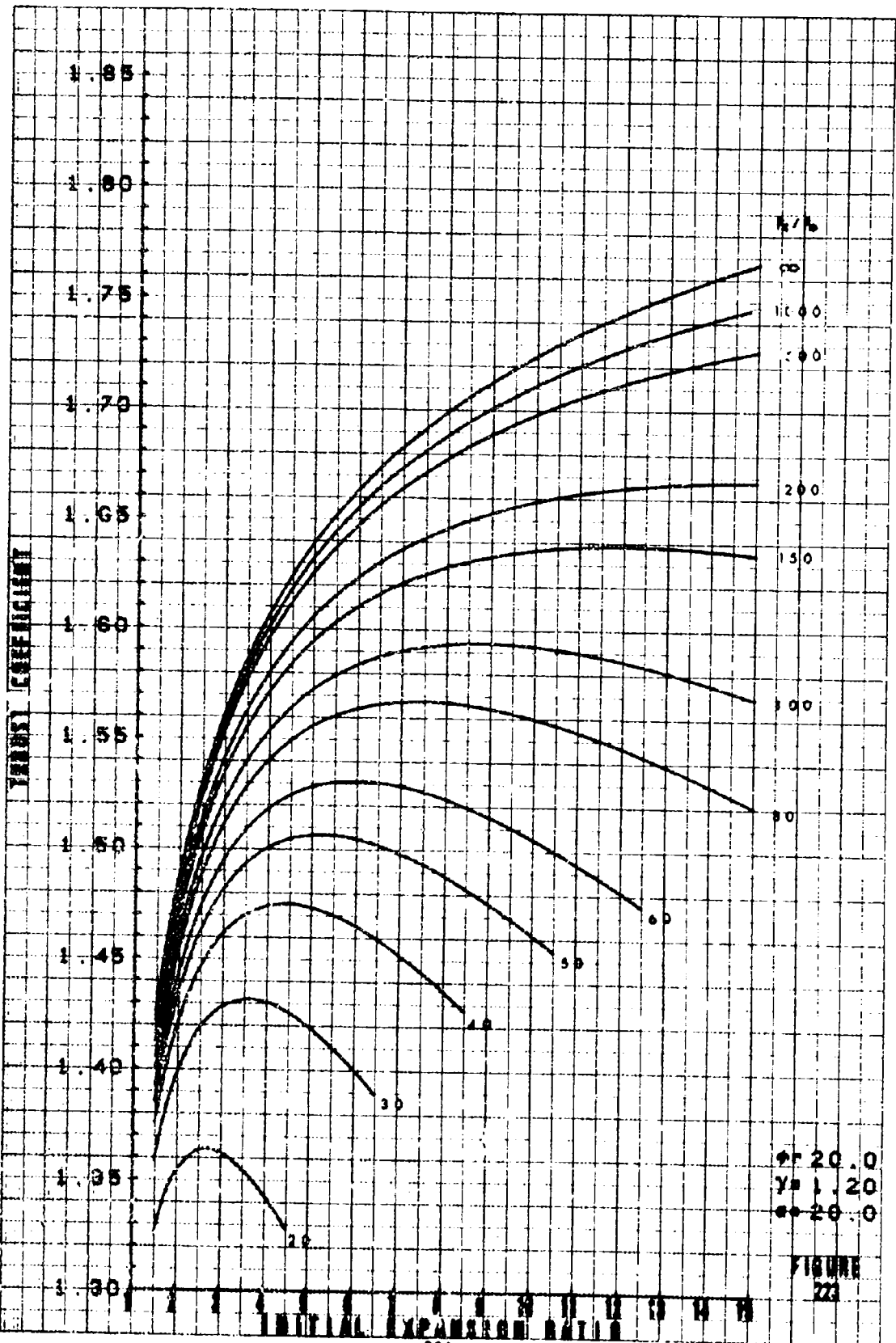














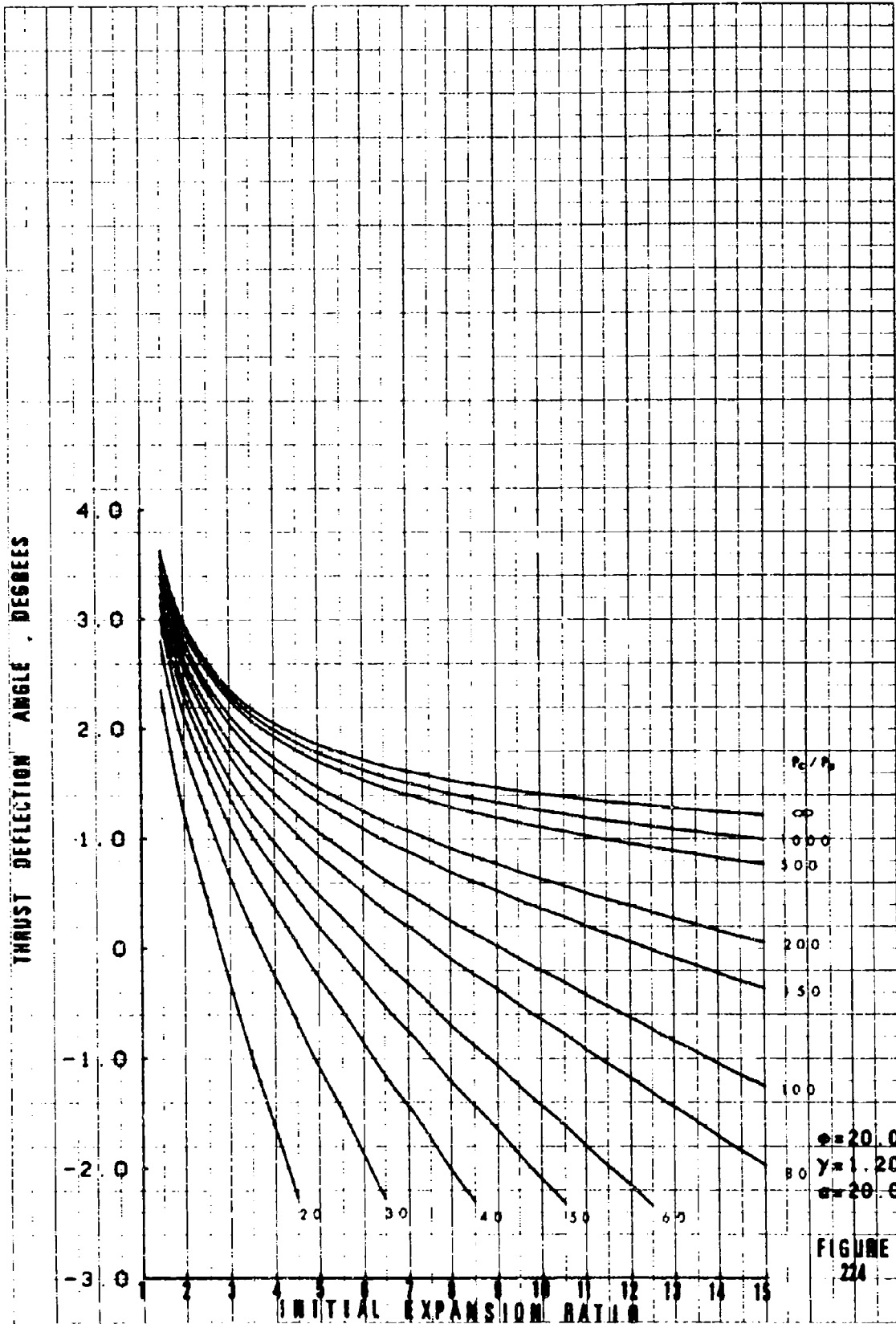
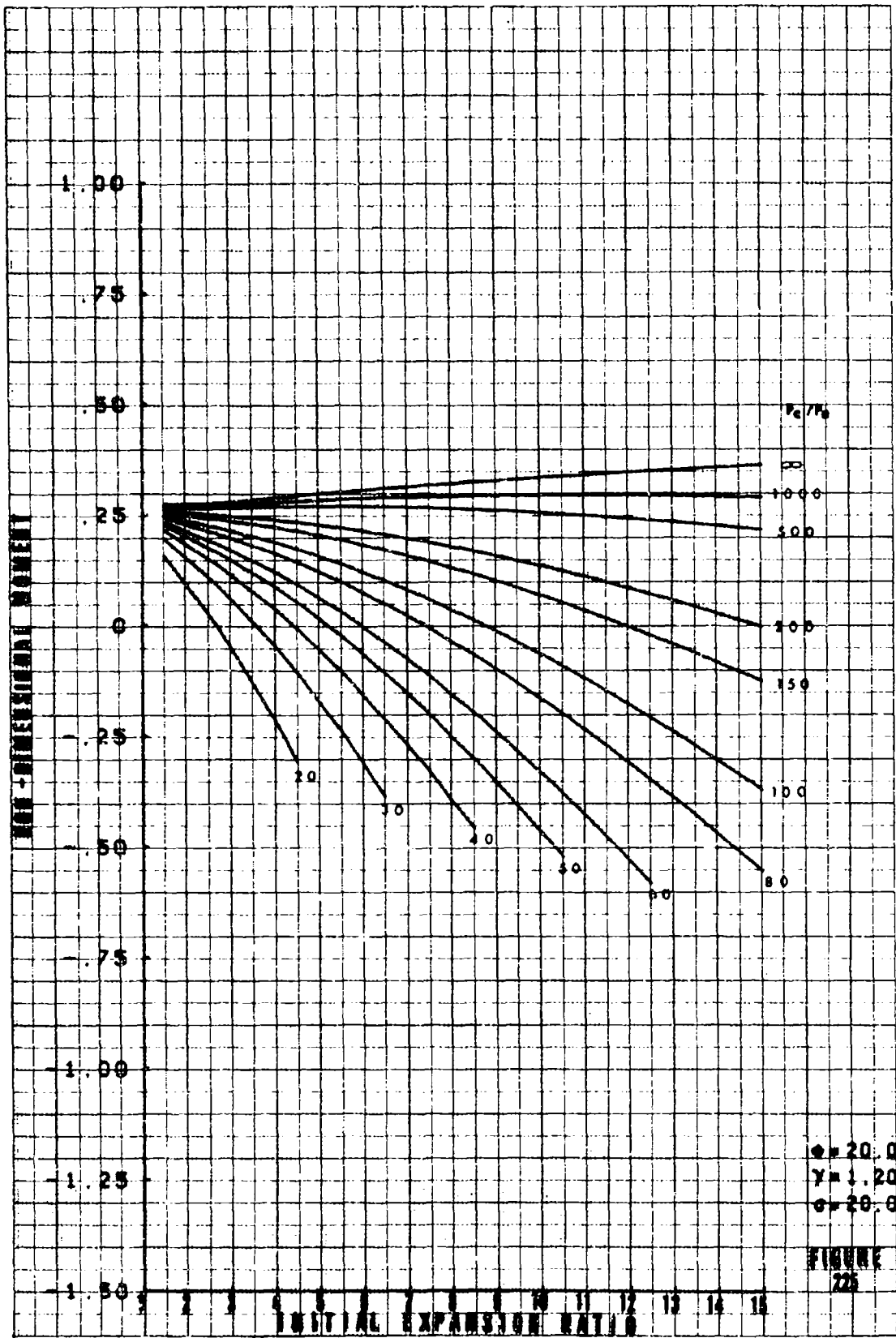
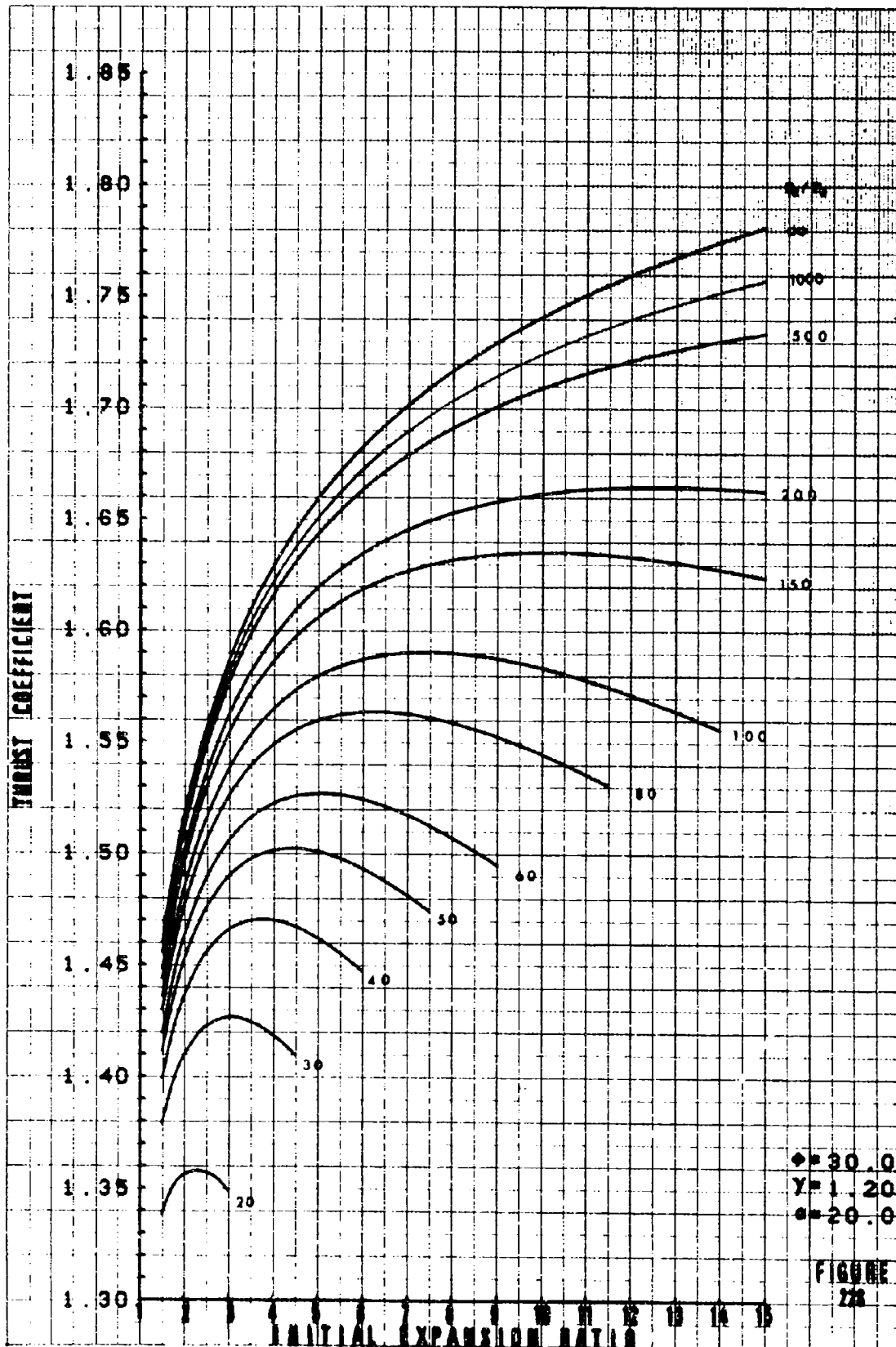


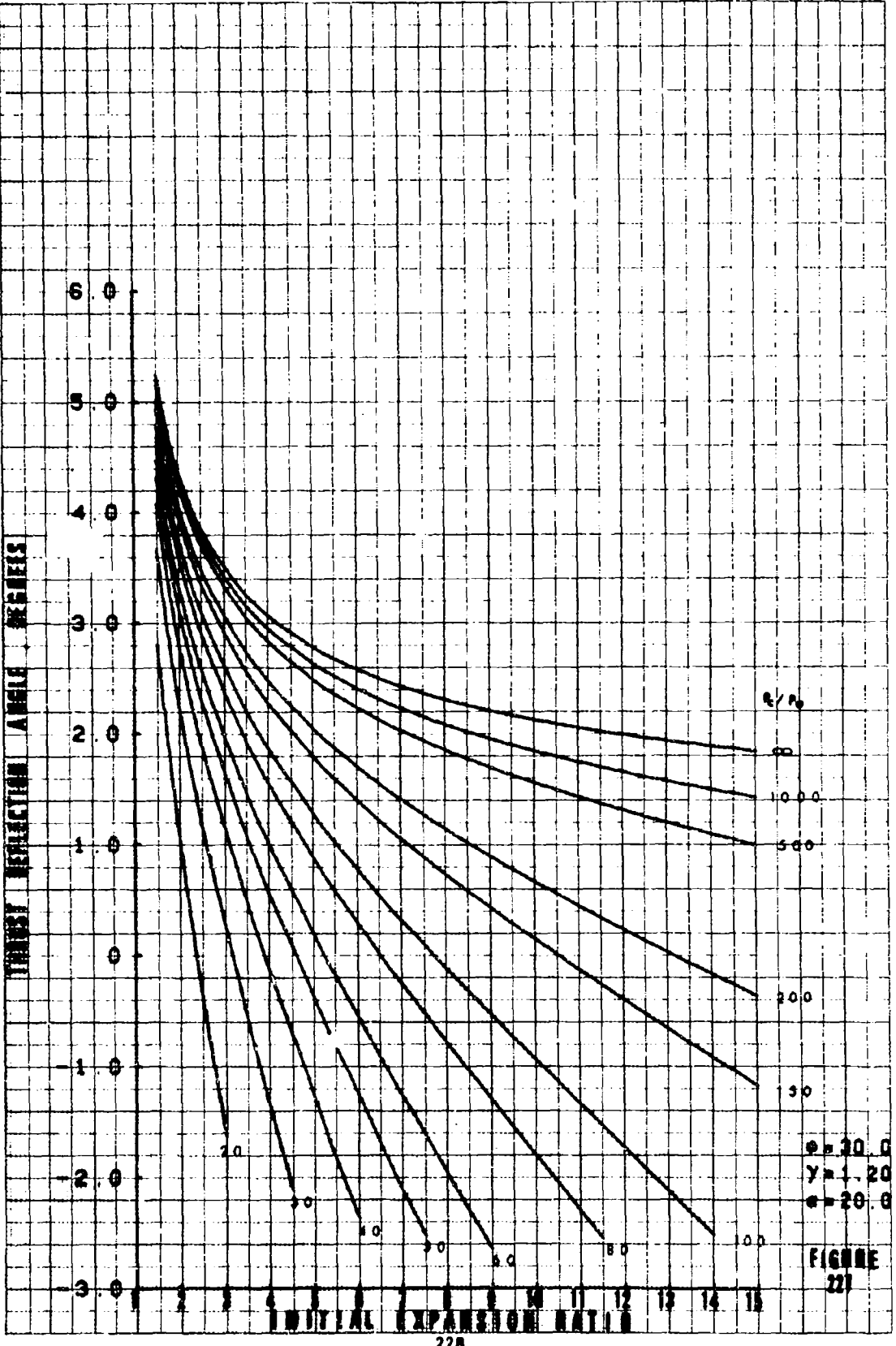
FIGURE 21A





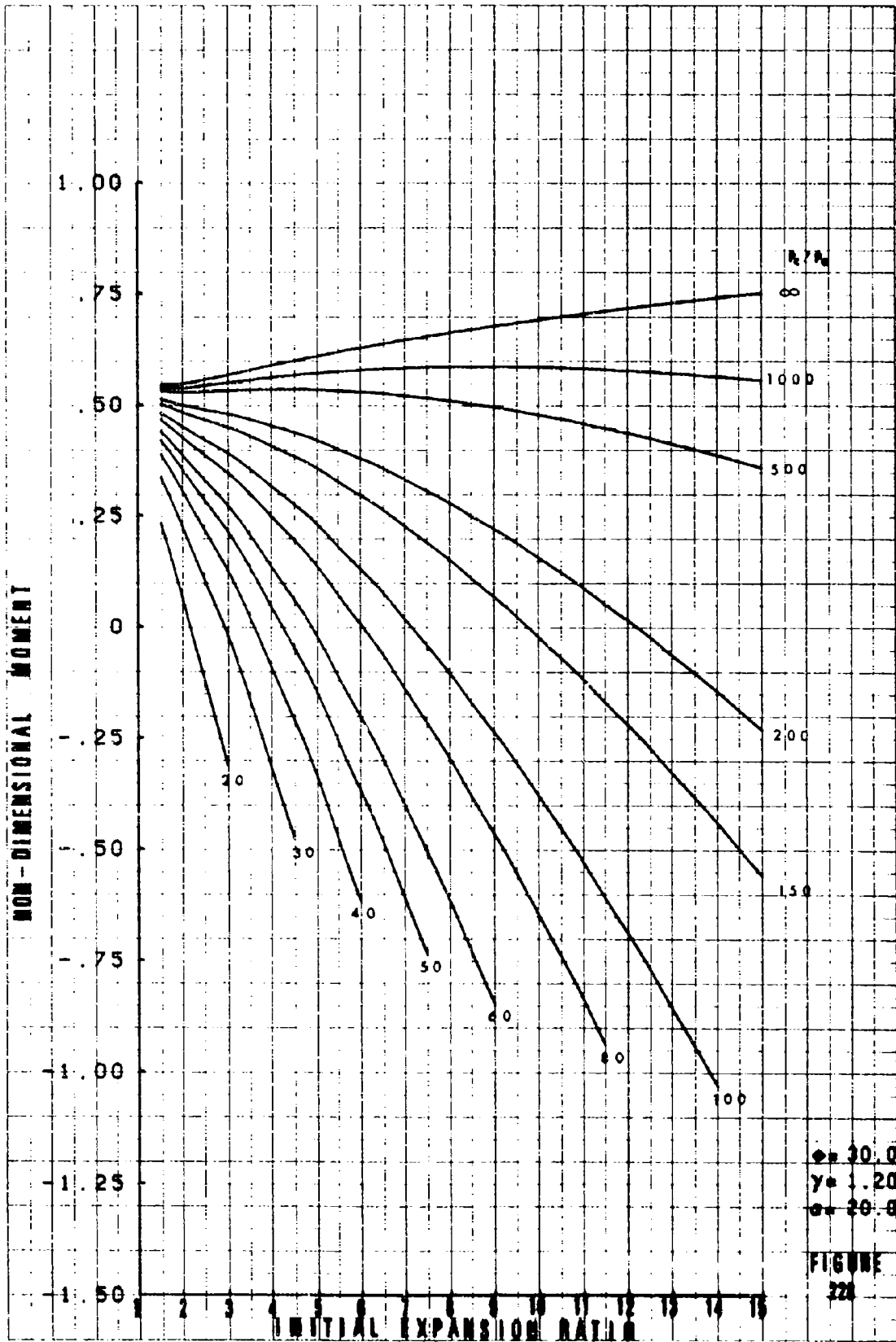
◆ = 30.0  
 Y = 1.20  
 ● = 20.0

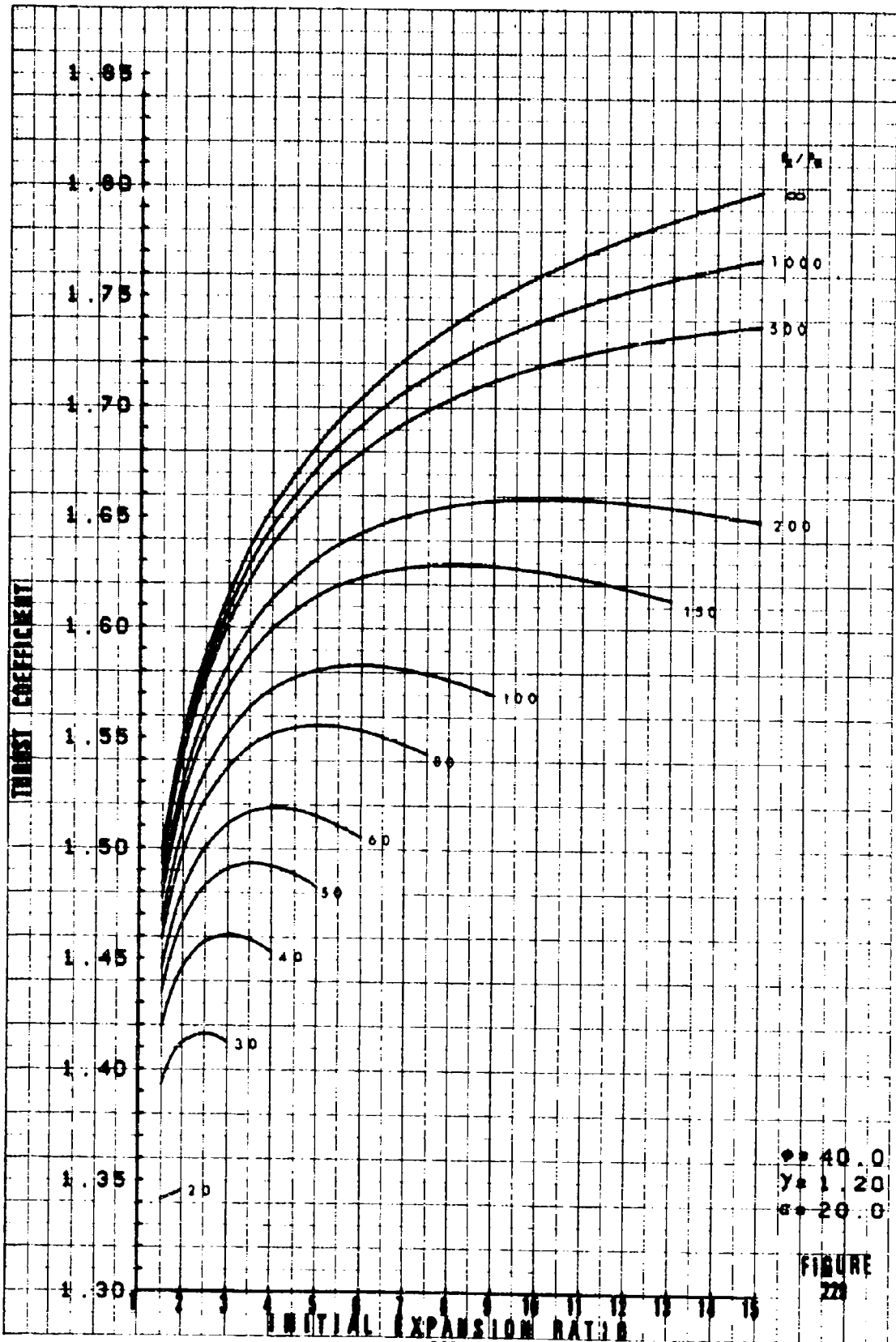
FIGURE 228



**FIGURE 227**

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 RESEARCH REPORT 432  
 NATIONAL AERONAUTICS AND SPACE ADMINISTRATION





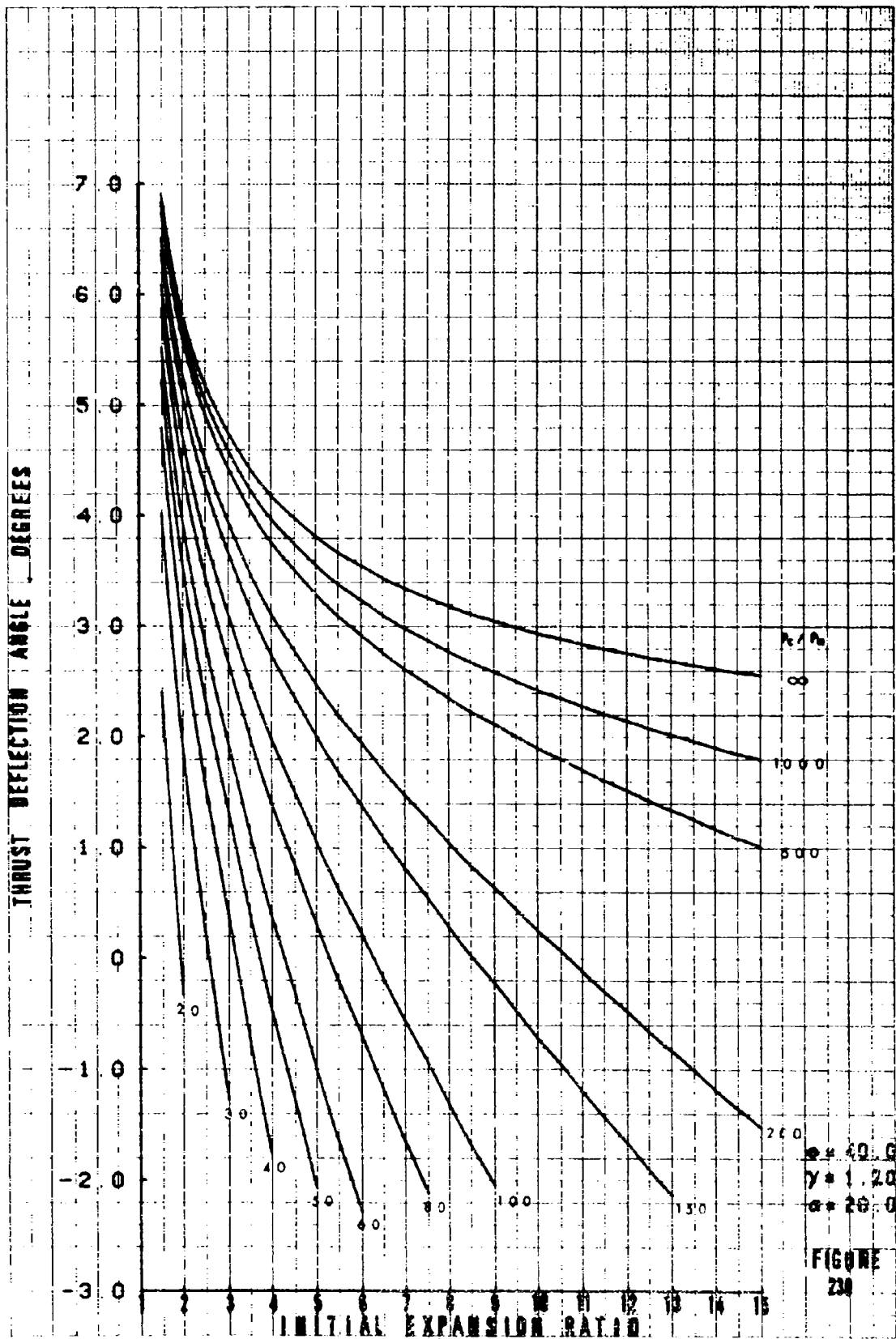
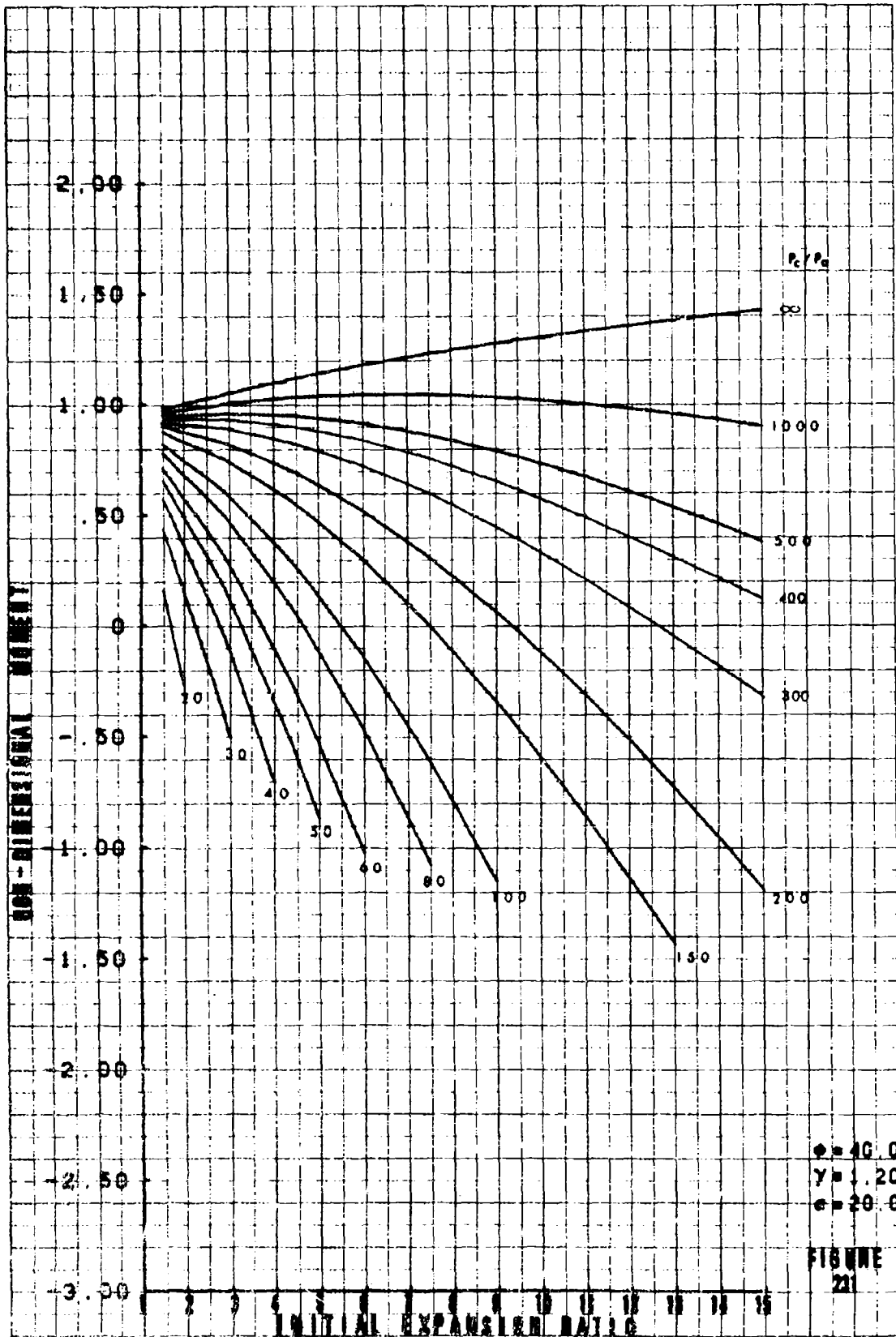


FIGURE 230



$\phi = 40.0$   
 $\gamma = 1.20$   
 $\sigma = 20.8$

FIGURE 21



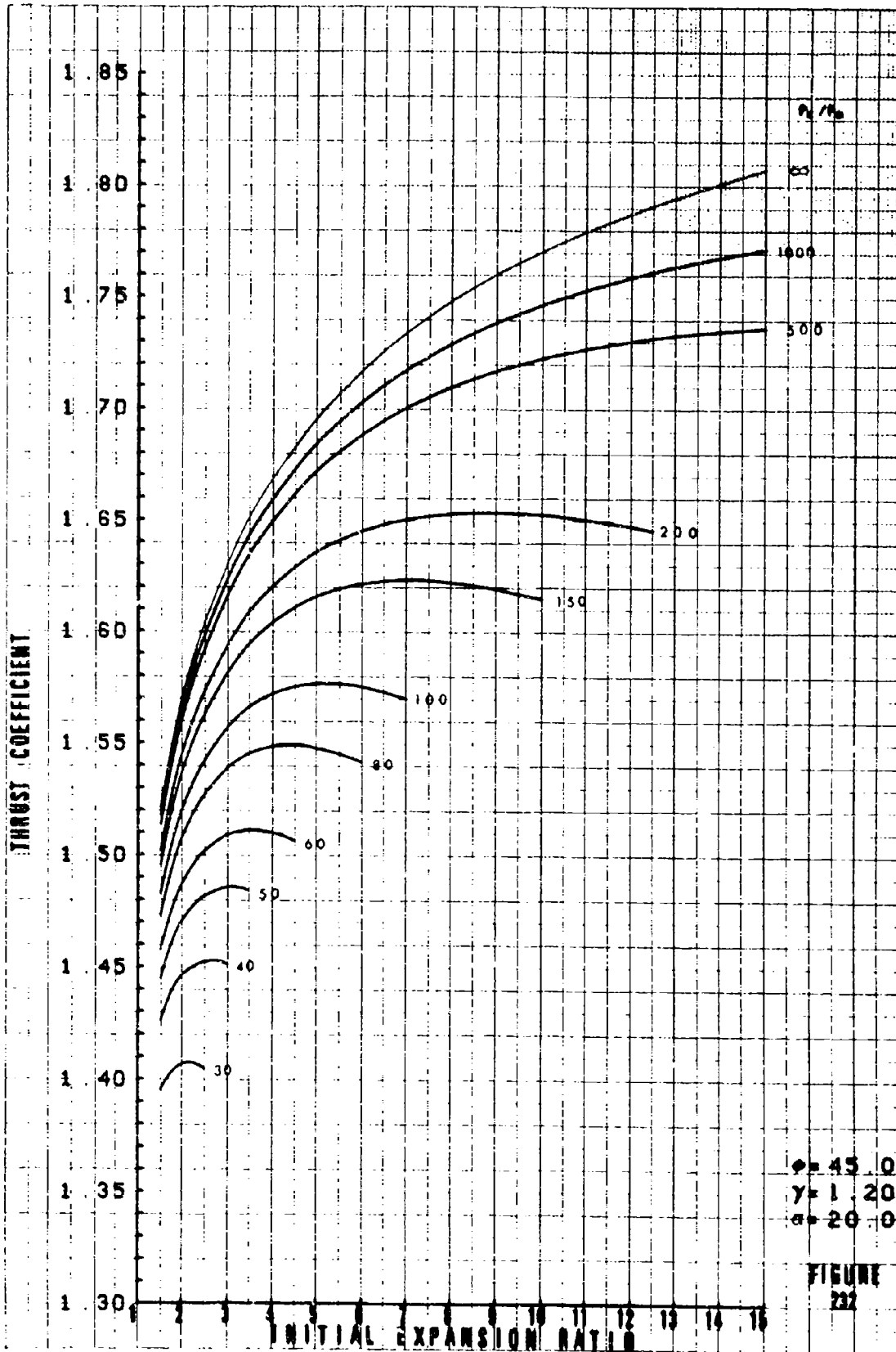
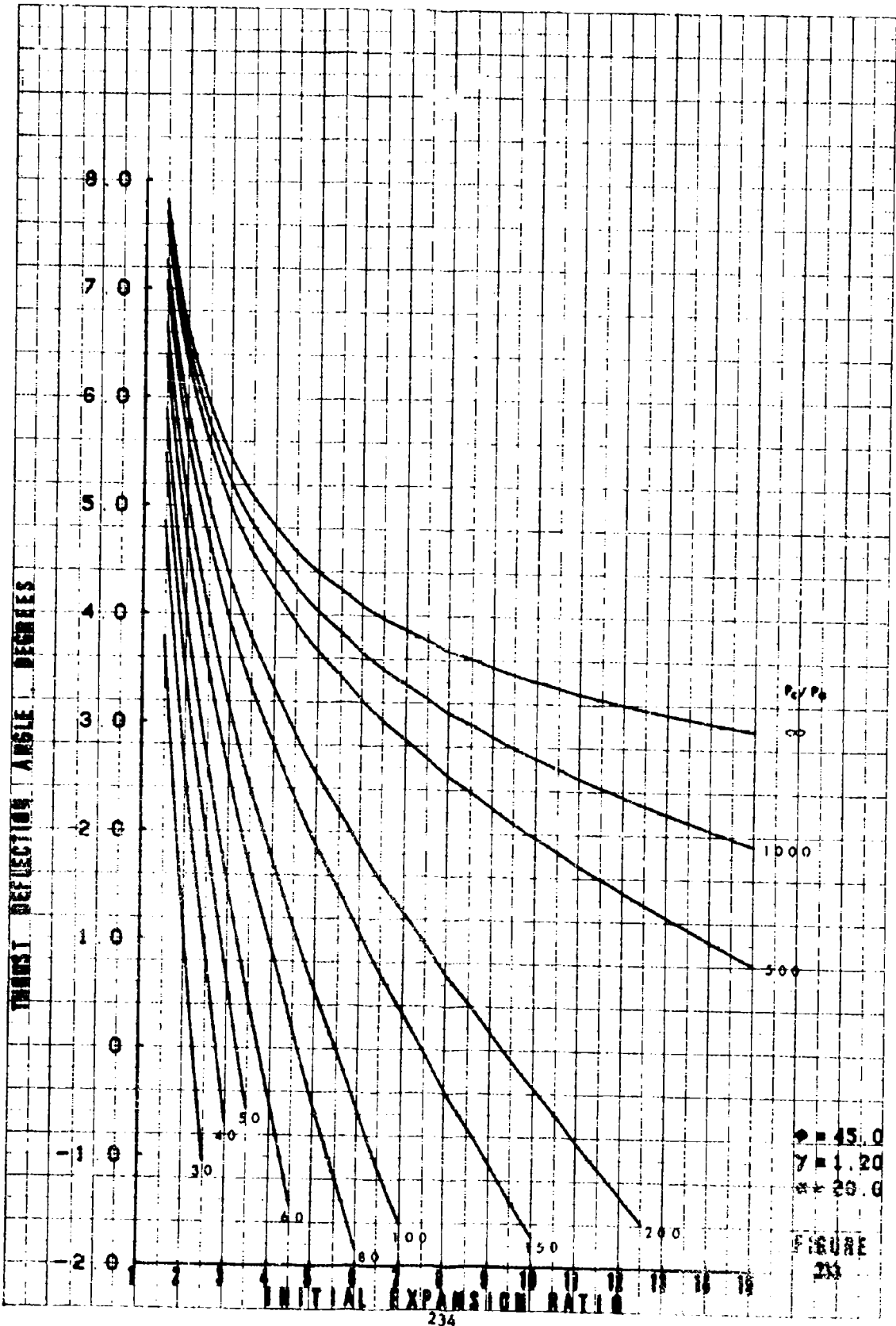
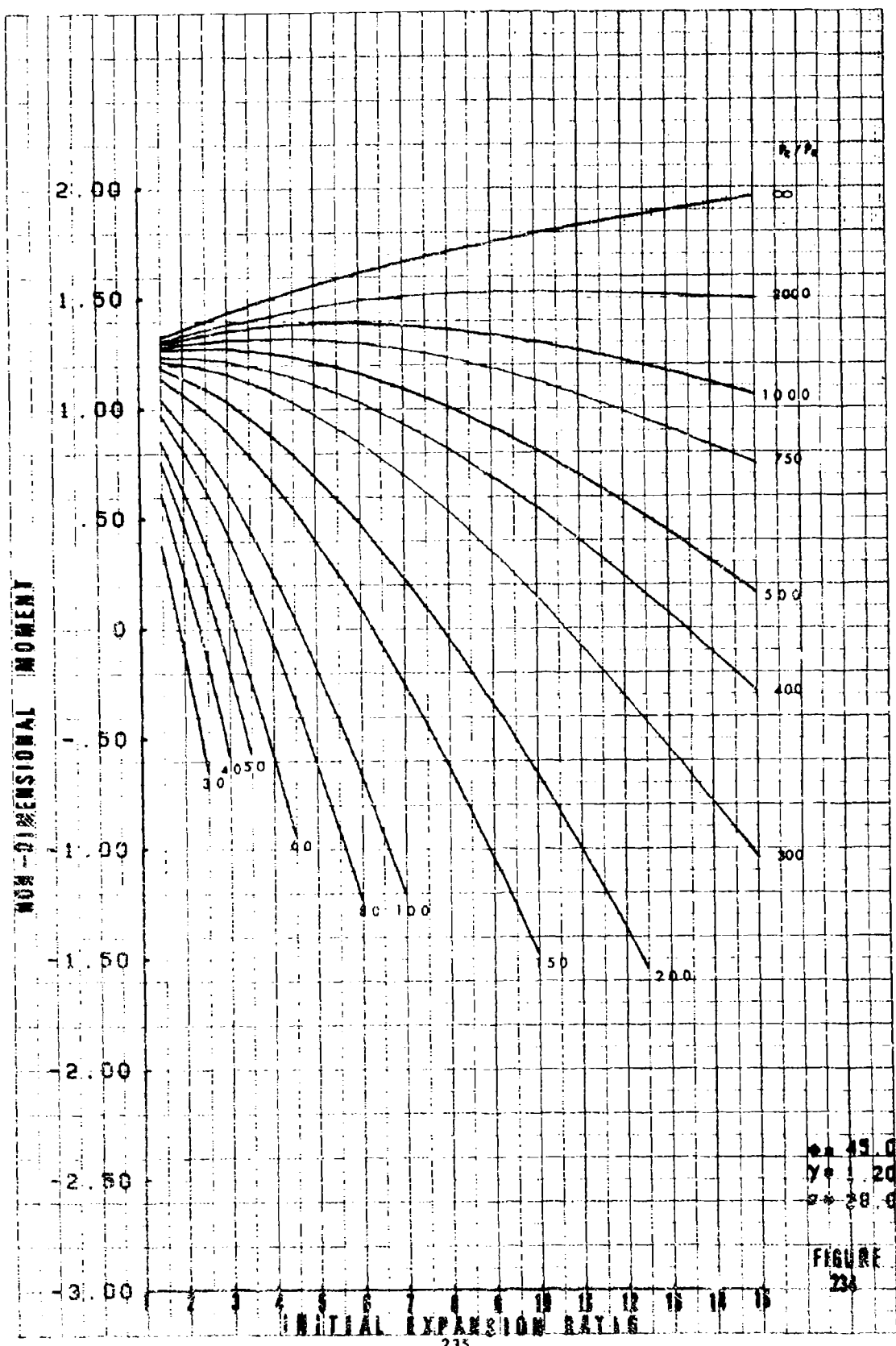


FIGURE 232



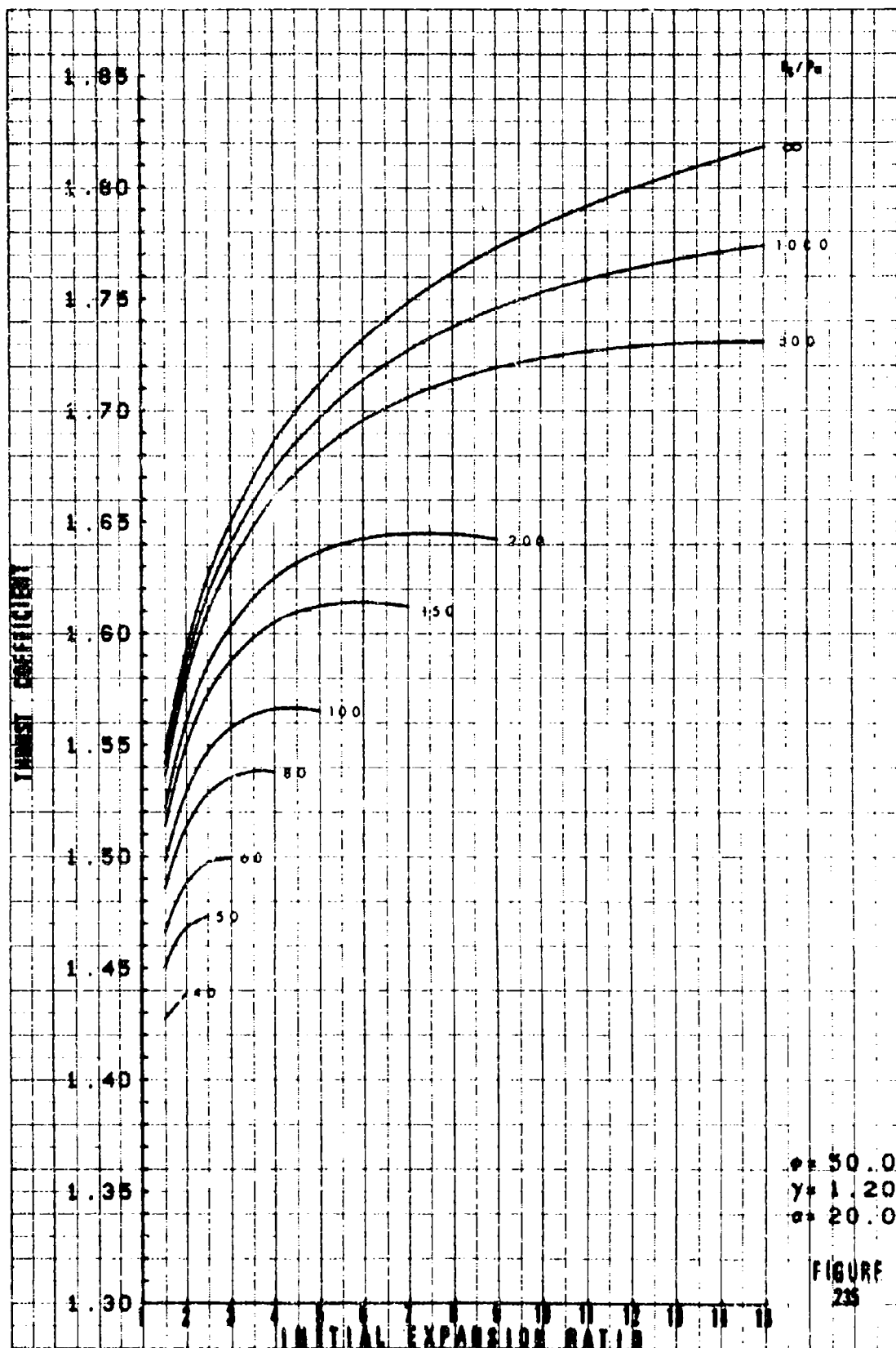
$P_2/P_0$   
 $\infty$   
 1000  
 500  
 200  
 100  
 50  
 40  
 30

FIGURE  
 233



\* 49.0  
 \* 20  
 \* 28.0

FIGURE 23



$\bullet$  = 50.0  
 $\gamma$  = 1.20  
 $\sigma$  = 20.0

FIGURE 235

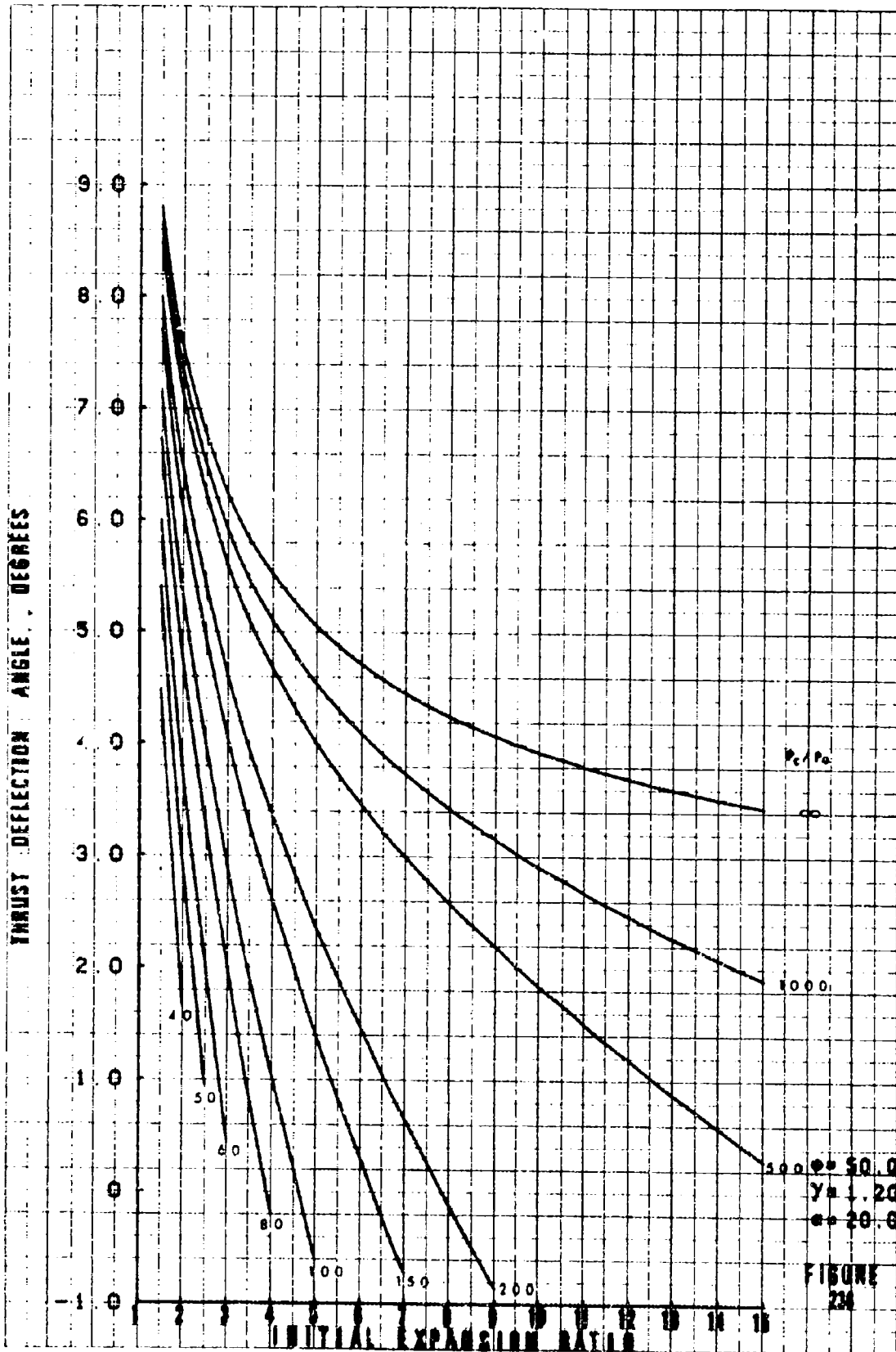
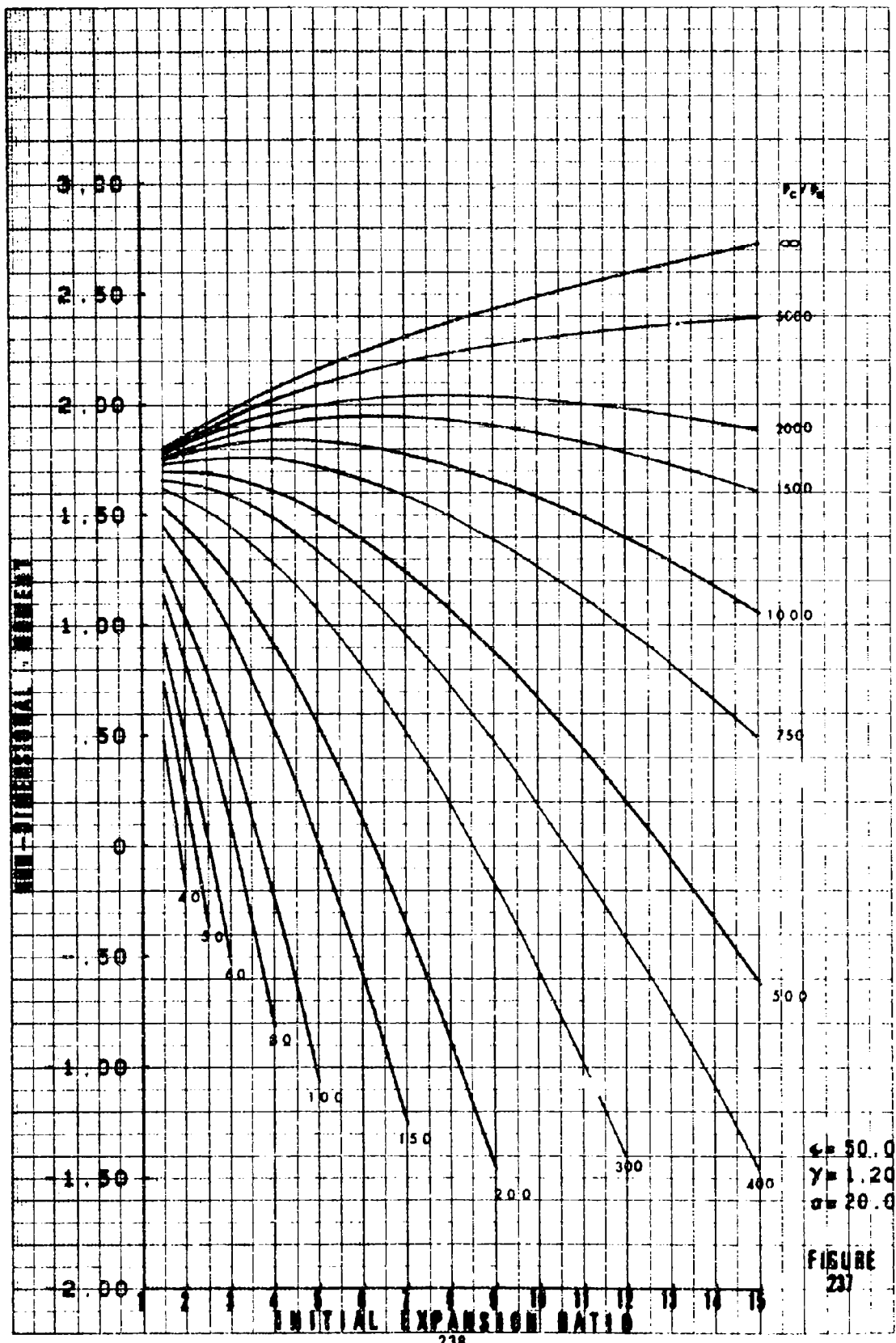


FIGURE 234



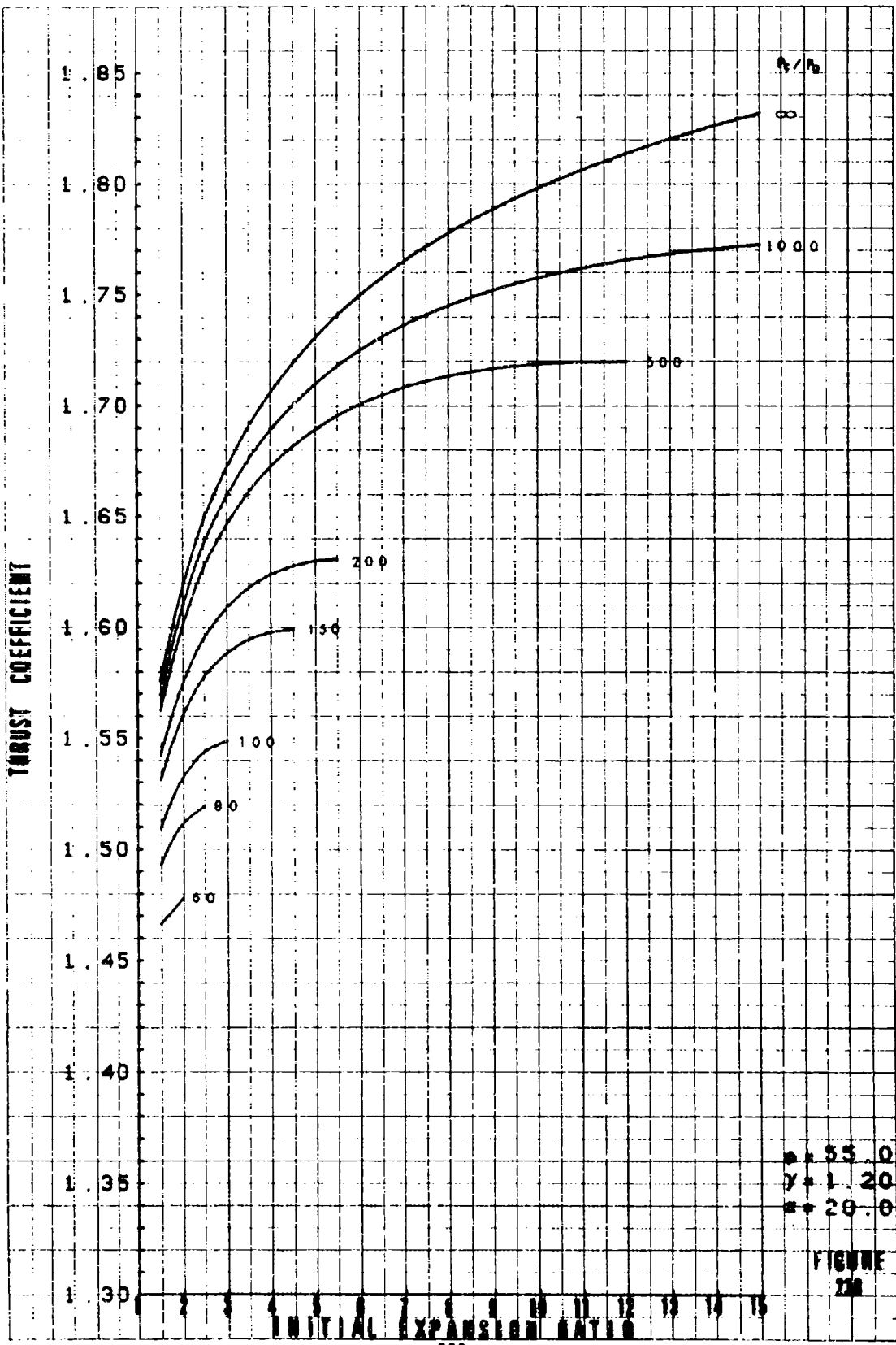
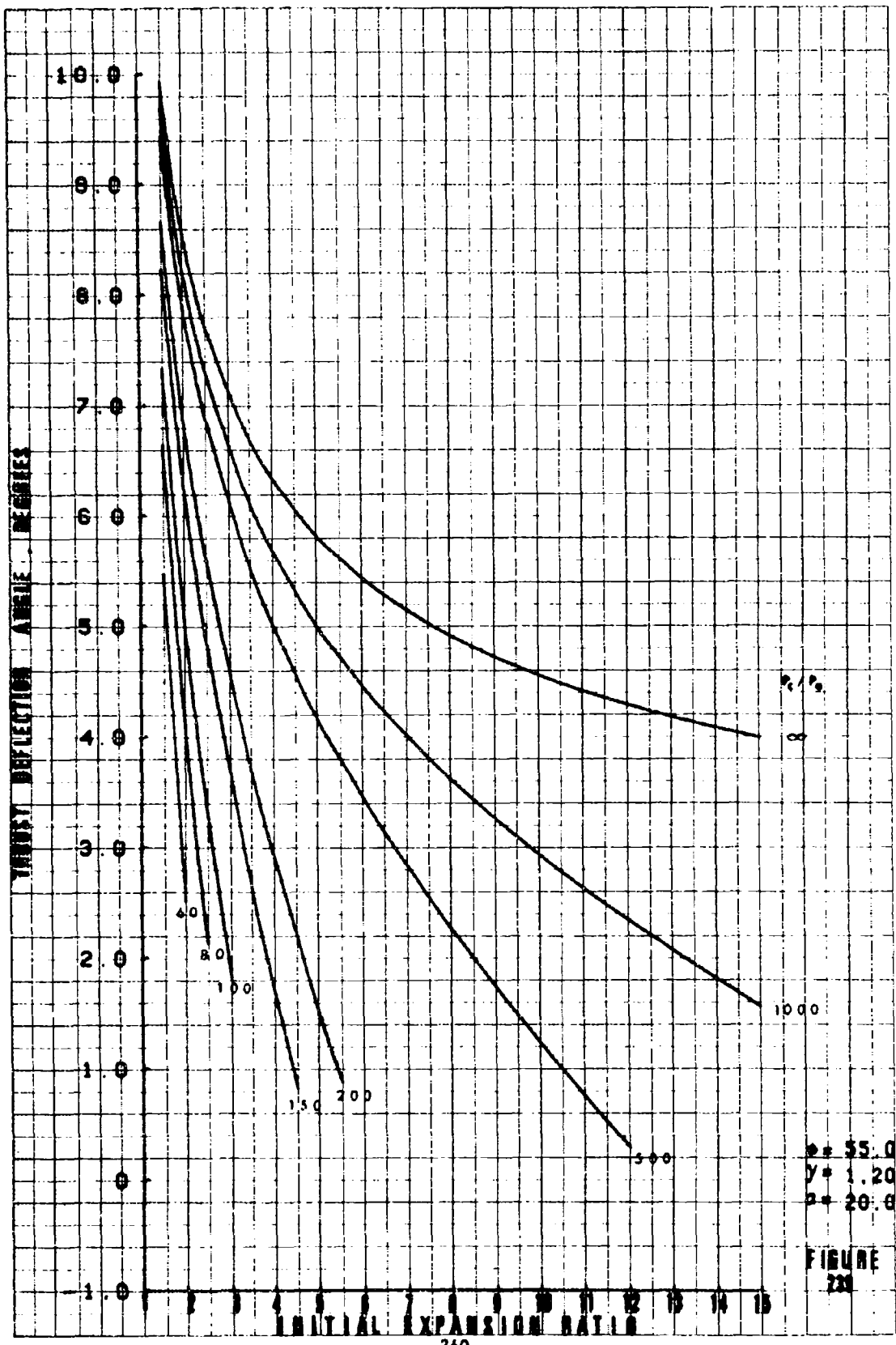
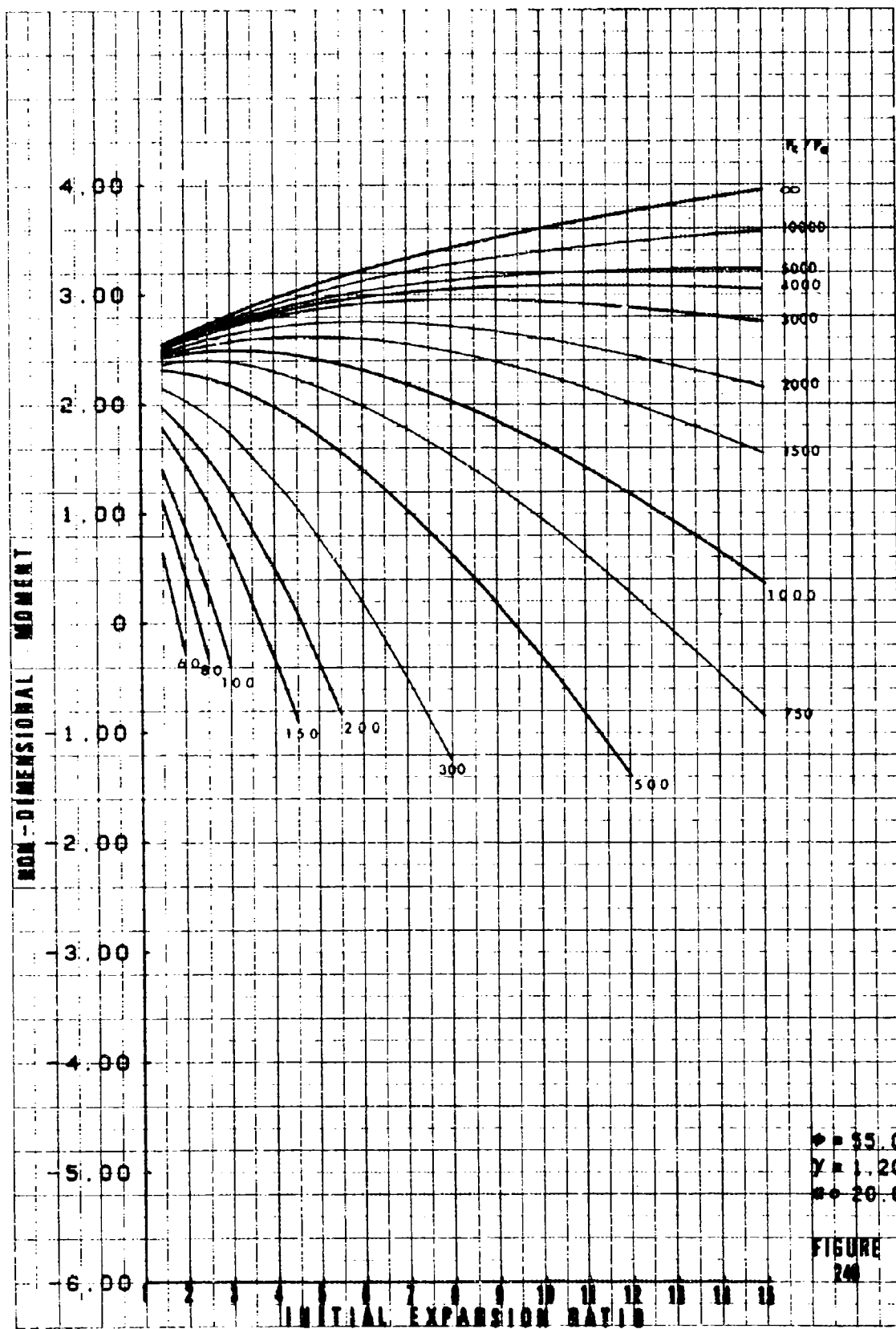


FIGURE 238







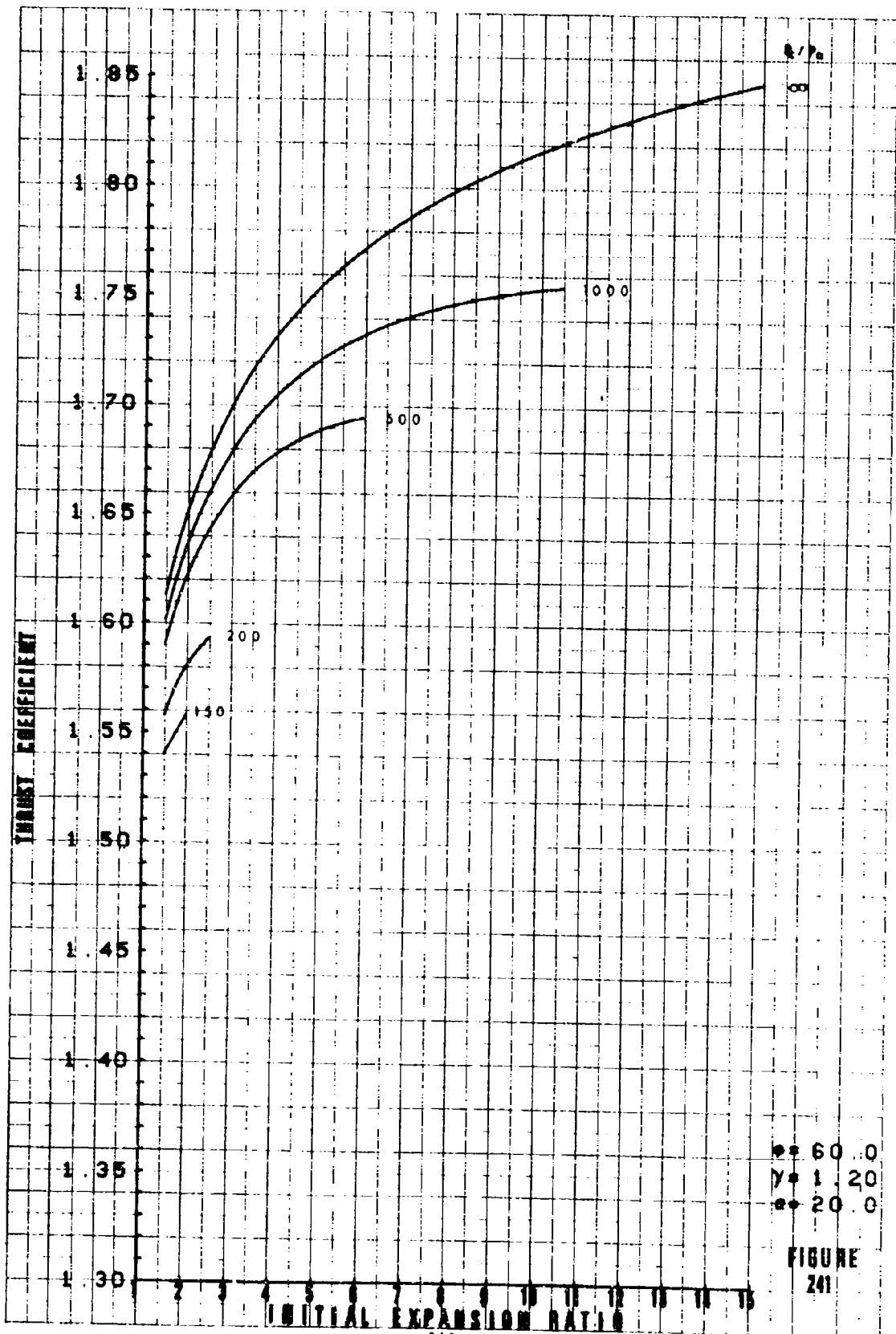


FIGURE 241

THRUST DEFLECTION ANGLE, DEGREES

20.0  
18.0  
16.0  
14.0  
12.0  
10.0  
8.0  
6.0  
4.0  
2.0  
0  
-2.0

2 3 4 5 6 7 8 9 10 11 12 13 14 15

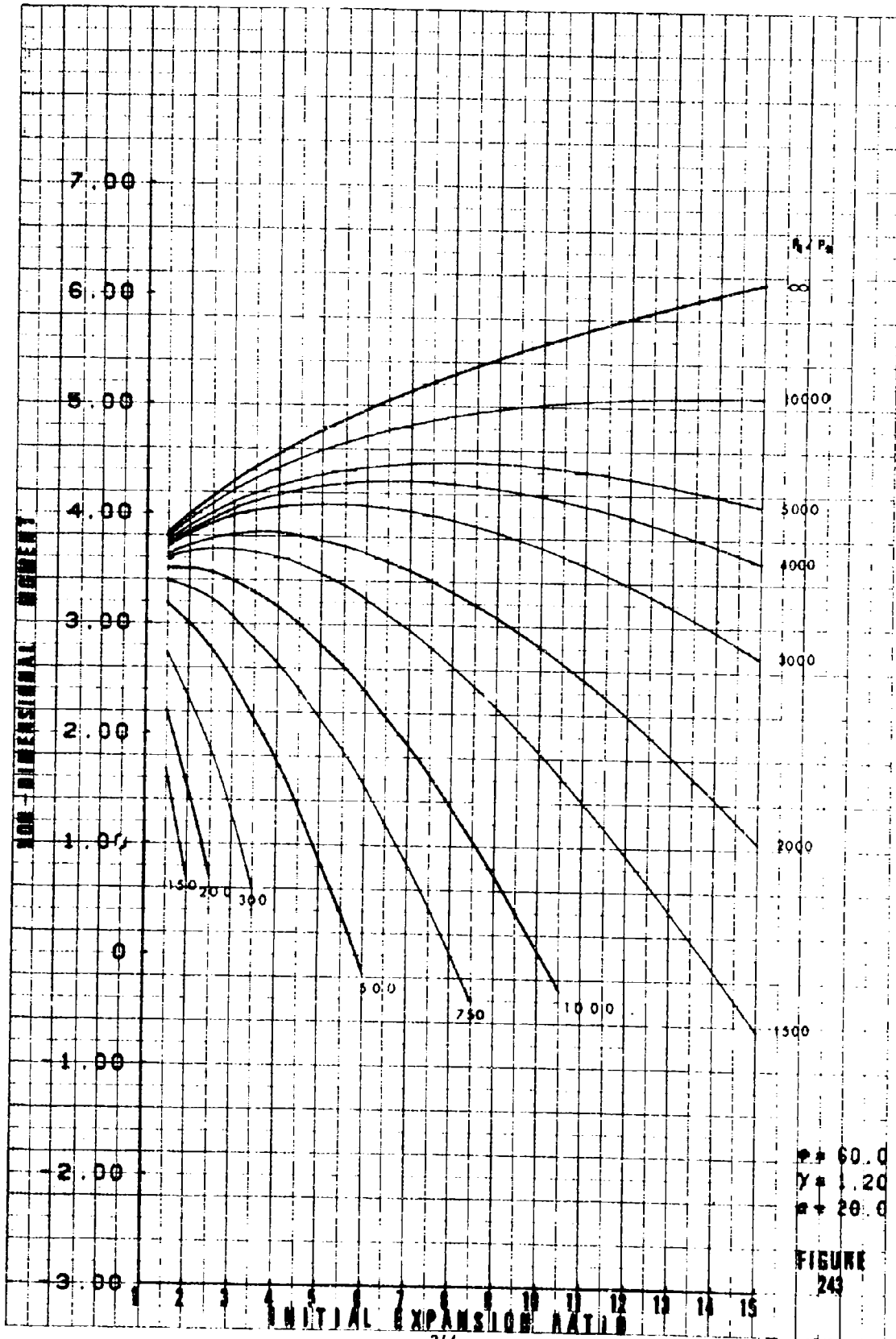
INITIAL EXPANSION RATIO

15.0  
20.0  
50.0  
100.0

$P_c/P_0$   
8

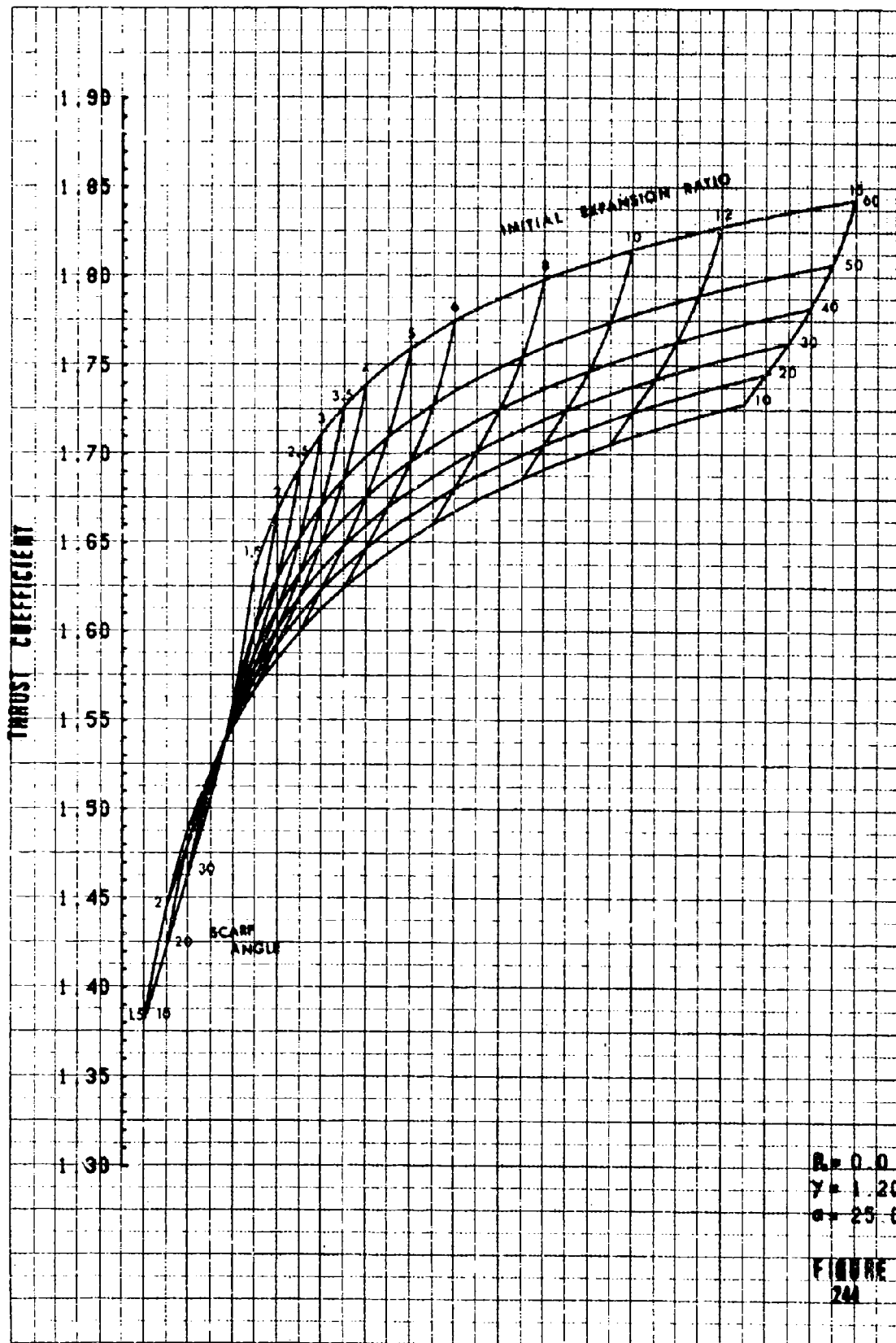
$\phi = 60.0$   
 $\gamma = 1.20$   
 $\sigma = 20.0$

FIGURE  
243



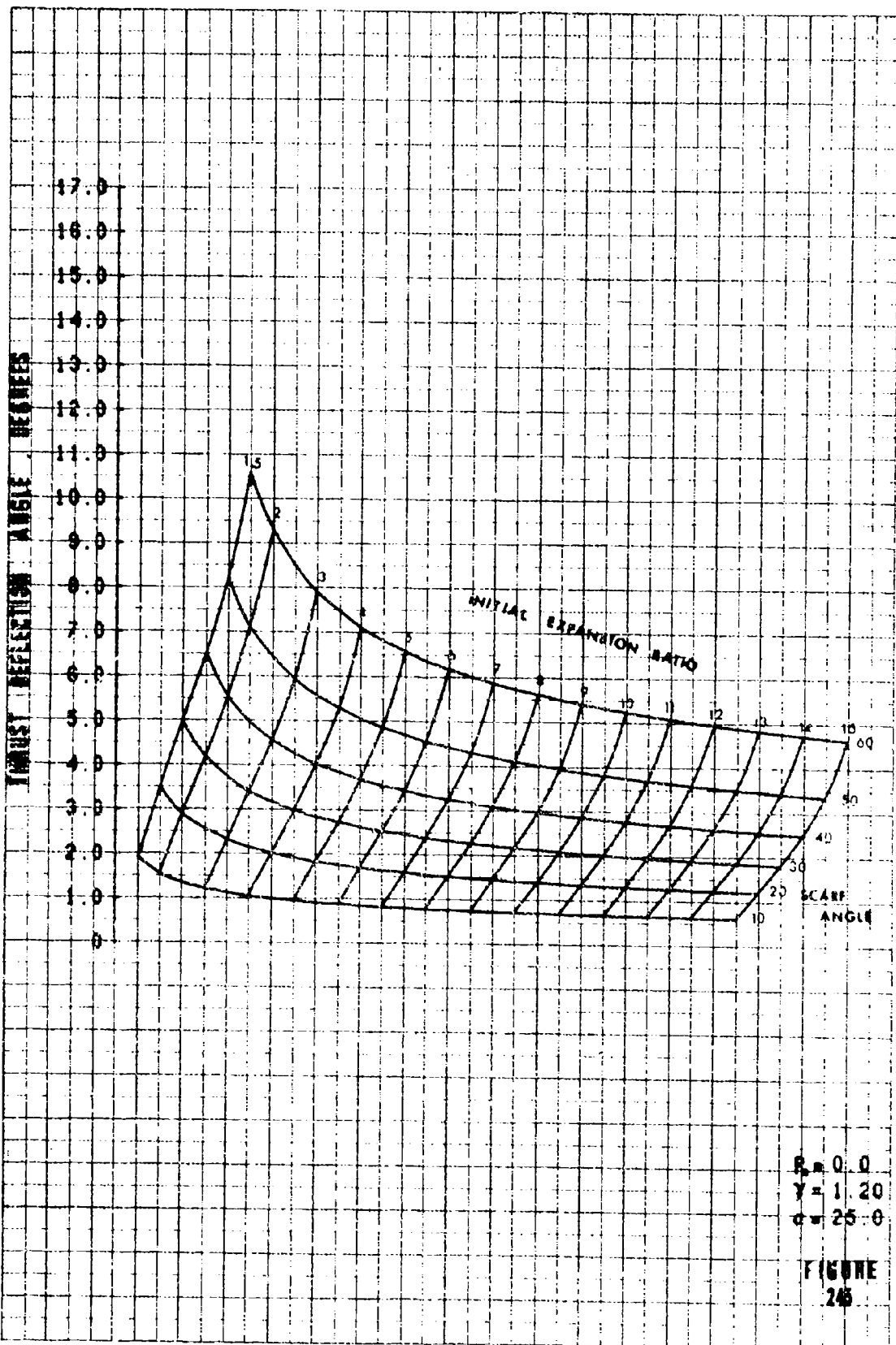
$\bullet \bullet 60.0$   
 $\gamma = 1.20$   
 $\bullet \bullet 20.0$

FIGURE 243



R. P. O. O.  
 Y. P. 1. 20  
 G. P. 25. 6

FIGURE  
 244



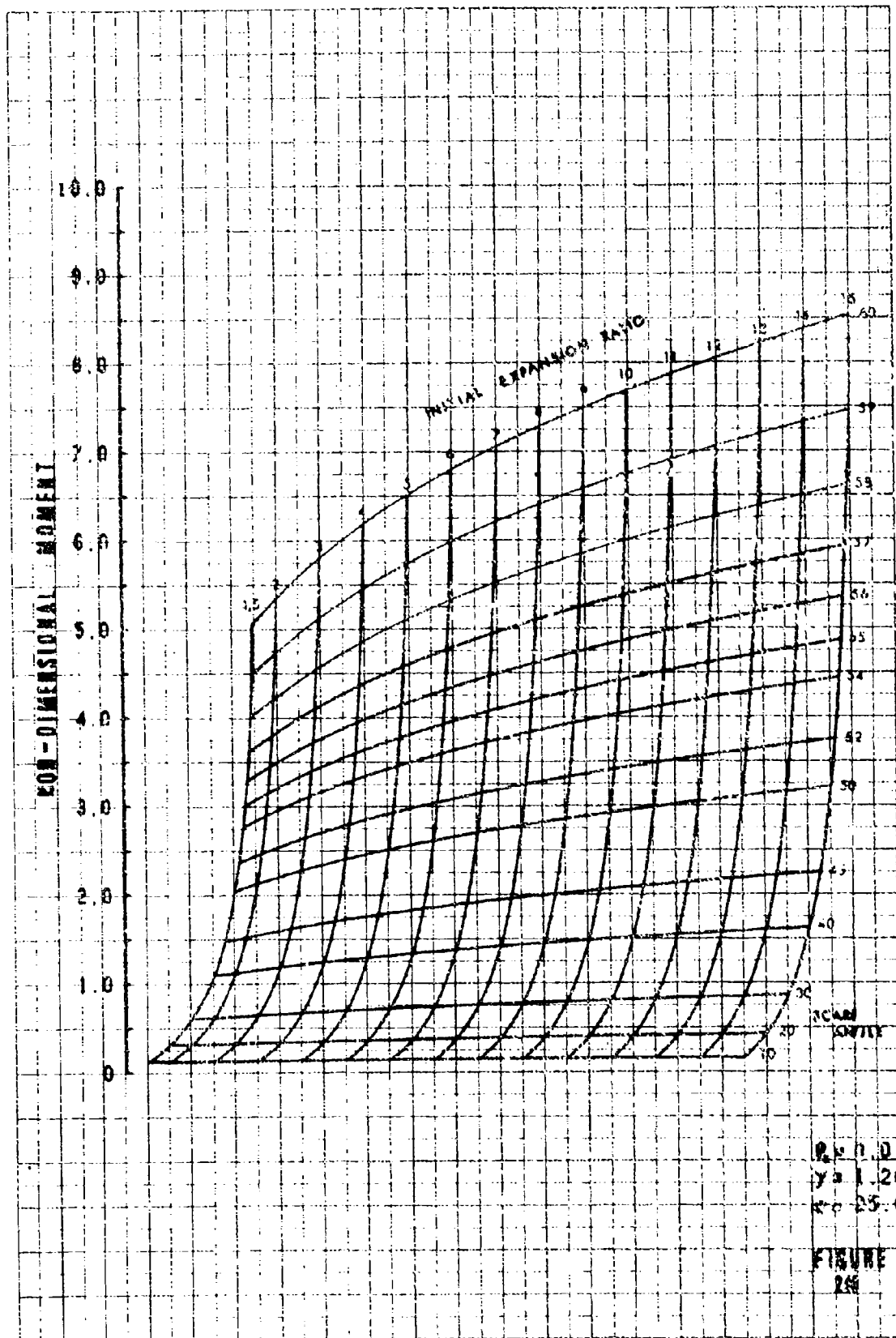
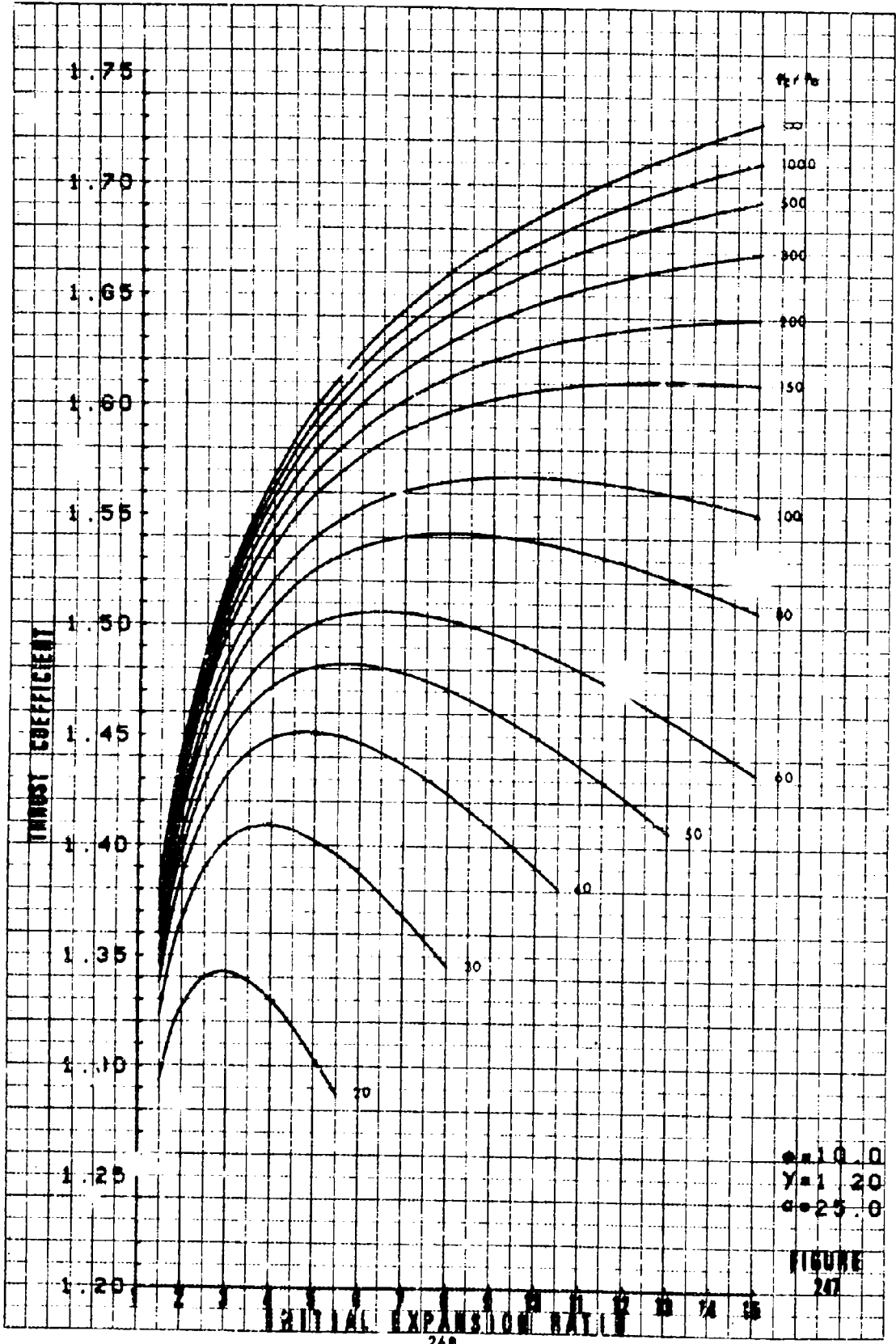
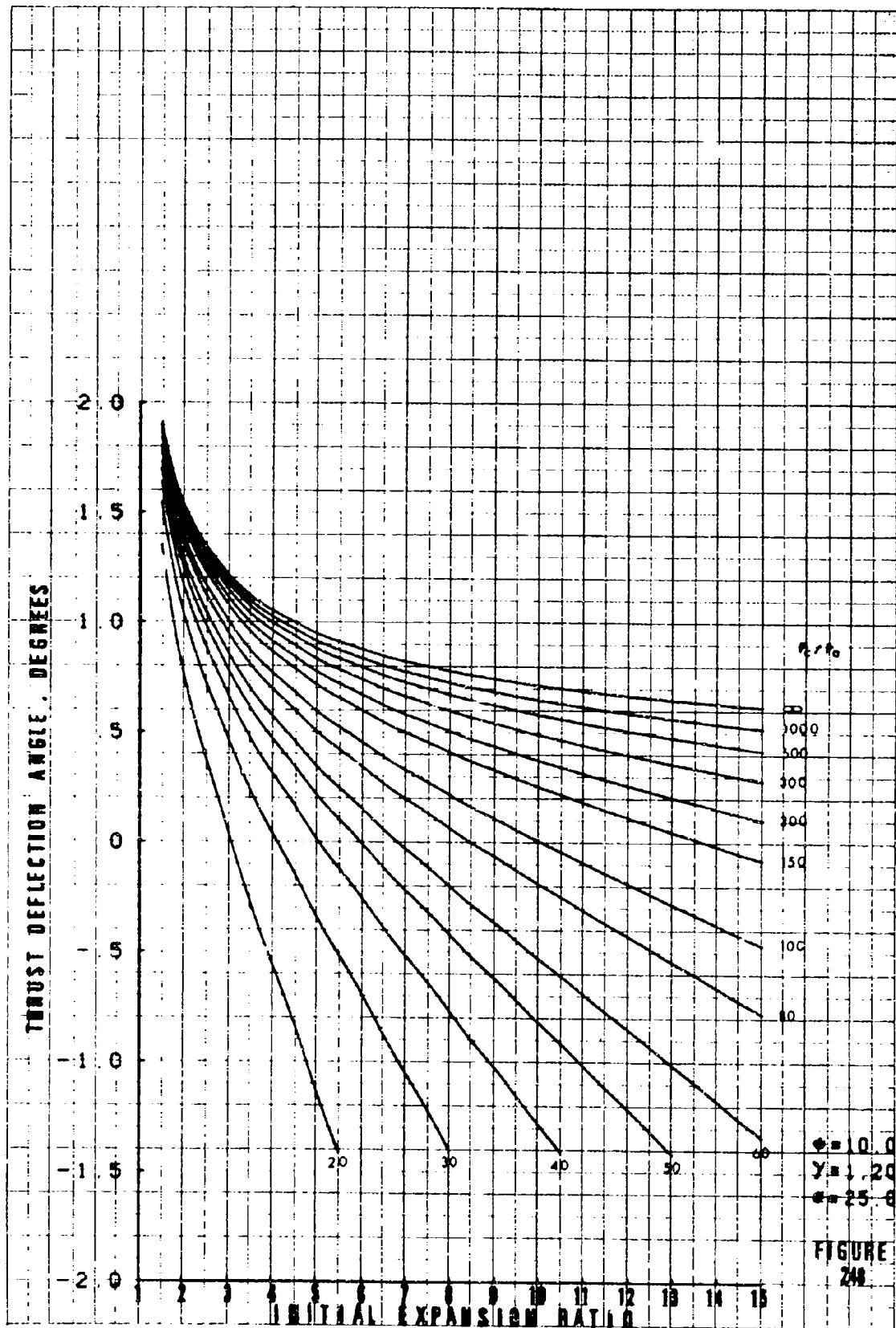


FIGURE  
246







$\phi = 10.0$   
 $\gamma = 1.20$   
 $\sigma = 25.8$

FIGURE 249

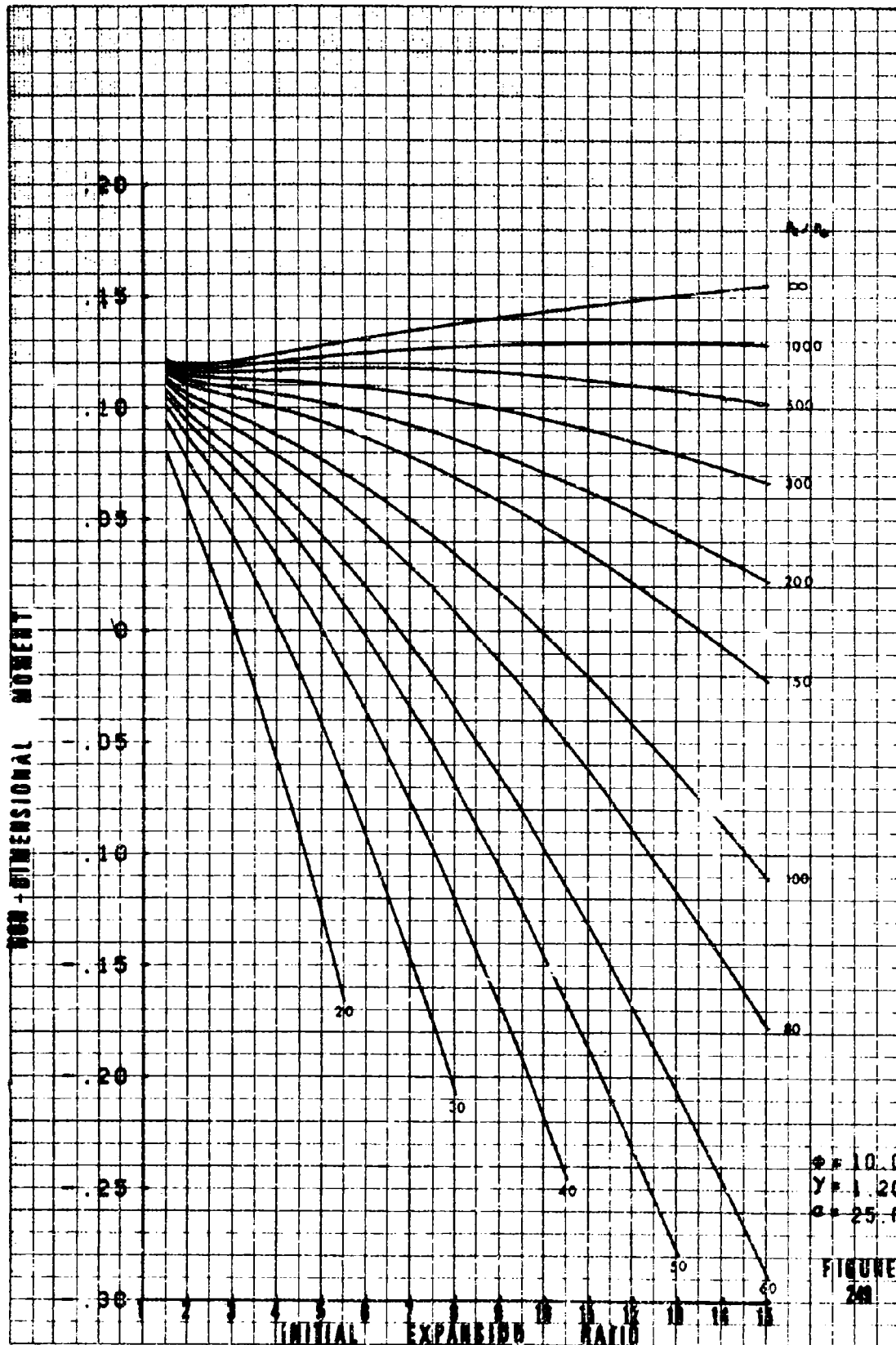
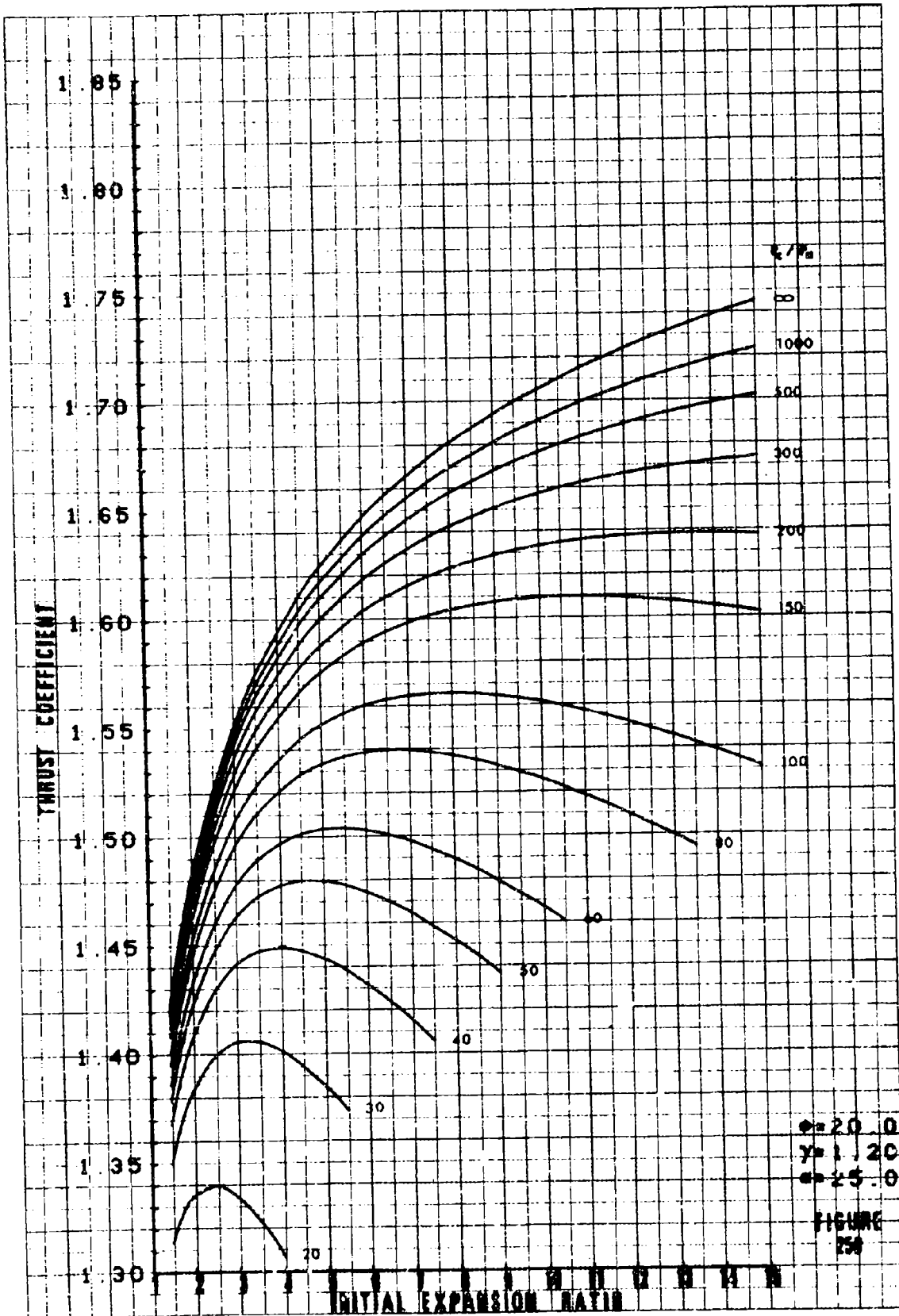
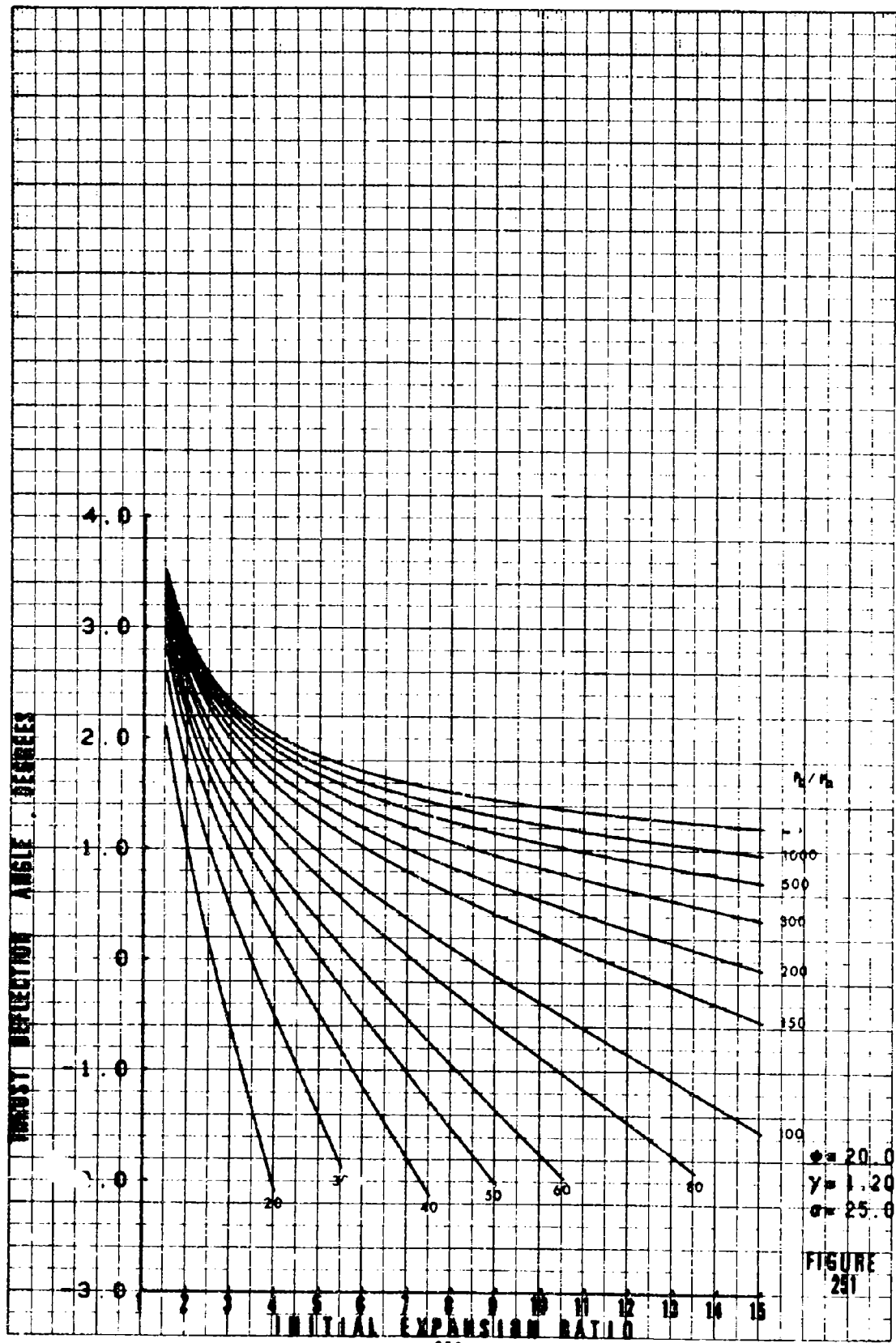
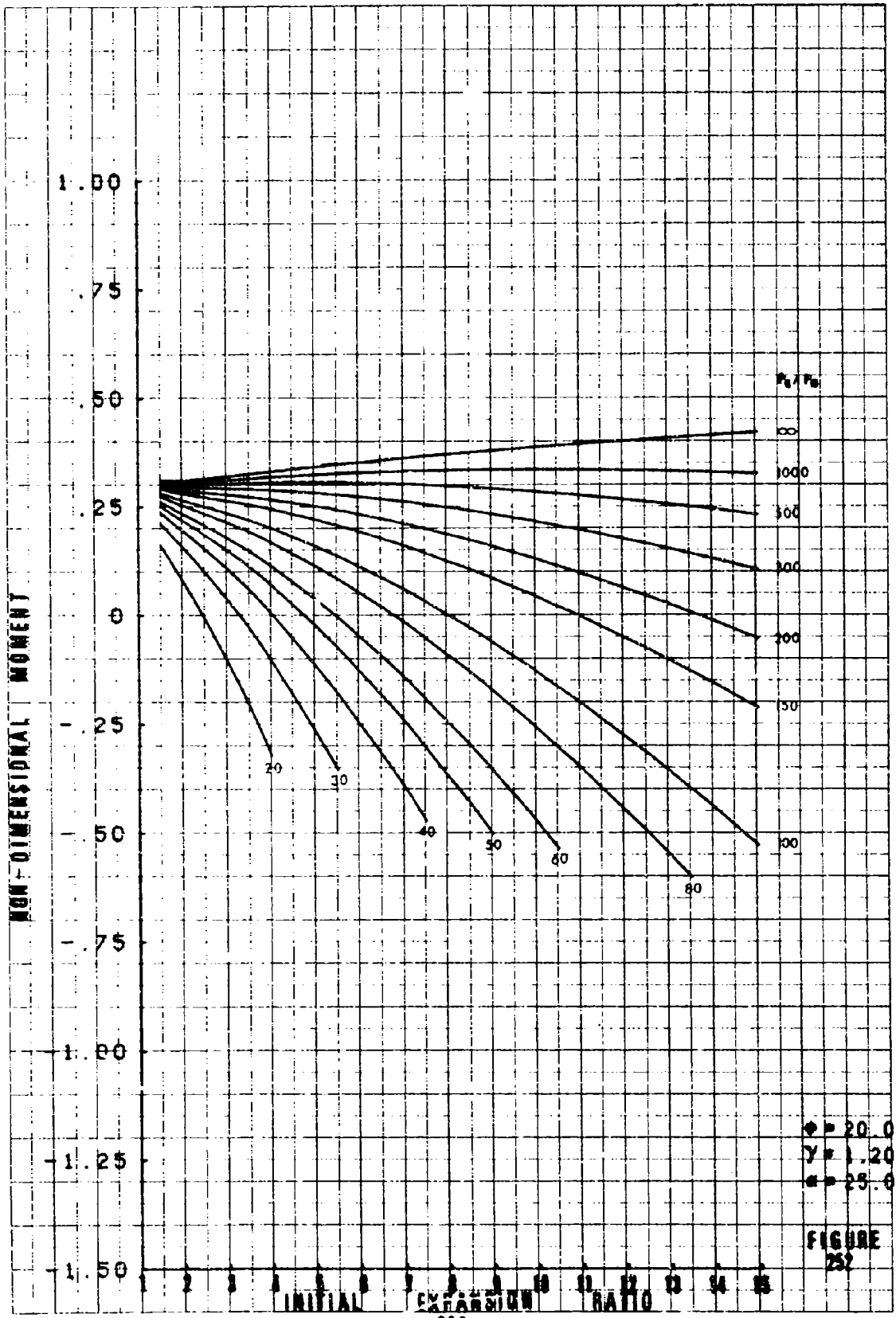
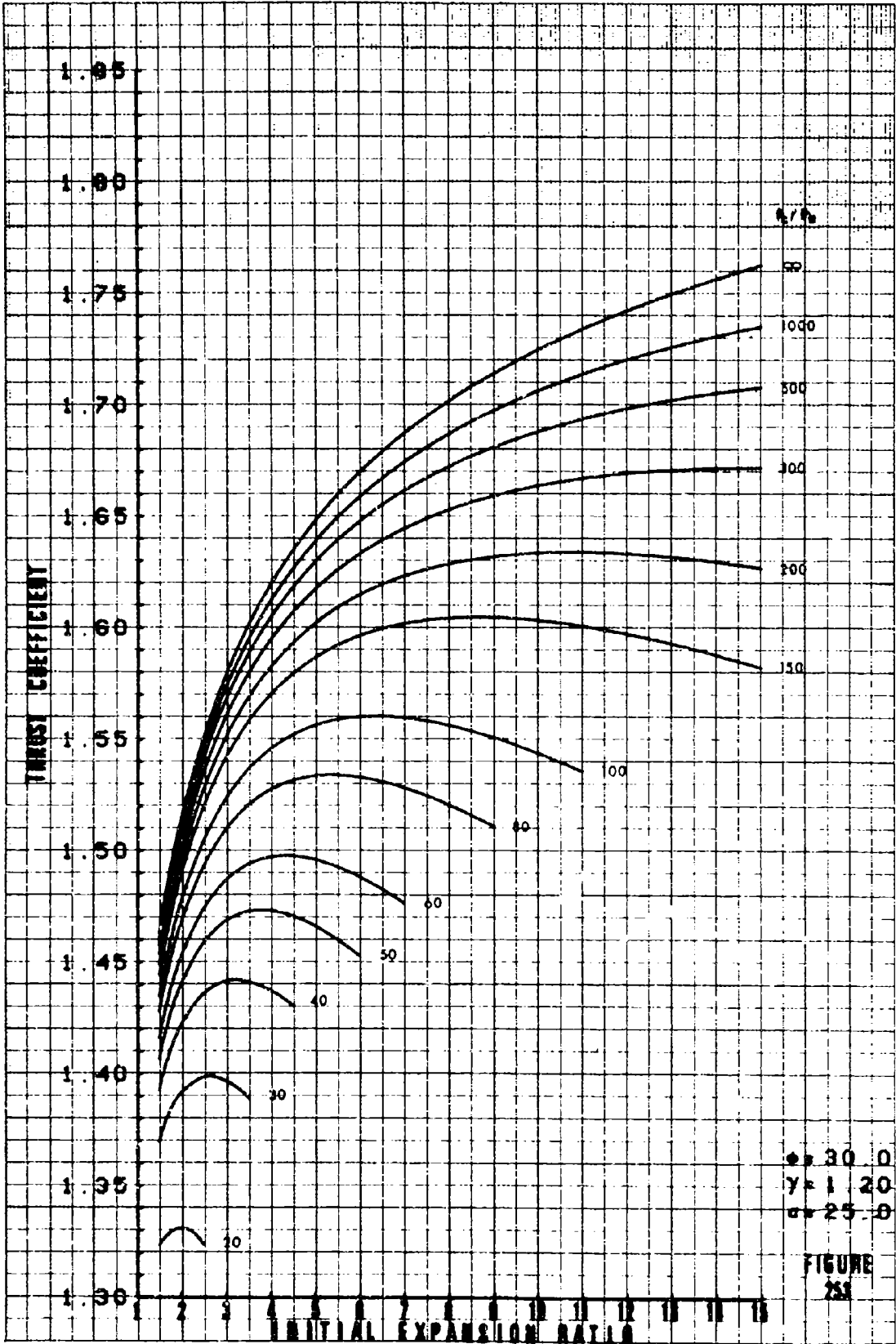


FIGURE 20



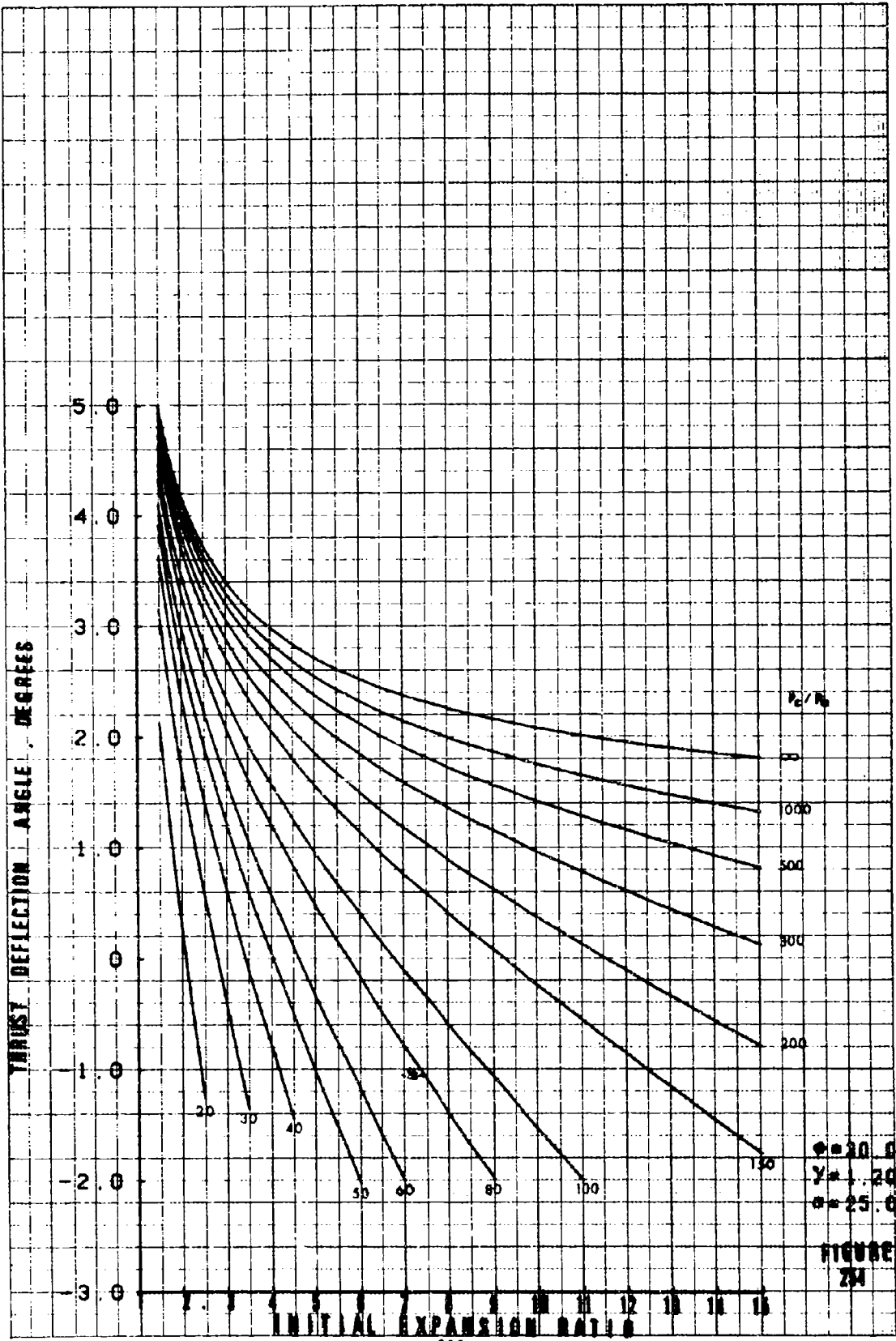






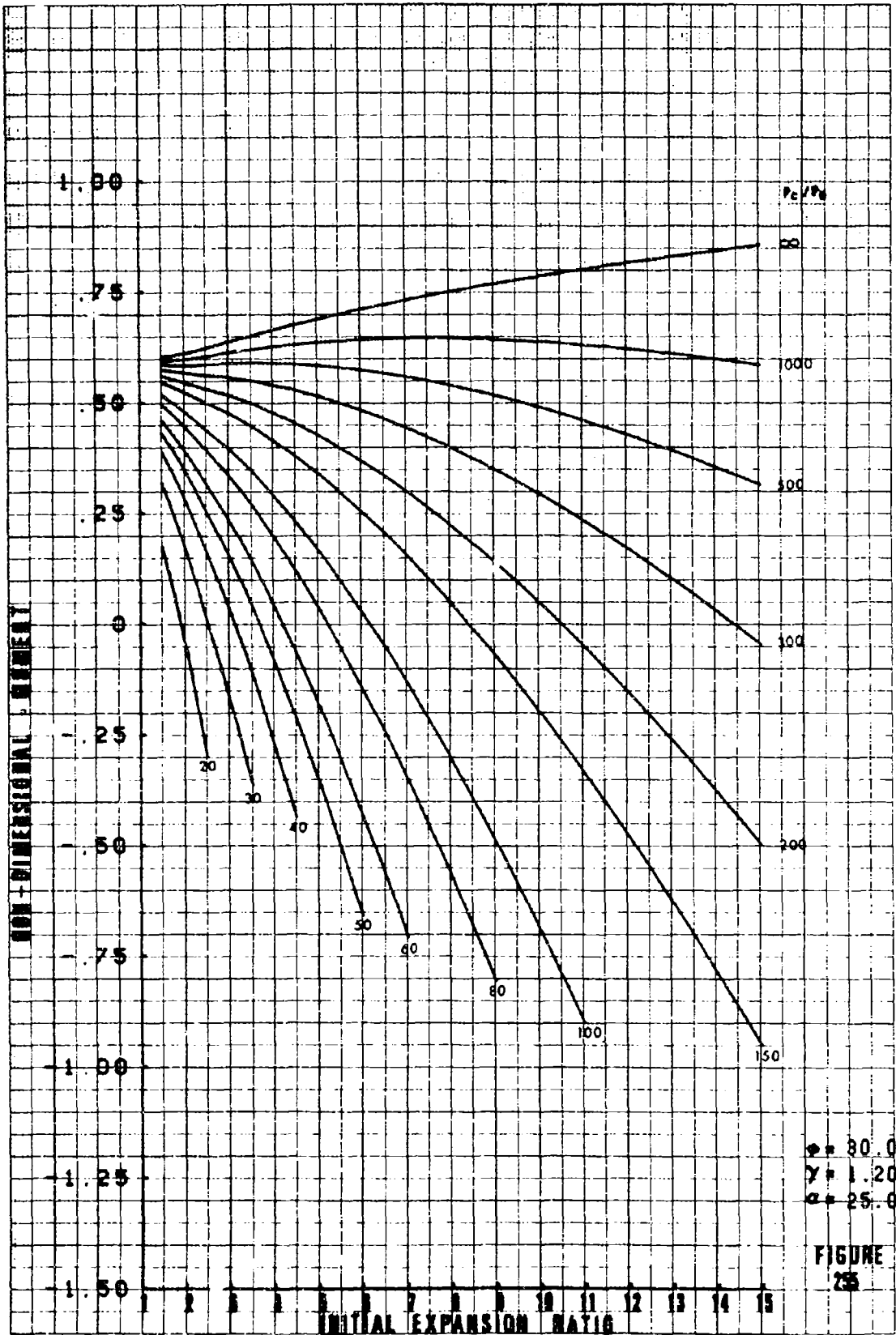
$\bullet$  30 0  
 $\gamma = 1.20$   
 $\square$  25 0

FIGURE 25A

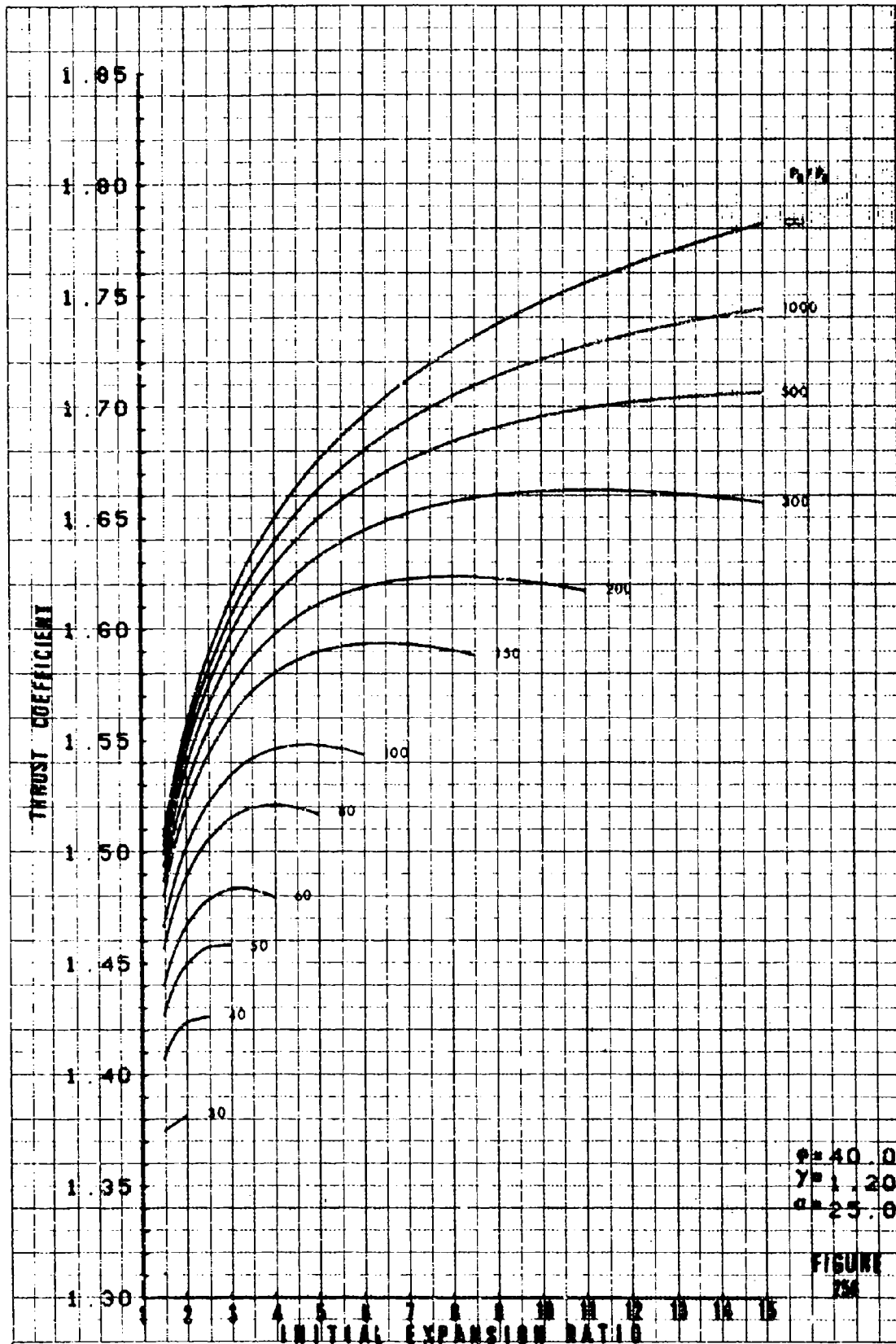


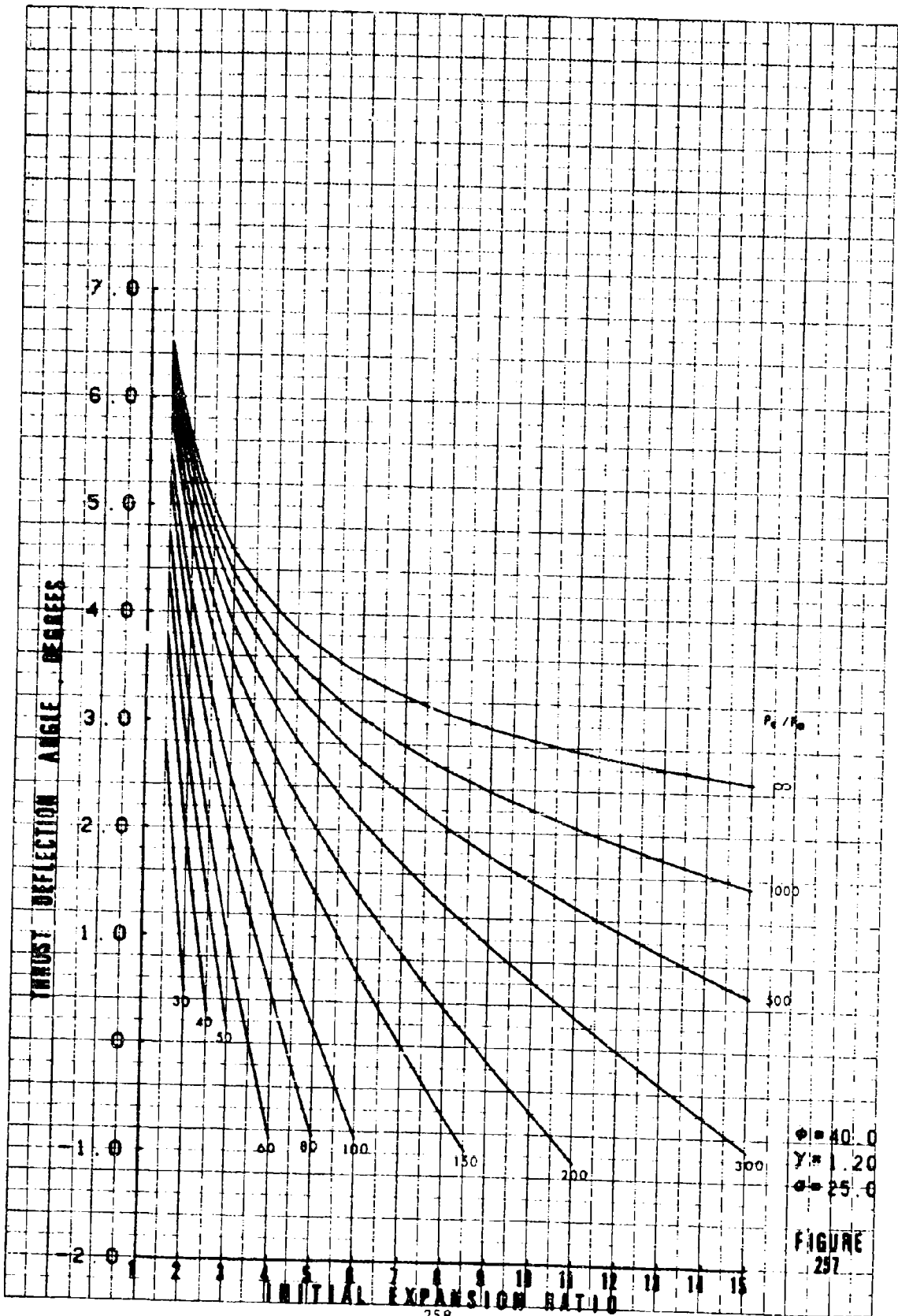
$\phi = 30.0$   
 $\gamma = 1.20$   
 $\alpha = 25.0$

FIGURE 284



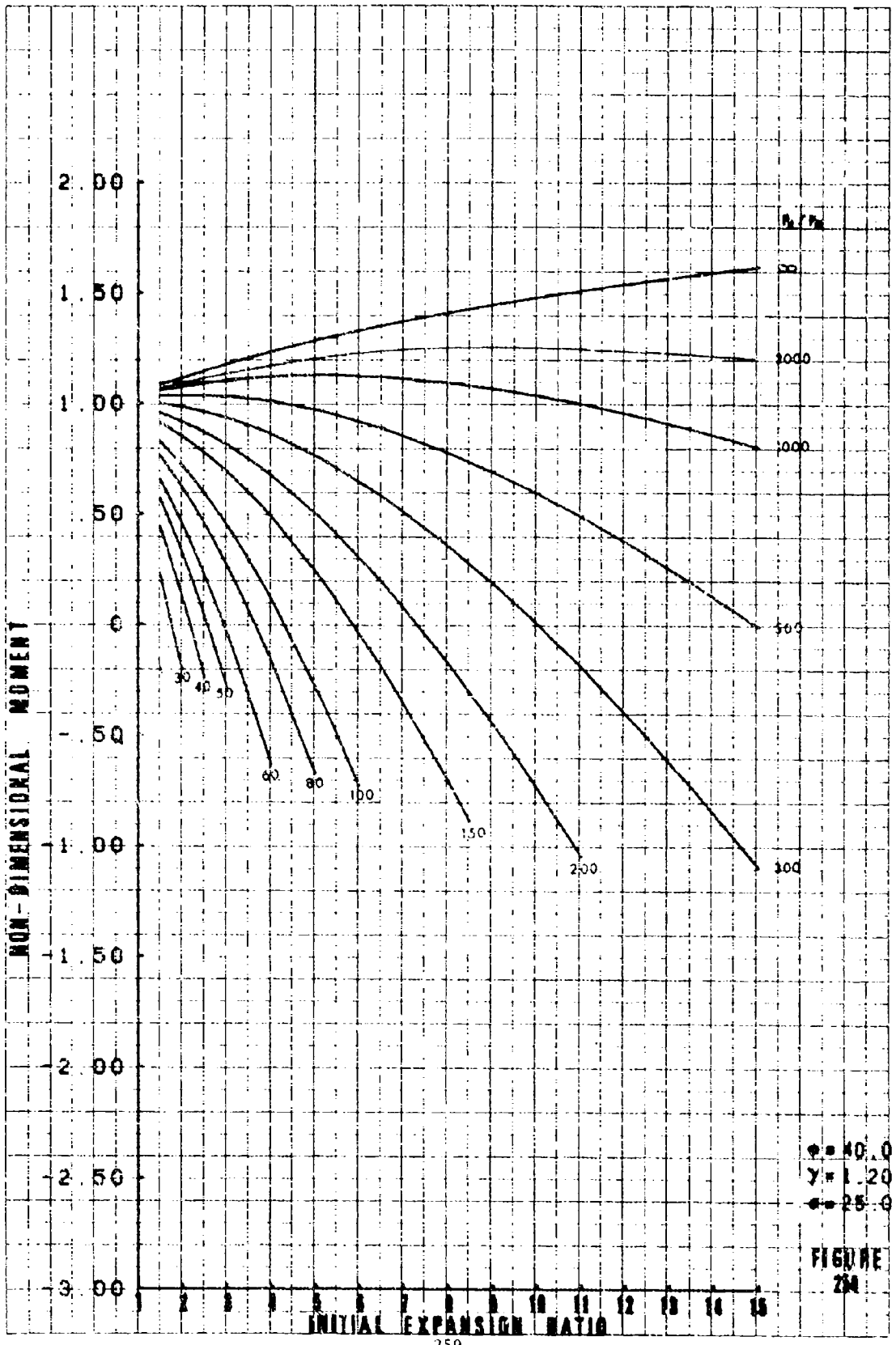


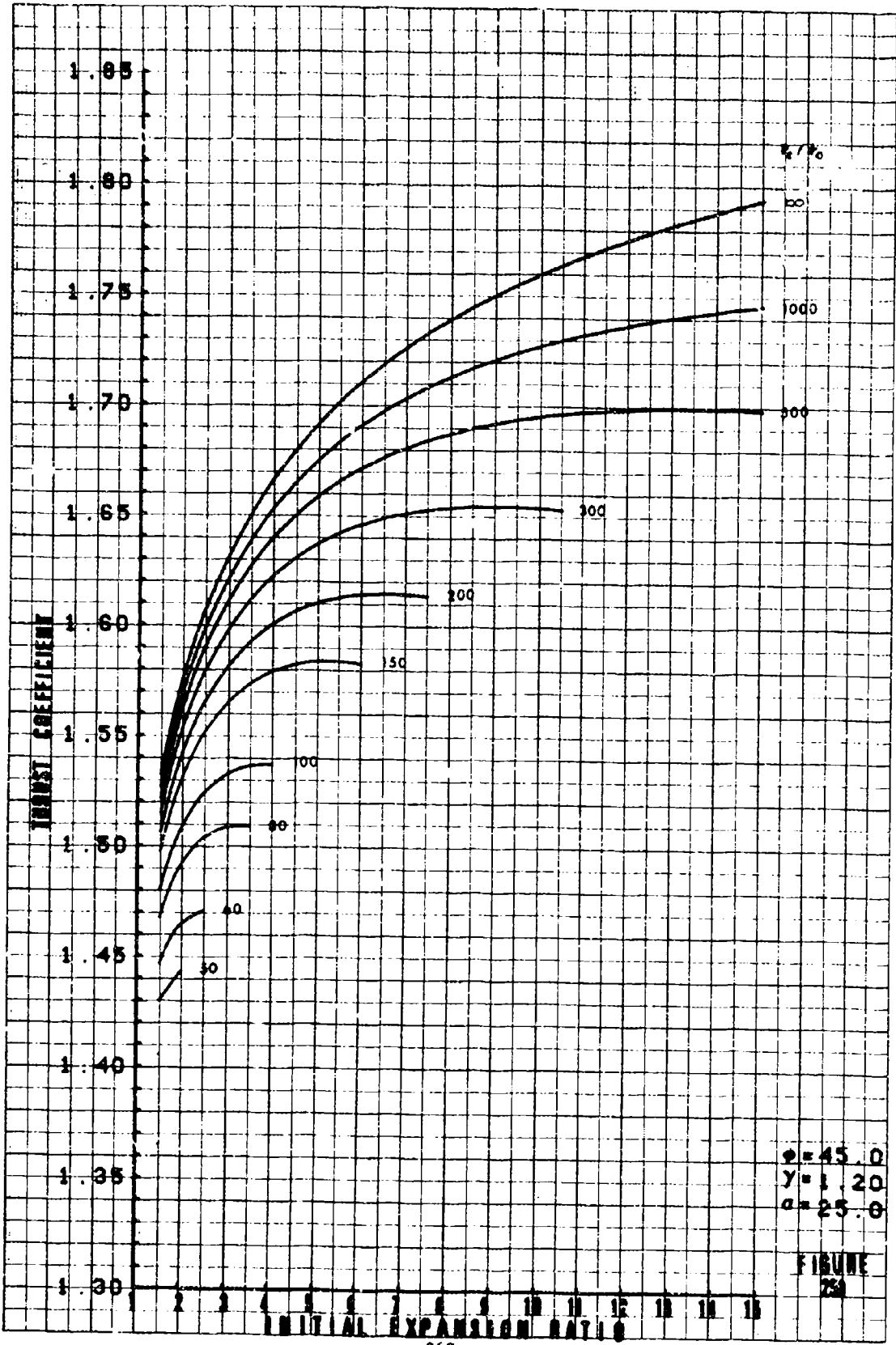




$\phi = 40.0$   
 $\gamma = 1.20$   
 $\alpha = 25.0$

FIGURE 297





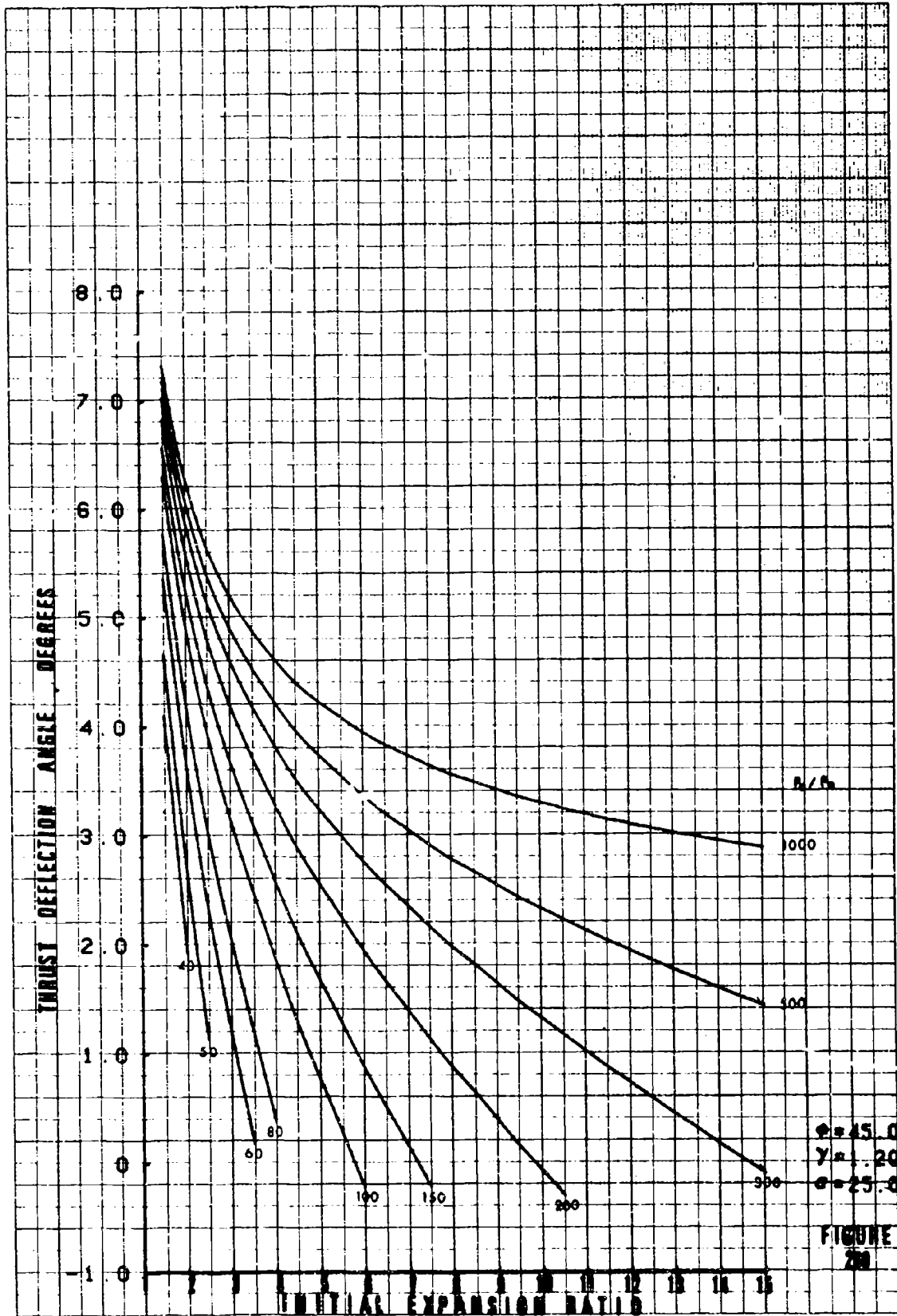
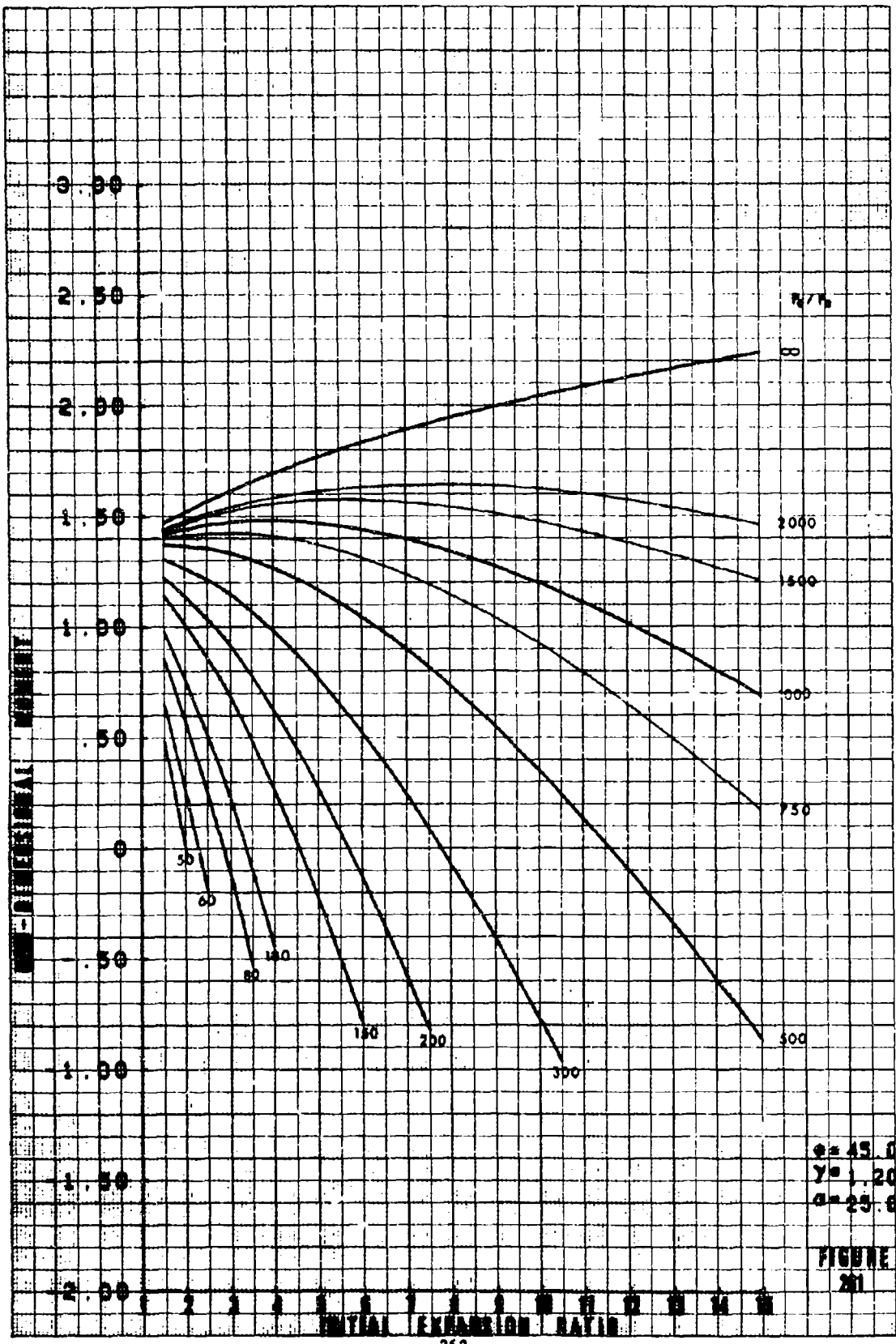
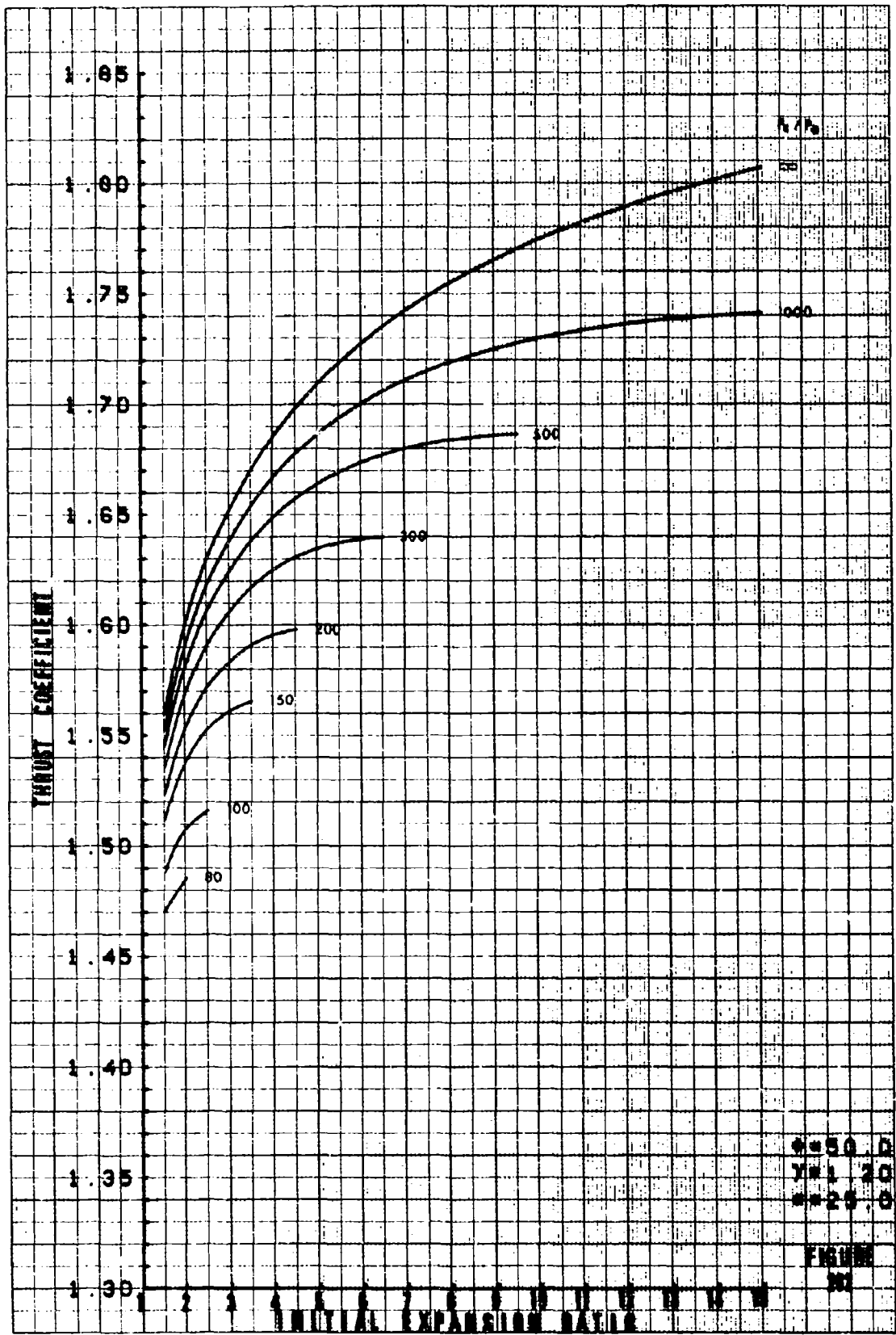
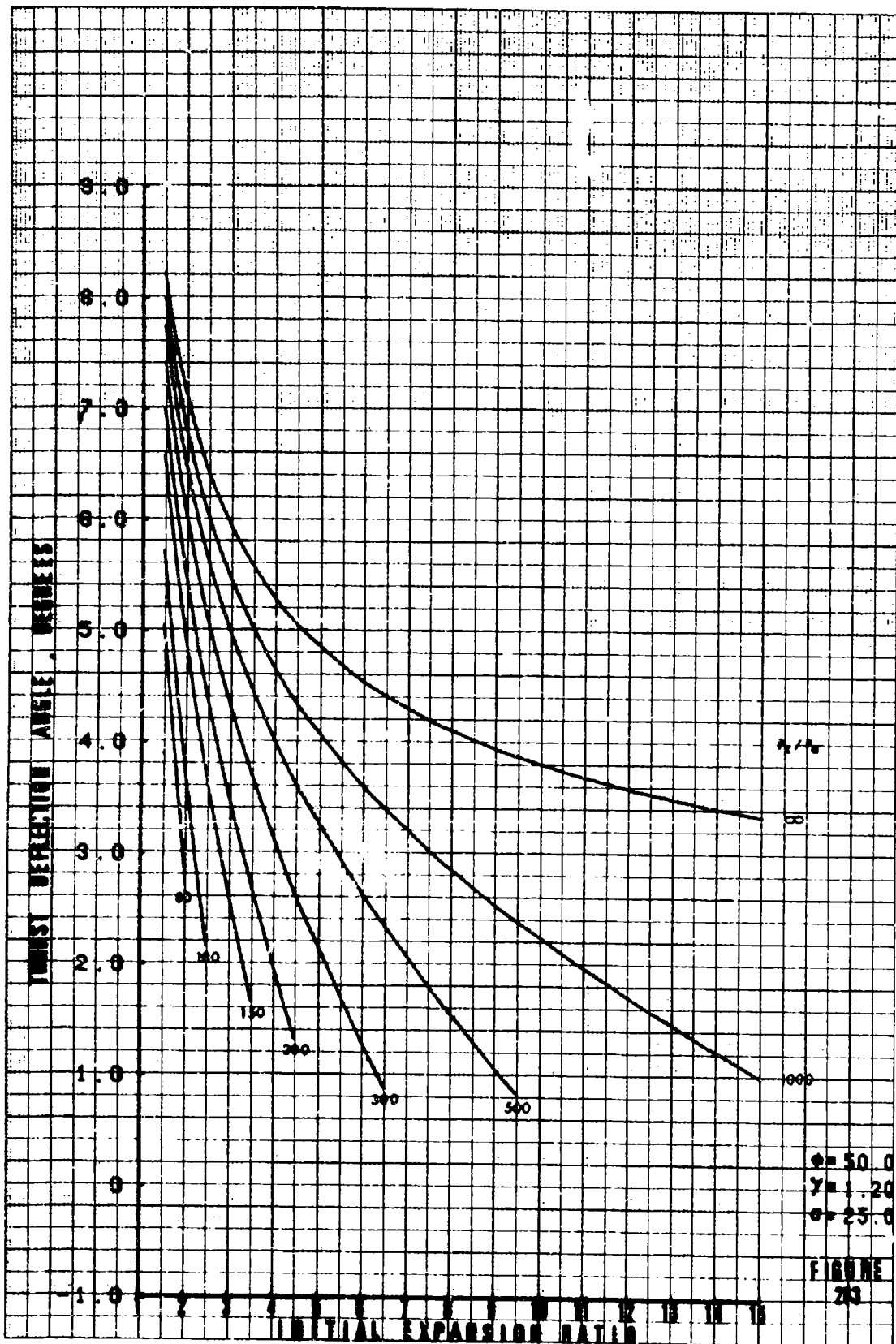


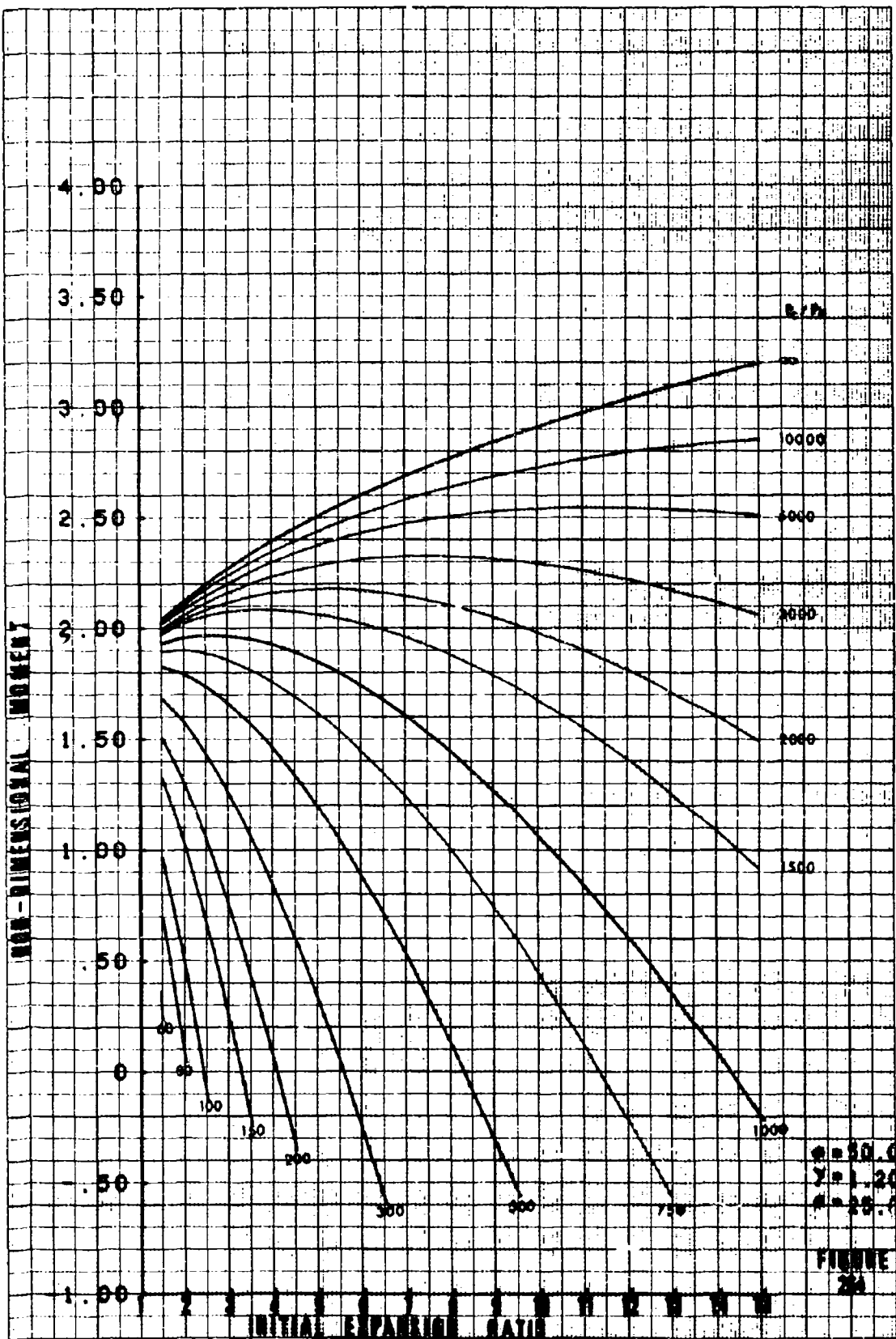
FIGURE 20

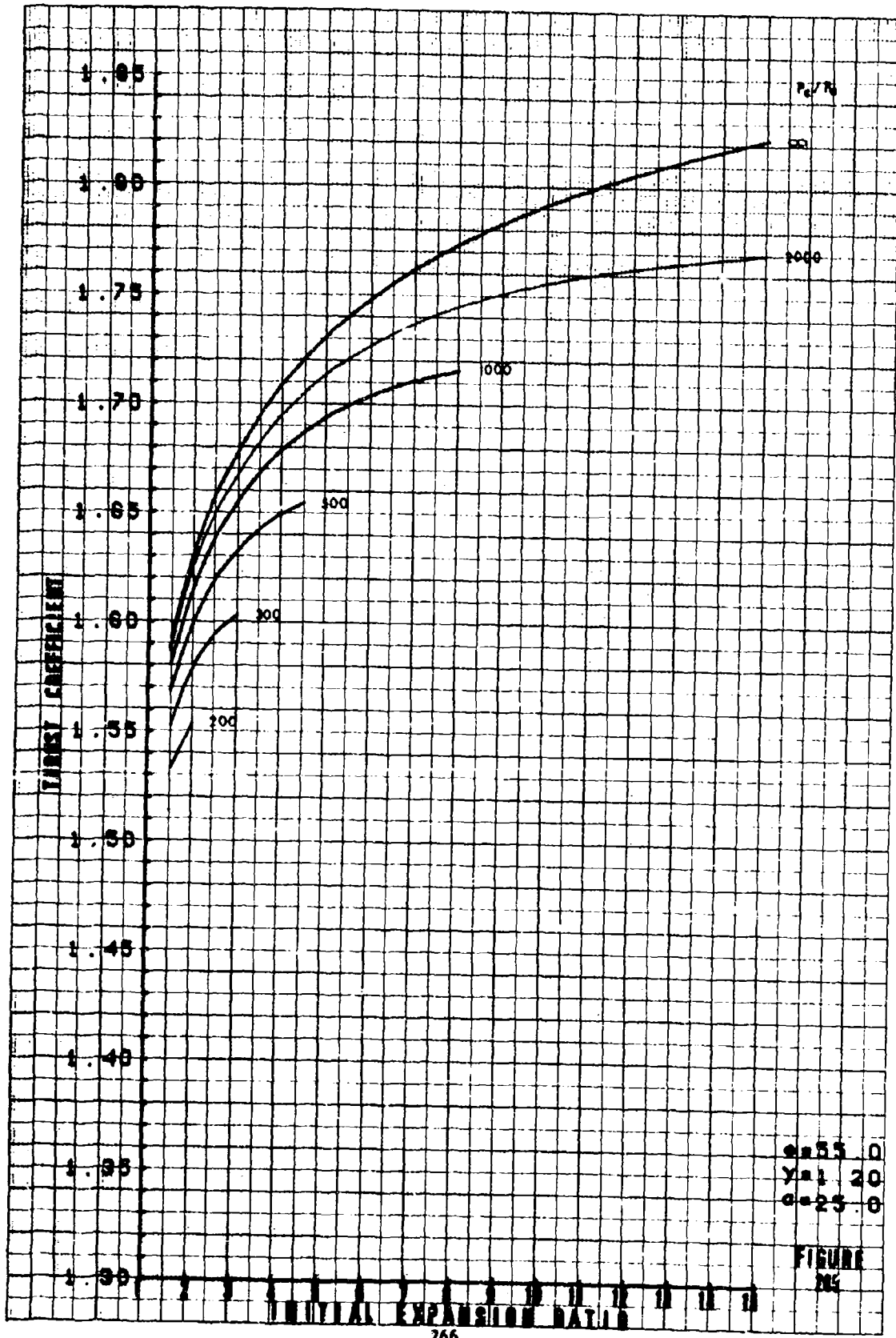


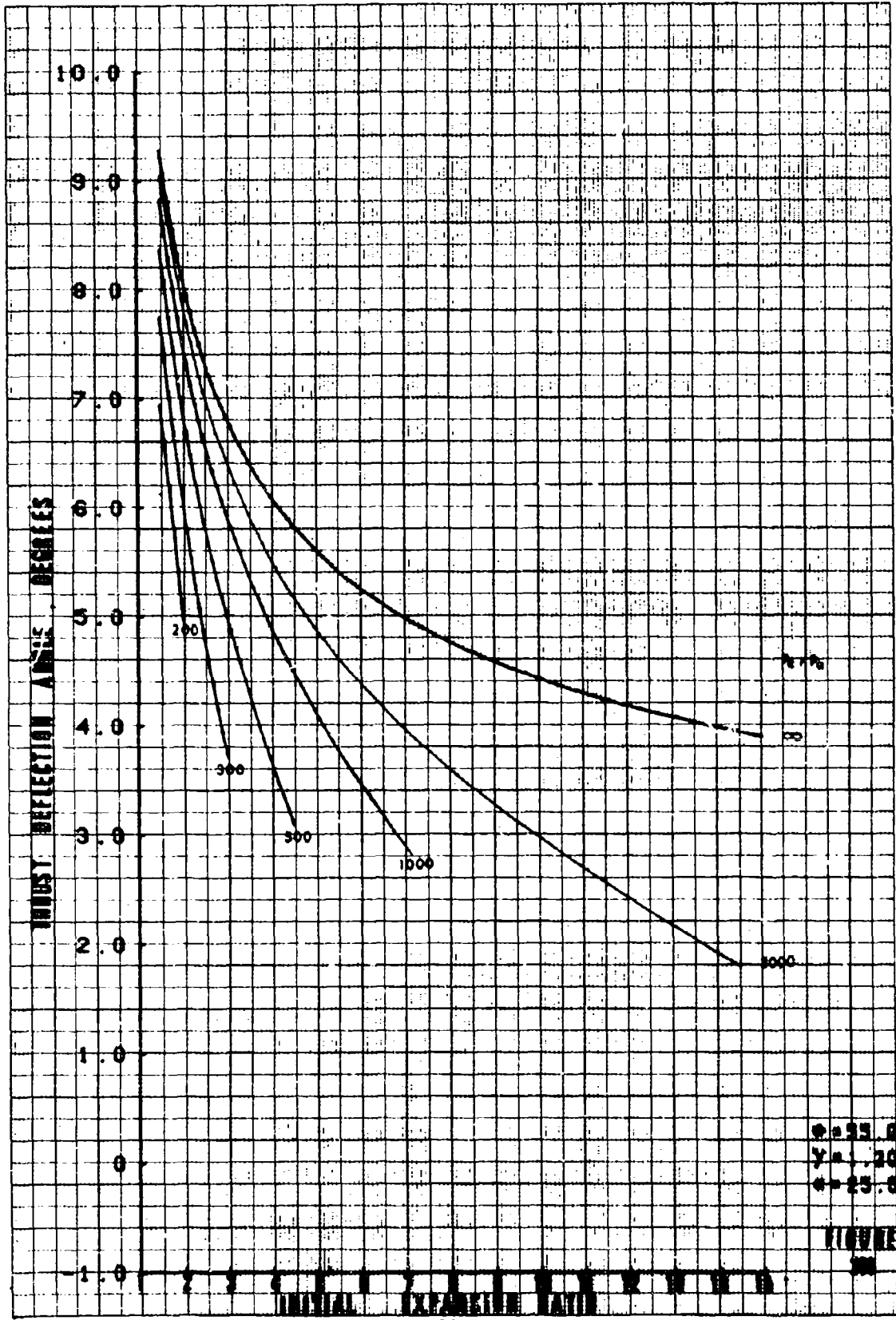


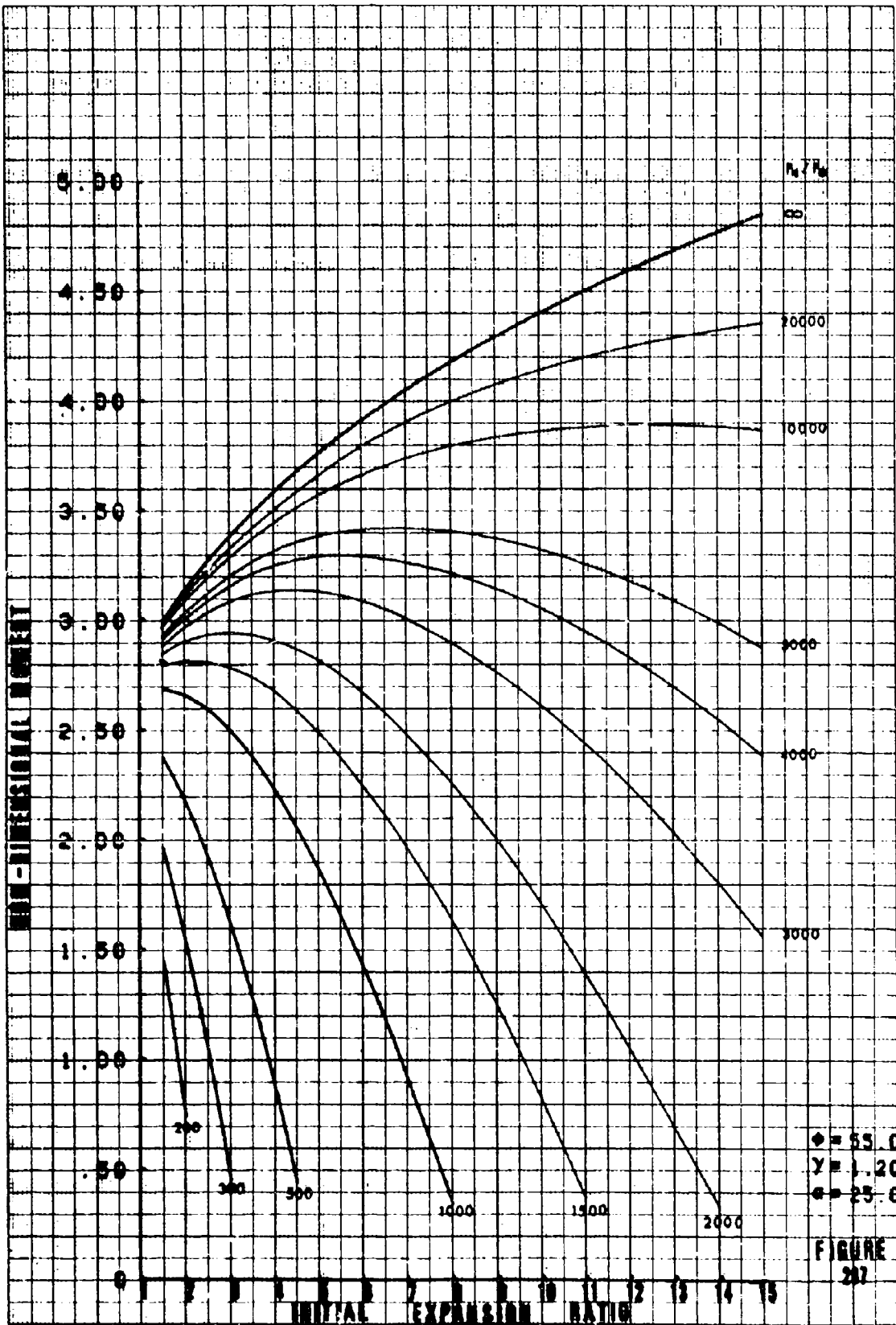


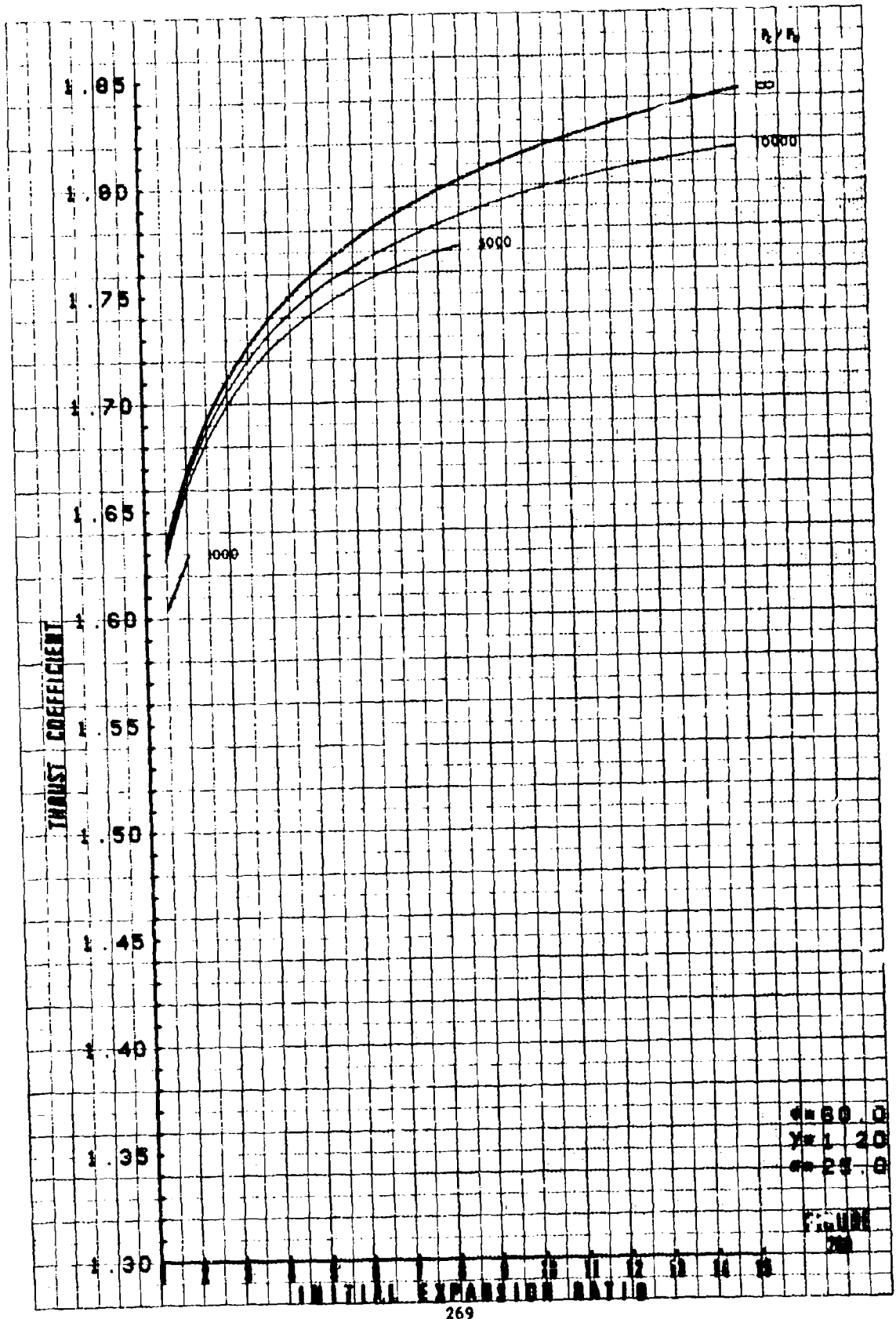


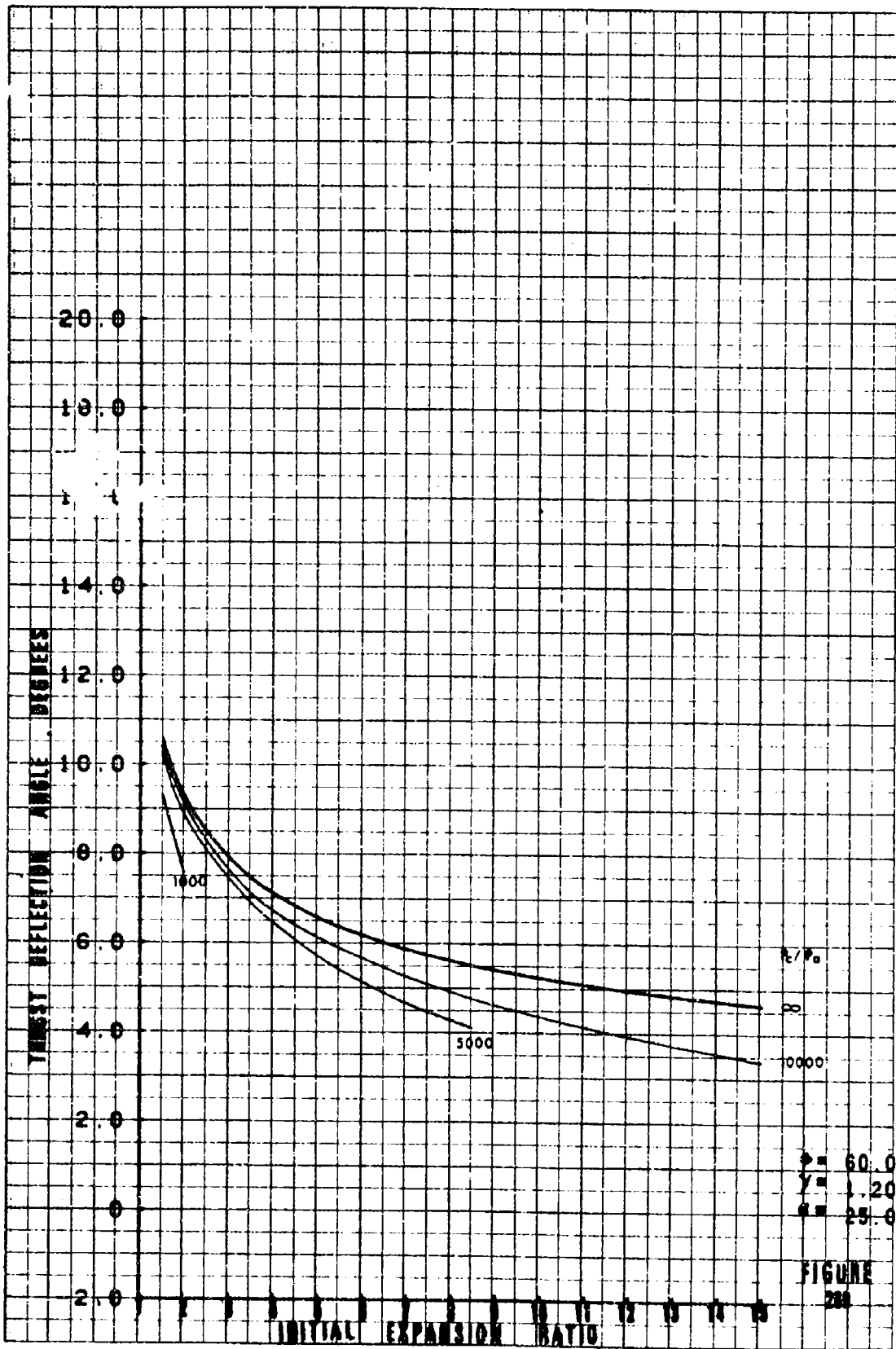


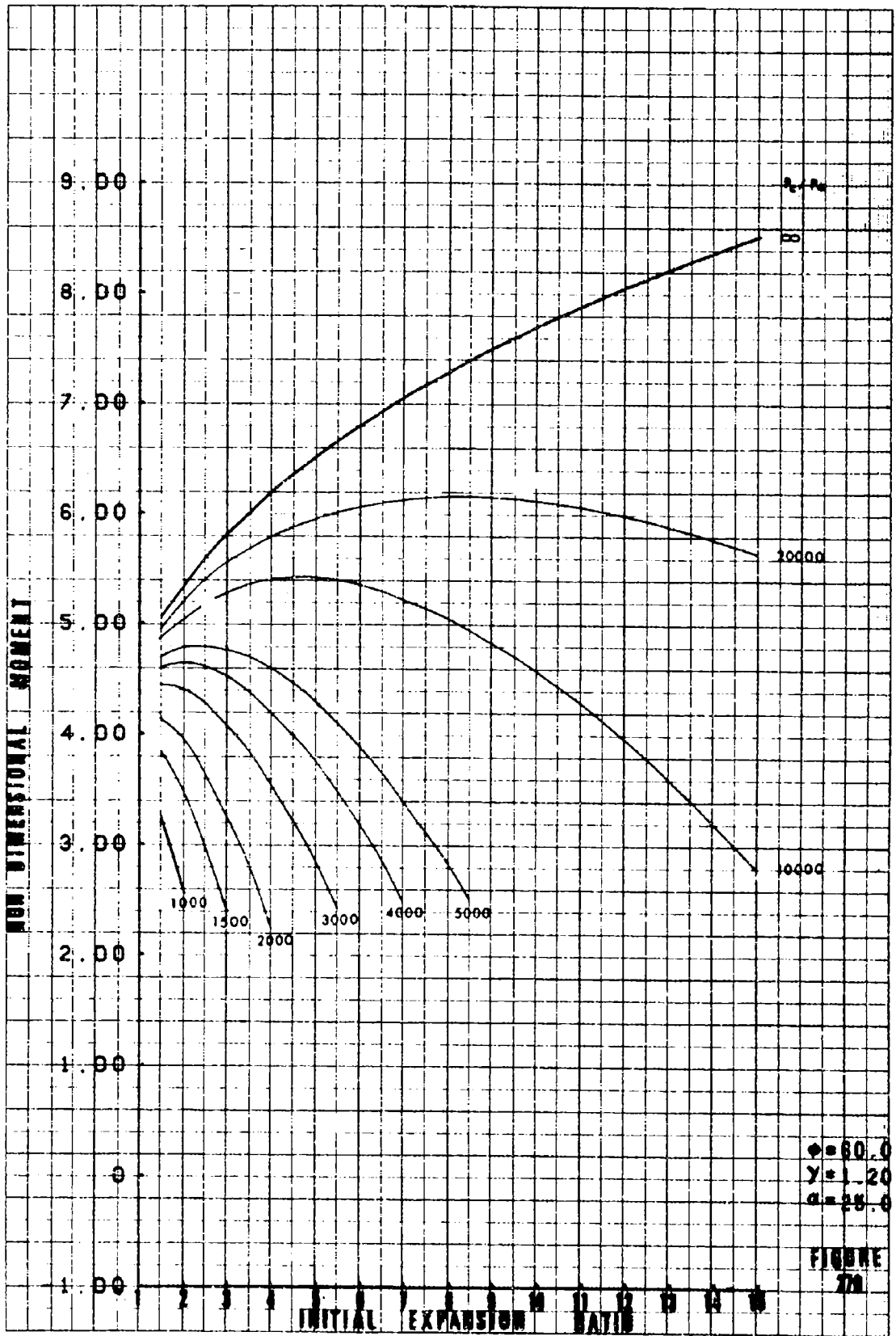


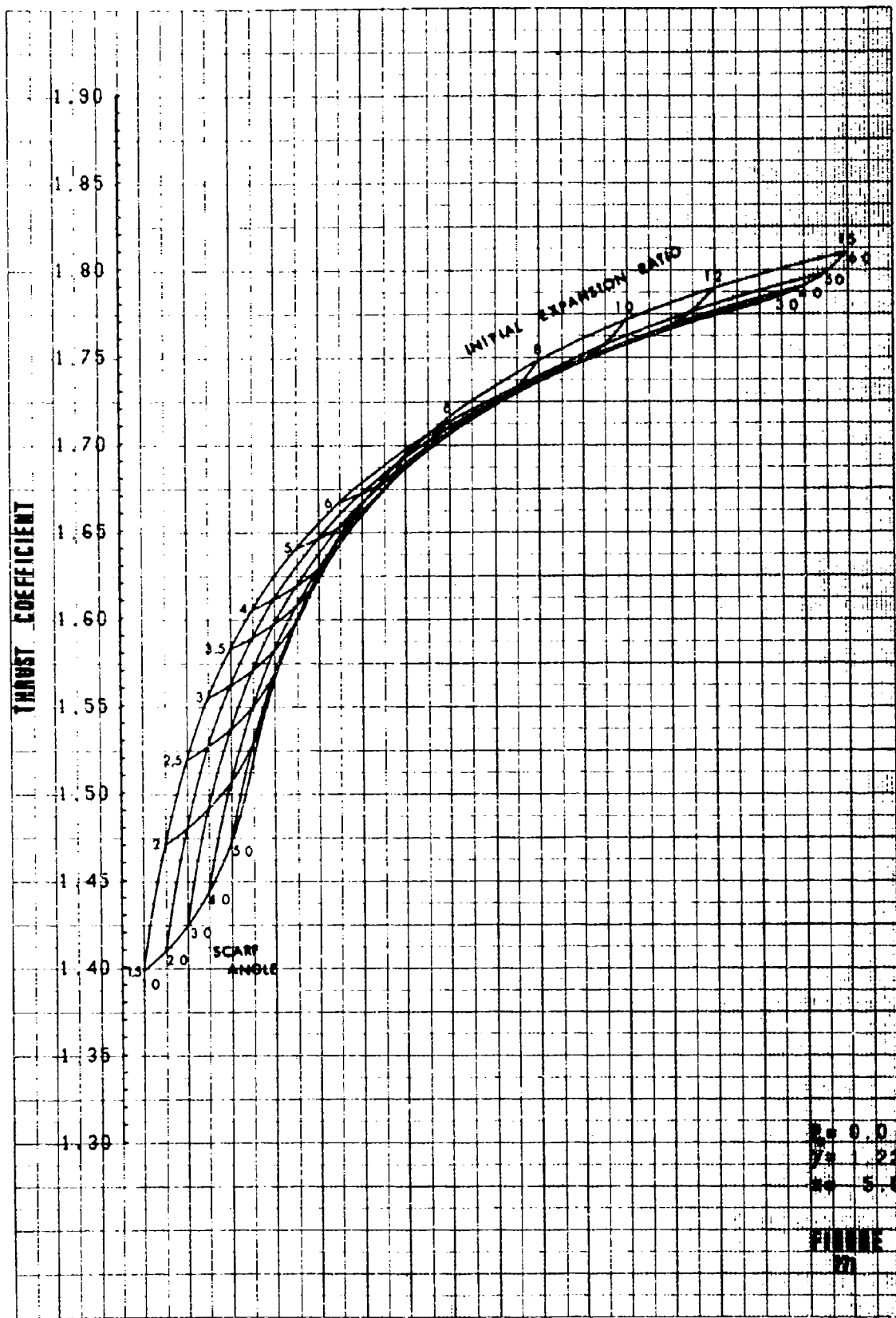




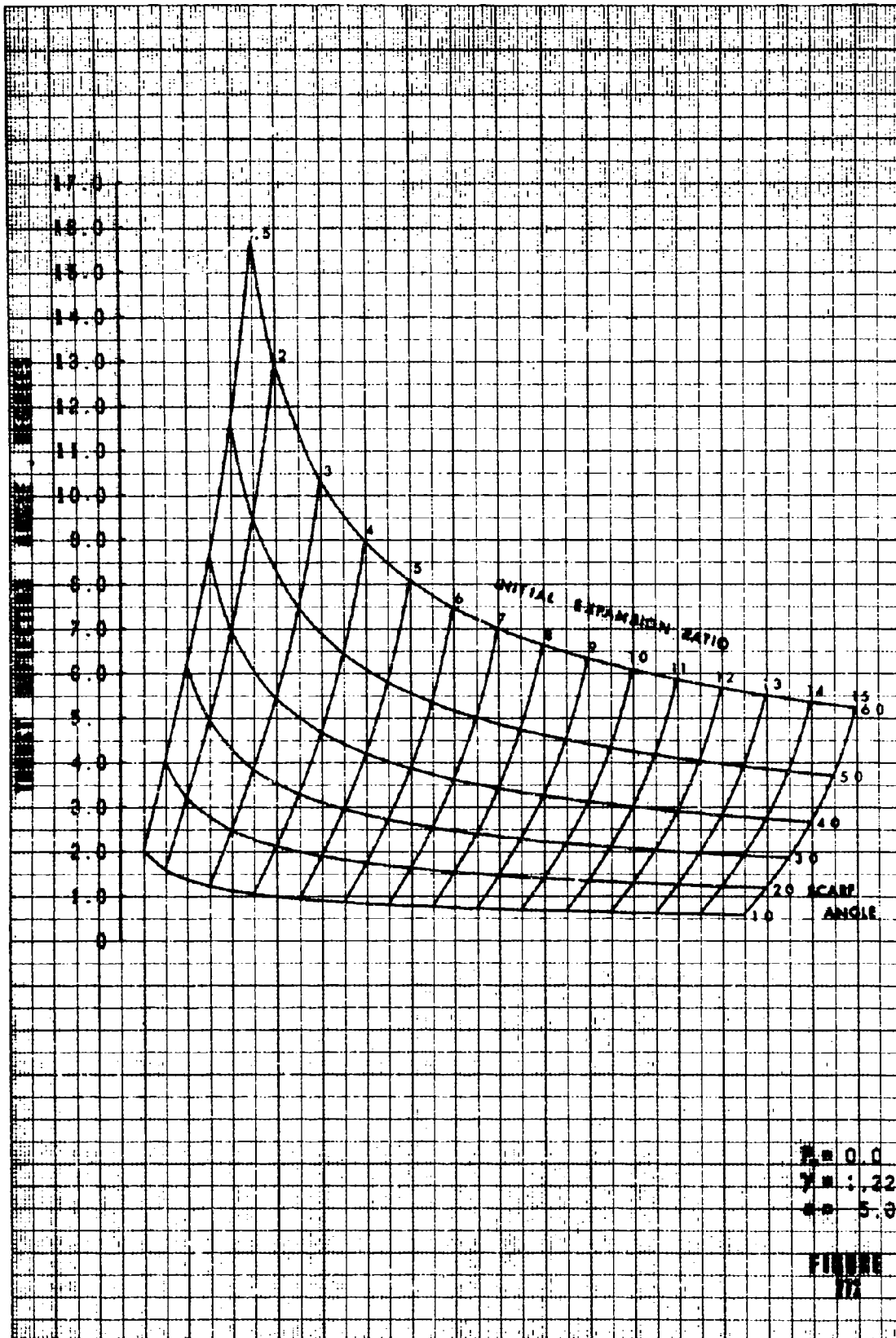






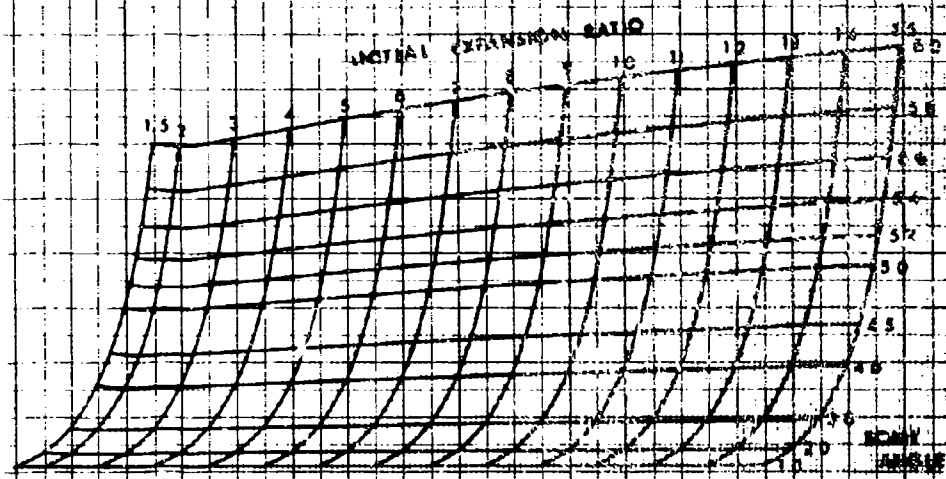






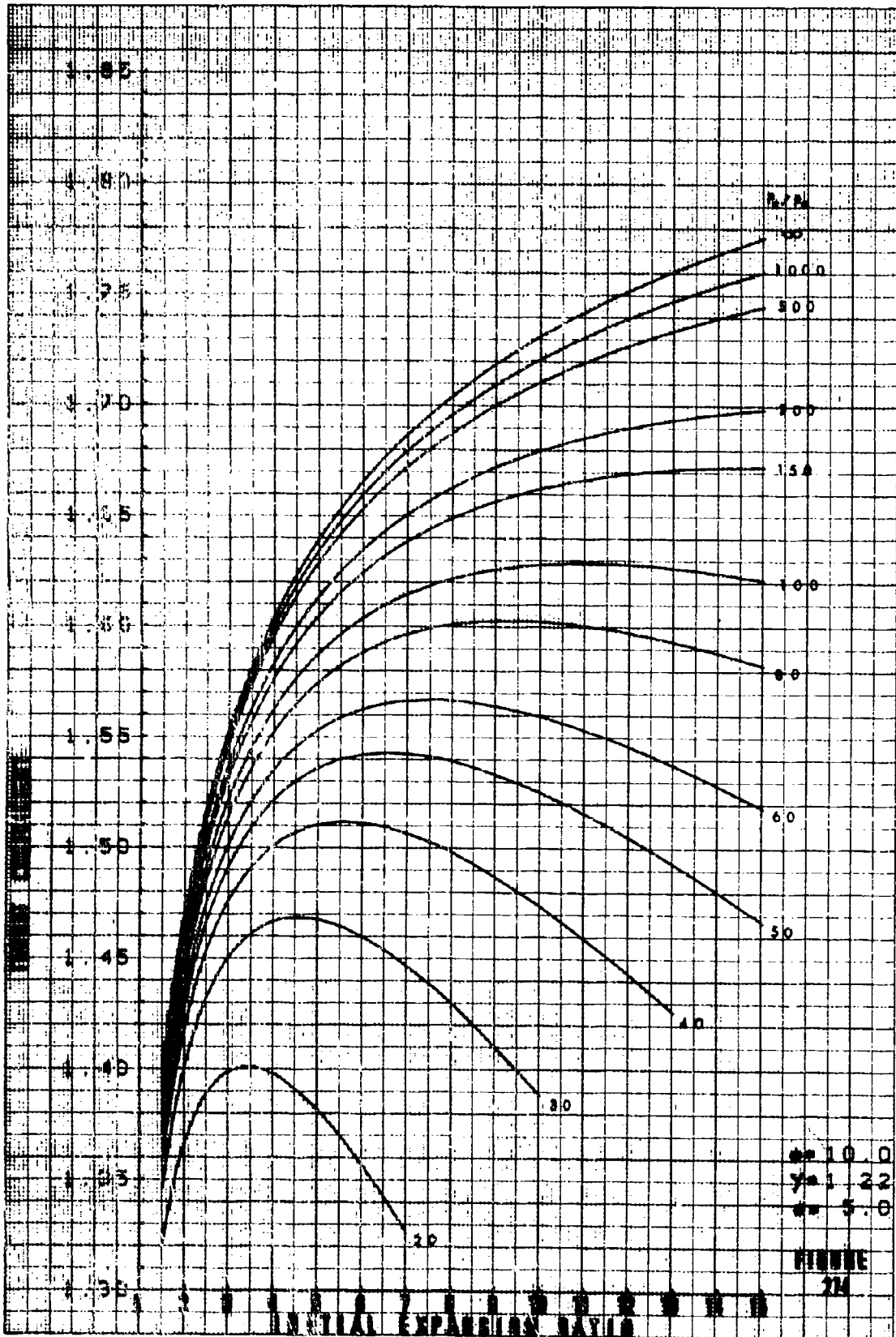
BI-DIMENSIONAL MOMENT

10.0  
9.0  
8.0  
7.0  
6.0  
5.0  
4.0  
3.0  
2.0  
1.0  
0



SCALE  
INCHES

FIGURE  
10



$\mu = 10.0$   
 $\gamma = 1.22$   
 $\alpha = 5.0$

FIGURE 24

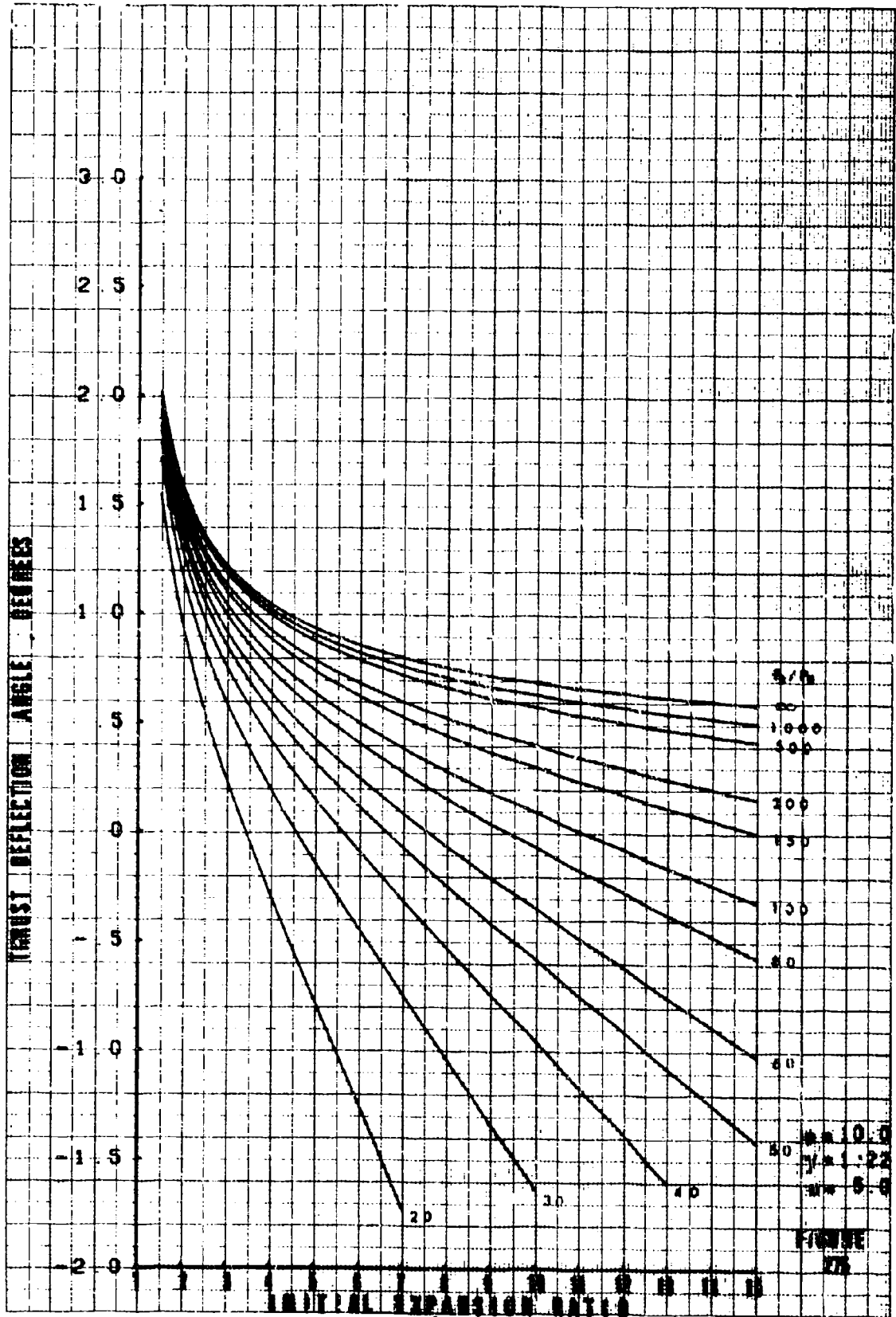
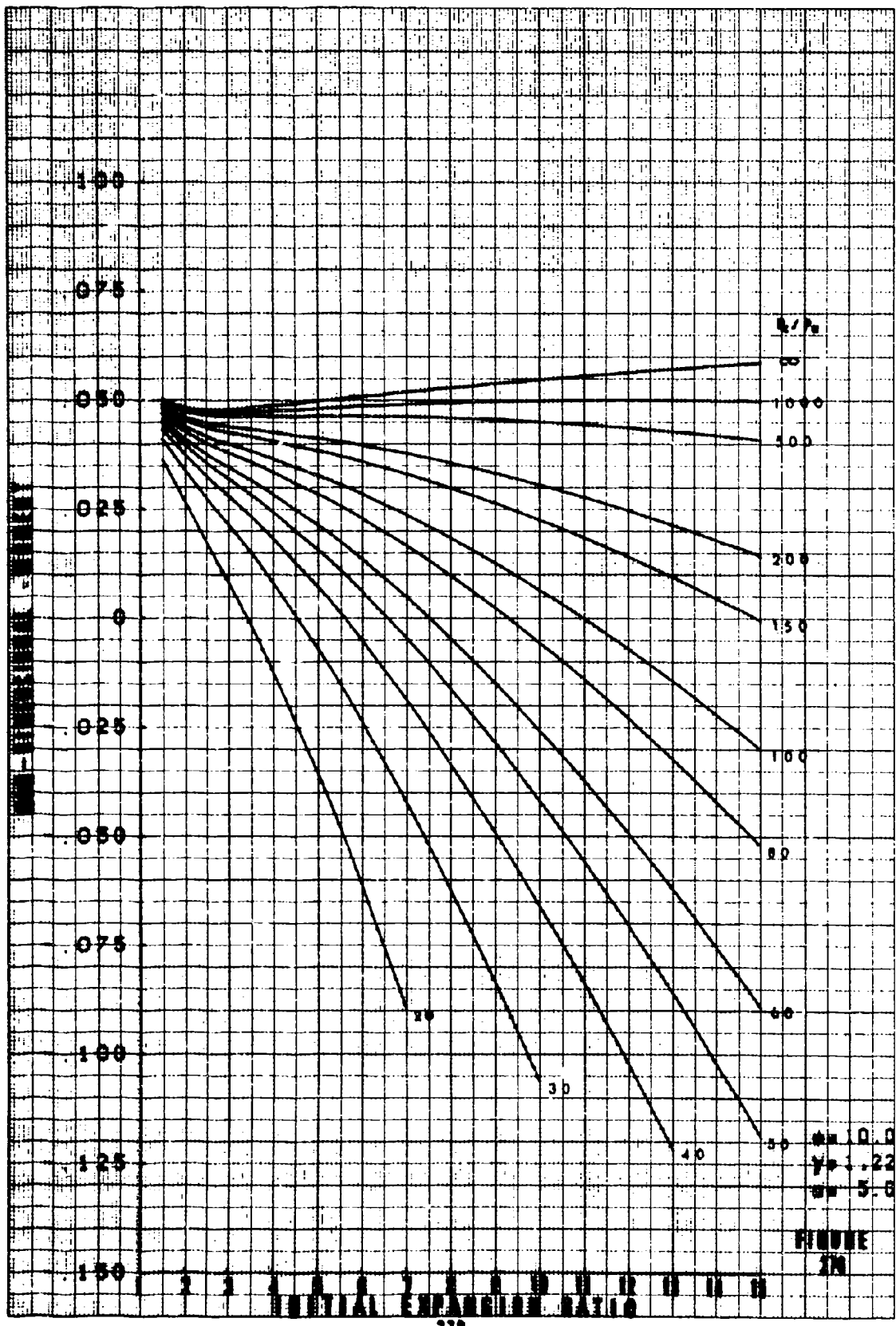
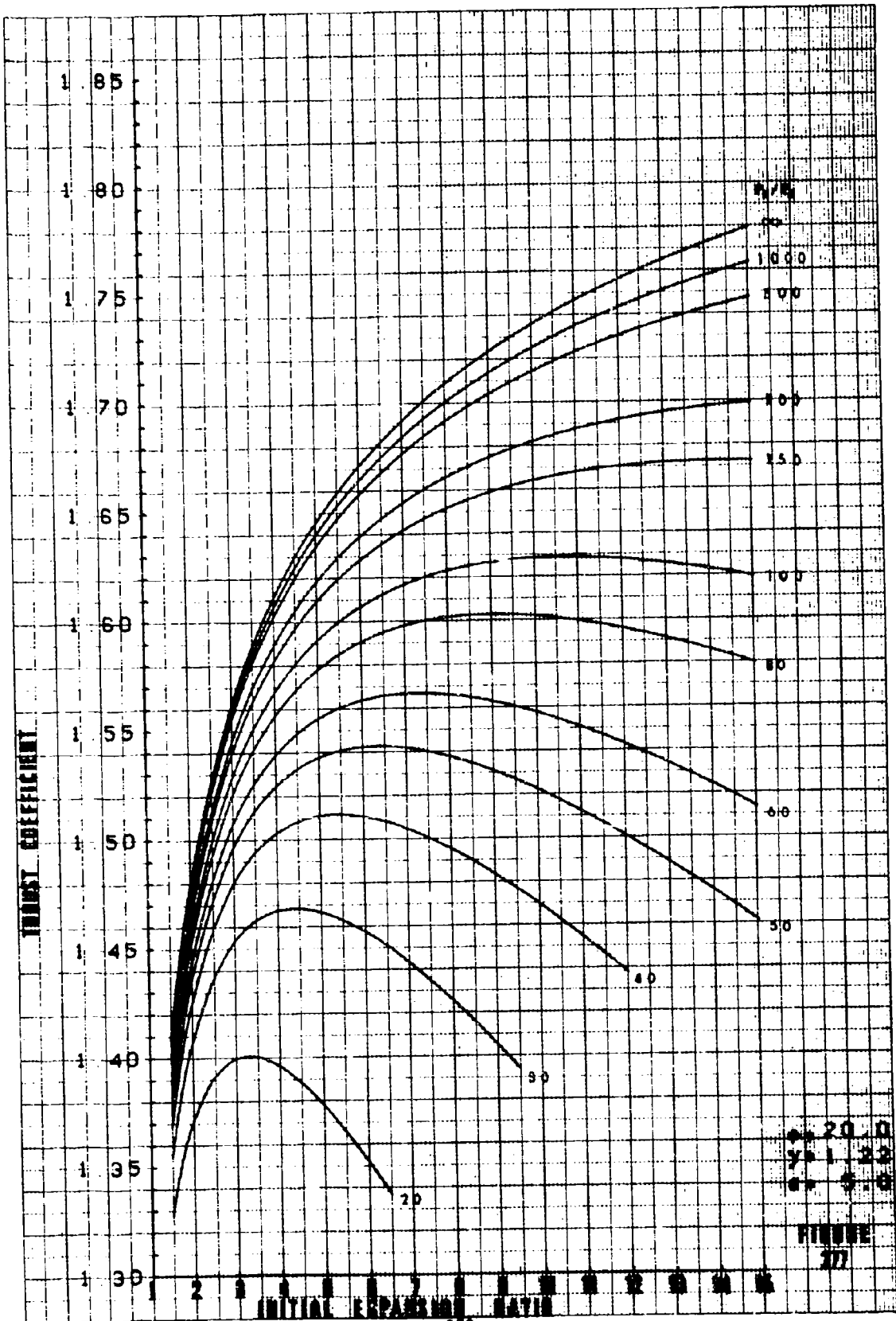


FIGURE 775





$\gamma = 1.4$   
 $\theta = 90^\circ$

FIGURE 277

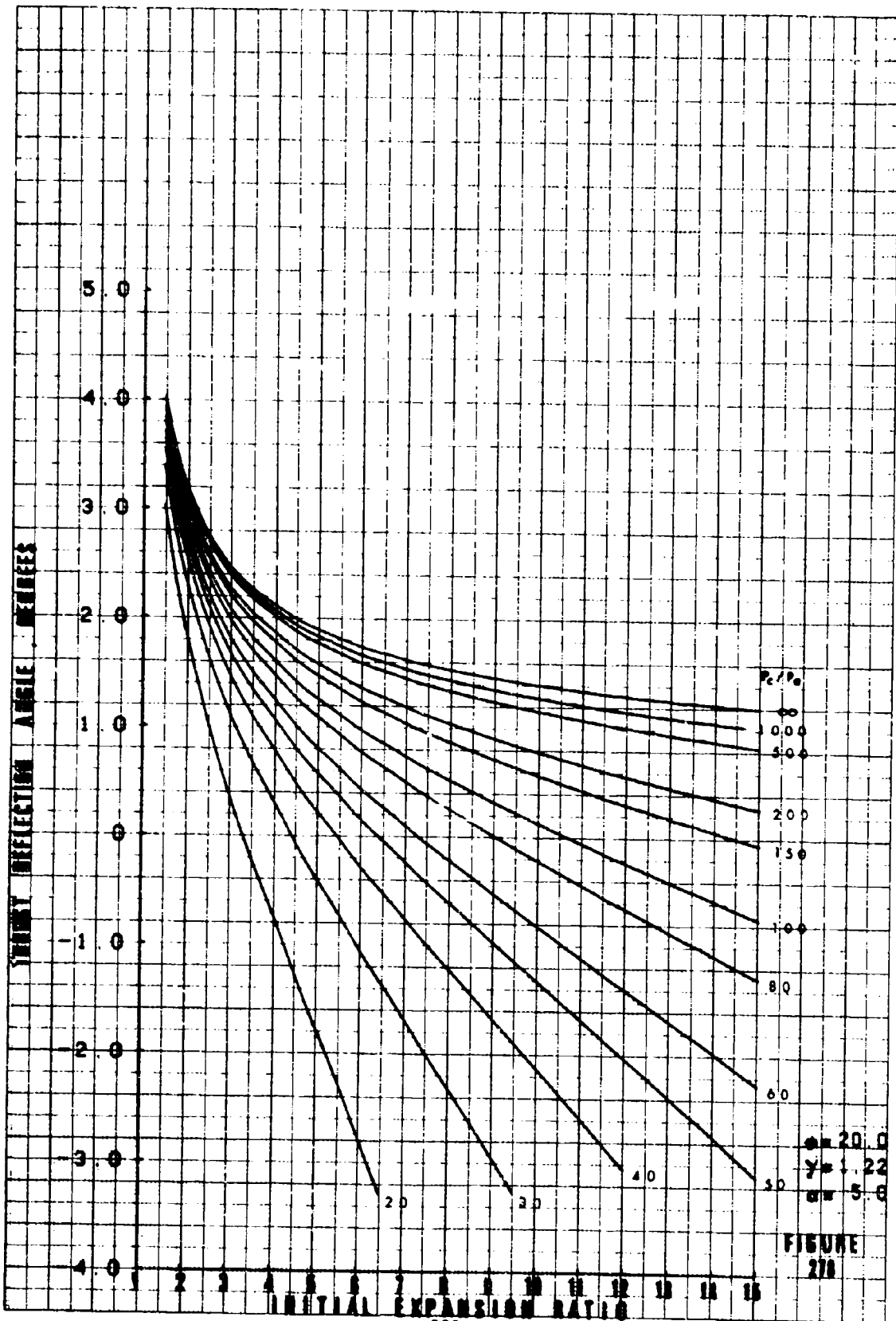
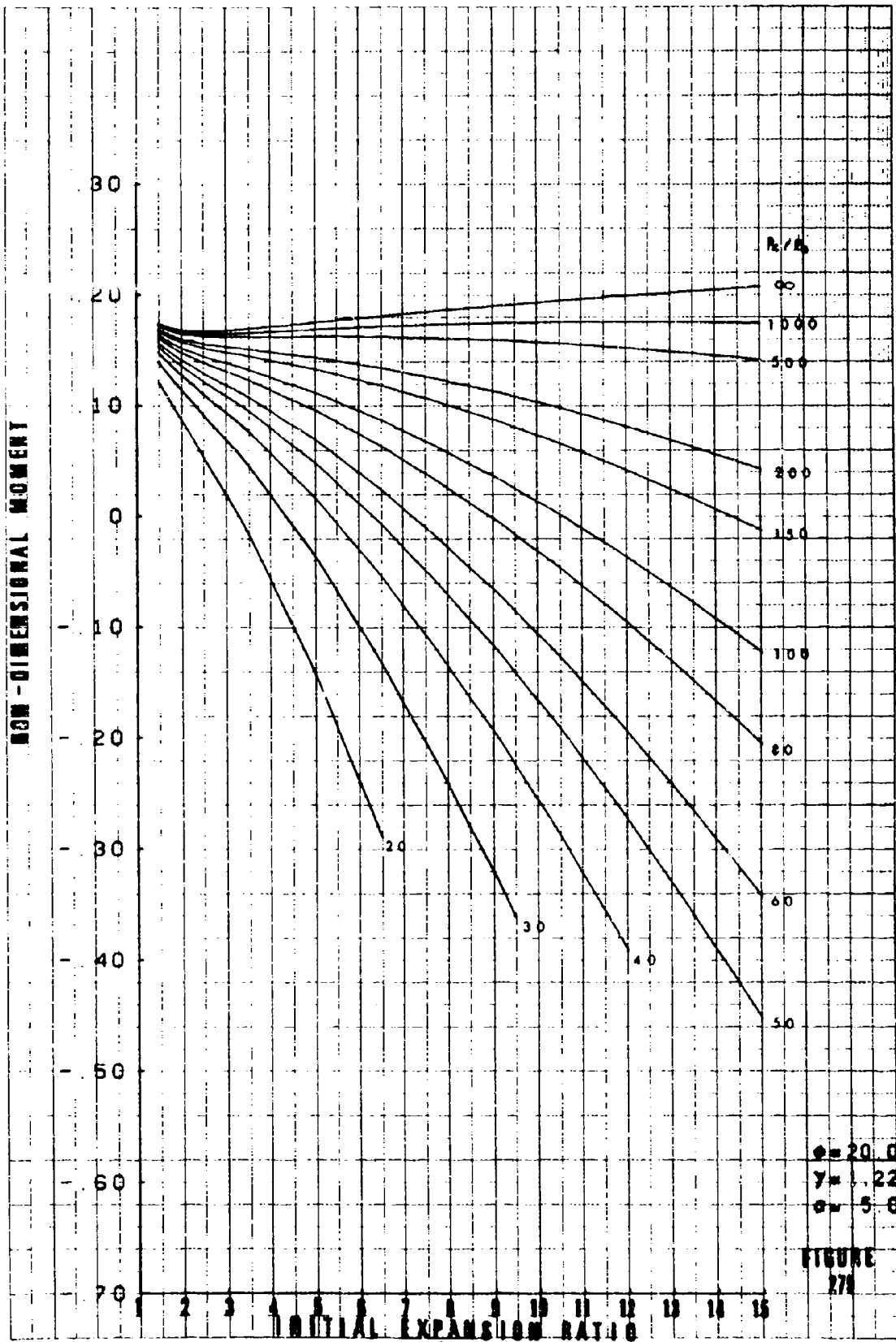
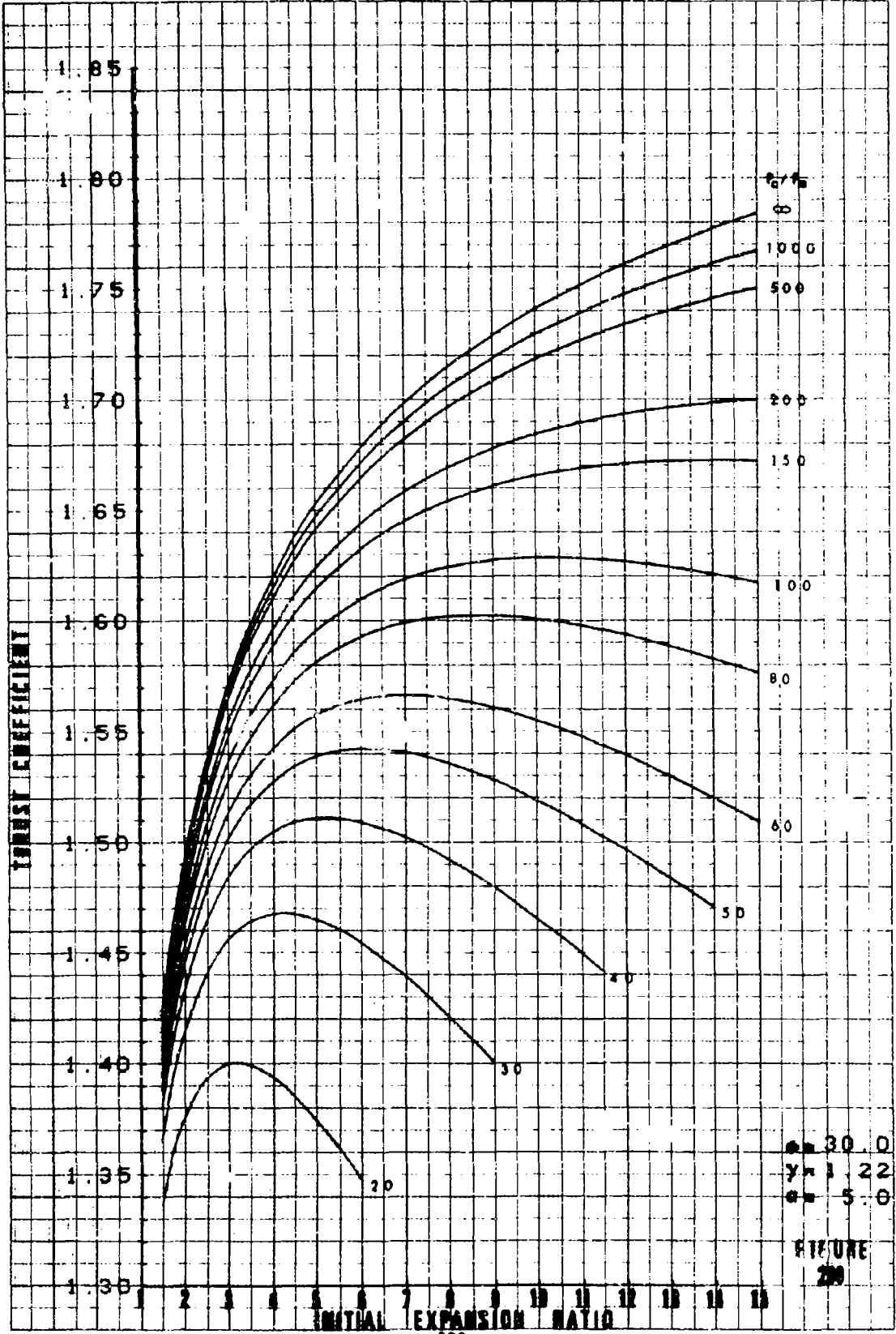


FIGURE 270







30.0  
 1.22  
 5.0

FIGURE 200

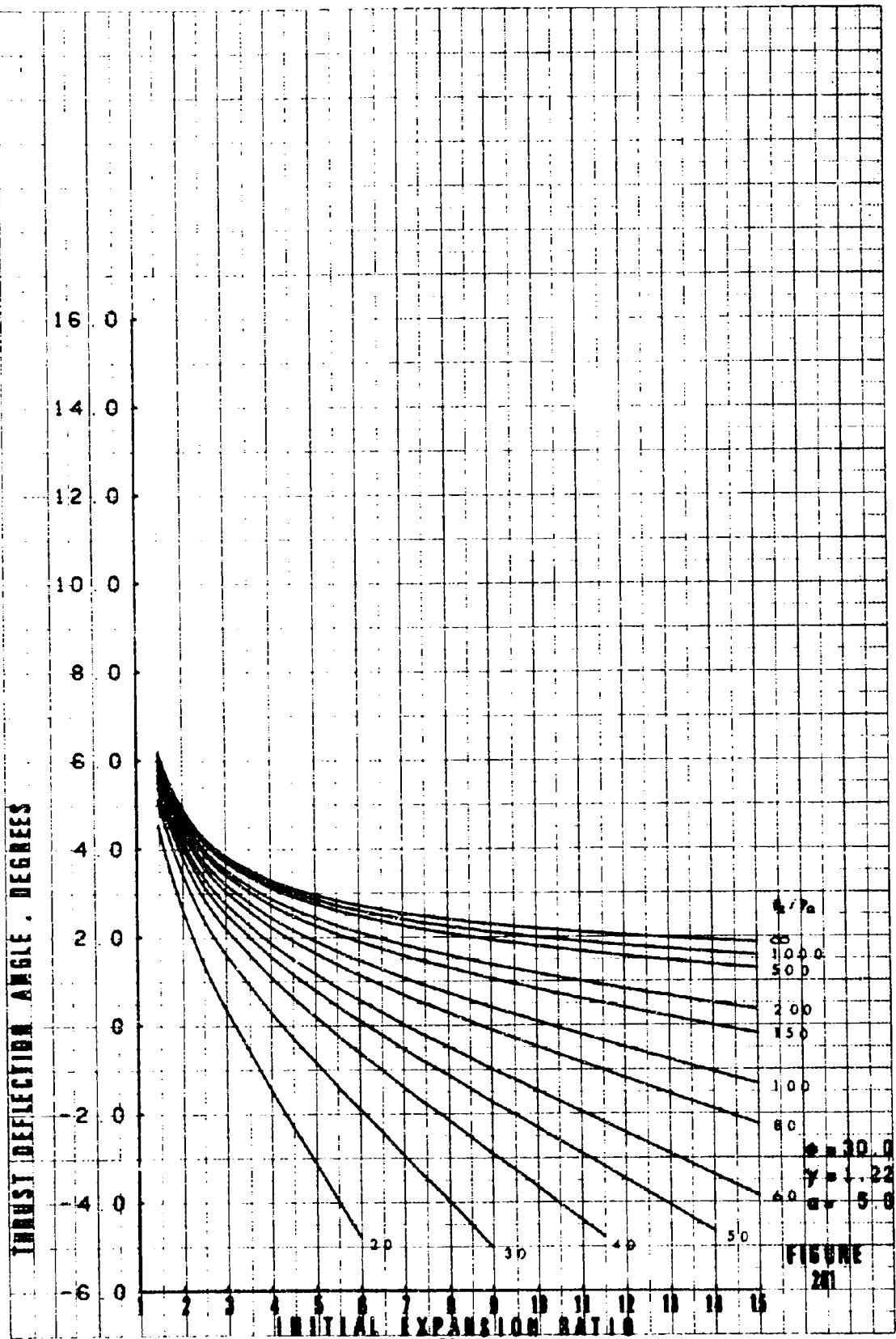
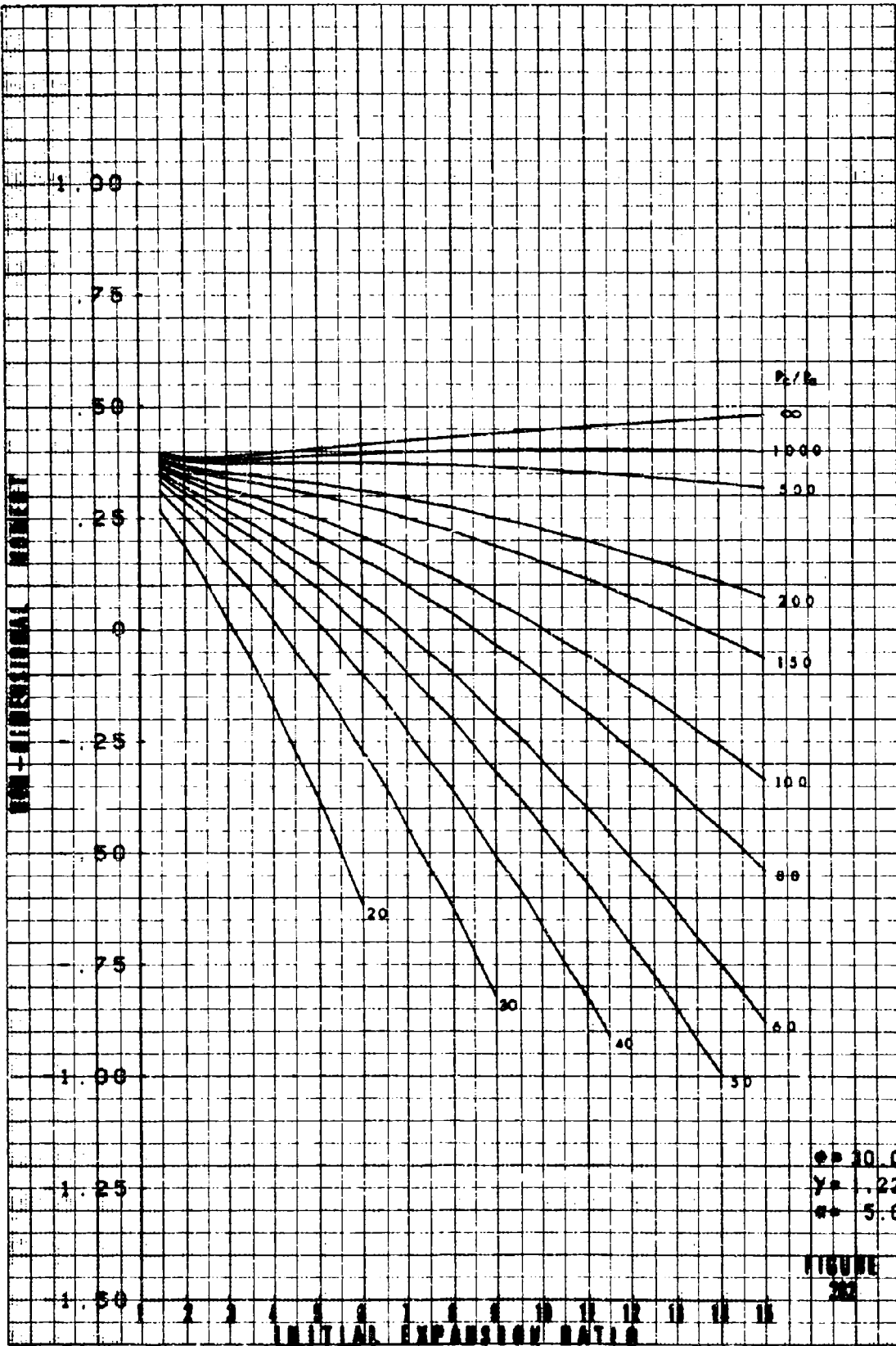
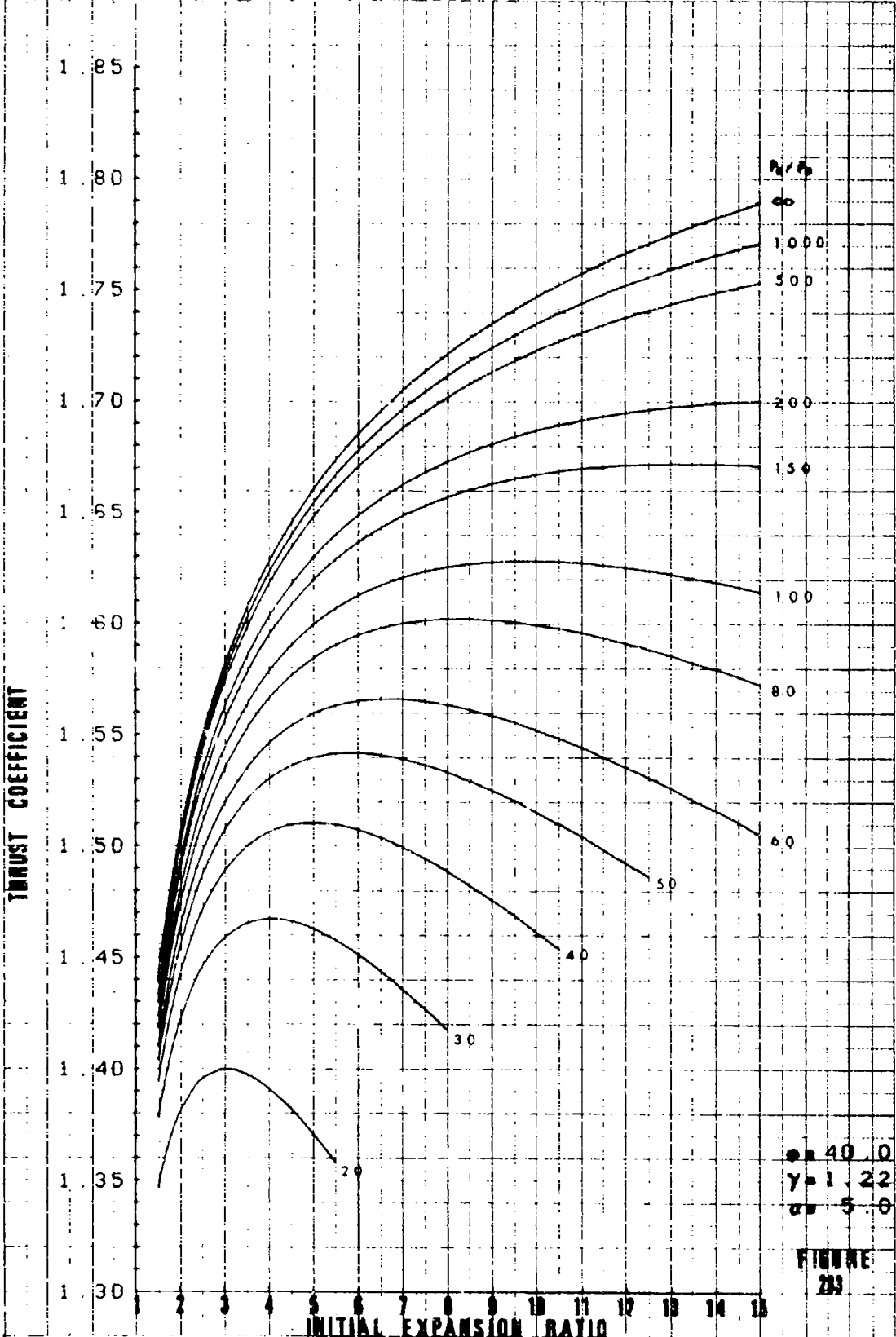


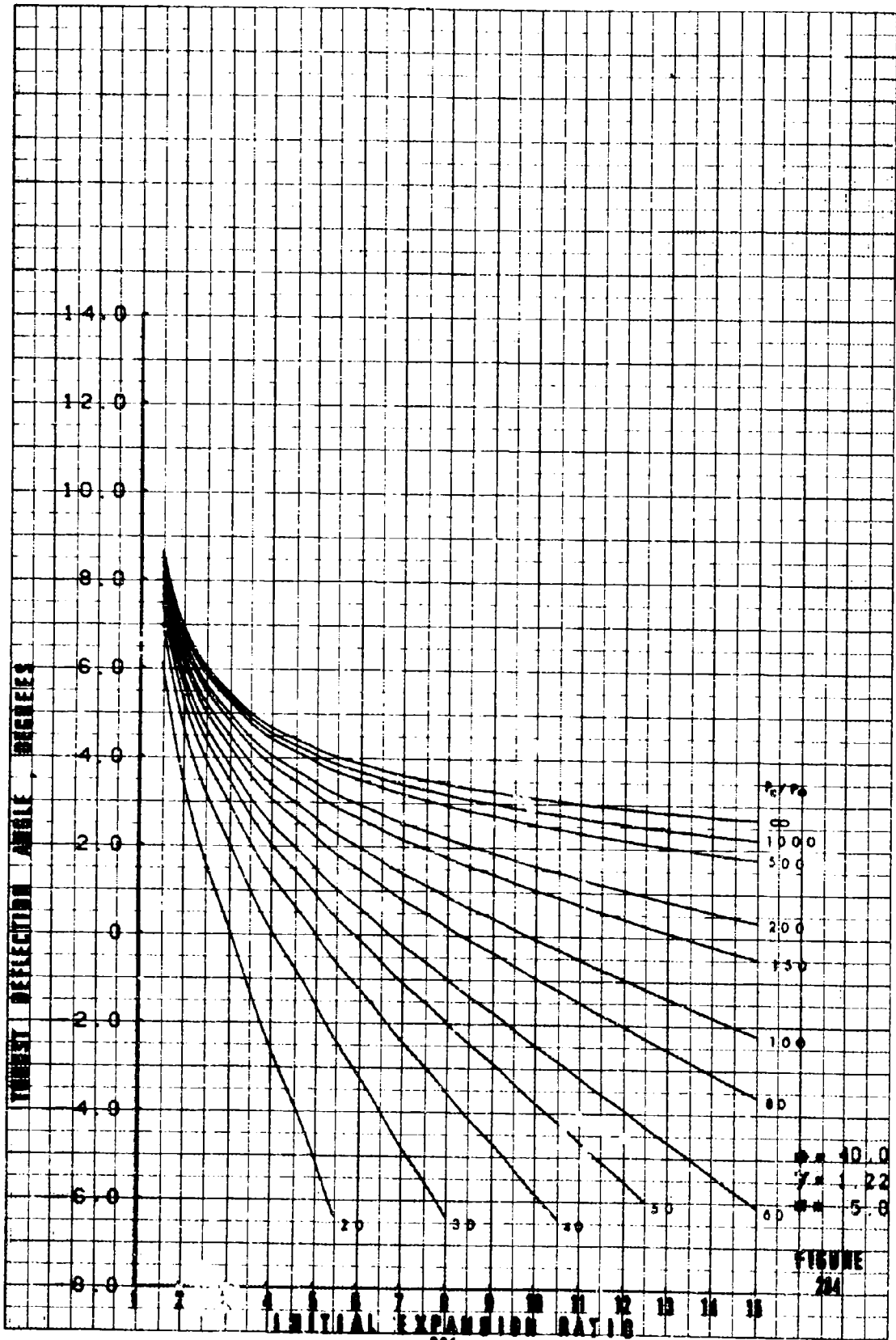
FIGURE 201

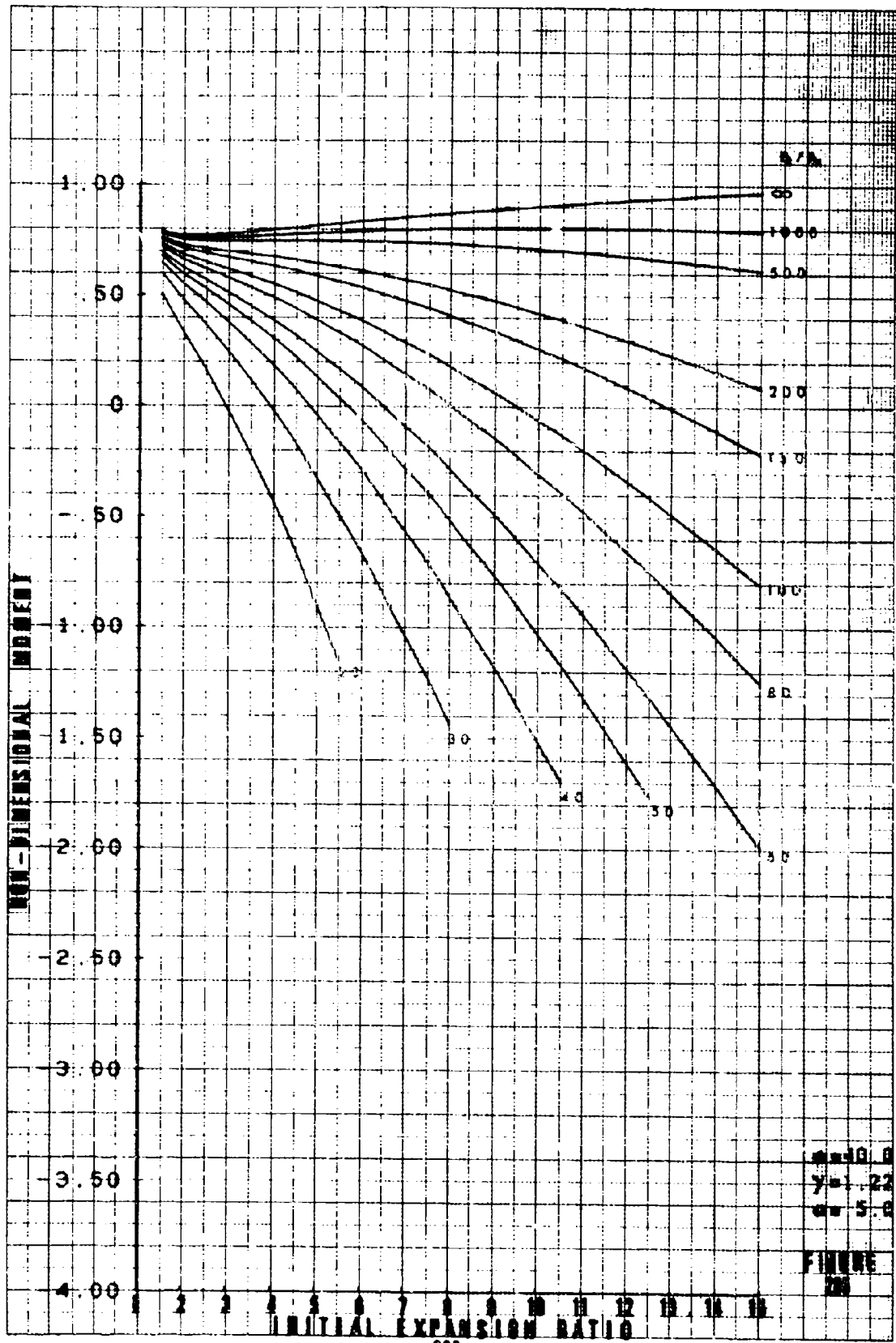


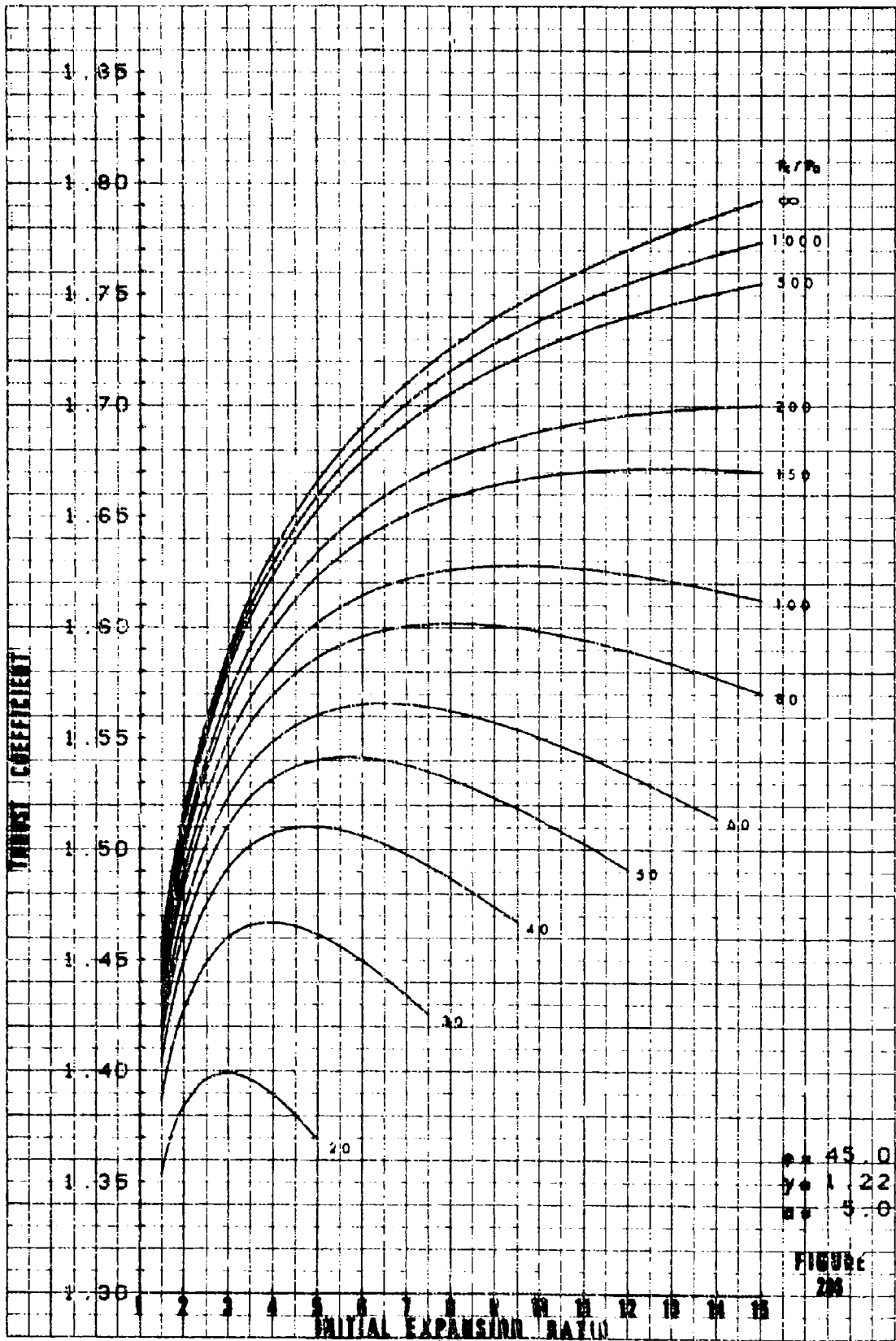


$\gamma = 1.22$   
 $\alpha = 5.0$

FIGURE 283







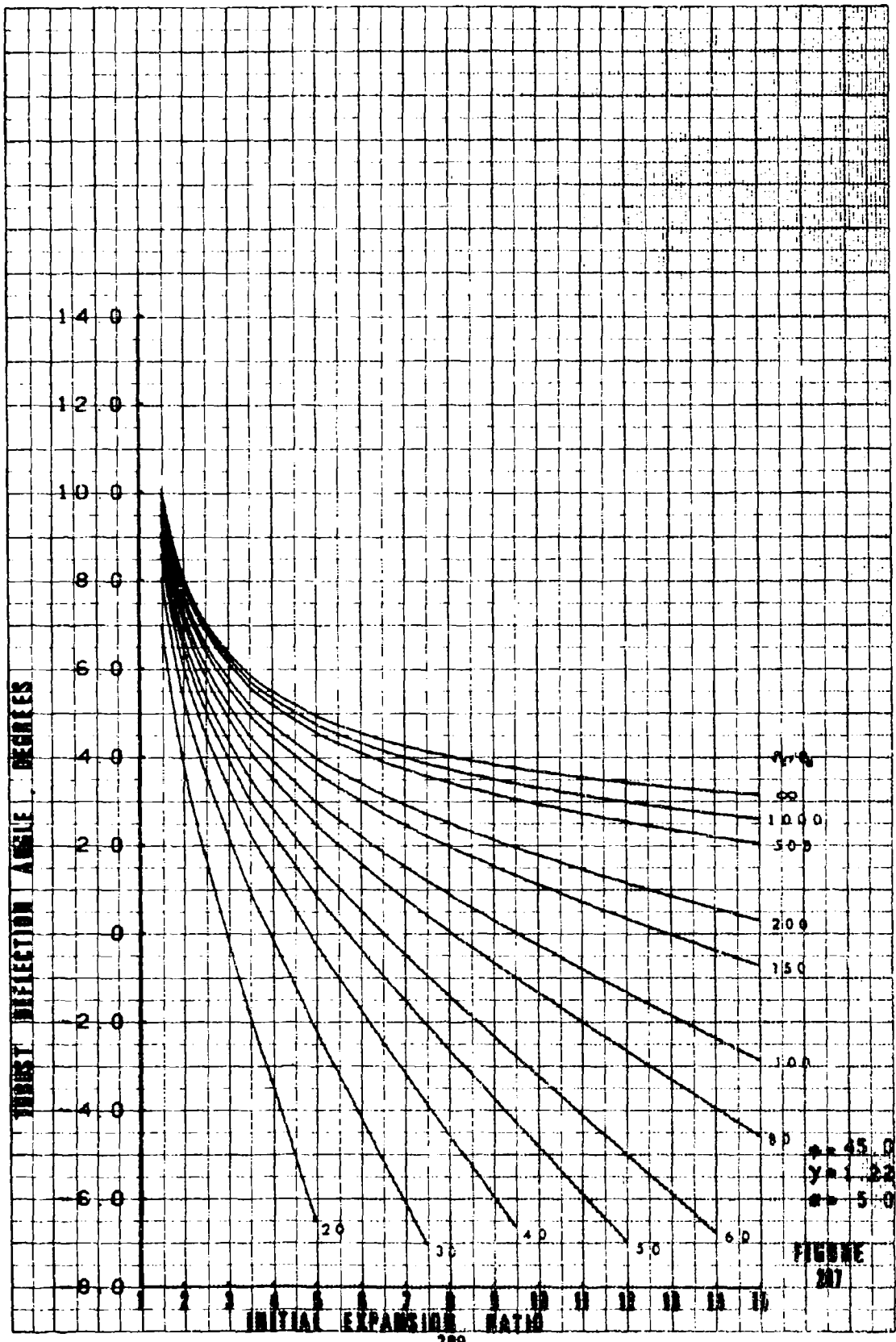
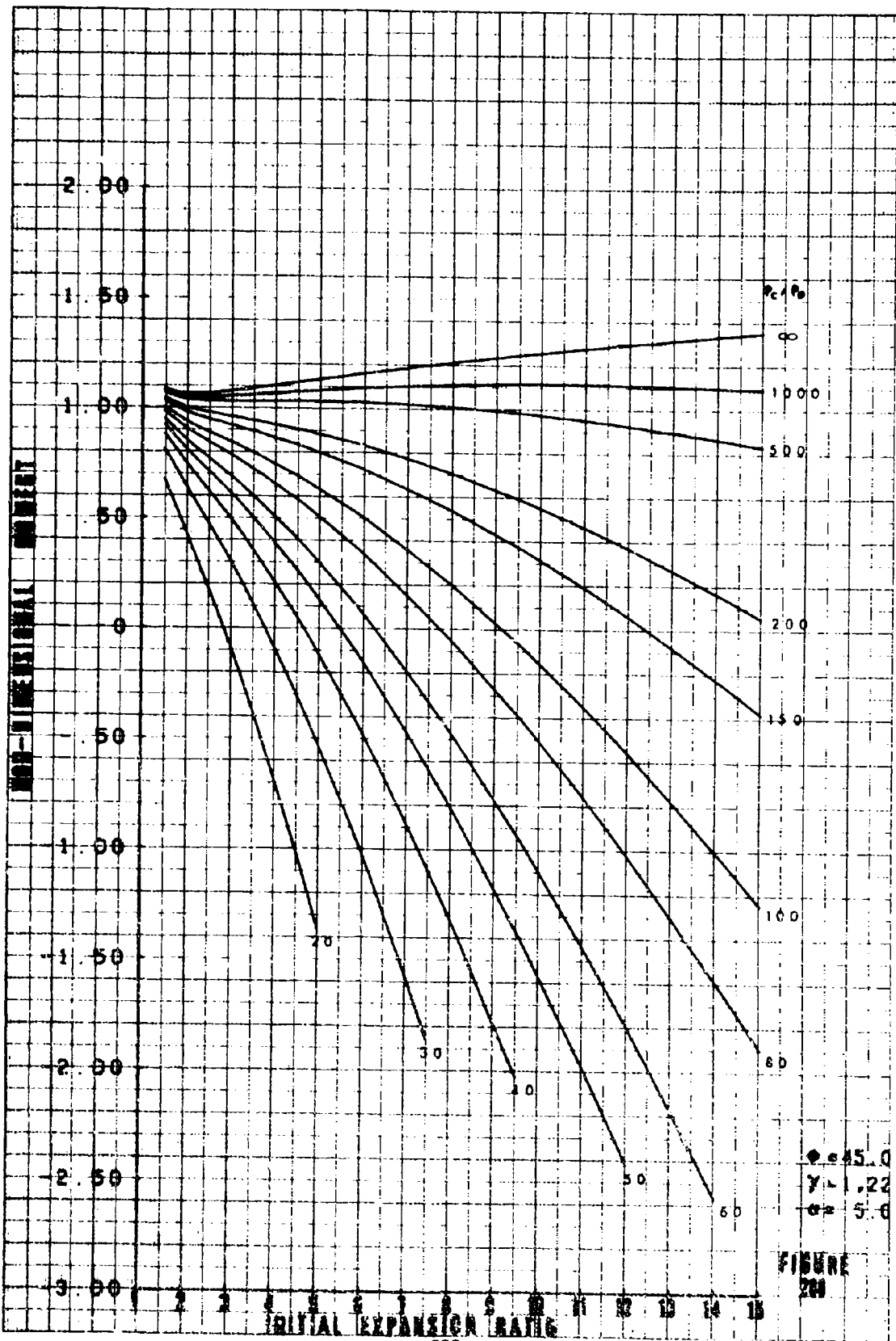


FIGURE 207





$\phi = 45.0$   
 $\gamma = 1.22$   
 $\sigma = 5.6$

FIGURE 200

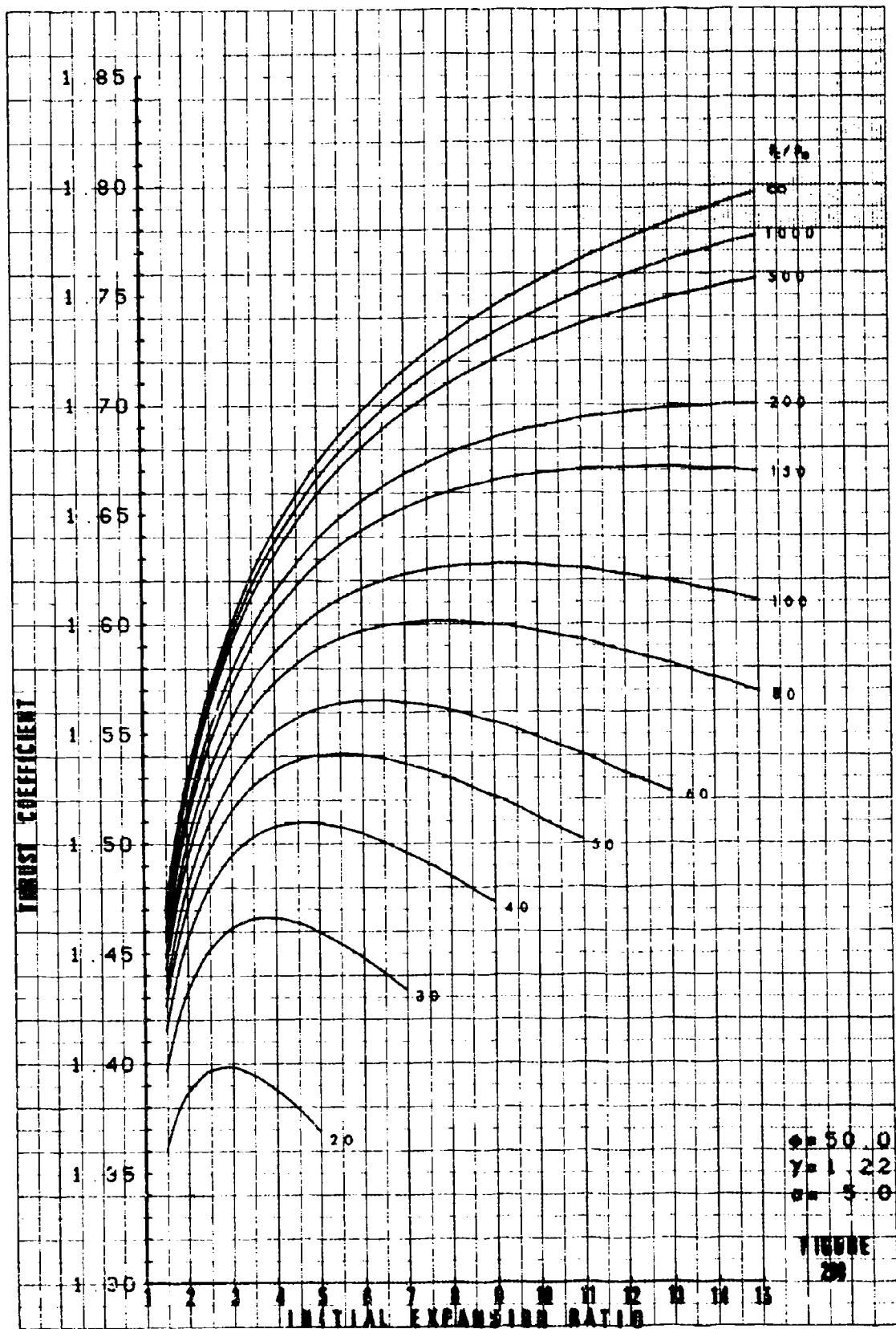
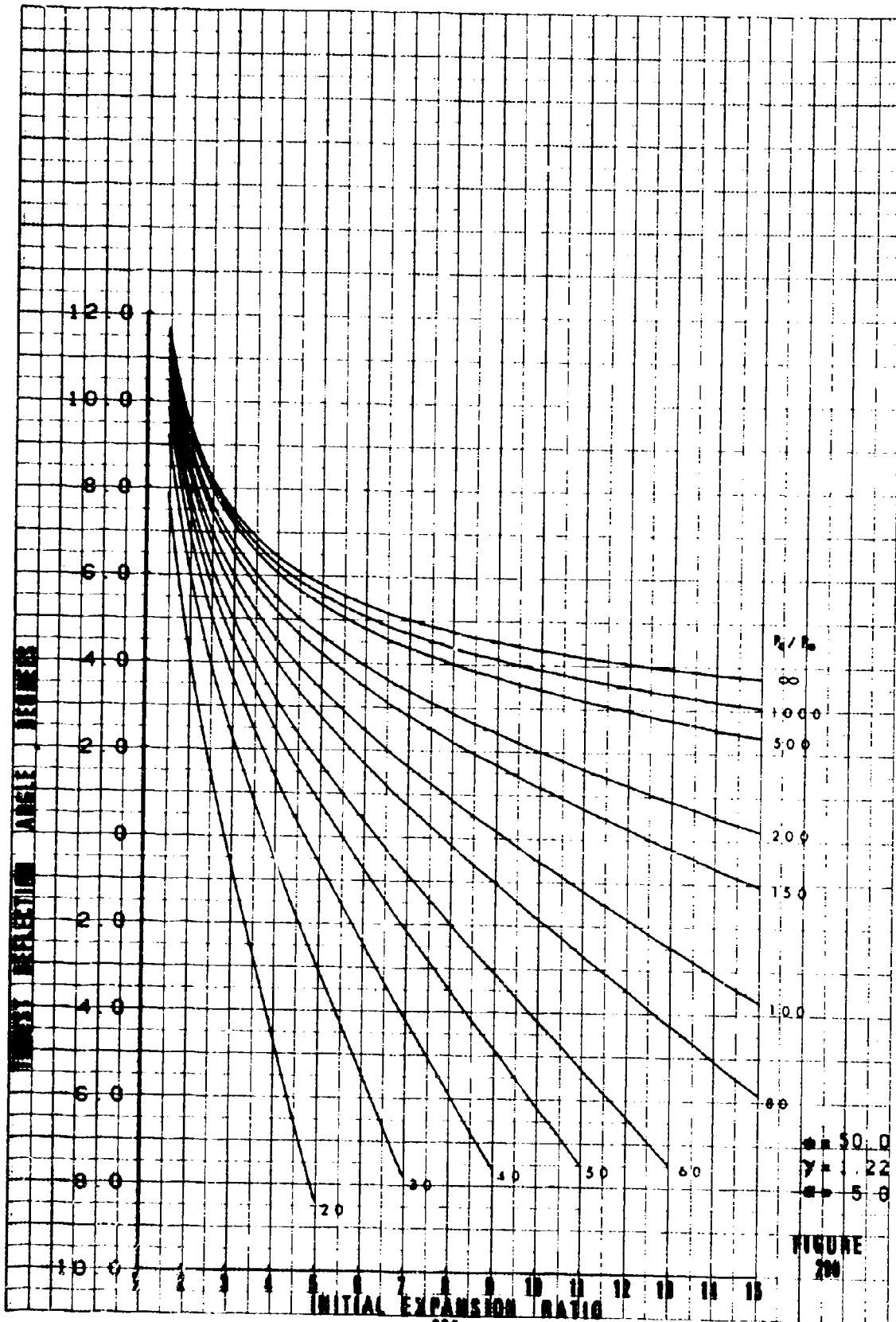
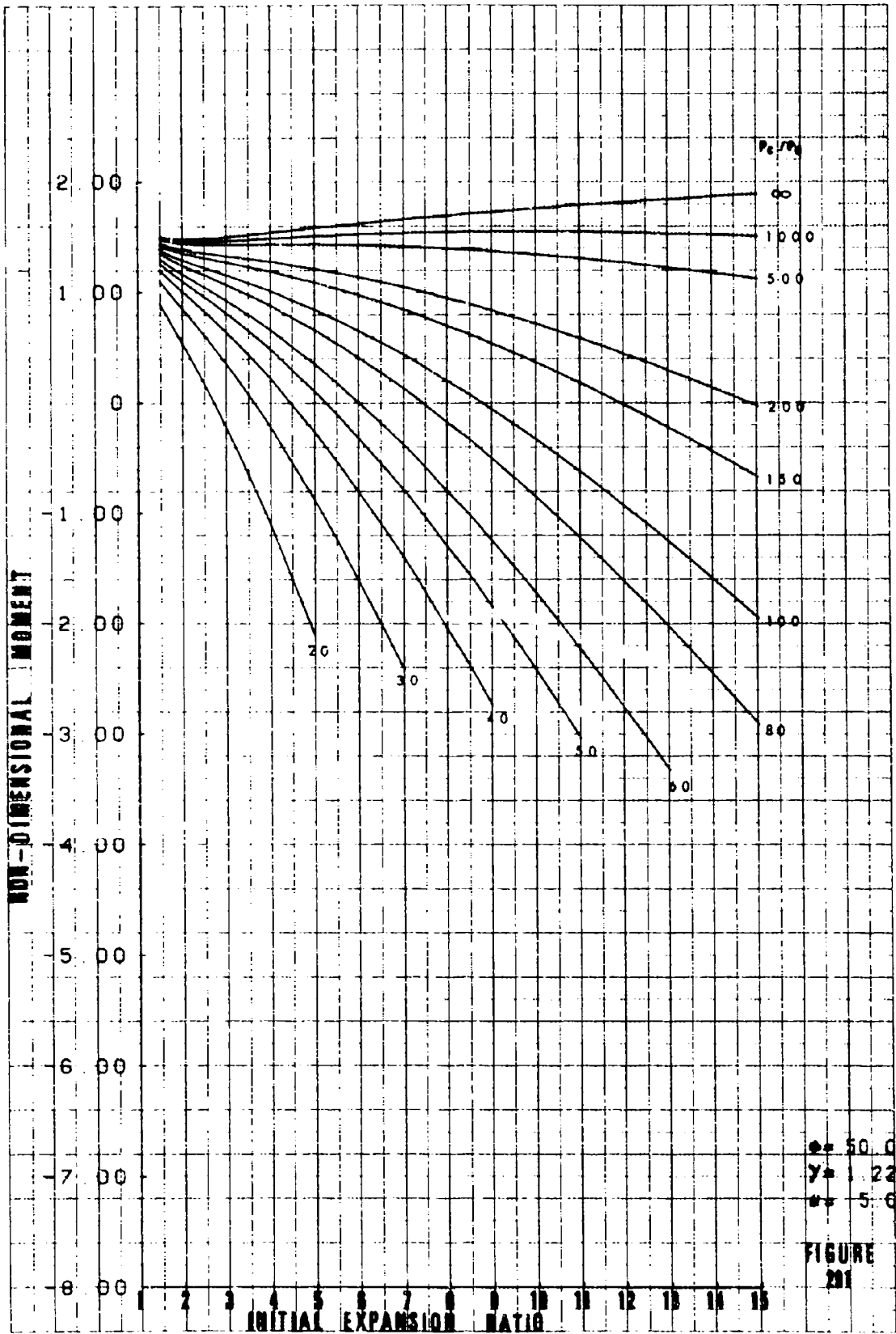
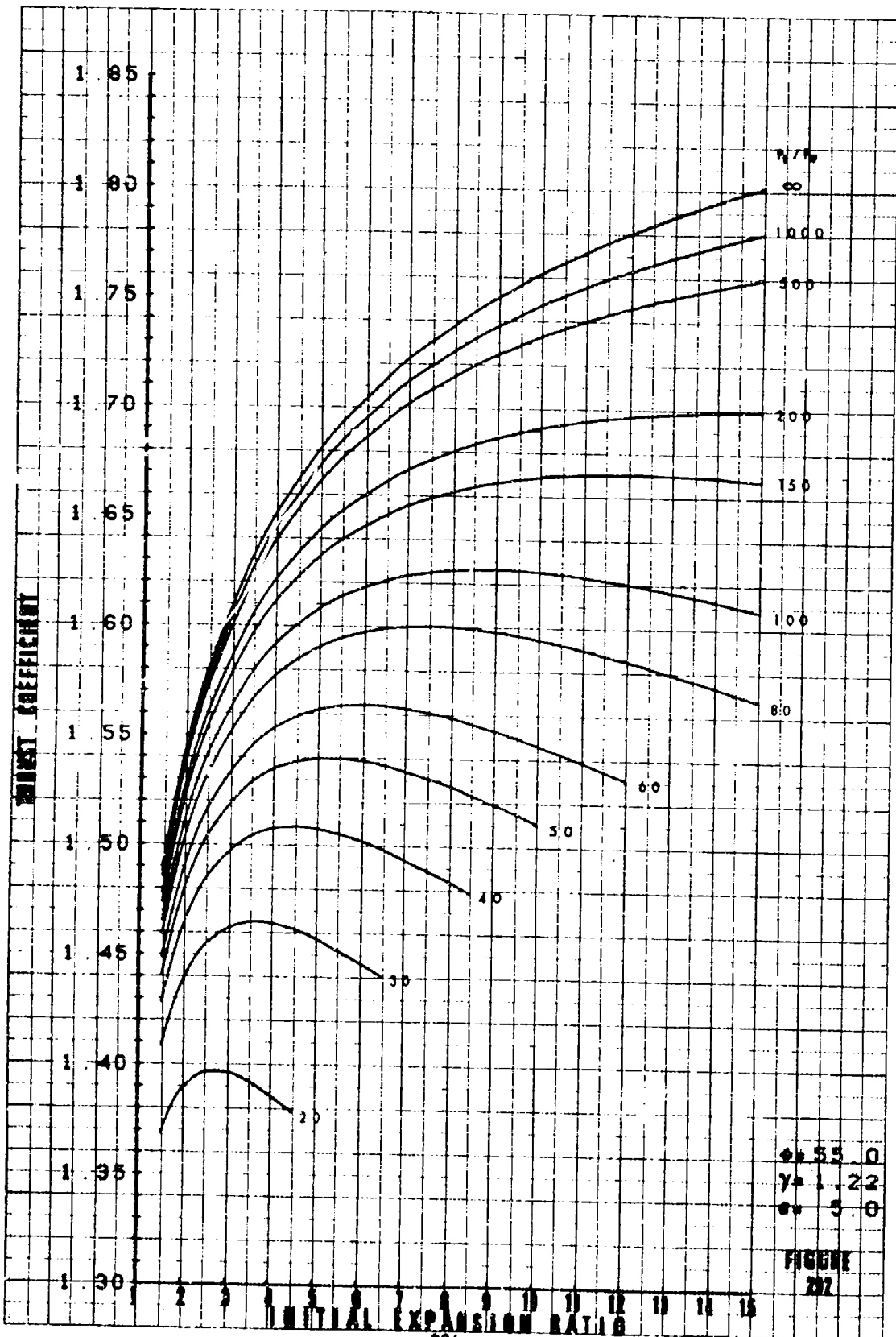


FIGURE 299







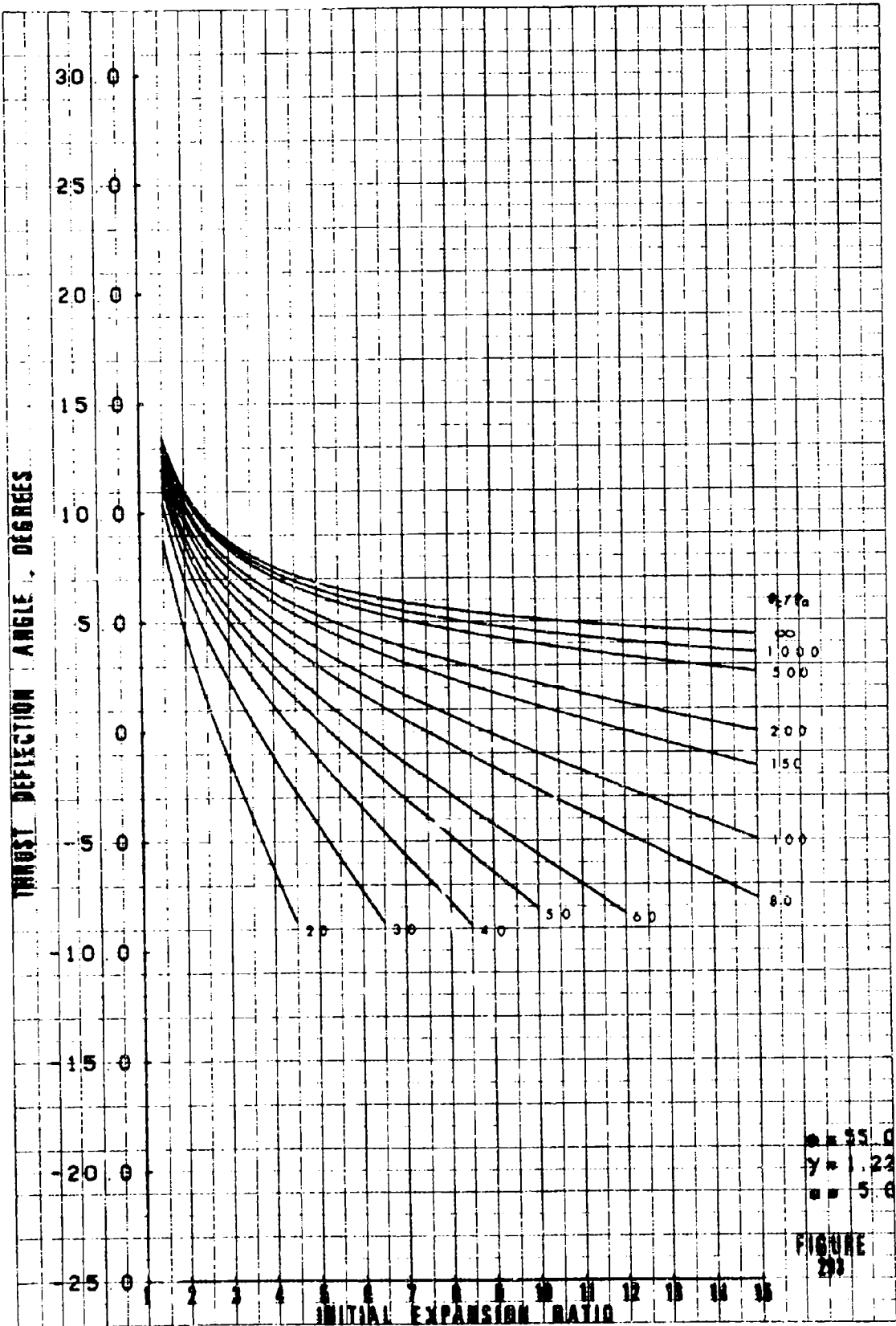
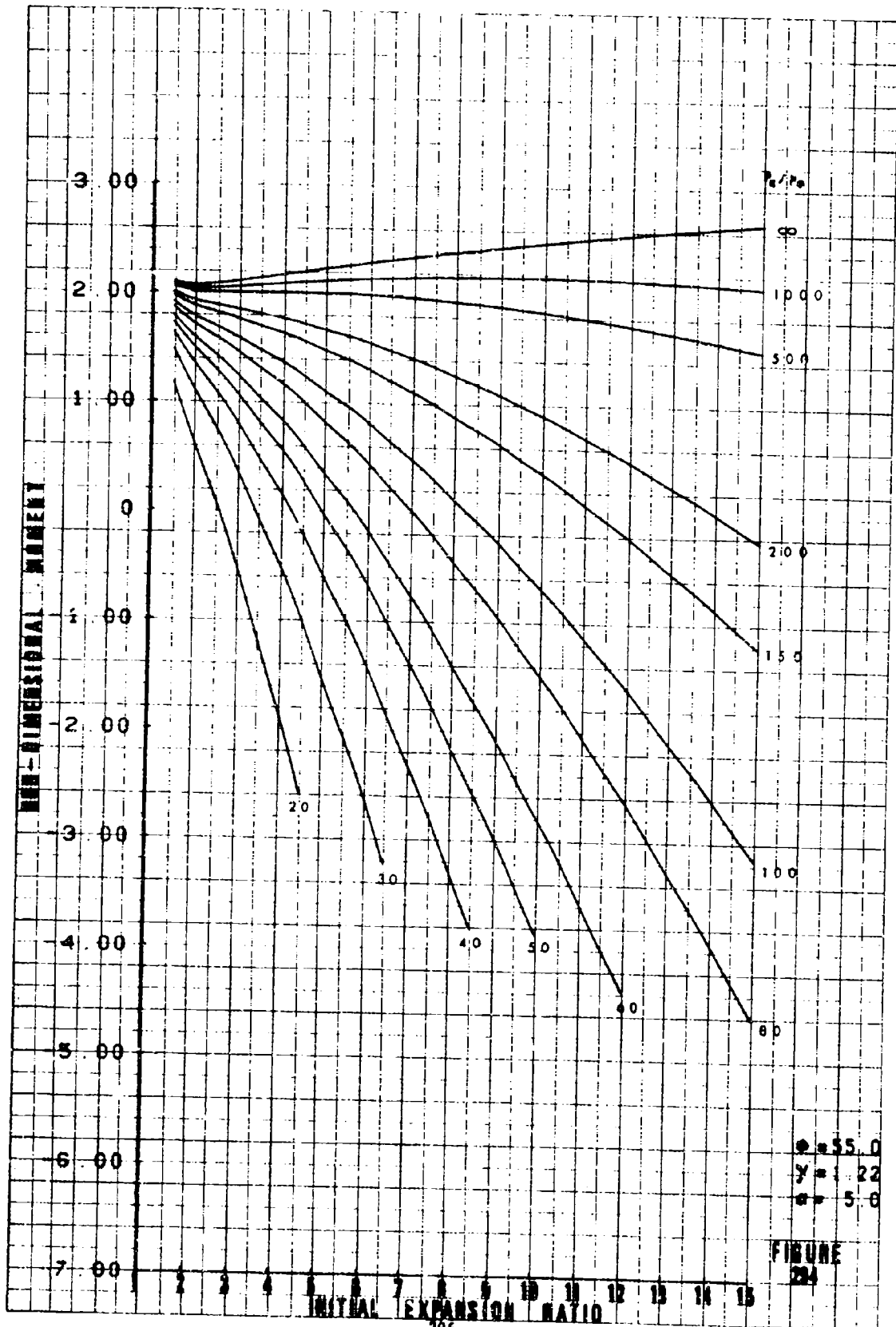
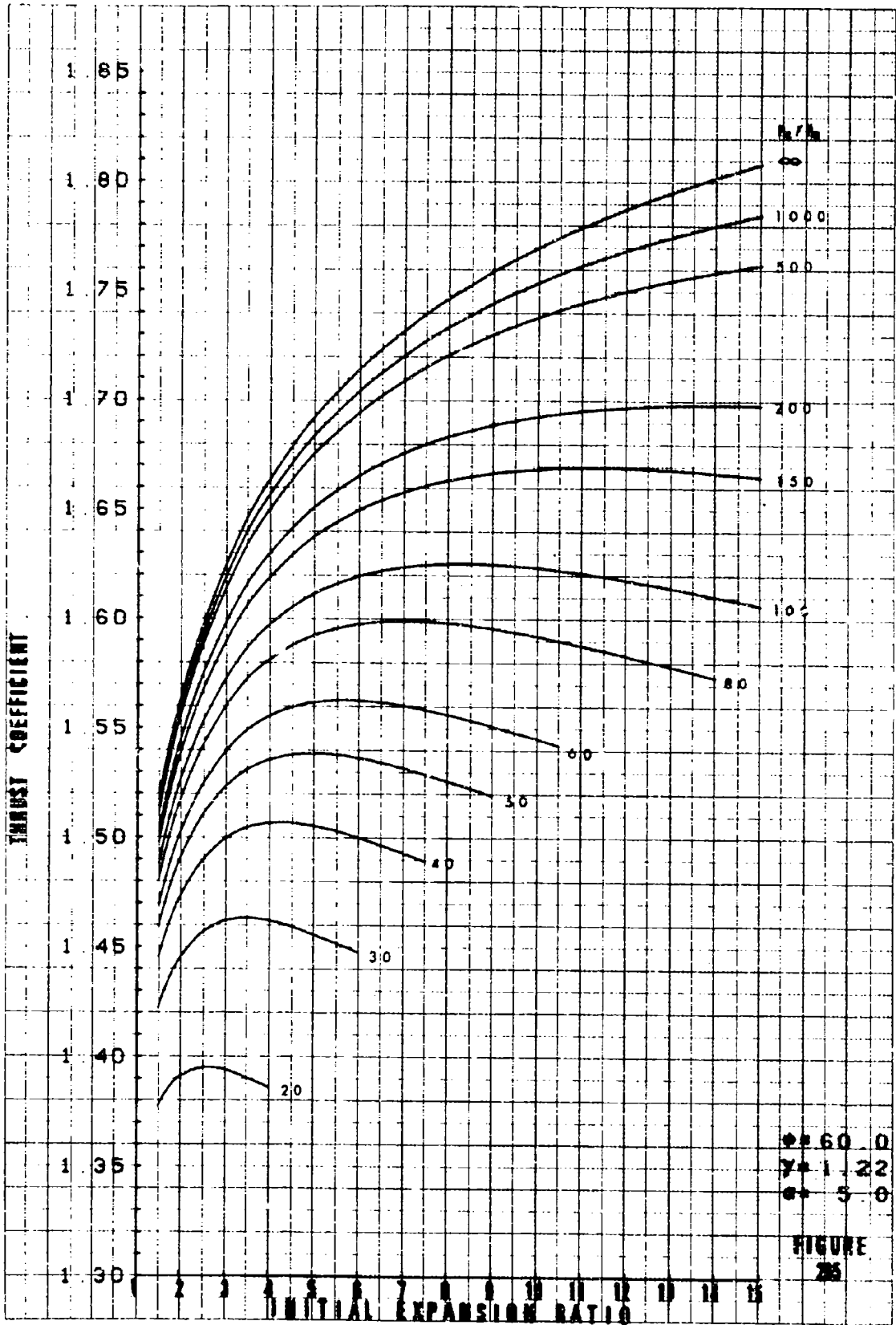


FIGURE 293





◆ 60.0  
 \* 1.22  
 ● 5.0

FIGURE 25



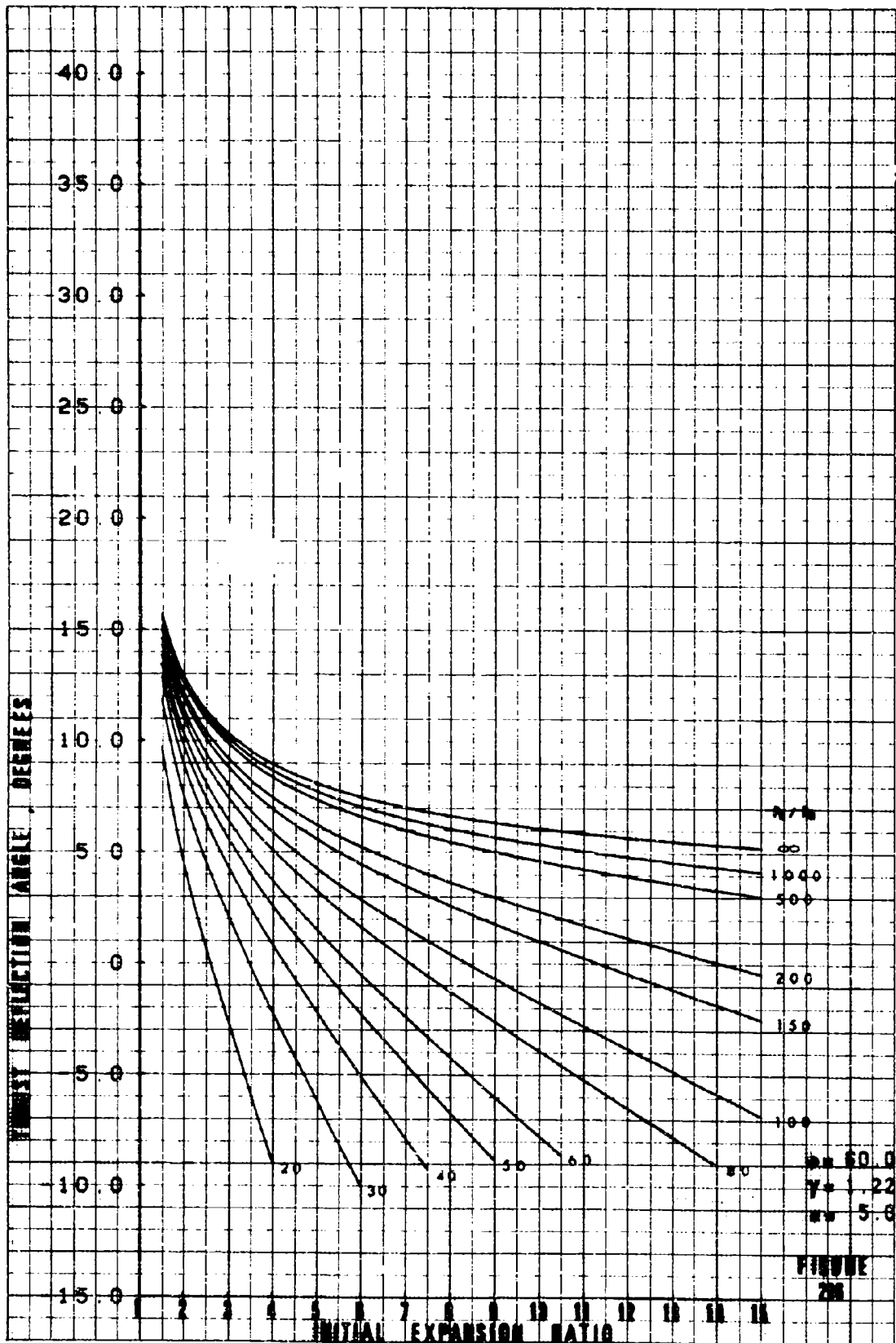
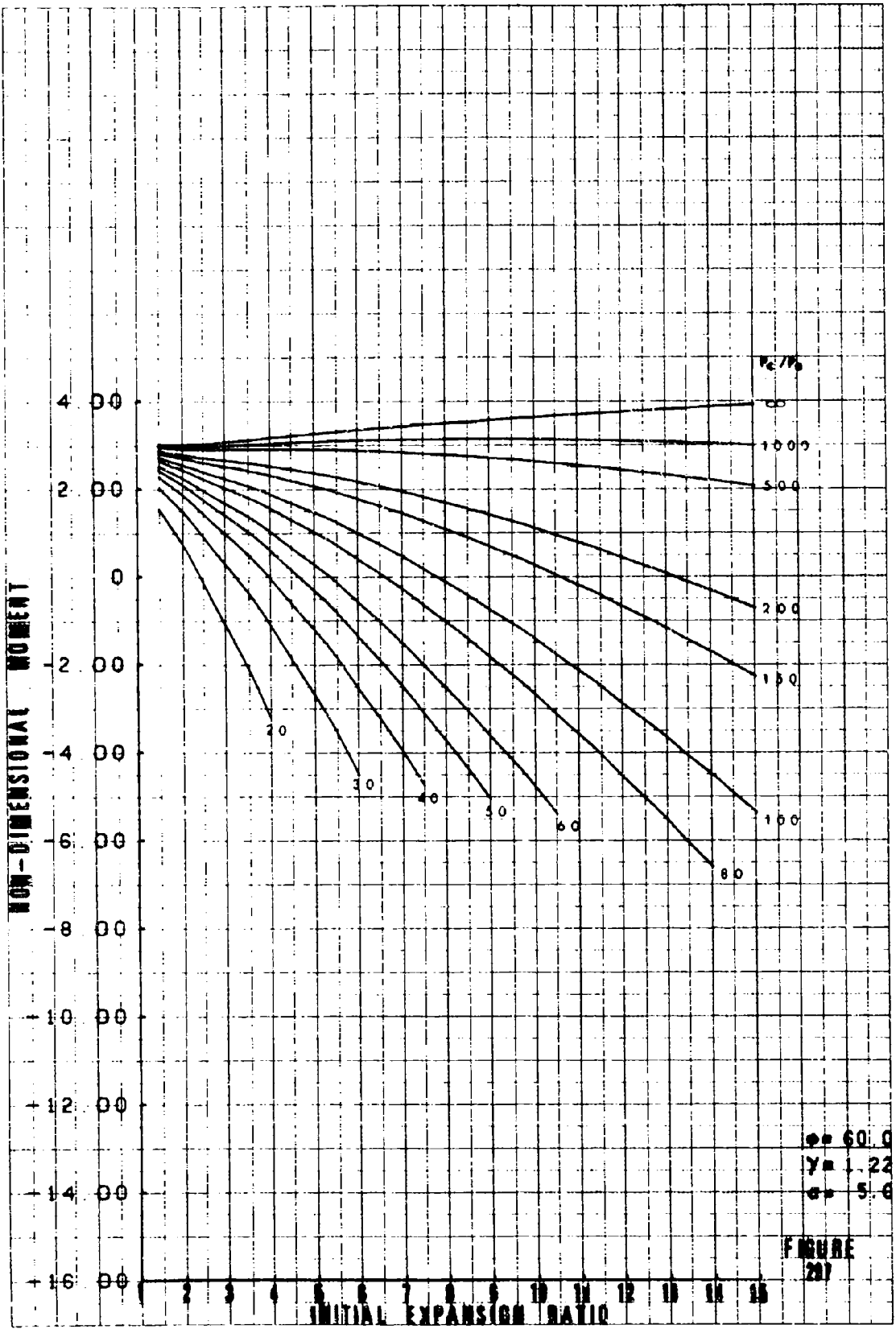
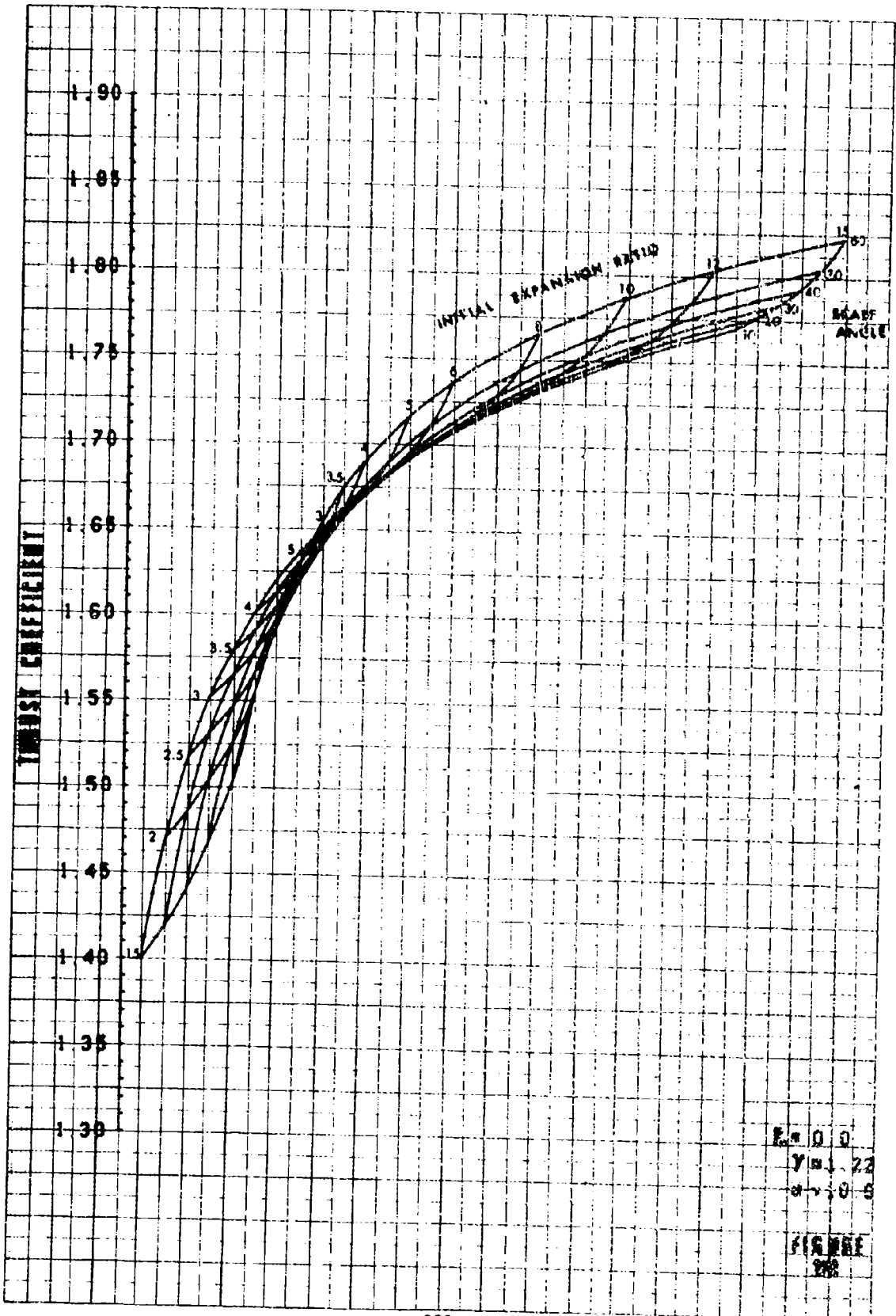
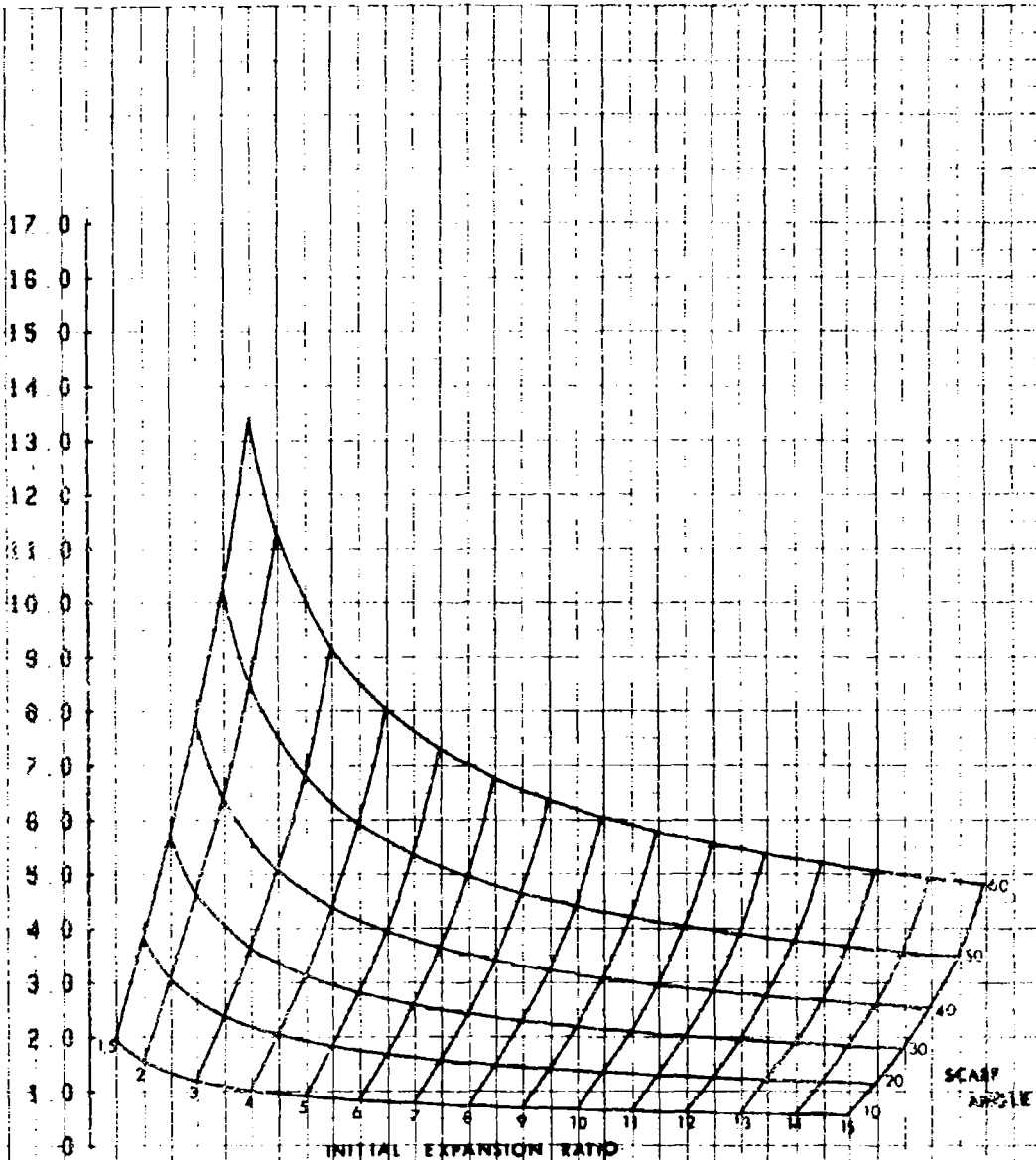


FIGURE 20



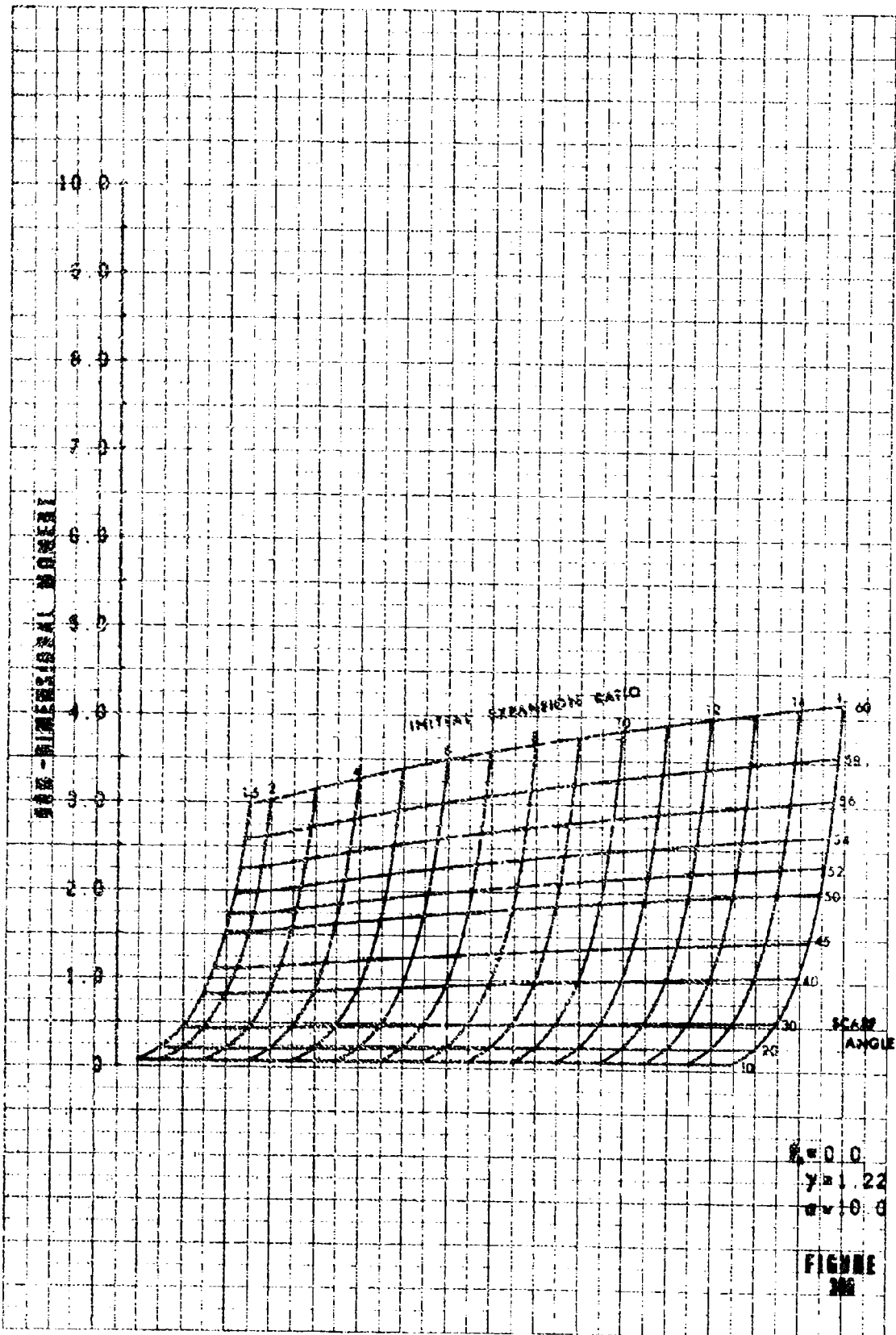


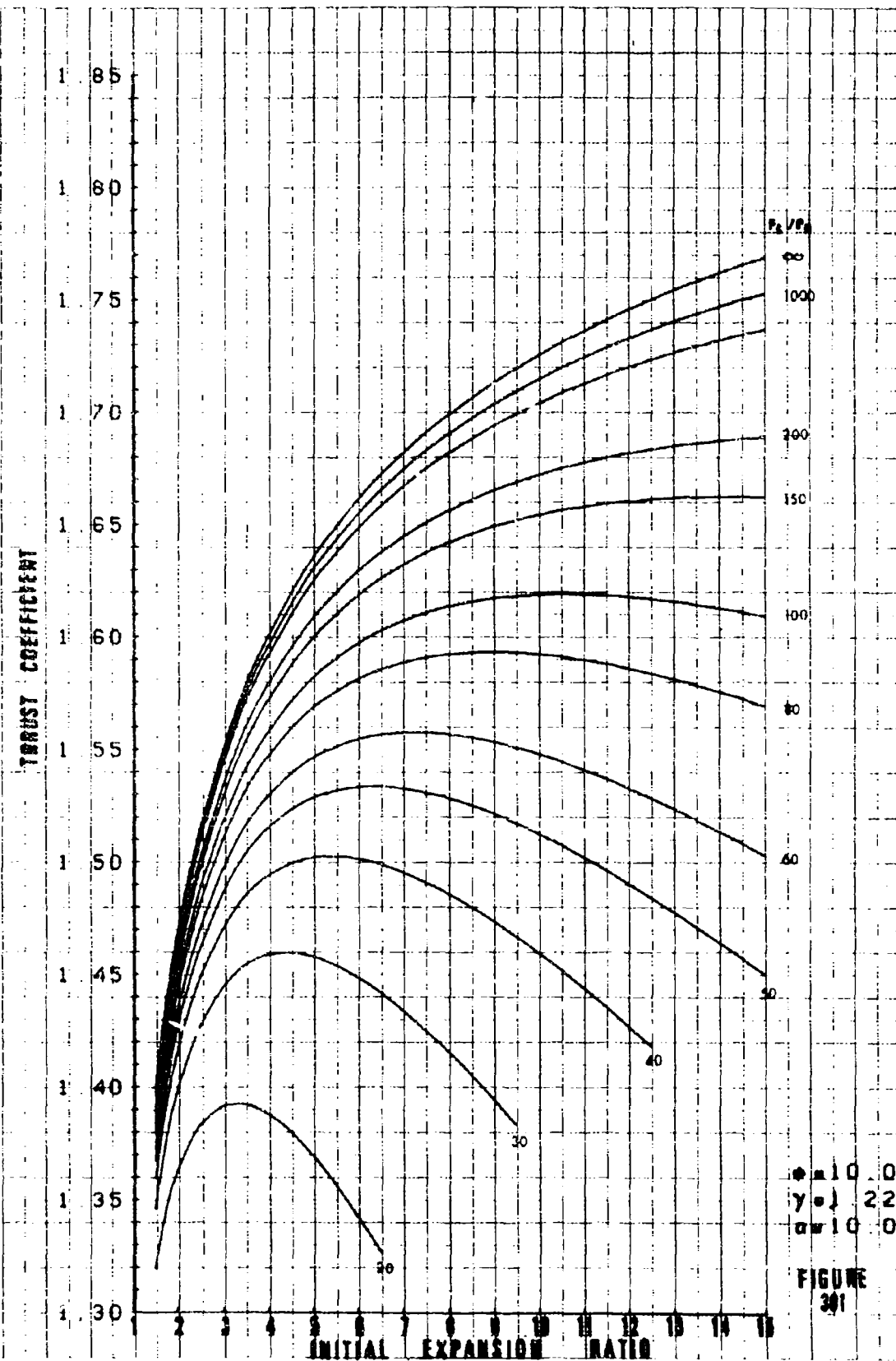
THRUST DEFLECTION ANGLE, DEGREES



$R = 0.0$   
 $\gamma = 1.22$   
 $\sigma = 10.0$

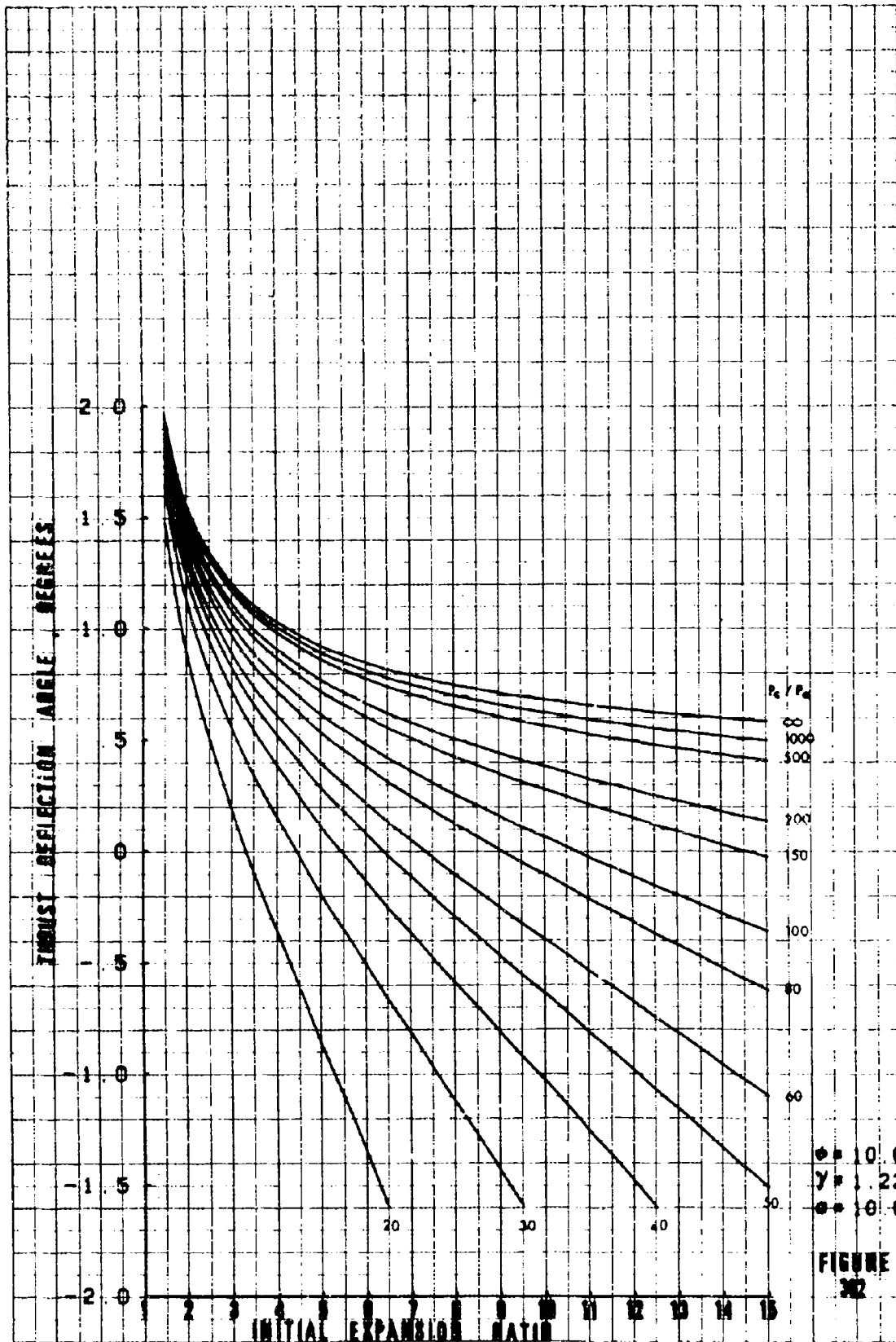
FIGURE 209





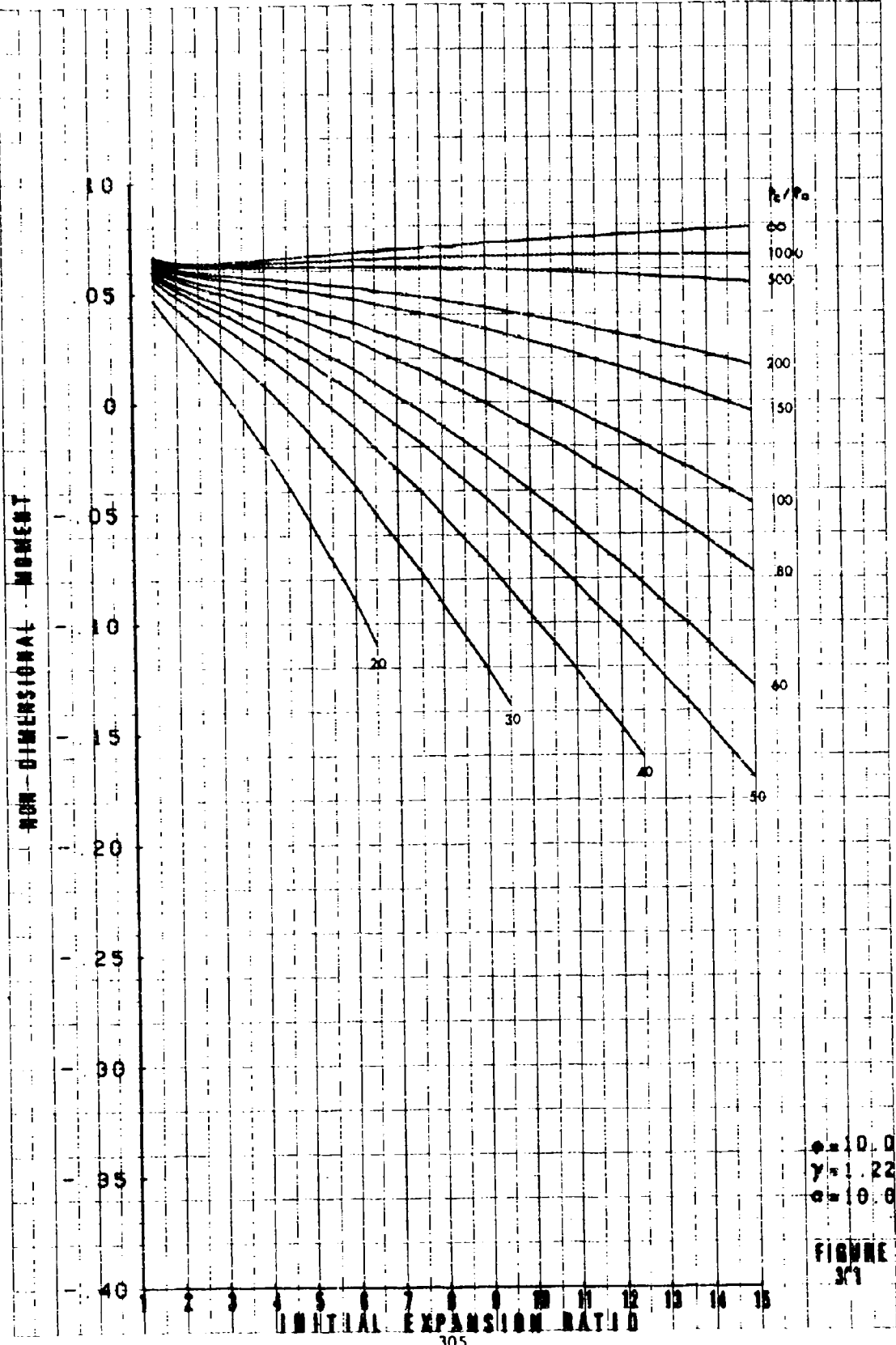
$\mu = 10.0$   
 $\gamma = 1.22$   
 $\alpha = 10.0$

FIGURE 301



$\bullet$  10.0  
 $\bullet$  22  
 $\bullet$  30.0

FIGURE 32



$\phi = 10.0$   
 $\gamma = 1.22$   
 $\alpha = 10.0$

FIGURE 31



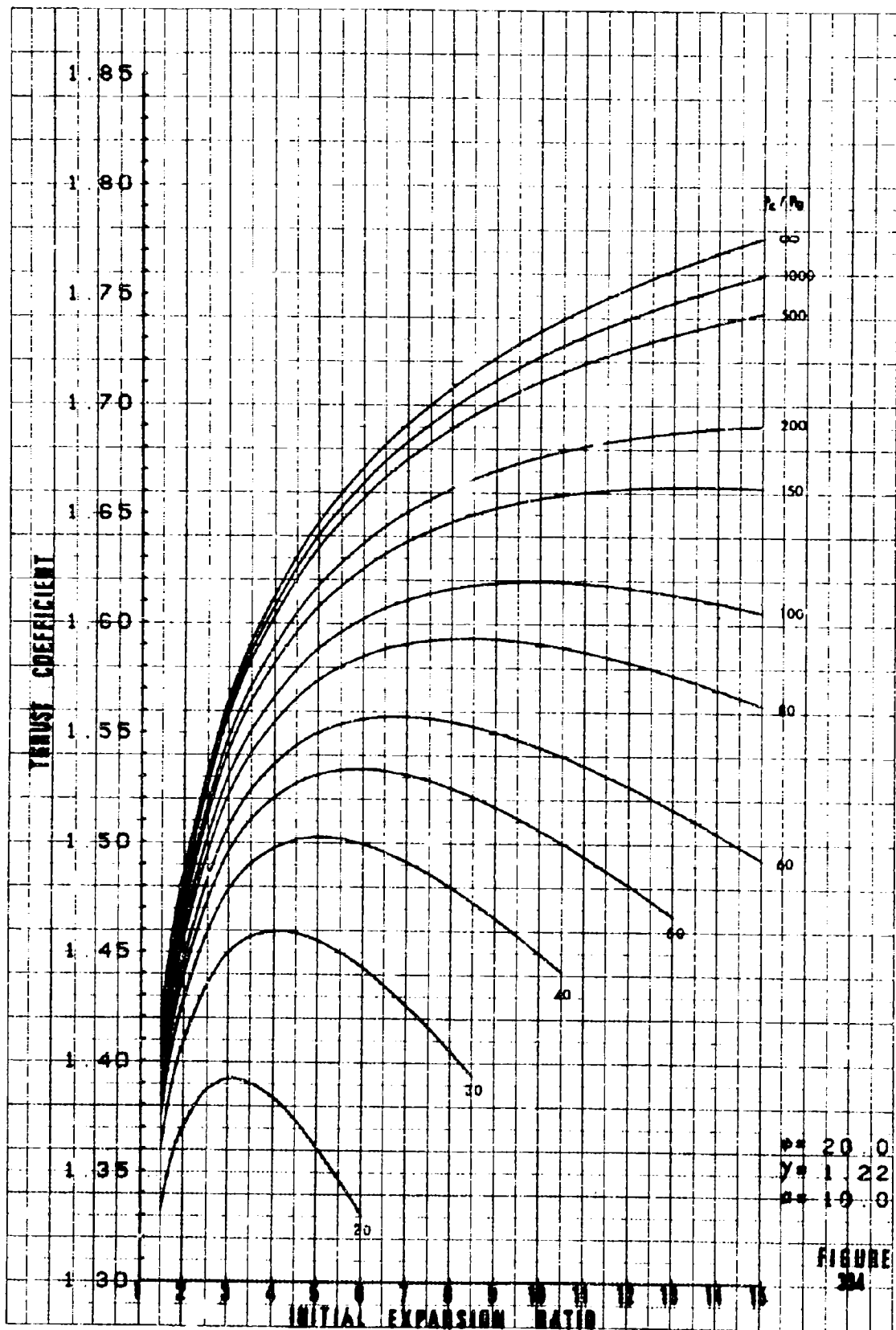
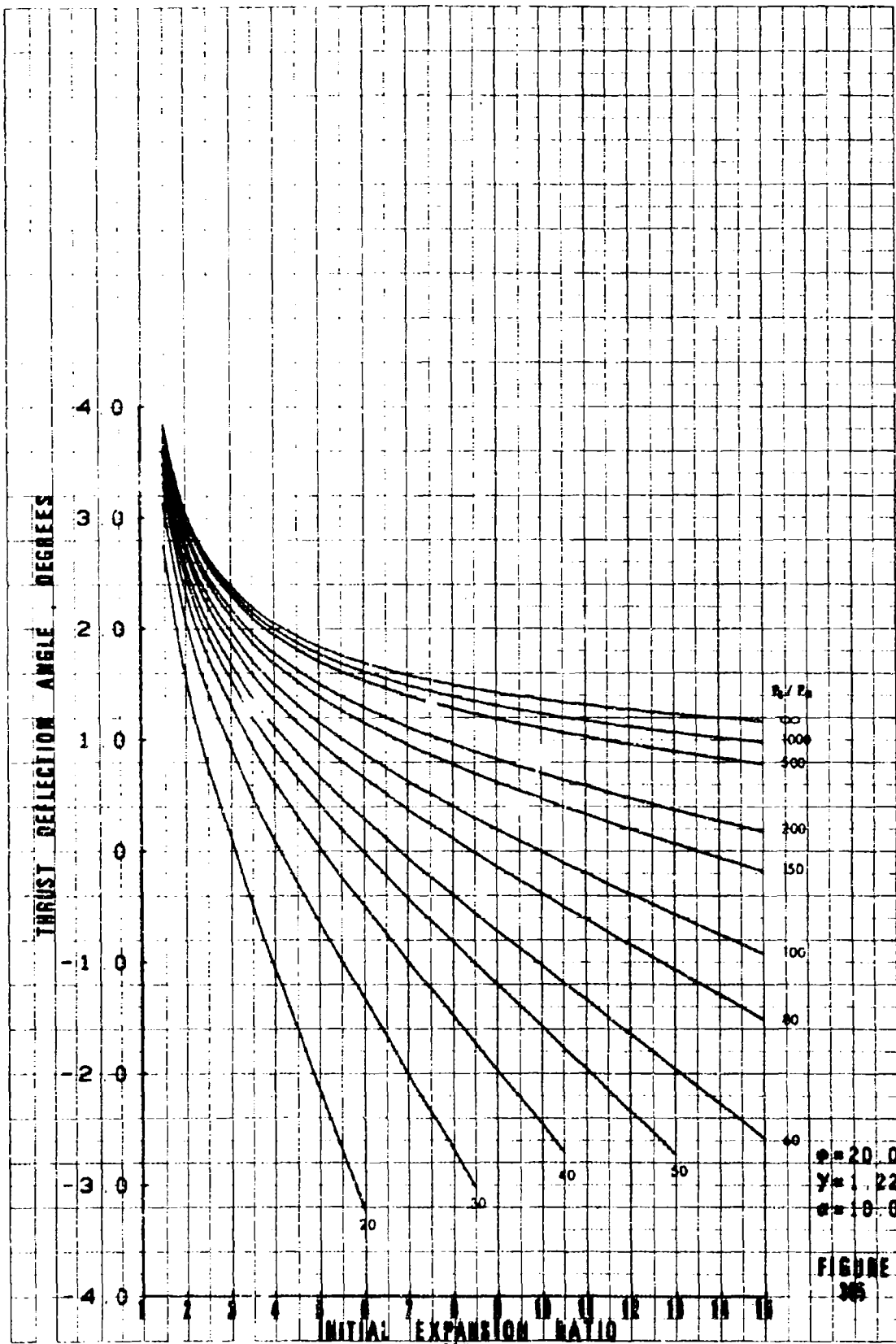
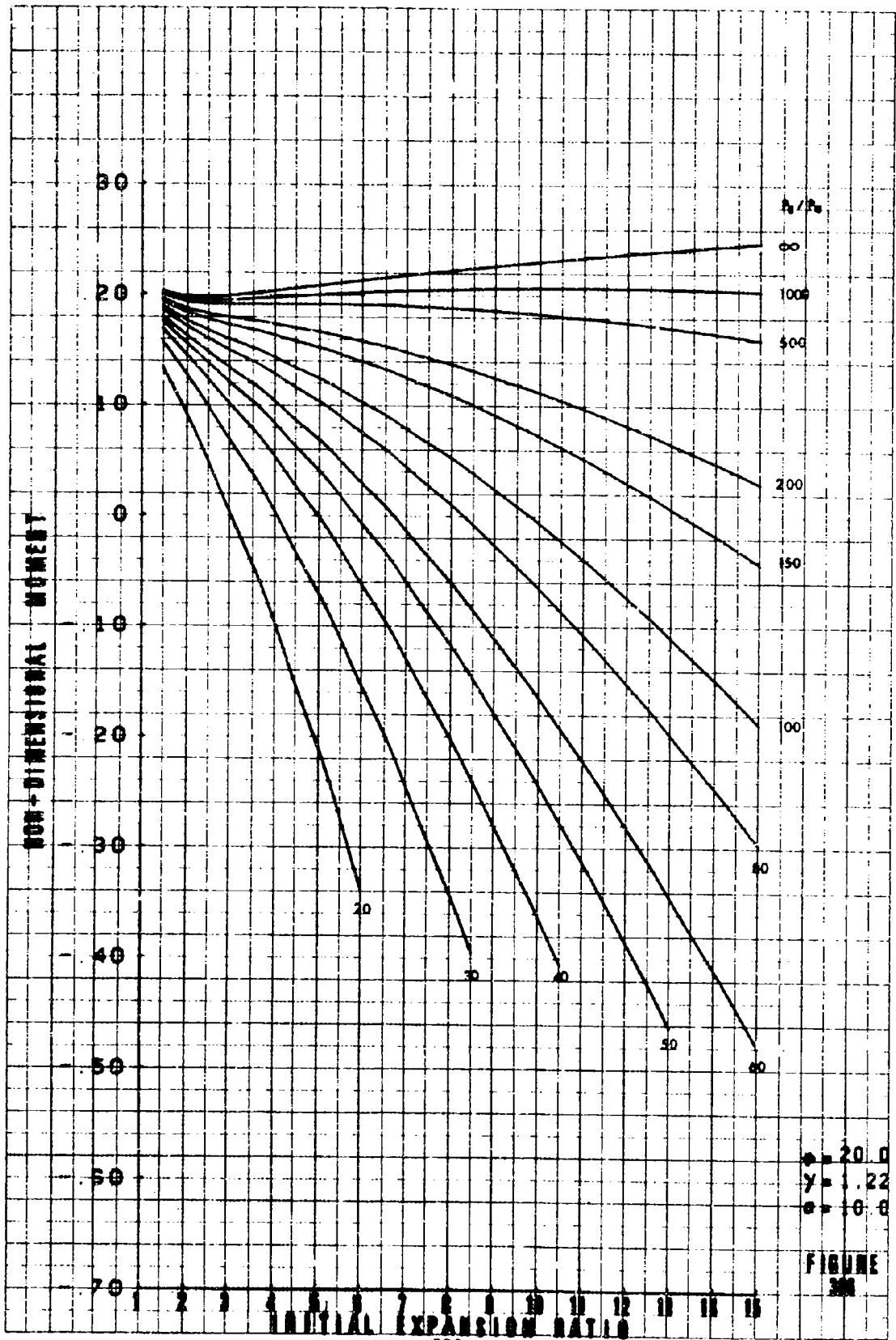


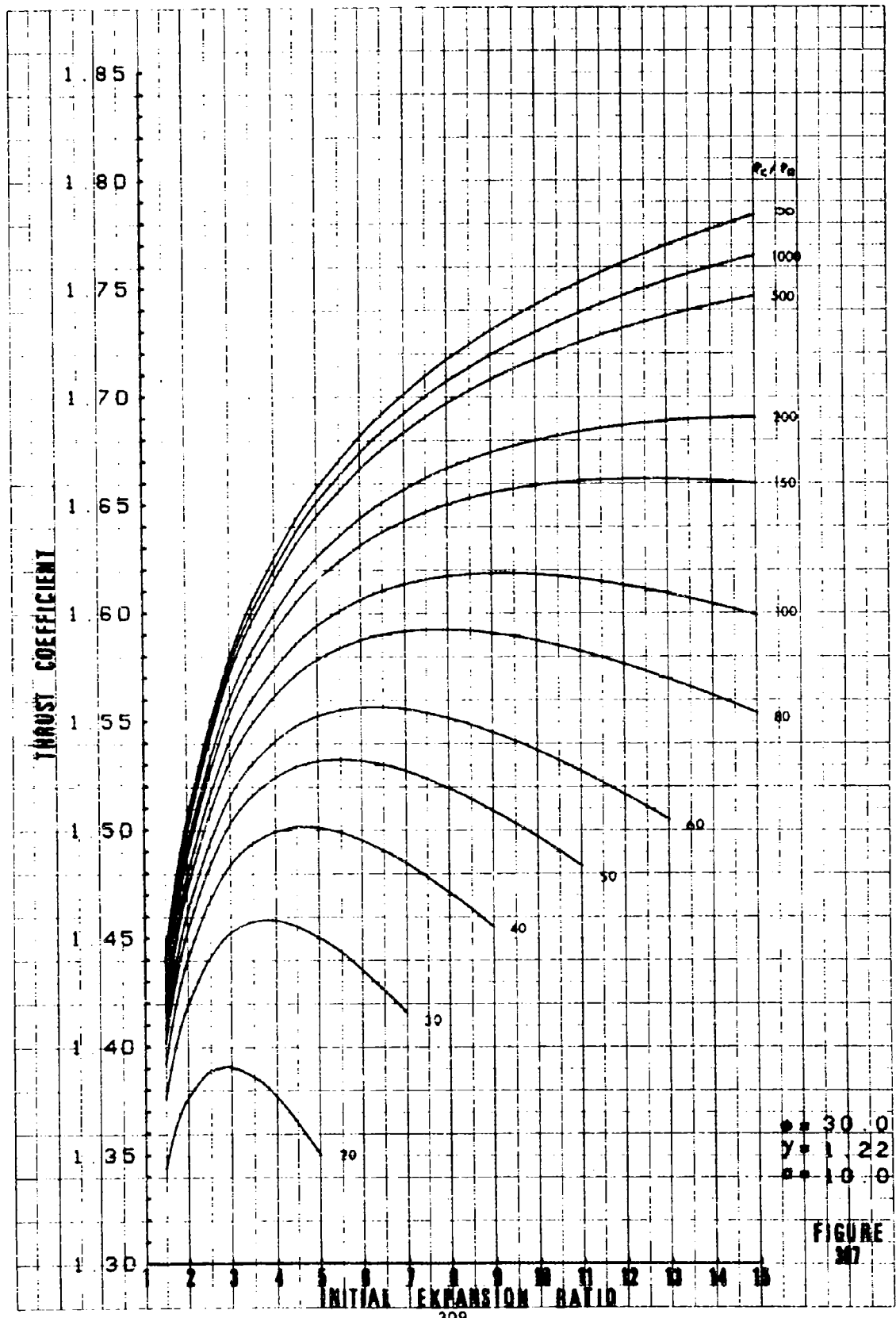
FIGURE 34



$\alpha = 20.0$   
 $\gamma = 1.22$   
 $\beta = 10.0$

FIGURE 36





$\bullet = 30.0$   
 $\gamma = 1.22$   
 $\square = 10.0$

FIGURE 27

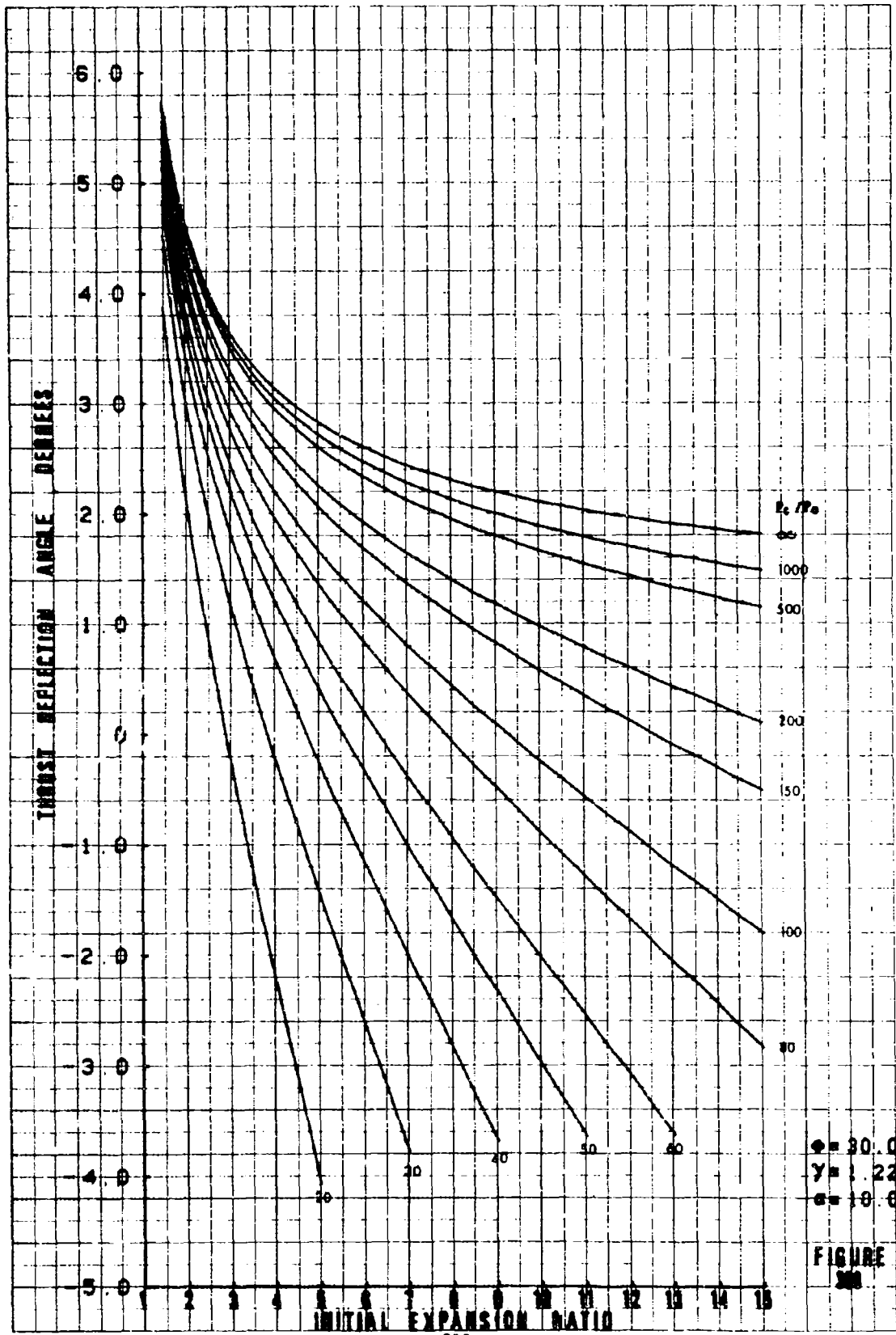
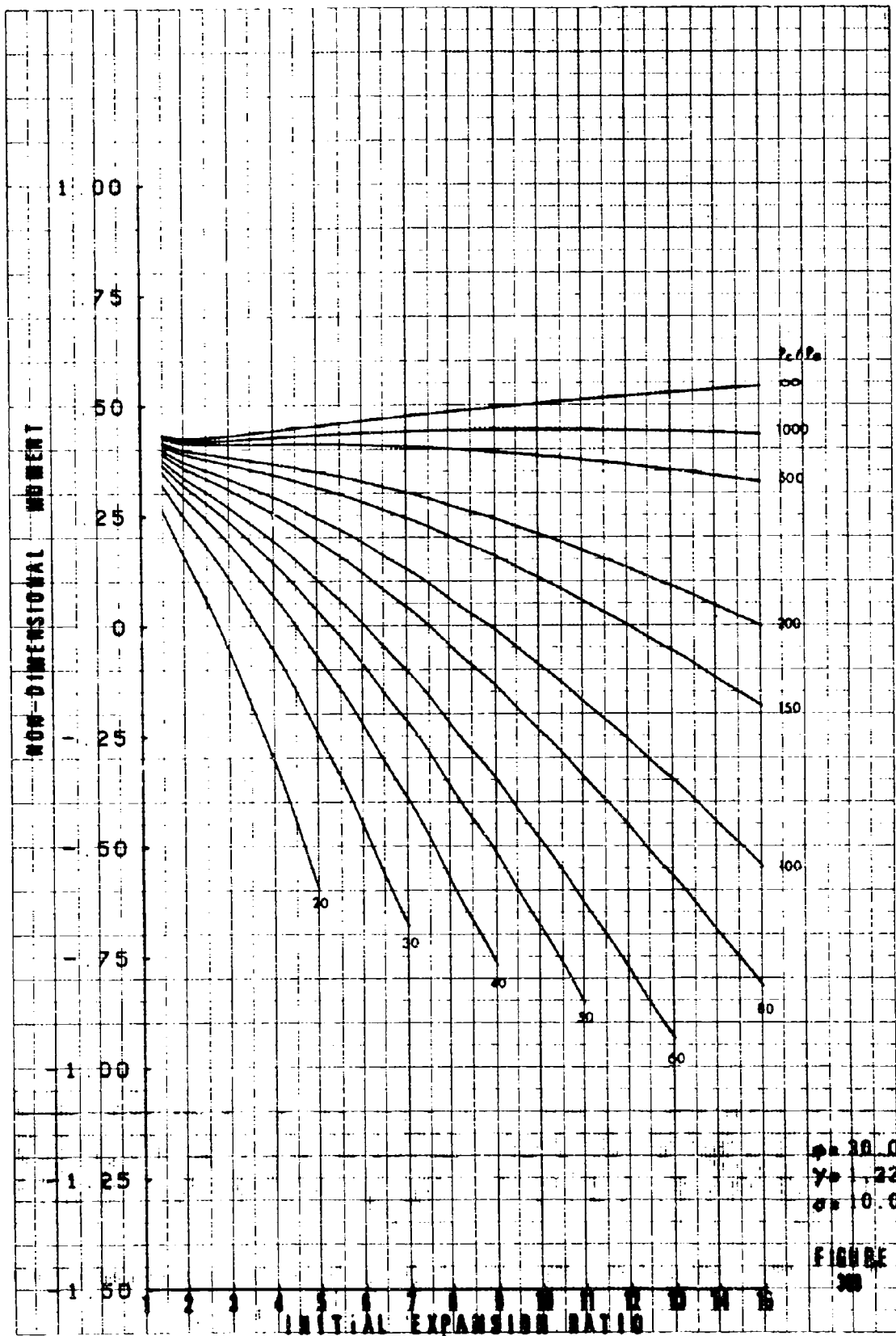


FIGURE 200



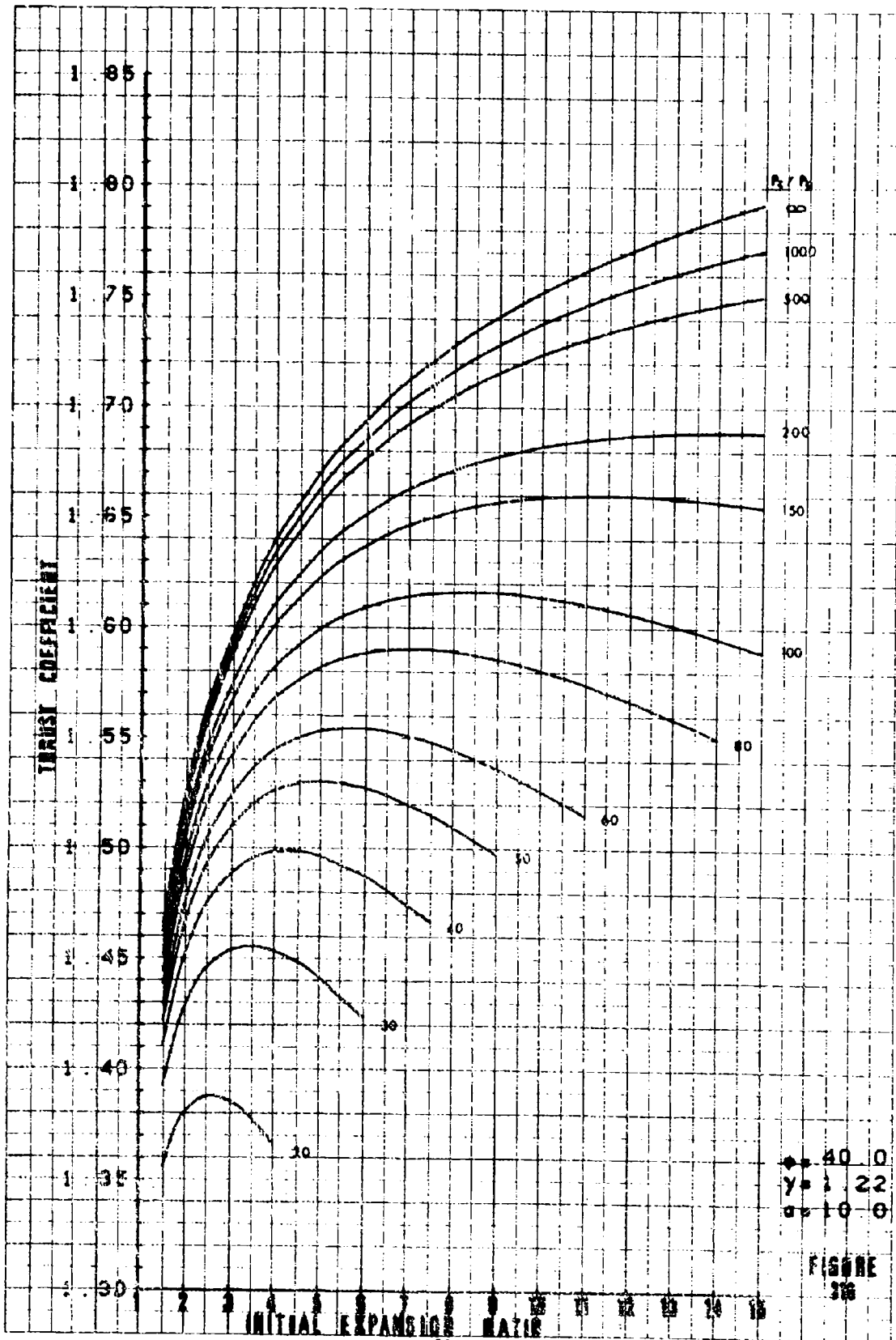


FIGURE 308



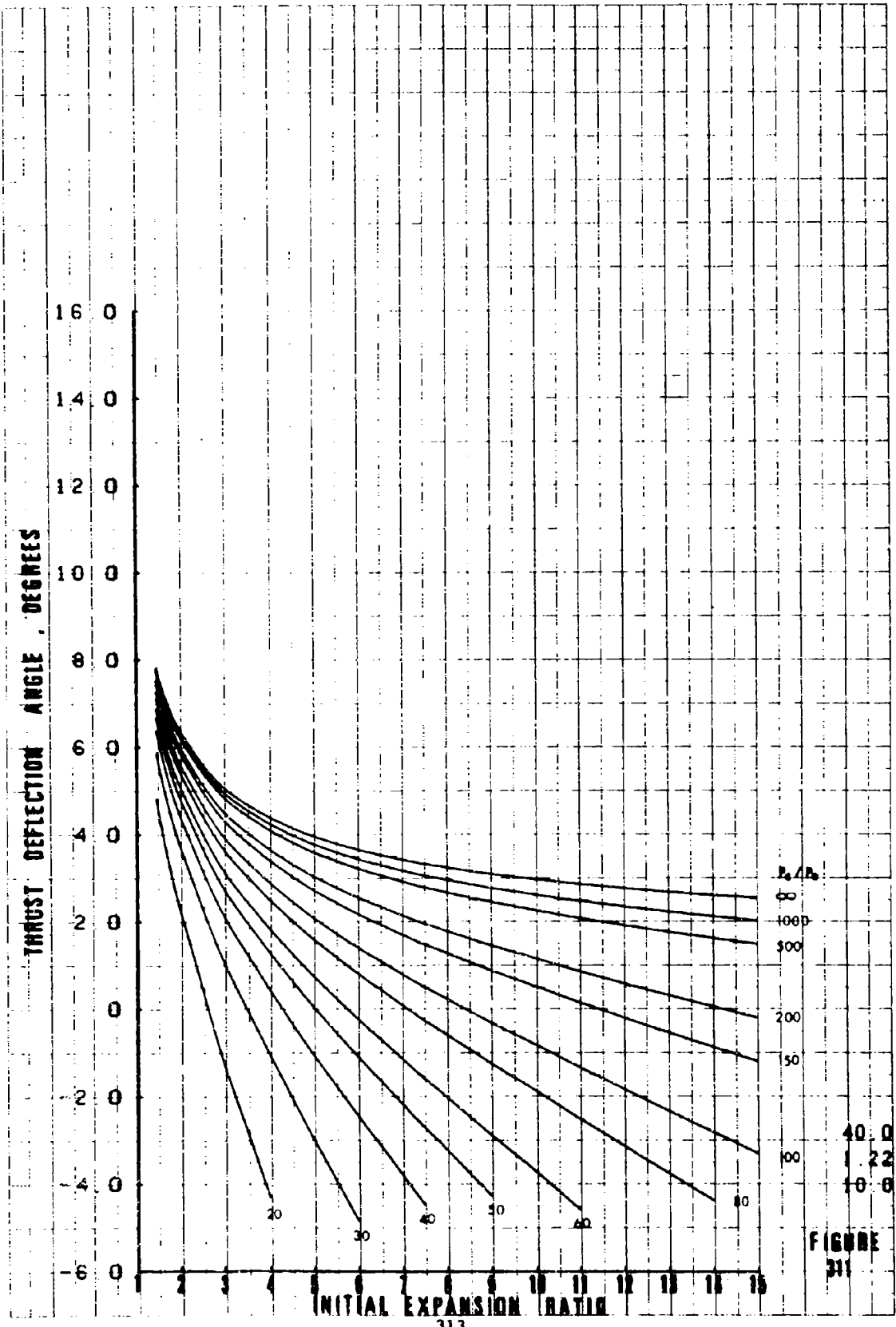
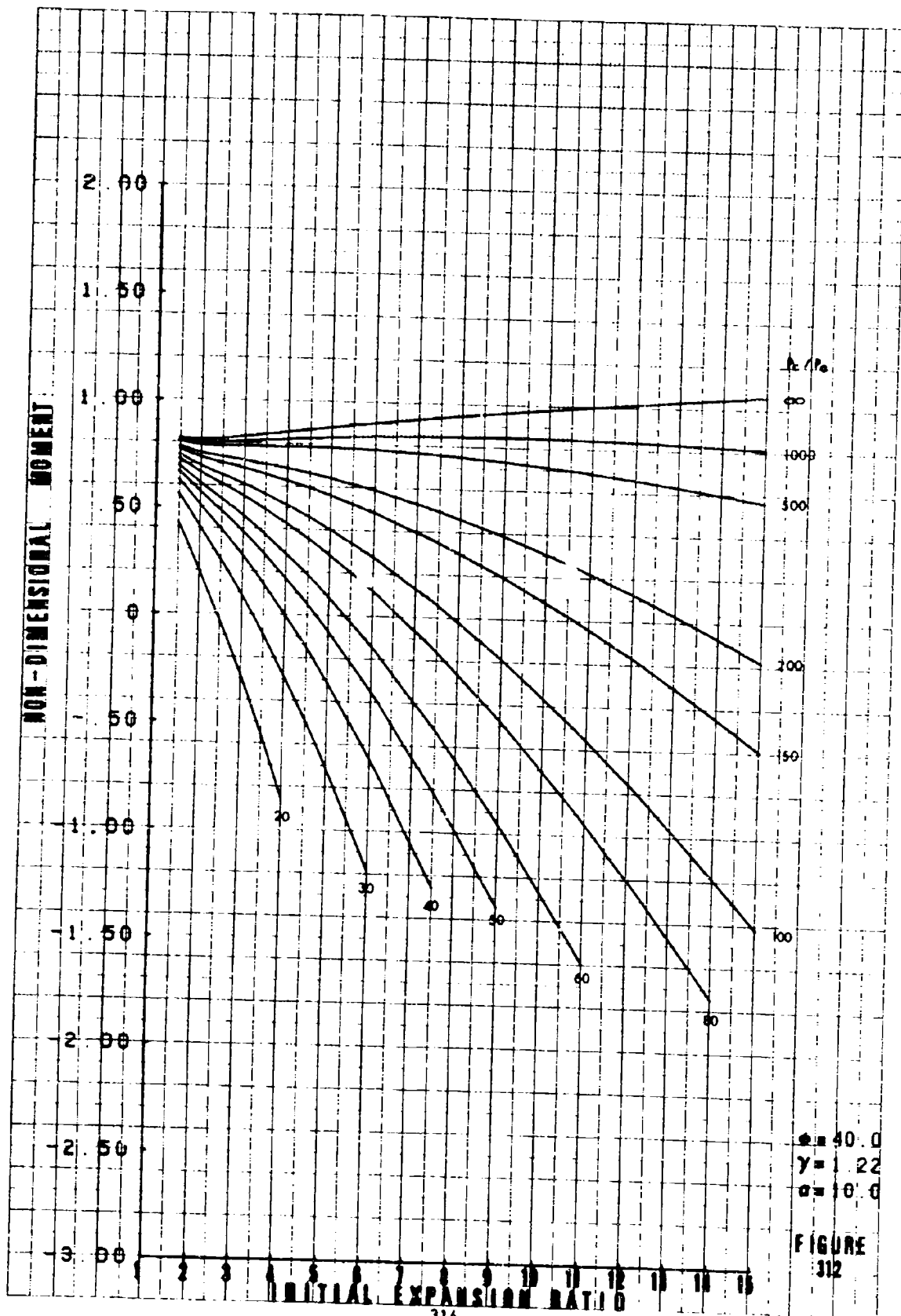


FIGURE 311





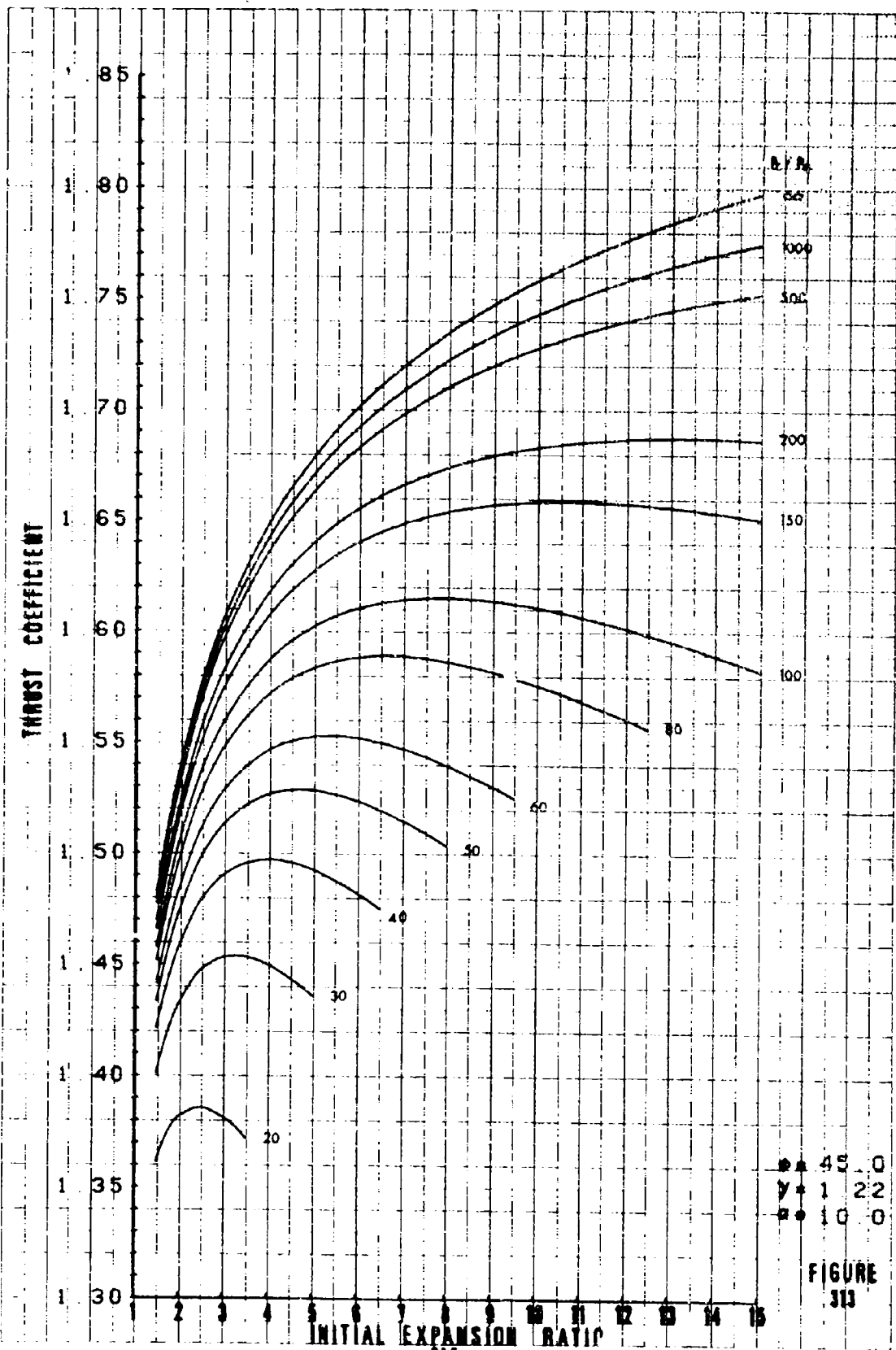
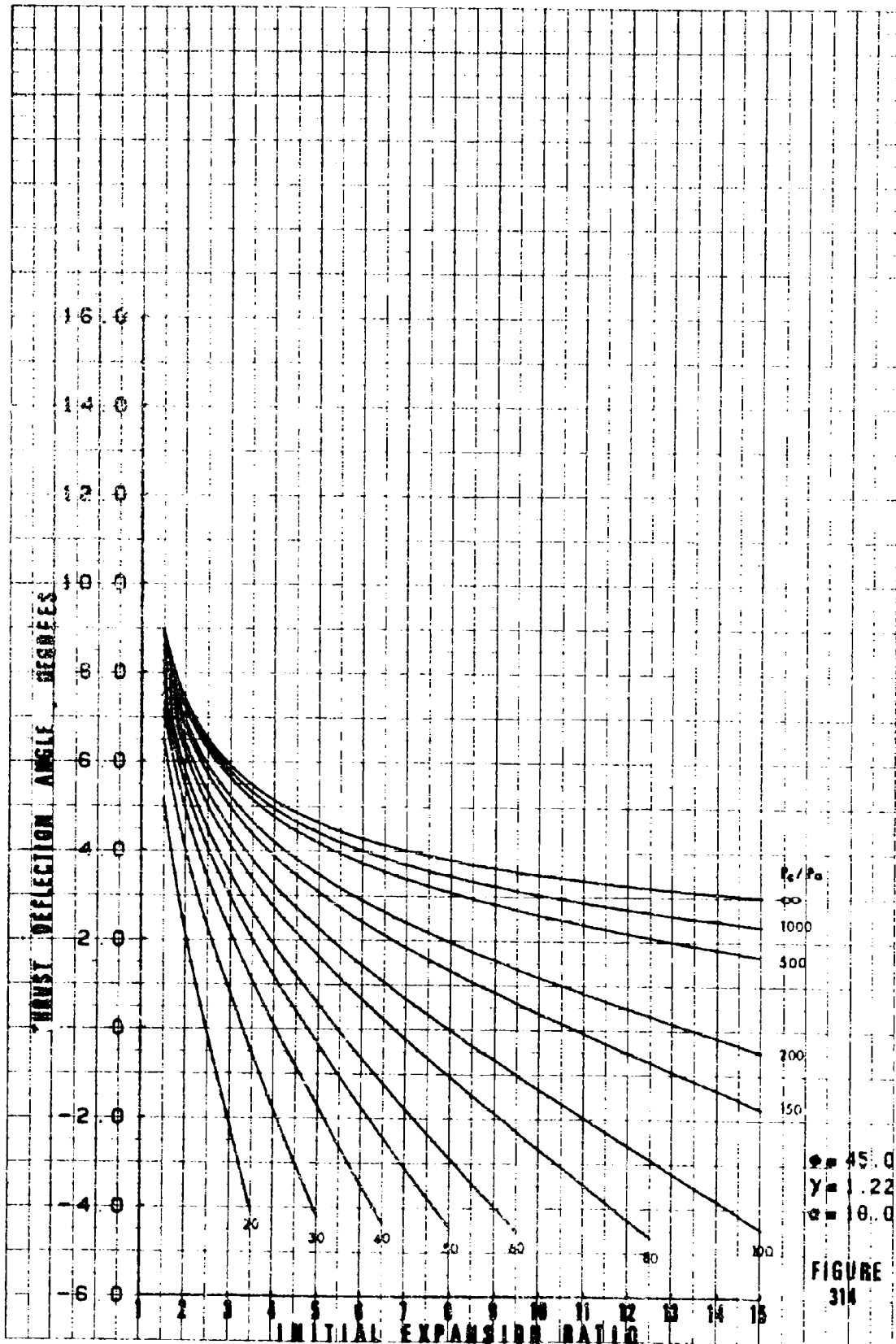
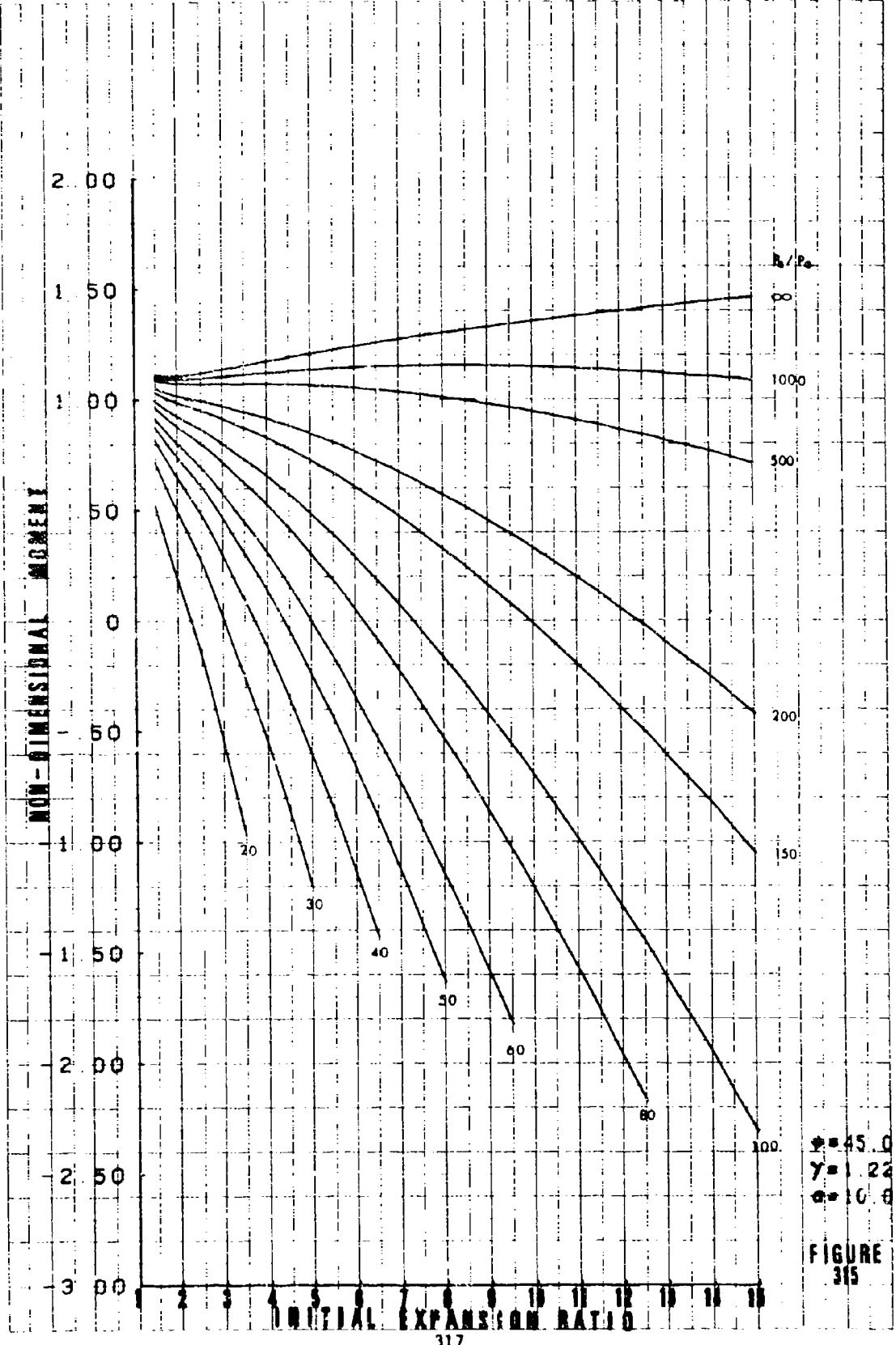


FIGURE 313





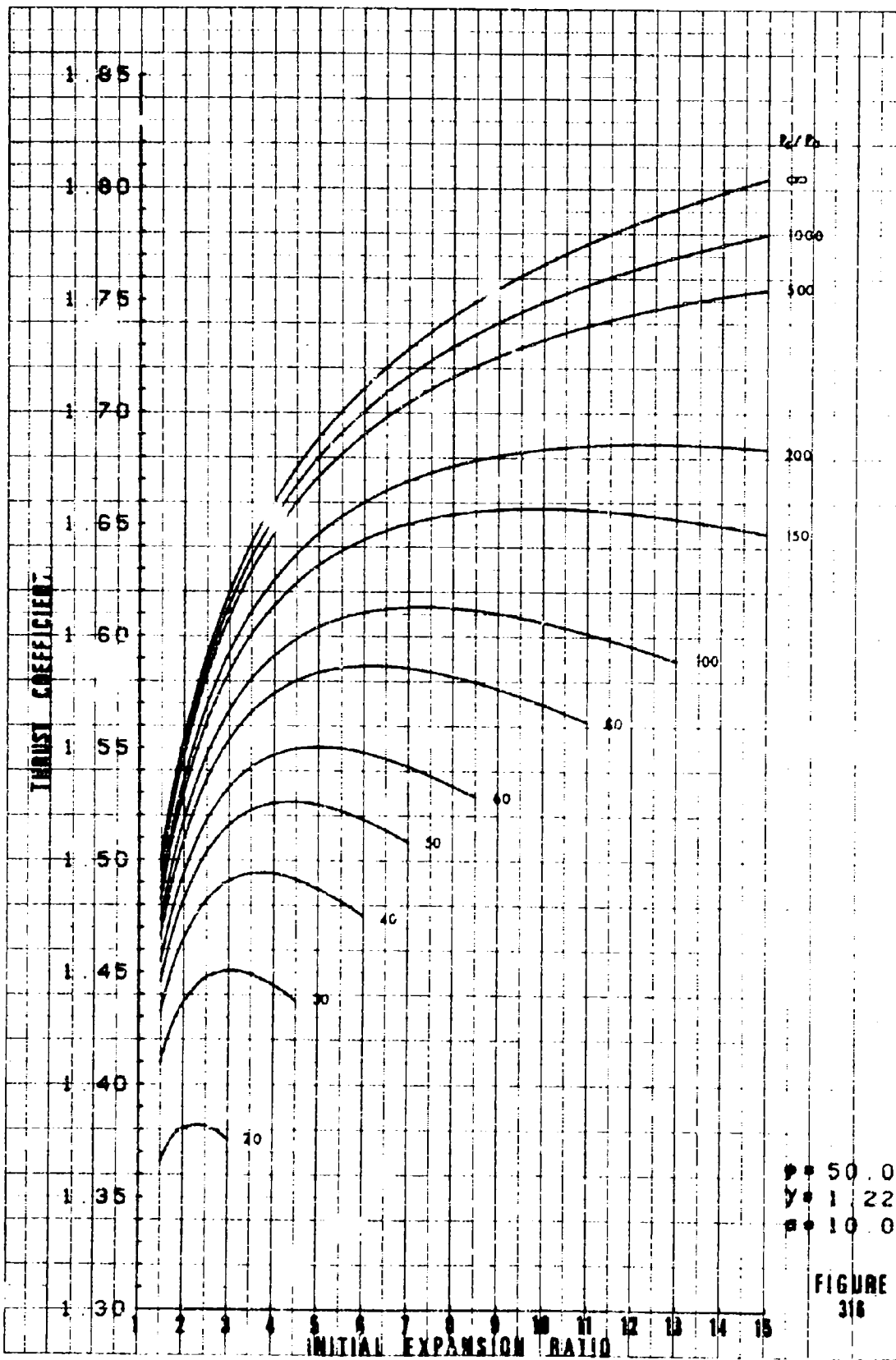


FIGURE 318

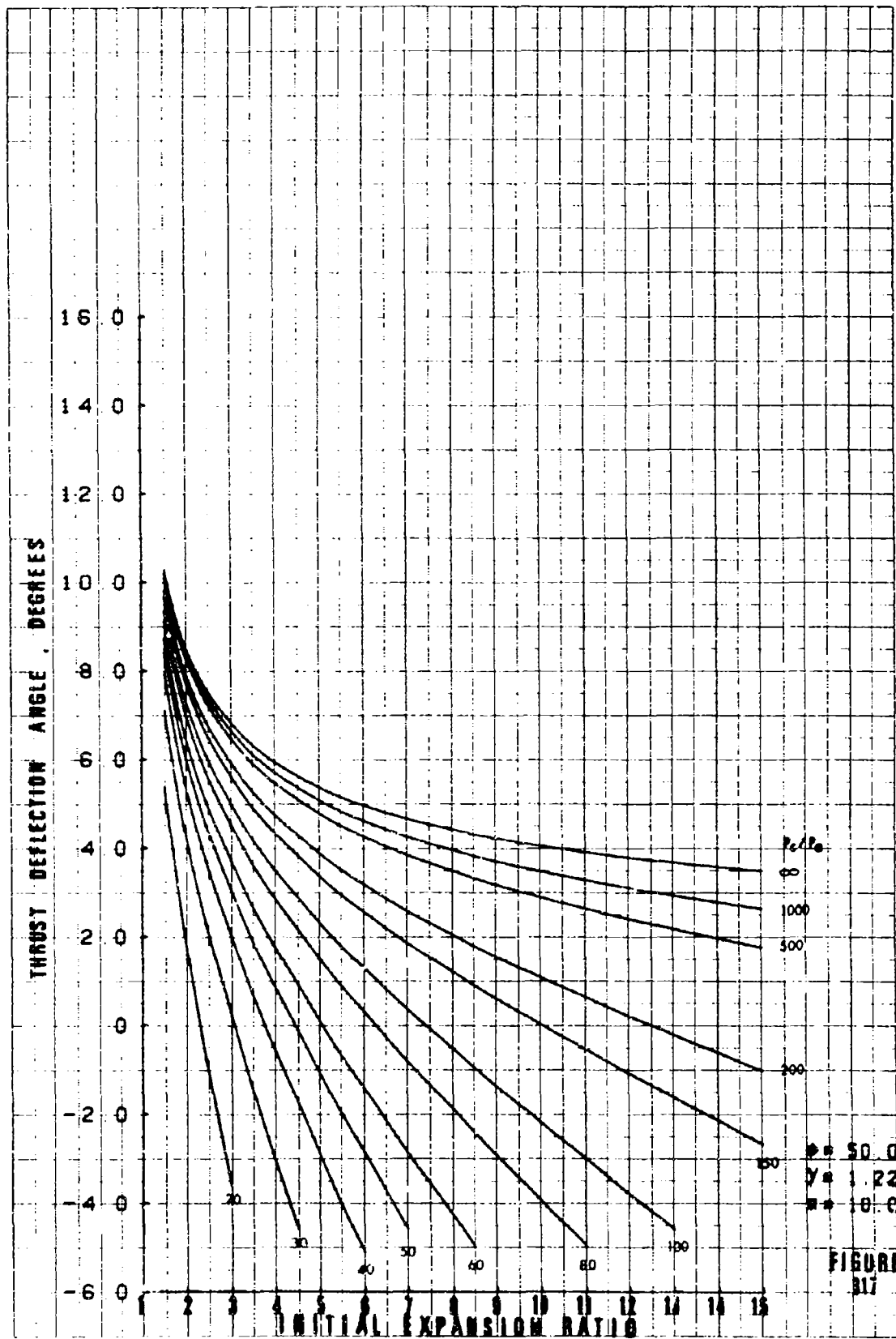
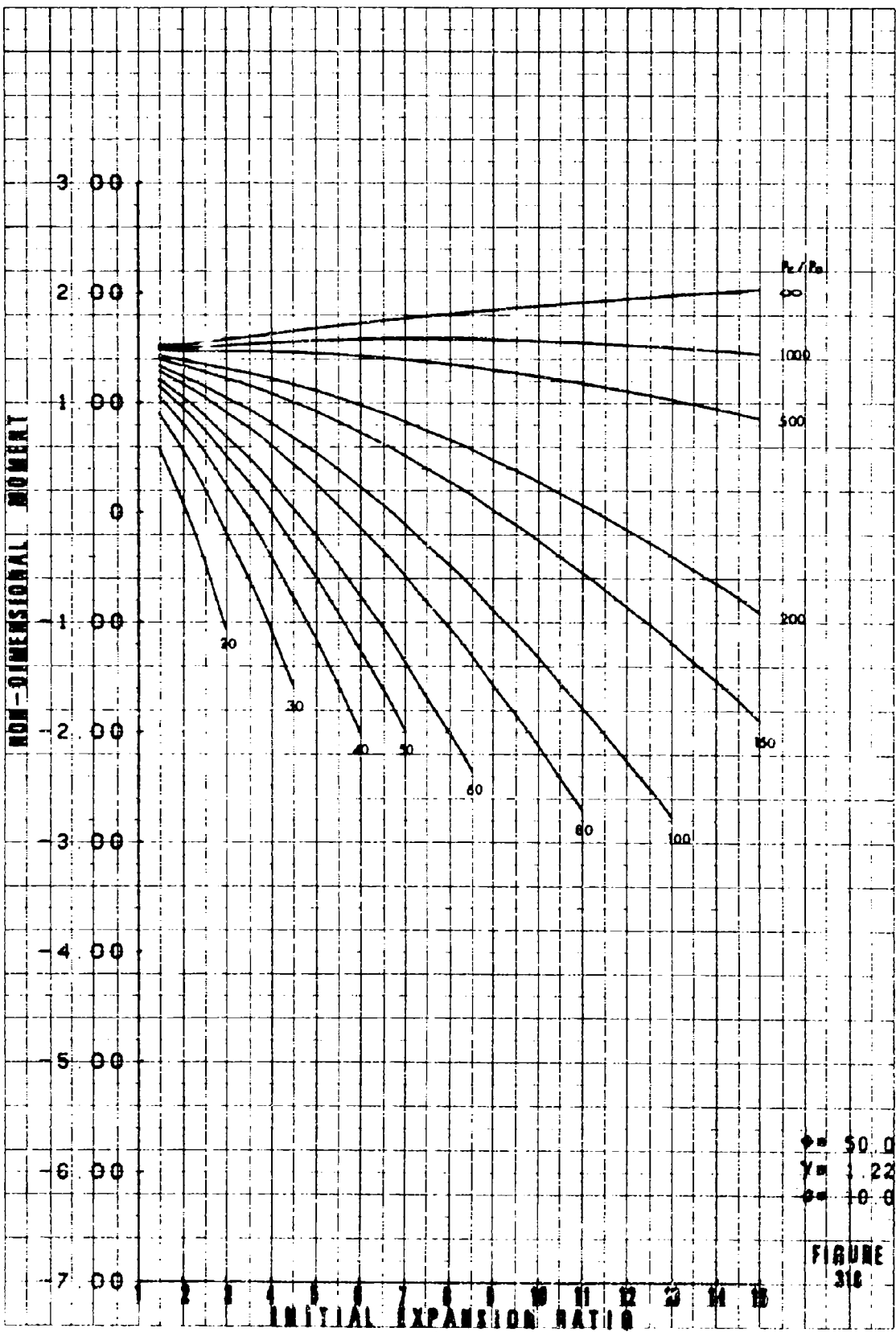
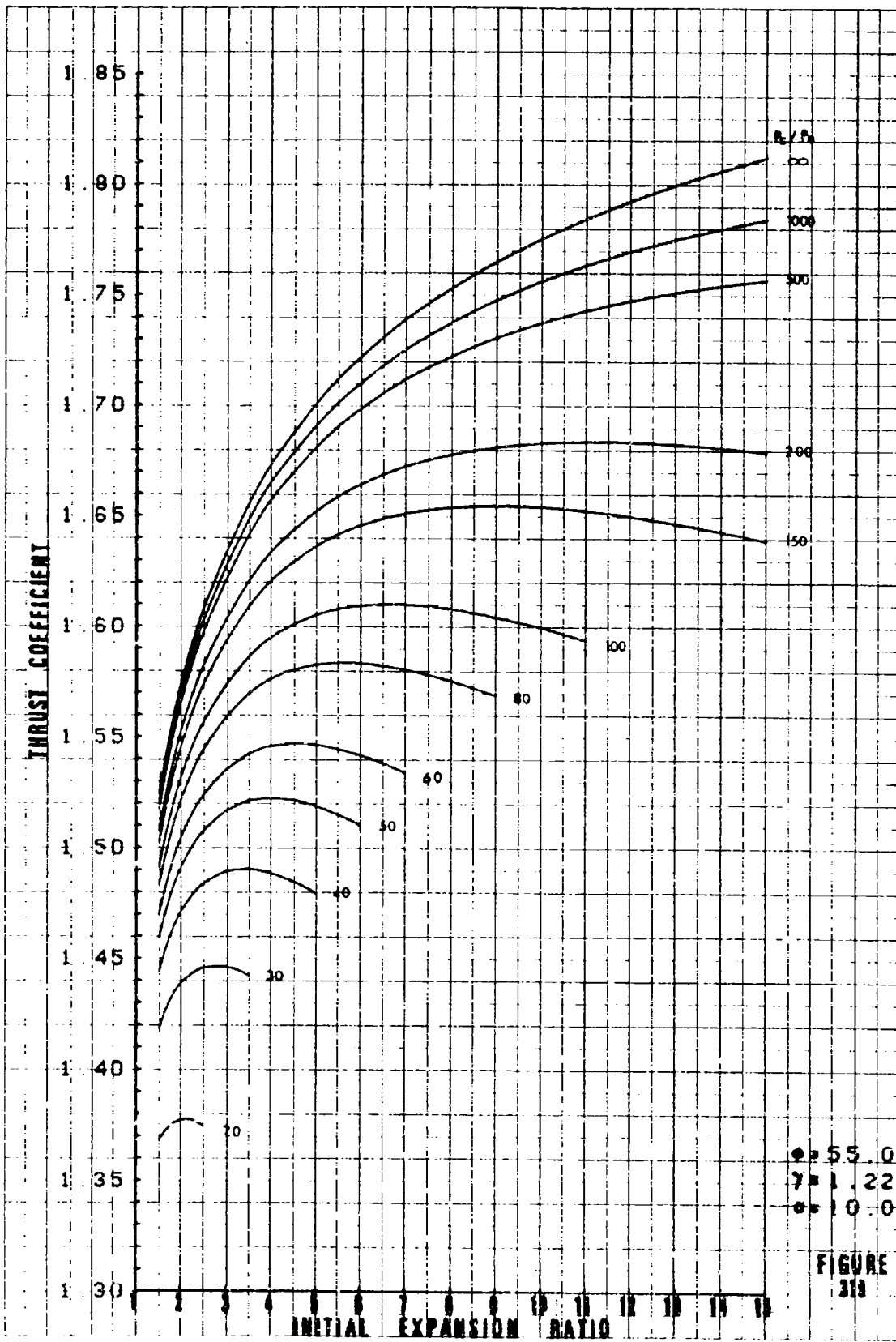


FIGURE 317

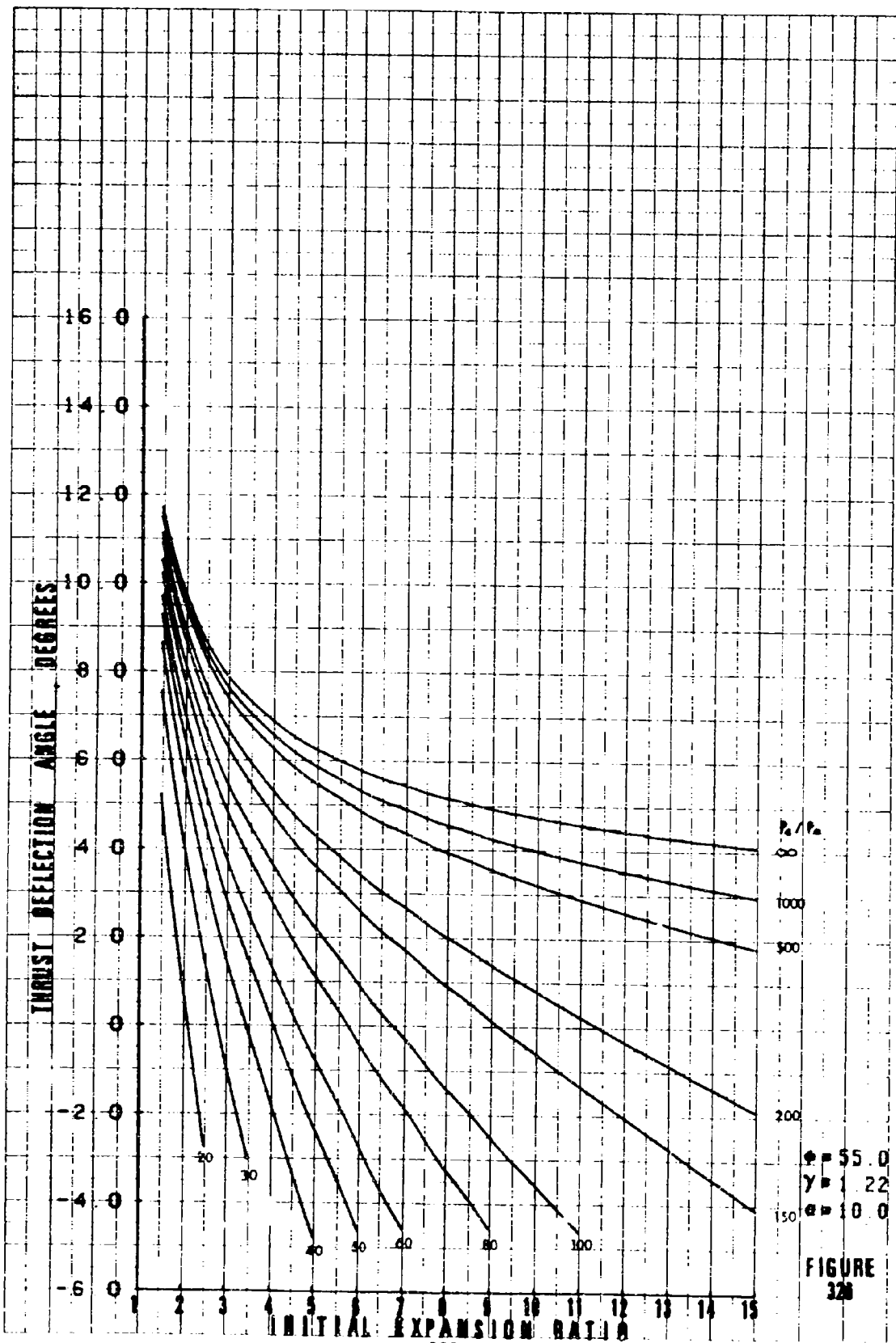




$\gamma = 1.22$   
 $\mu = 10.0$

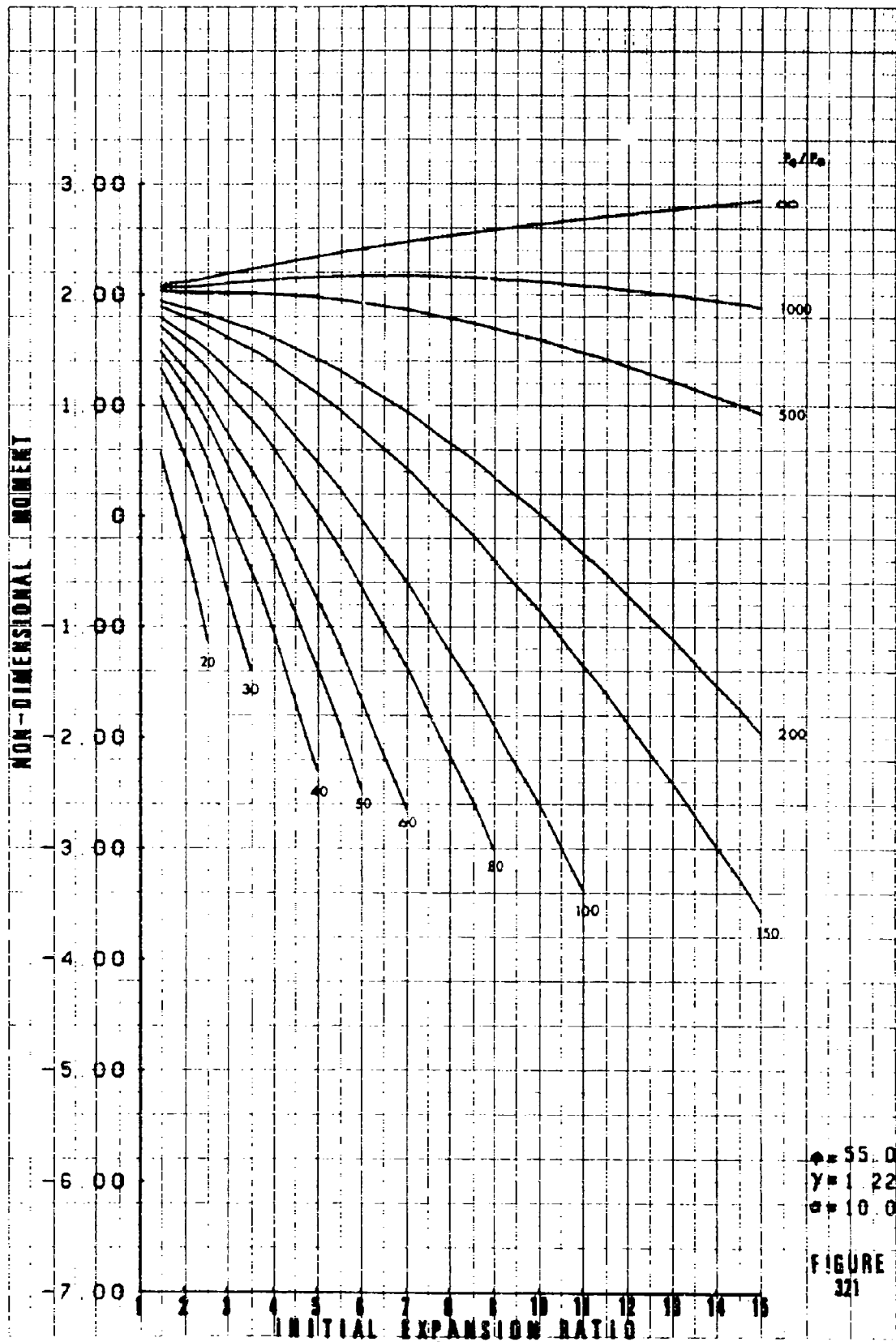
FIGURE 319





$\phi = 55.0$   
 $\gamma = 1.22$   
 $\epsilon = 10.0$

FIGURE 328



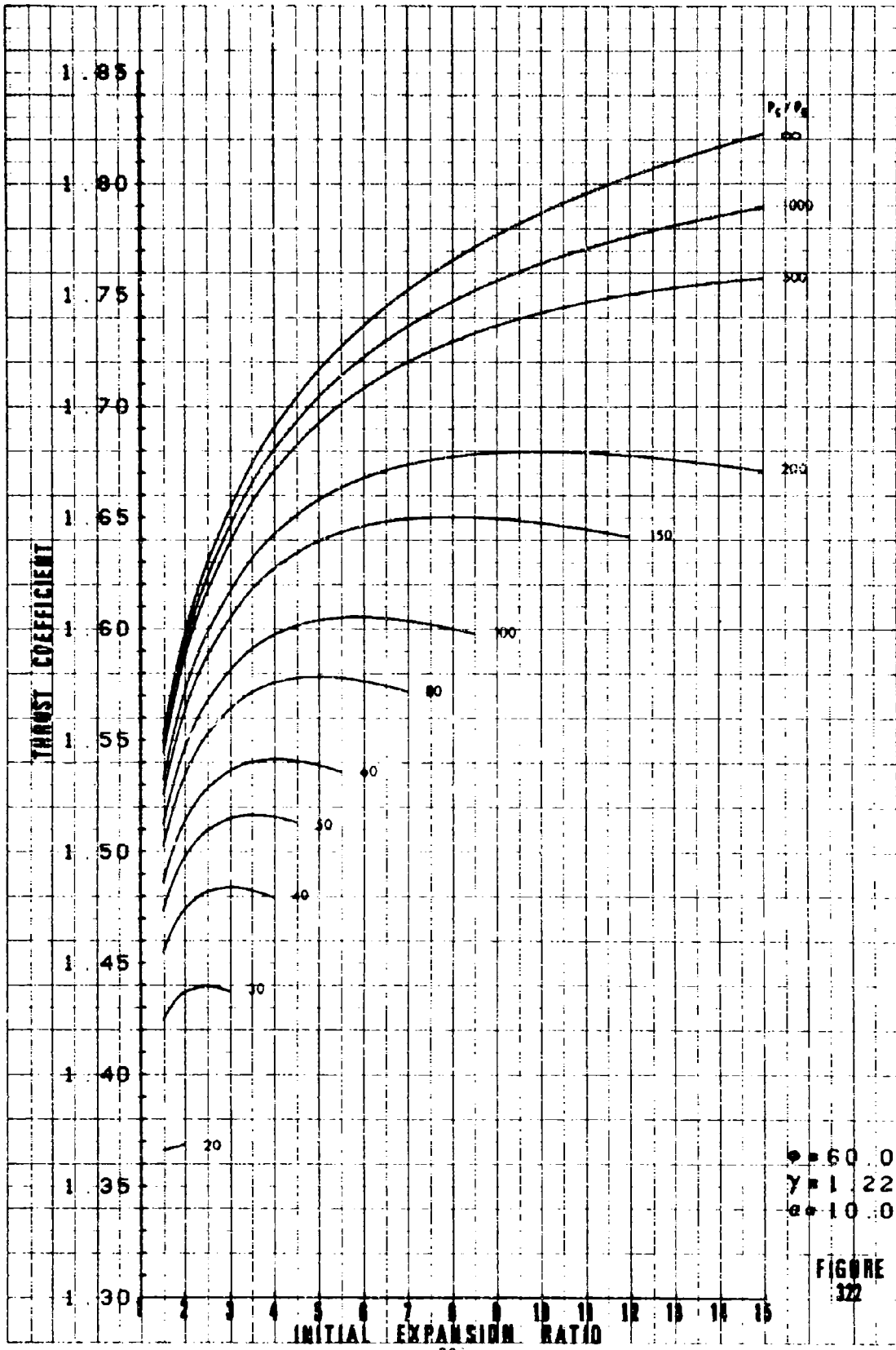


FIGURE 322

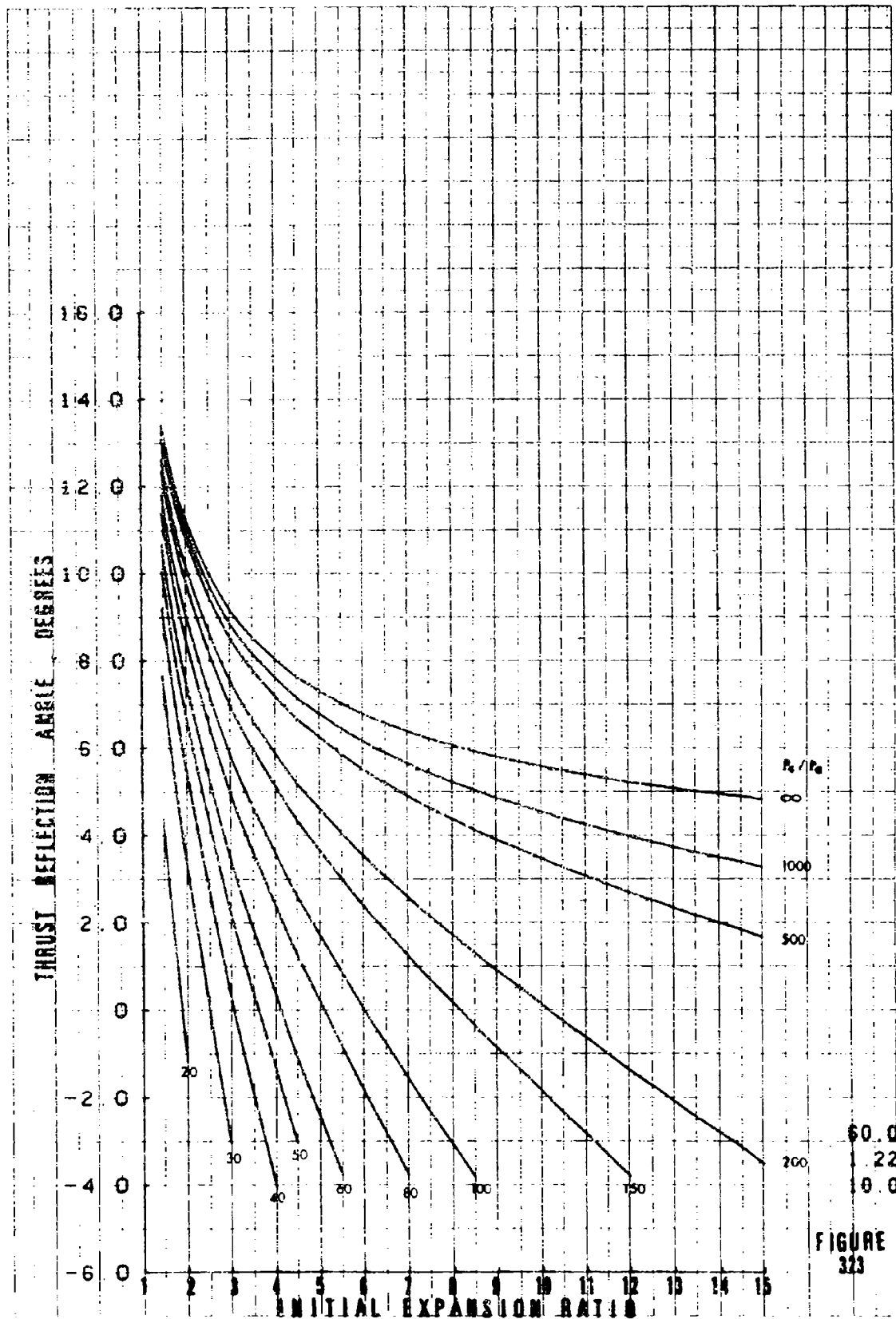


FIGURE 323

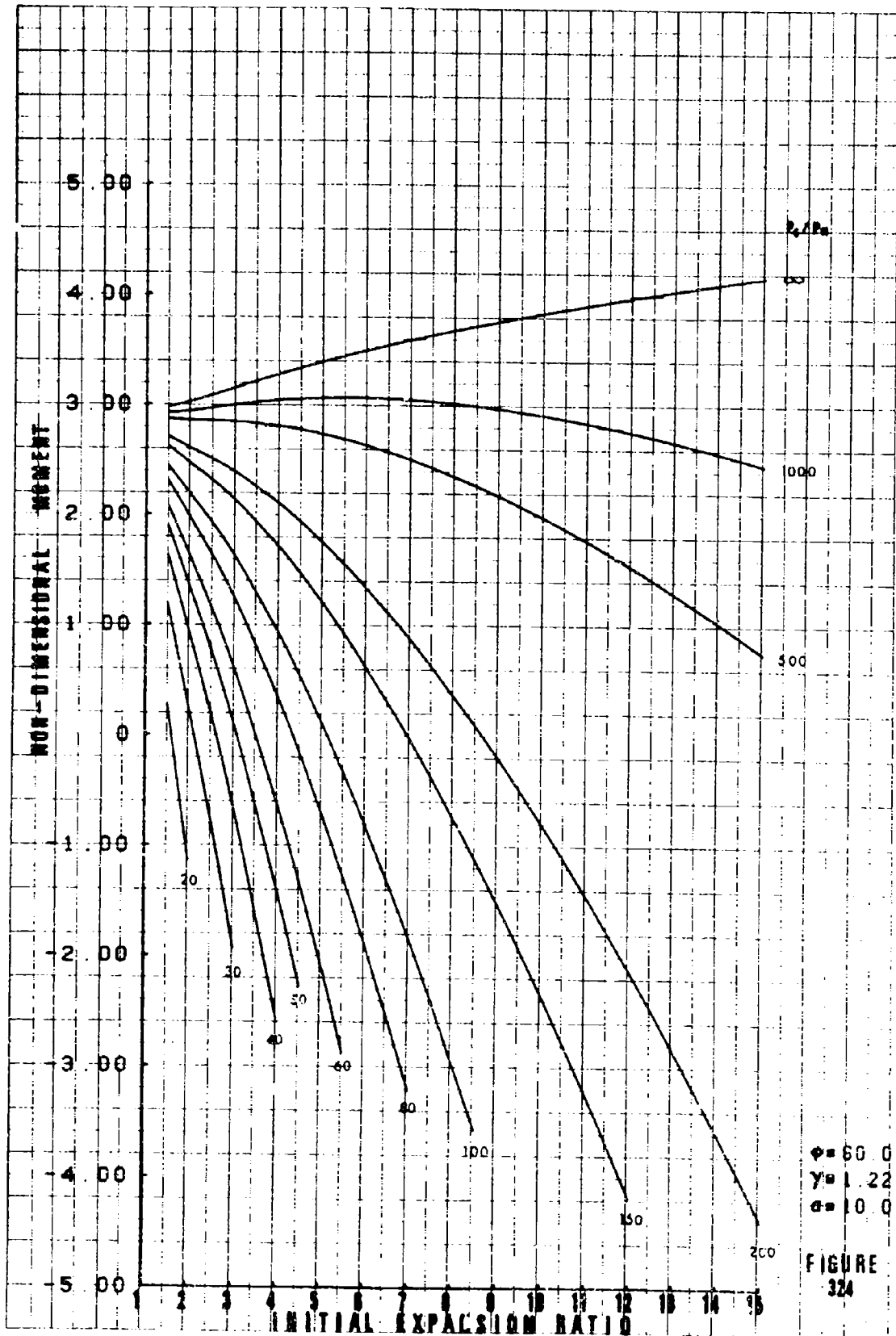
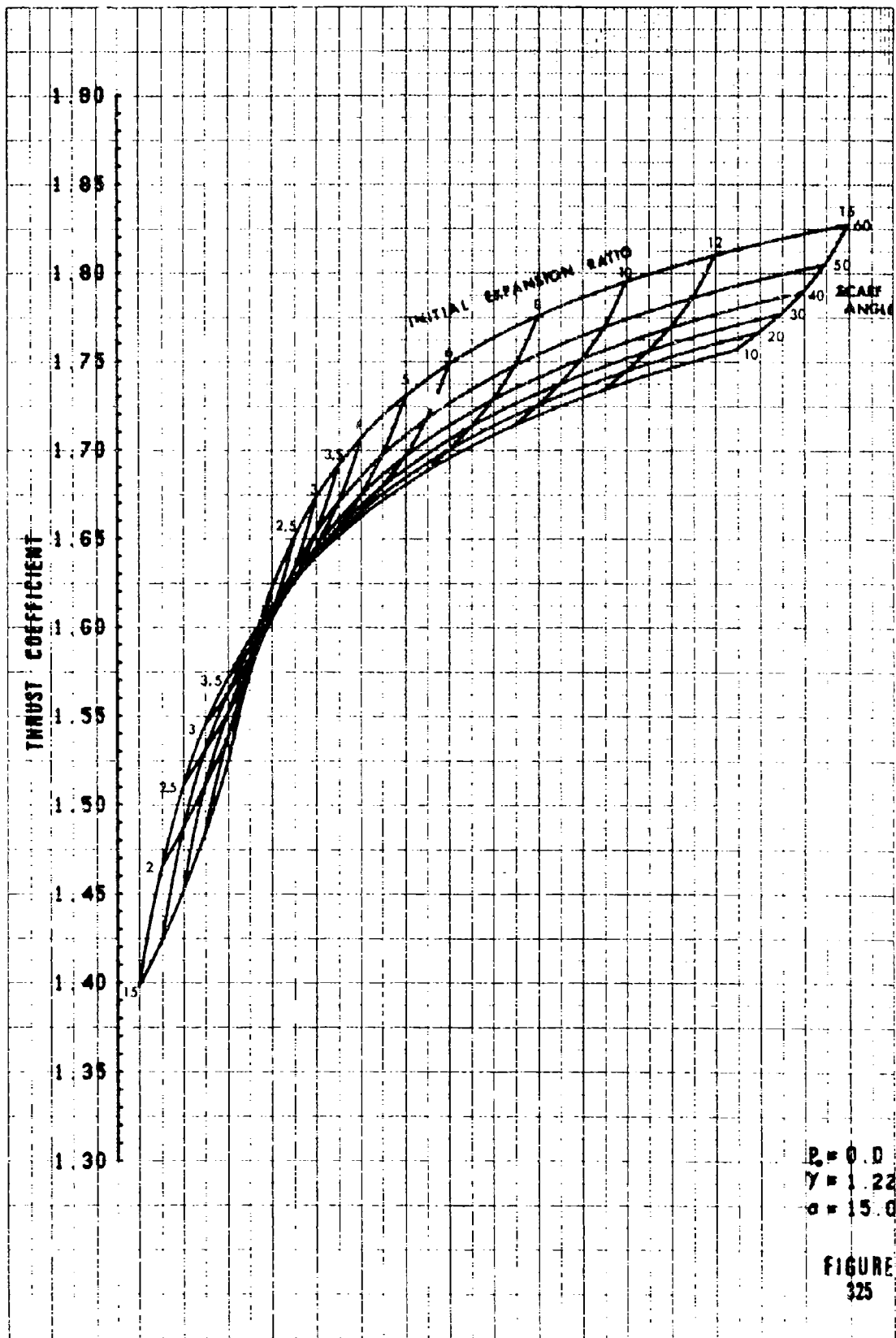
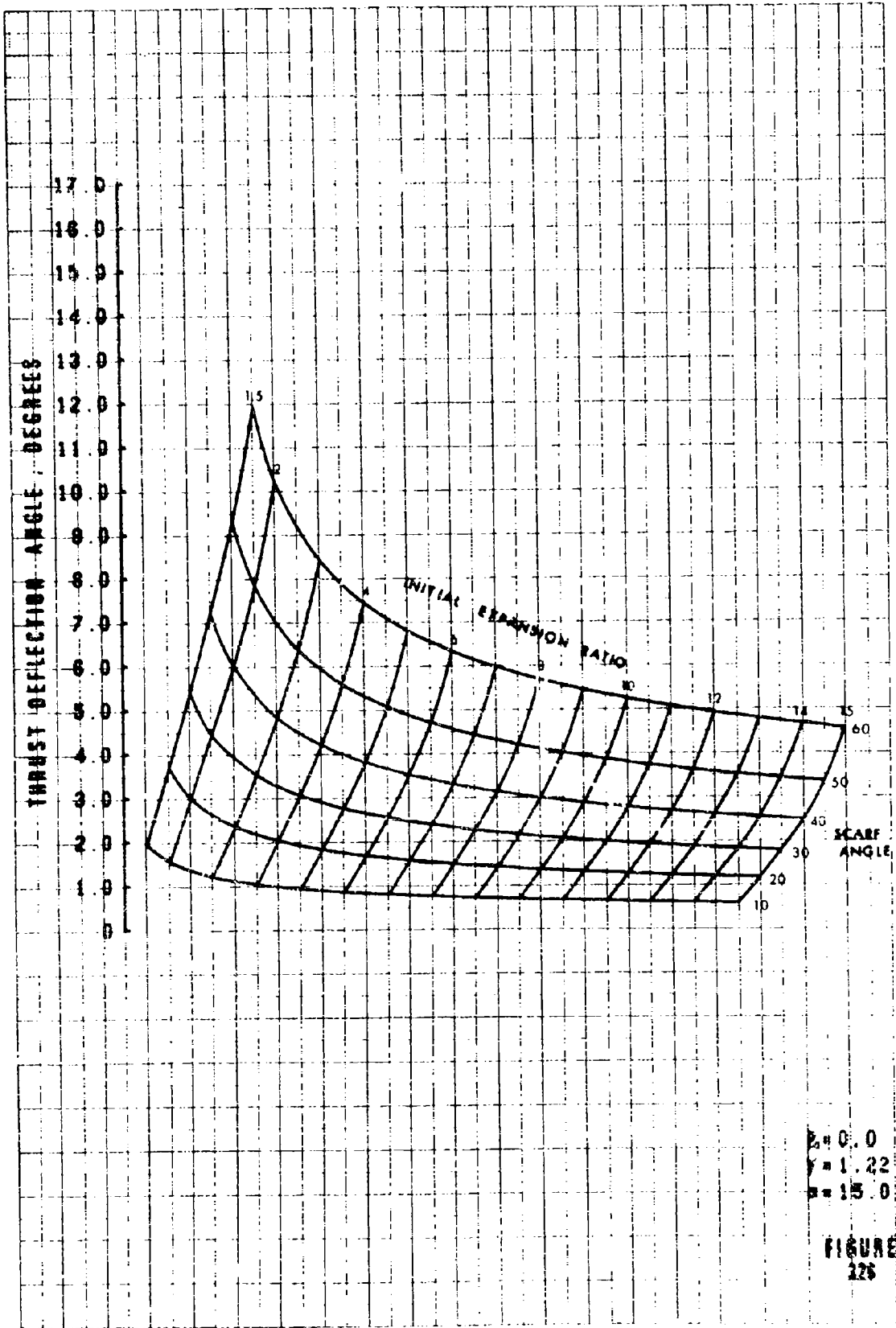


FIGURE 324



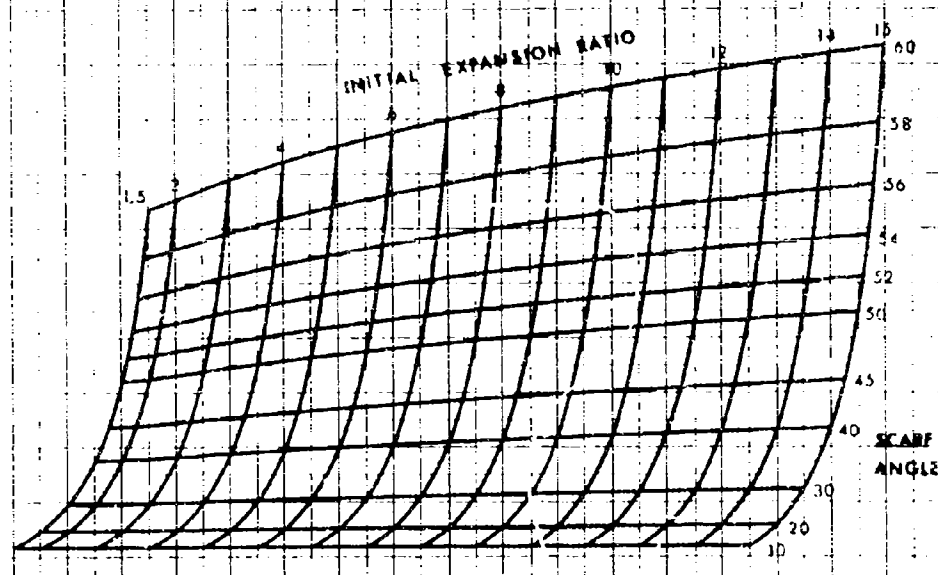


$\beta = 0.0$   
 $\gamma = 1.22$   
 $\alpha = 15.0$

FIGURE 226

NON-DIMENSIONAL MOMENT

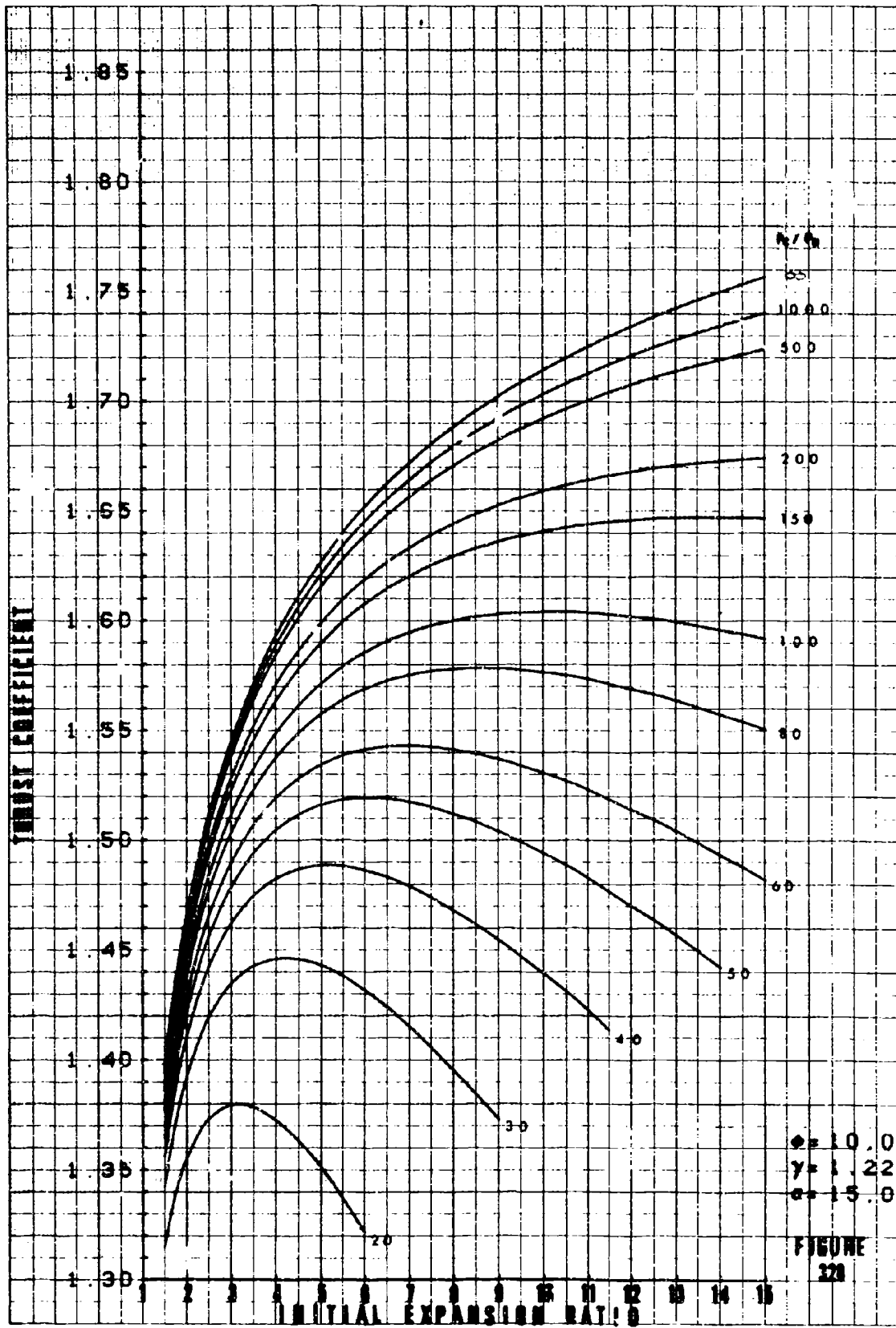
10.0  
9.0  
8.0  
7.0  
6.0  
5.0  
4.0  
3.0  
2.0  
1.0  
0



$P_0 = 0.0$   
 $\gamma = 1.22$   
 $\alpha = 5.0$

FIGURE 327





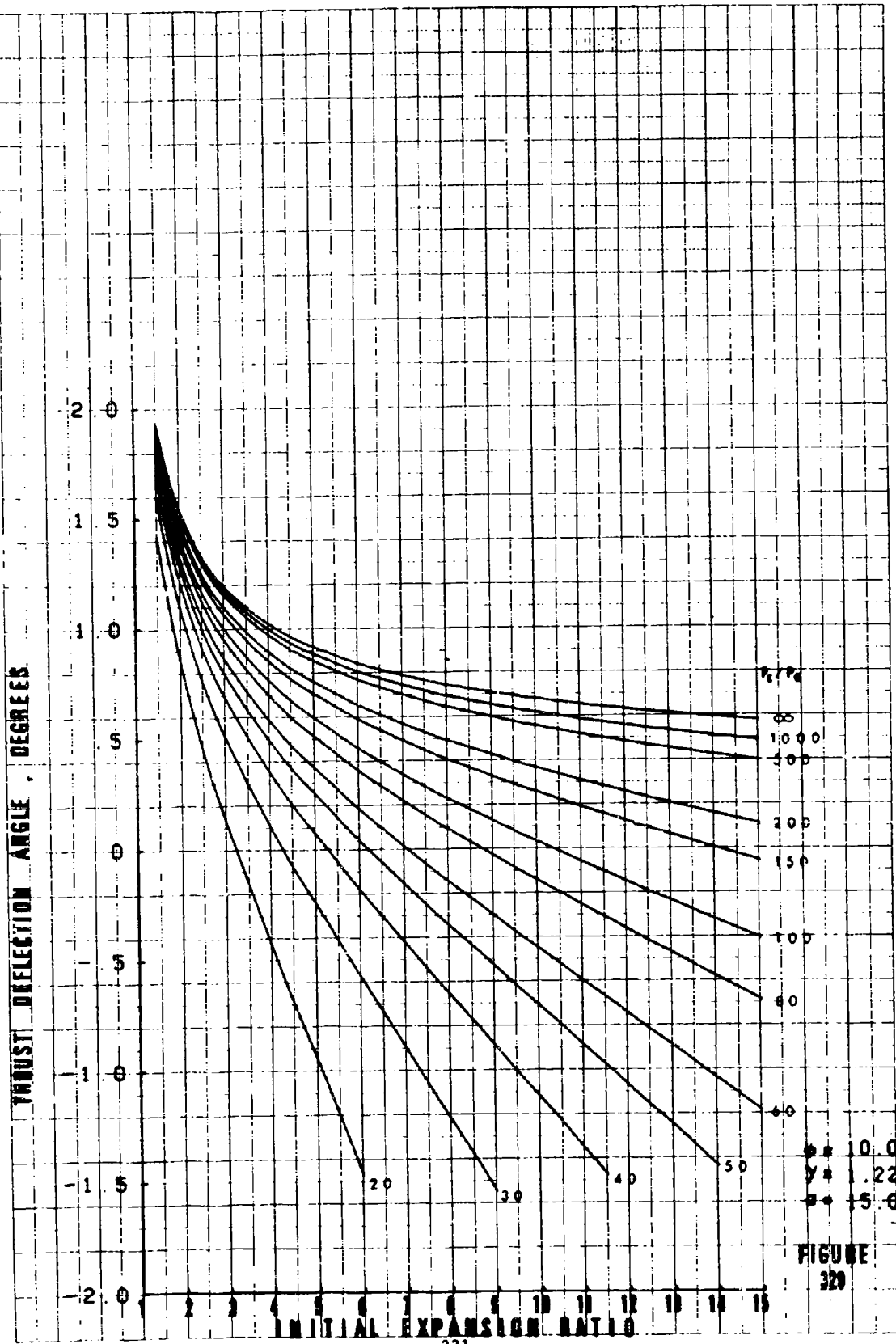
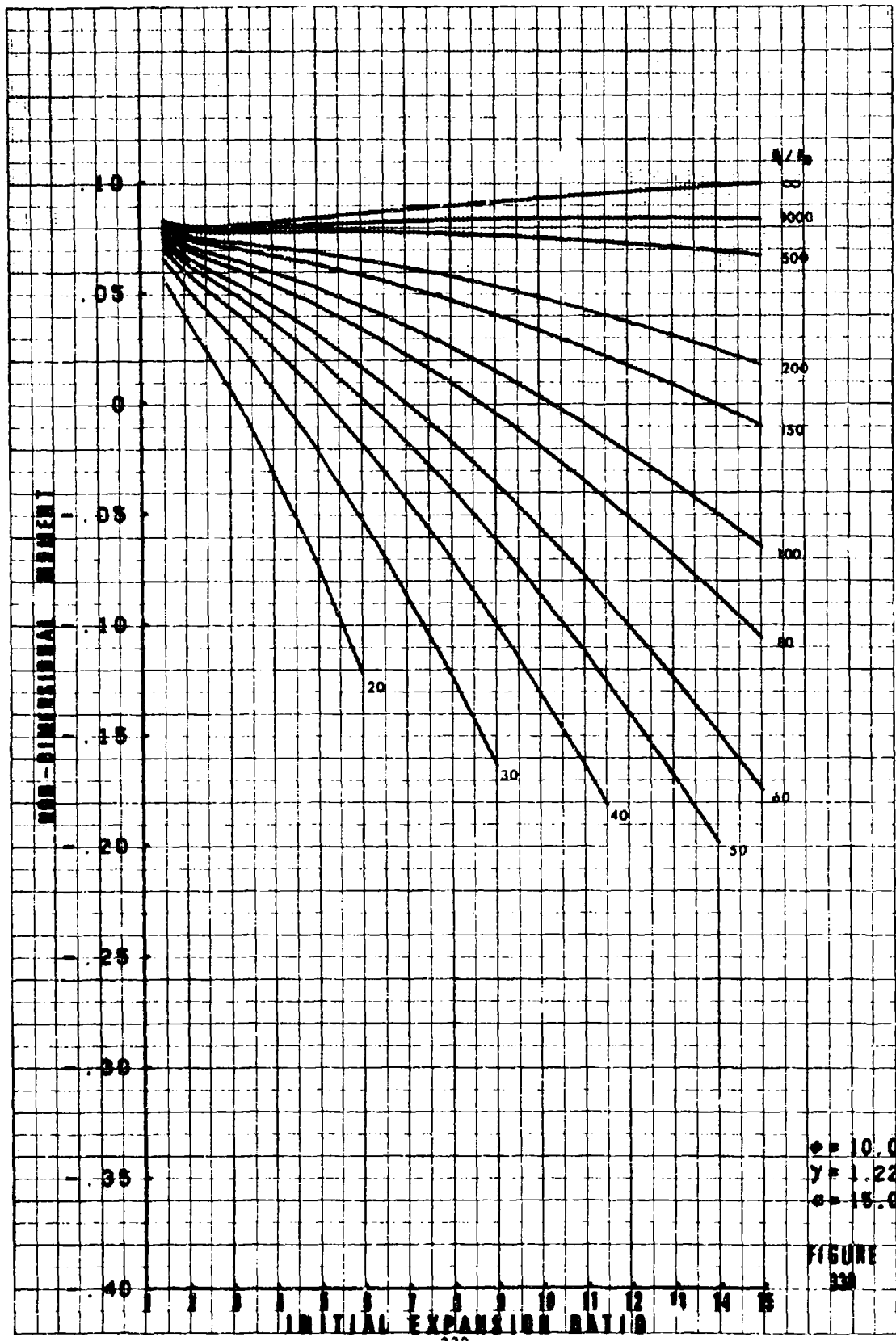
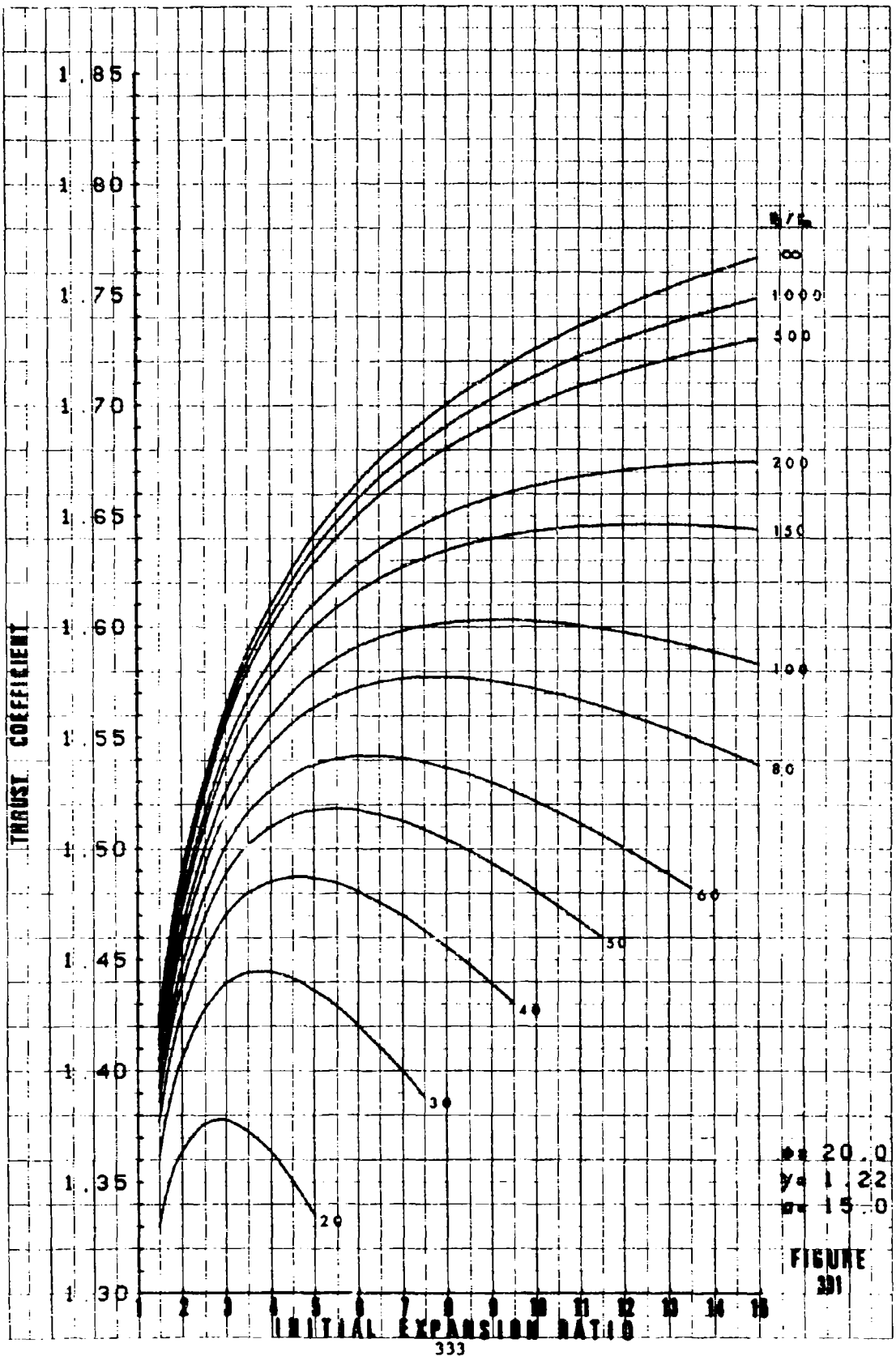


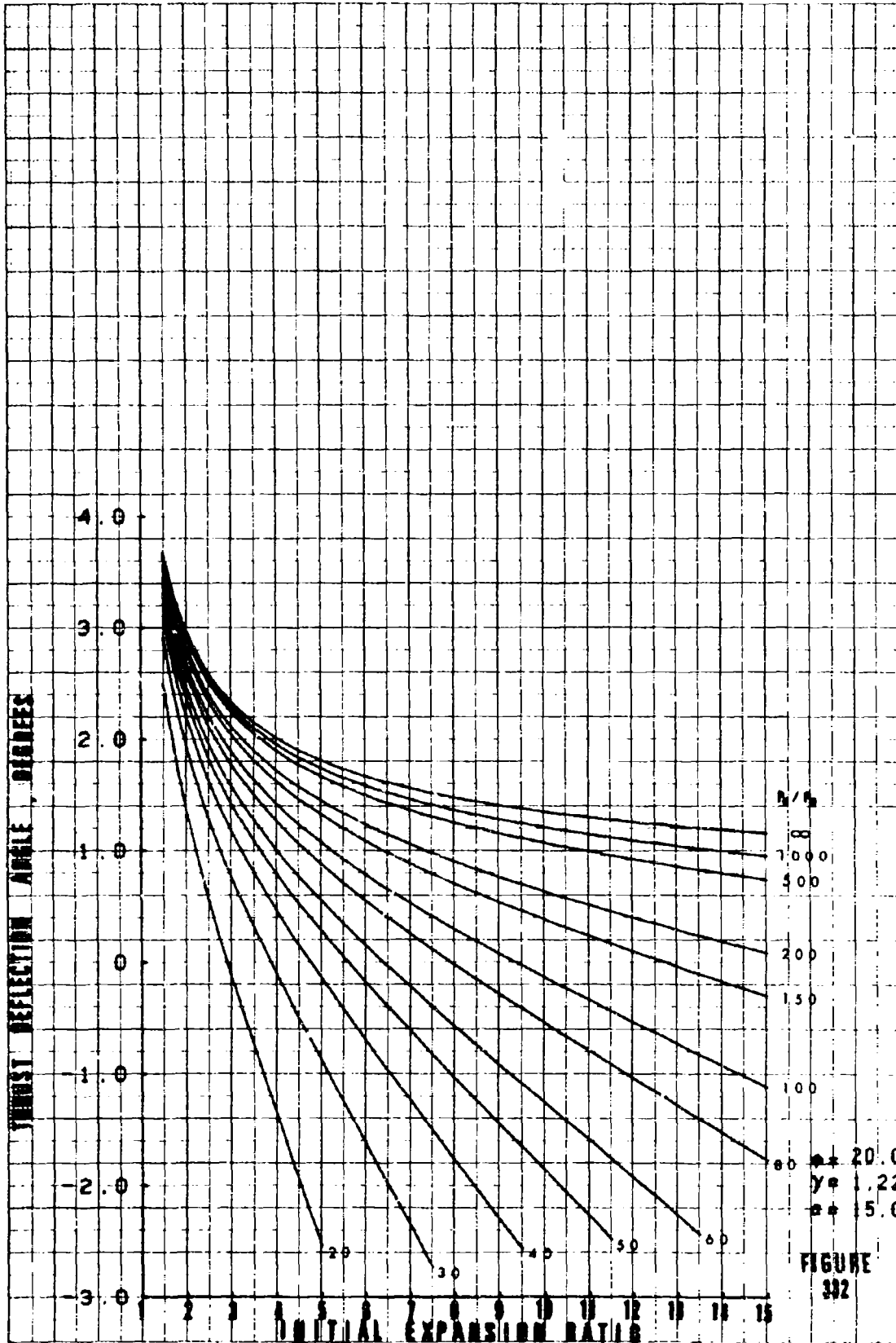
FIGURE 320



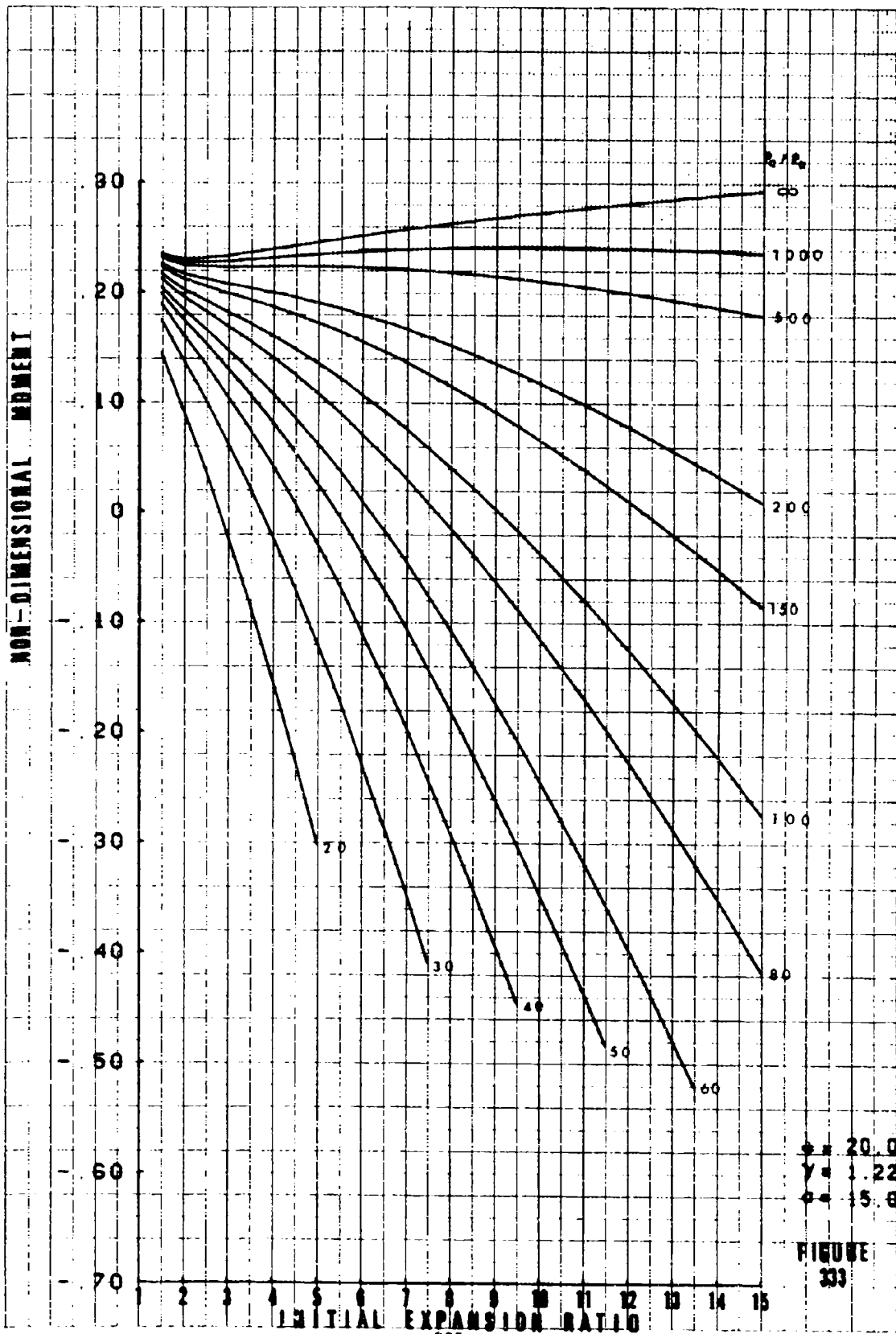


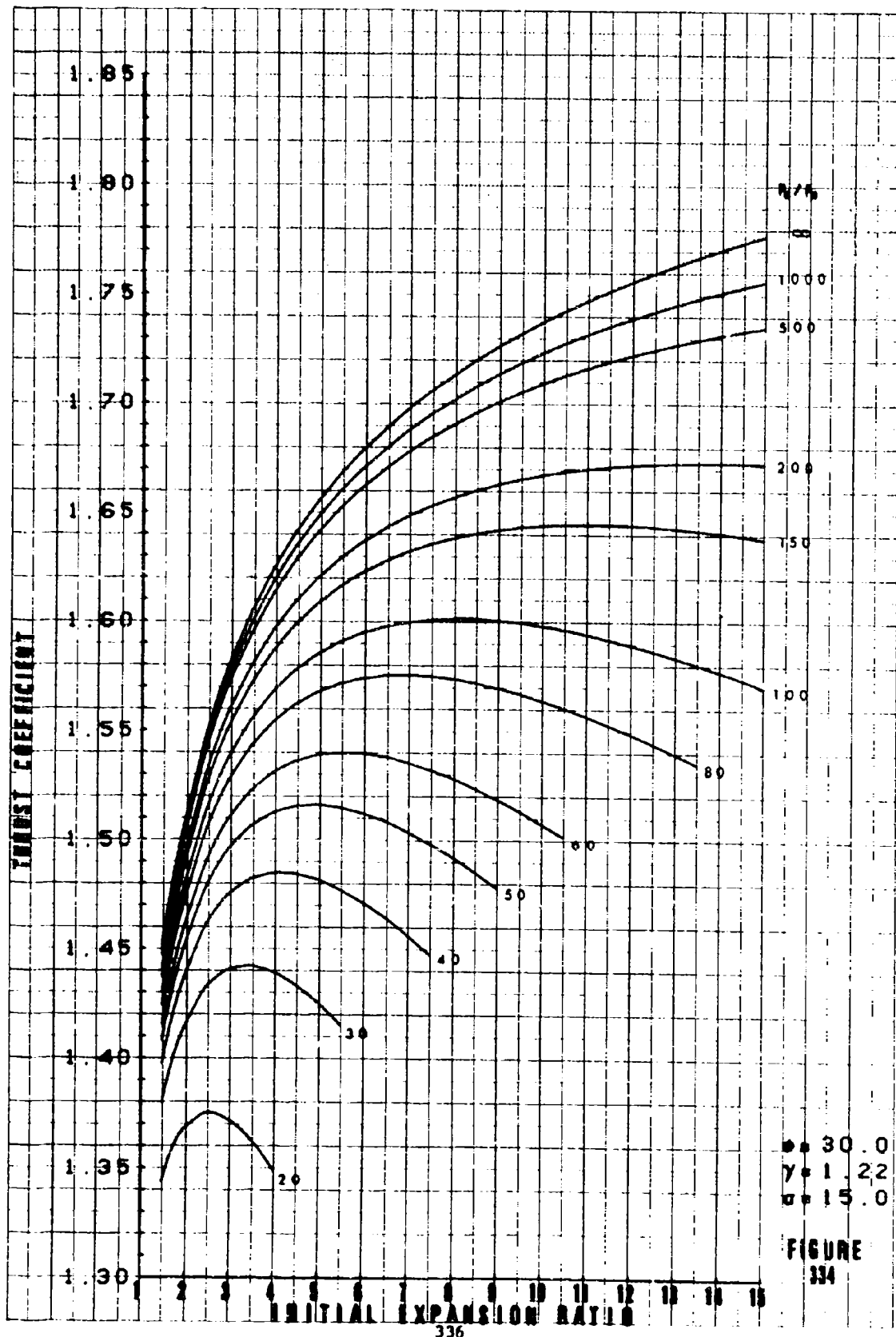
at 20.0  
 at 1.22  
 at 15.0

FIGURE 331



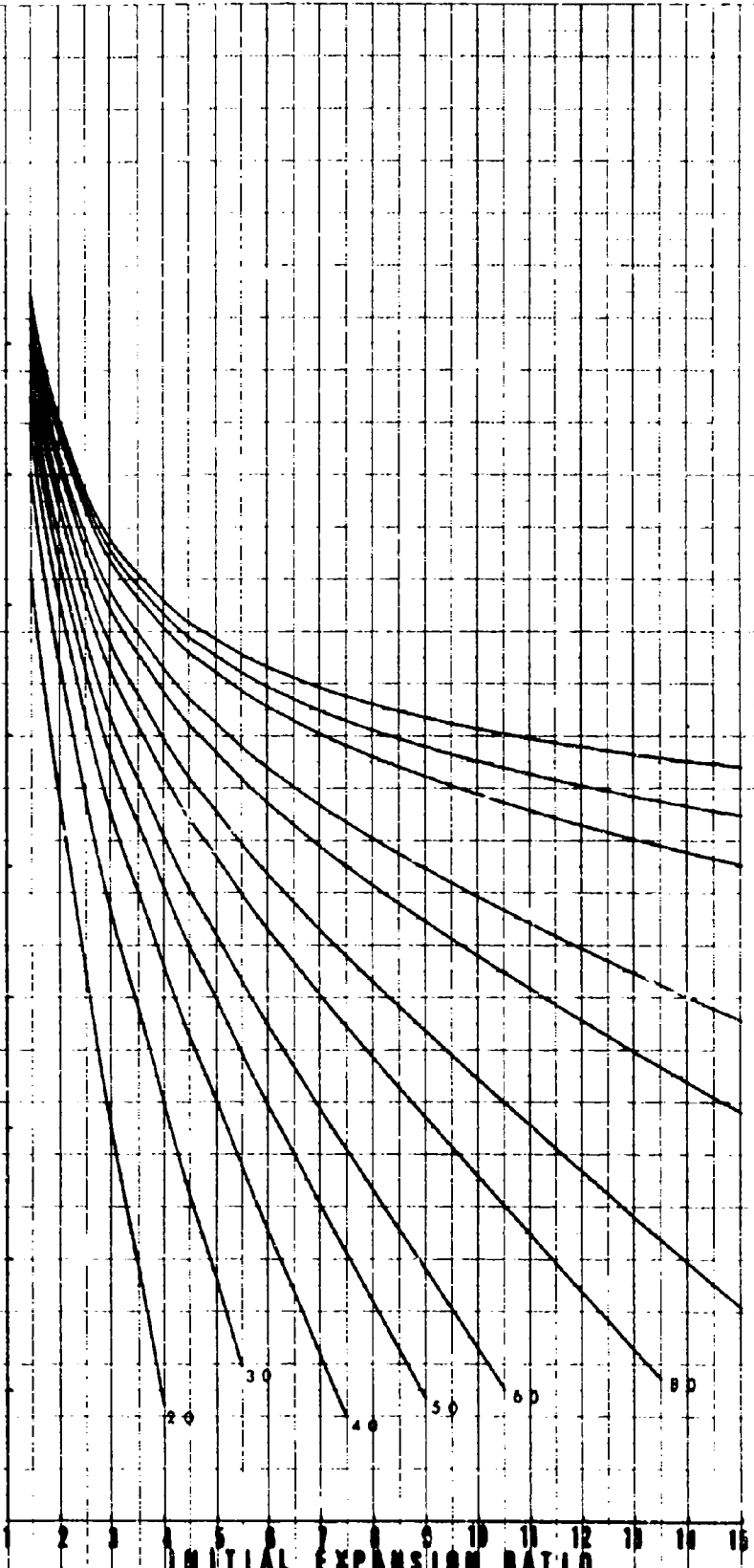
**FIGURE 302**





THRUST DEFLECTION ANGLE DEGREES

6.0  
5.0  
4.0  
3.0  
2.0  
1.0  
0  
-1.0  
-2.0  
-3.0  
-4.0



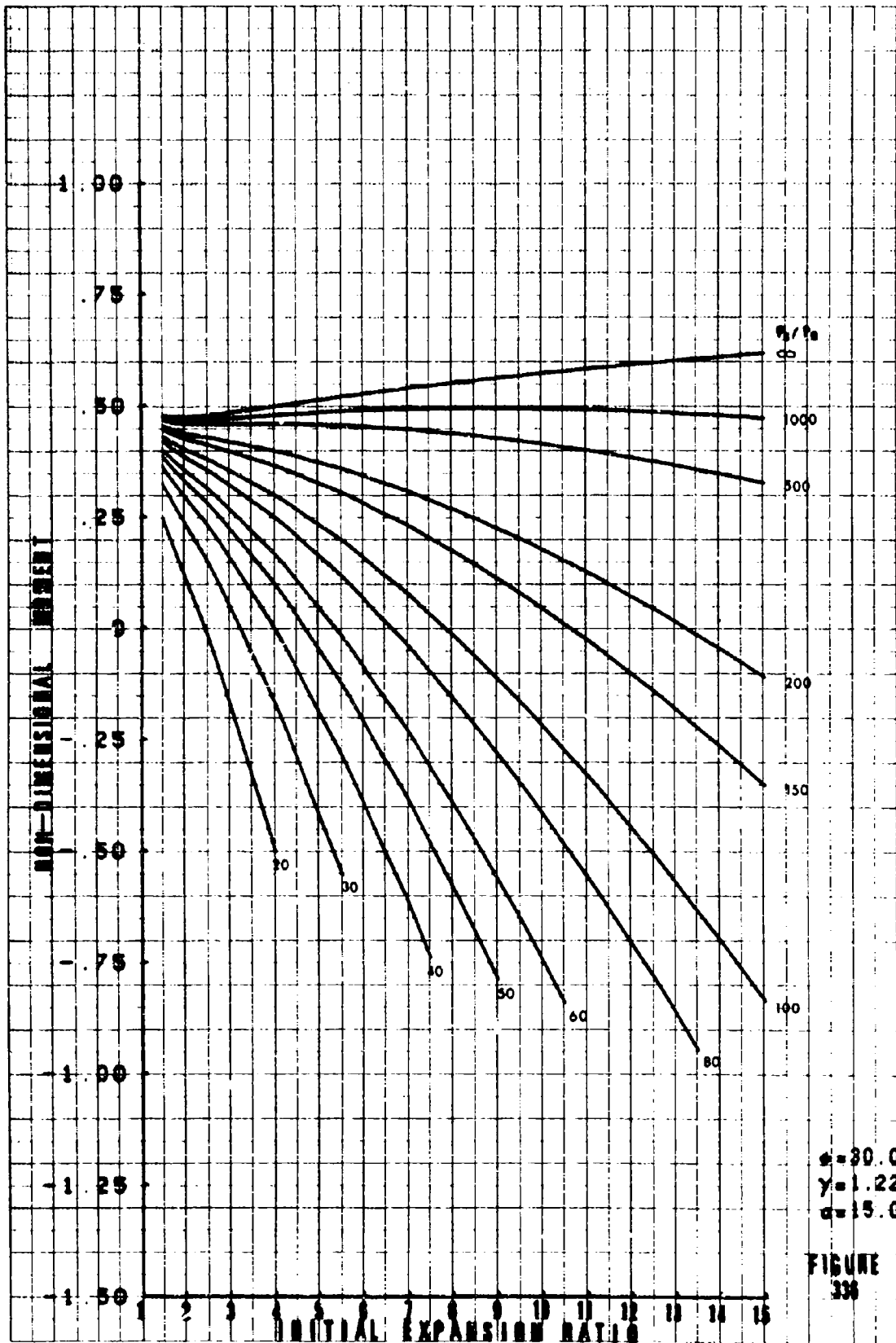
N/B  
infinity  
1000  
500  
200  
150  
100

••• 30.0  
y = 1.22  
□□□ 15.0

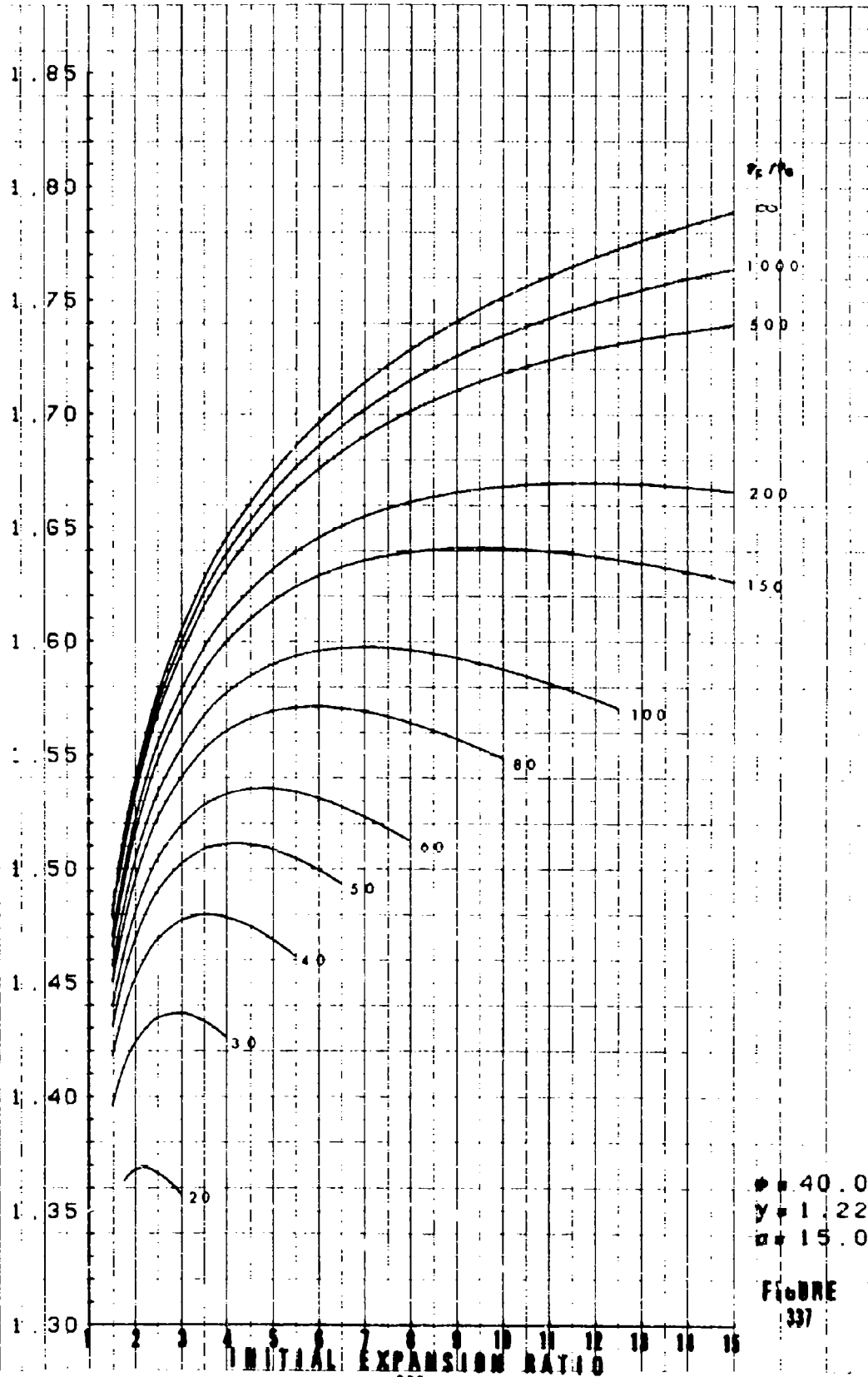
FIGURE 335

INITIAL EXPANSION RATIO





THRUST COEFFICIENT



◆ 40.0  
 y 1.22  
 □ 15.0

FIGURE 337

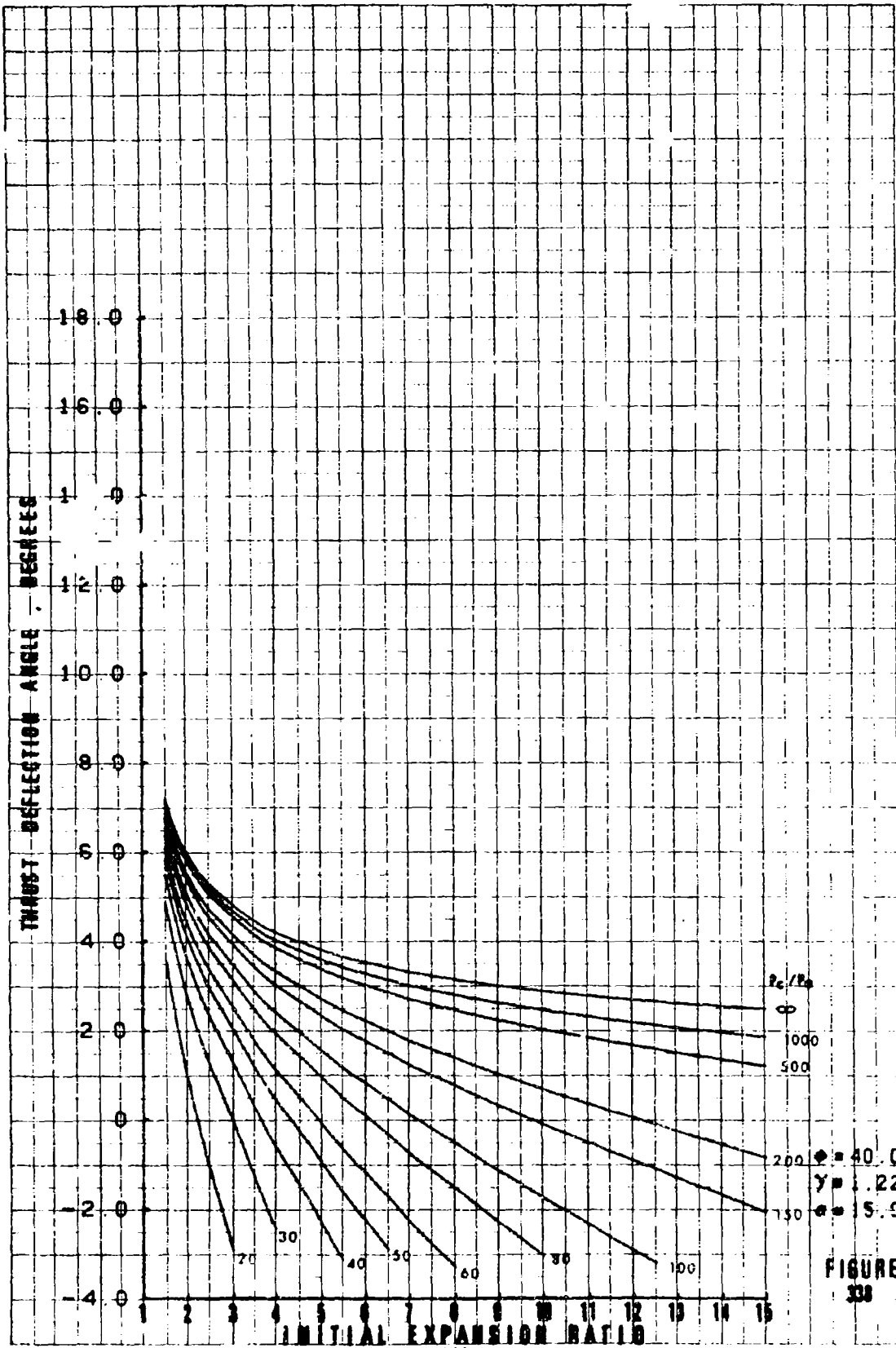
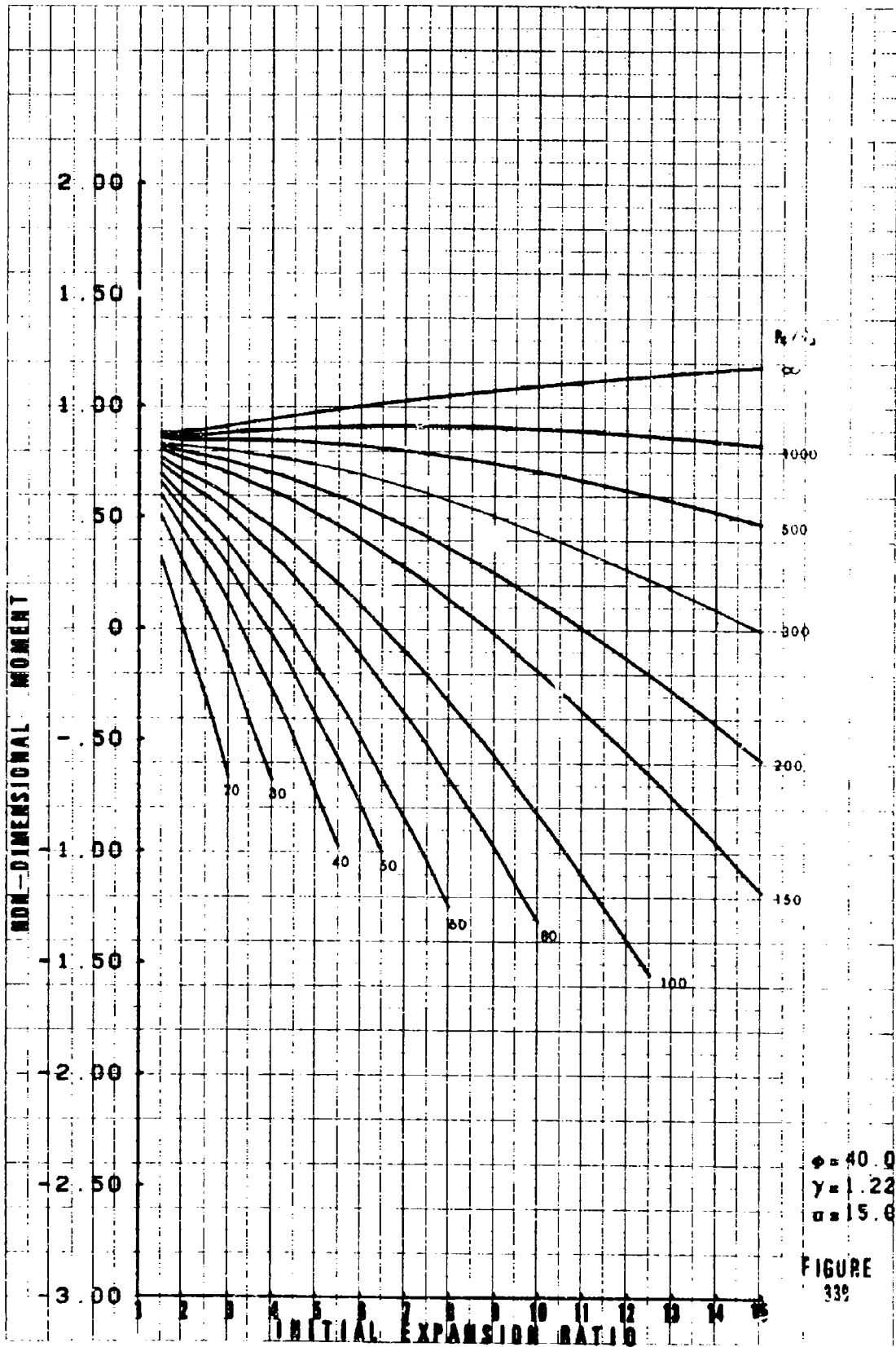
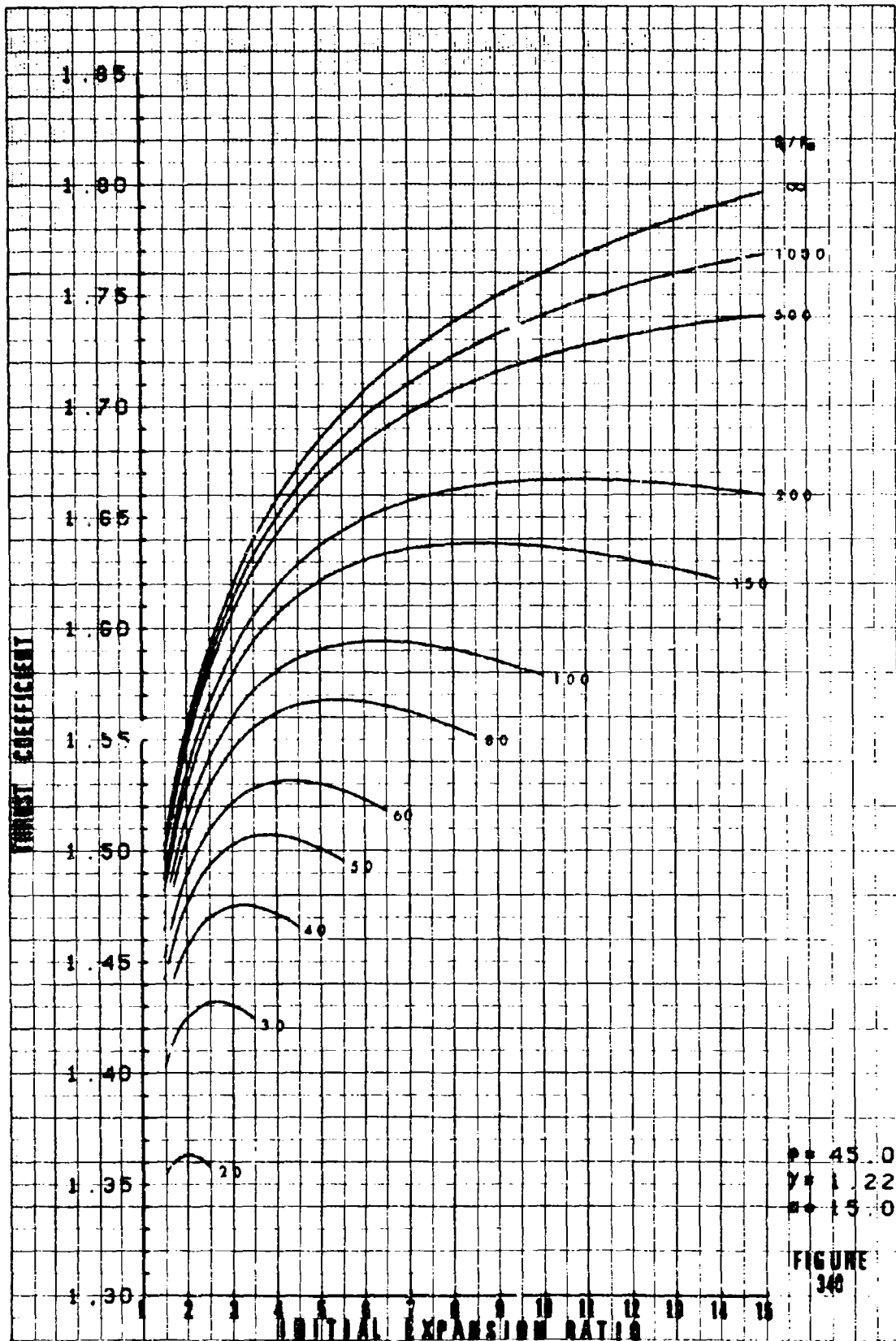


FIGURE 338





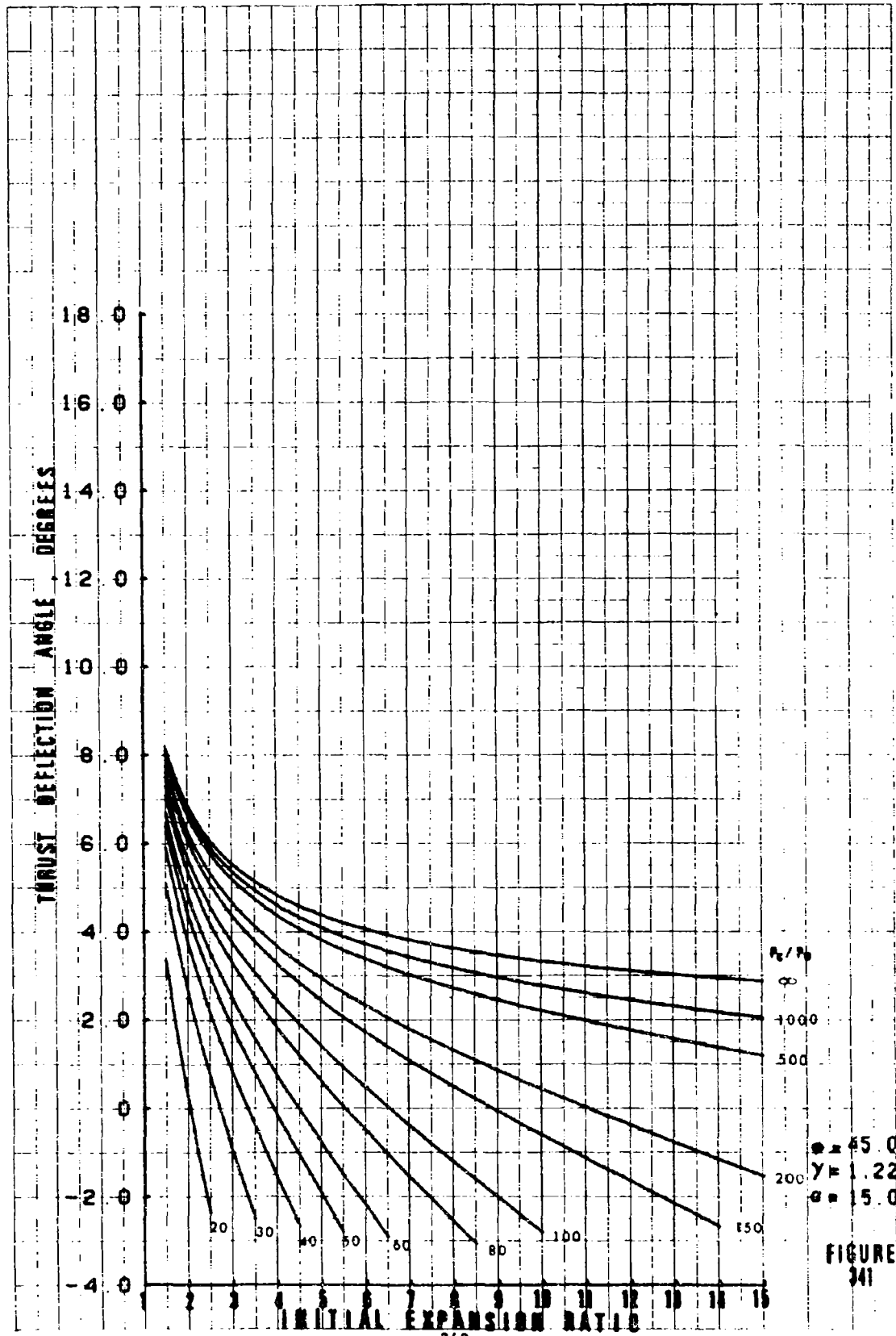
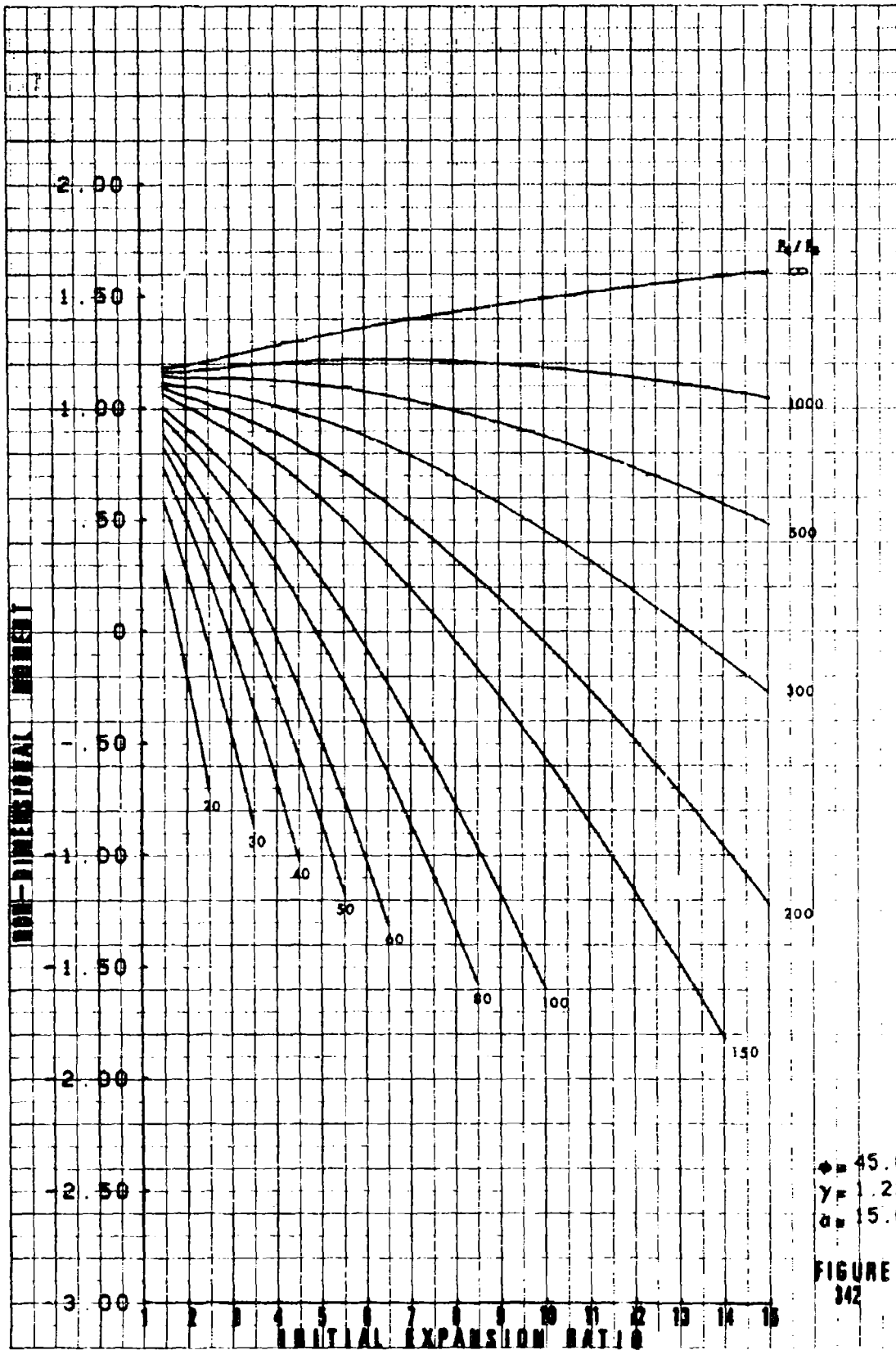


FIGURE 341



$\alpha = 45.0$   
 $\gamma = 1.22$   
 $\beta = 15.0$

FIGURE 342

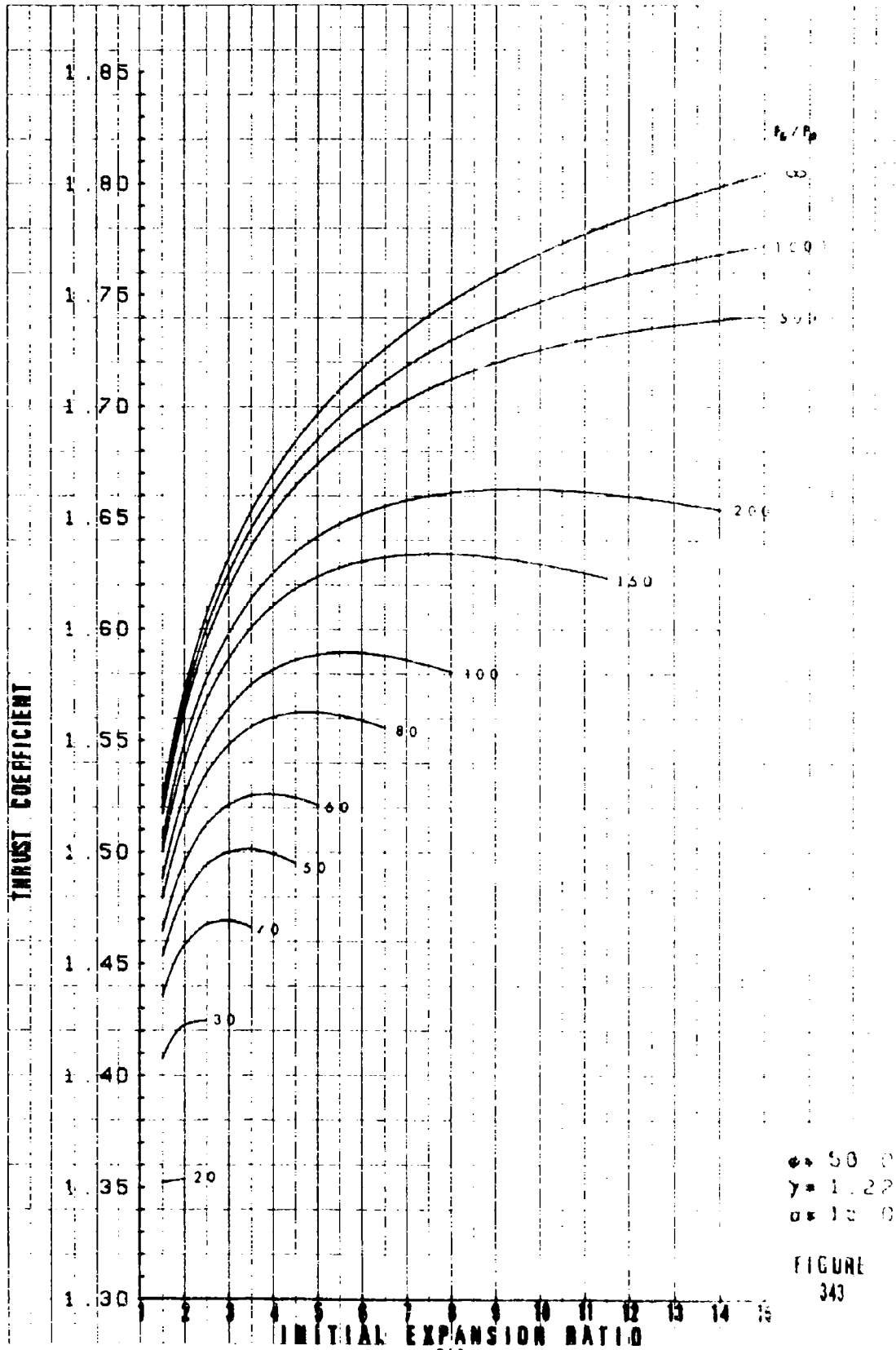
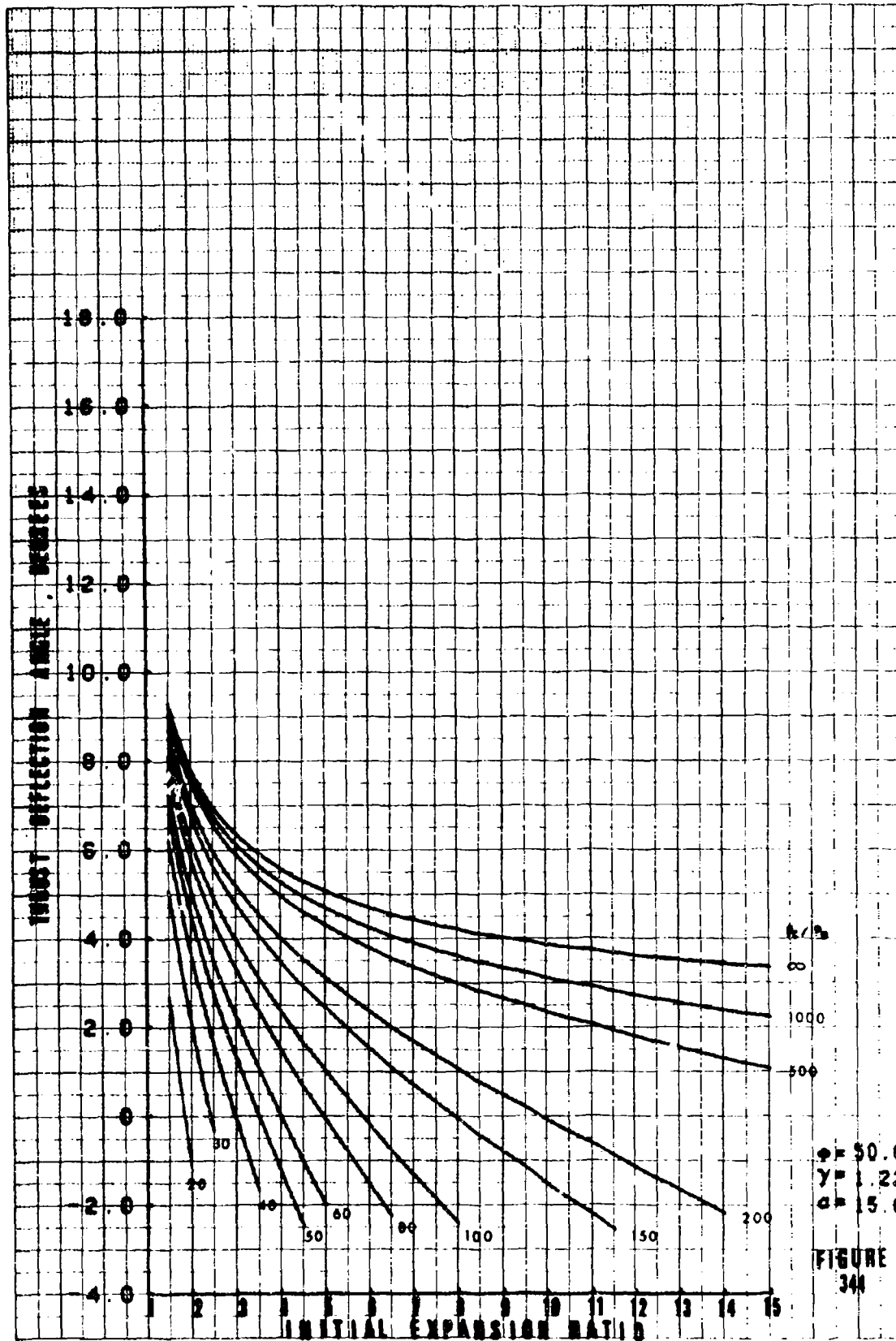
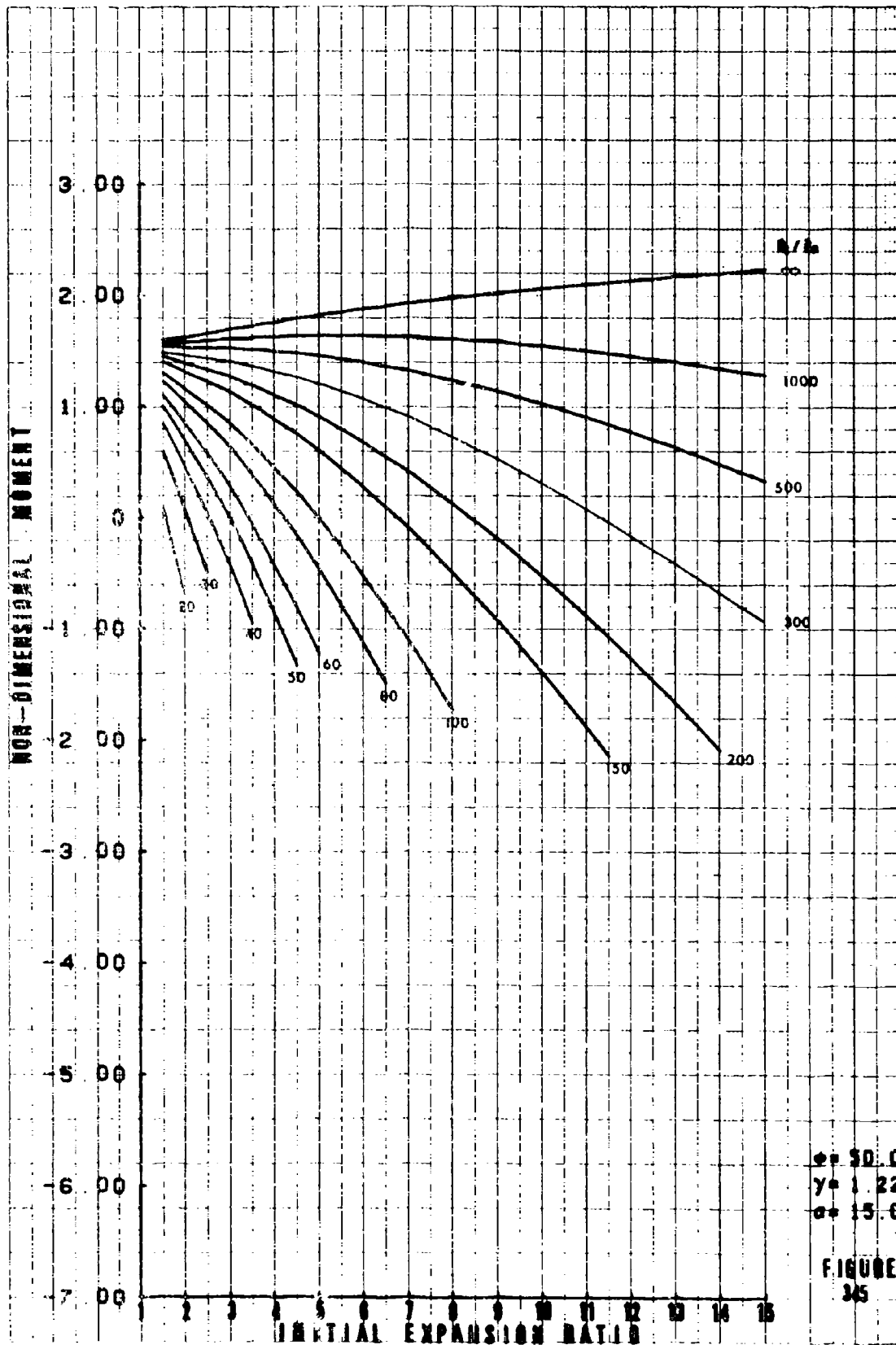
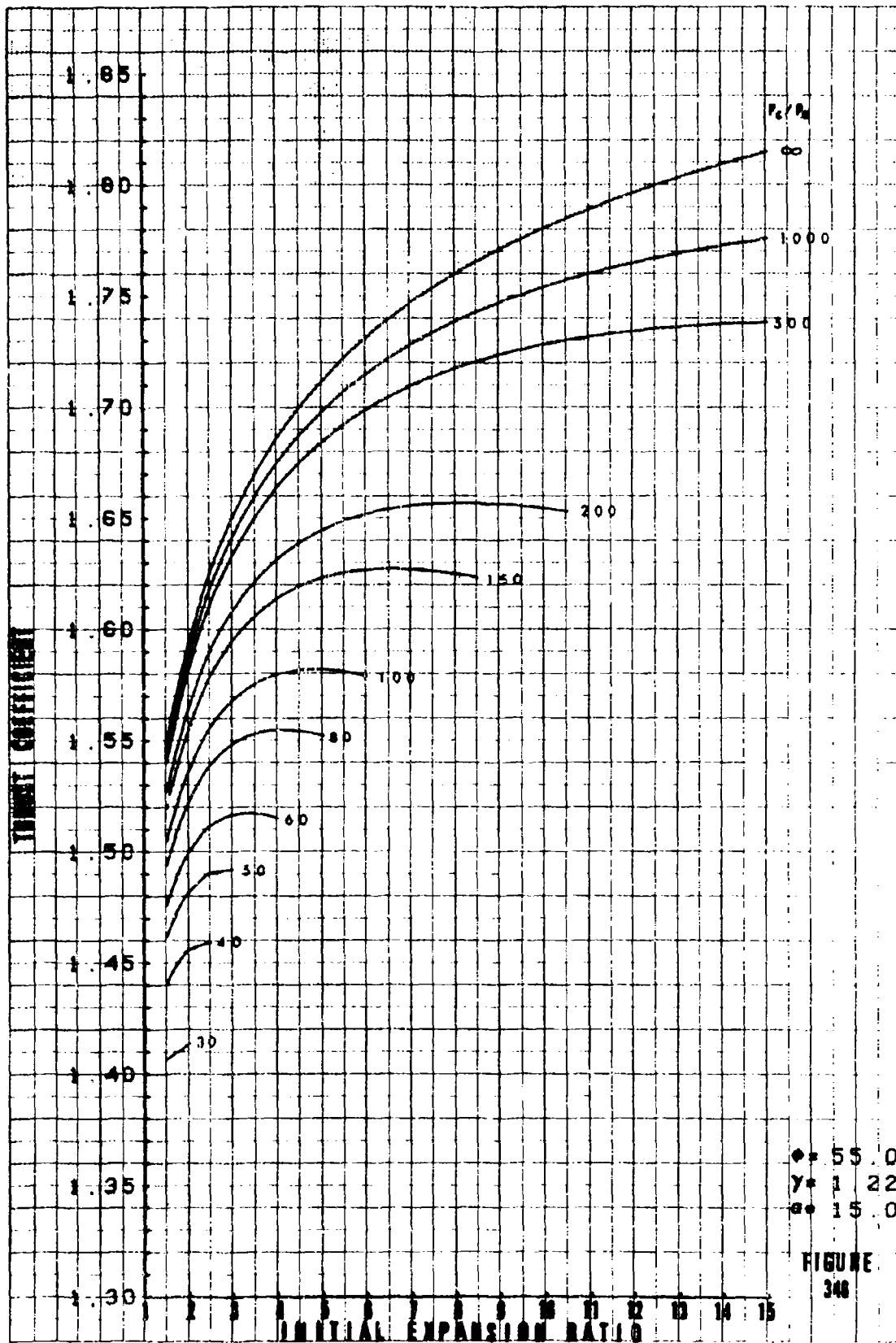


FIGURE 343









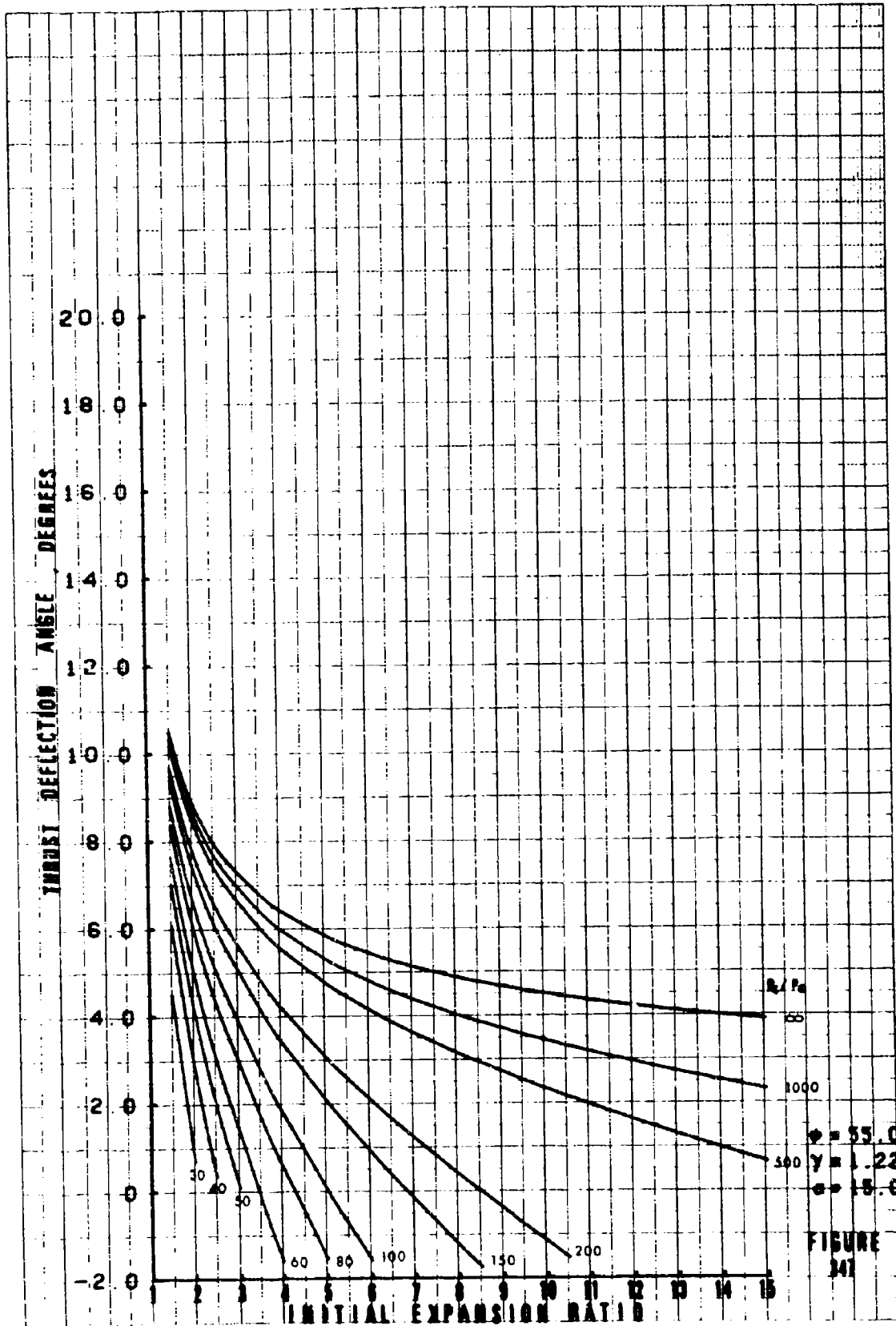
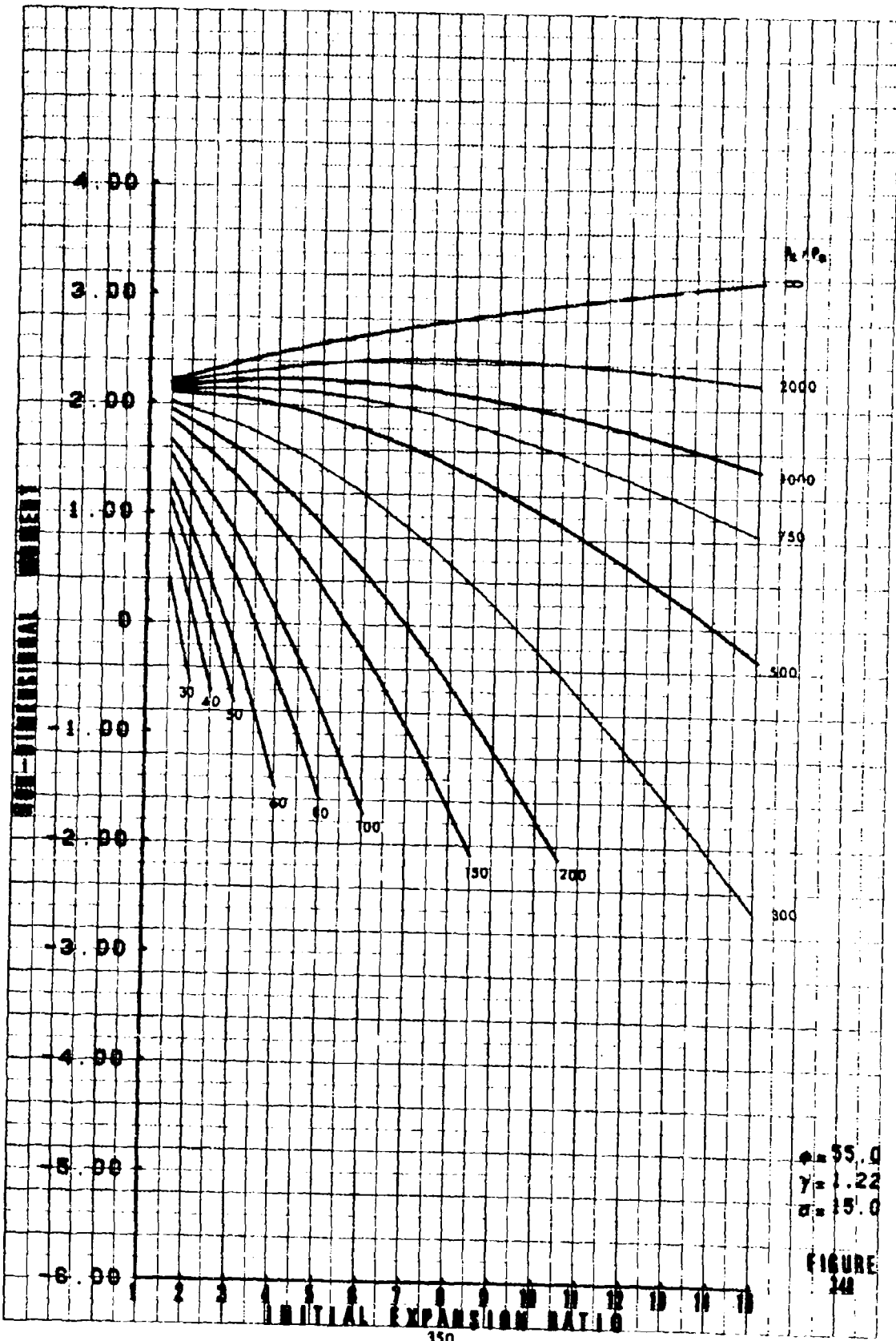
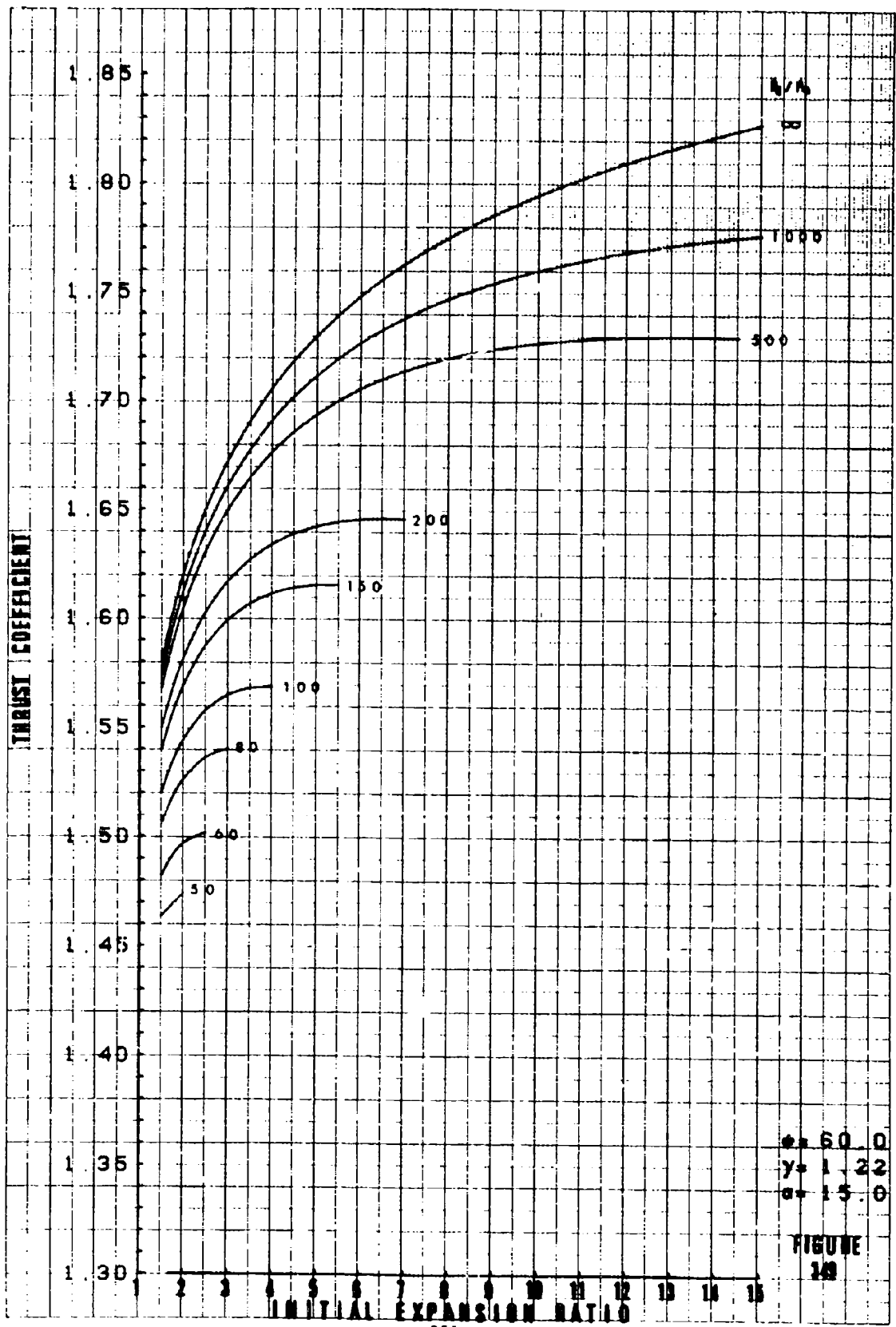


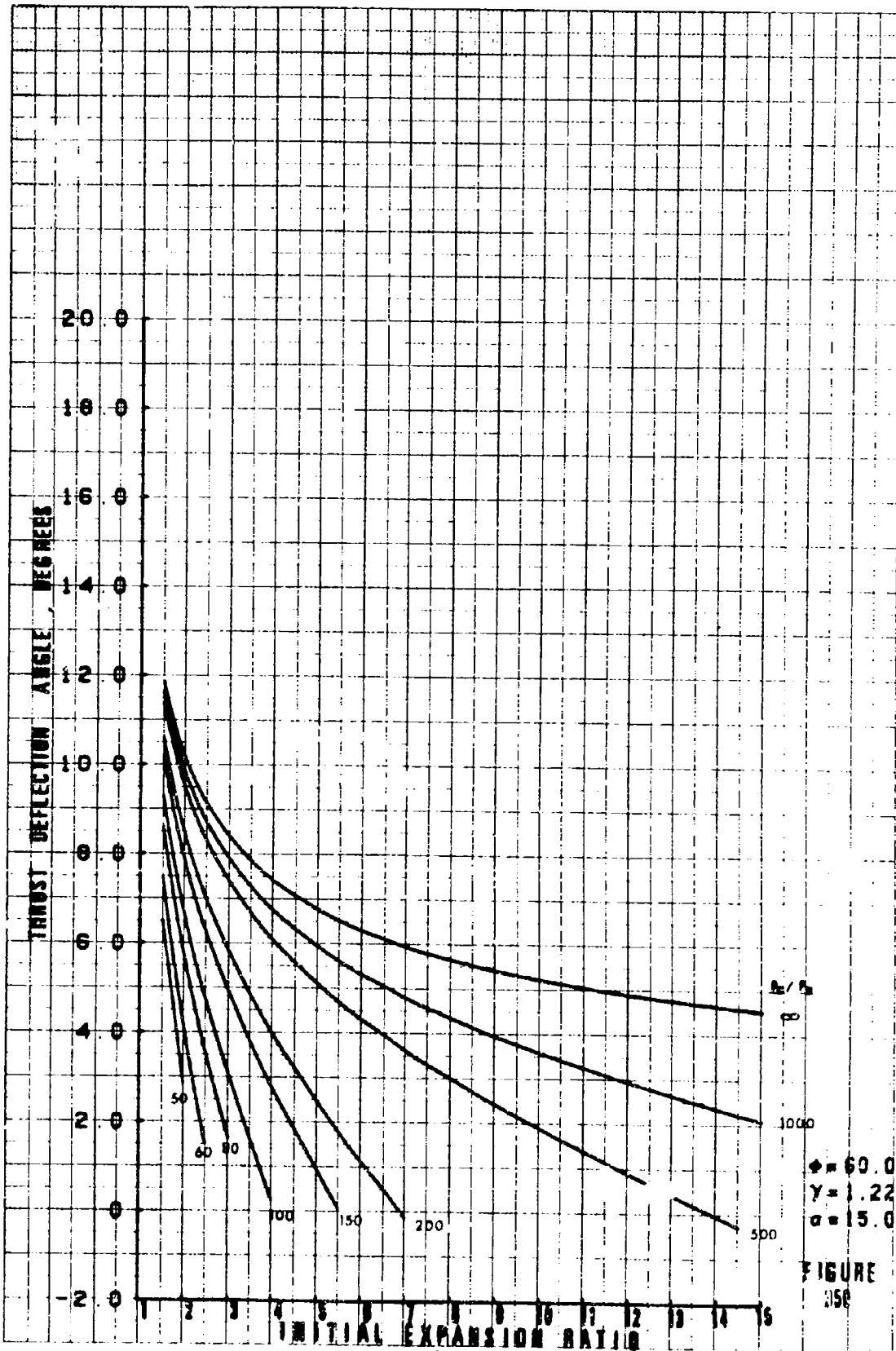
FIGURE 341





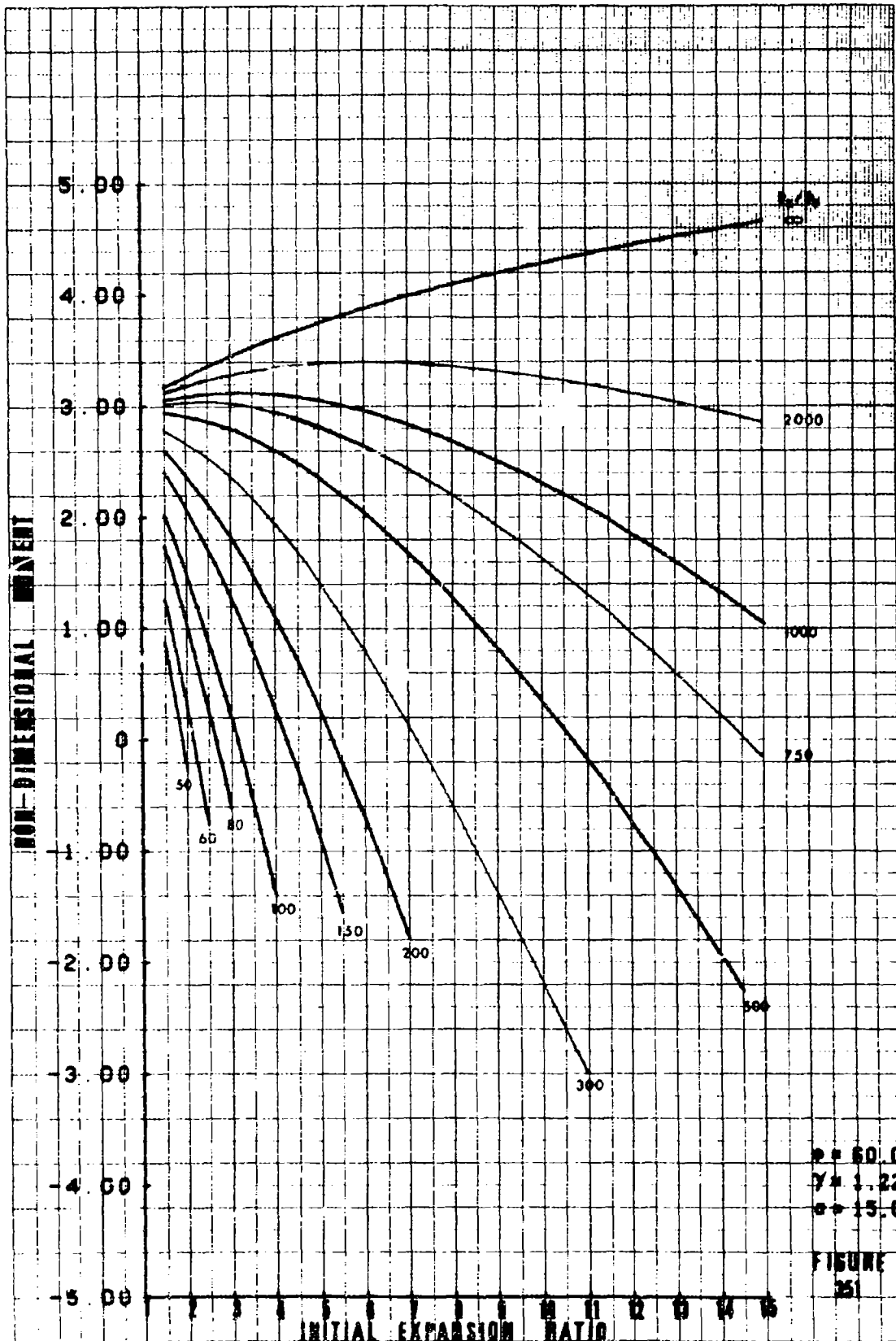
$\epsilon = 60.0$   
 $\gamma = 1.22$   
 $\sigma = 15.0$

FIGURE 249

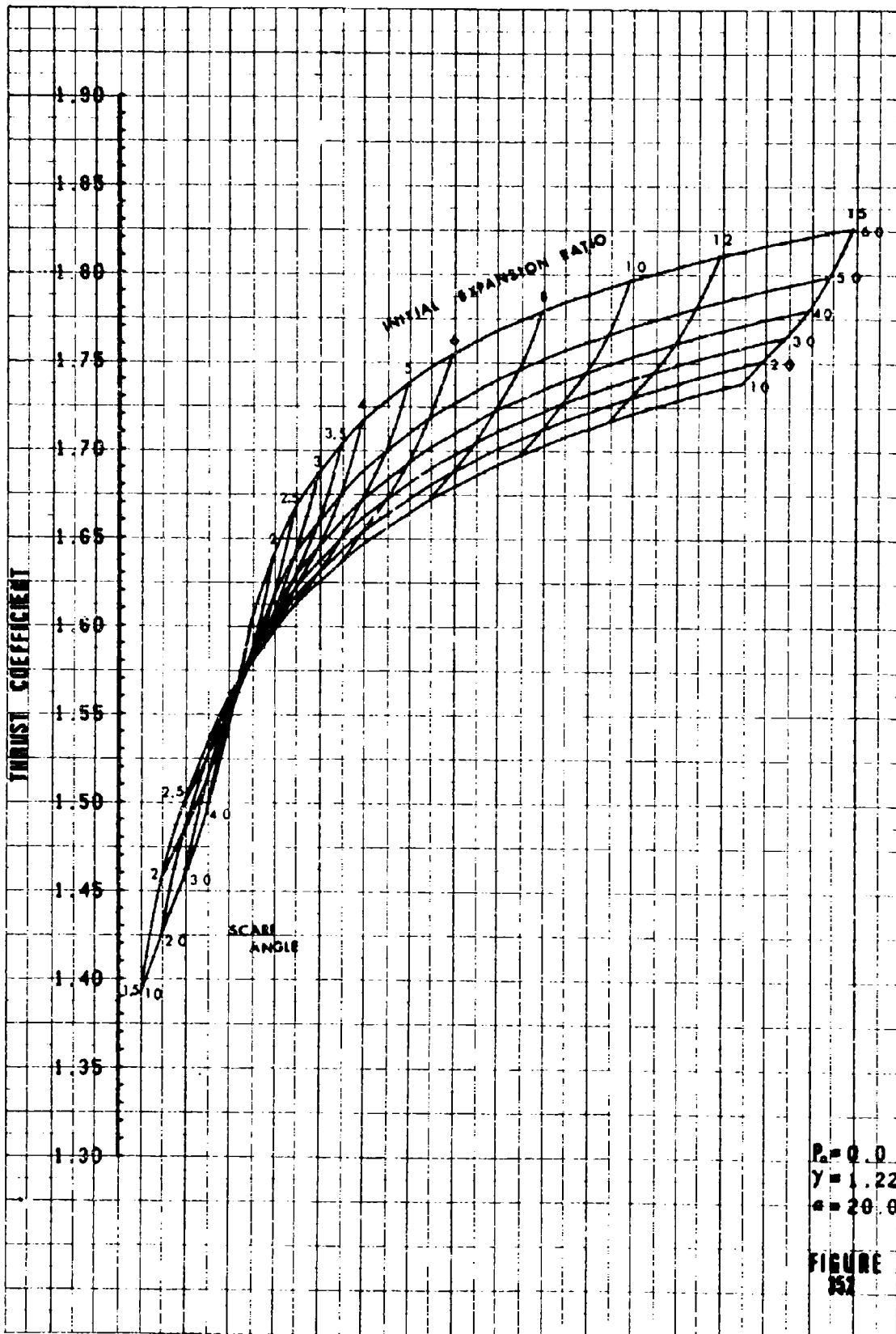


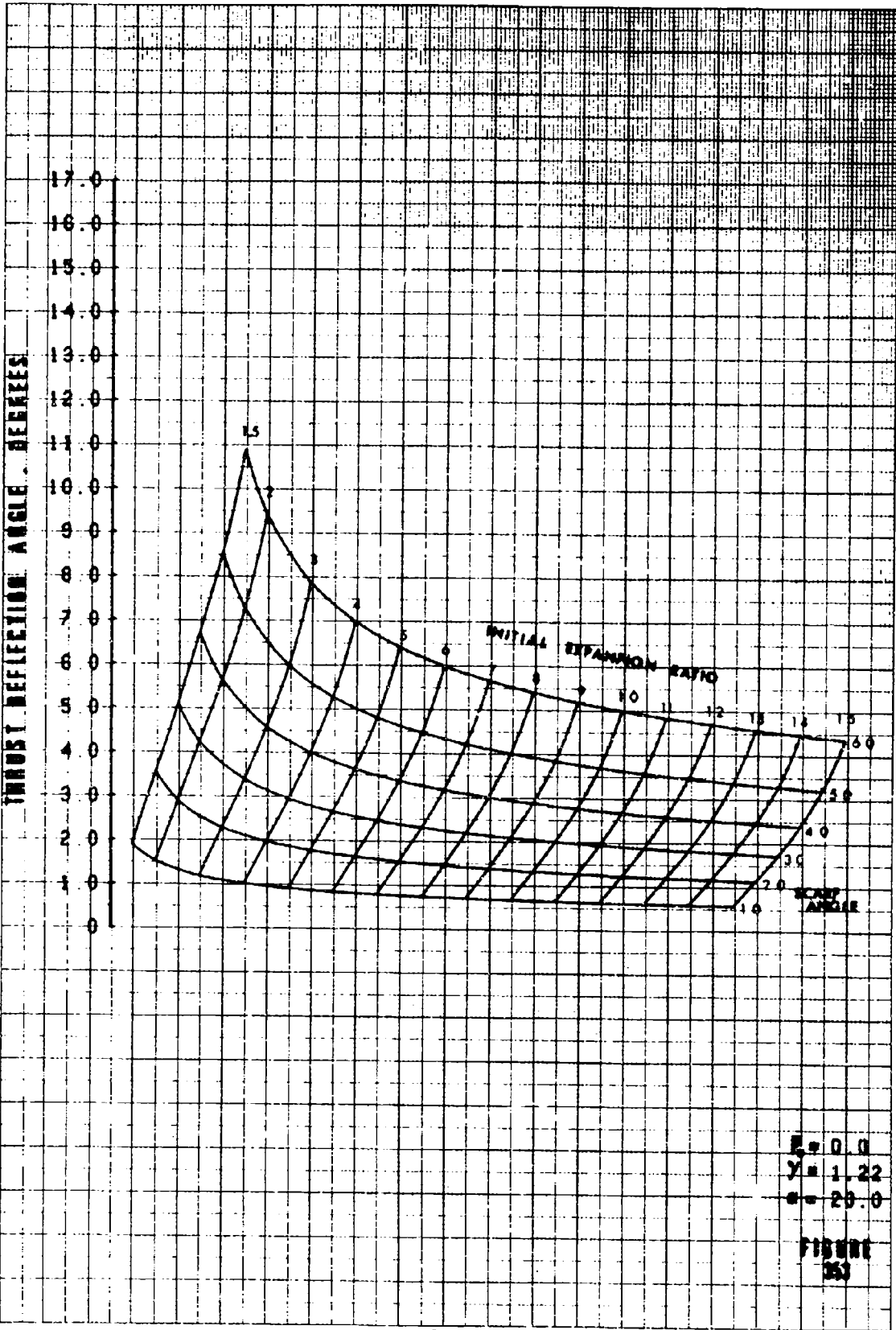
$\alpha = 60.0$   
 $\gamma = 1.22$   
 $\sigma = 15.0$

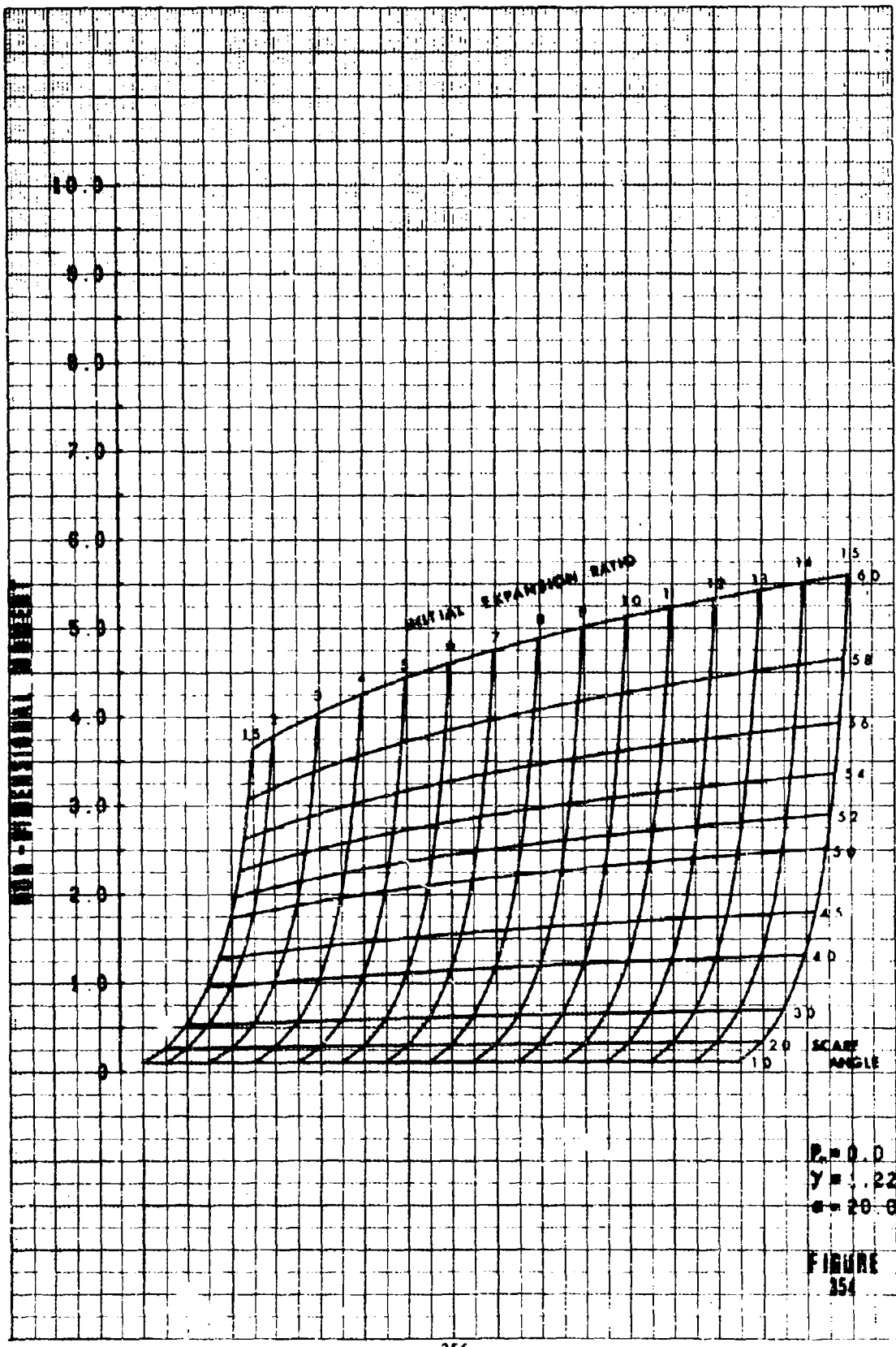
FIGURE 358





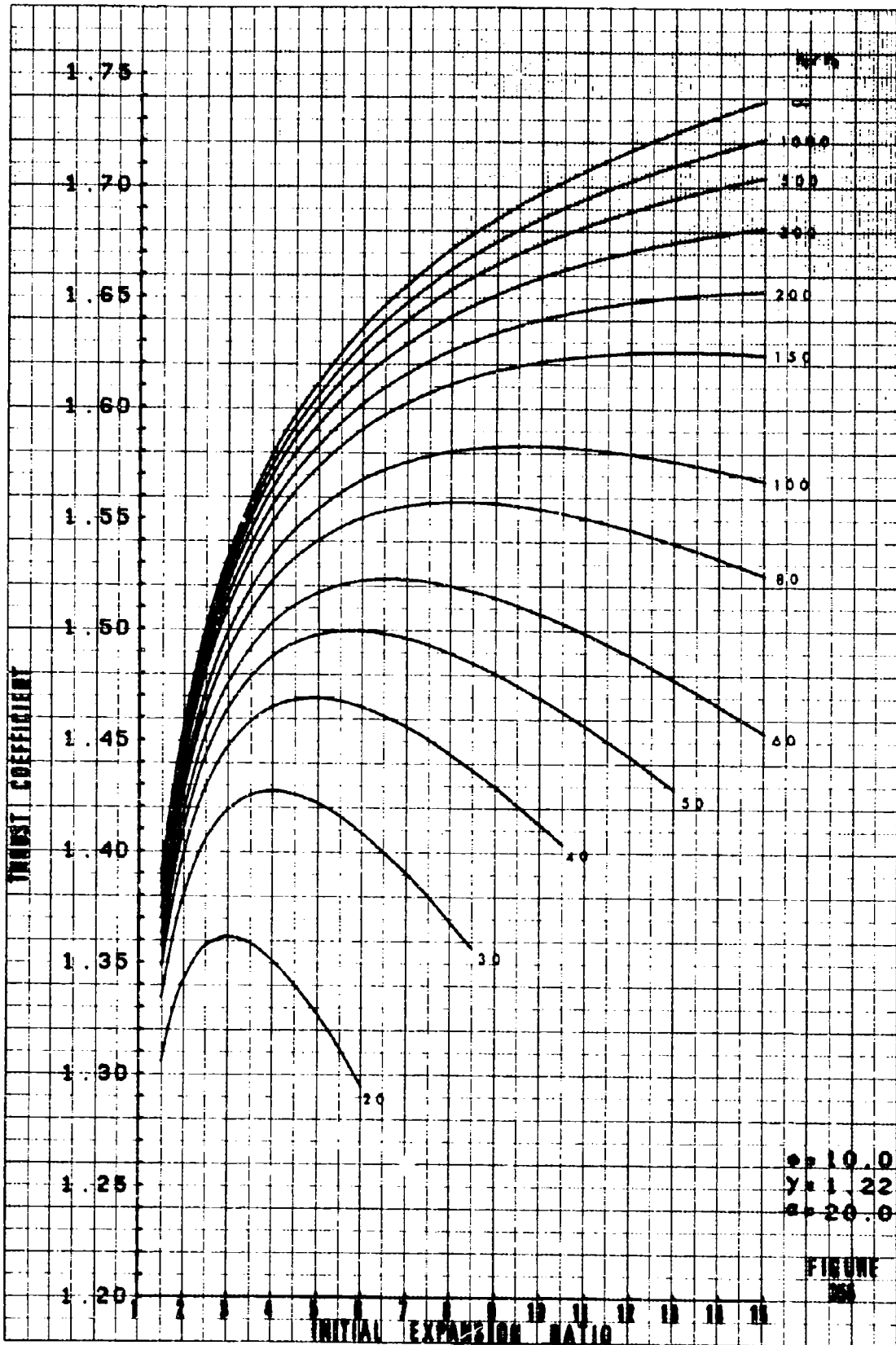






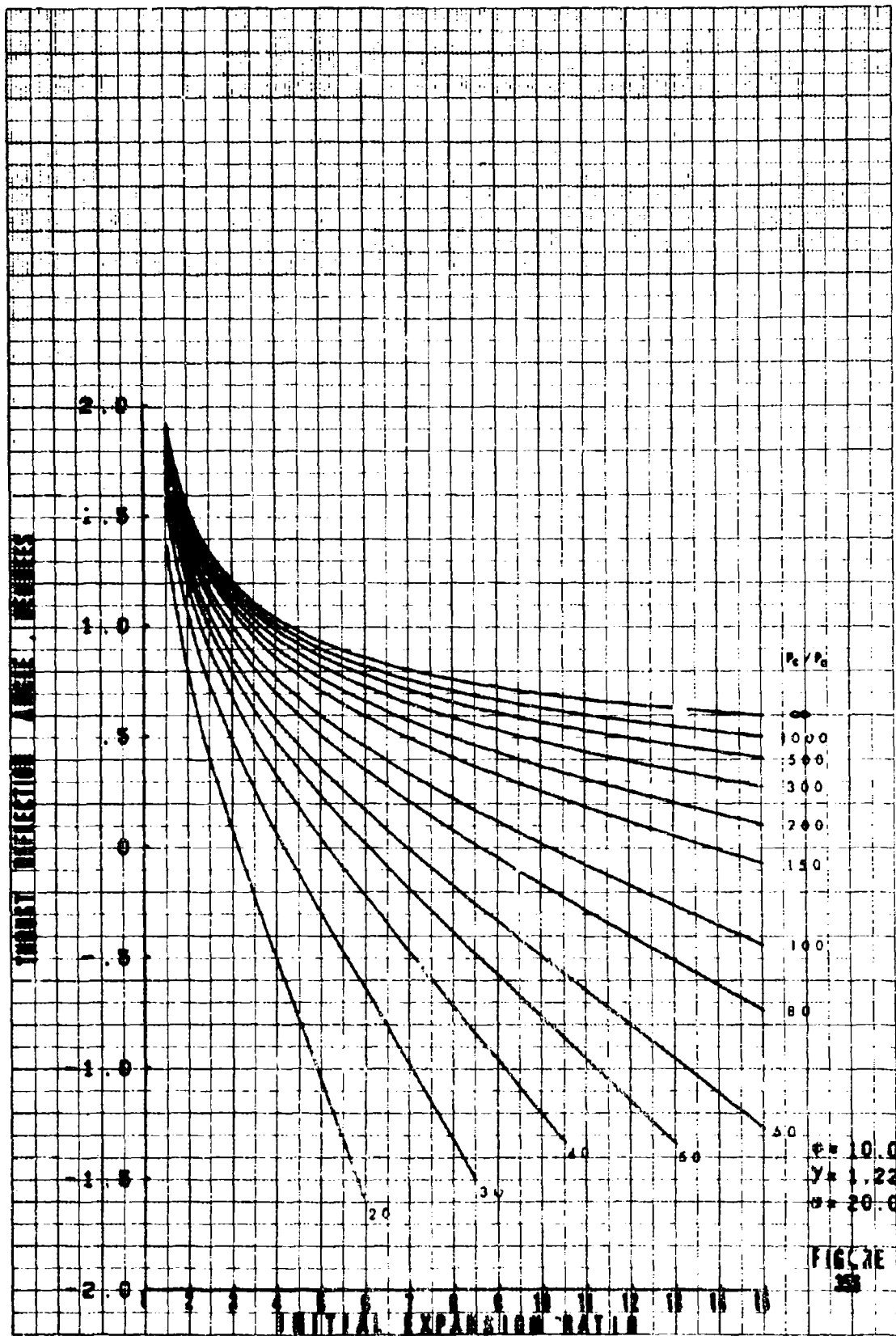
$P_0 = 0.0$   
 $\gamma = 1.22$   
 $\sigma = 20.0$

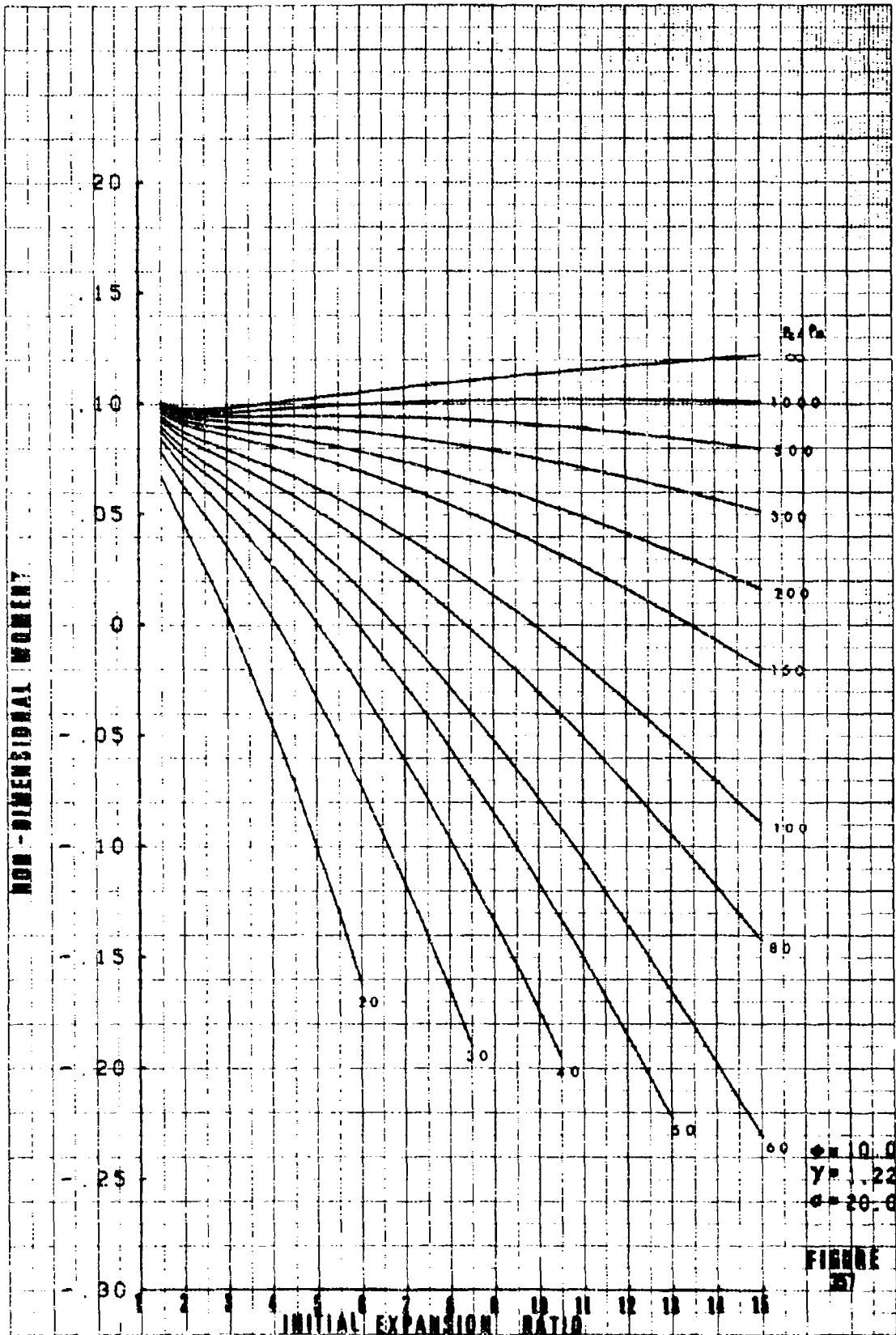
FIGURE  
354



10.0  
 1.22  
 20.0

FIGURE 25





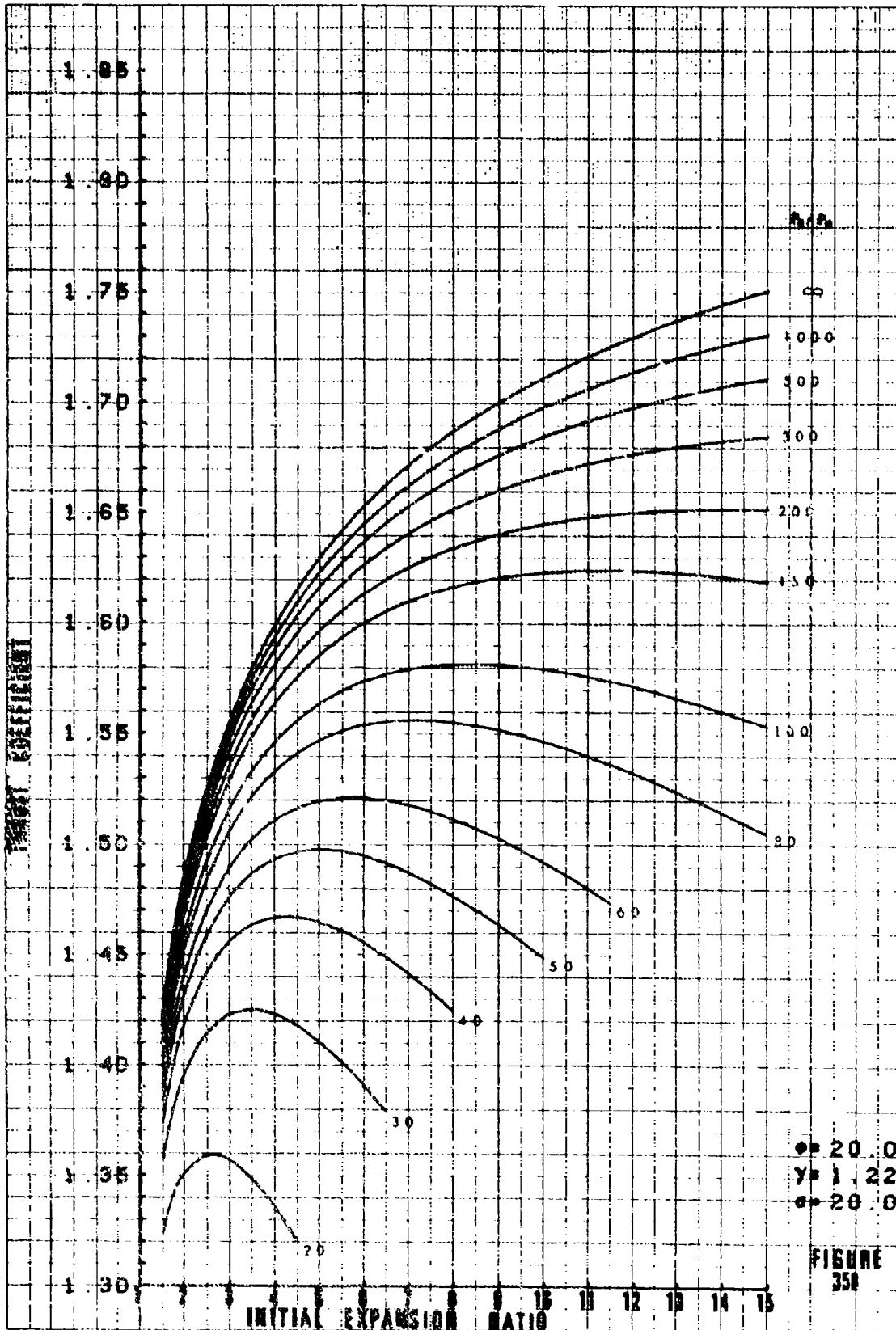
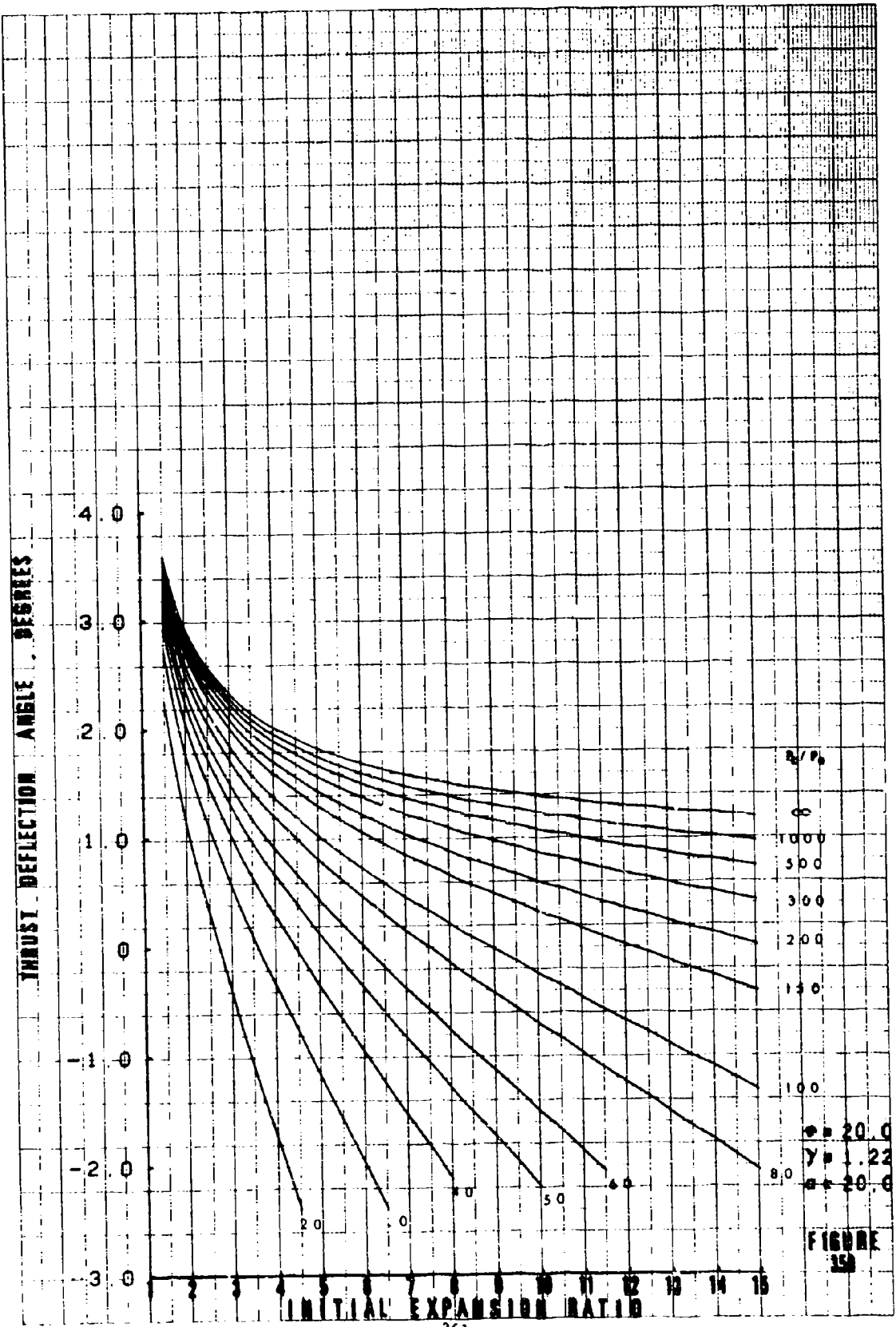
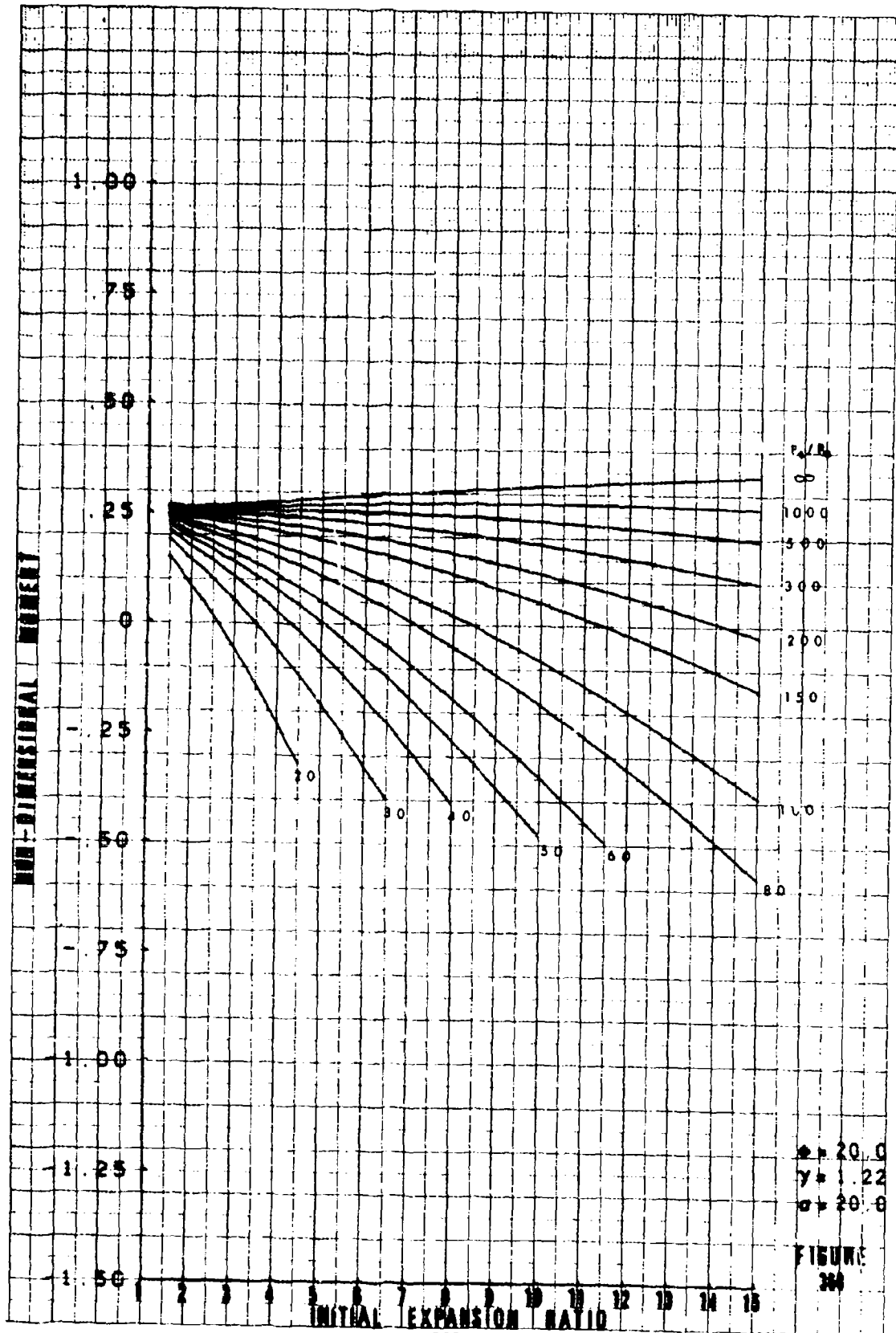


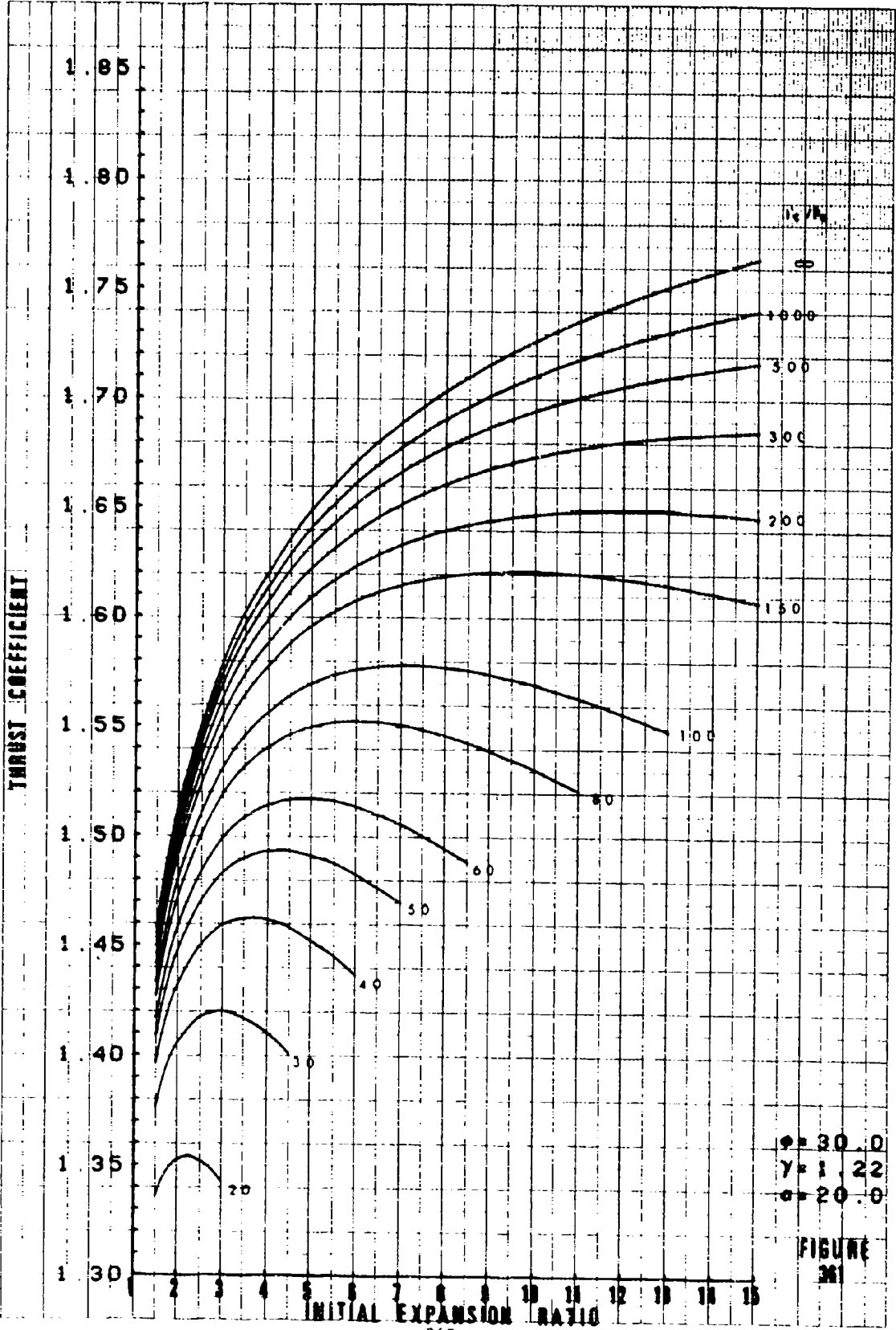
FIGURE 358



**FIGURE 15**







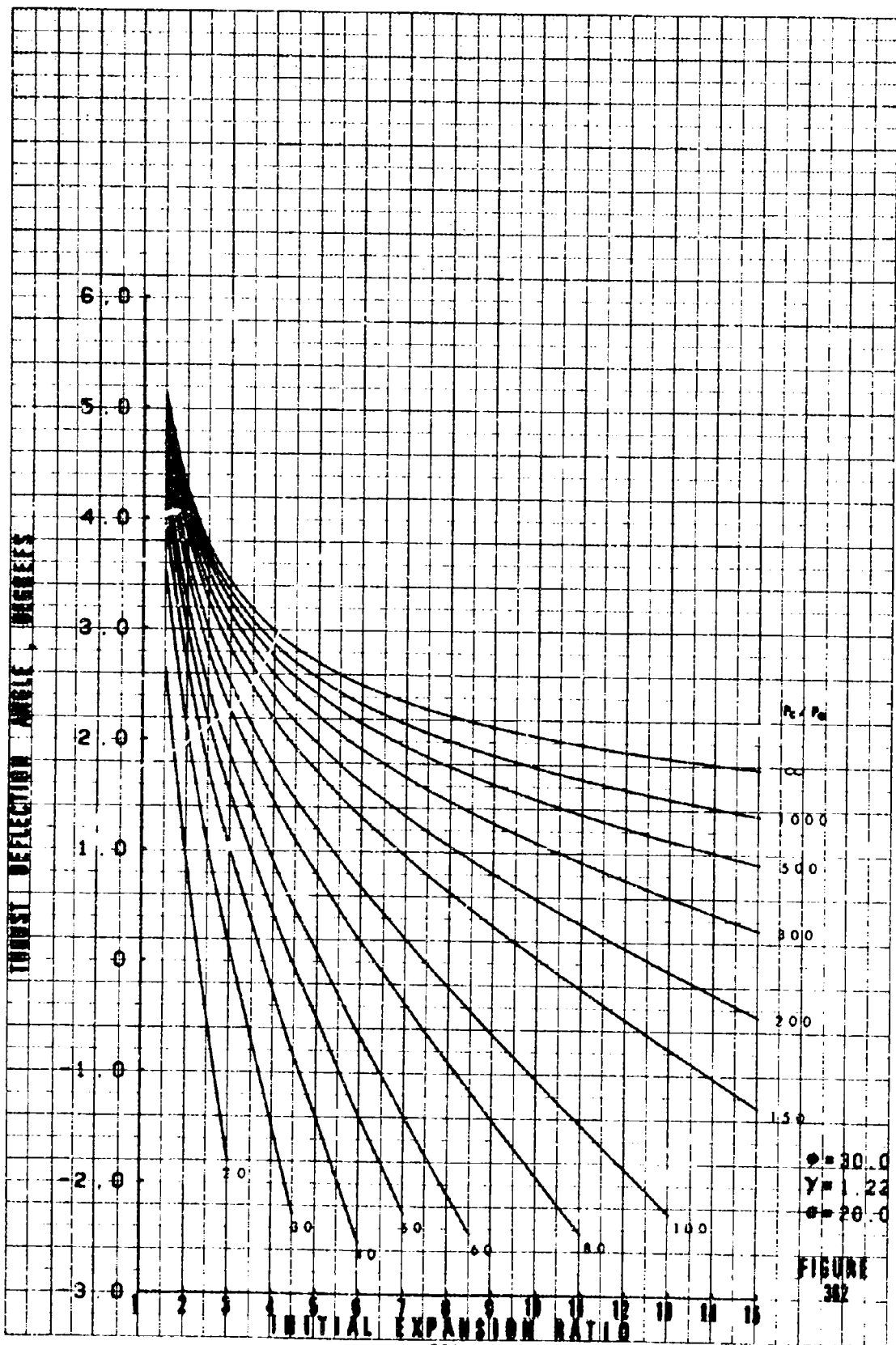
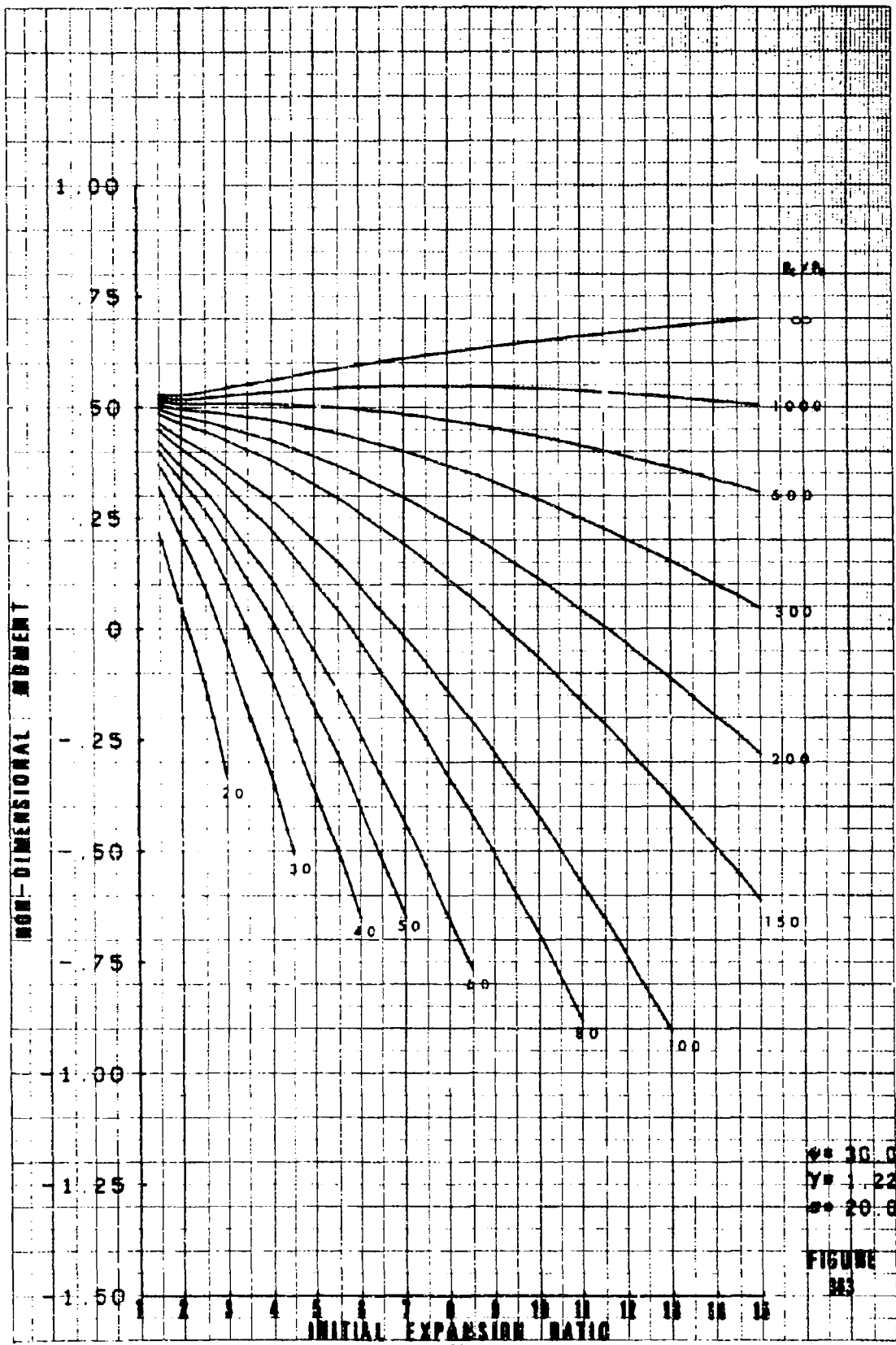


FIGURE 302



$\mu = 30.0$   
 $\gamma = 1.22$   
 $\sigma = 20.0$

FIGURE 263



◆ = 40.0  
 γ = 1.22  
 ● = 20.0

FIGURE 364

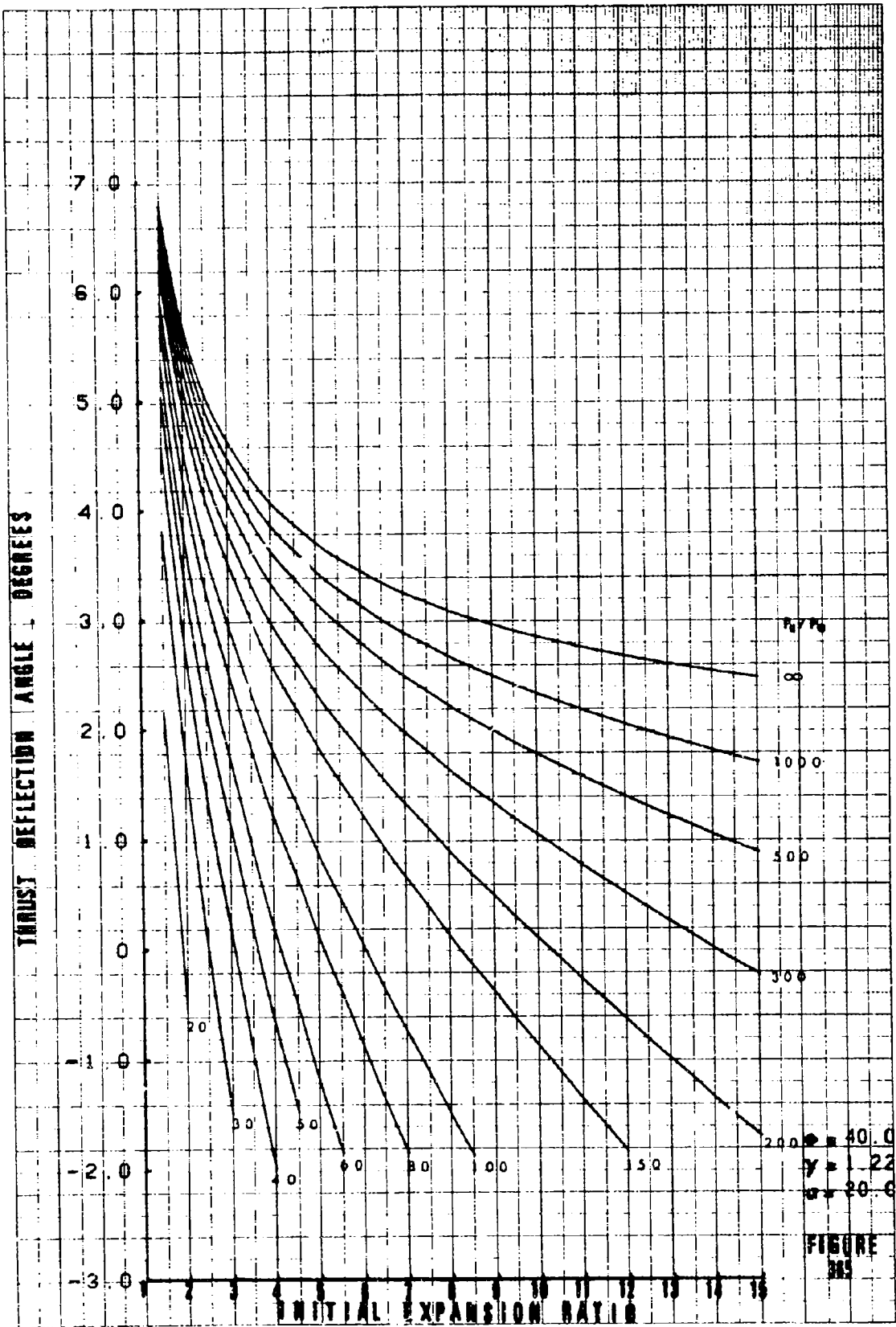
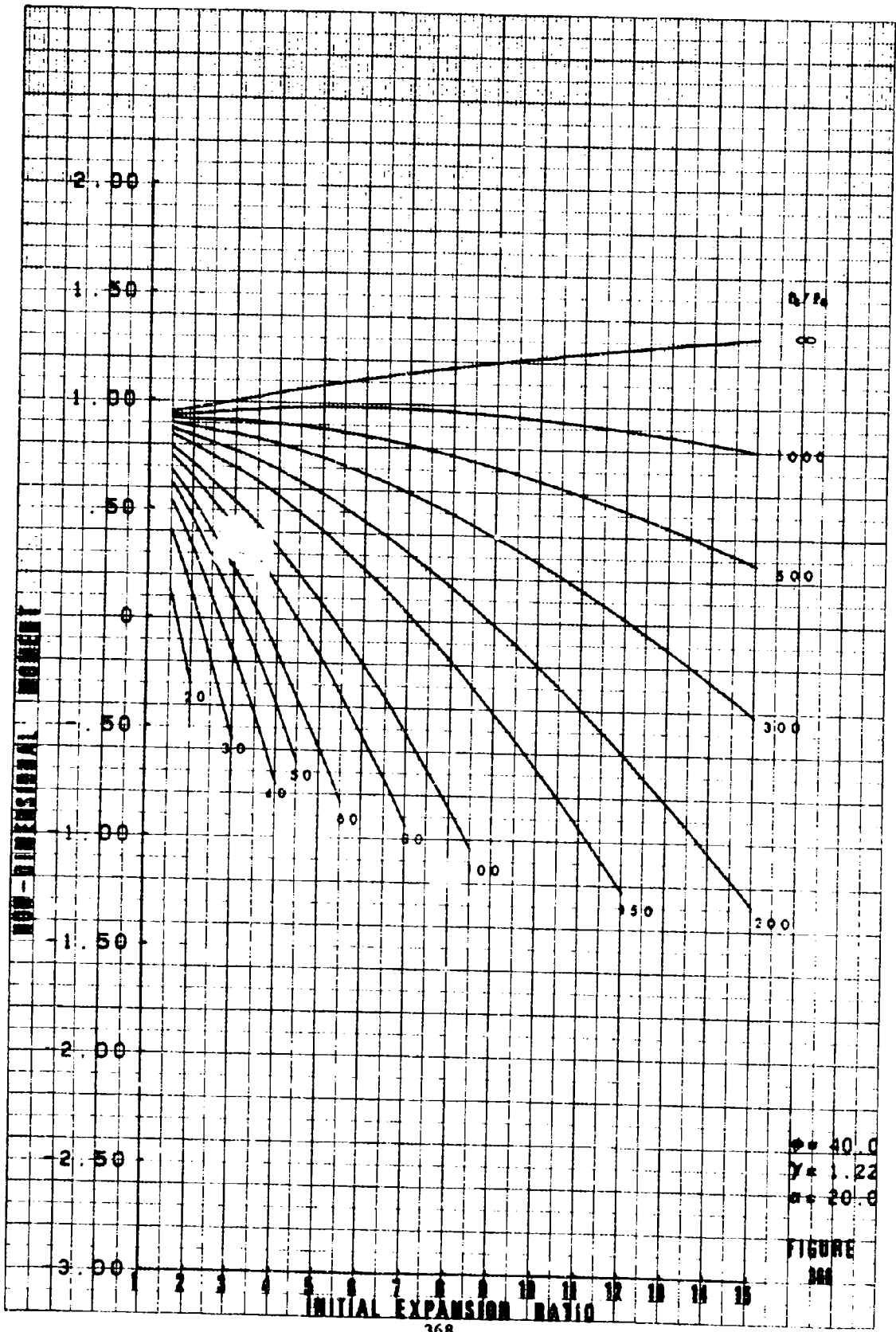
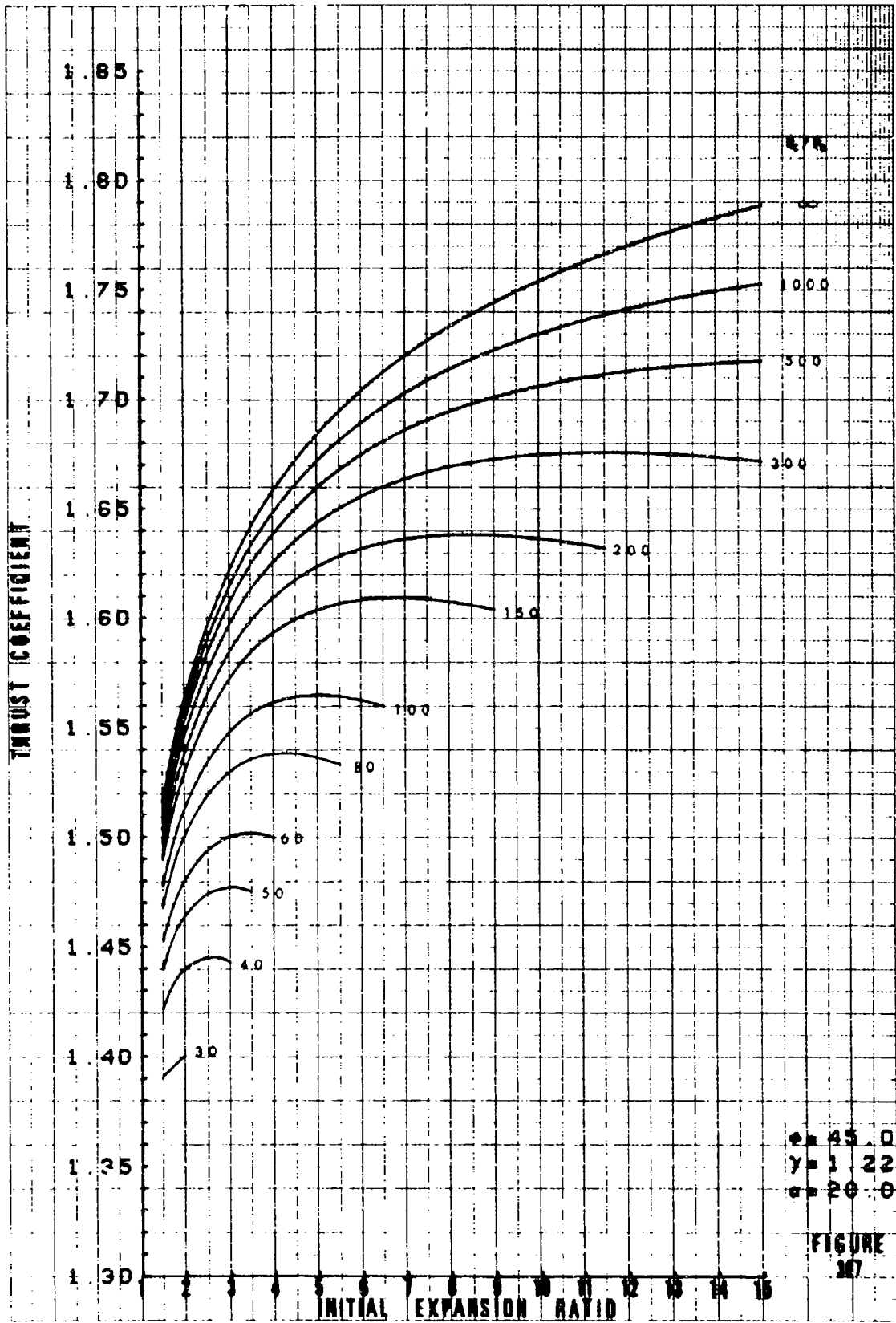


FIGURE 365





$x = 45.0$   
 $y = 1.22$   
 $z = 20.0$

FIGURE 207



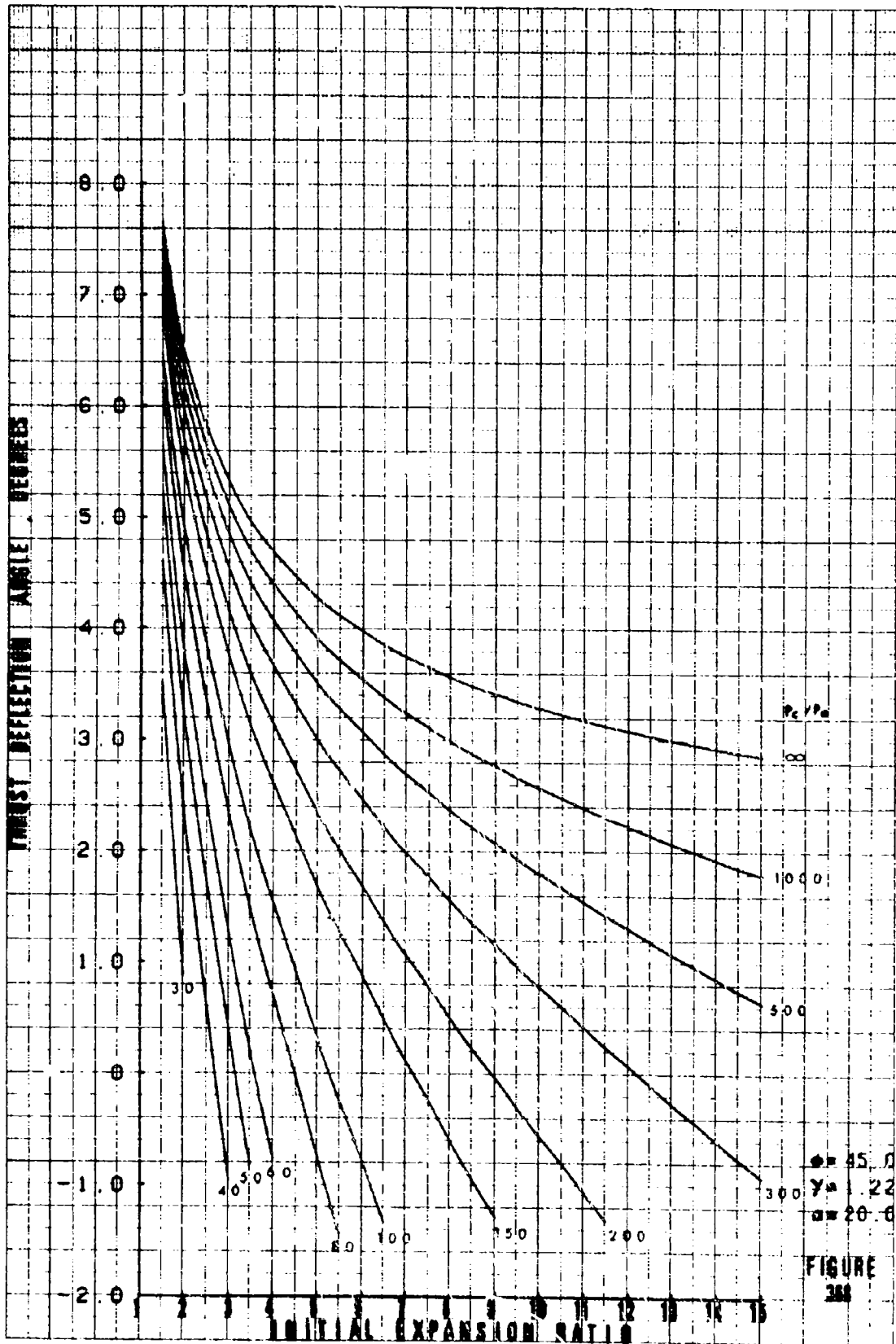
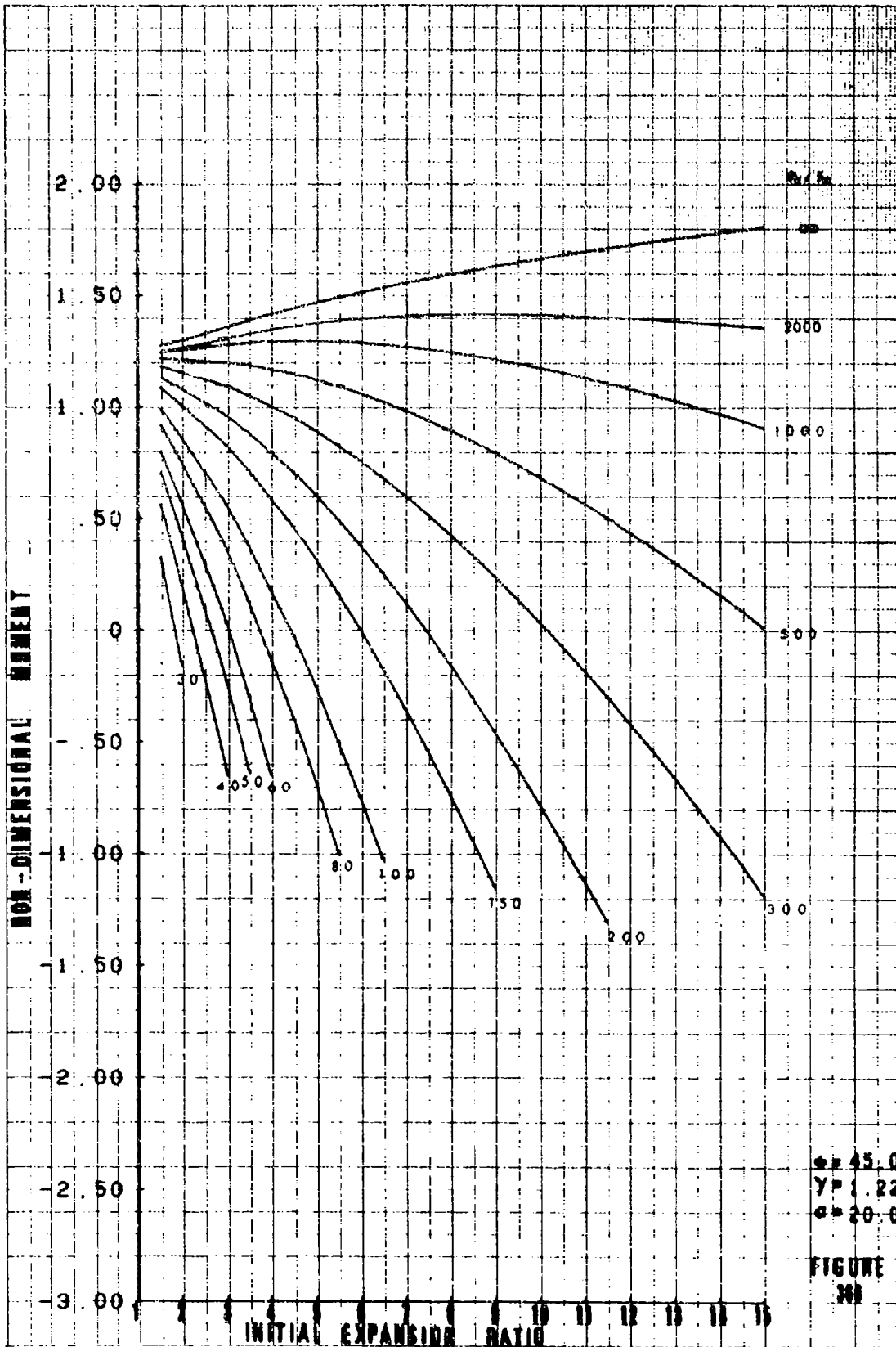
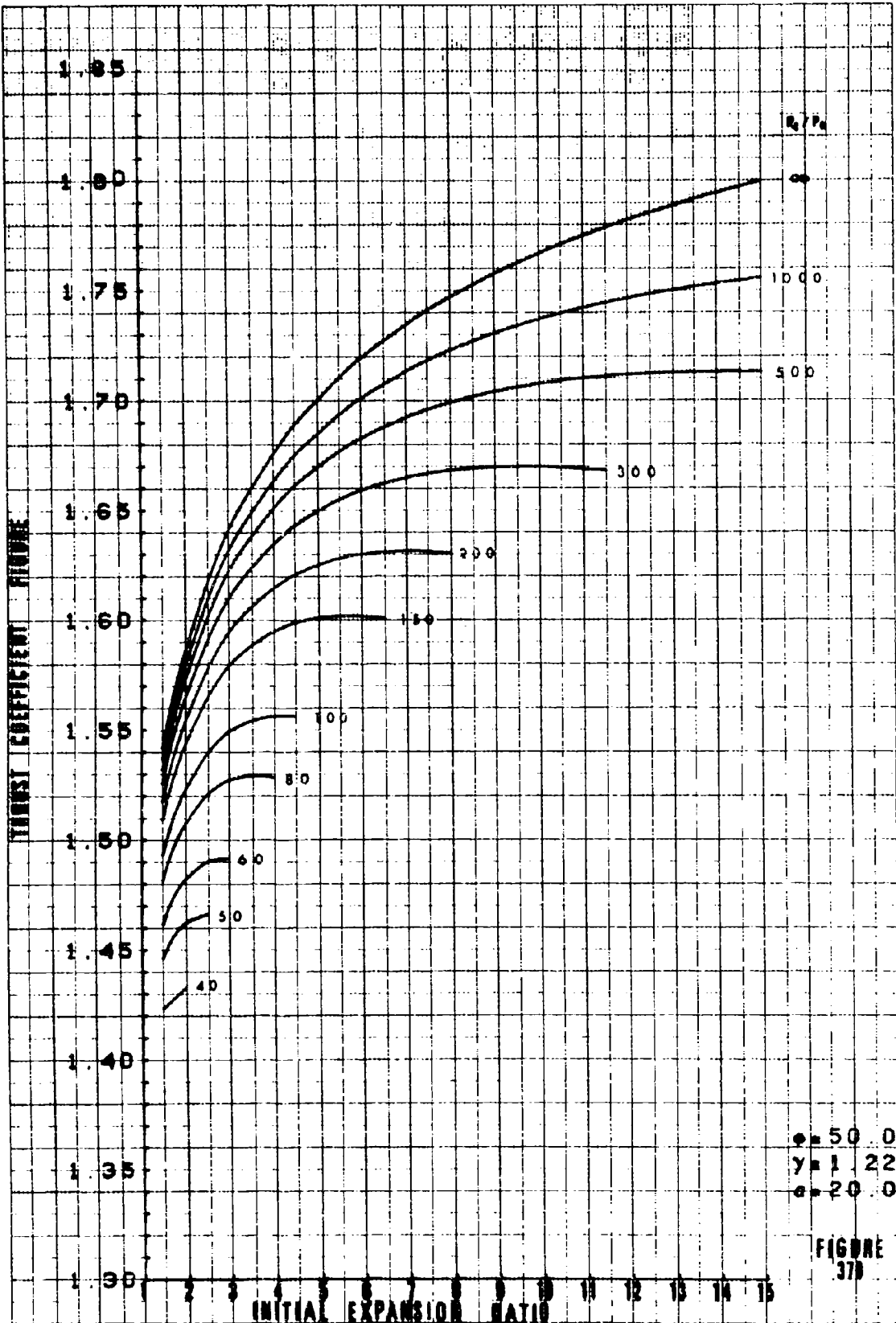
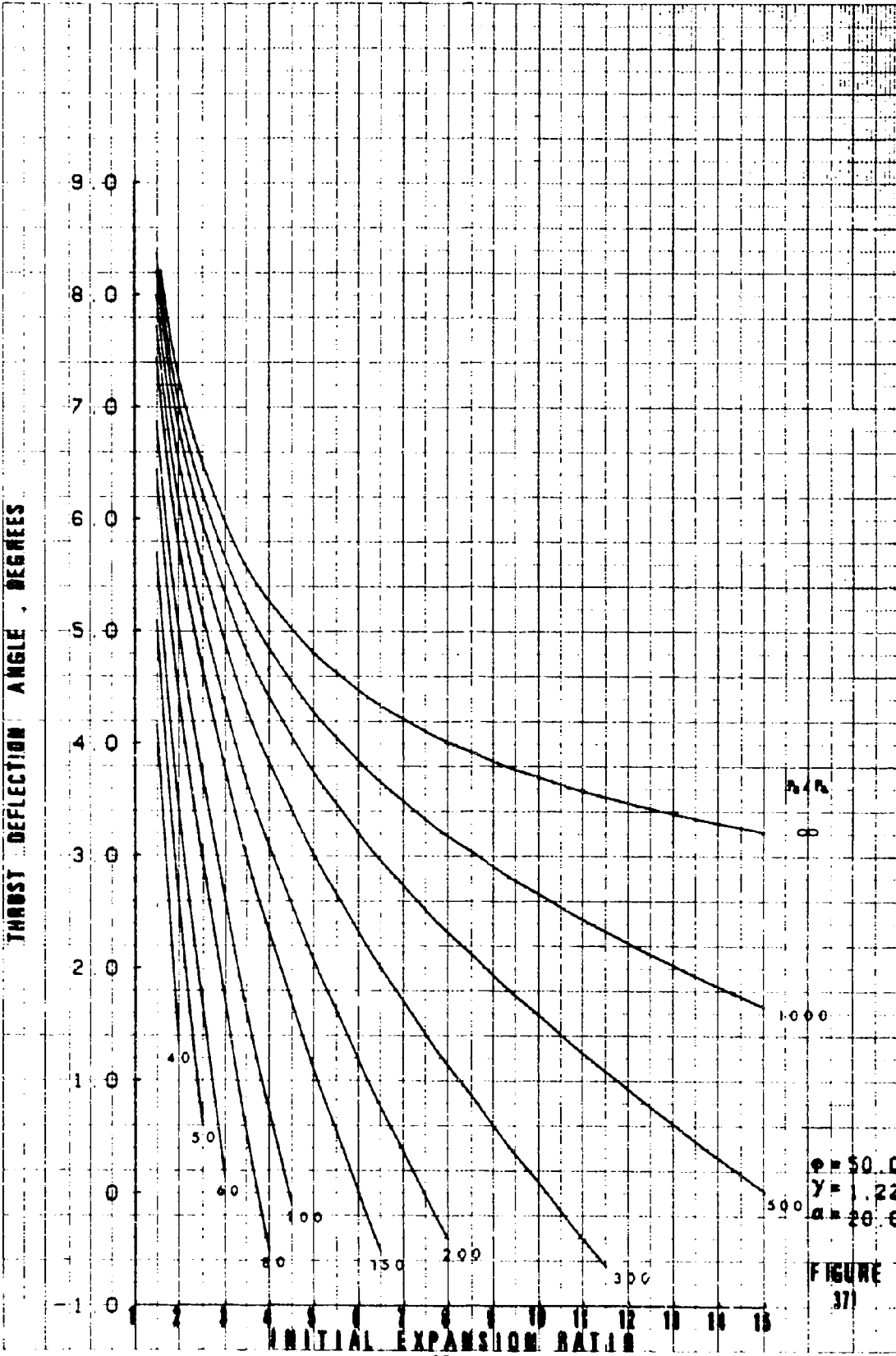


FIGURE 368



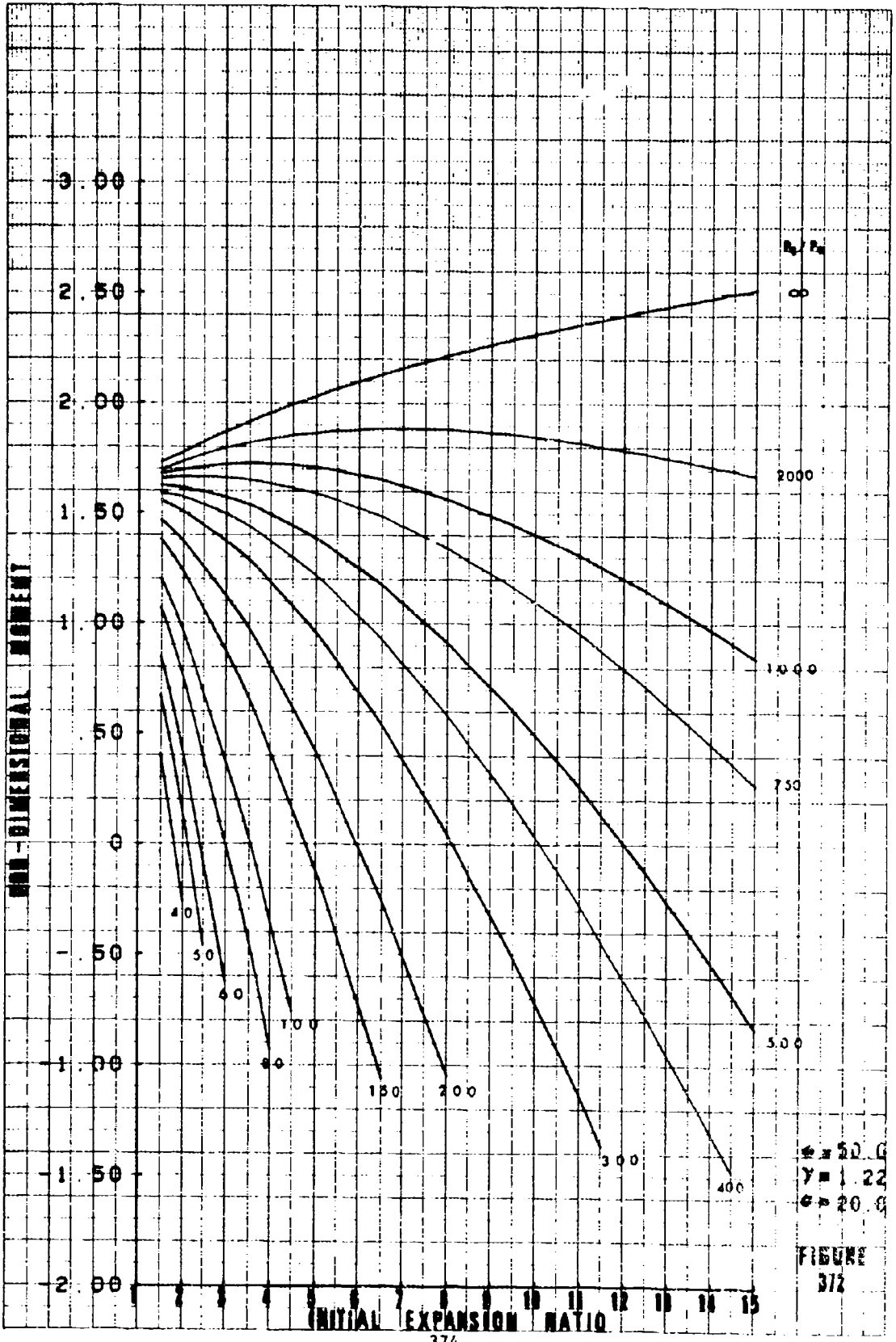


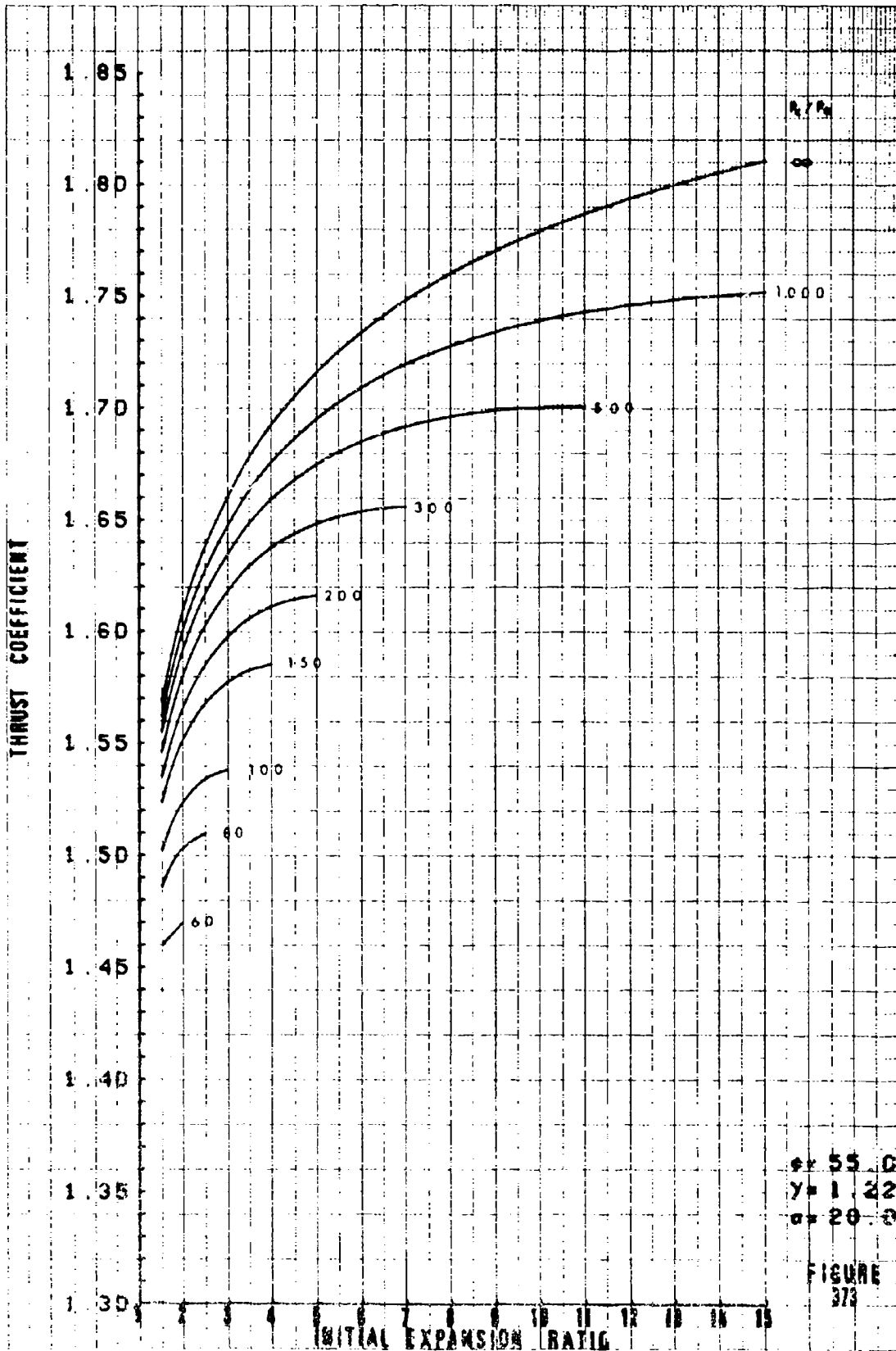
THRUST DEFLECTION ANGLE - DEGREES



$\phi = 50.0$   
 $\gamma = 1.22$   
 $\alpha = 20.0$

FIGURE 371





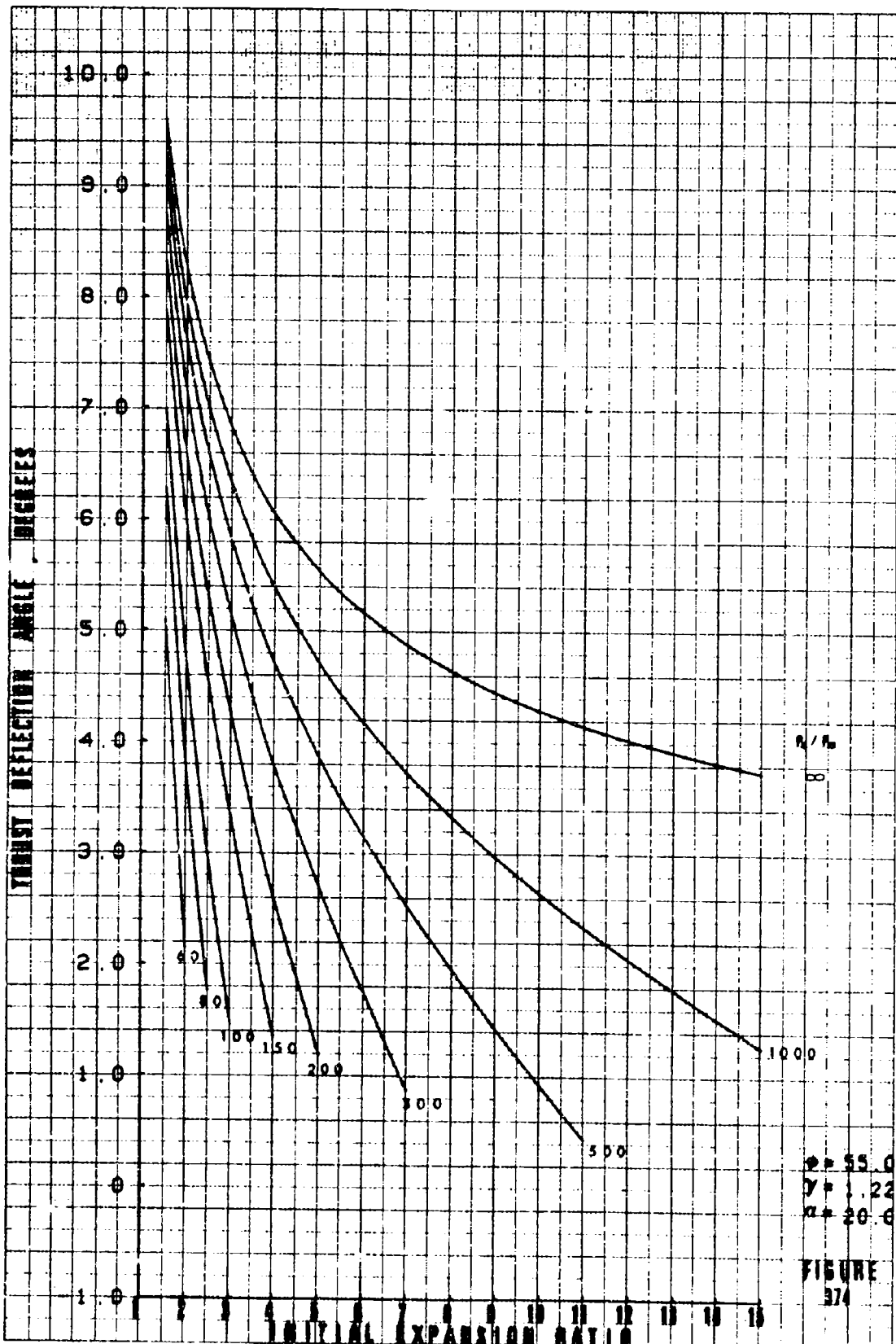


FIGURE 374

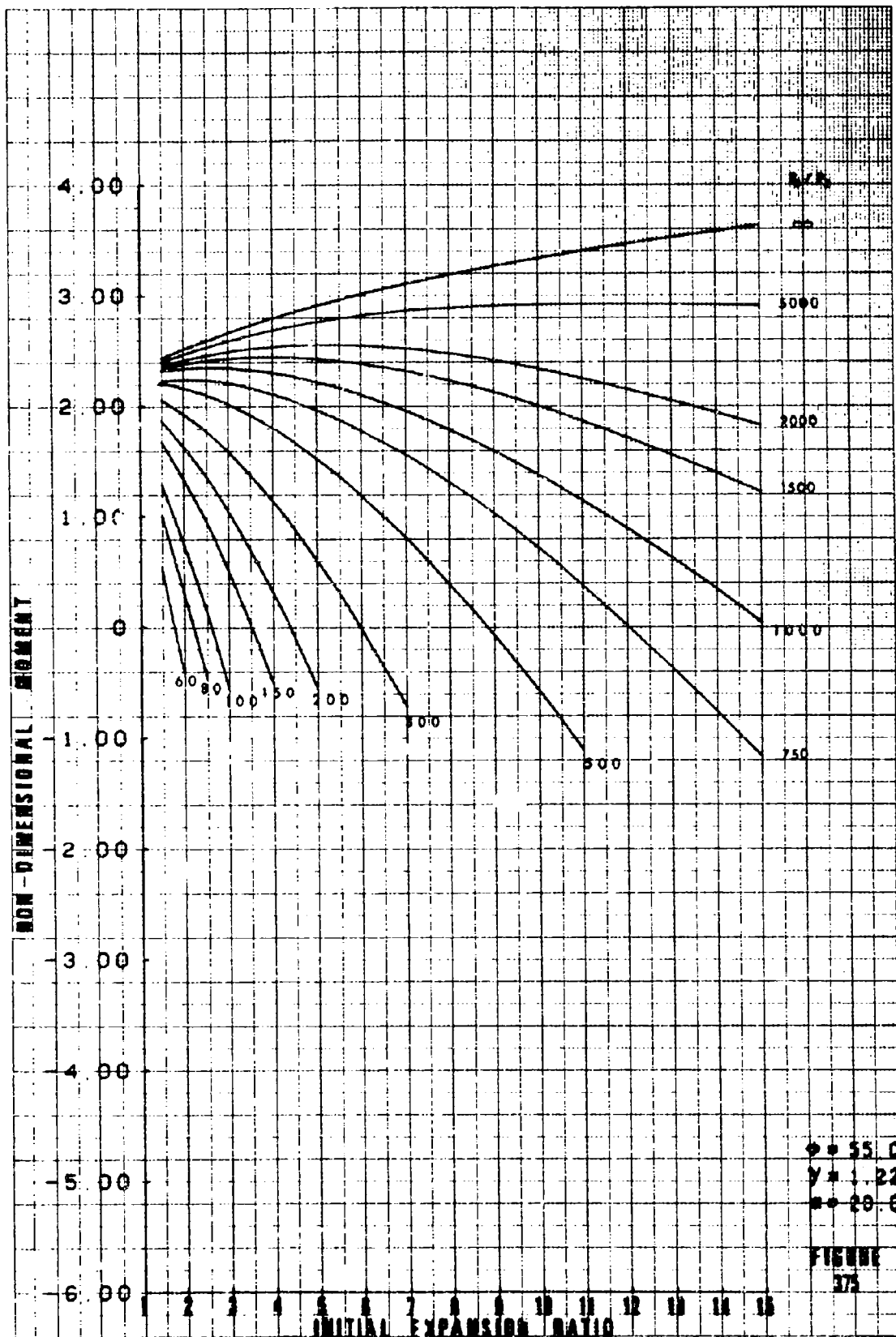
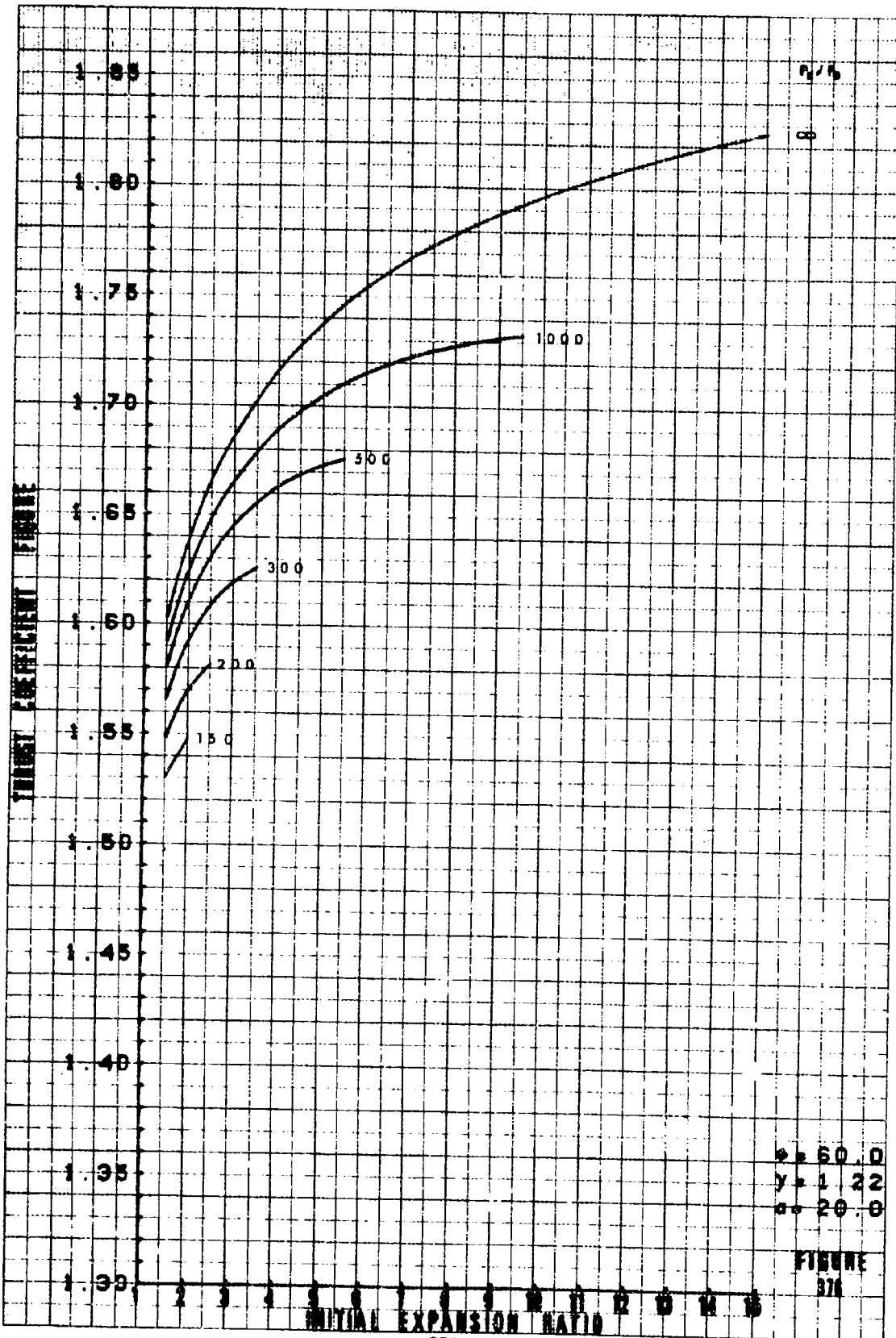
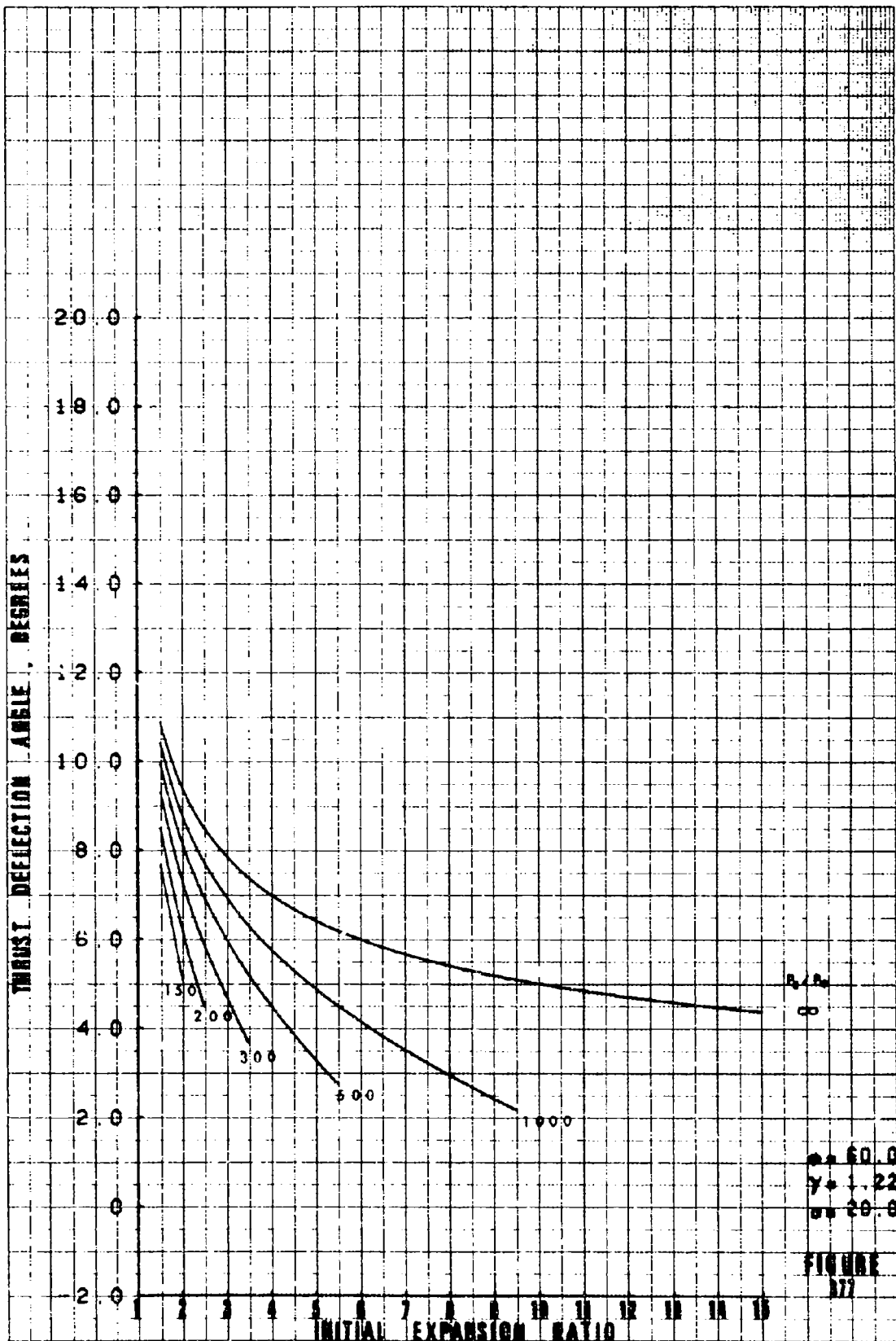


FIGURE 375

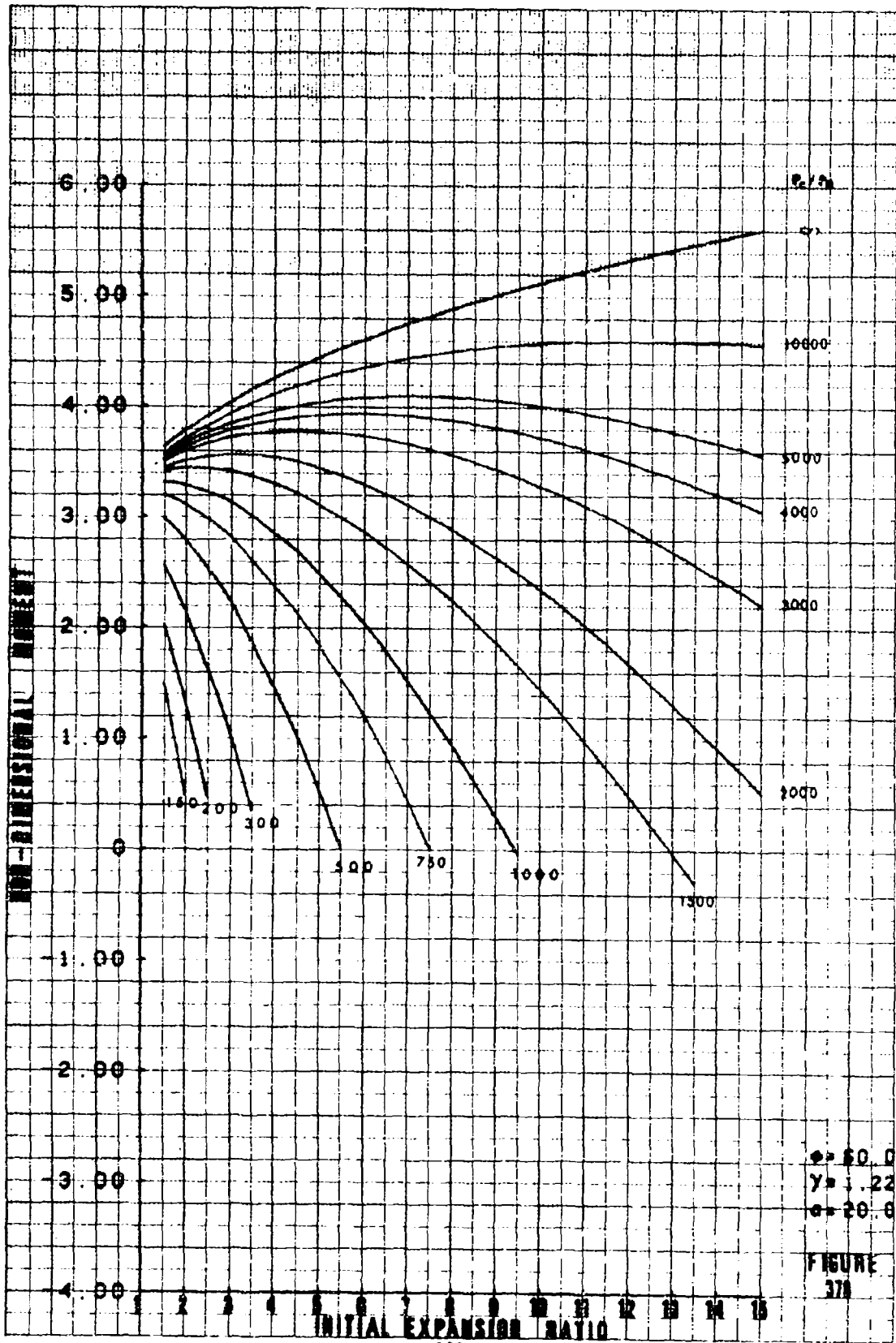


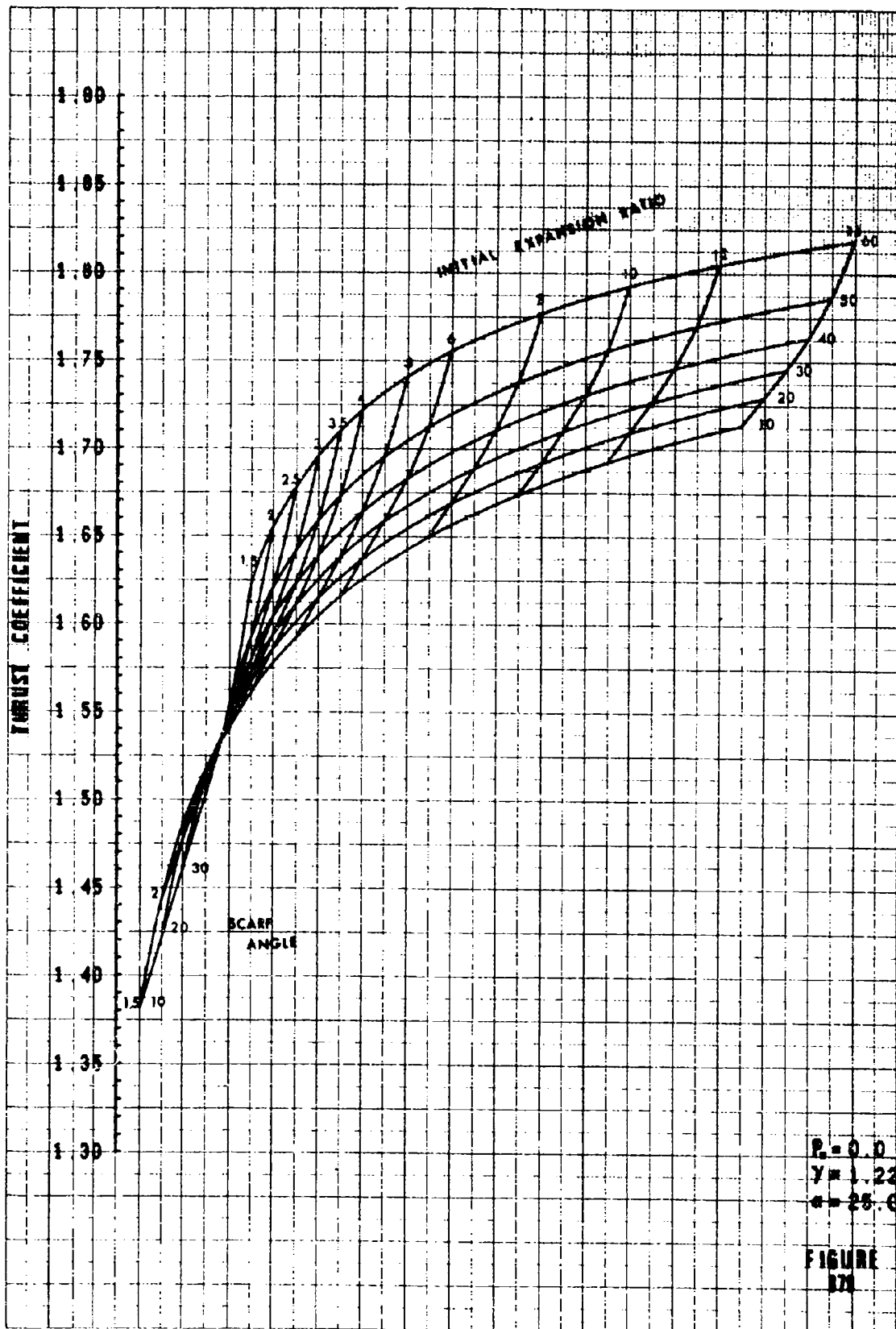


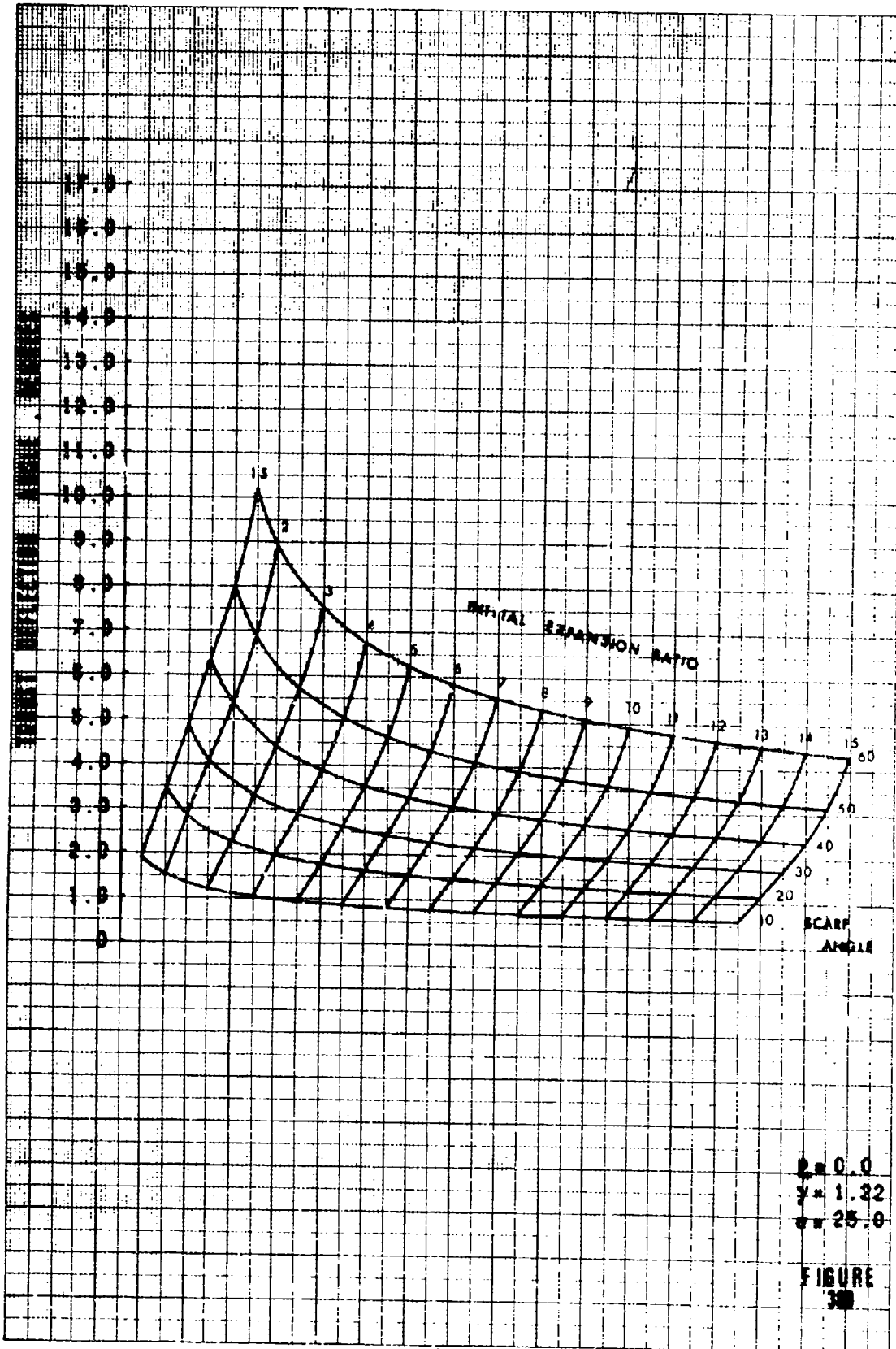


$\beta = 60.0$   
 $\gamma = 1.22$   
 $g = 20.0$

FIGURE 177

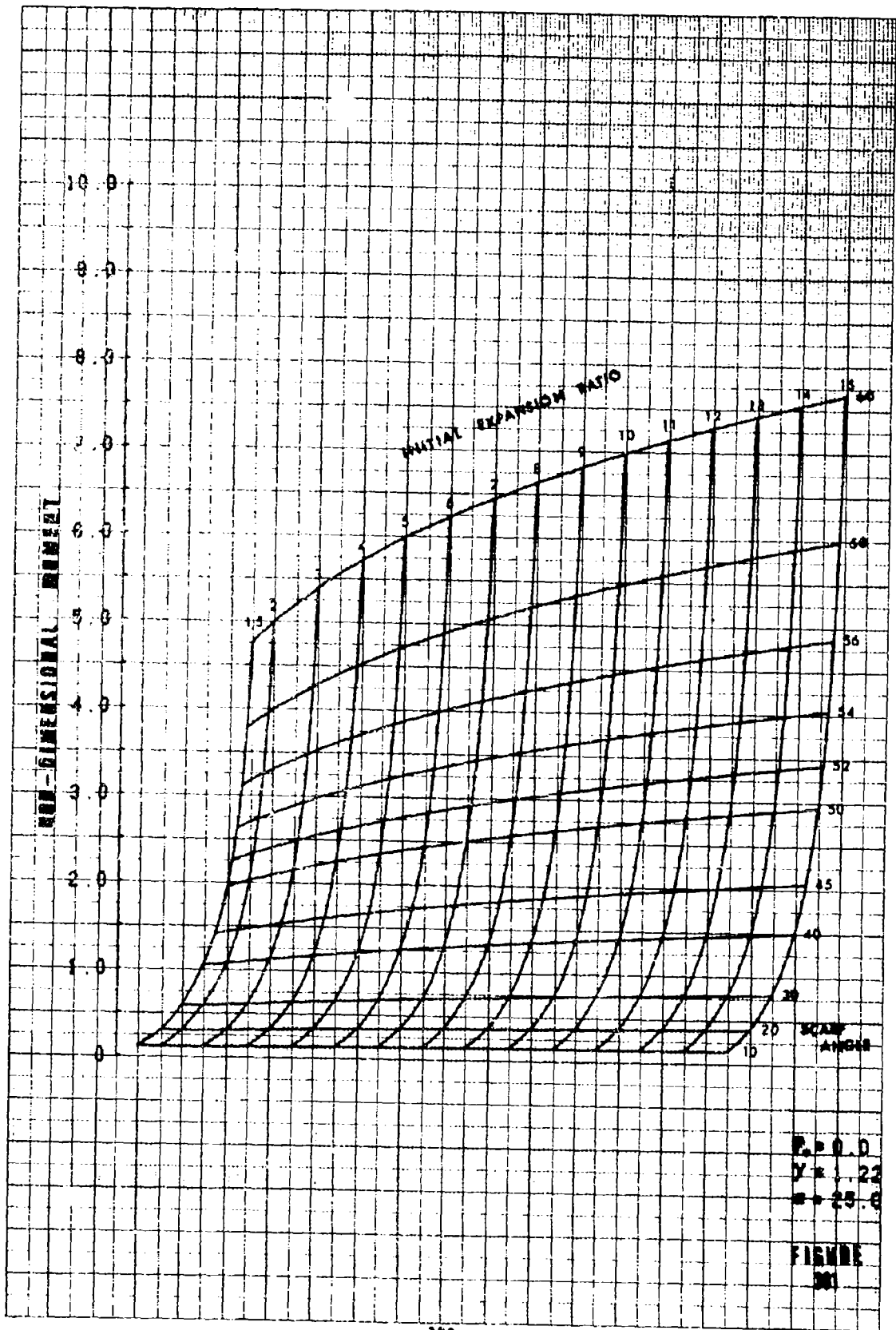


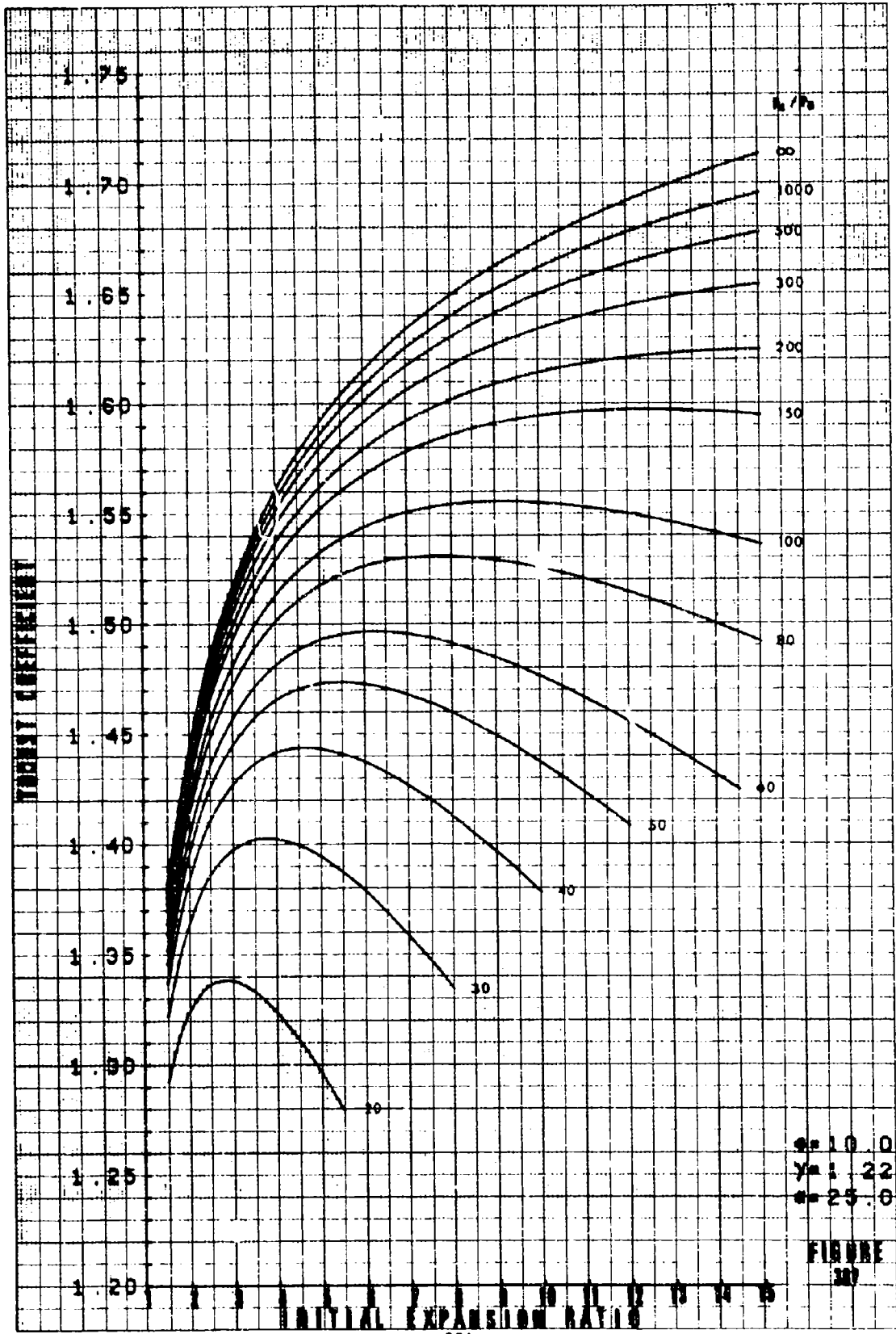


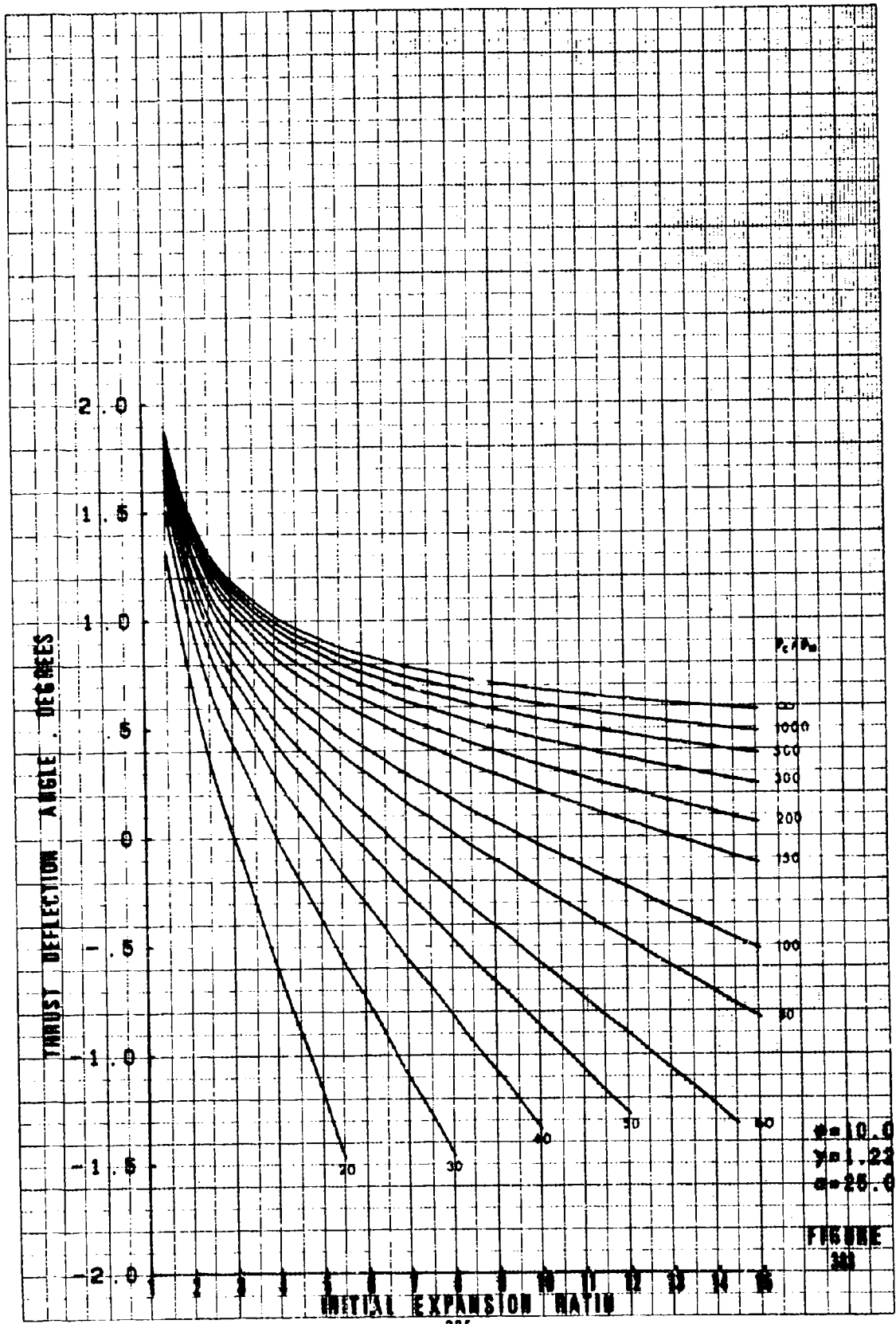


R = 0.0  
 Y = 1.22  
 W = 25.0

FIGURE  
 300



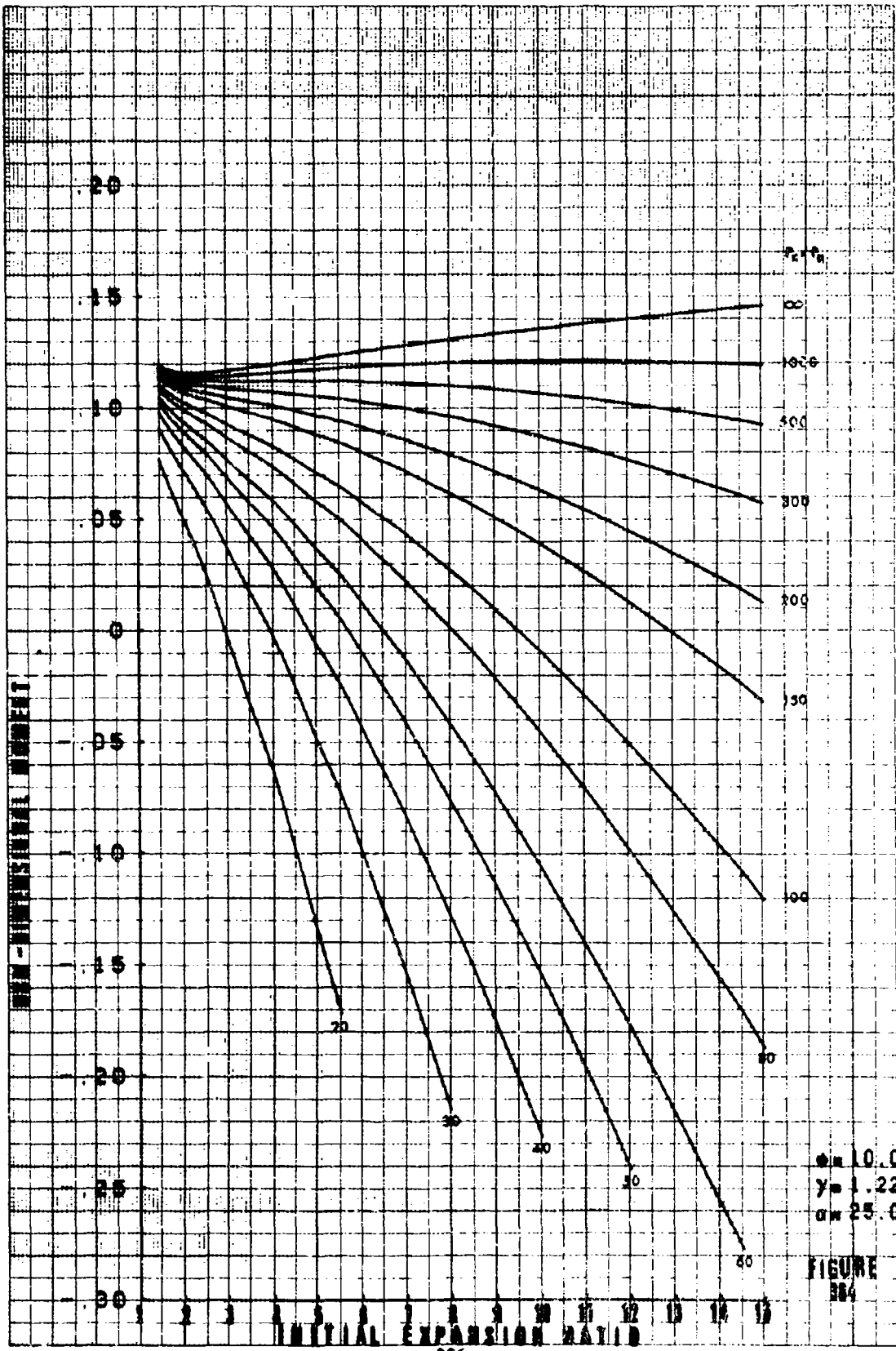


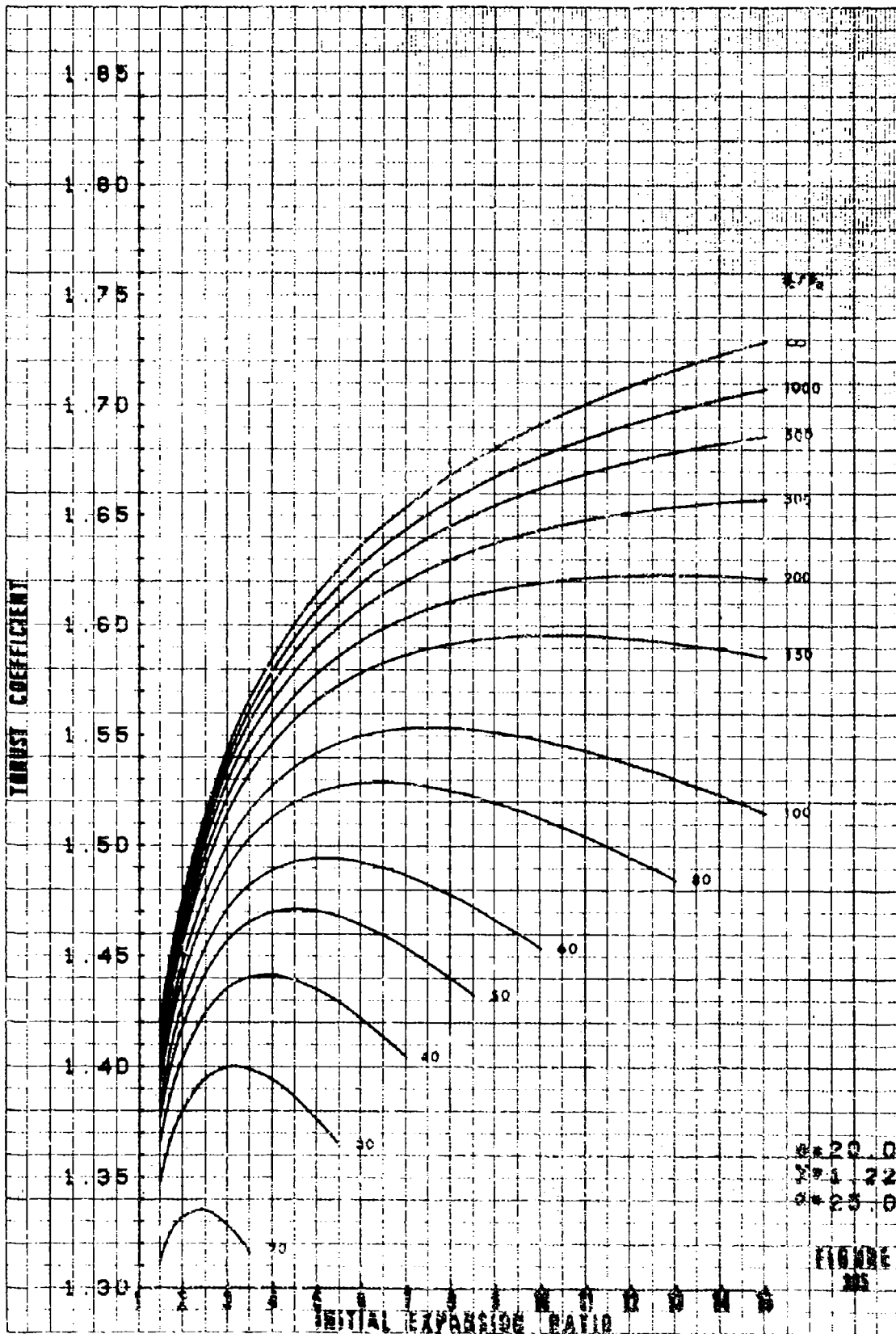


$\gamma = 10.0$   
 $\gamma = 1.22$   
 $\alpha = 25.0$

FIGURE 20







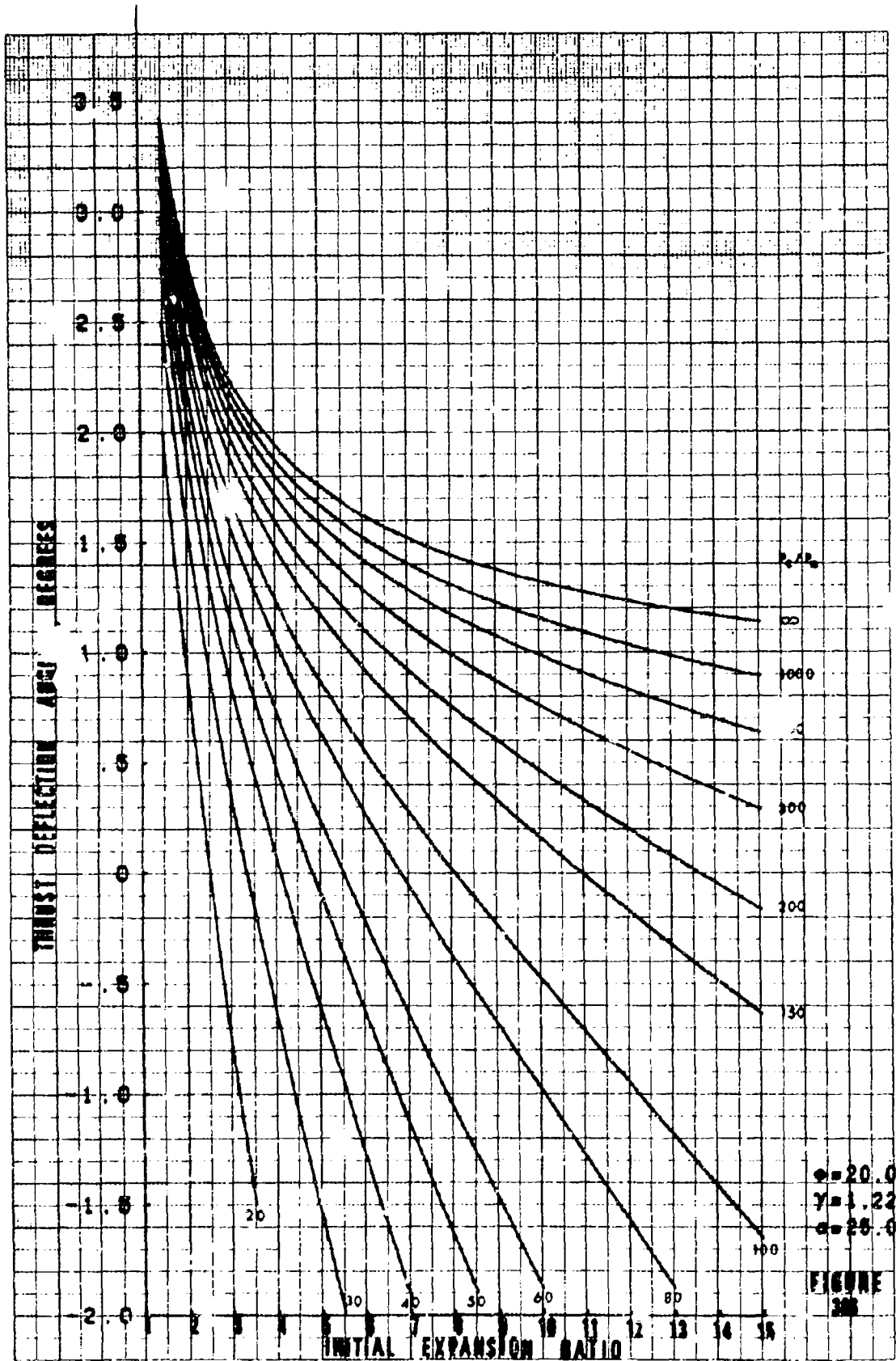
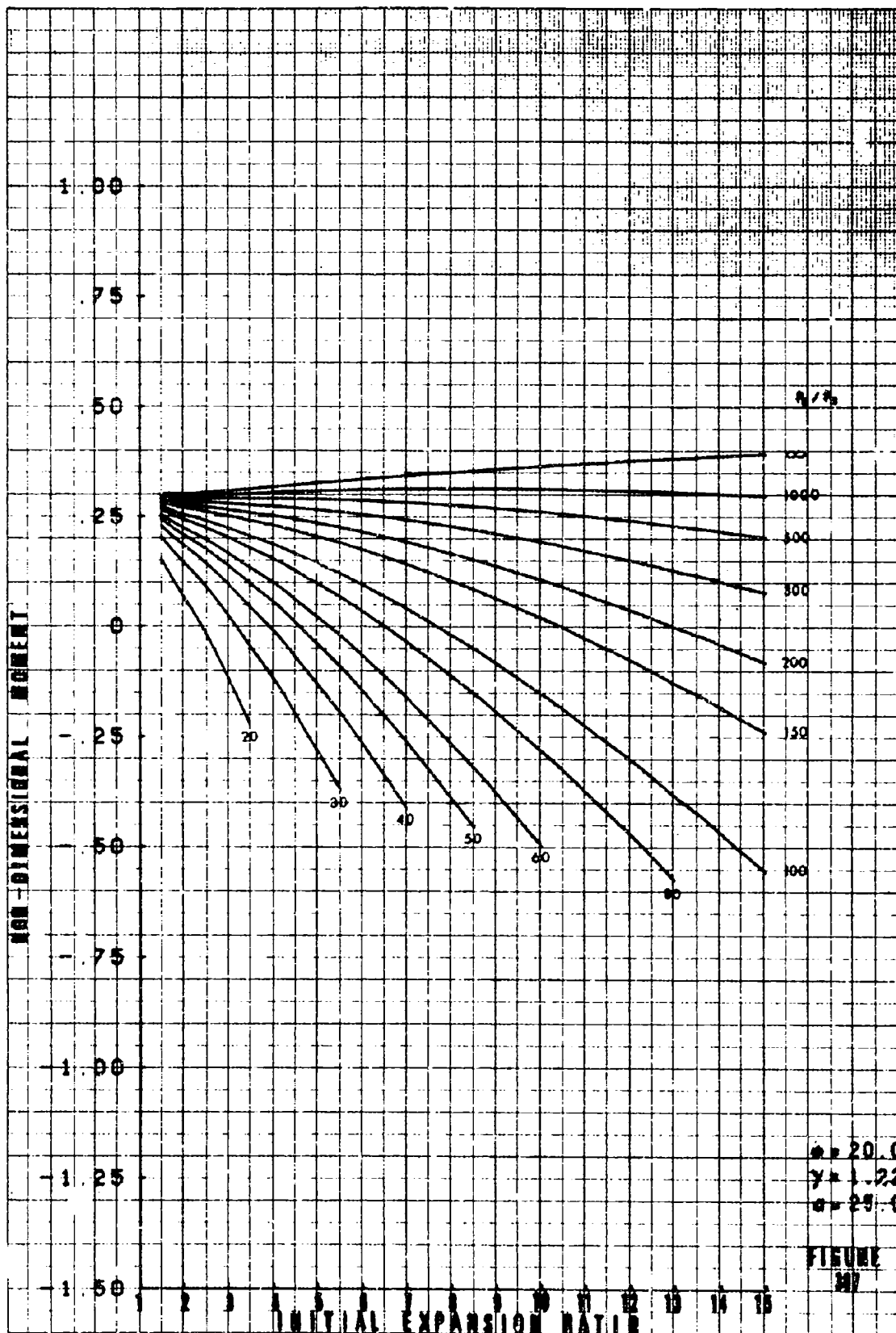
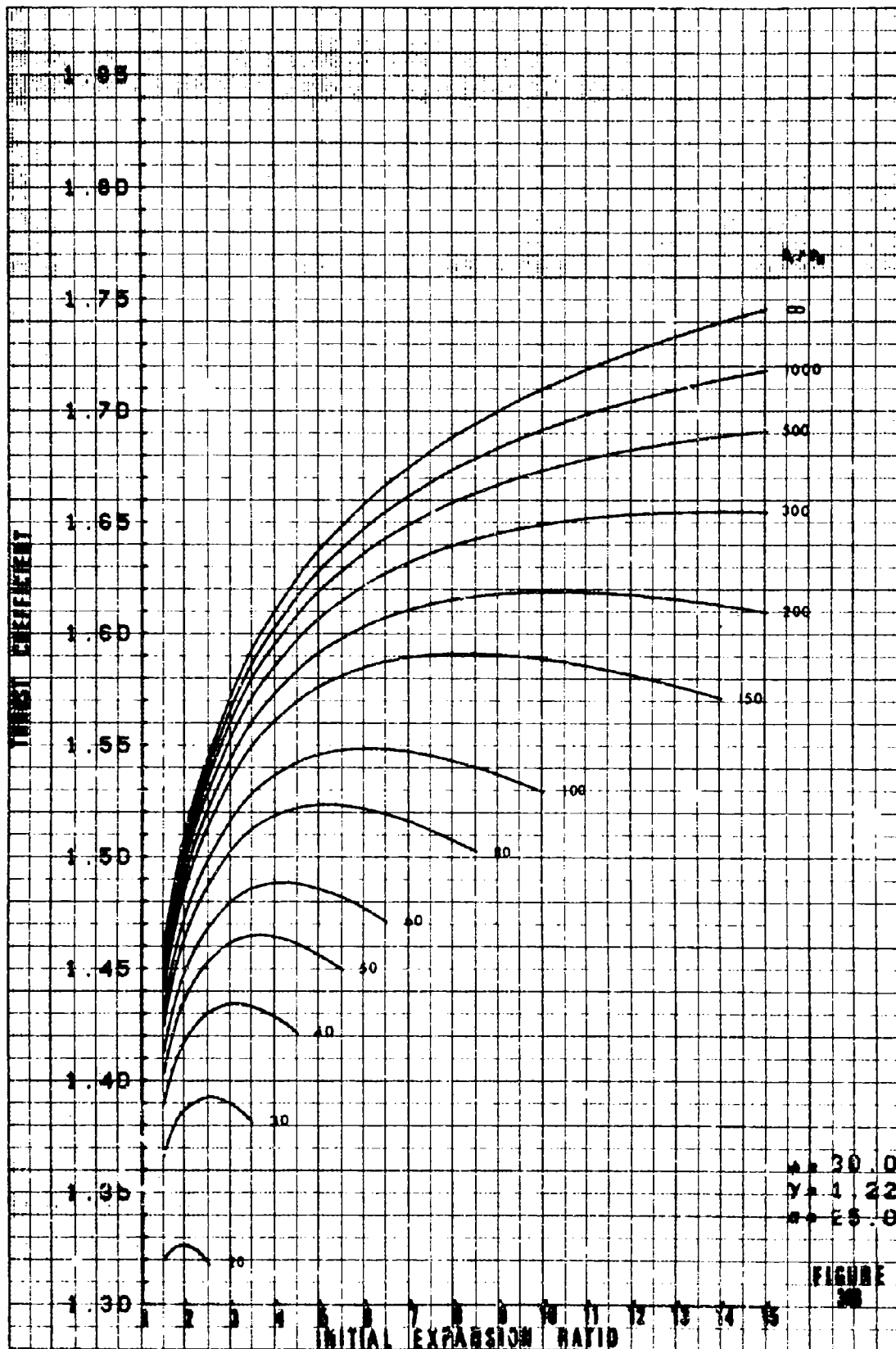


FIGURE 208





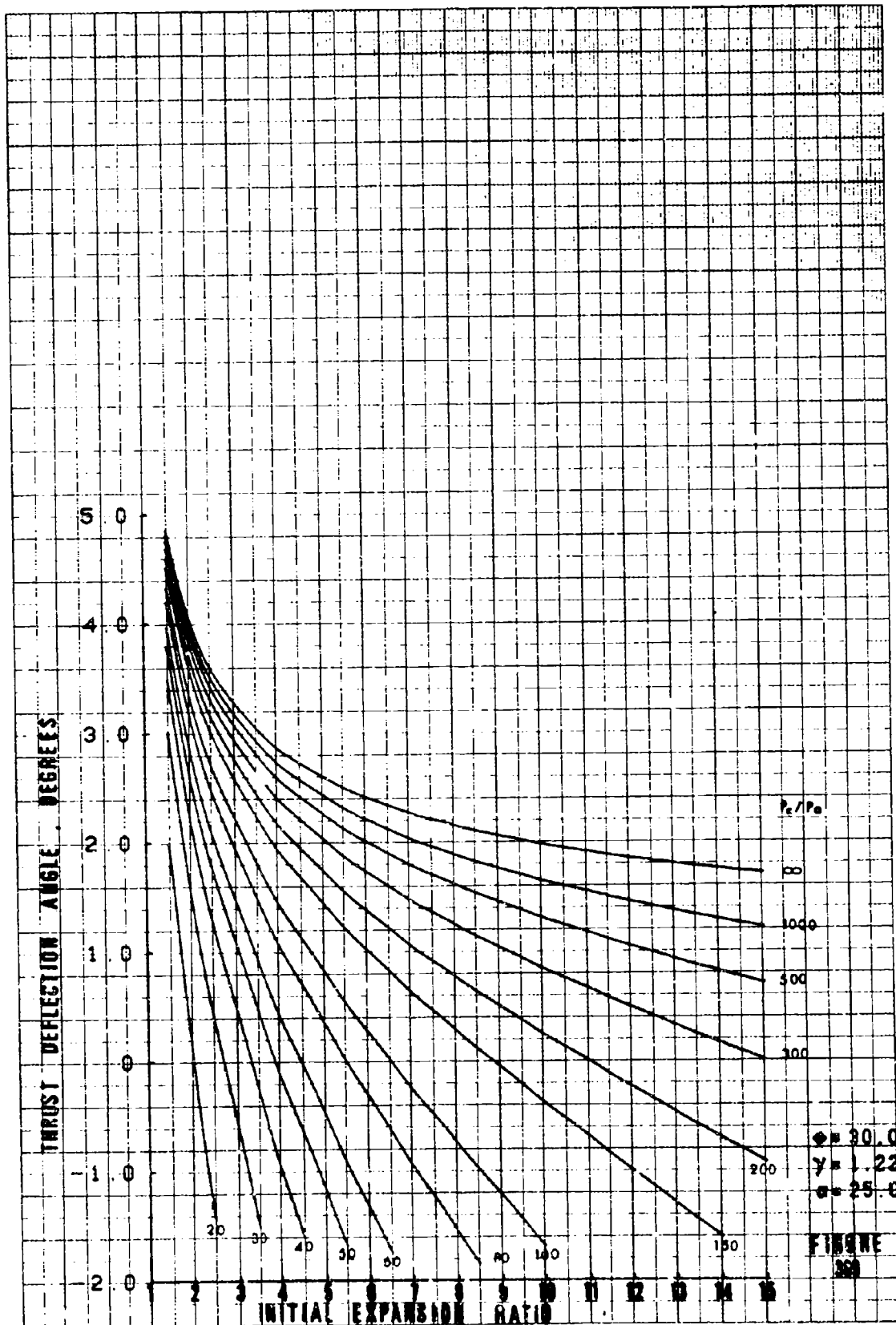
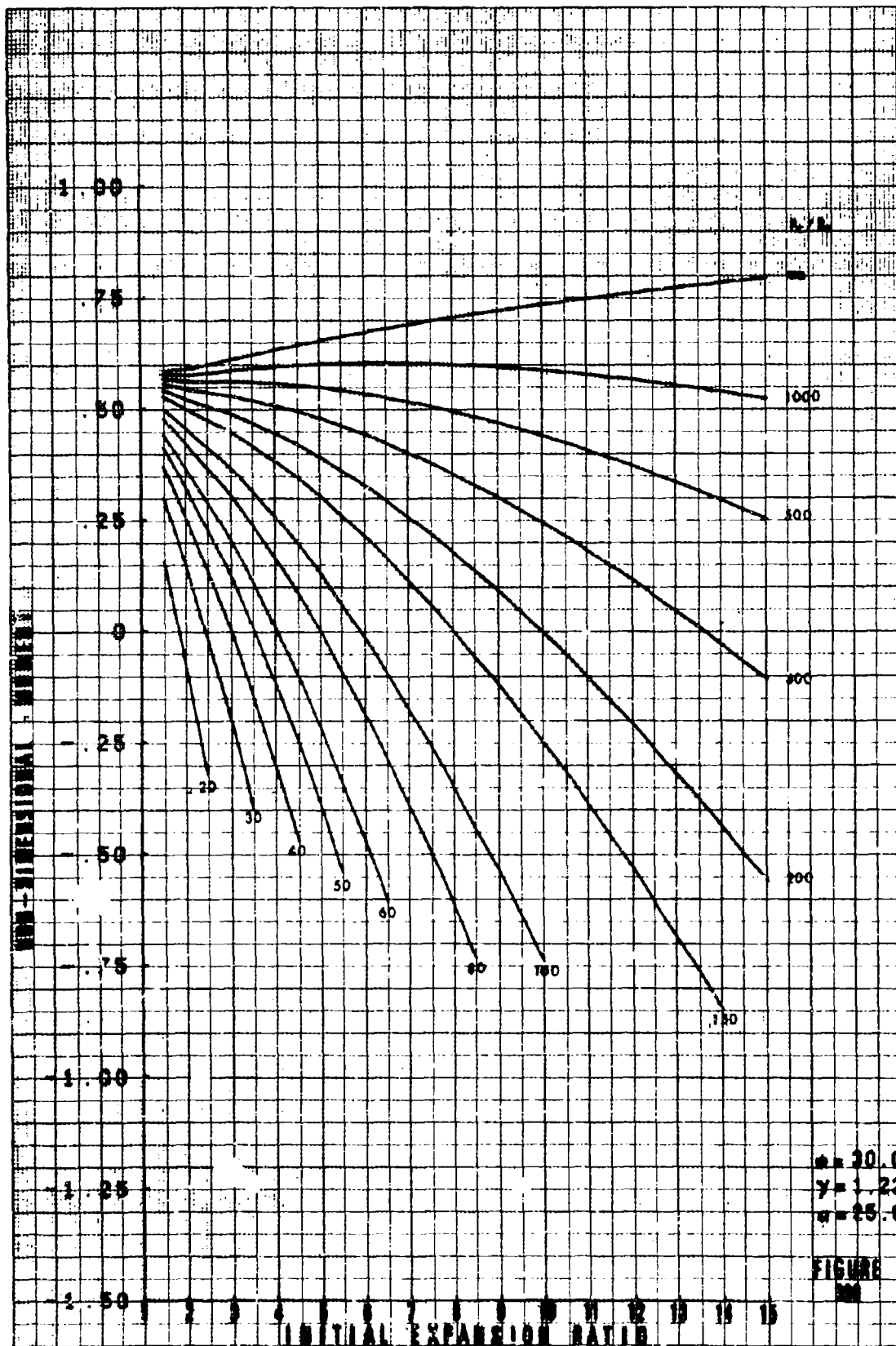


FIGURE 259



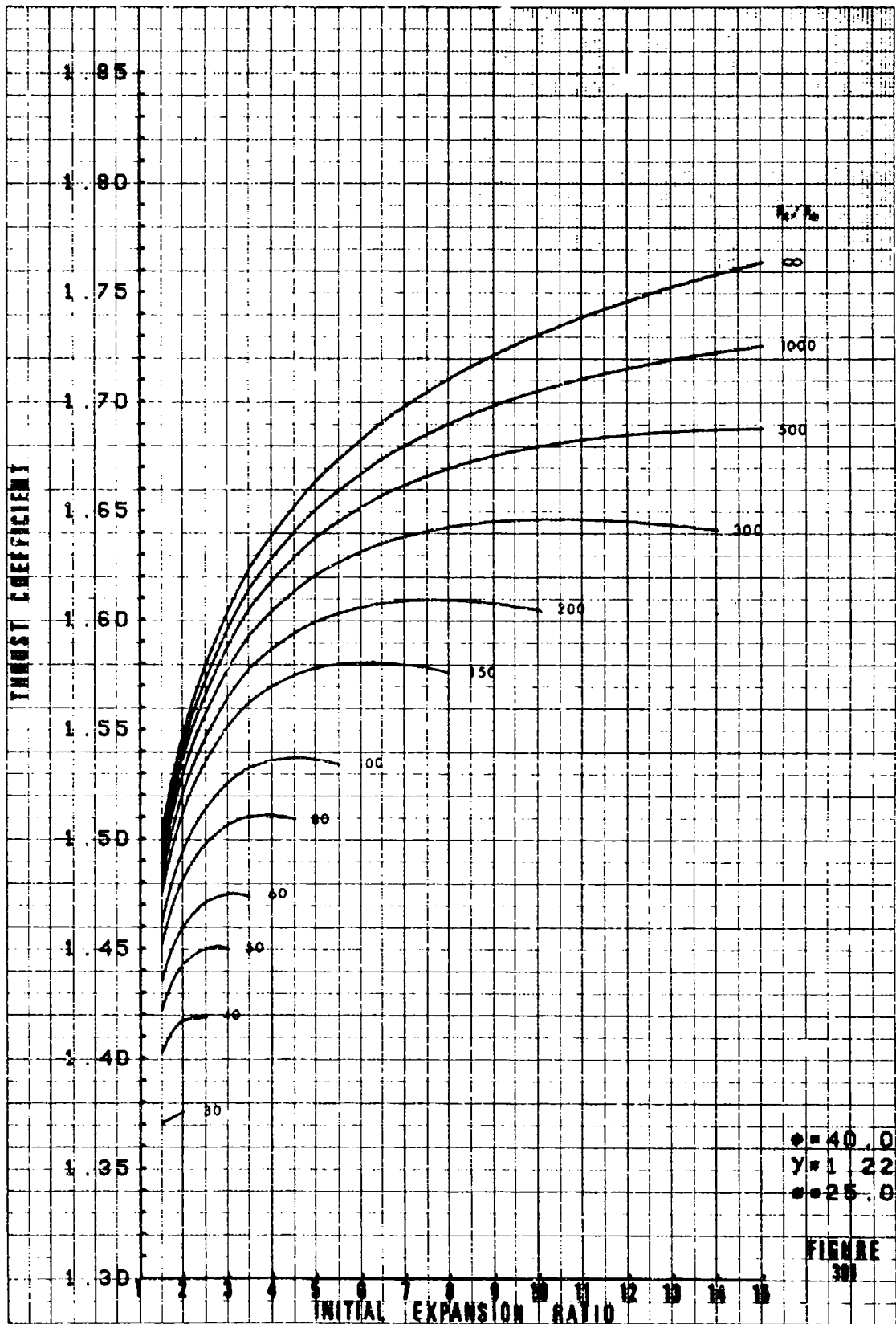
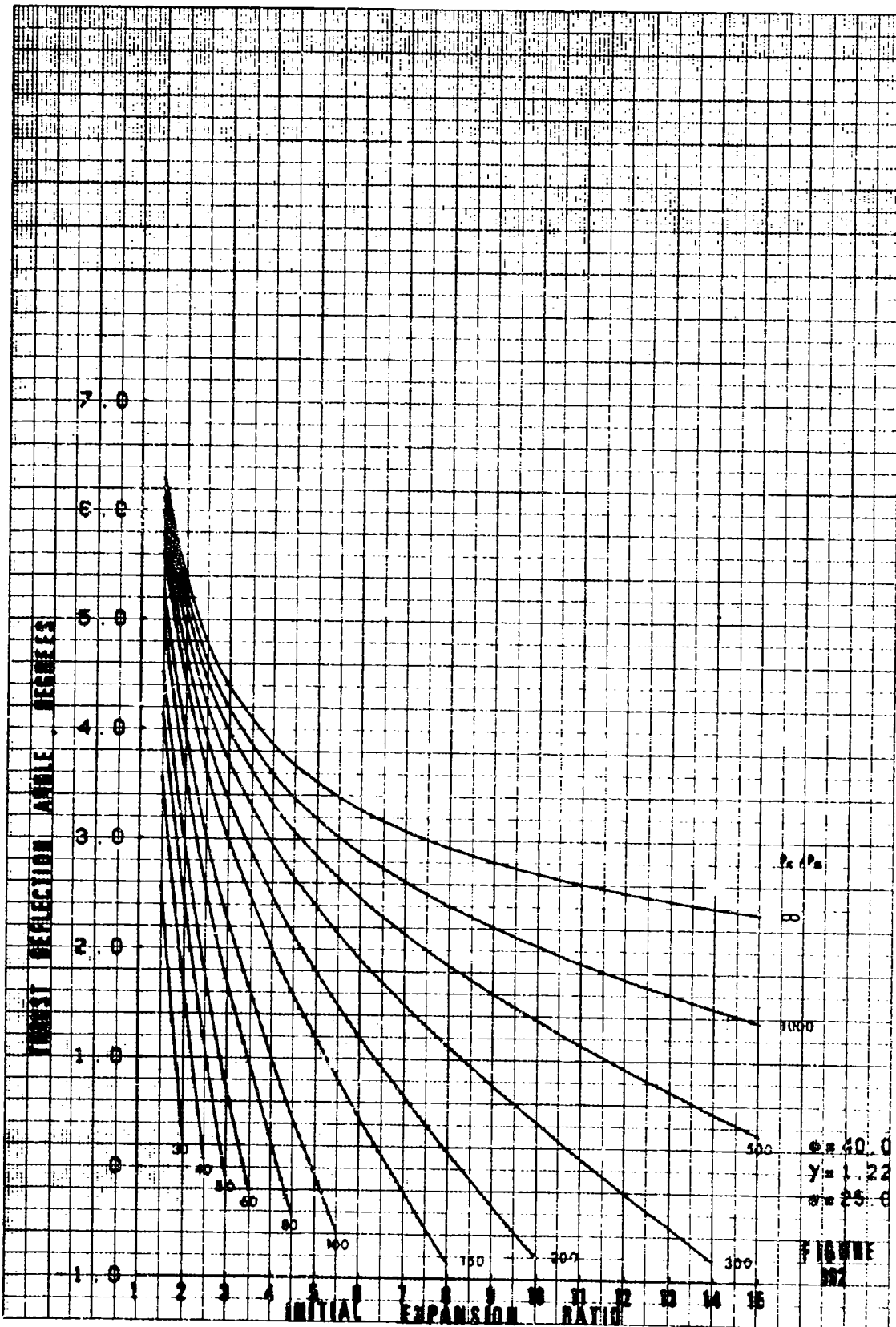
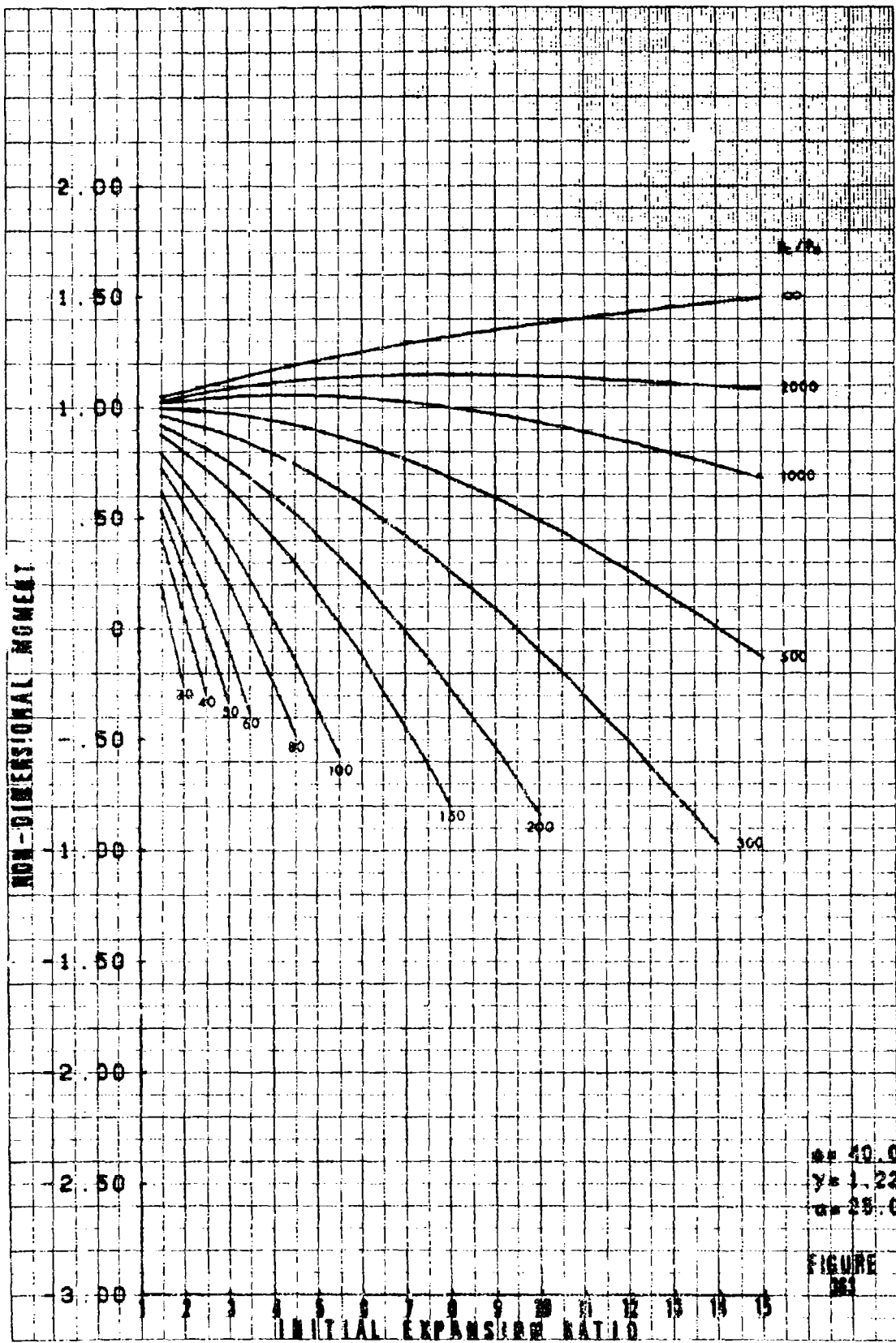
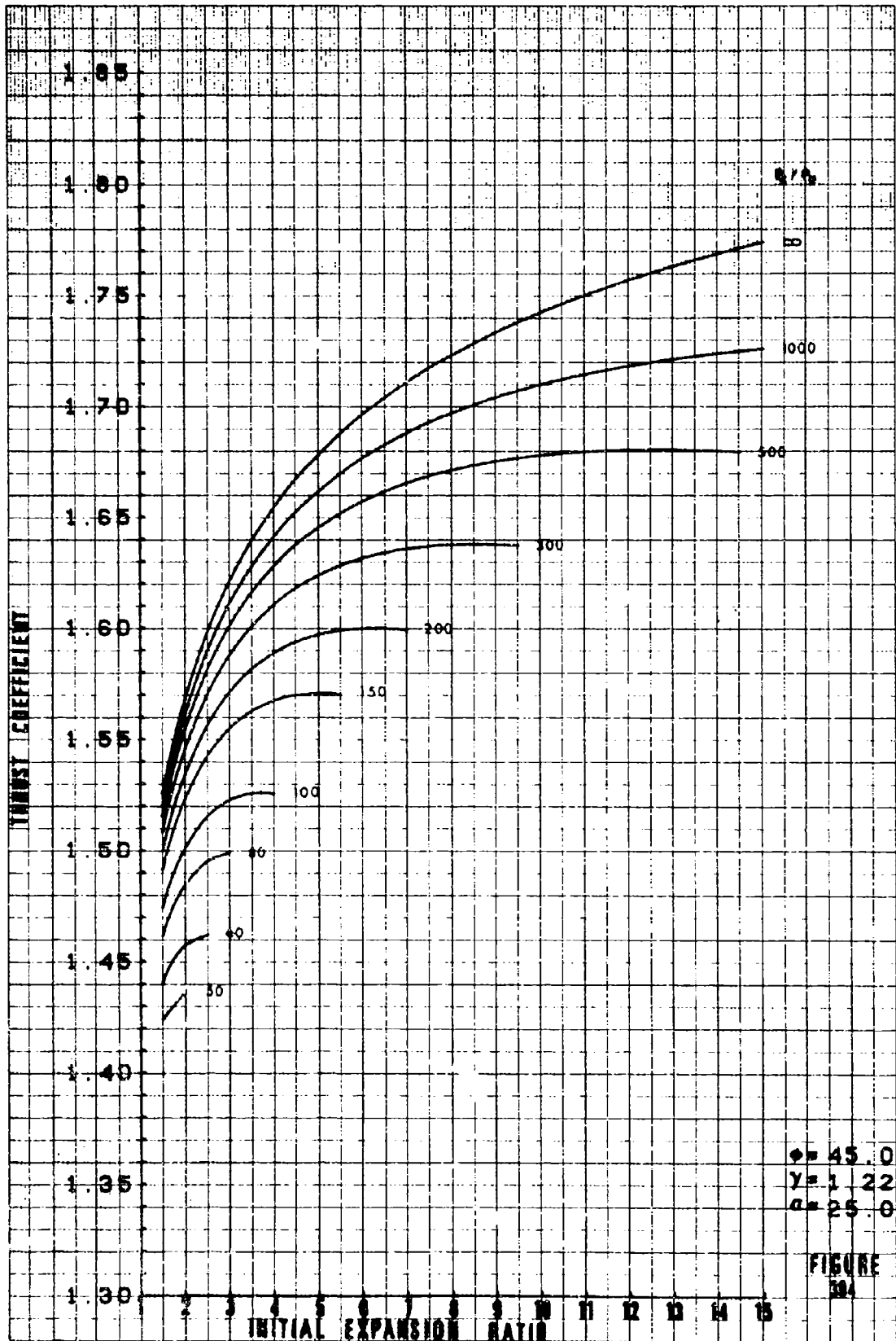


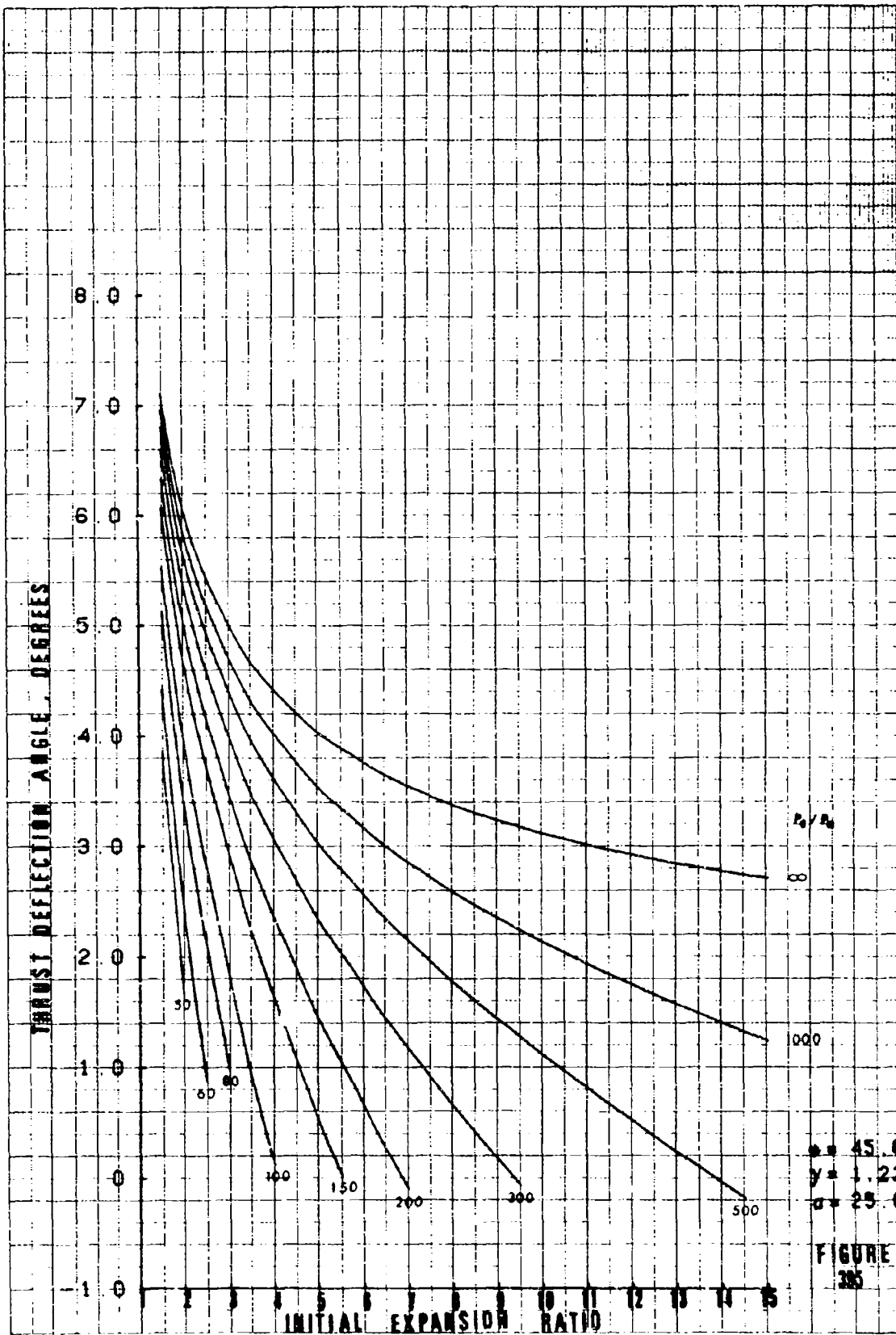
FIGURE 393





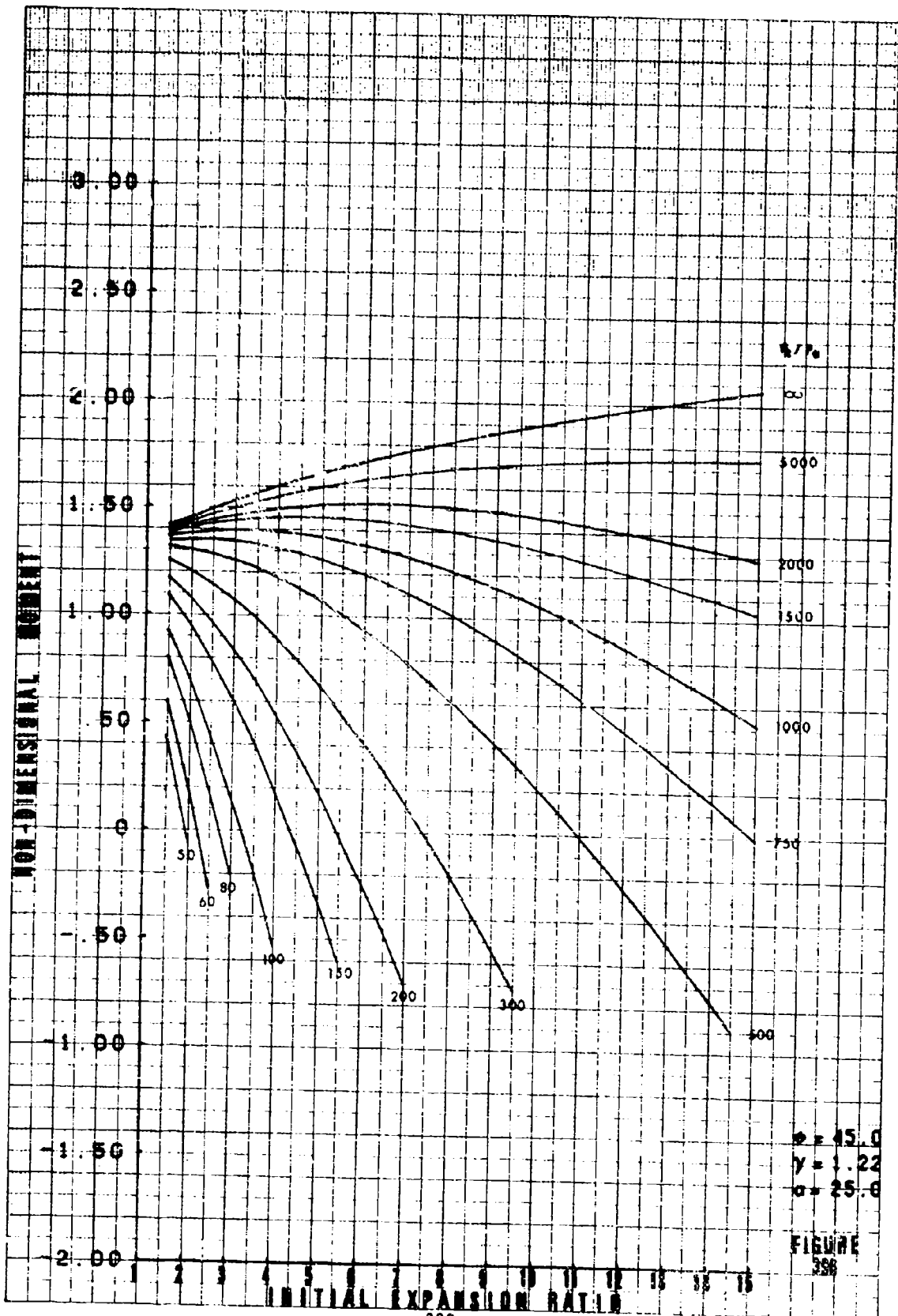


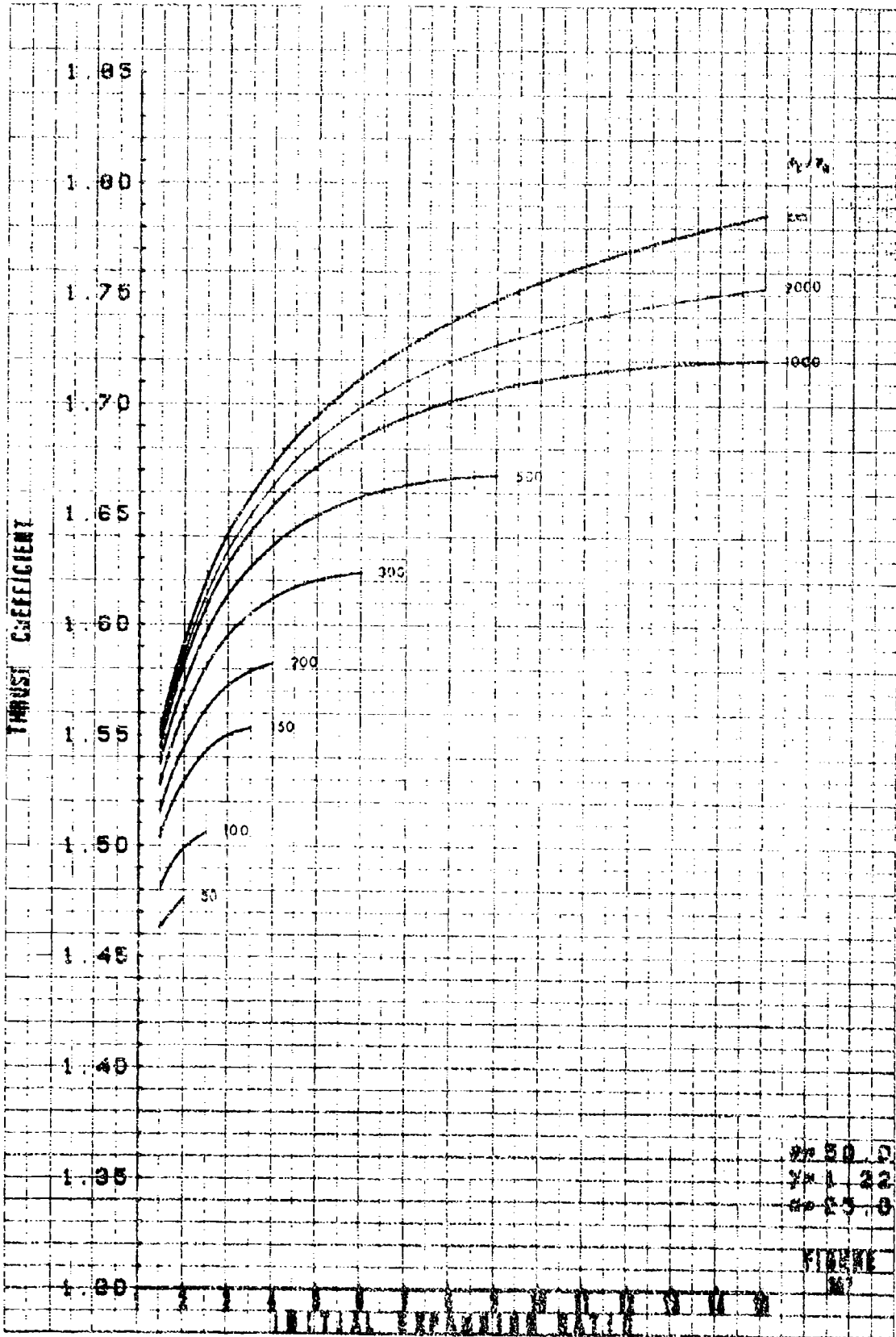




$\gamma = 1.22$   
 $\alpha = 25.0$

FIGURE 385





27-50-0  
 27-1-22  
 27-25-0

FIGURE 20

INITIAL EXPANSION RATIO

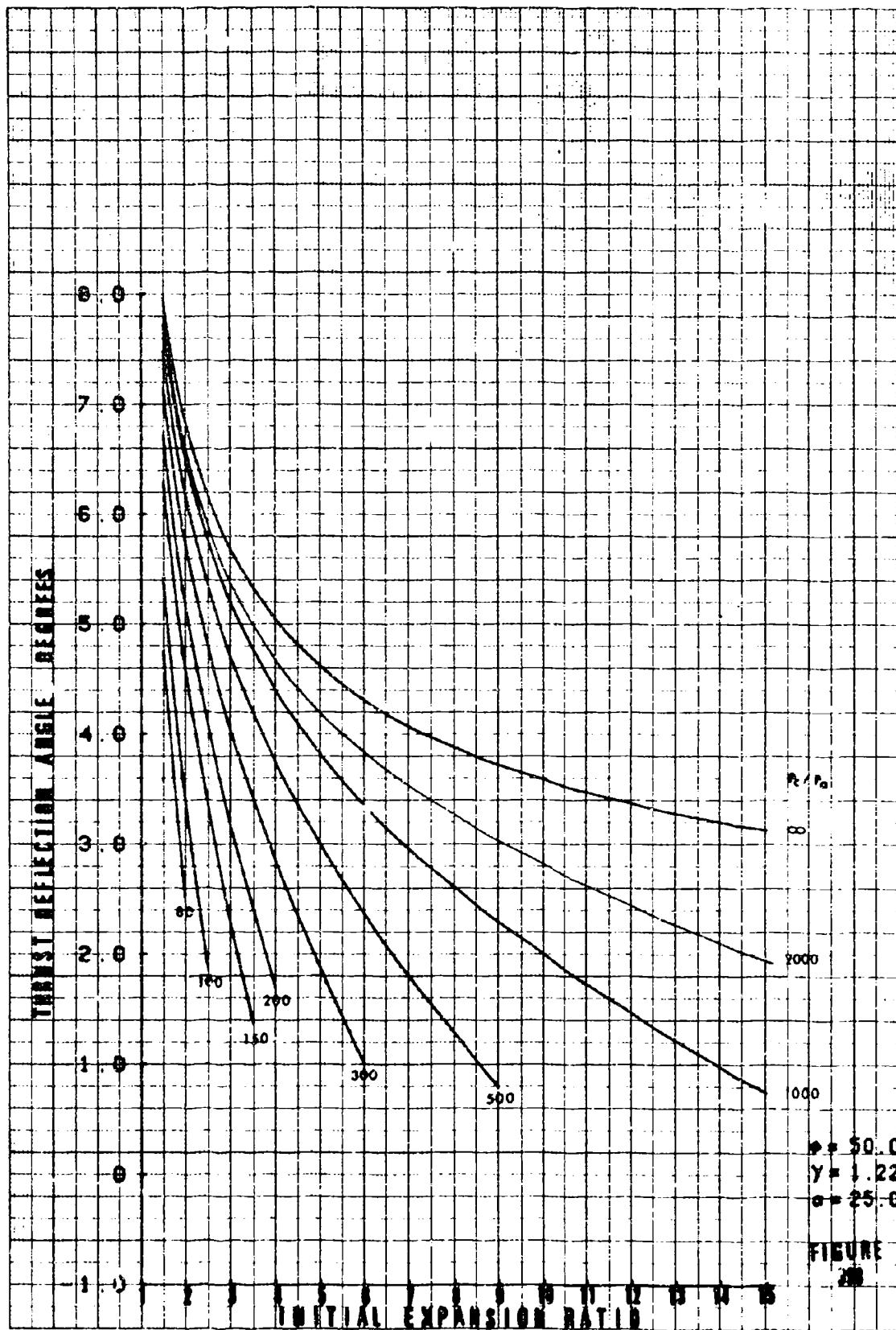
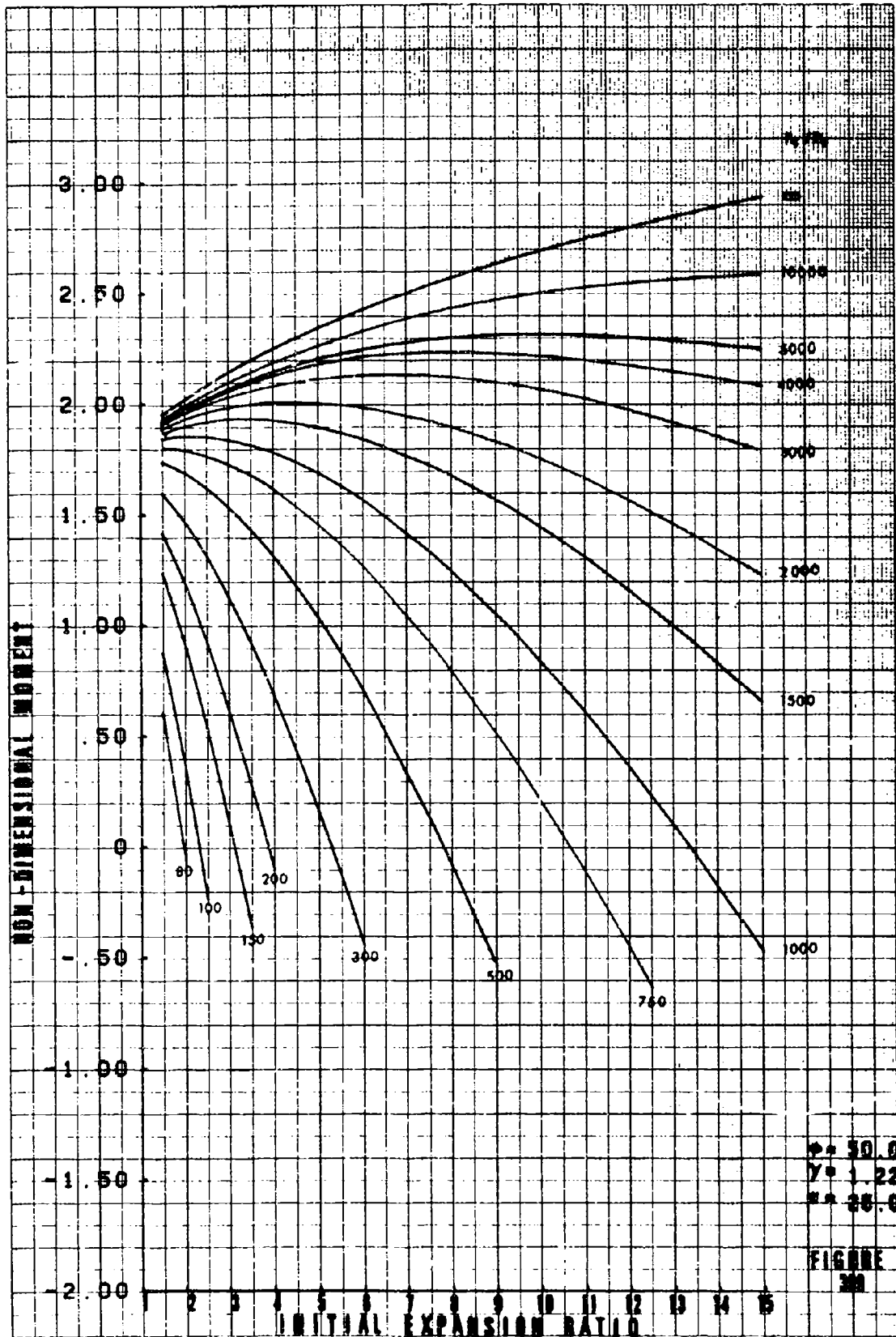
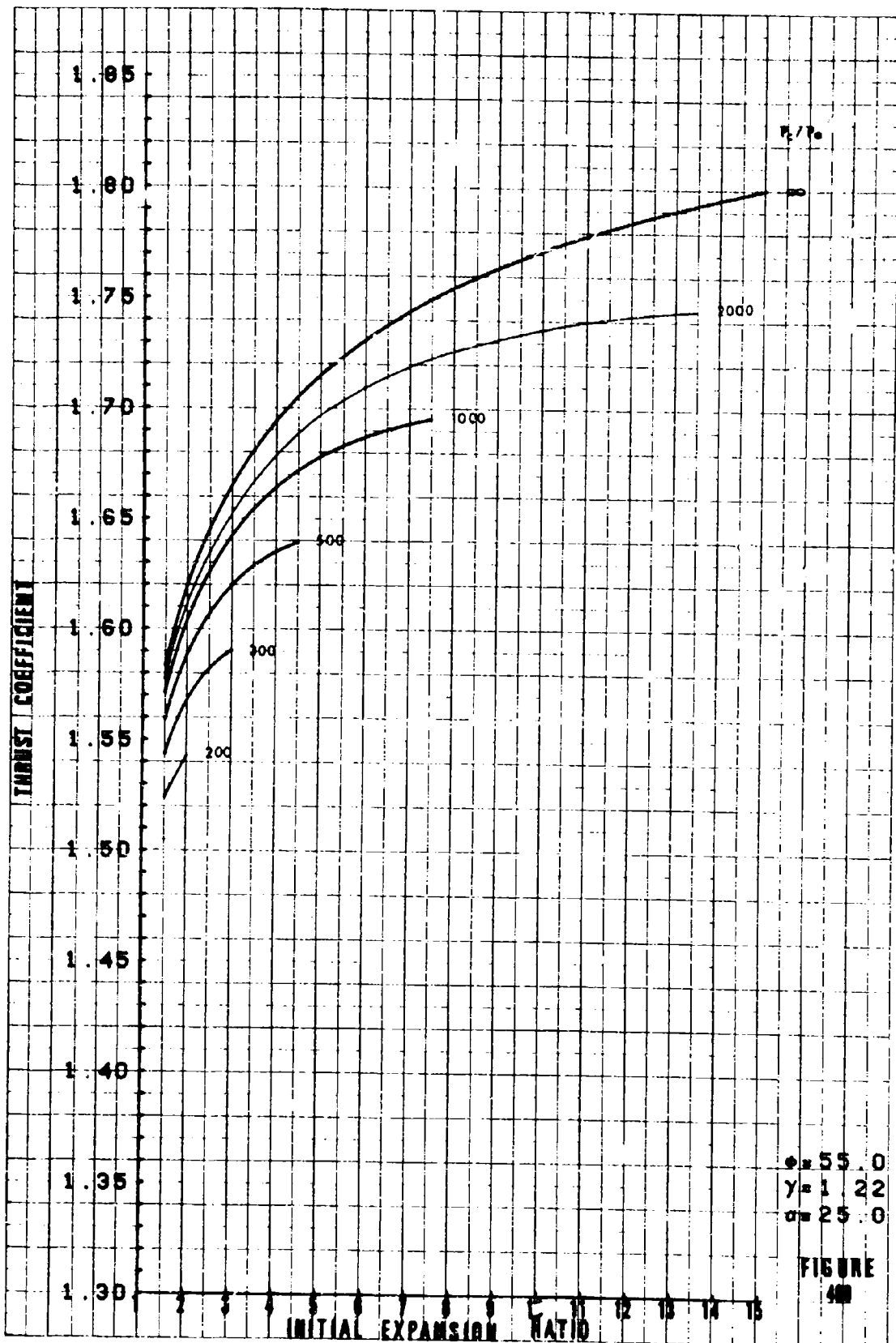


FIGURE 20

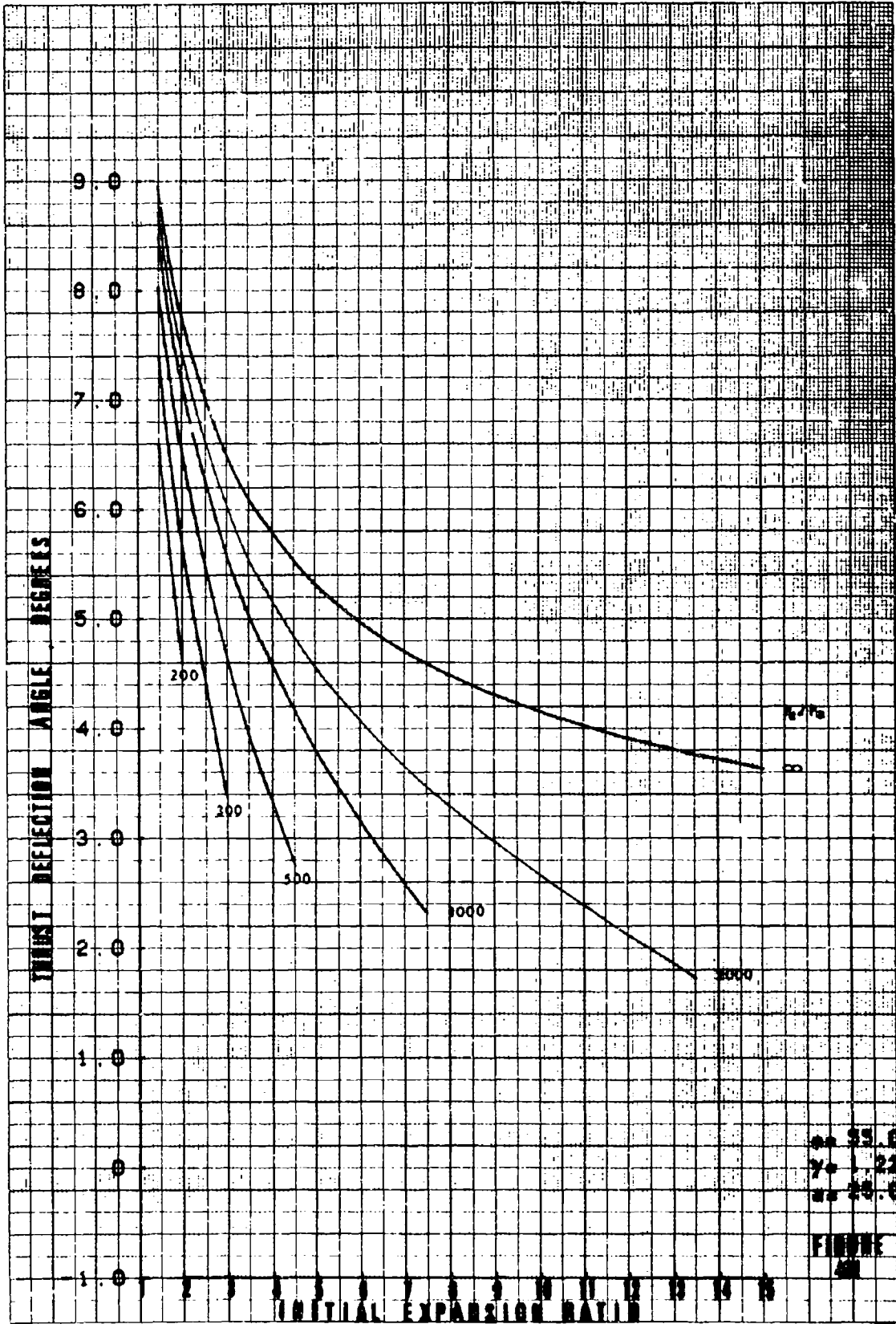






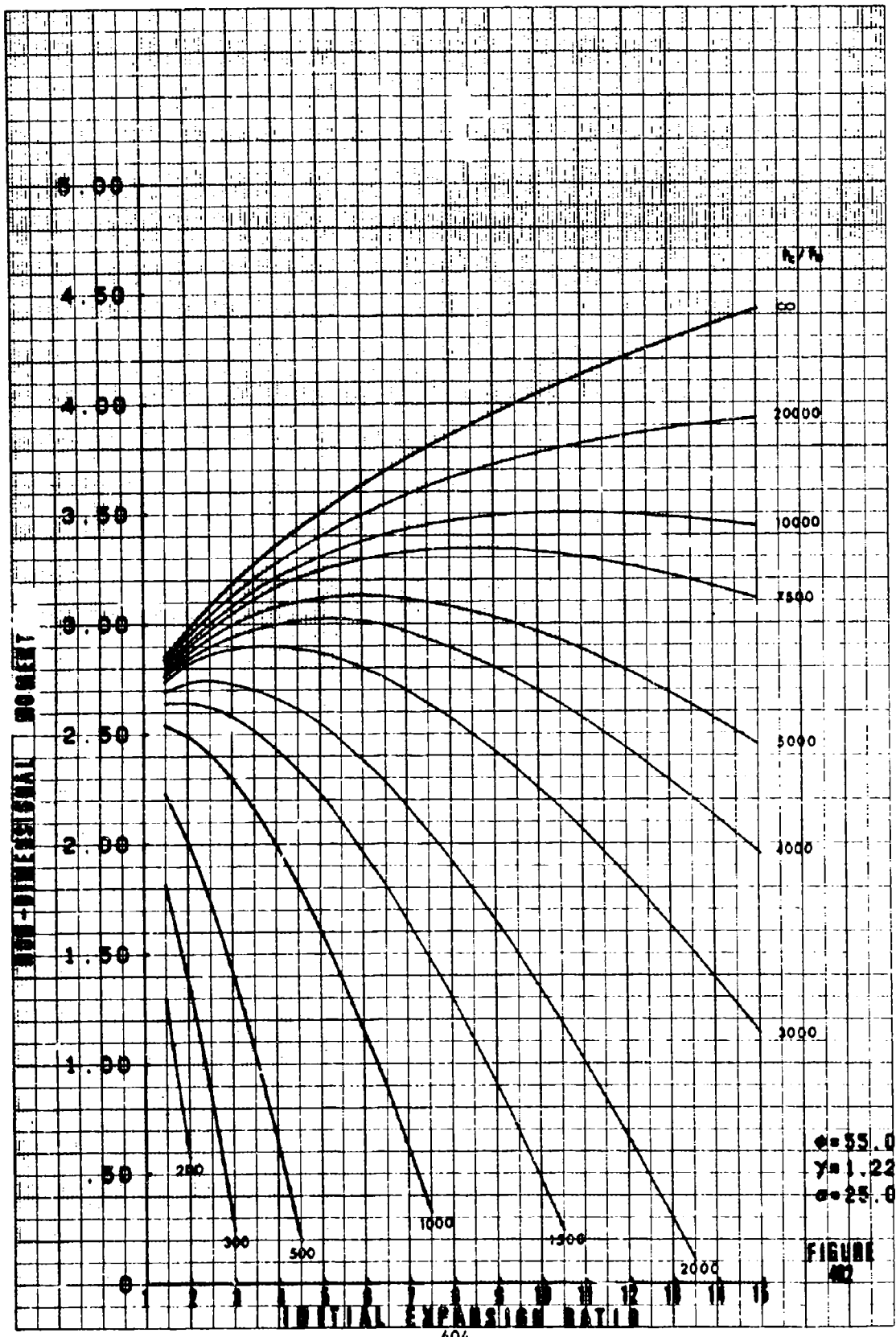
$\phi = 55.0$   
 $\gamma = 1.22$   
 $\sigma = 25.0$

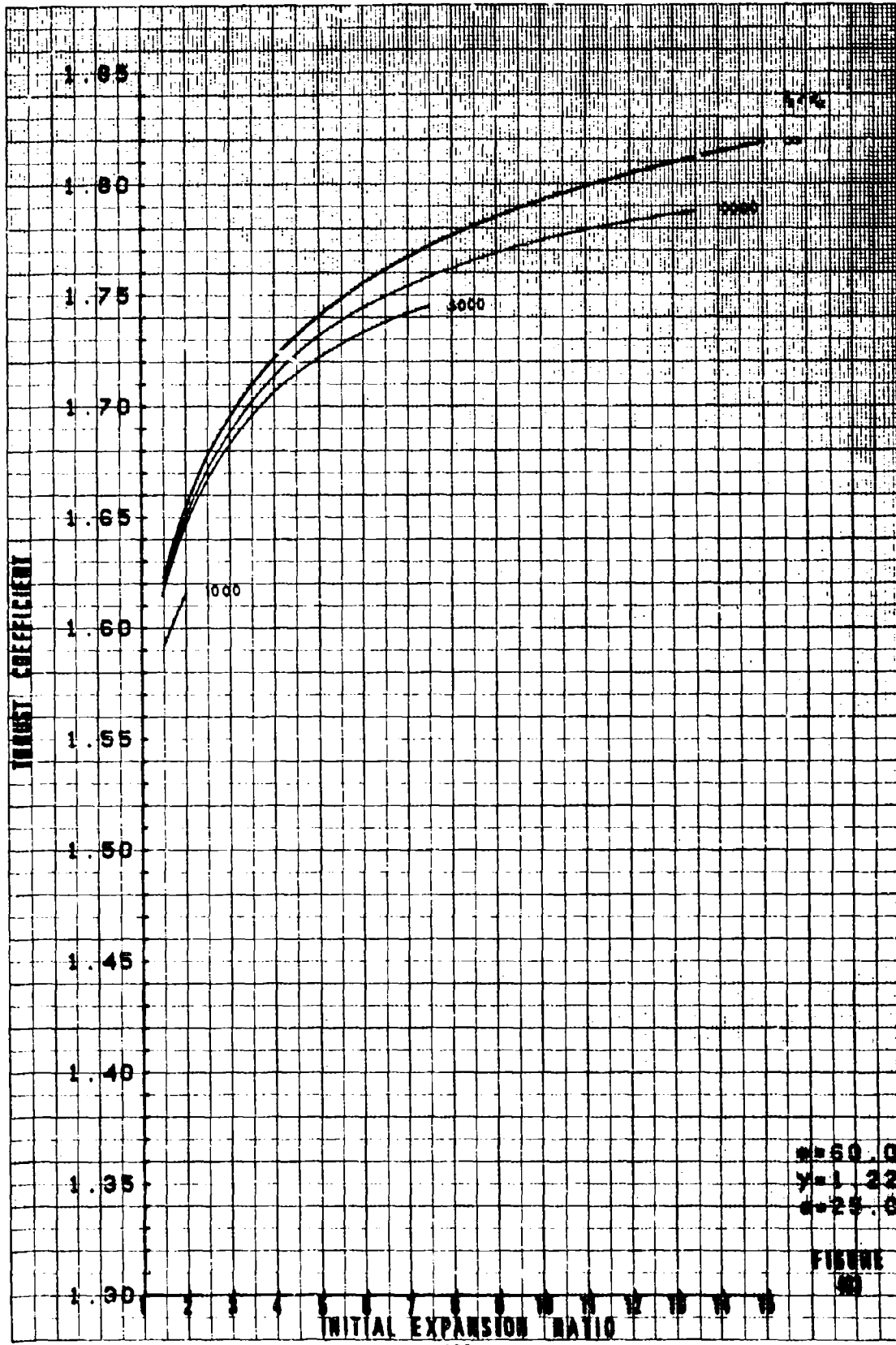
FIGURE 400

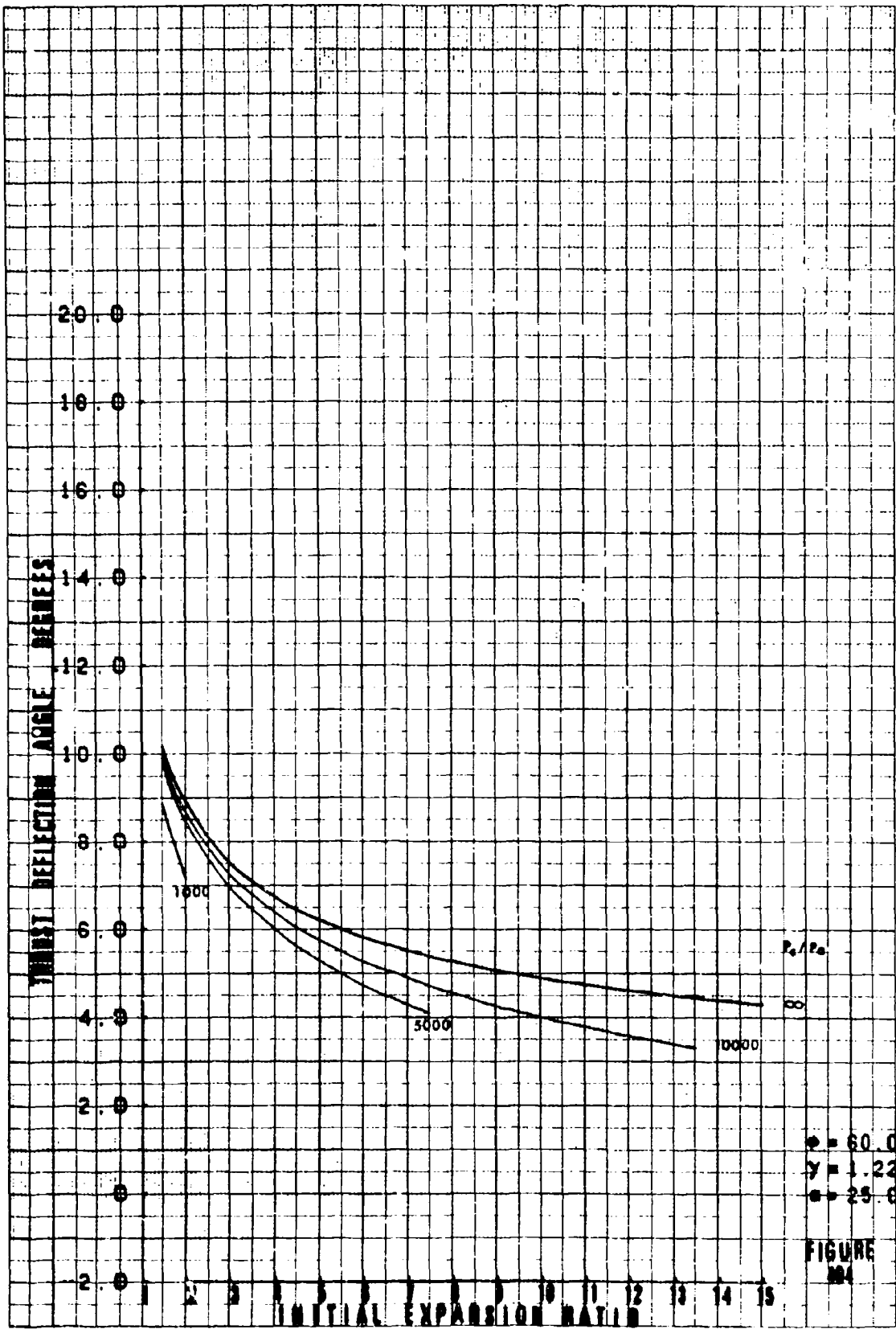


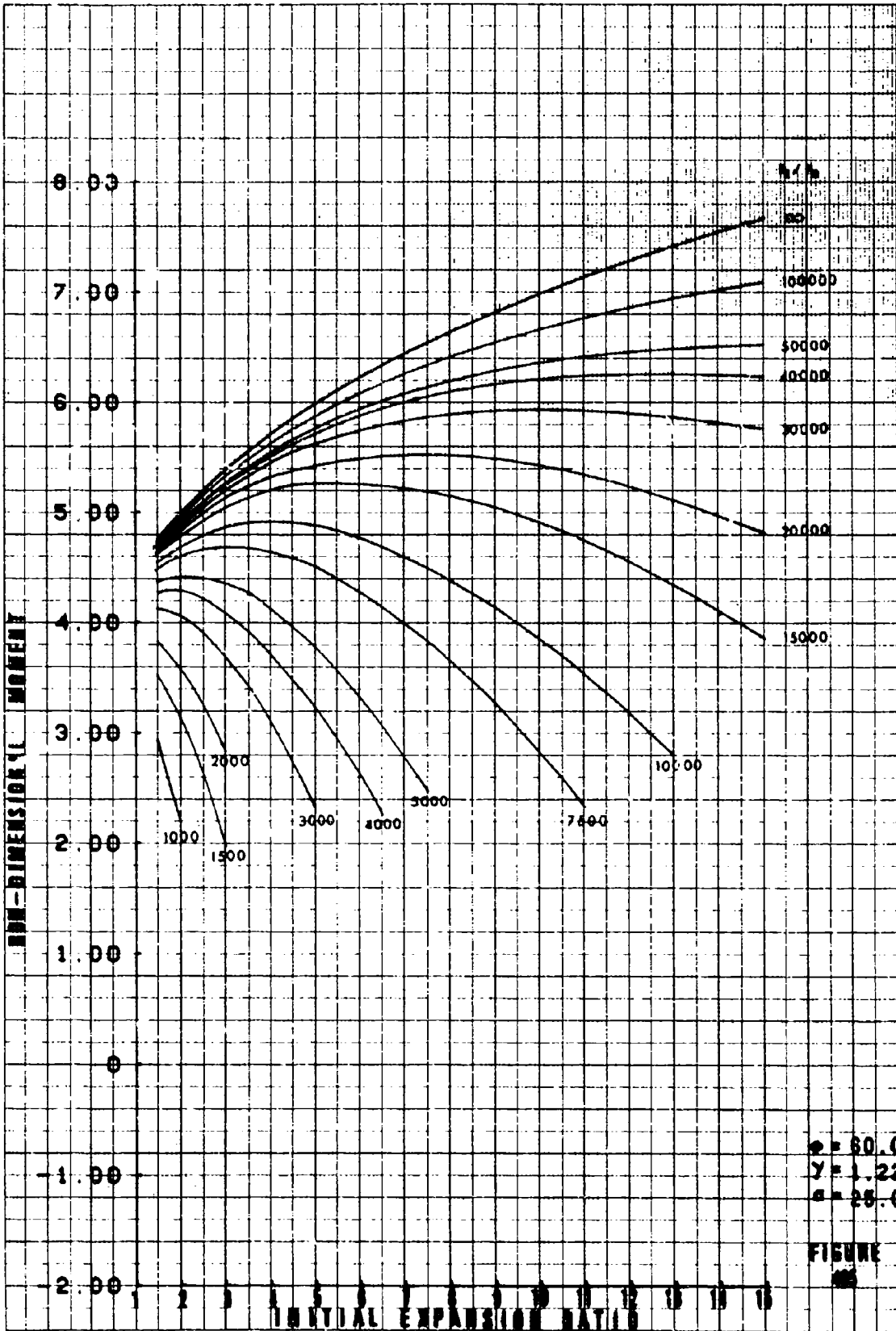
$\gamma = 1.22$   
 $\mu = 25.6$

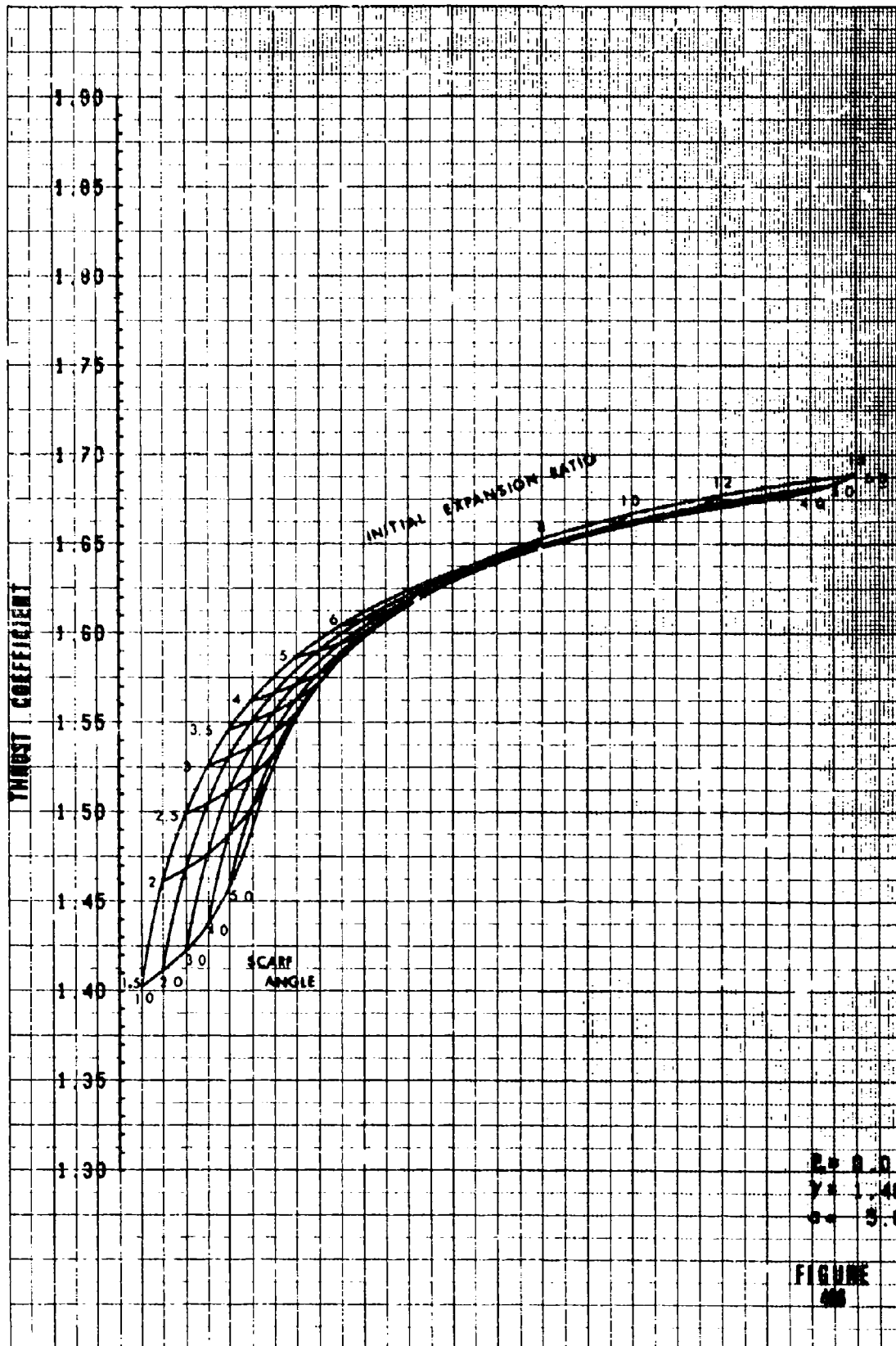
FIGURE 2

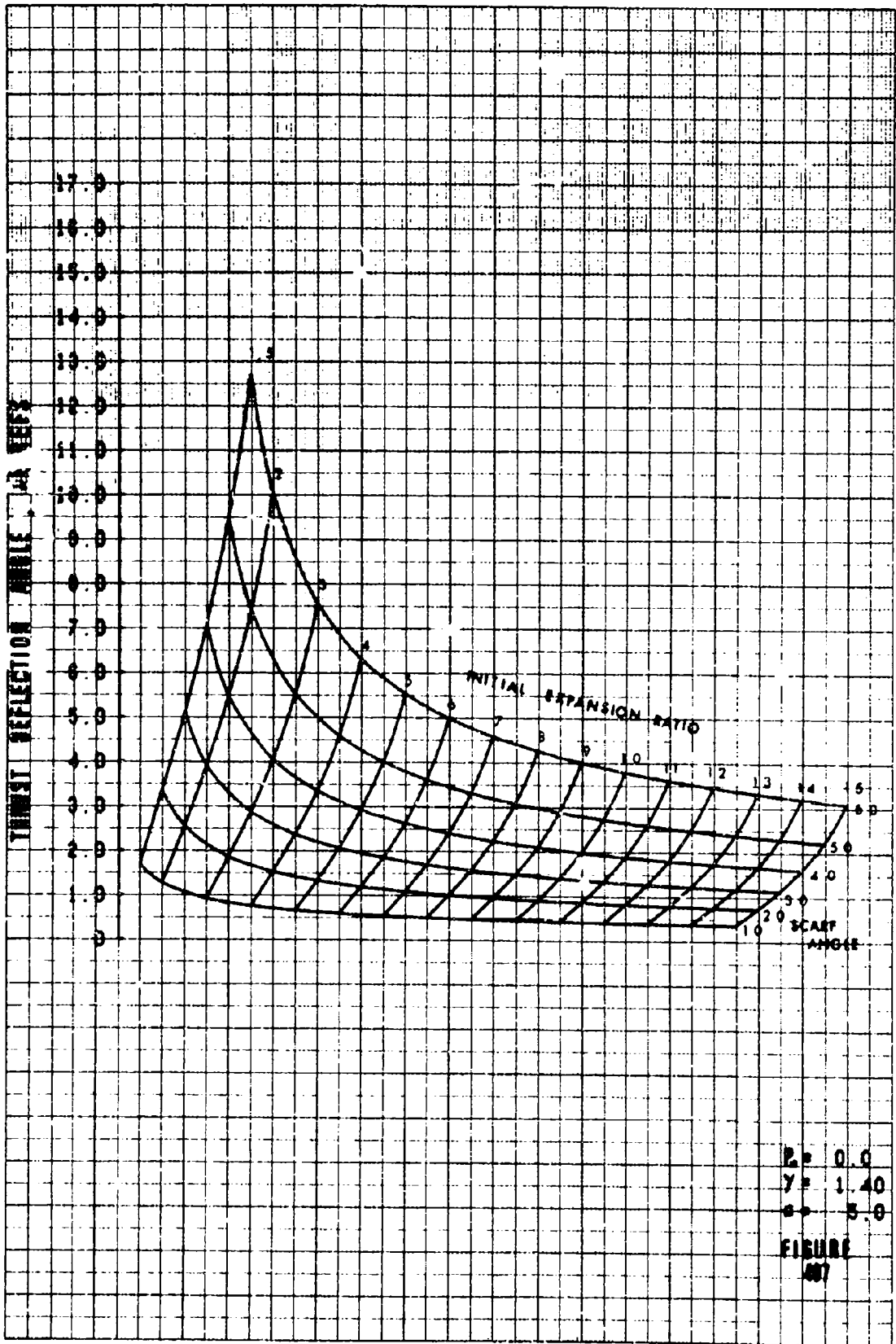




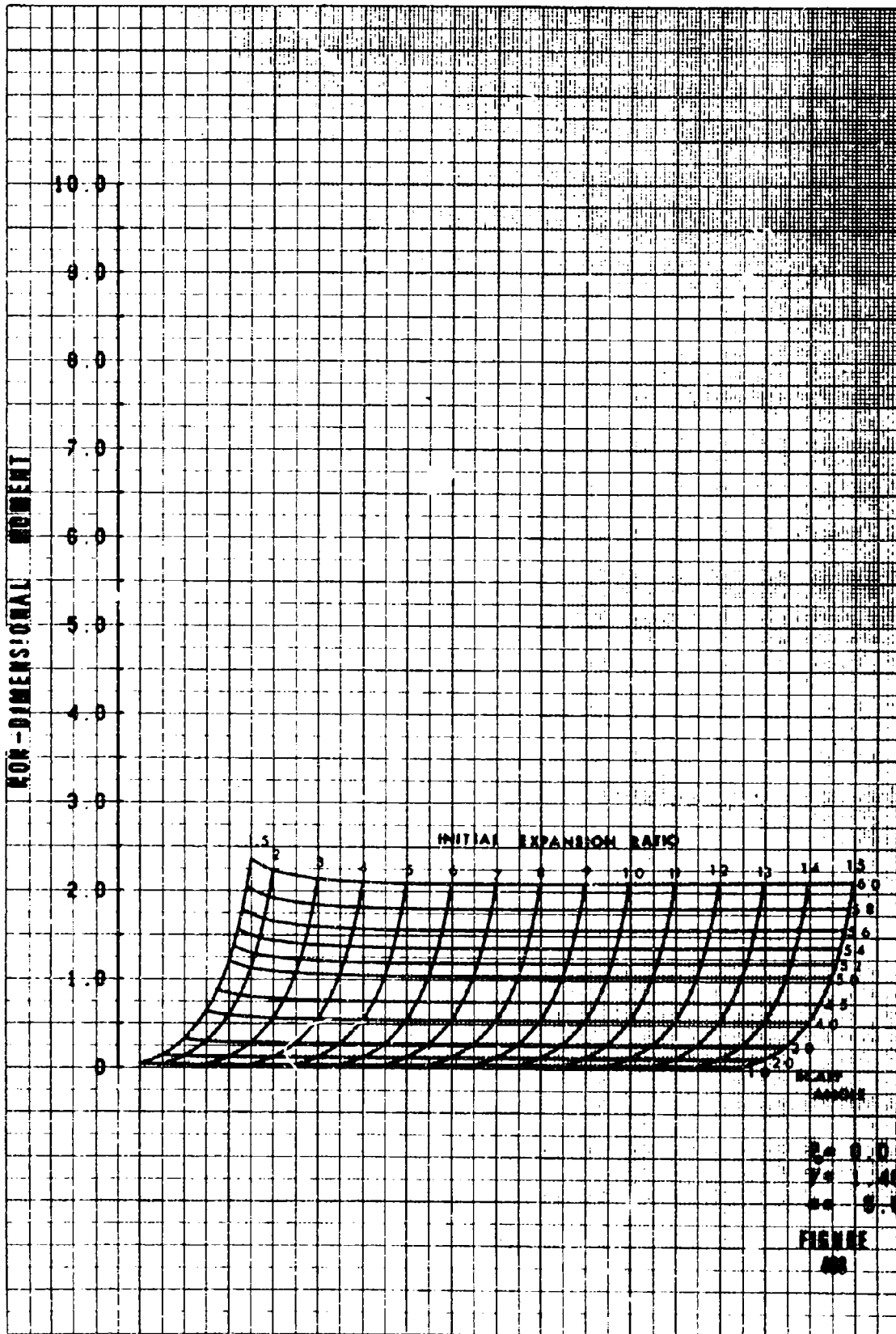


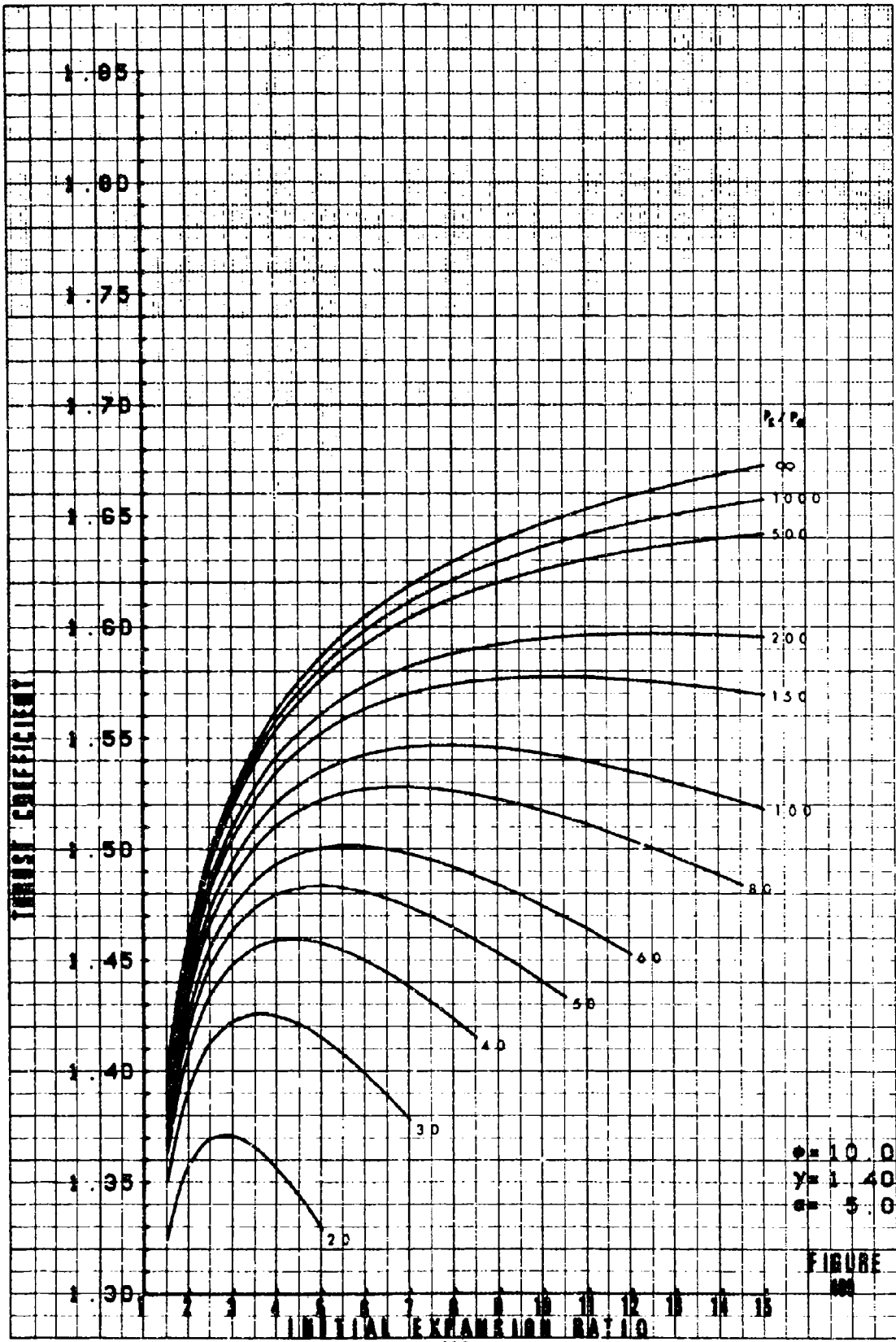


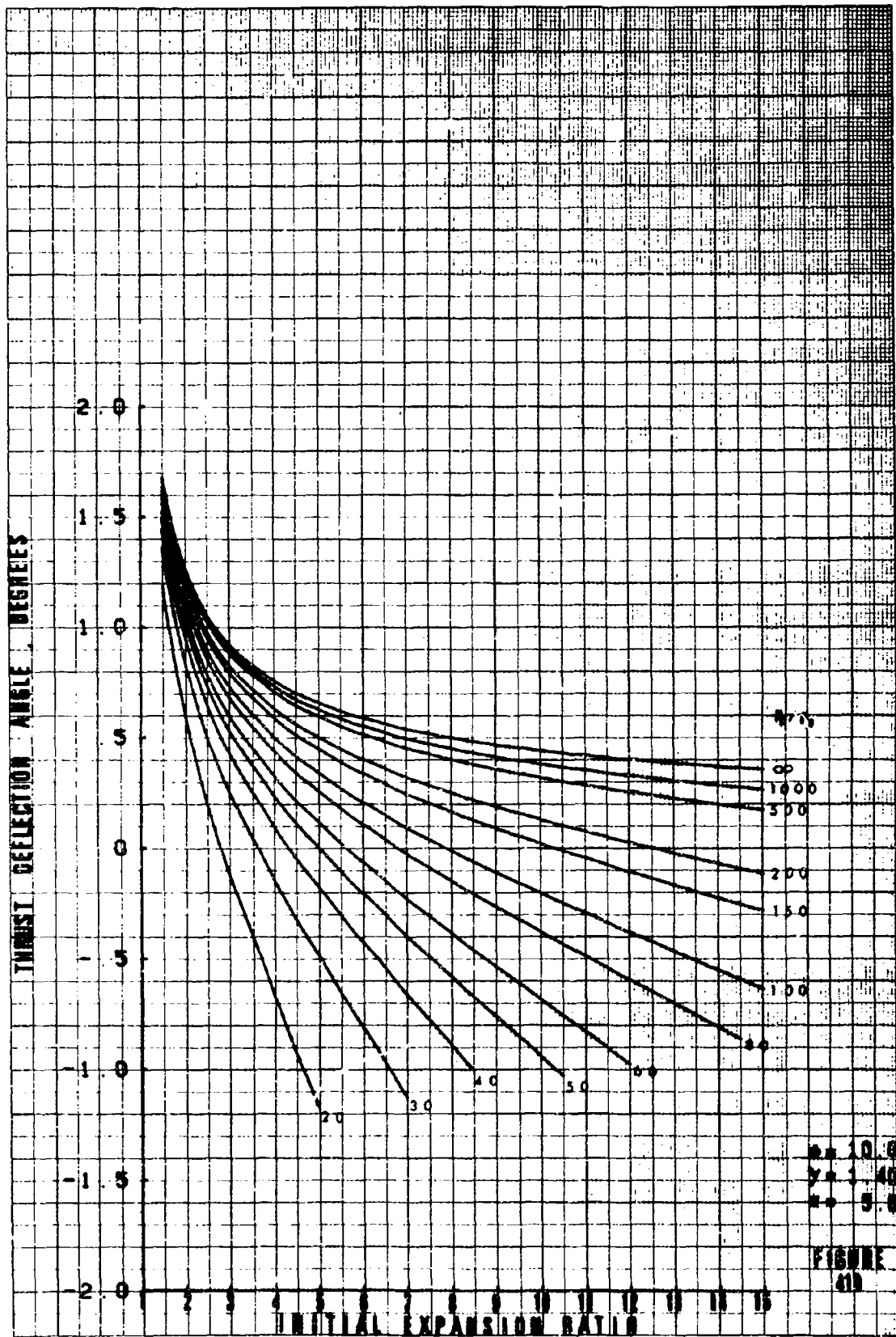


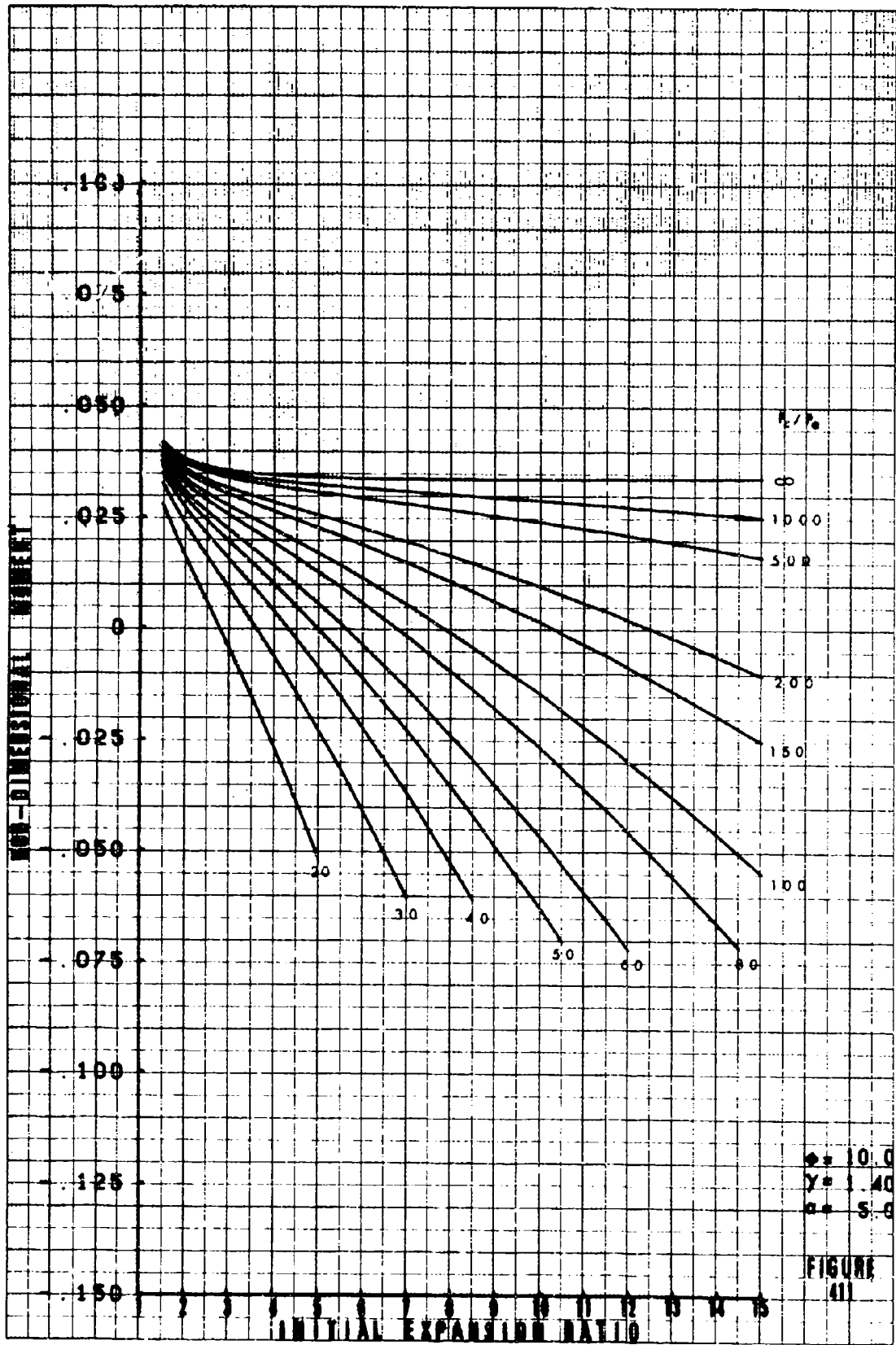












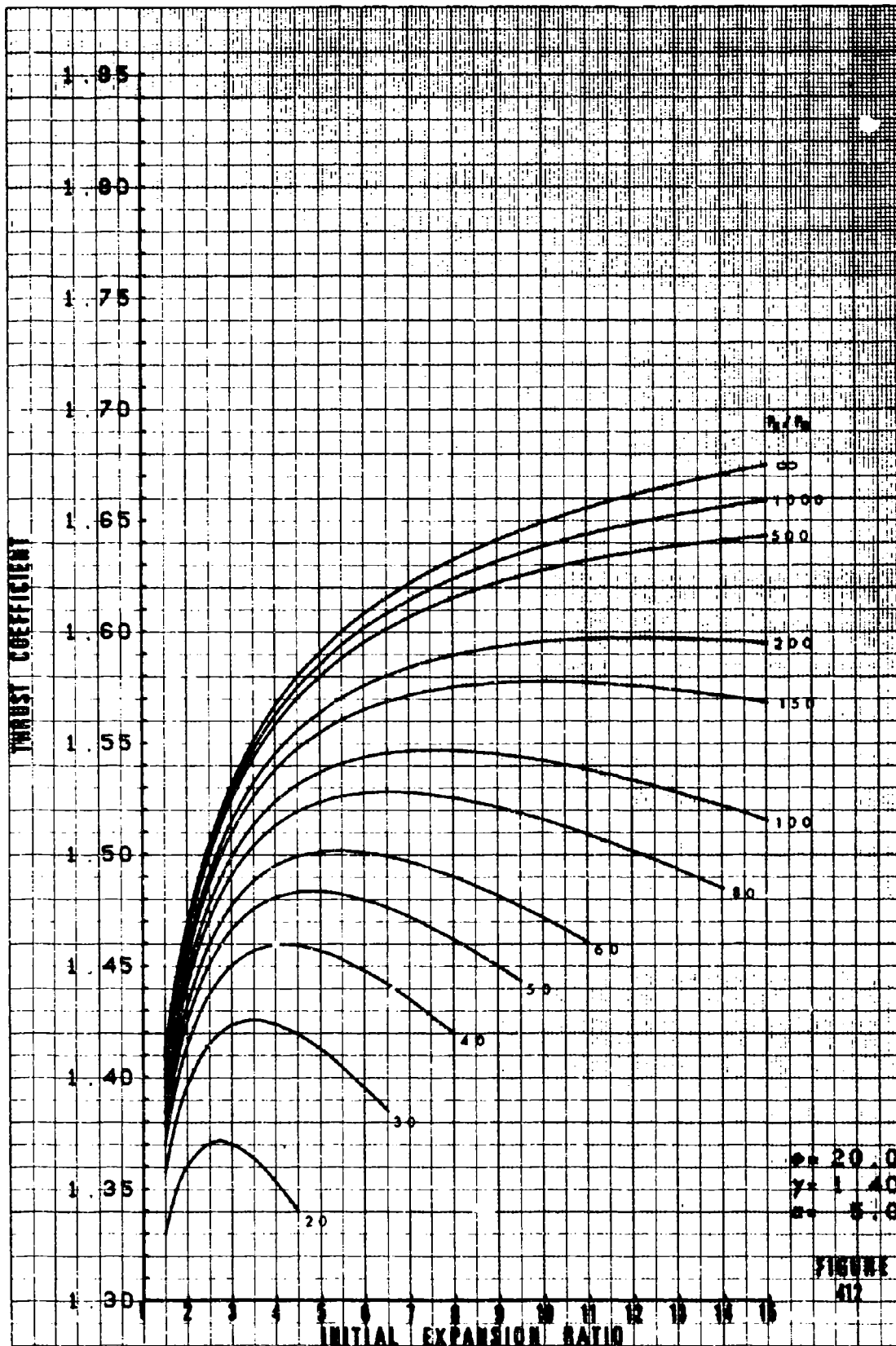
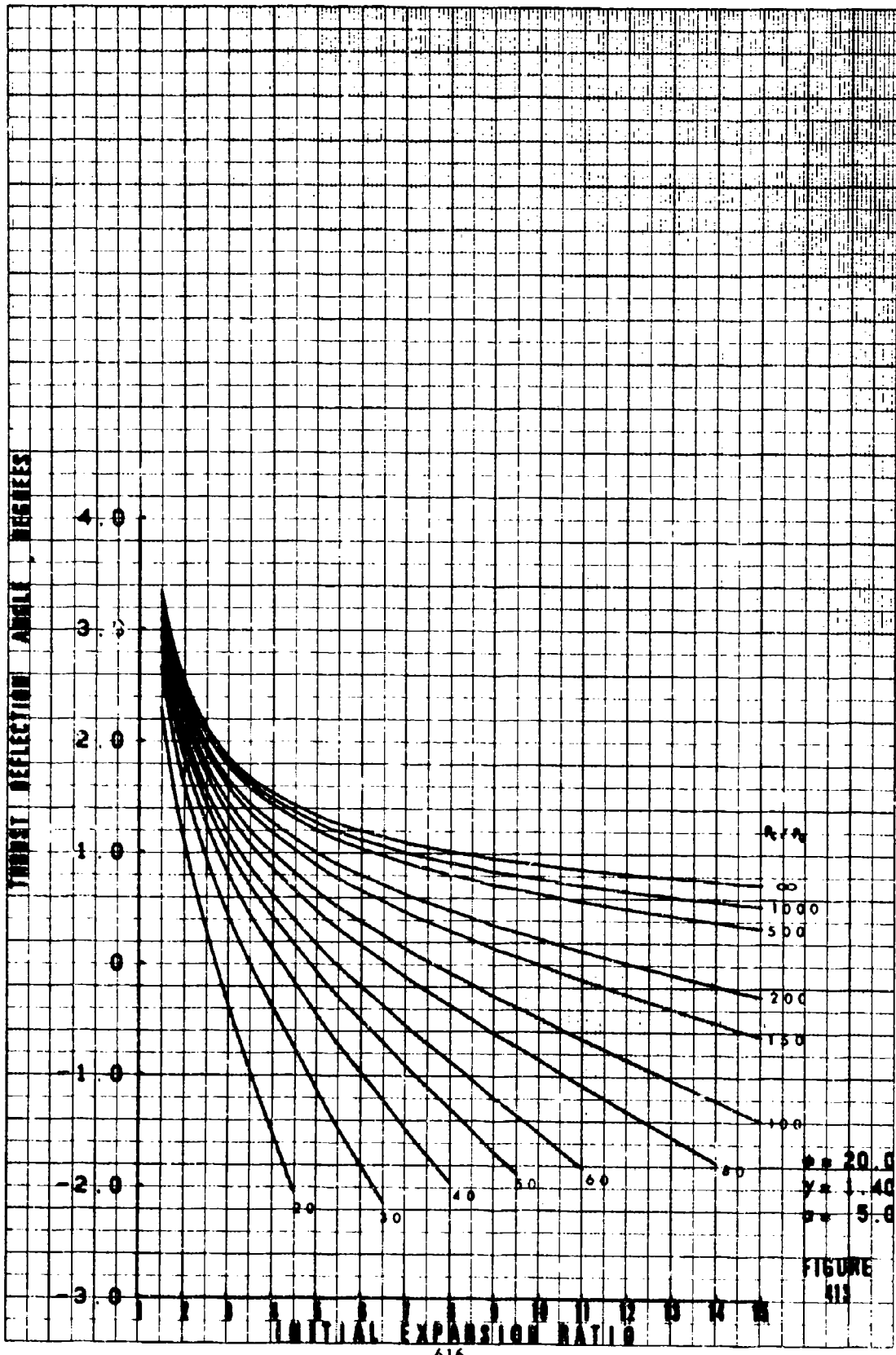
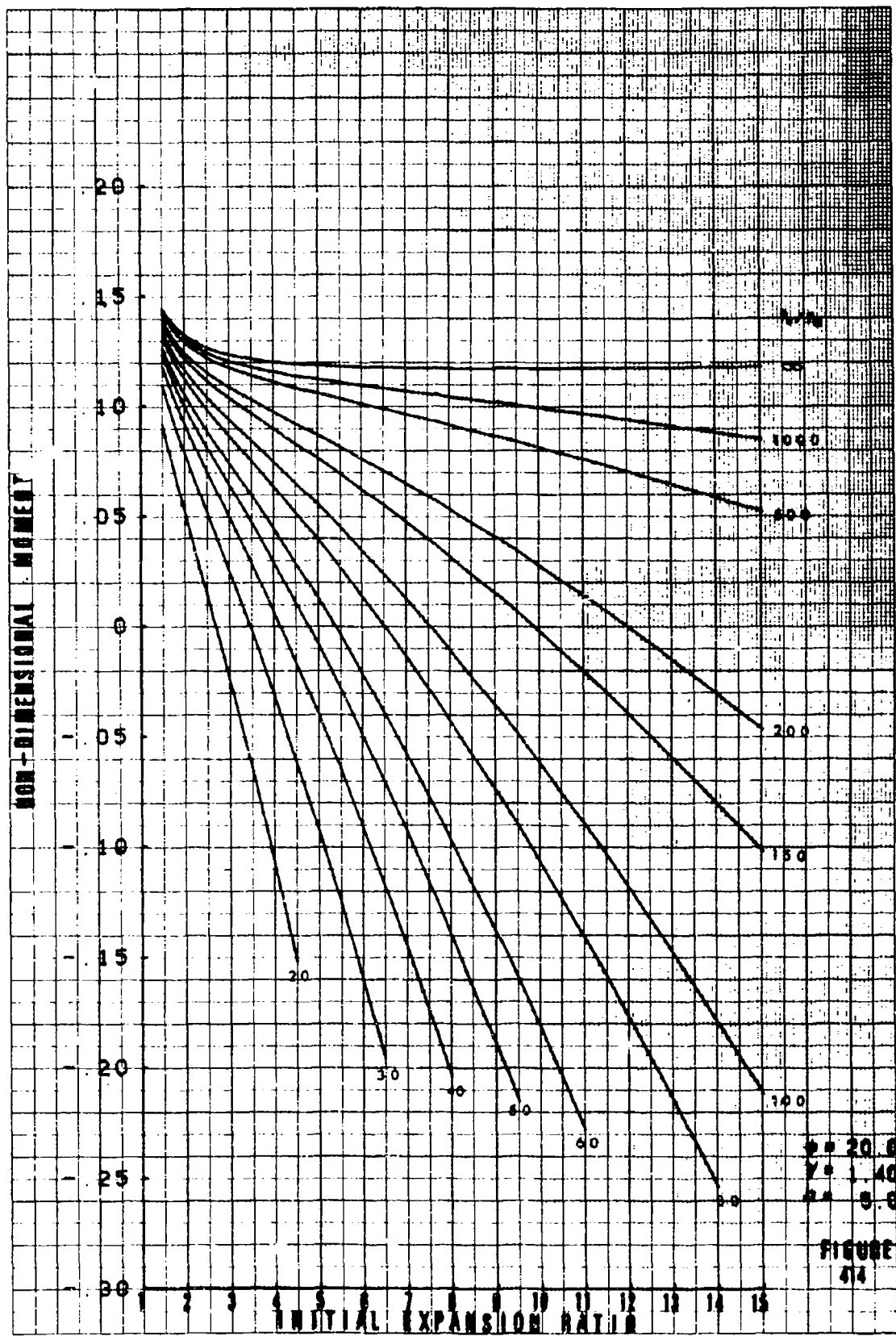
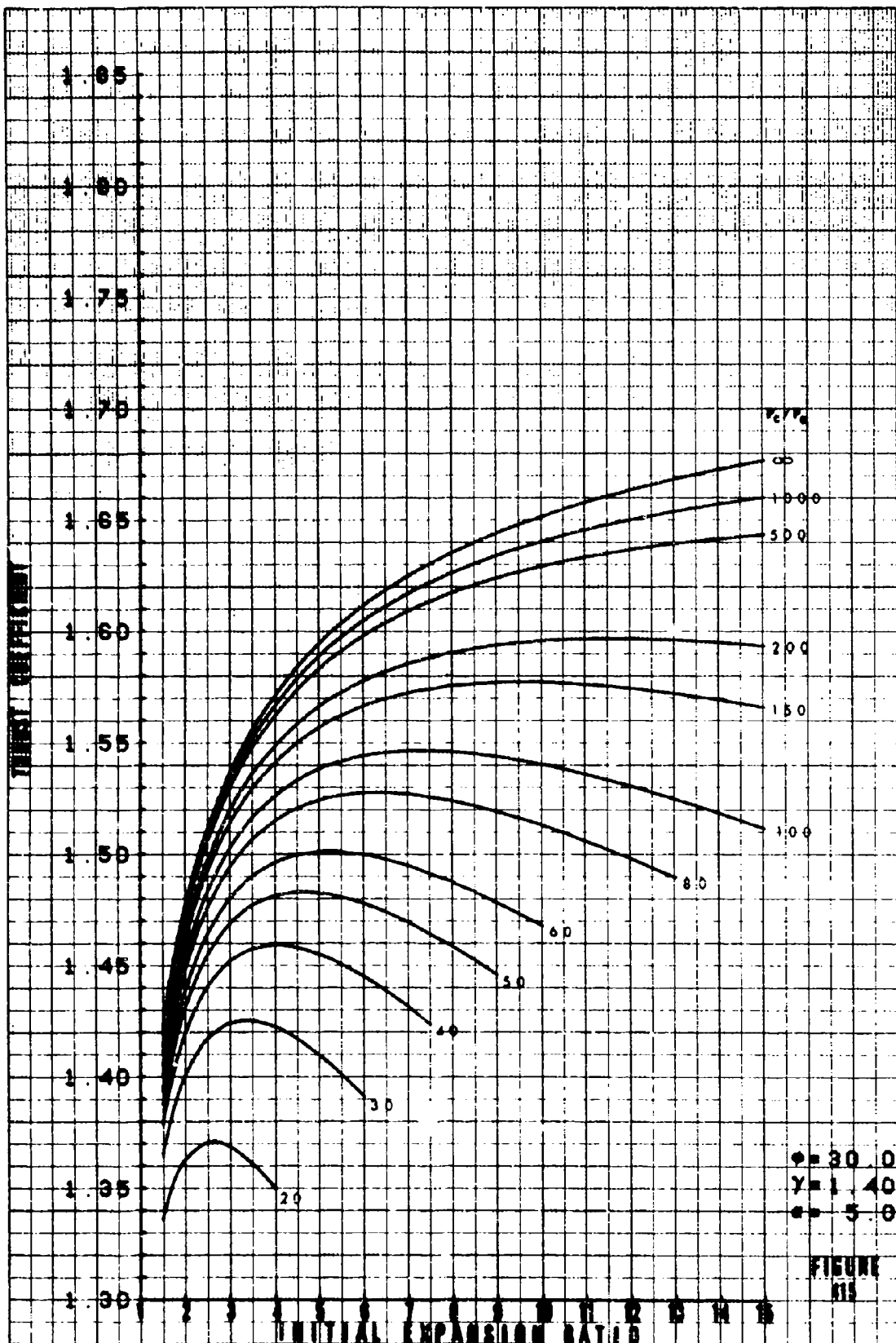


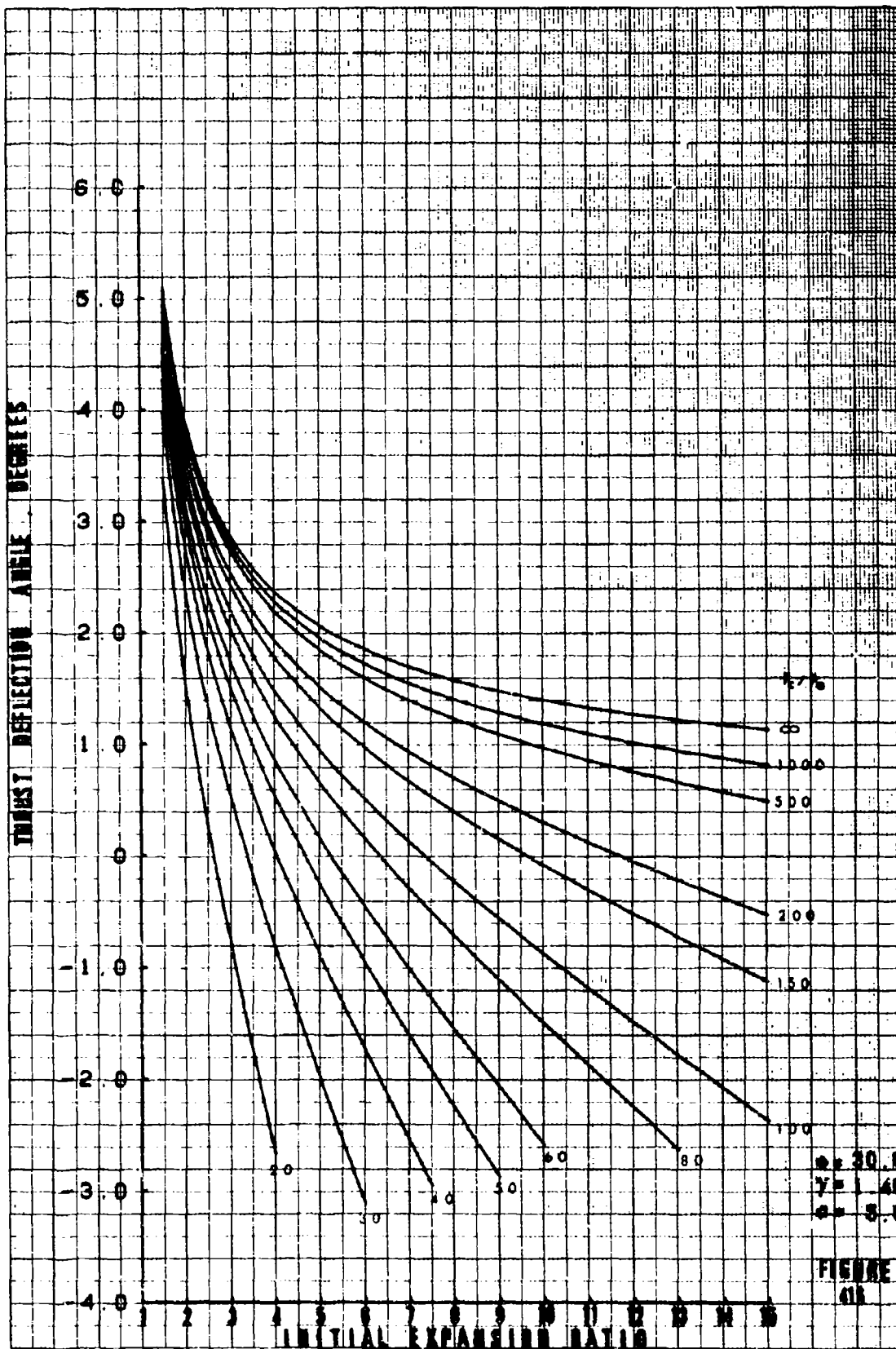
FIGURE 412



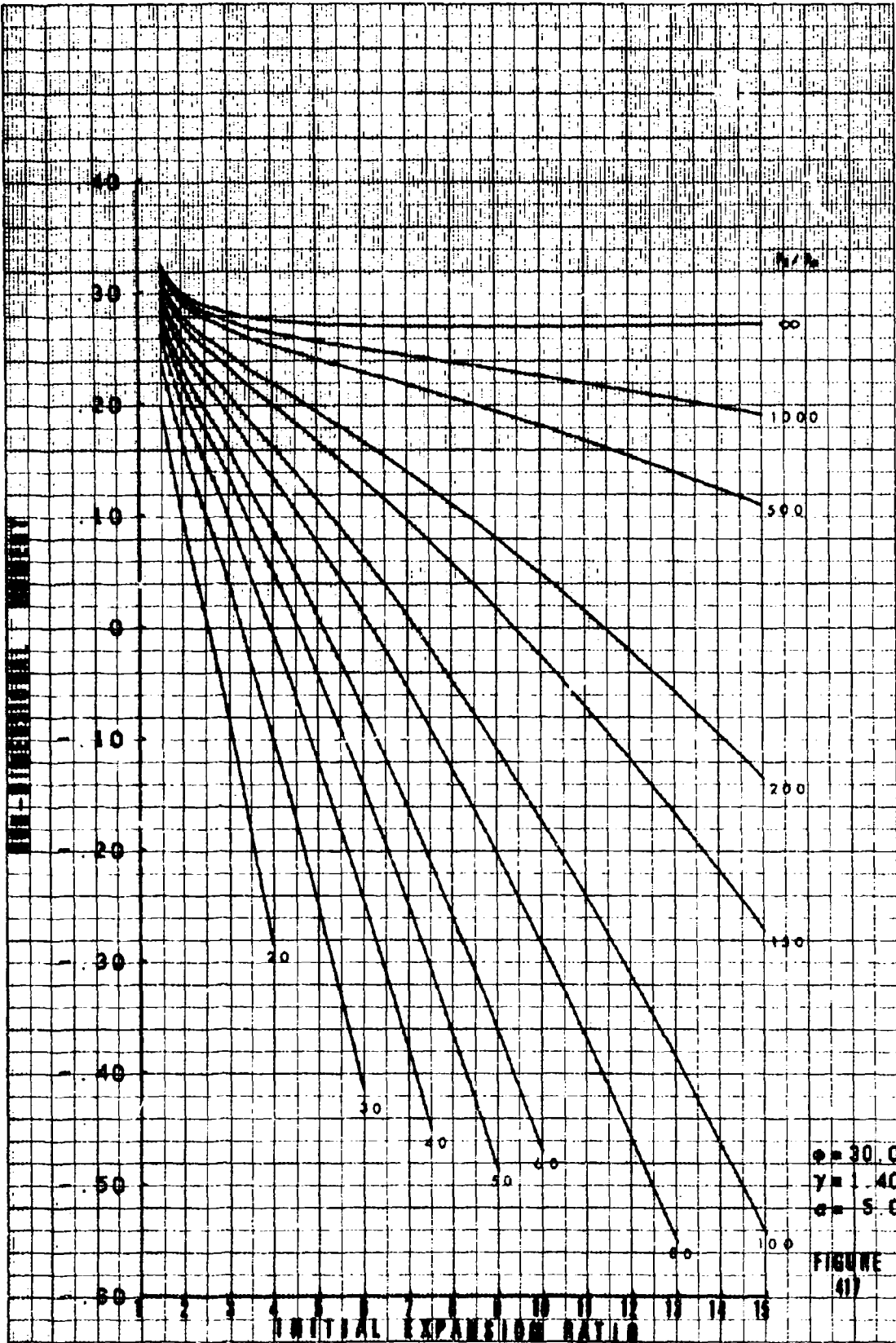


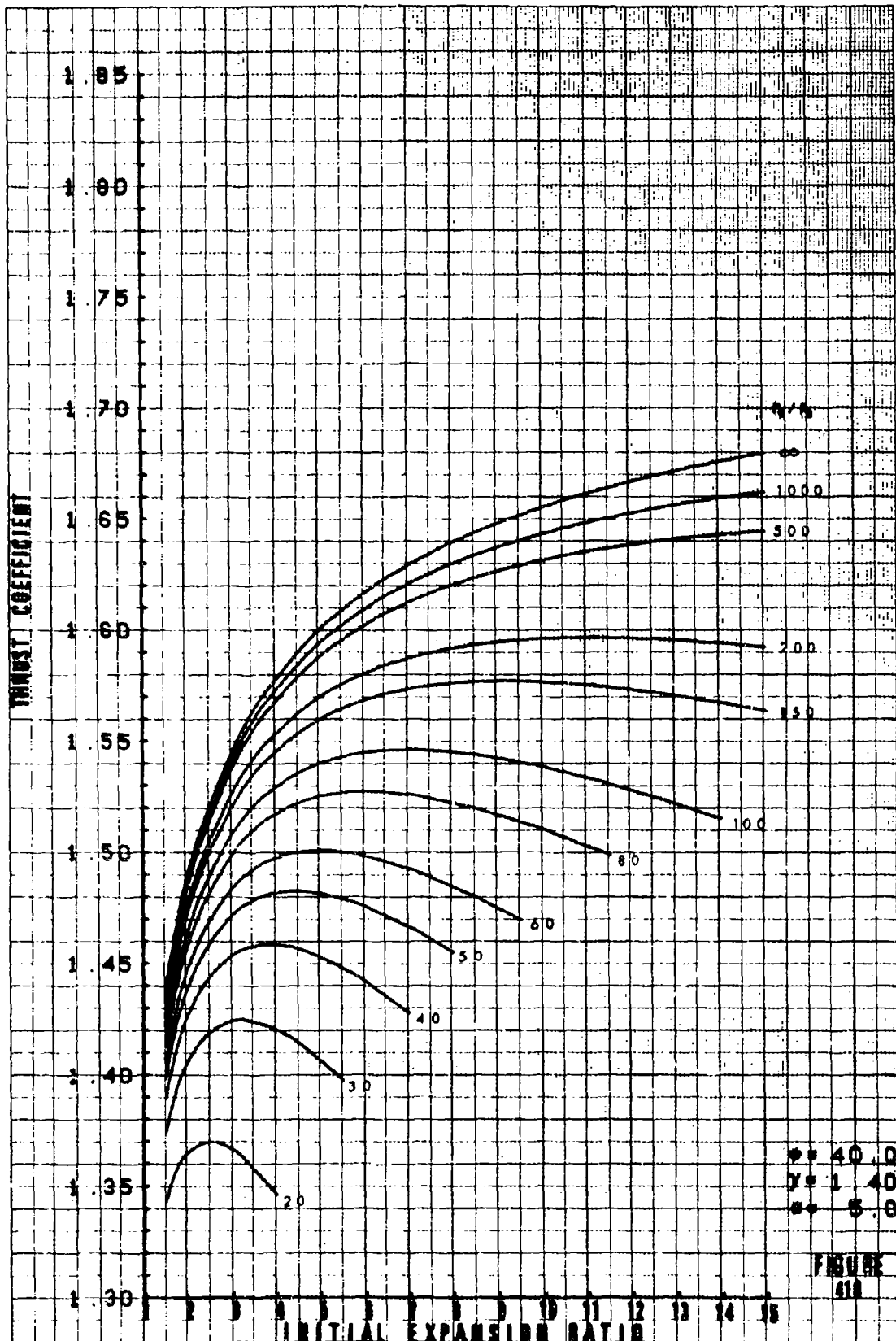


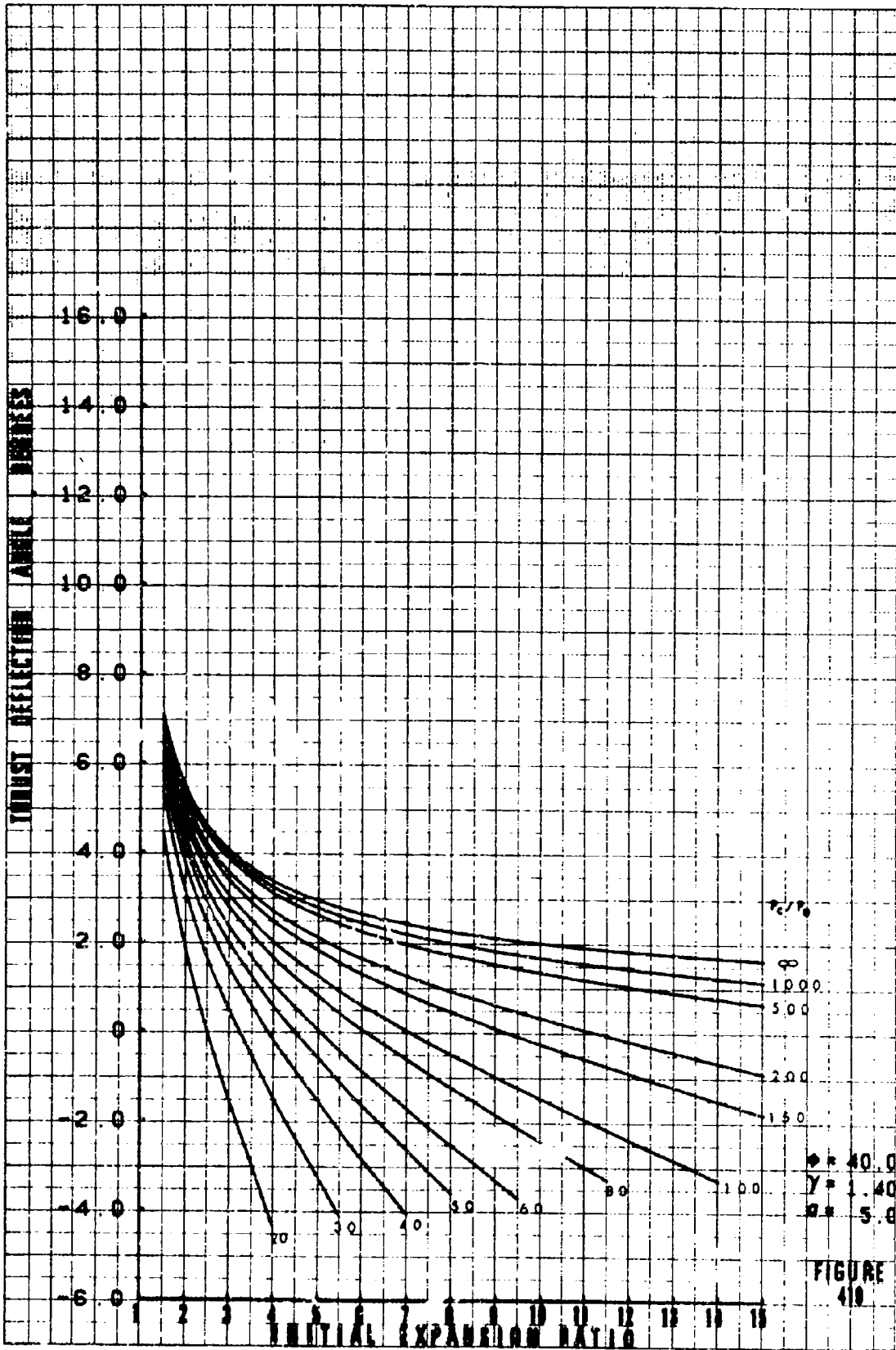


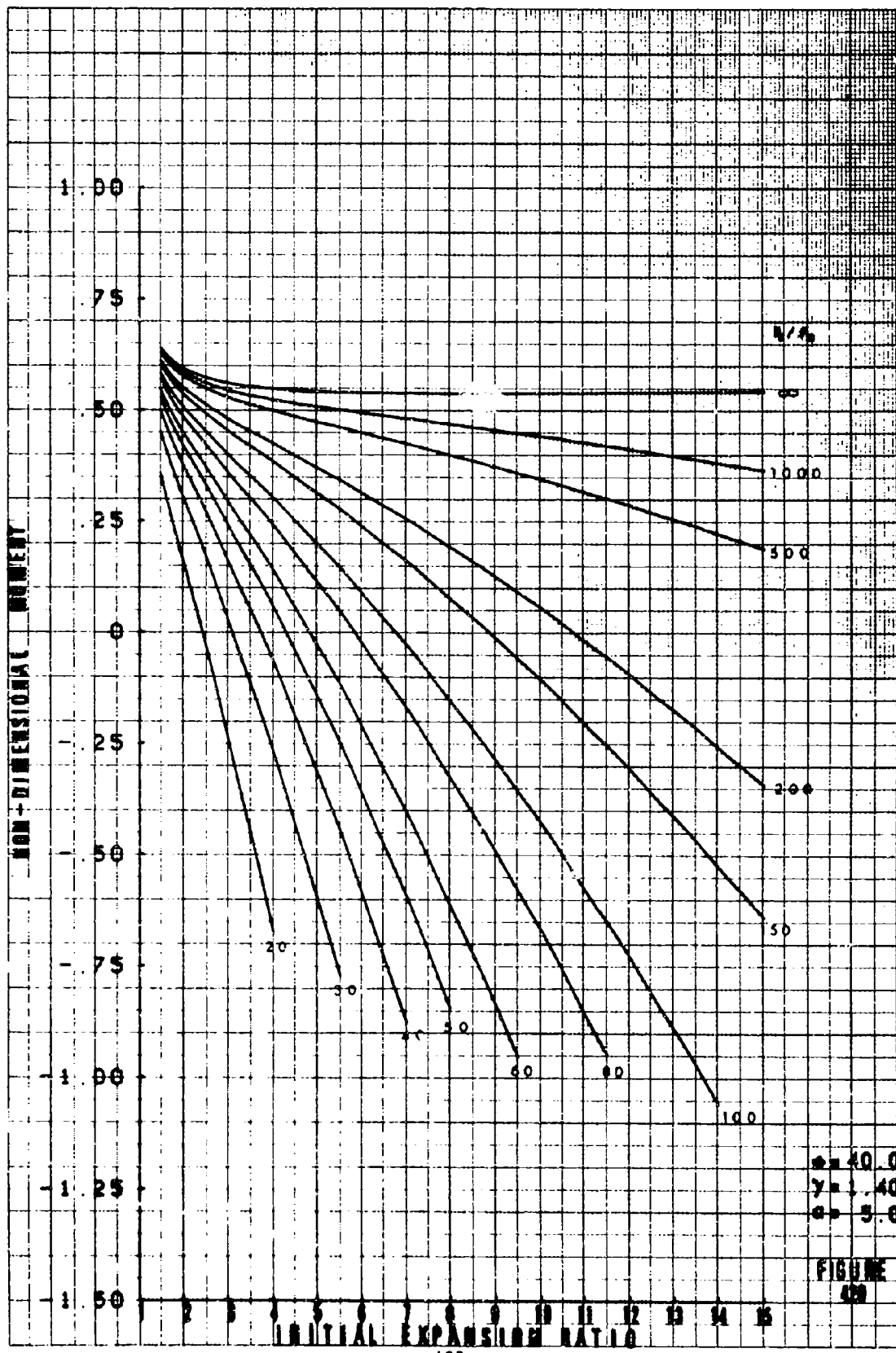


**FIGURE 4B**









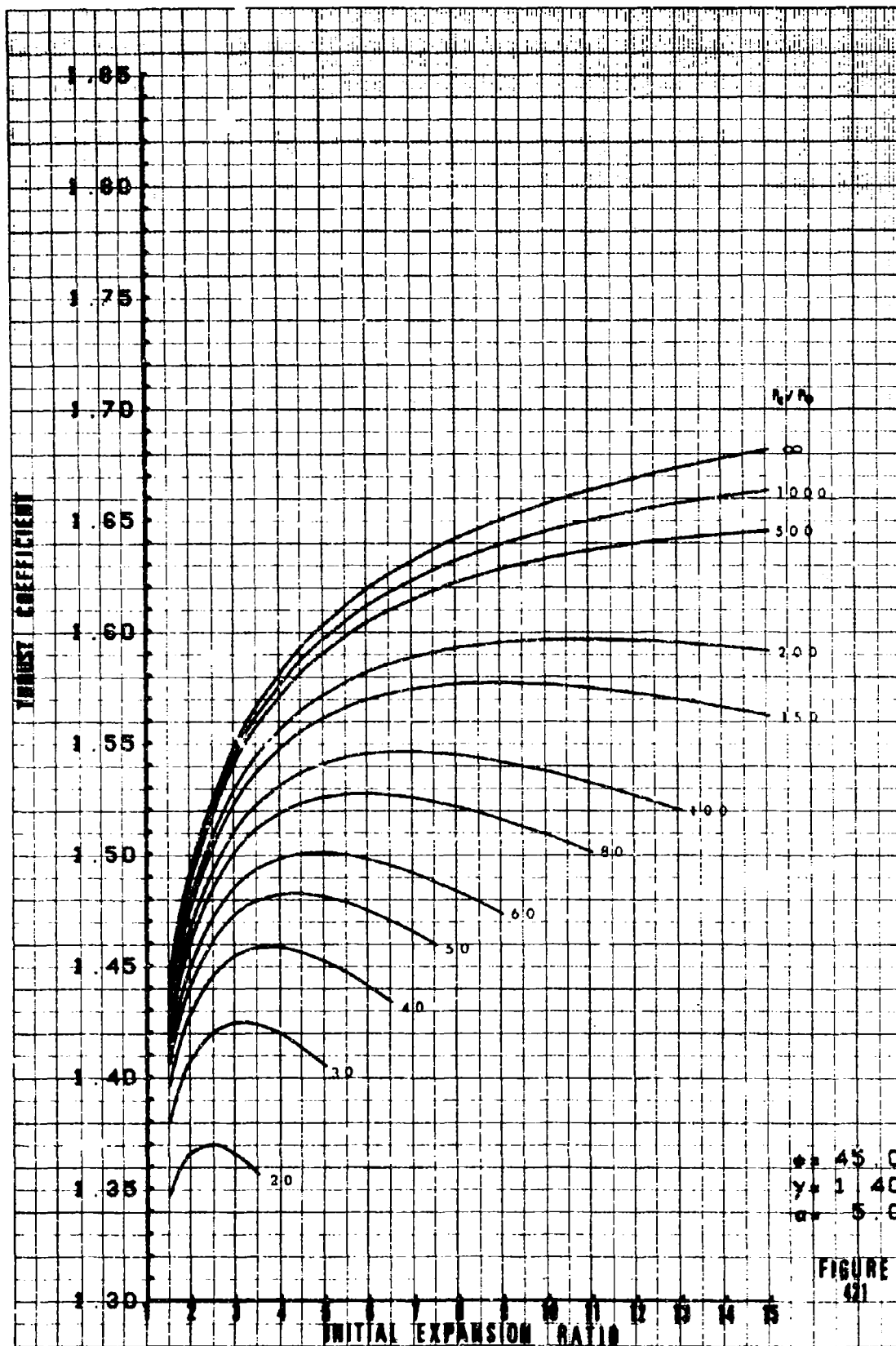


FIGURE 421

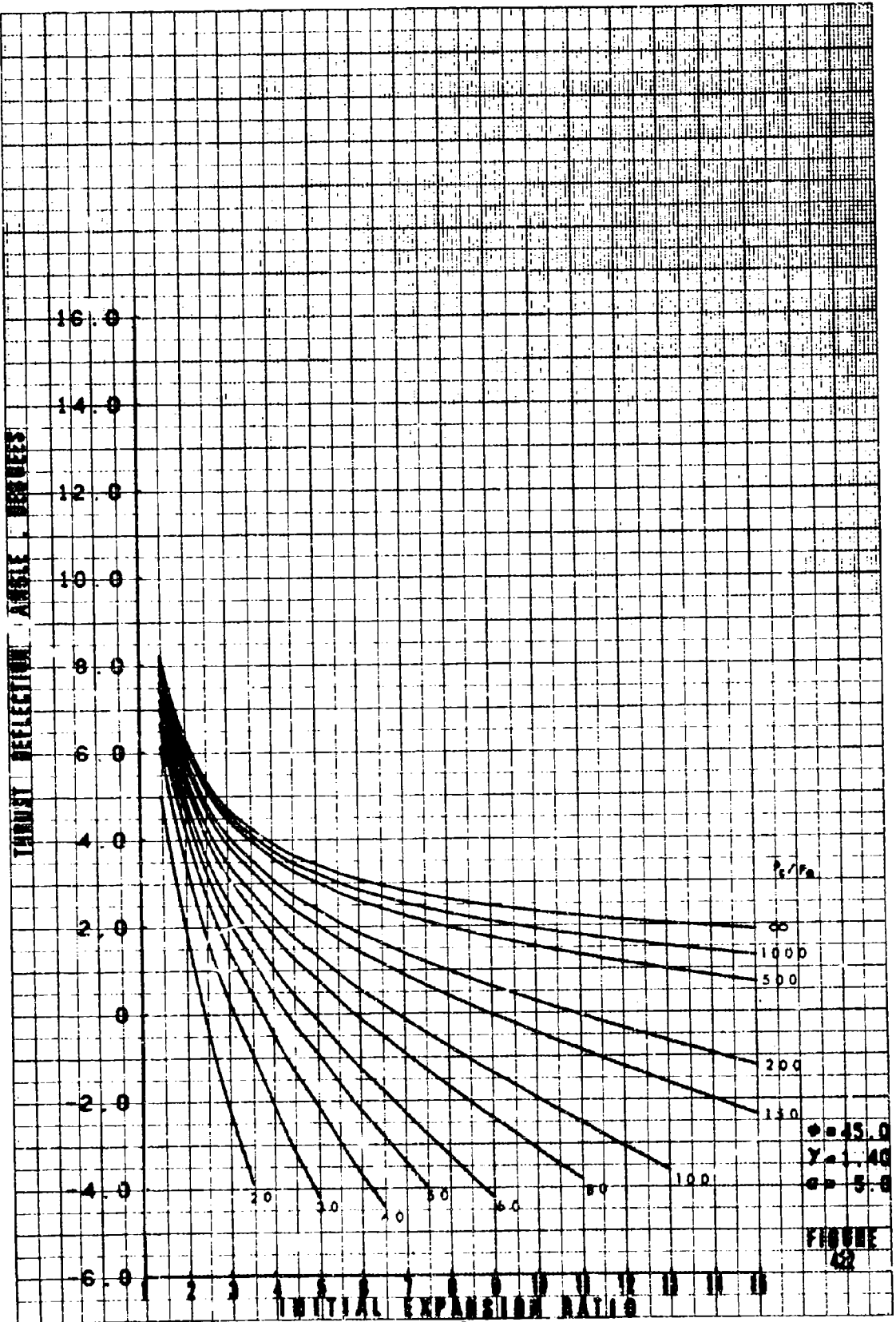
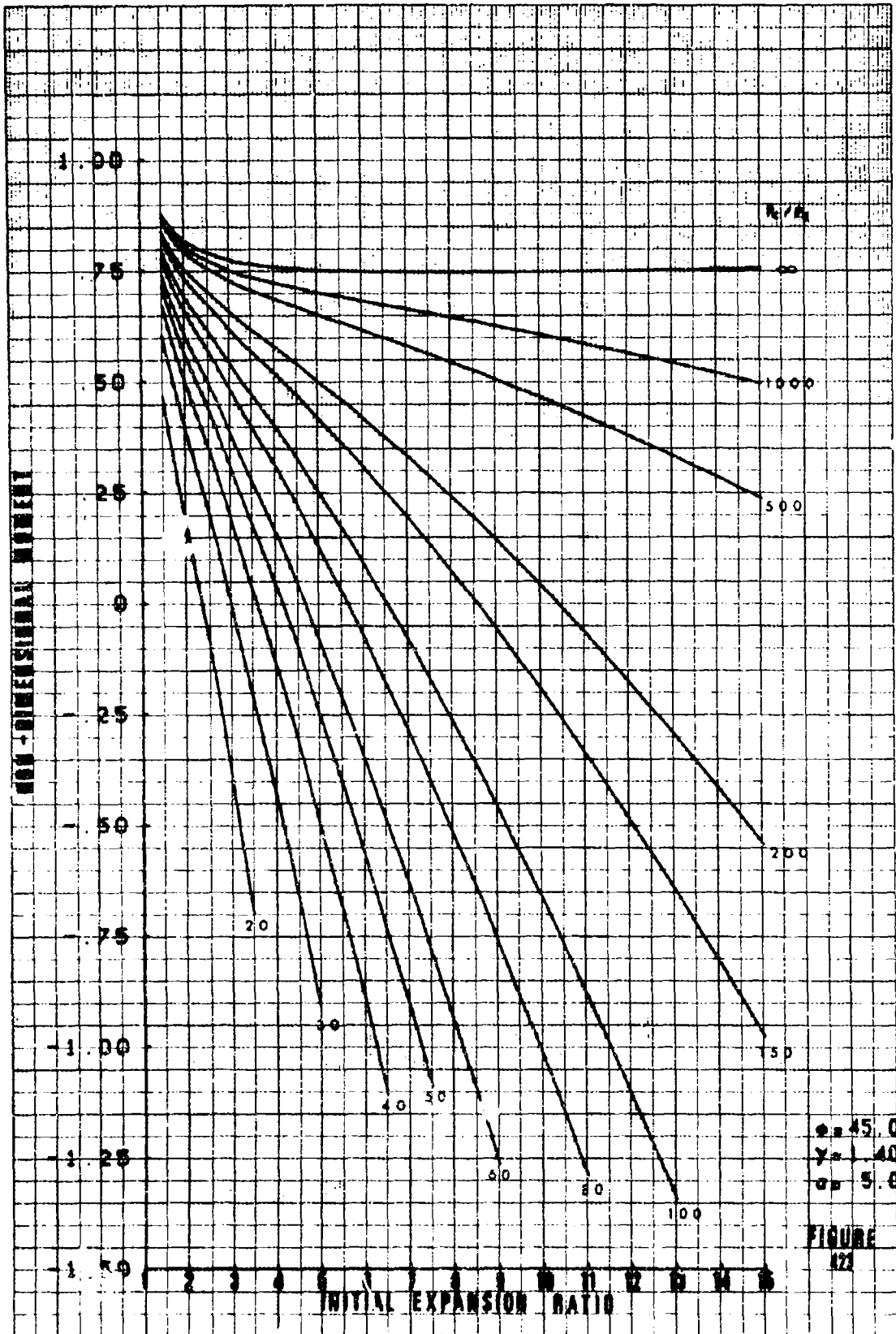


FIGURE 42





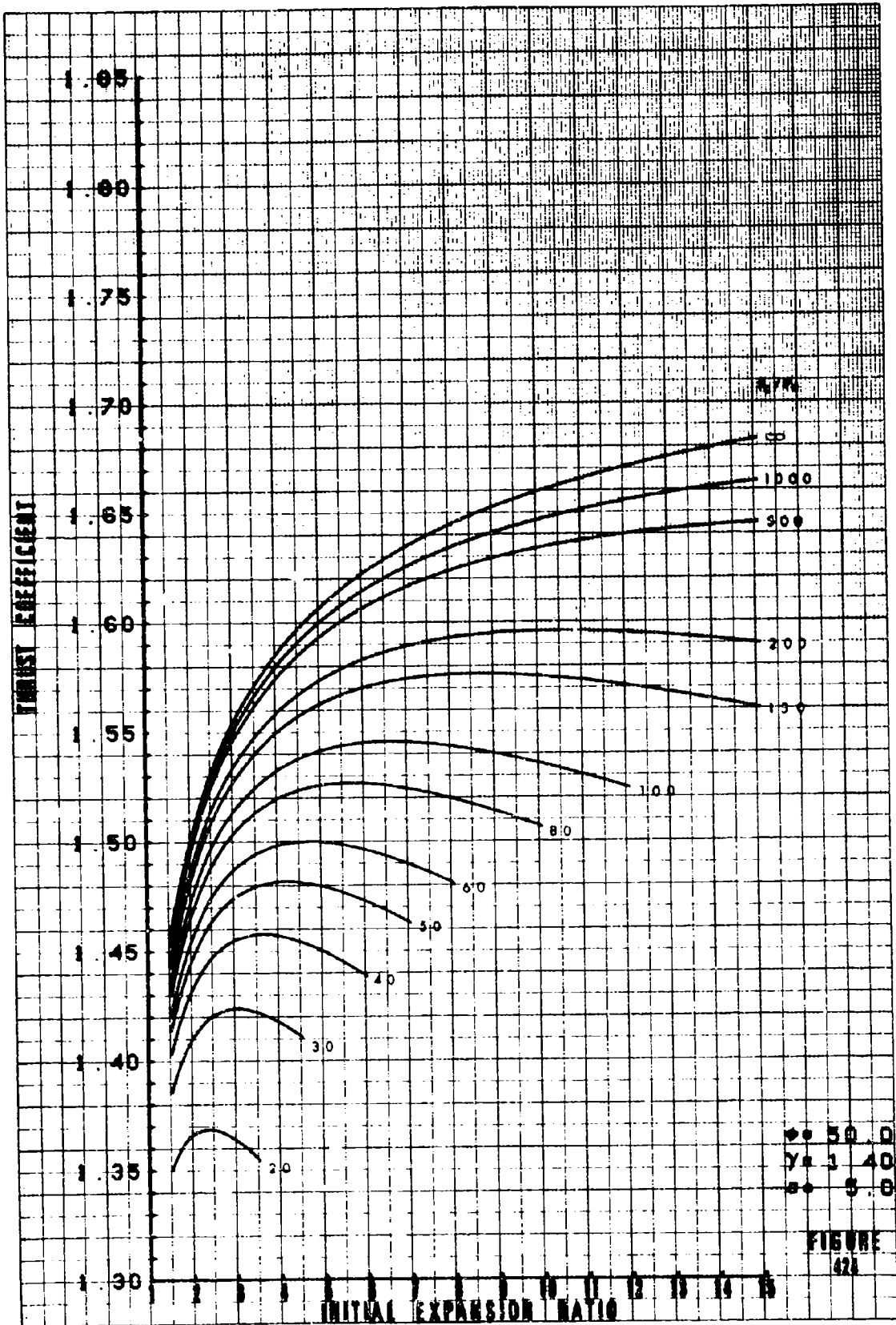
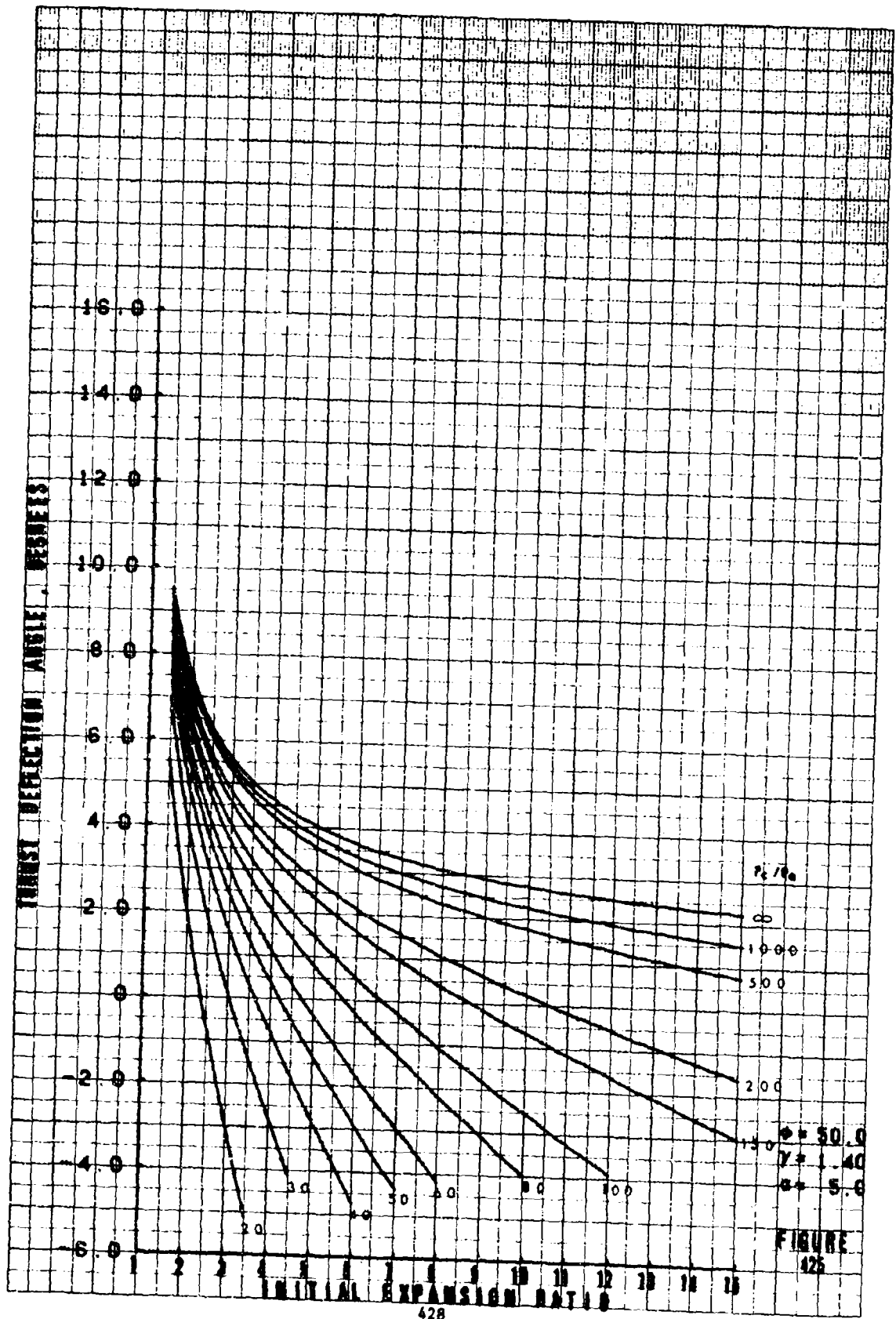
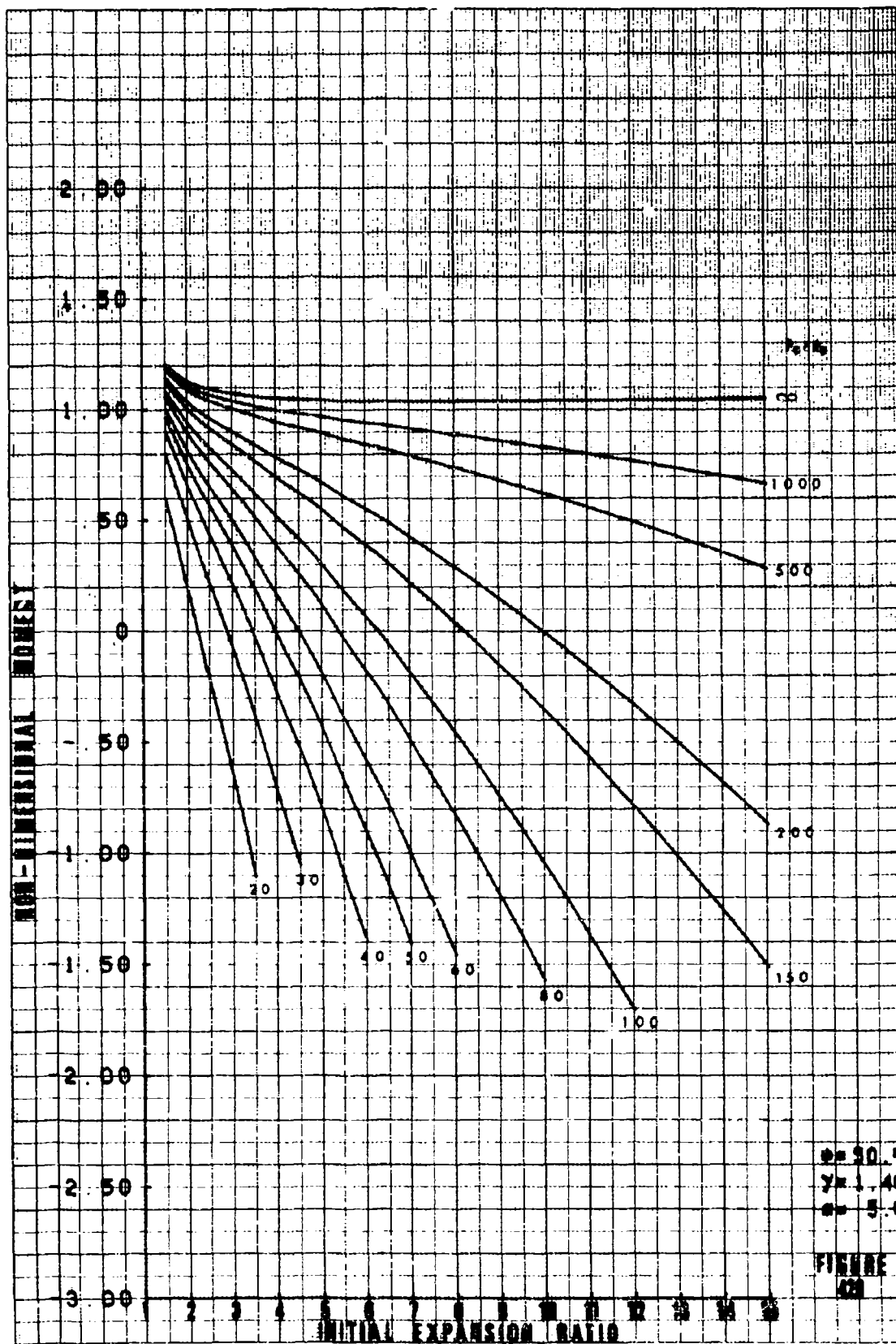
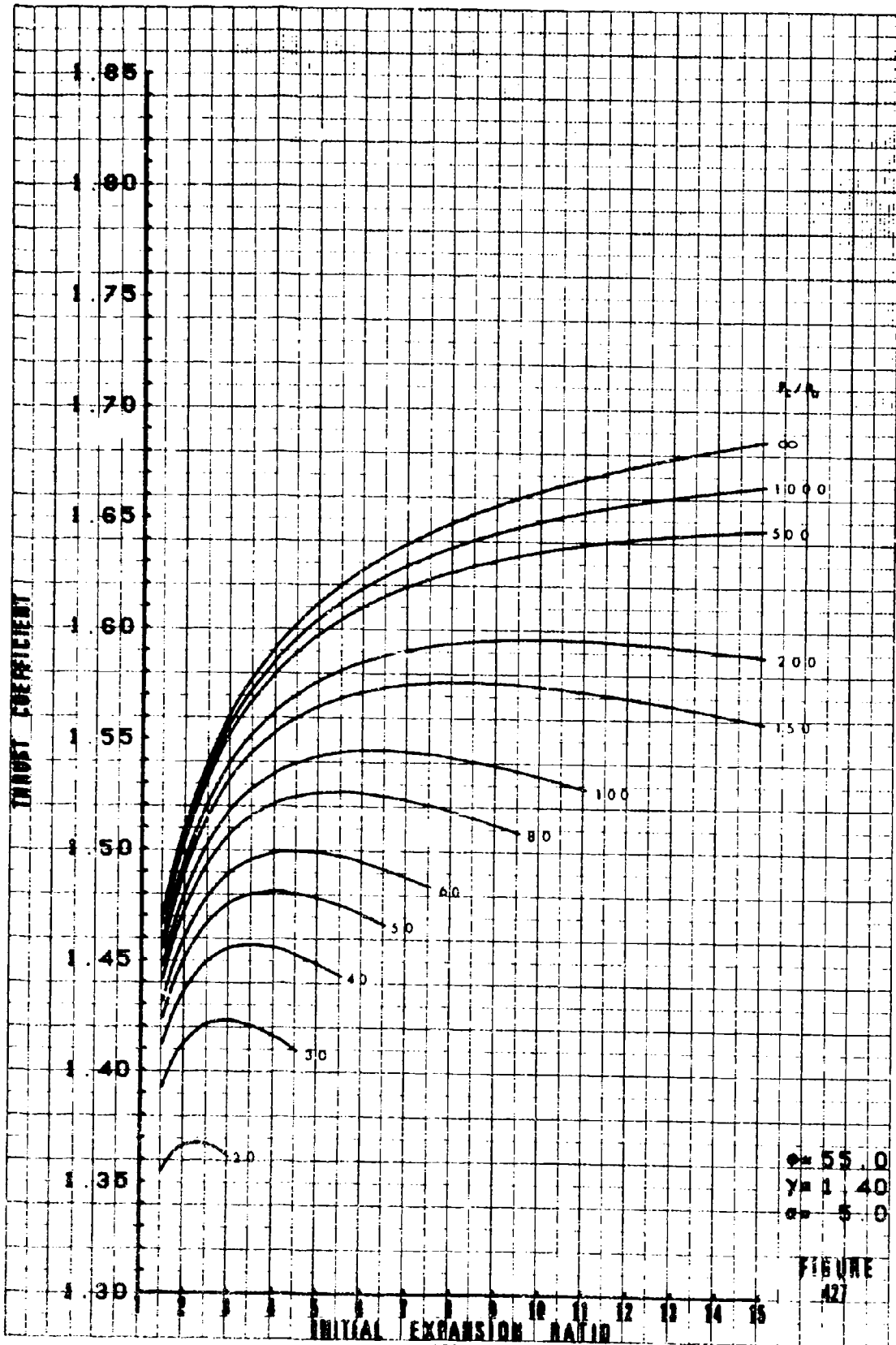
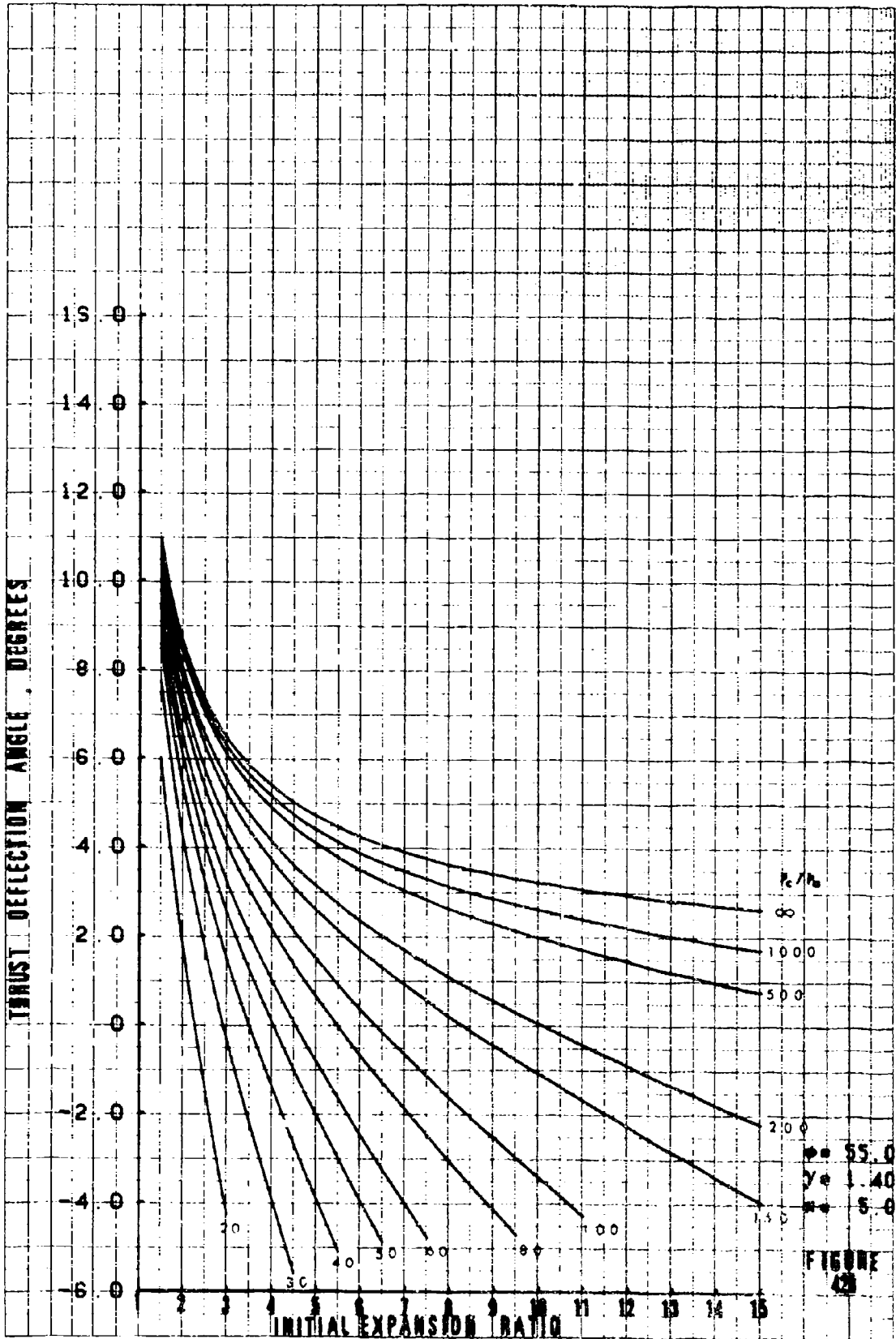


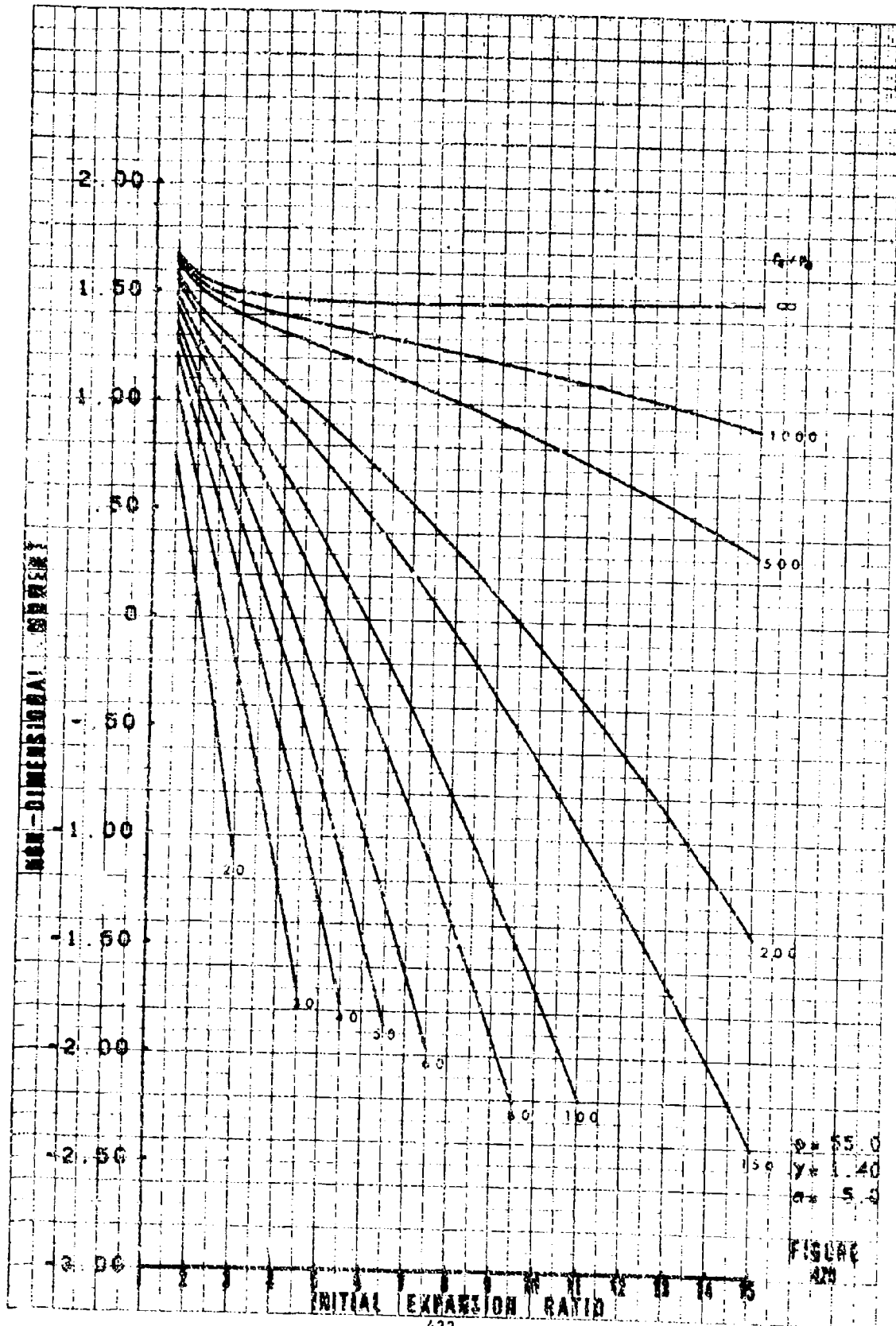
FIGURE 428

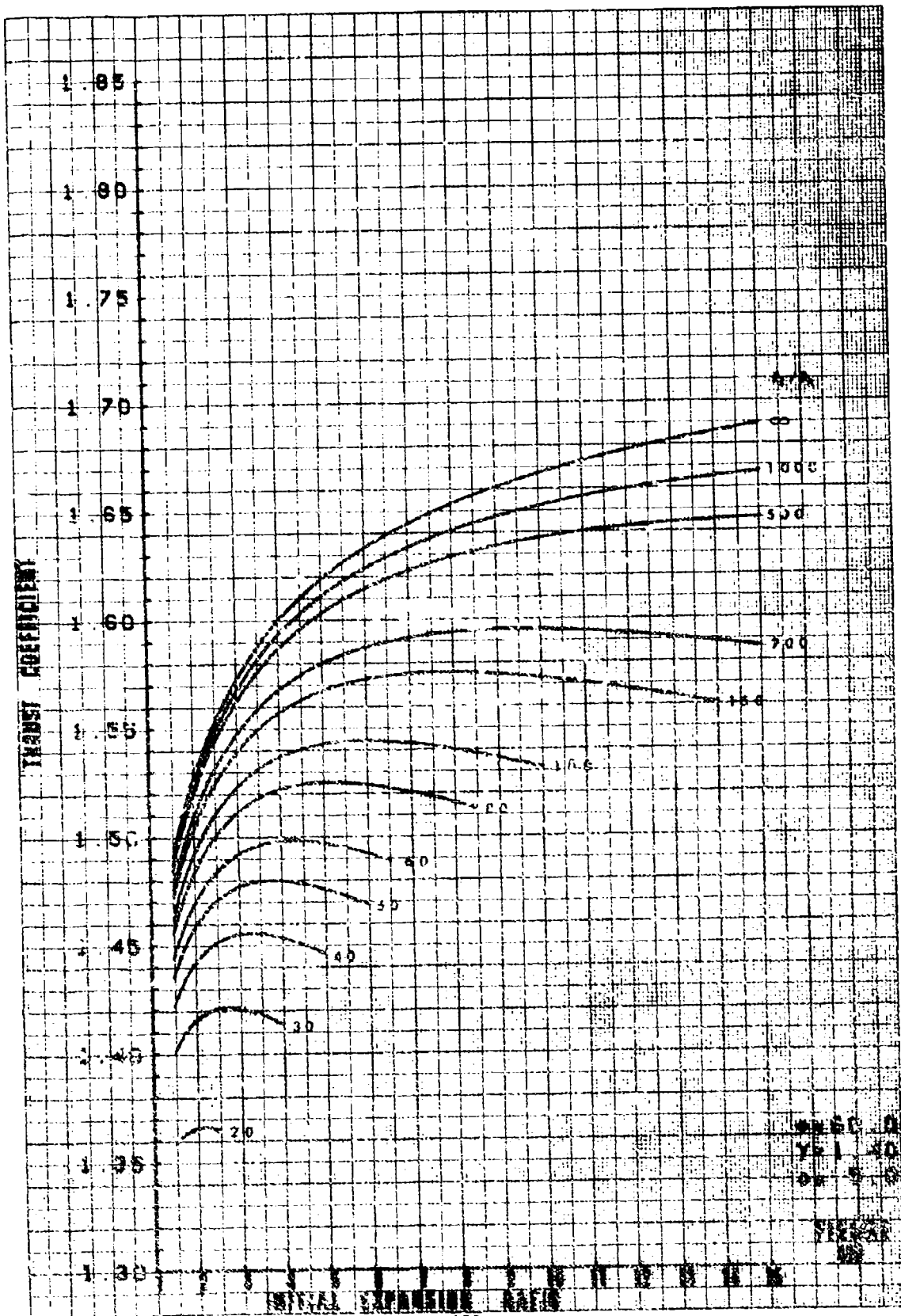












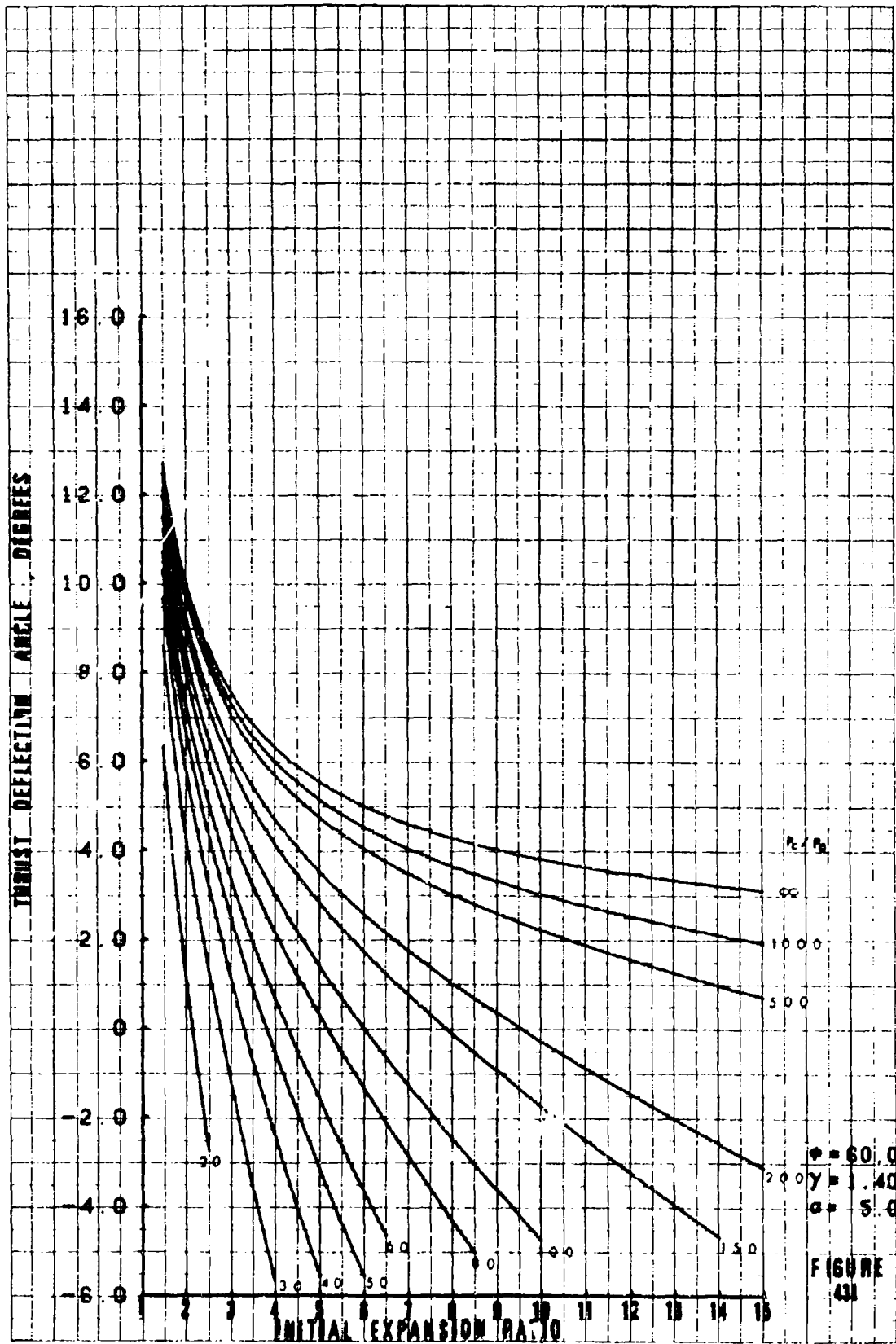
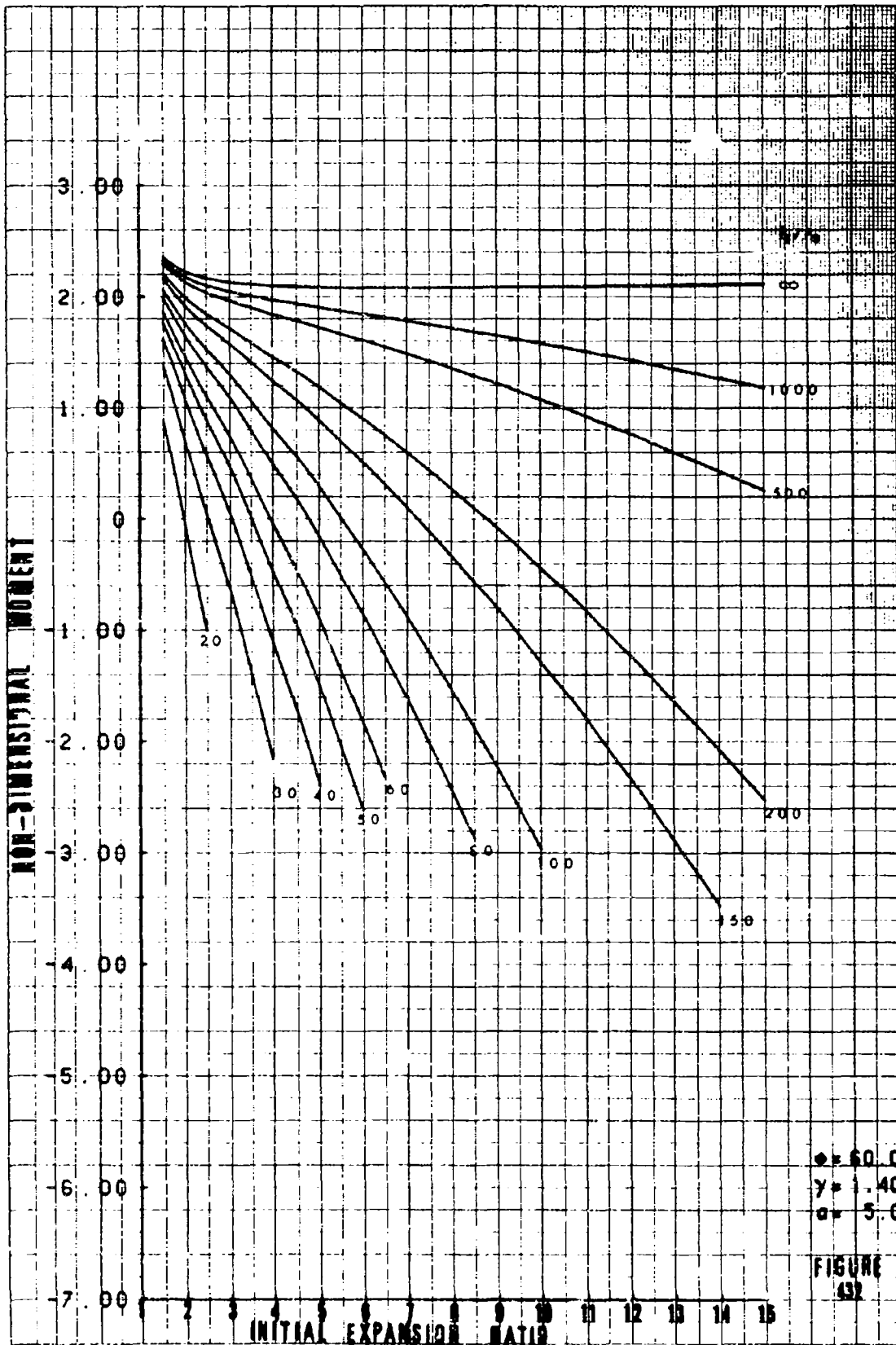


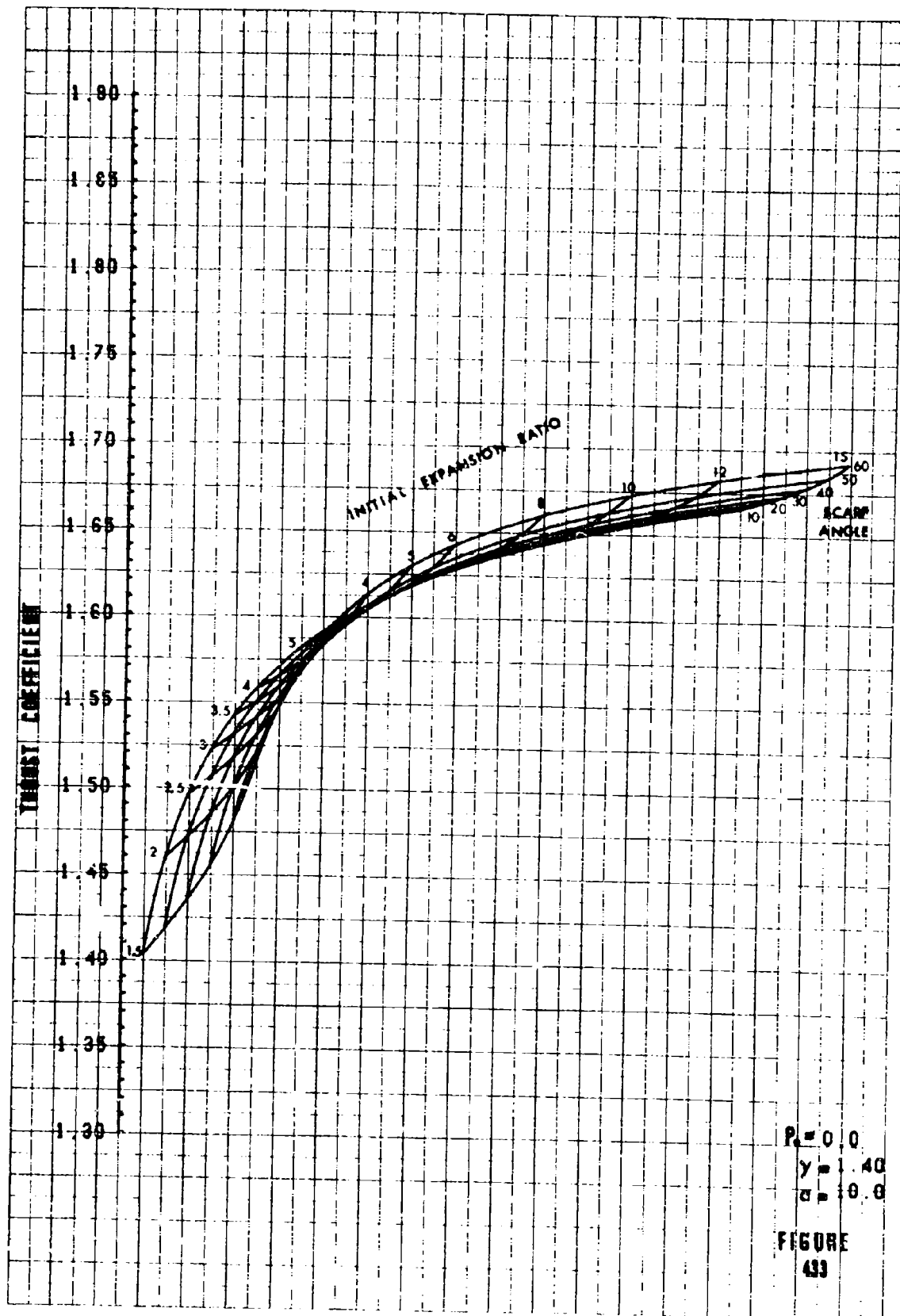
FIGURE 431

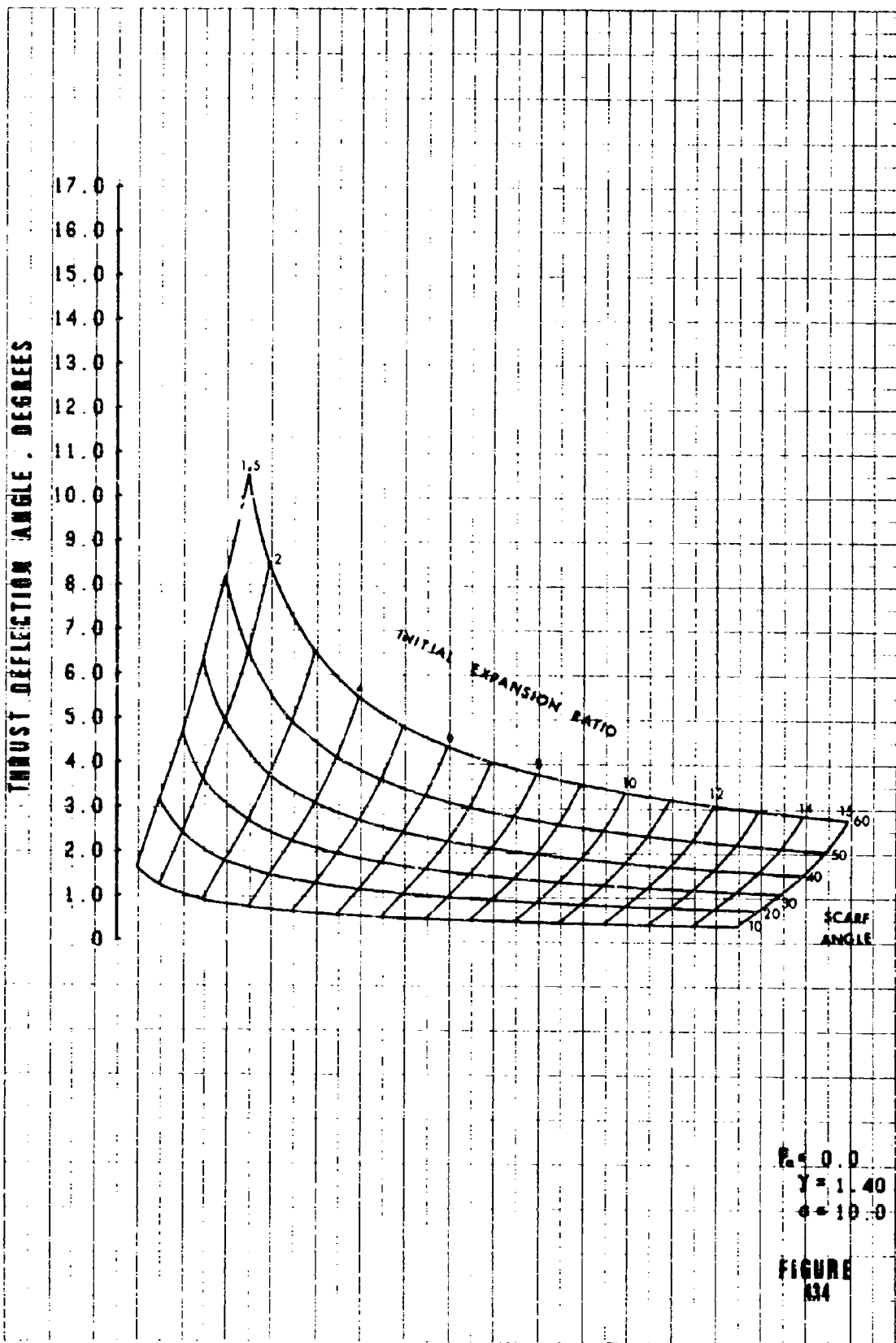


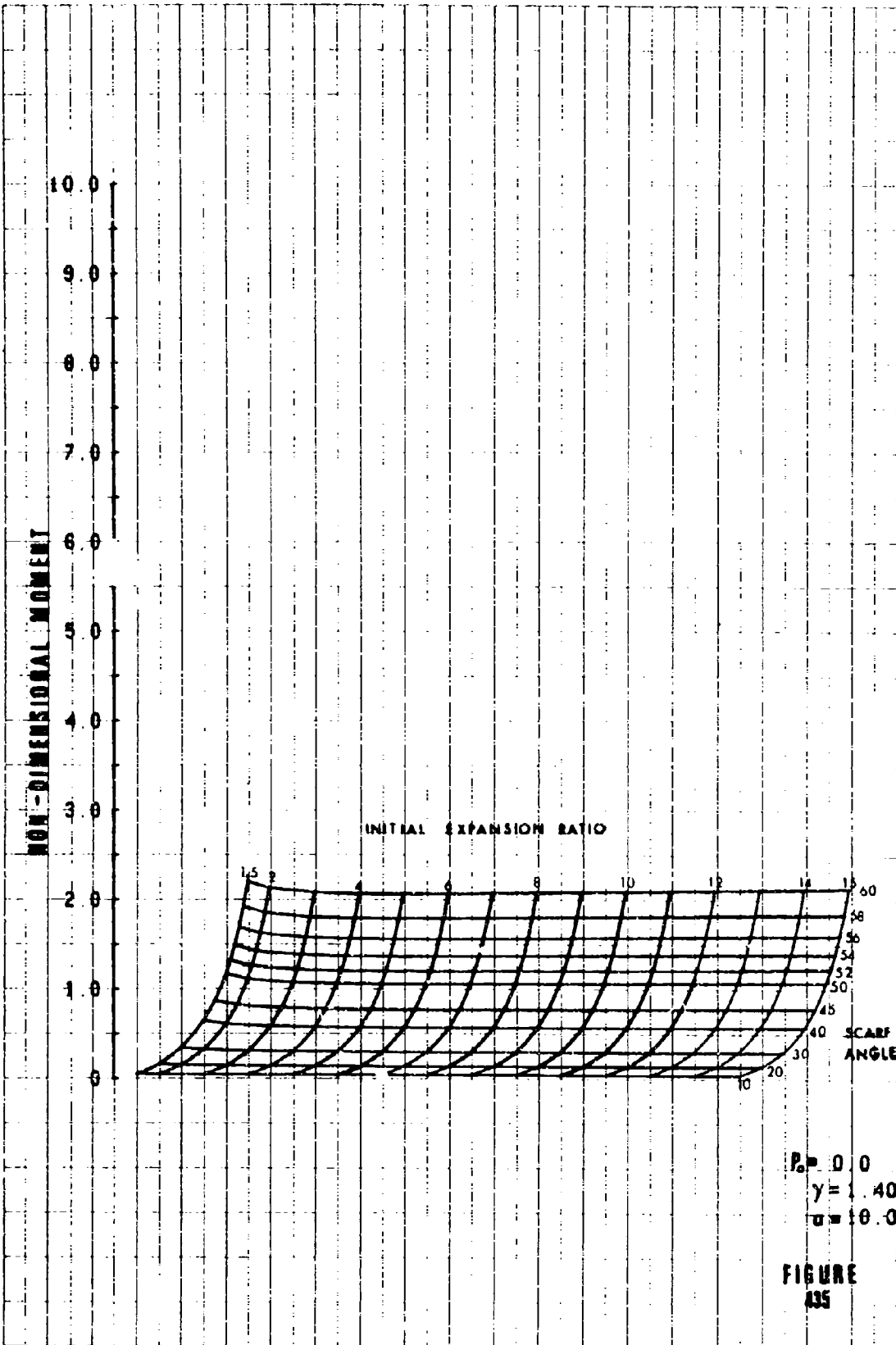


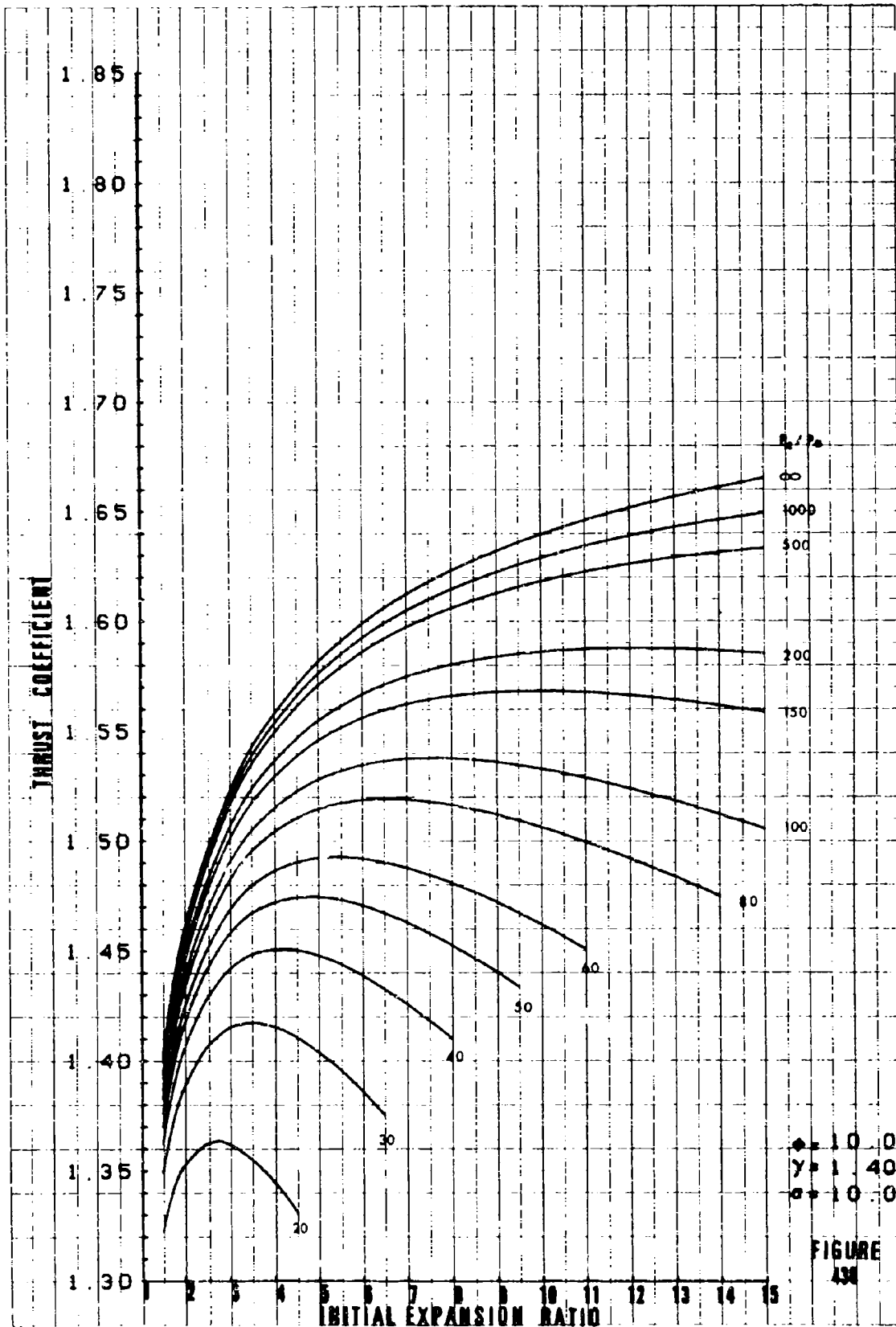
$\alpha = 60.0$   
 $\gamma = 1.40$   
 $\sigma = 5.6$

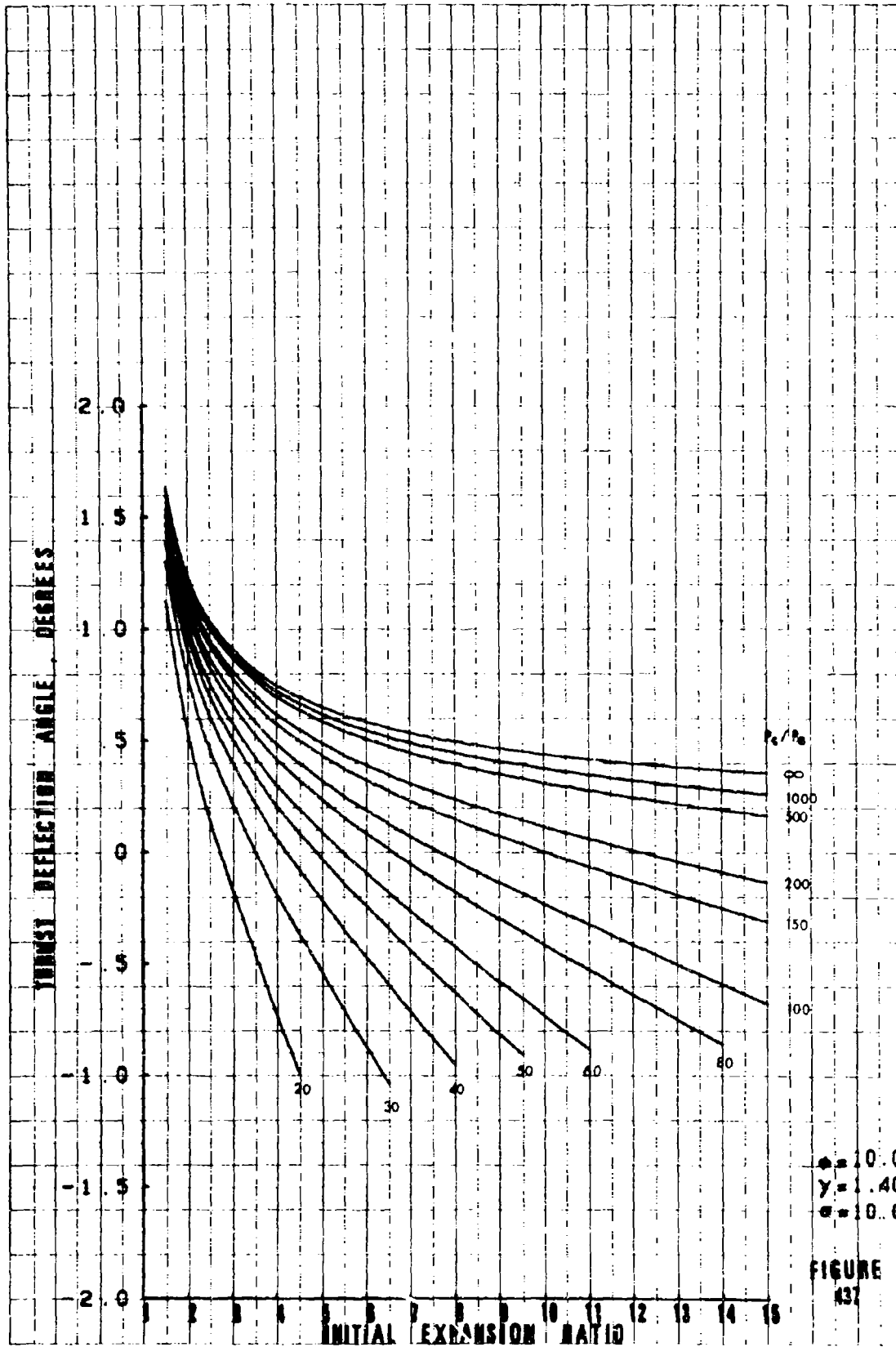
FIGURE 43

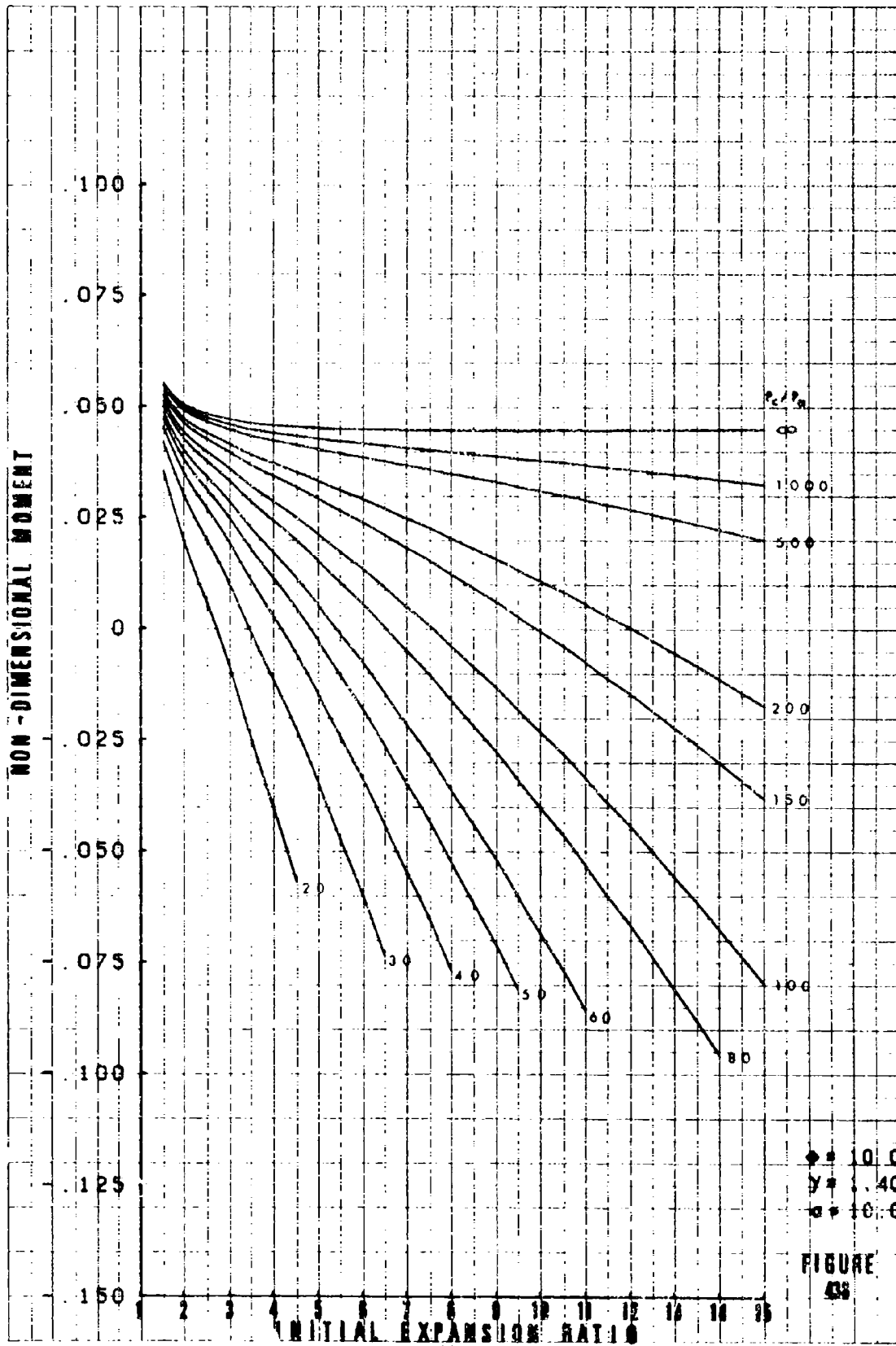












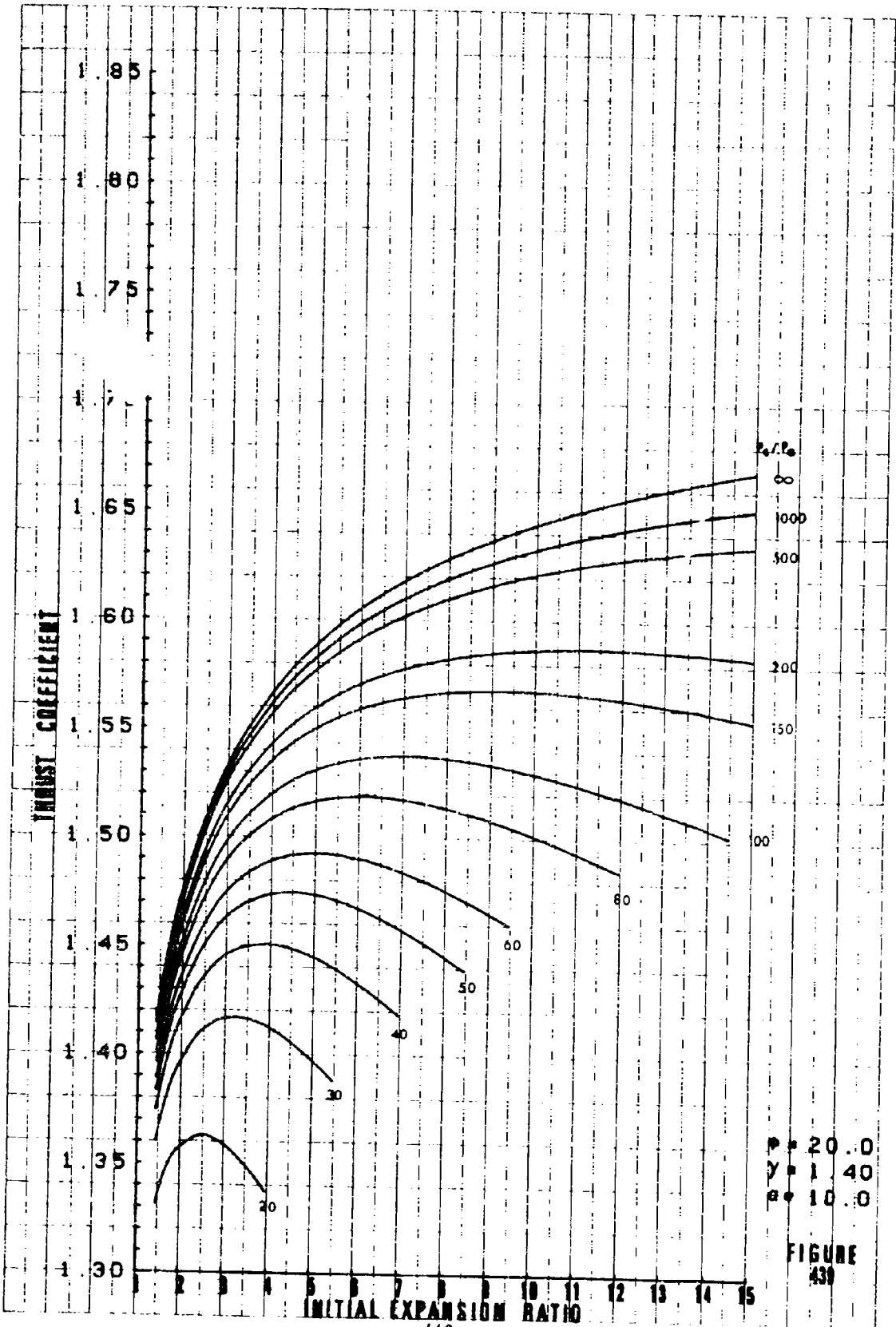


FIGURE 439



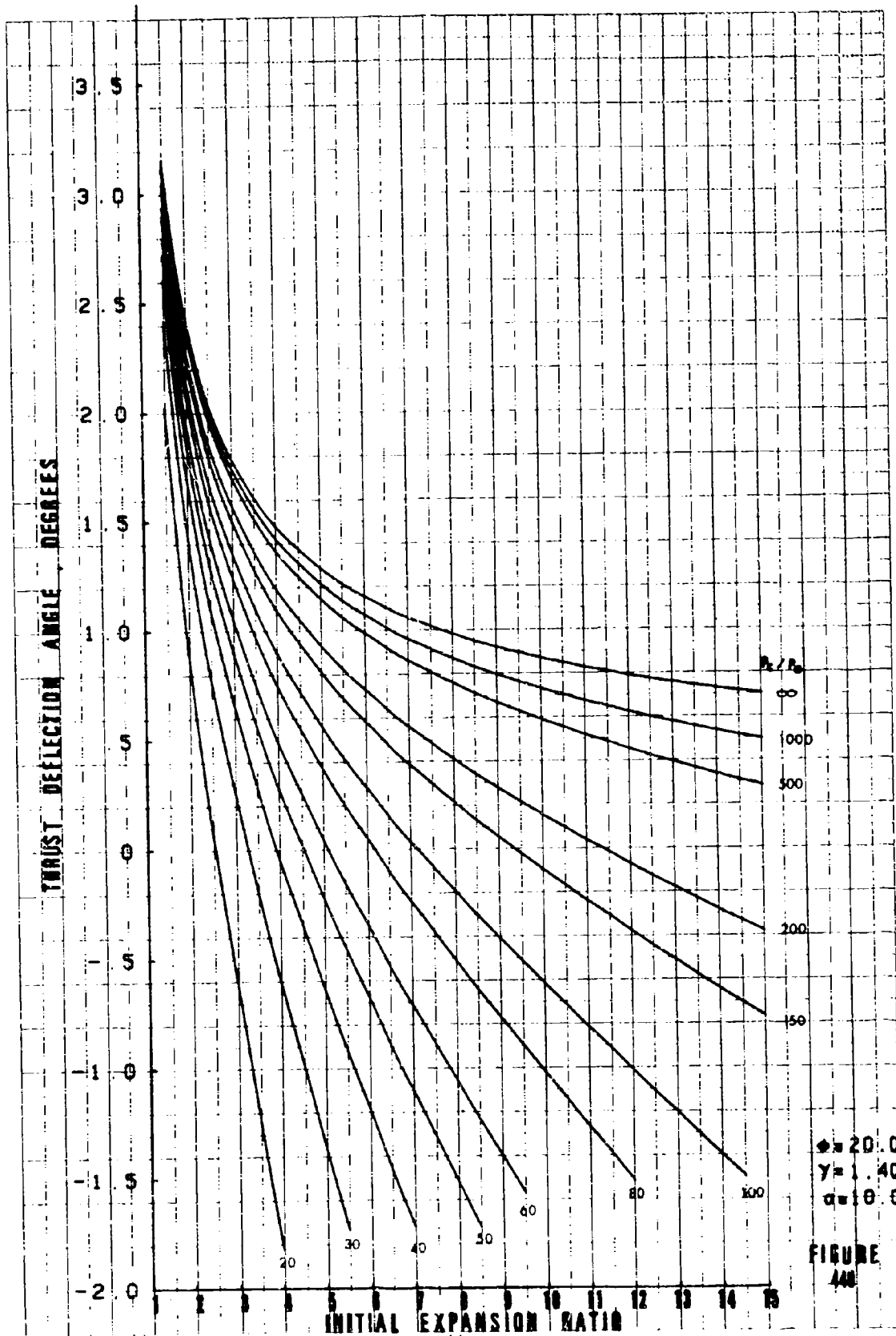
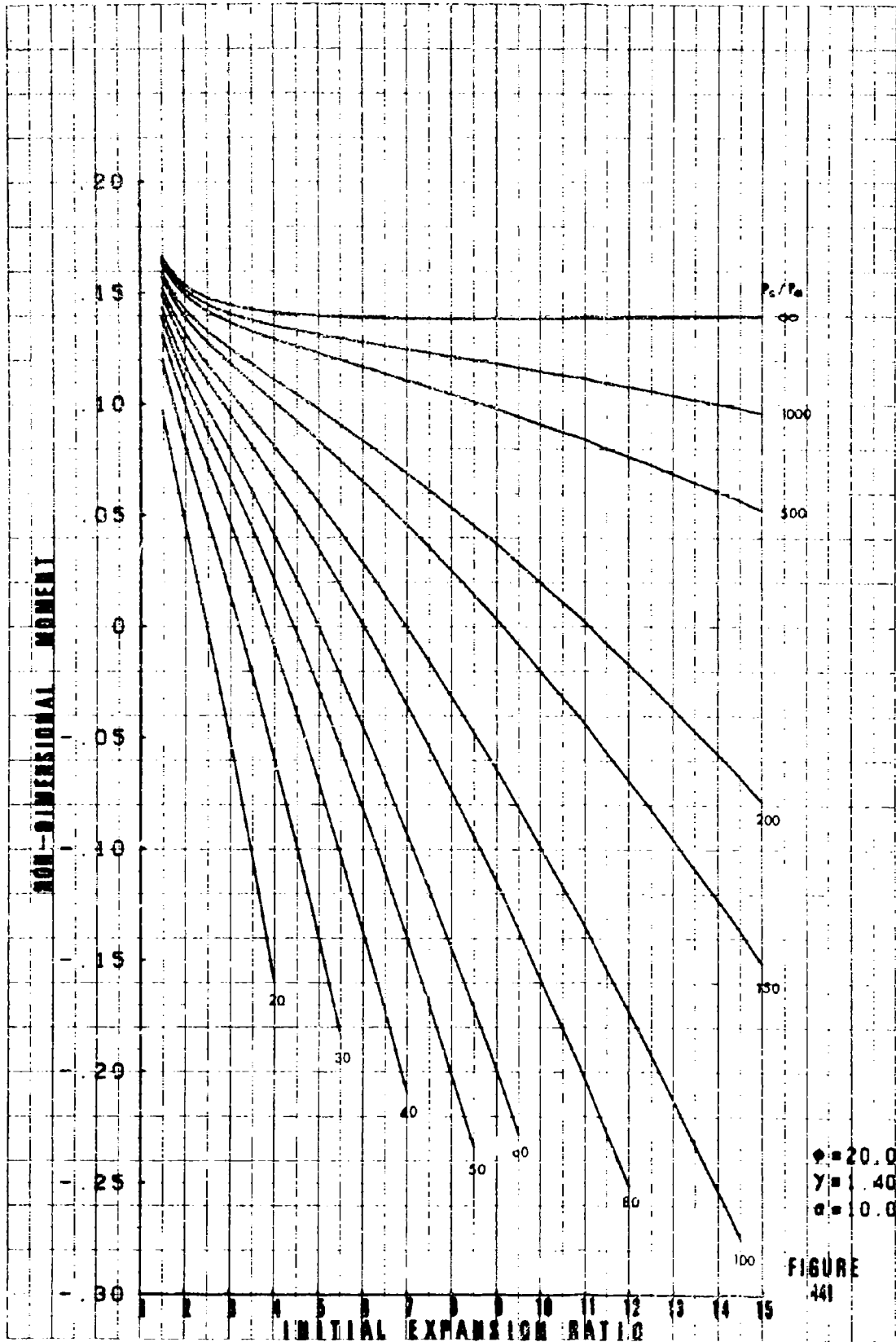


FIGURE 440



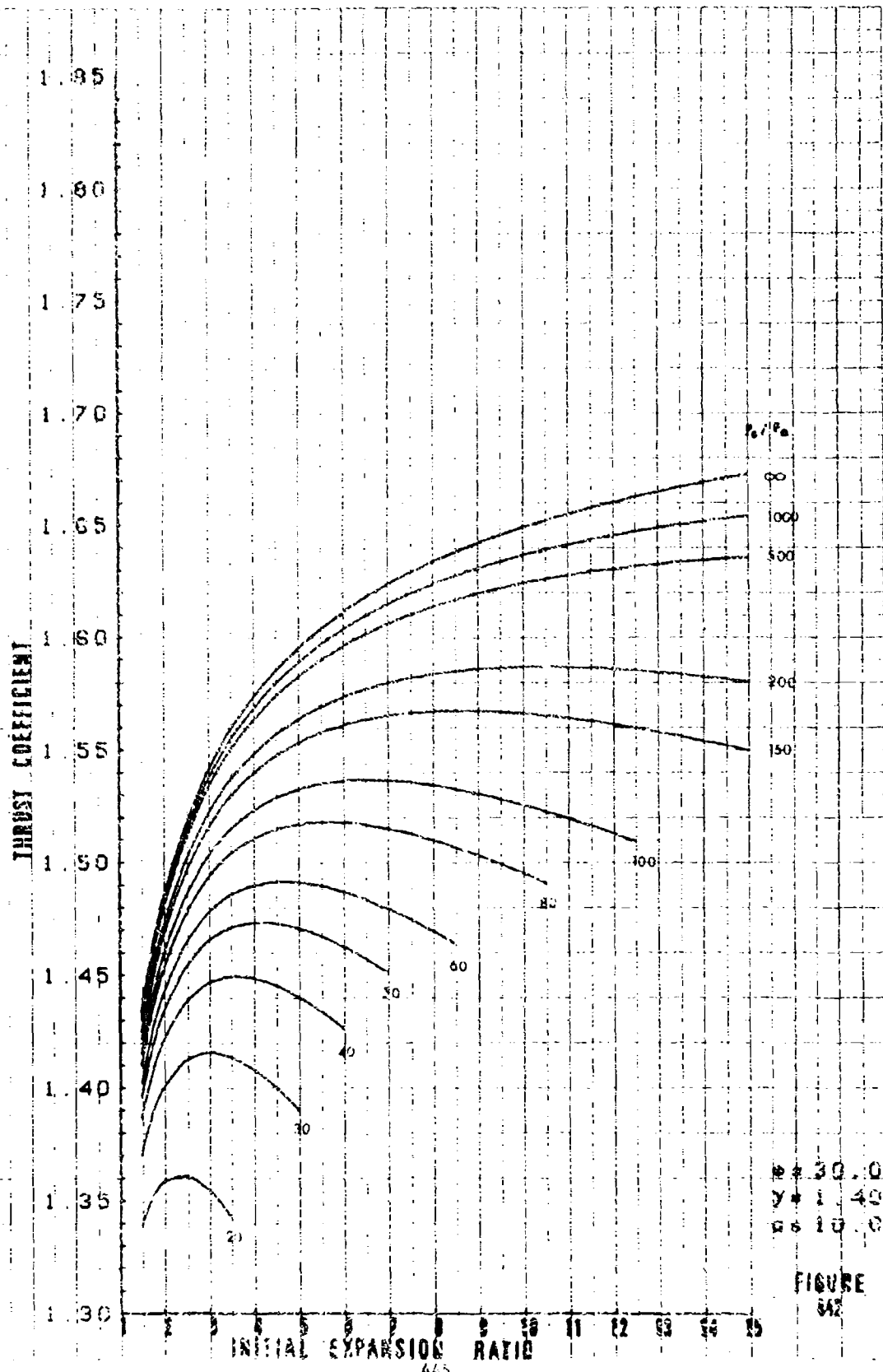


FIGURE 547

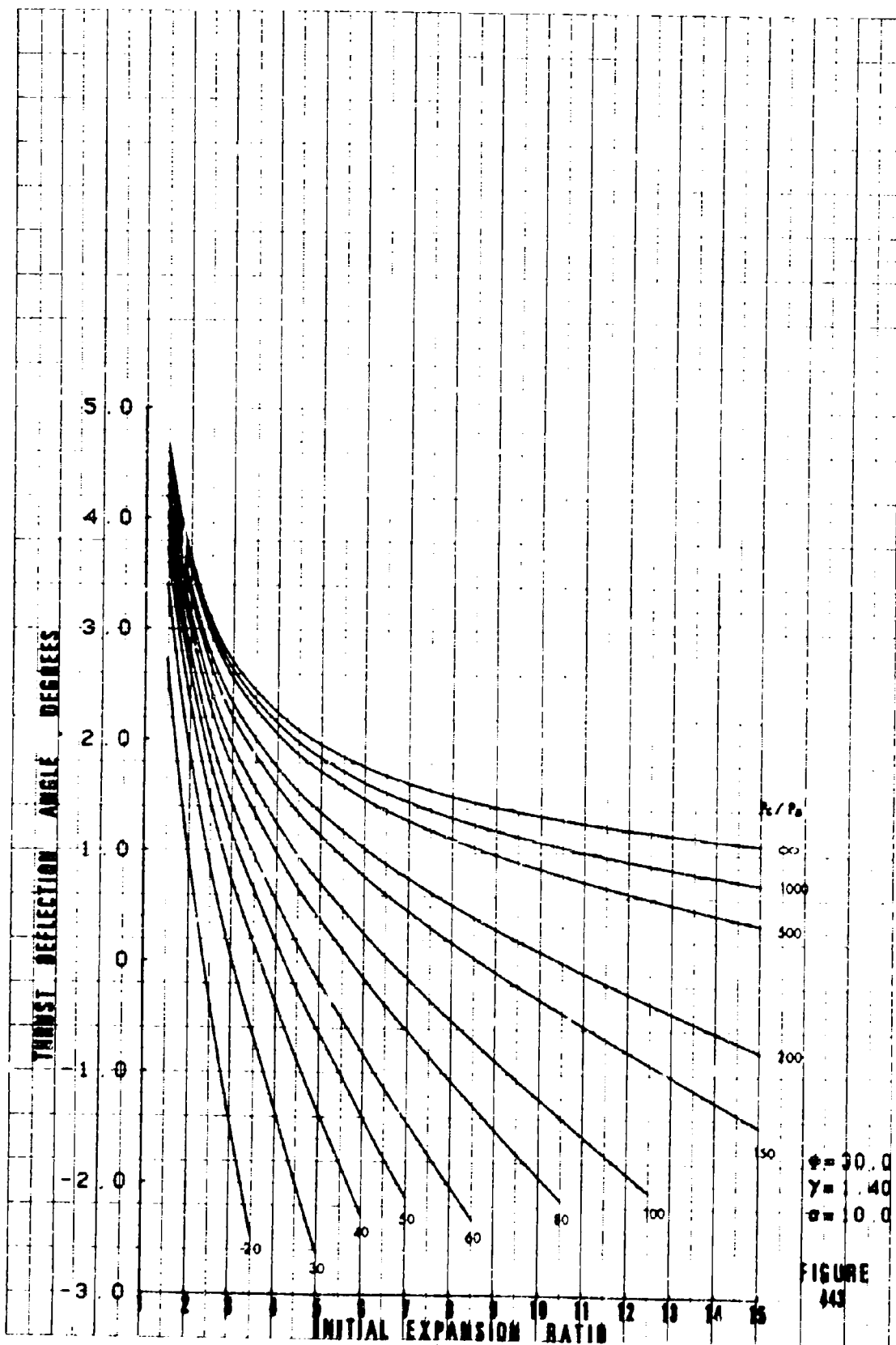
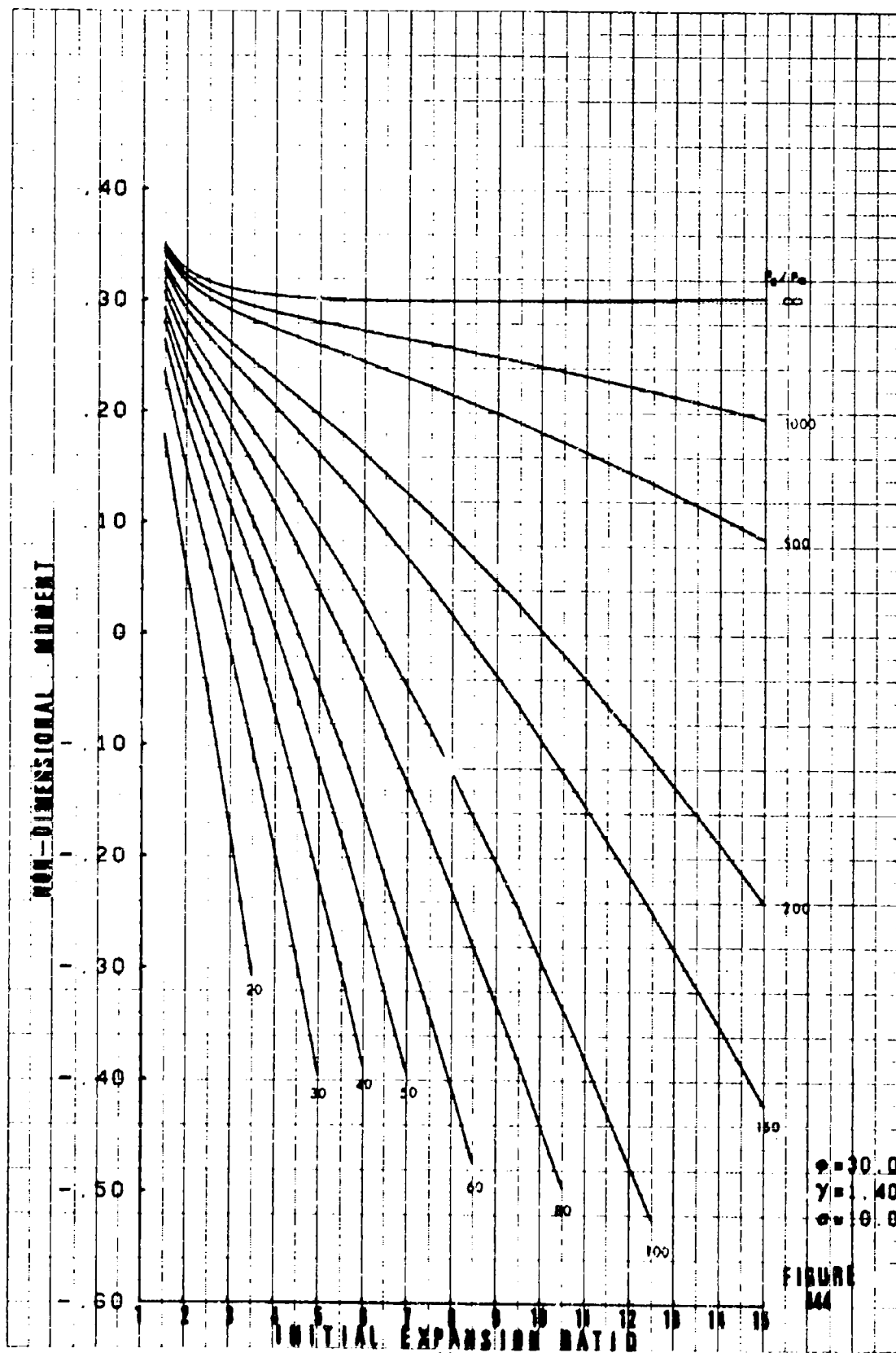
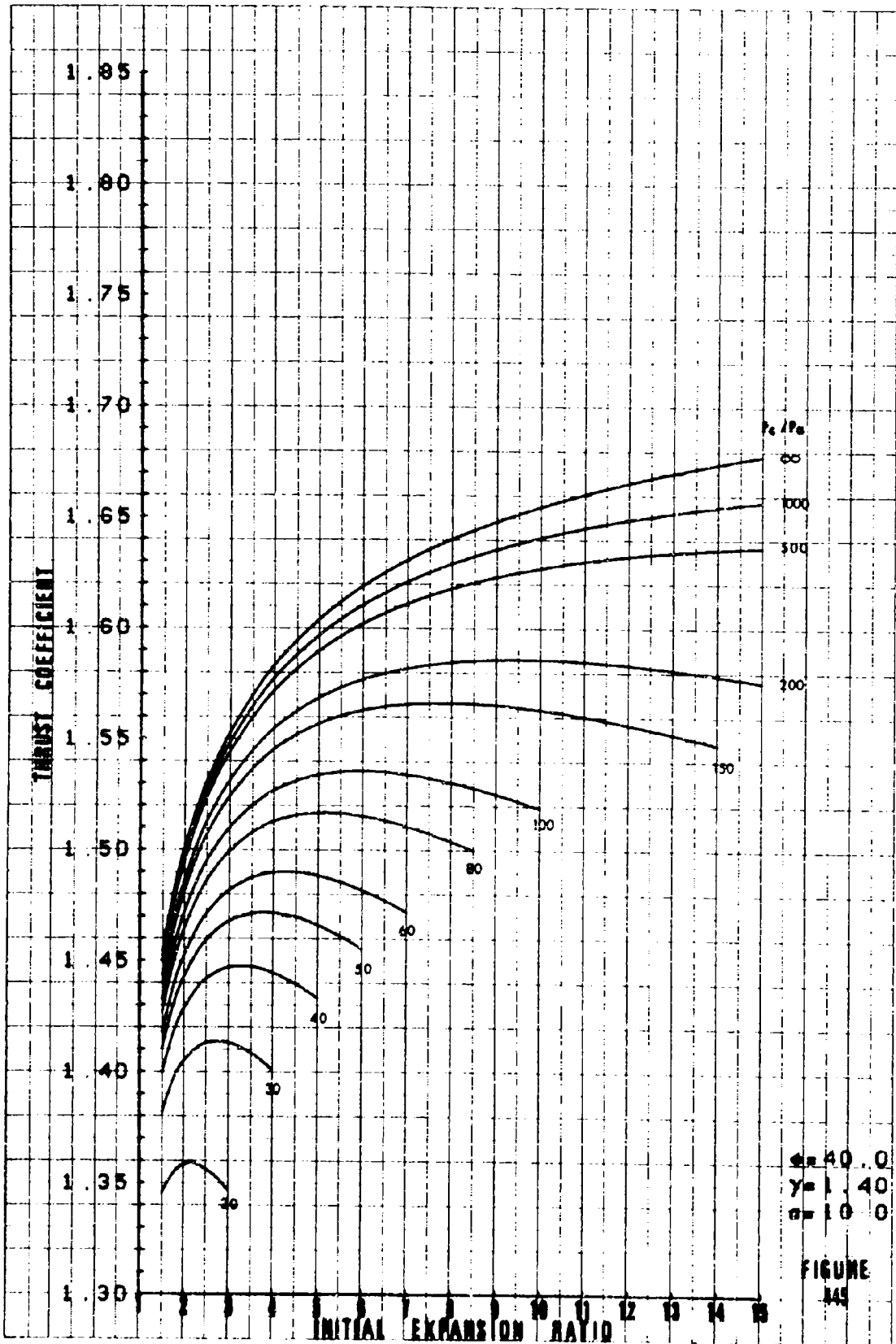
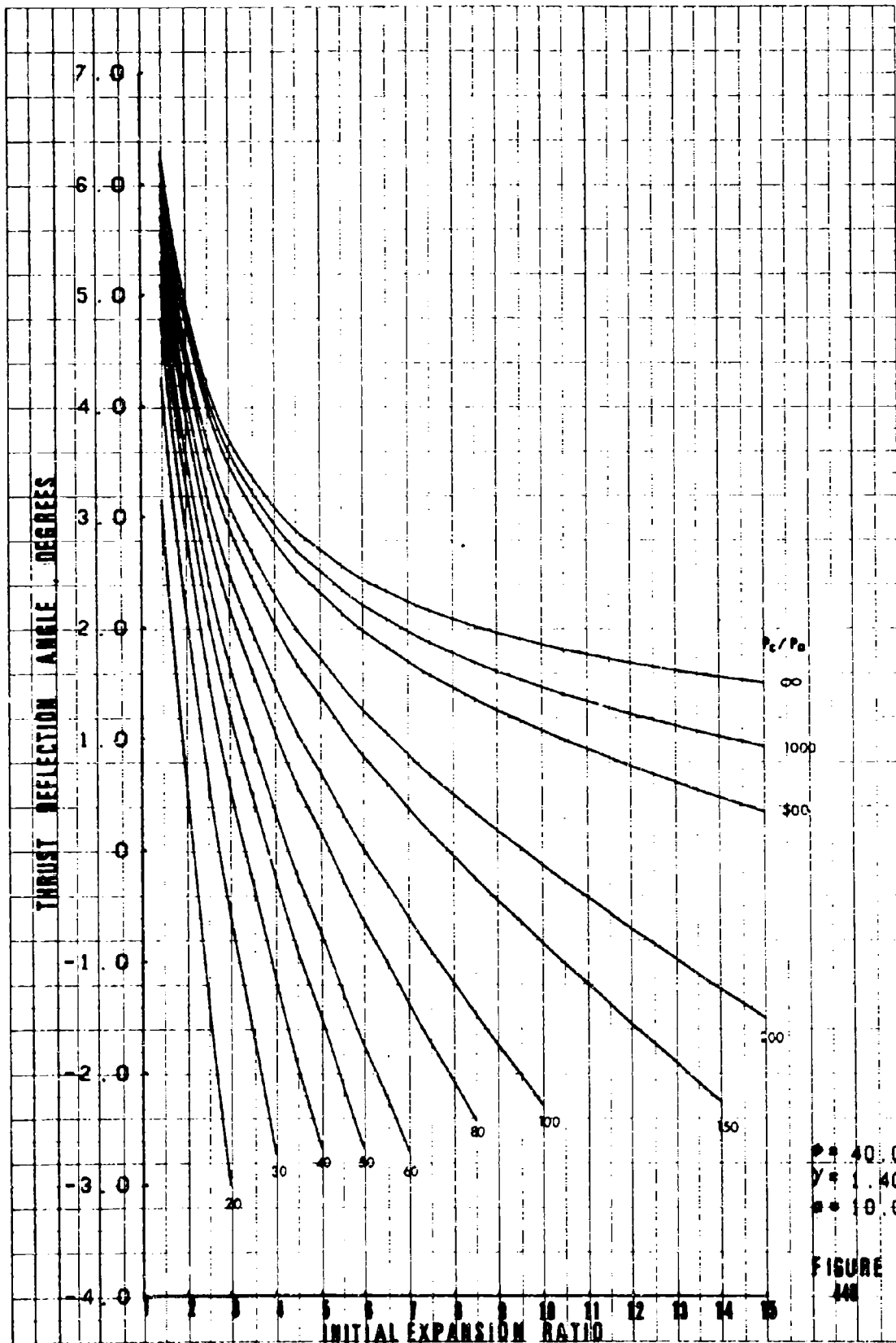


FIGURE 443

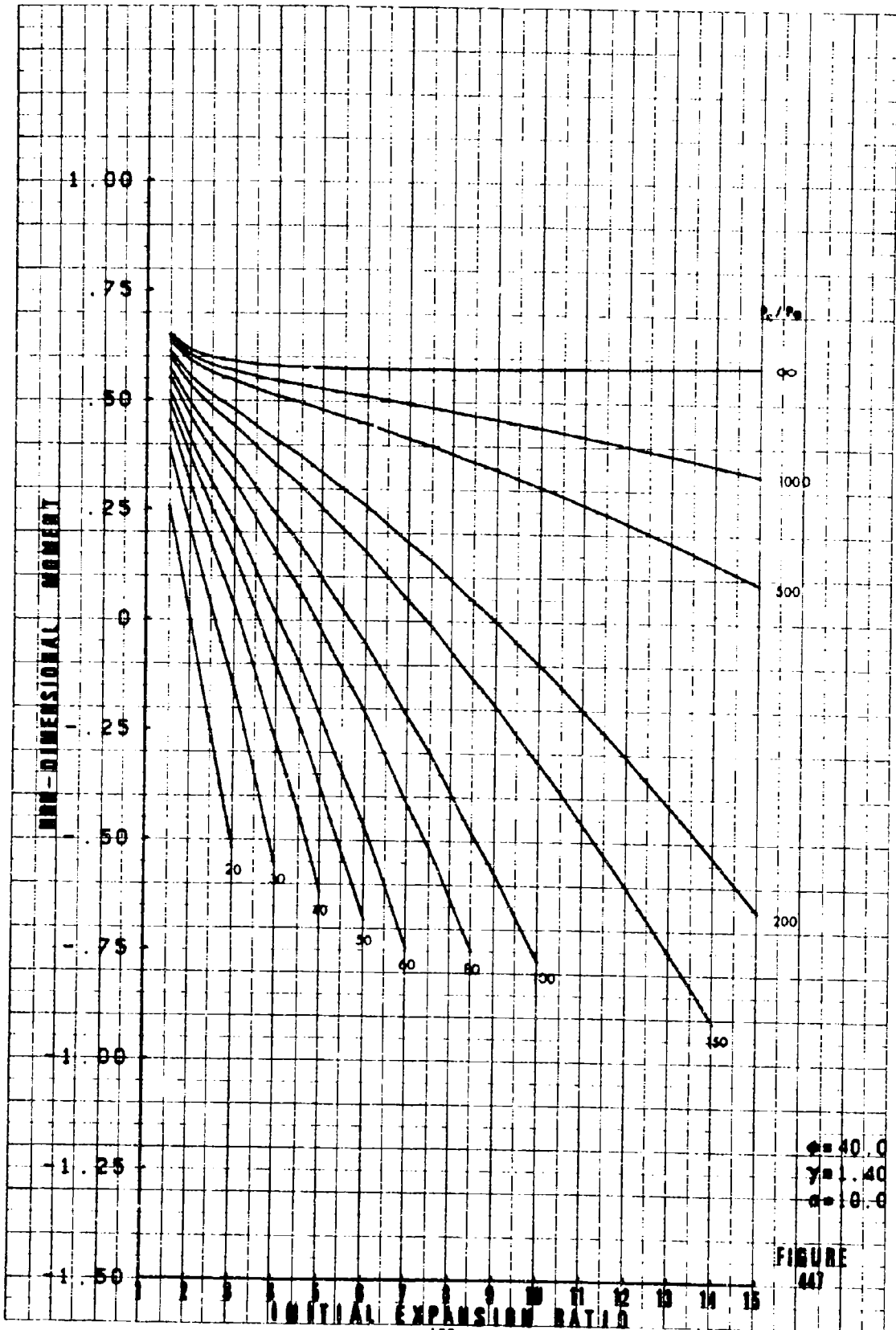




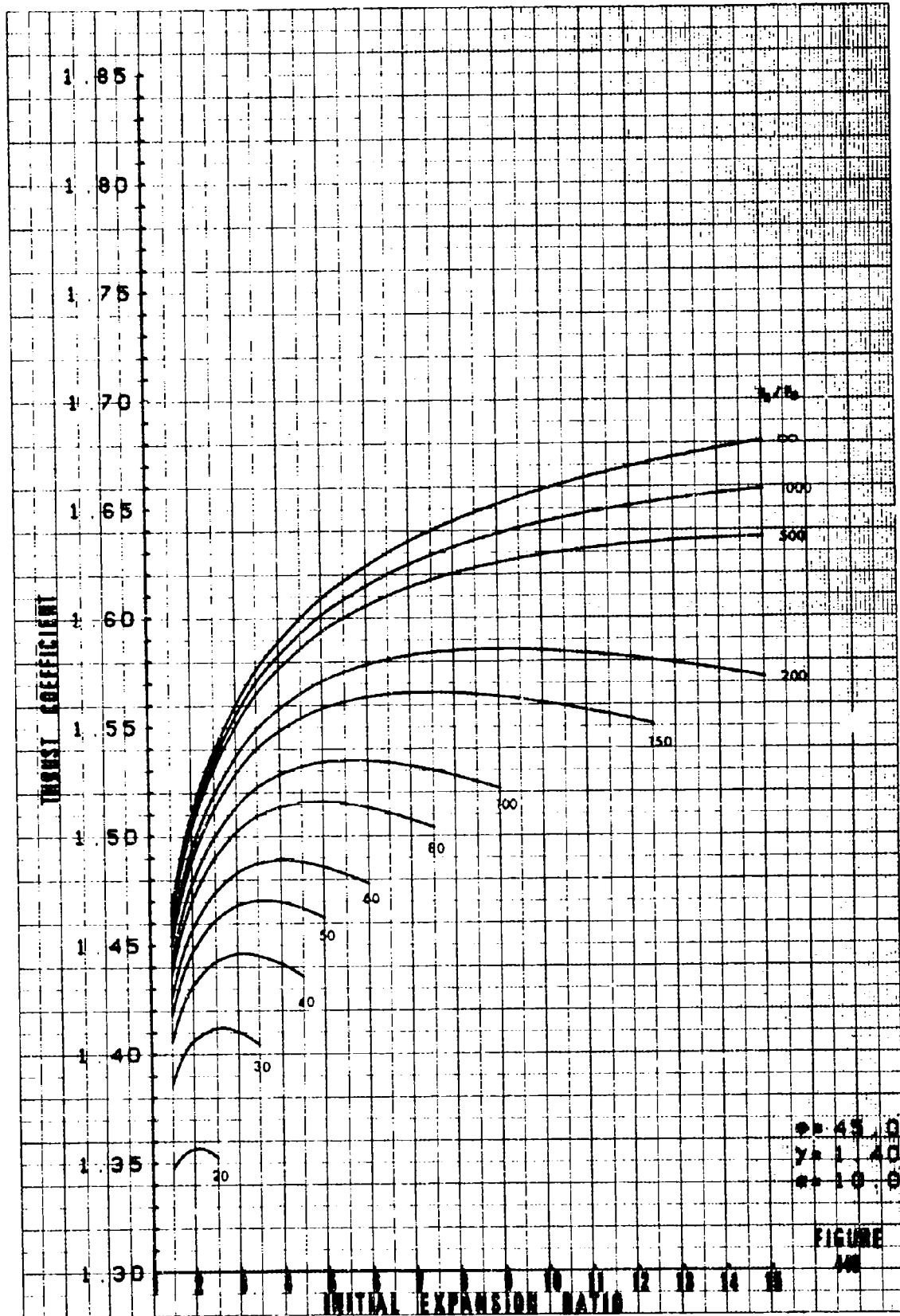


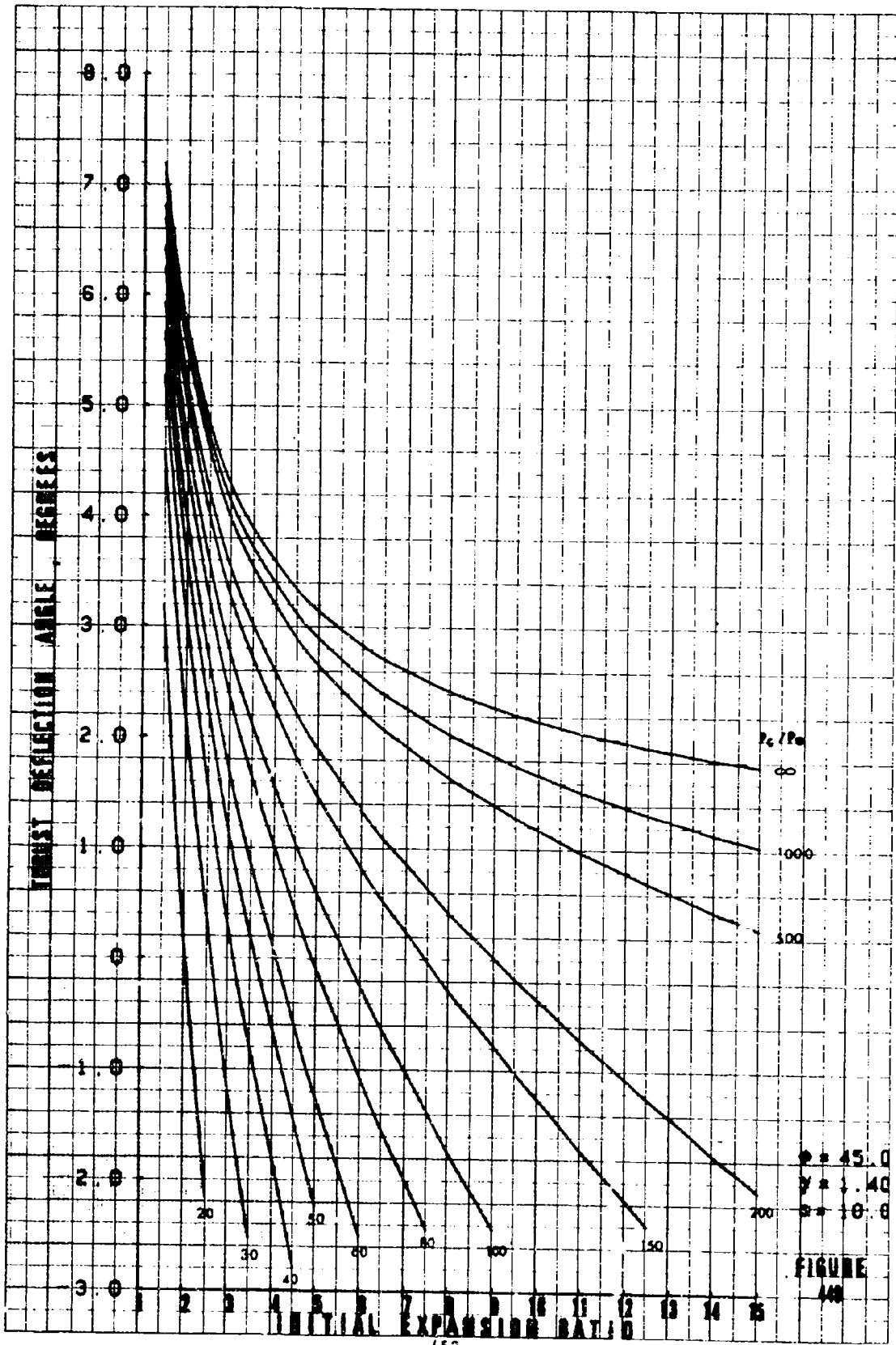
$\beta = 40.0$   
 $\gamma = 1.40$   
 $\mu = 10.0$

FIGURE 148

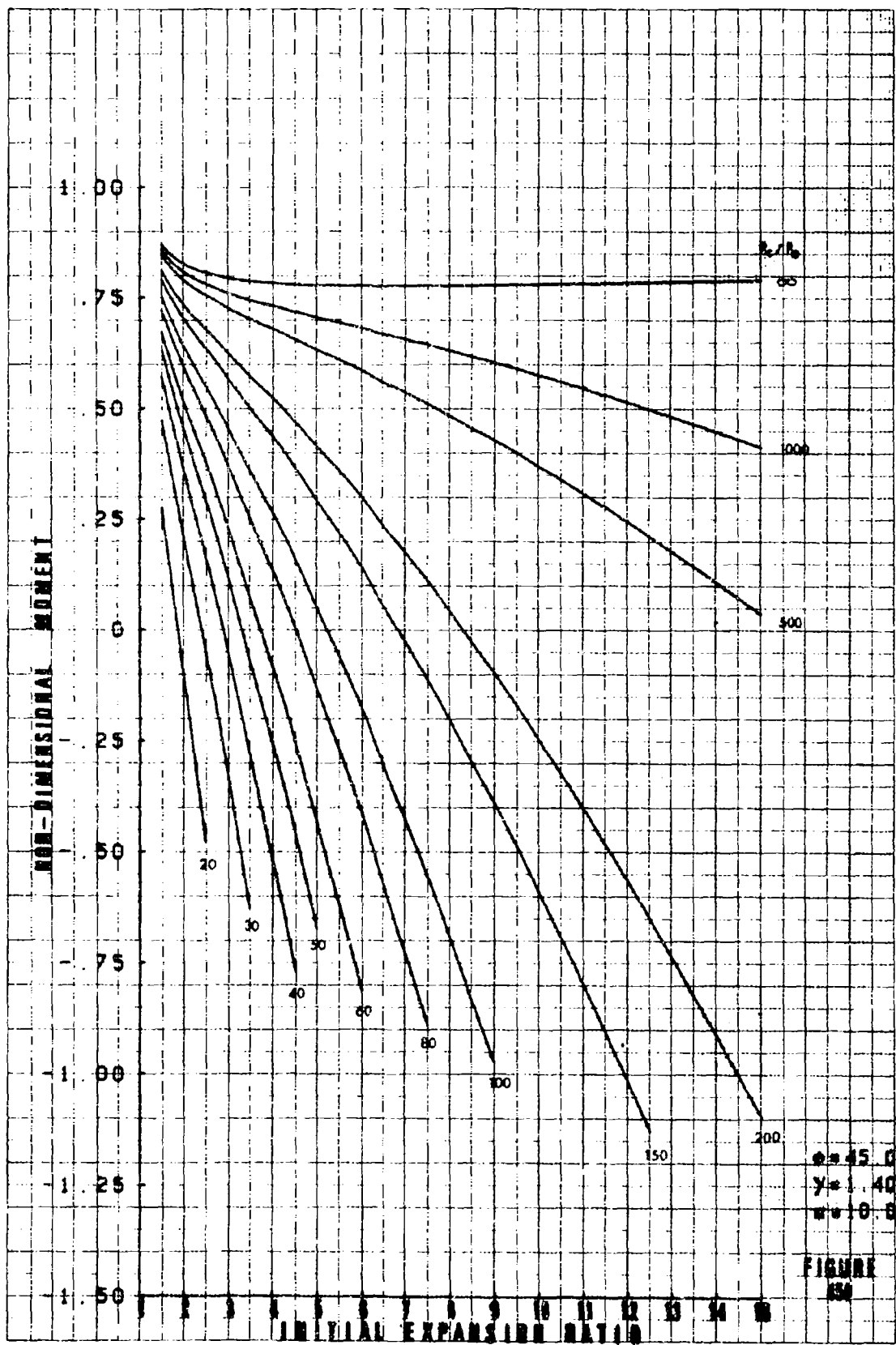


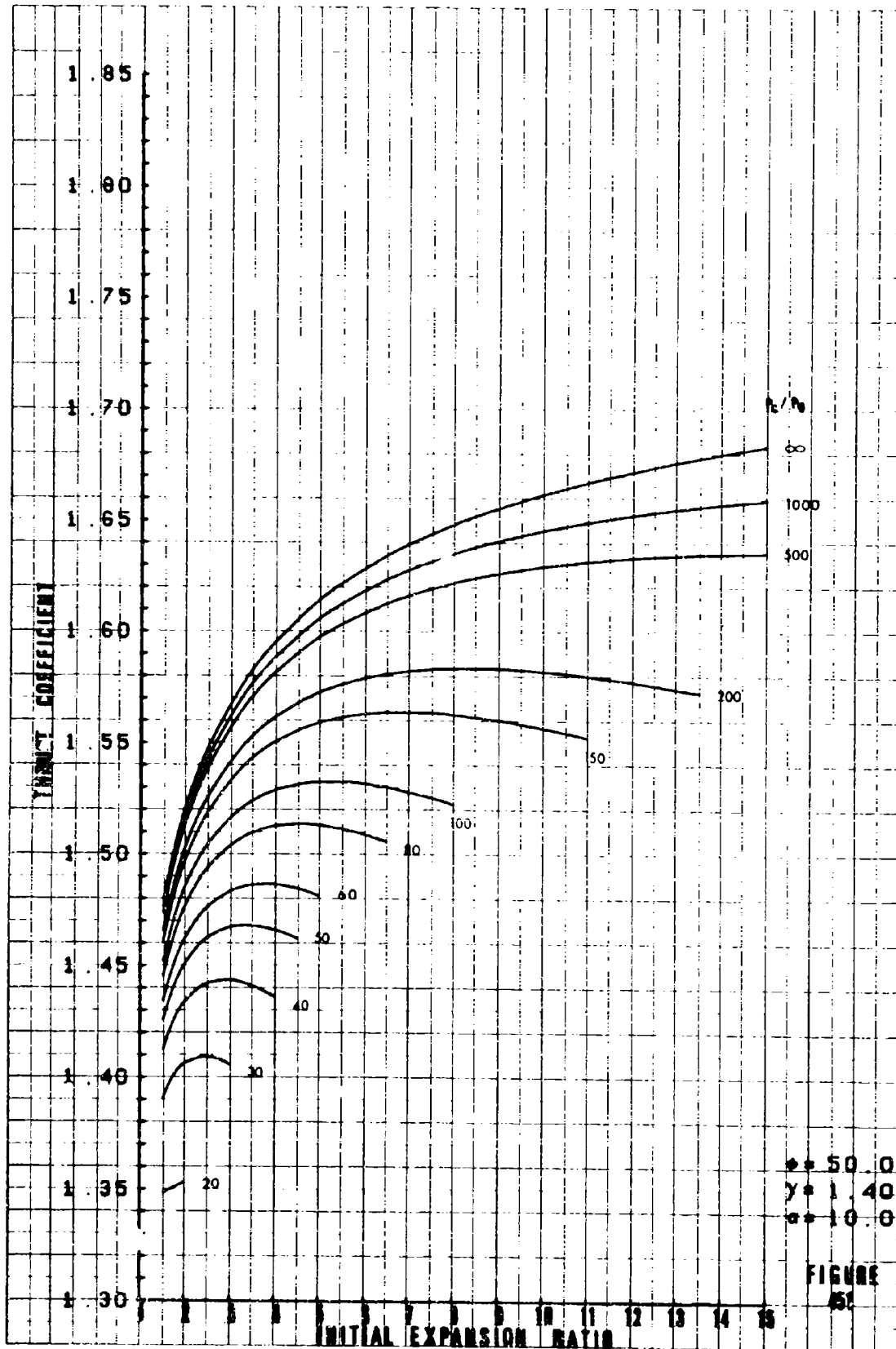






**FIGURE 148**





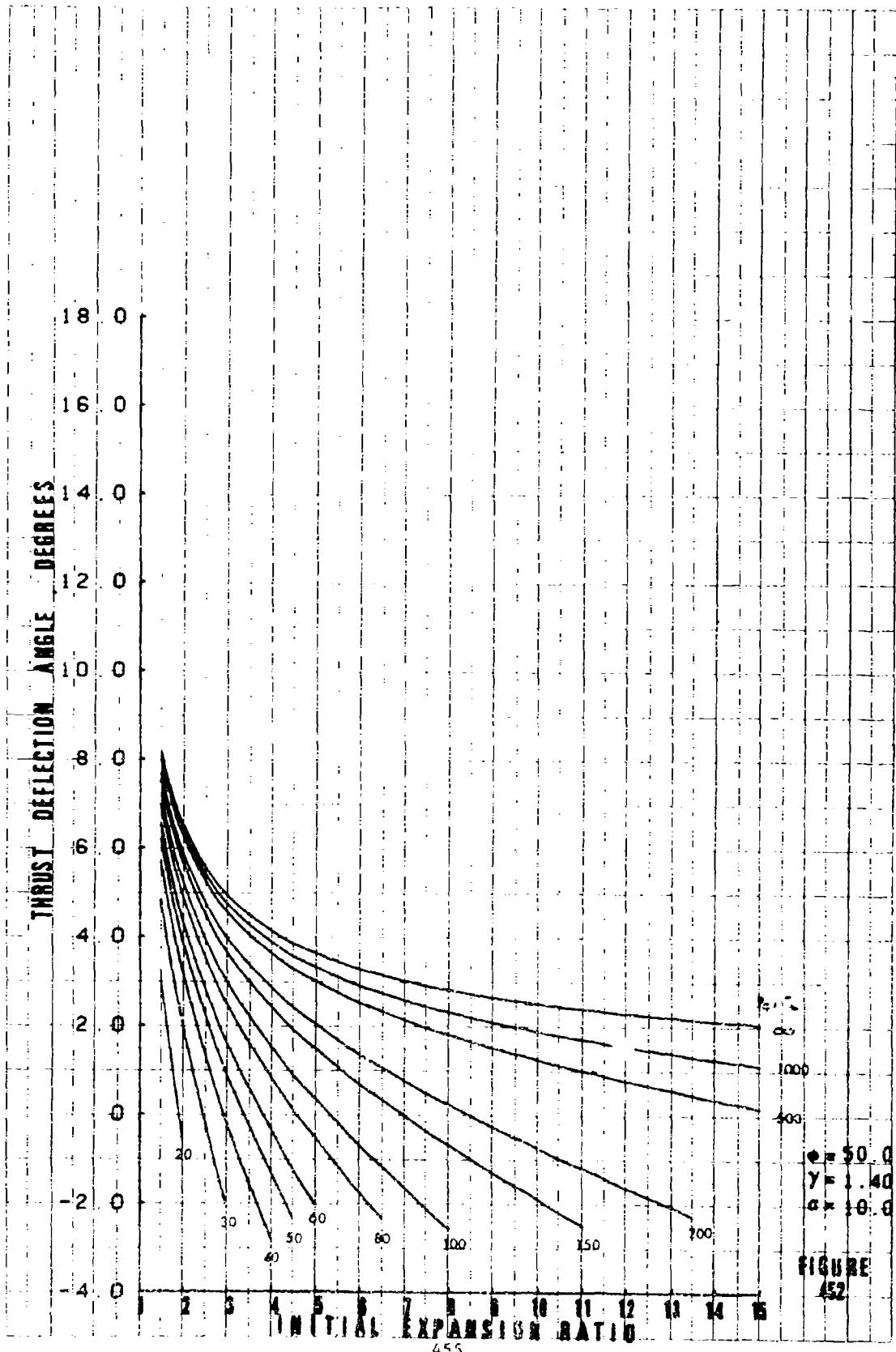
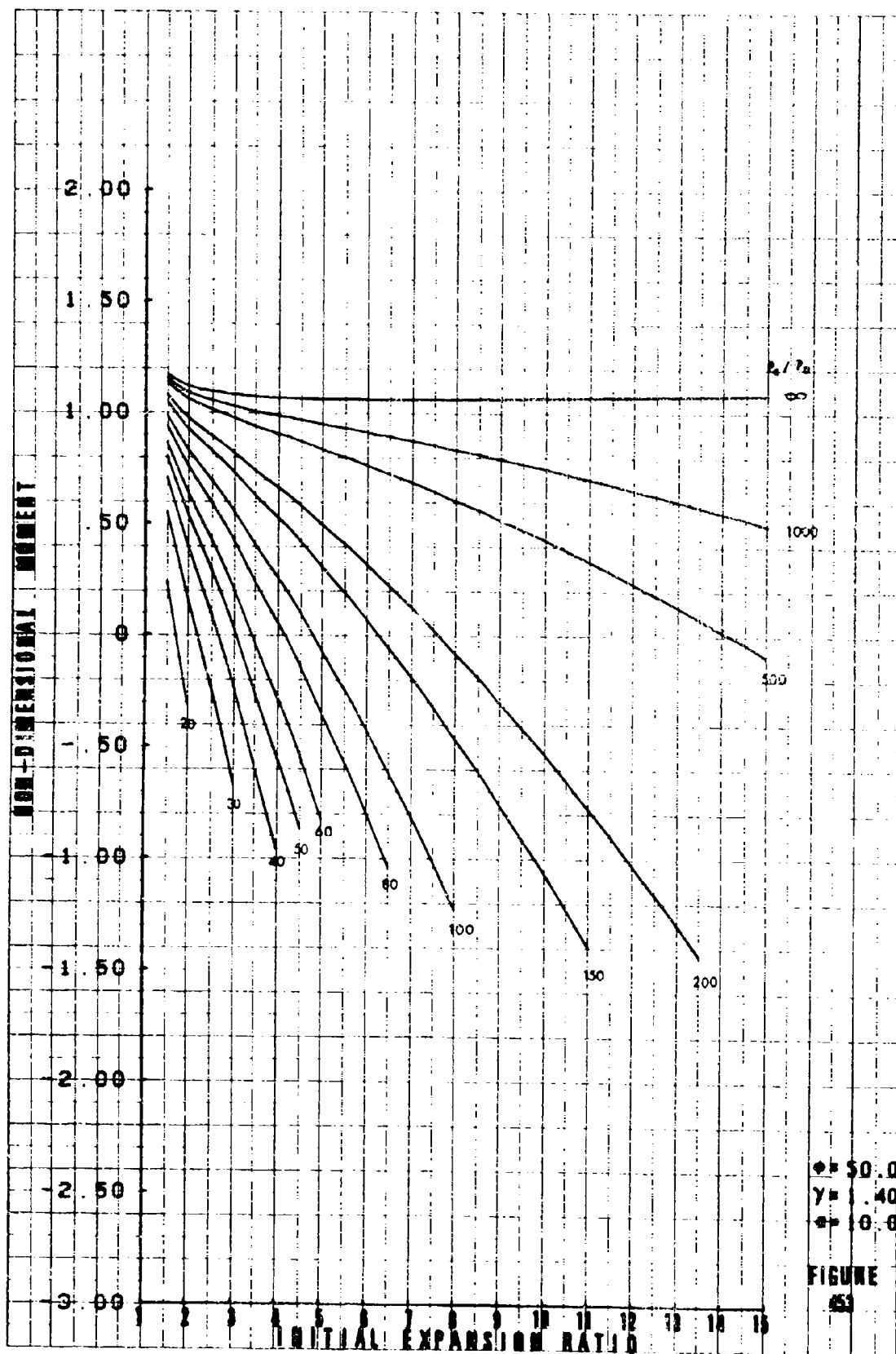
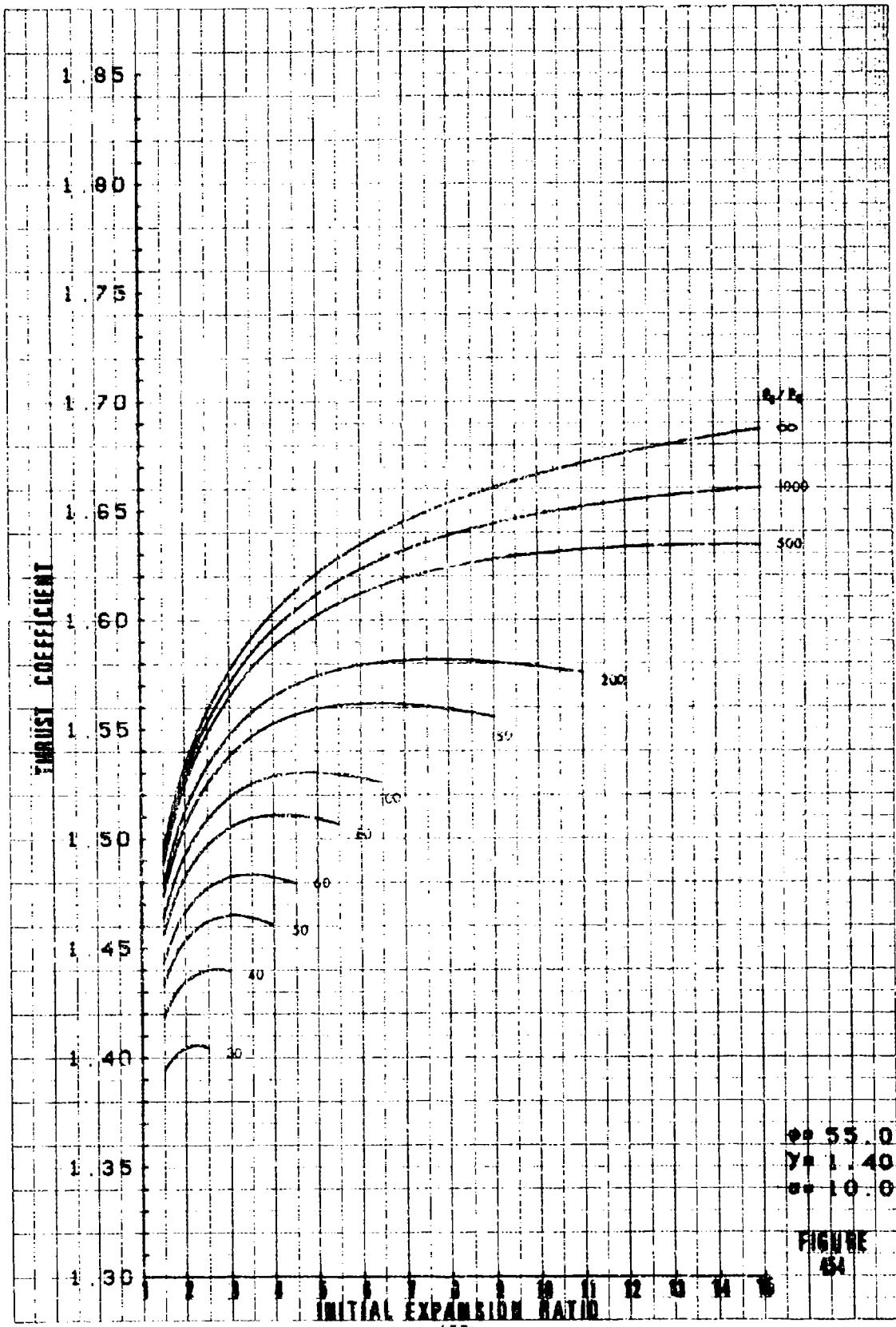
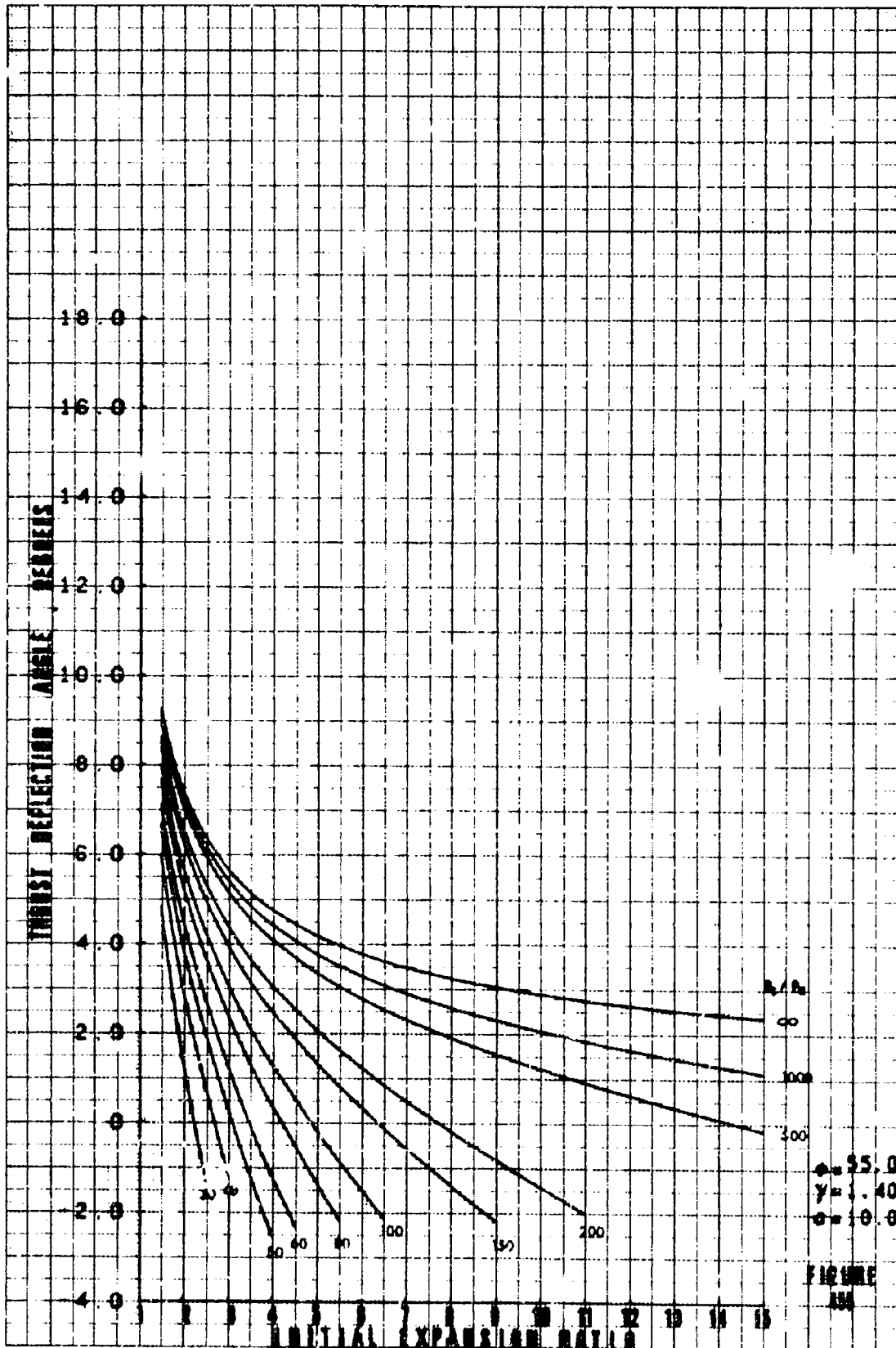


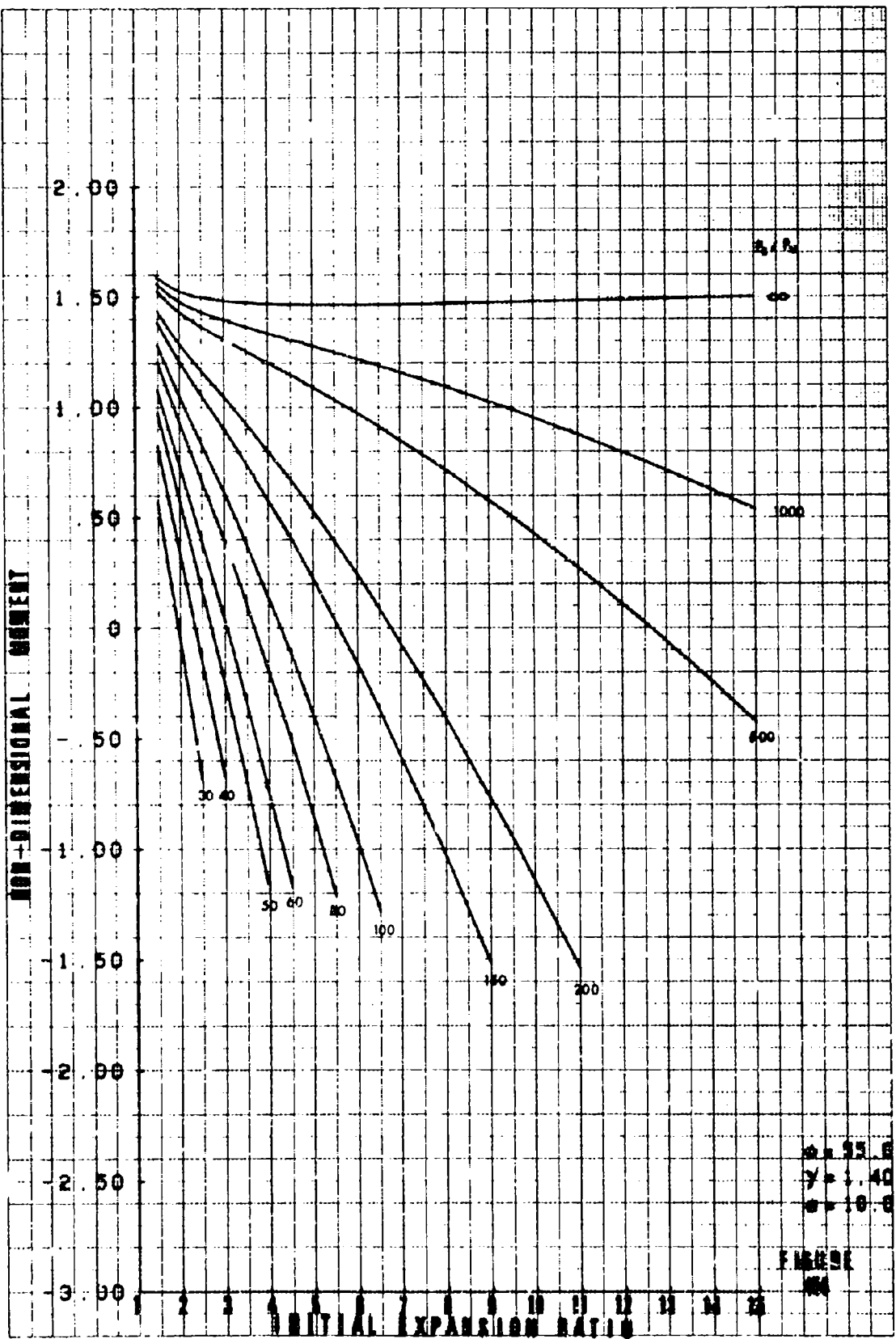
FIGURE 452

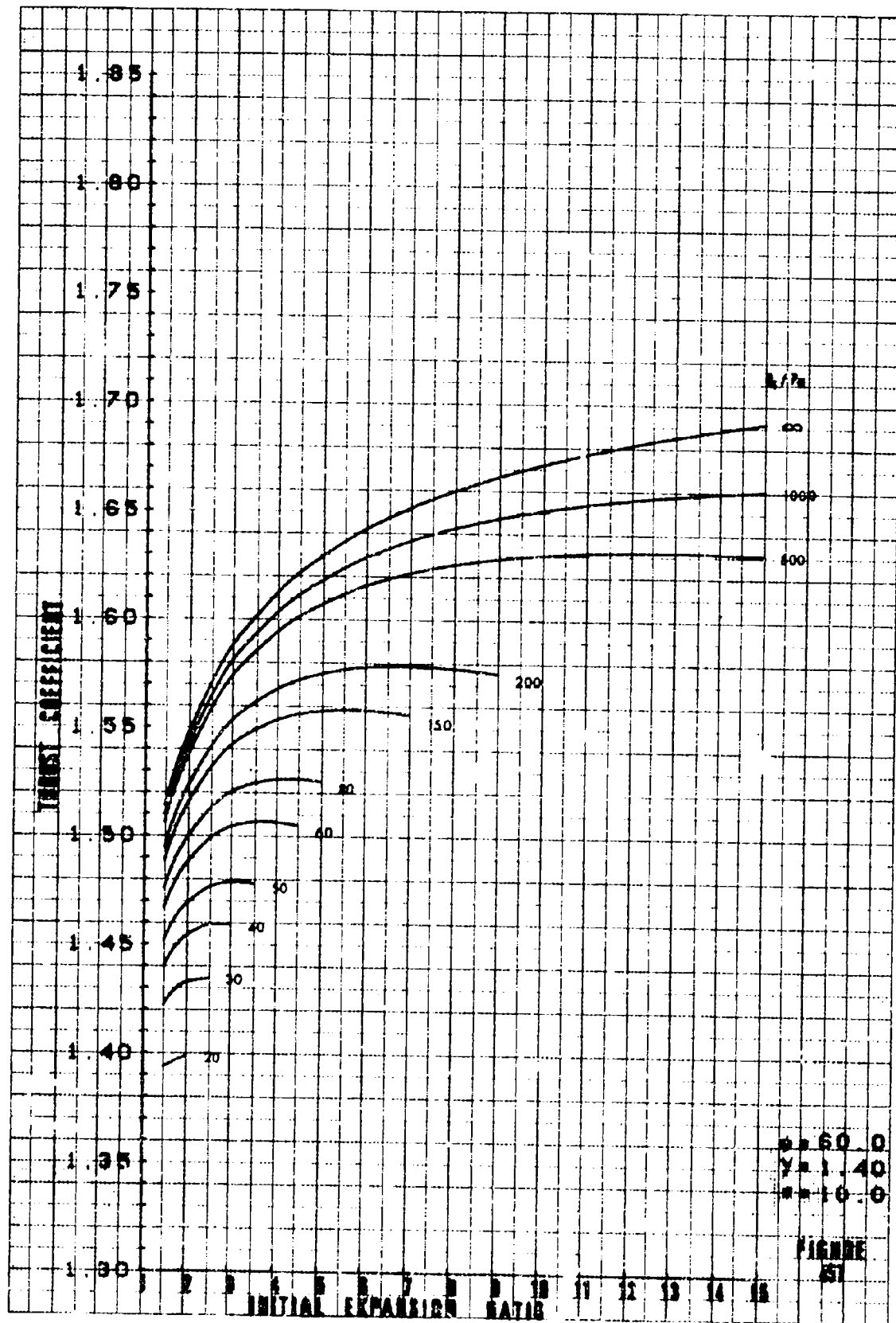












THRUST DEFLECTION ANGLE, DEGREES

20.0  
18.0  
16.0  
14.0  
12.0  
10.0  
8.0  
6.0  
4.0  
2.0  
-2.0

INITIAL EXPANSION RATIO

30 40 50 60 100 150 200

$\lambda/\lambda_0$

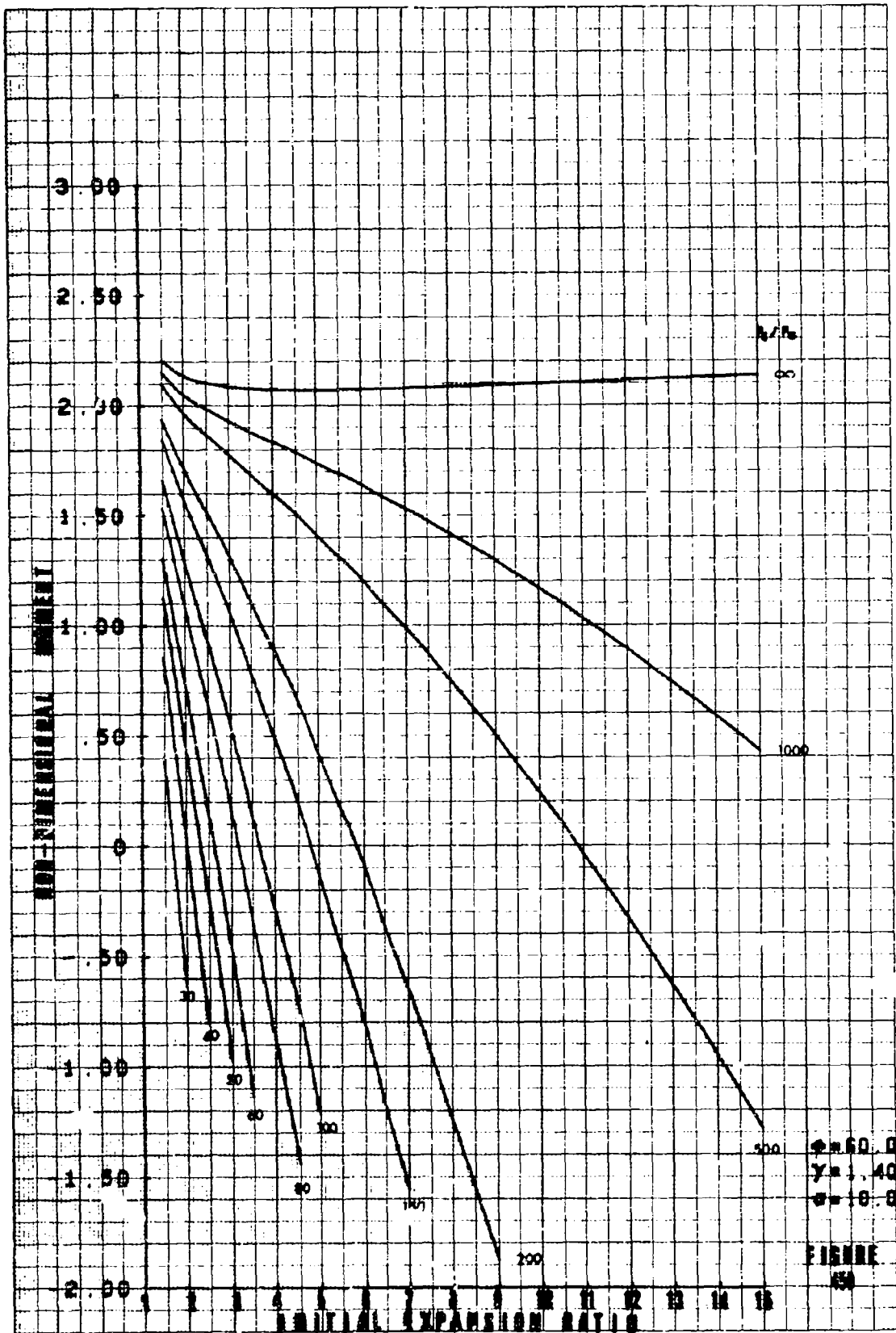
$\infty$

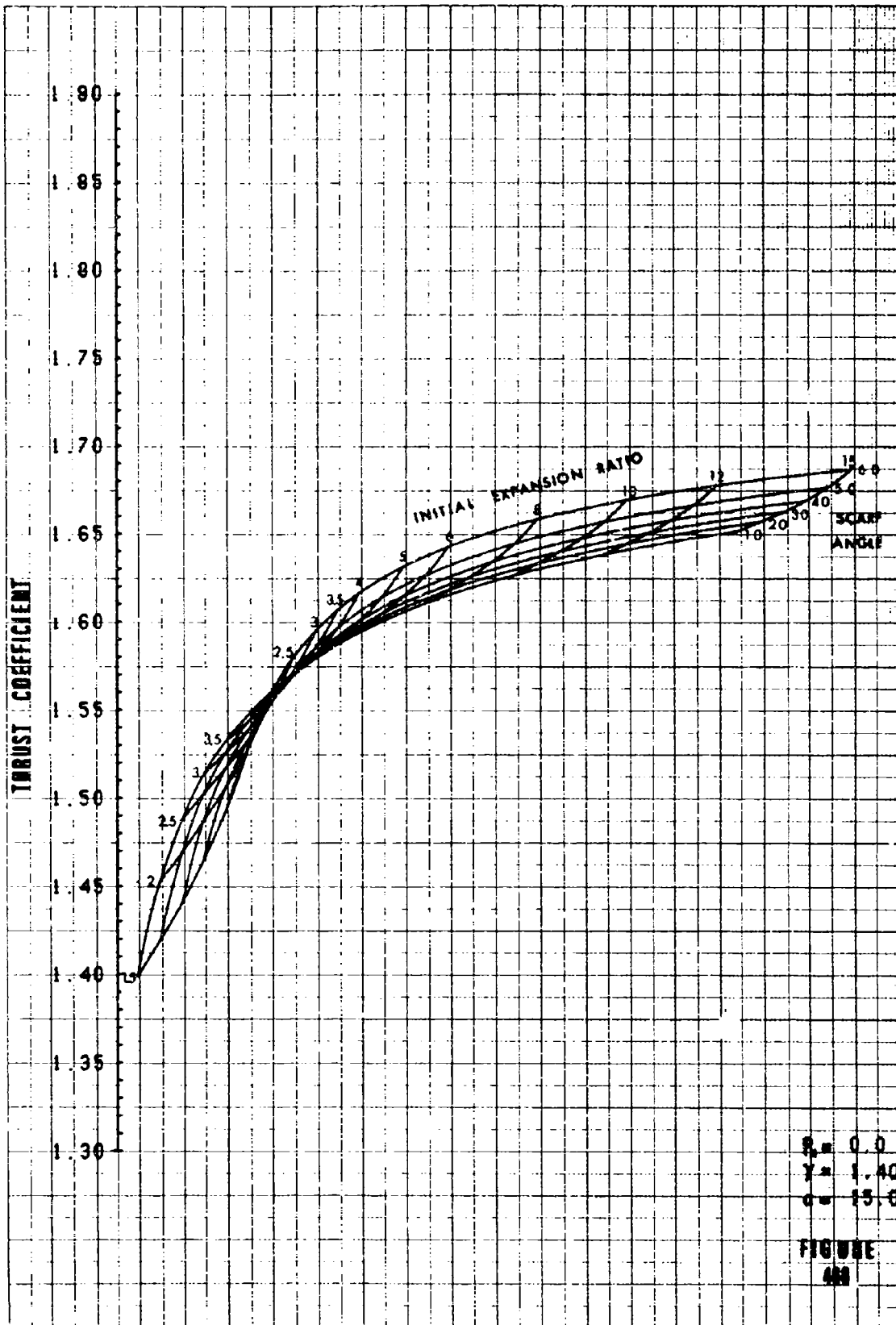
50.0

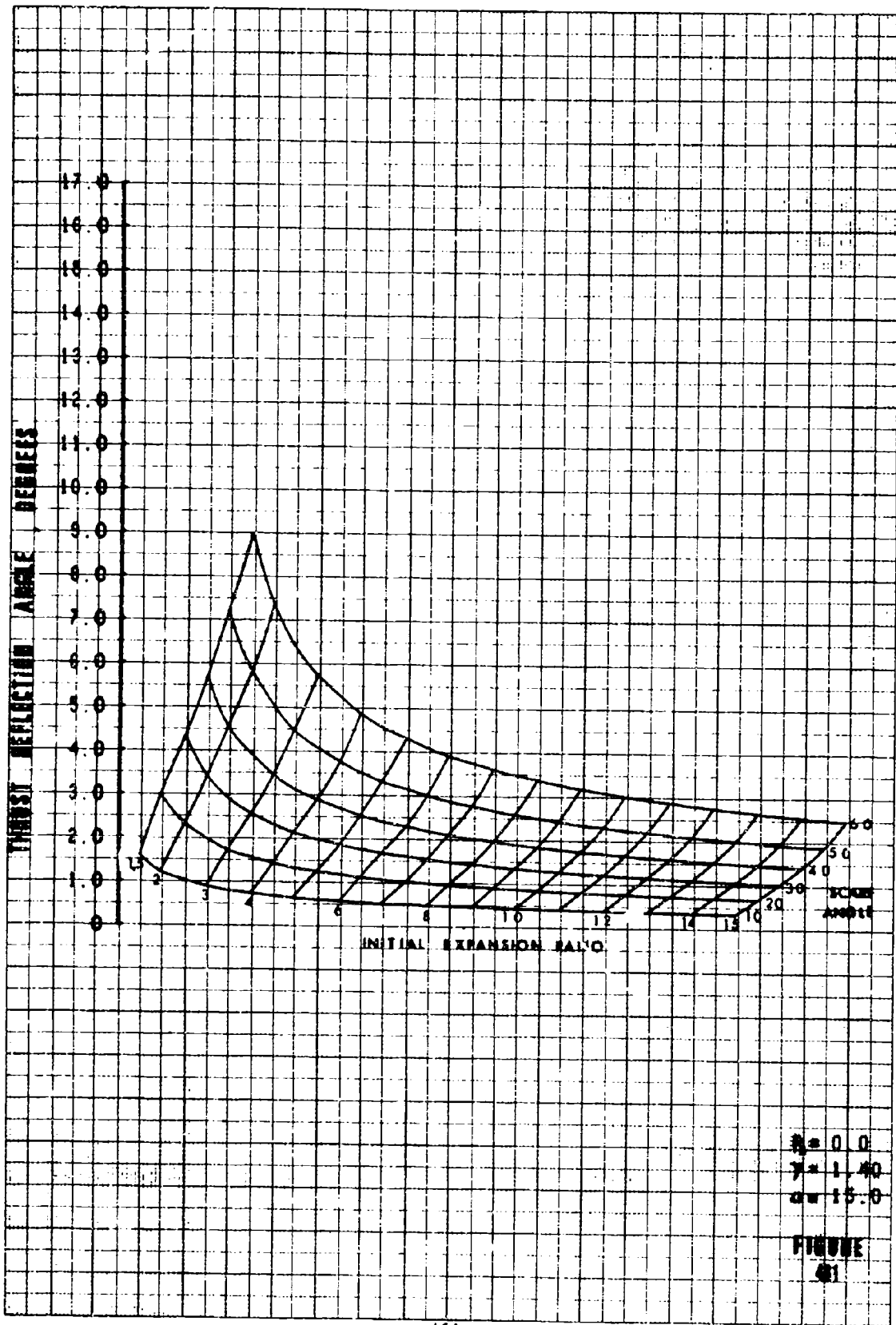
40

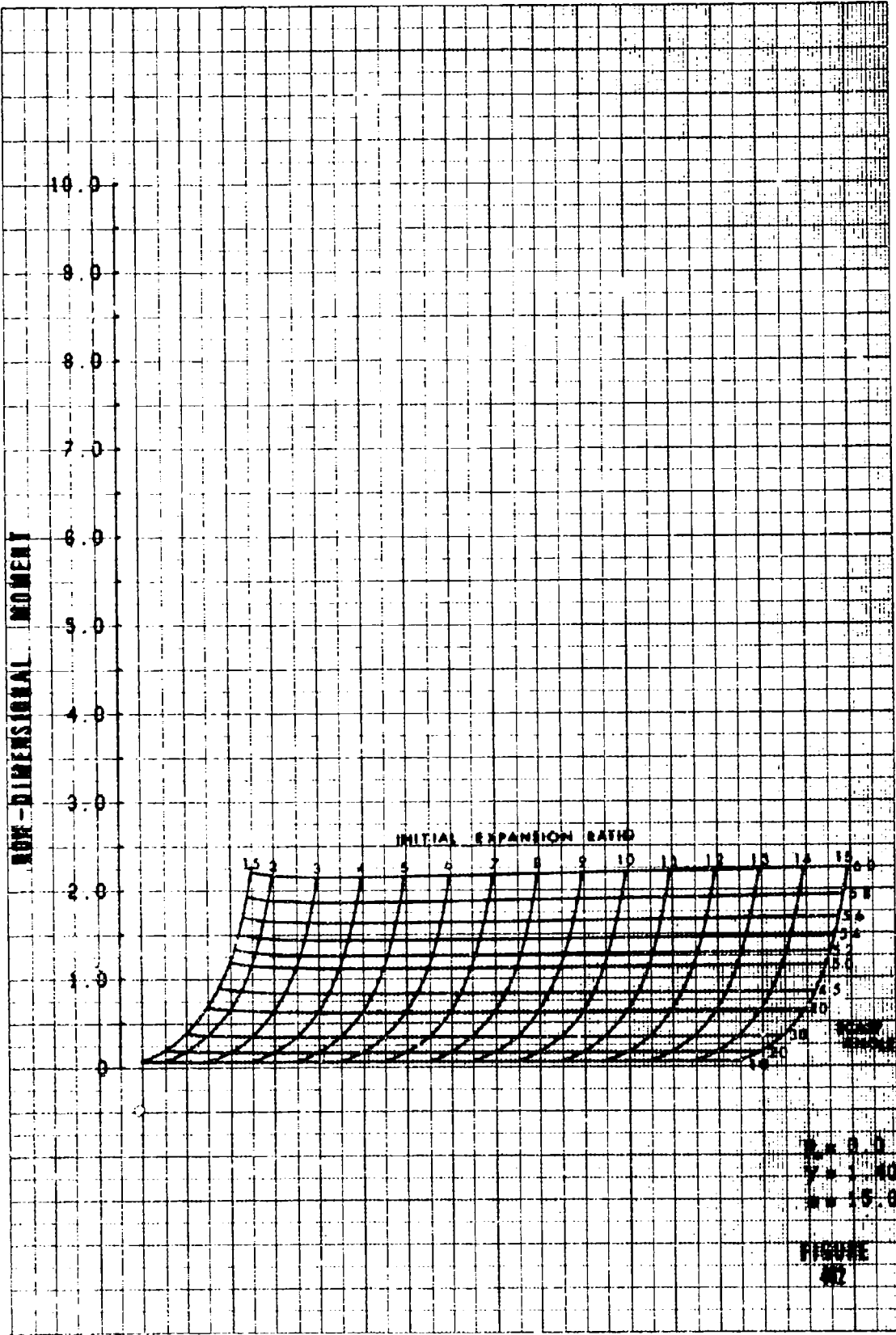
30.0

FIGURE 15









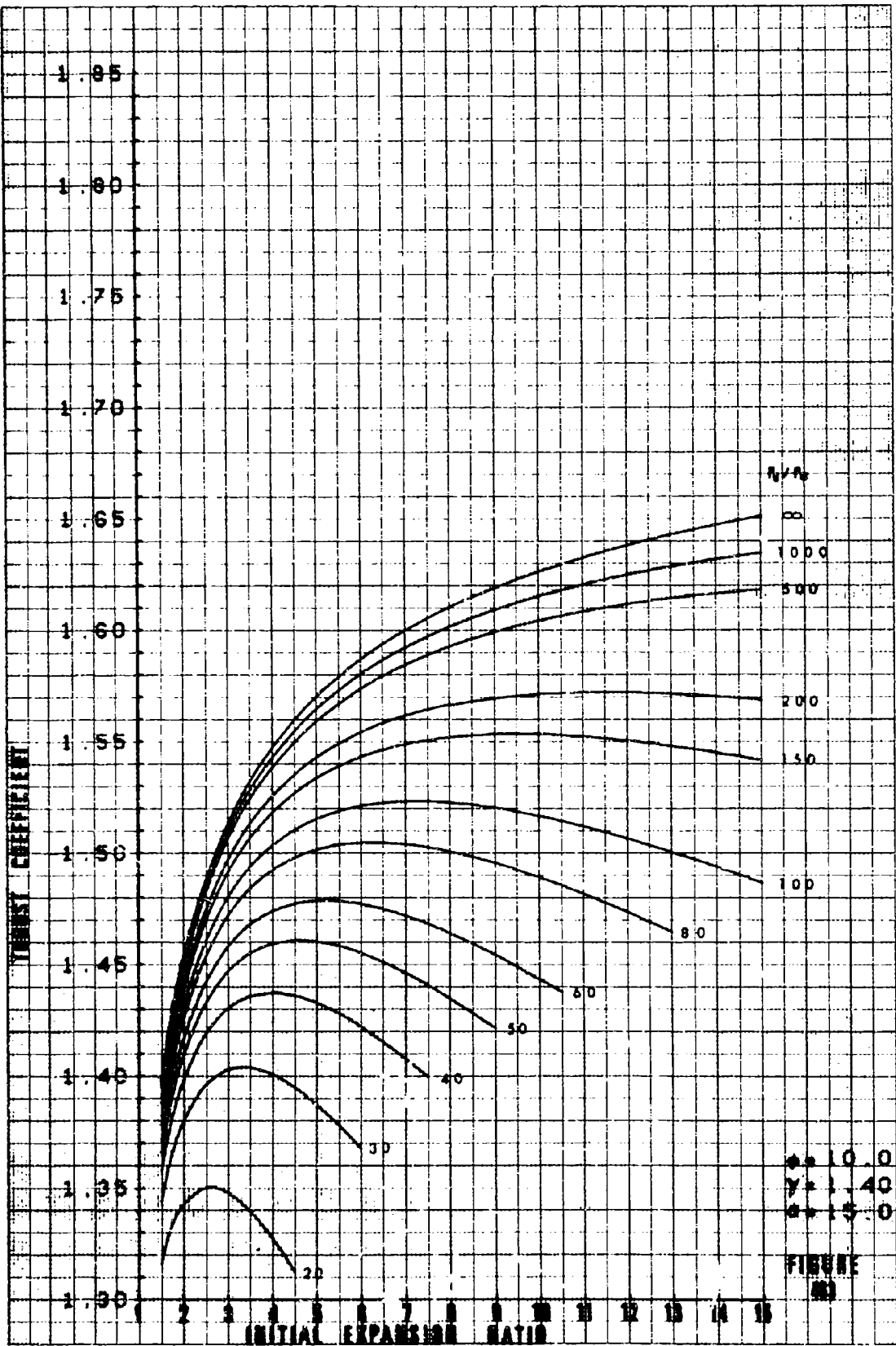


FIGURE 93



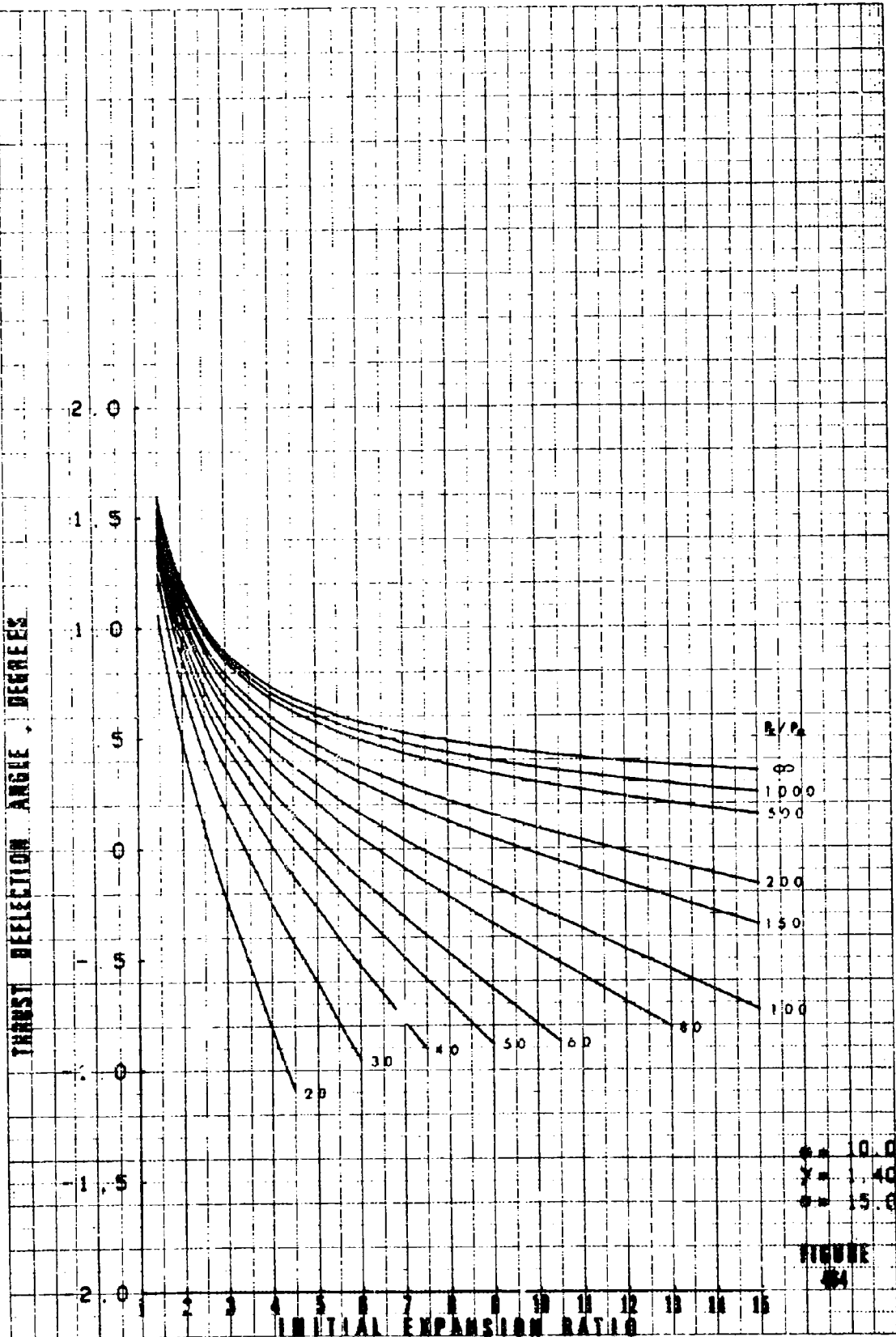
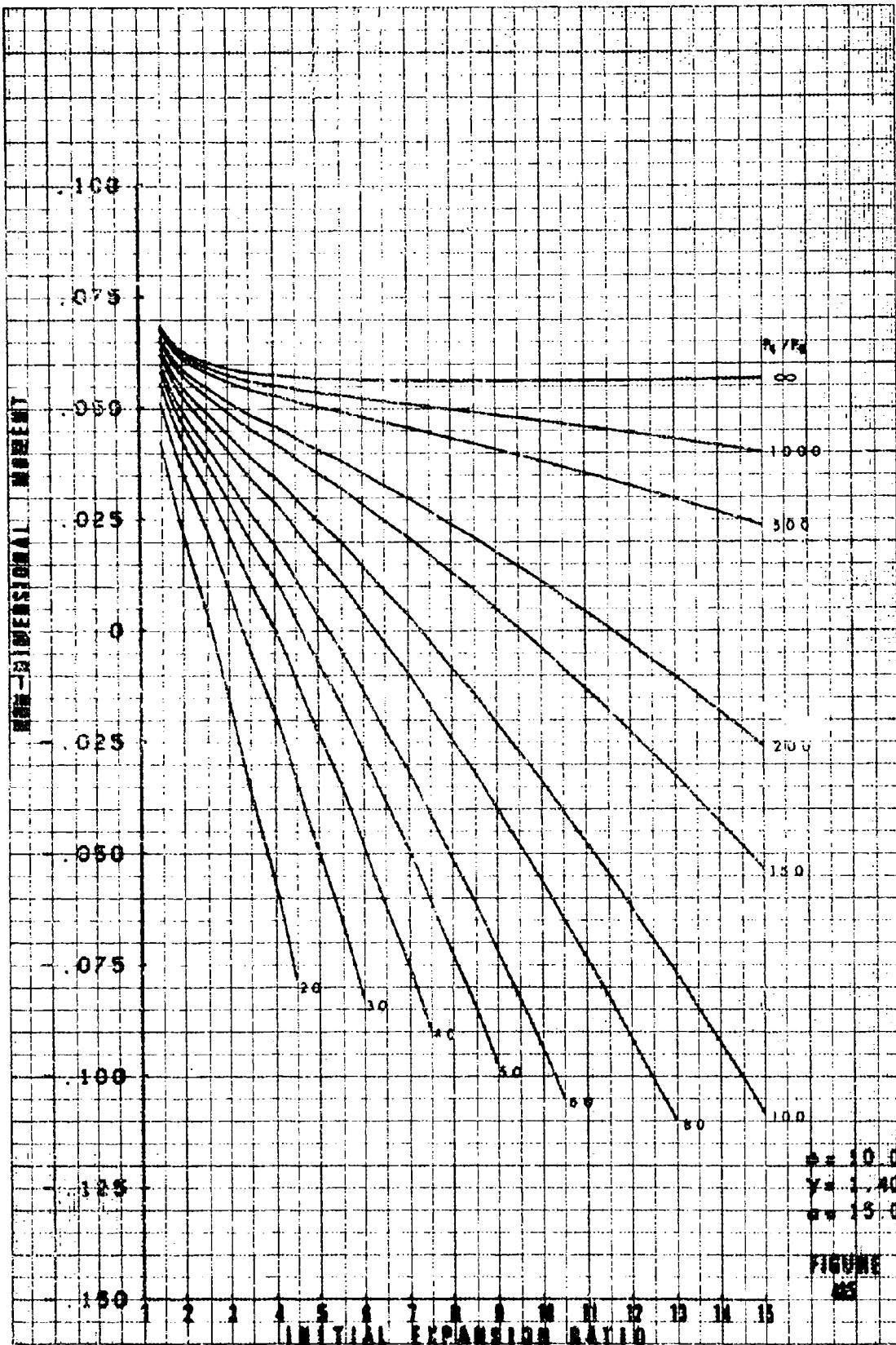


FIGURE 24



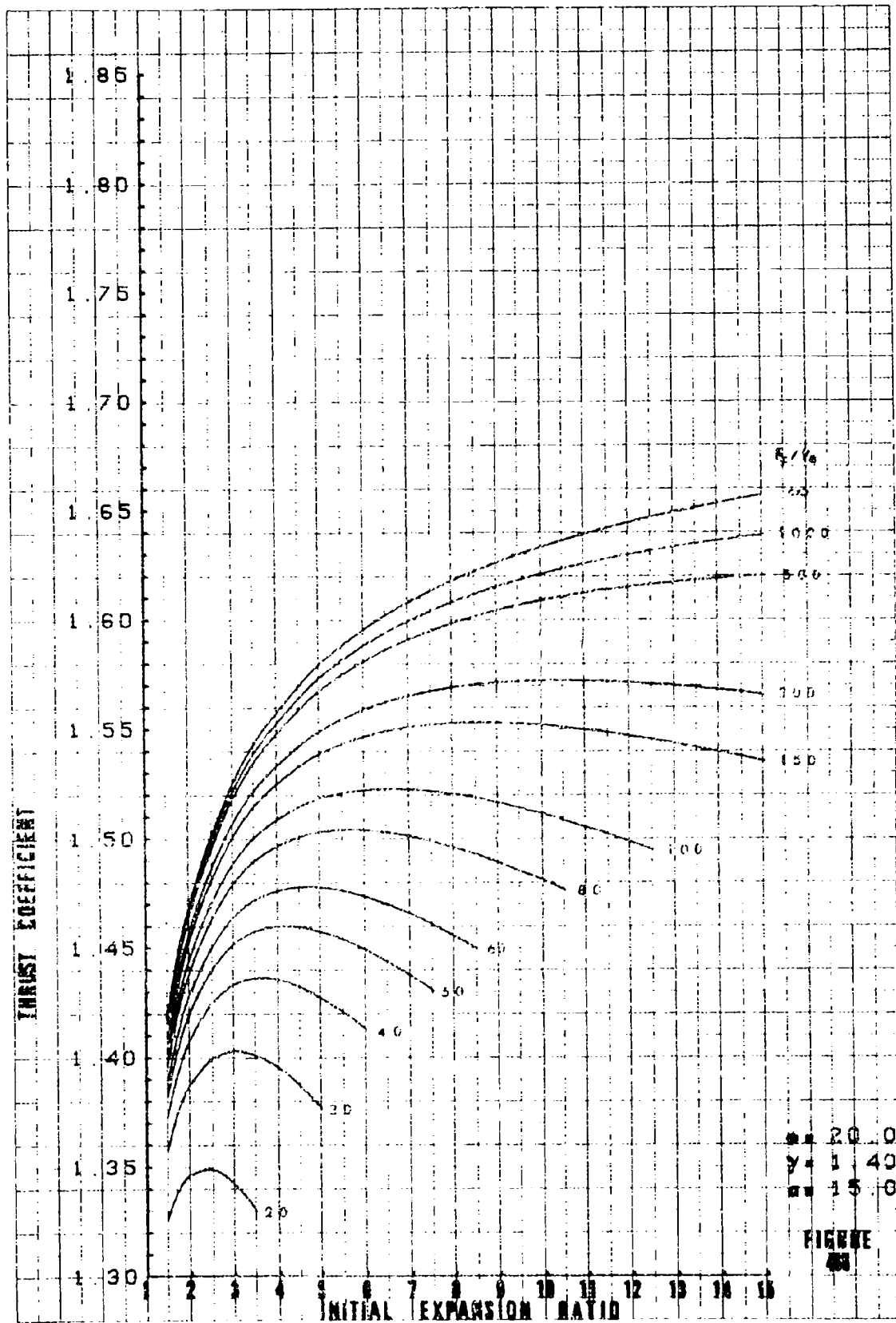
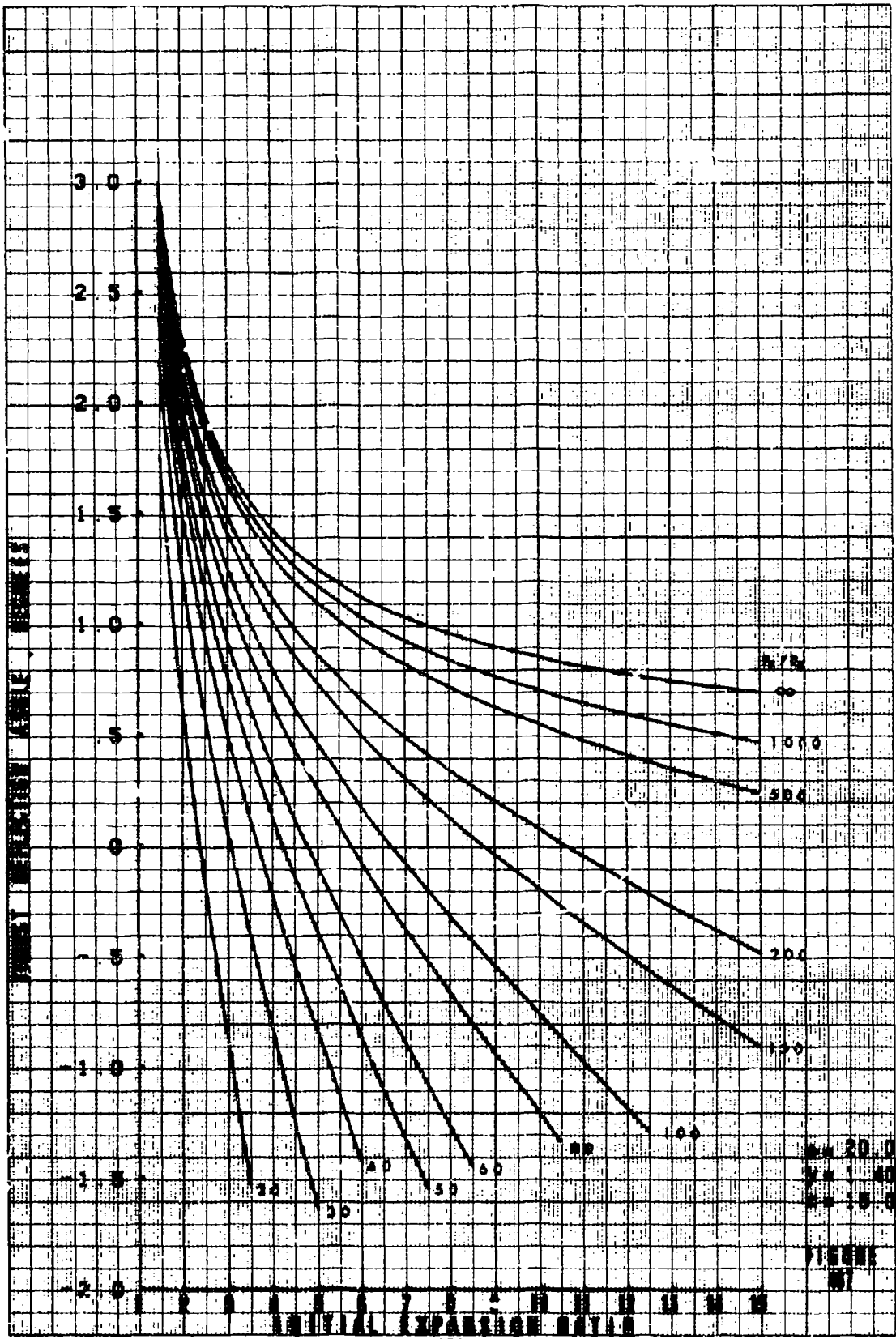
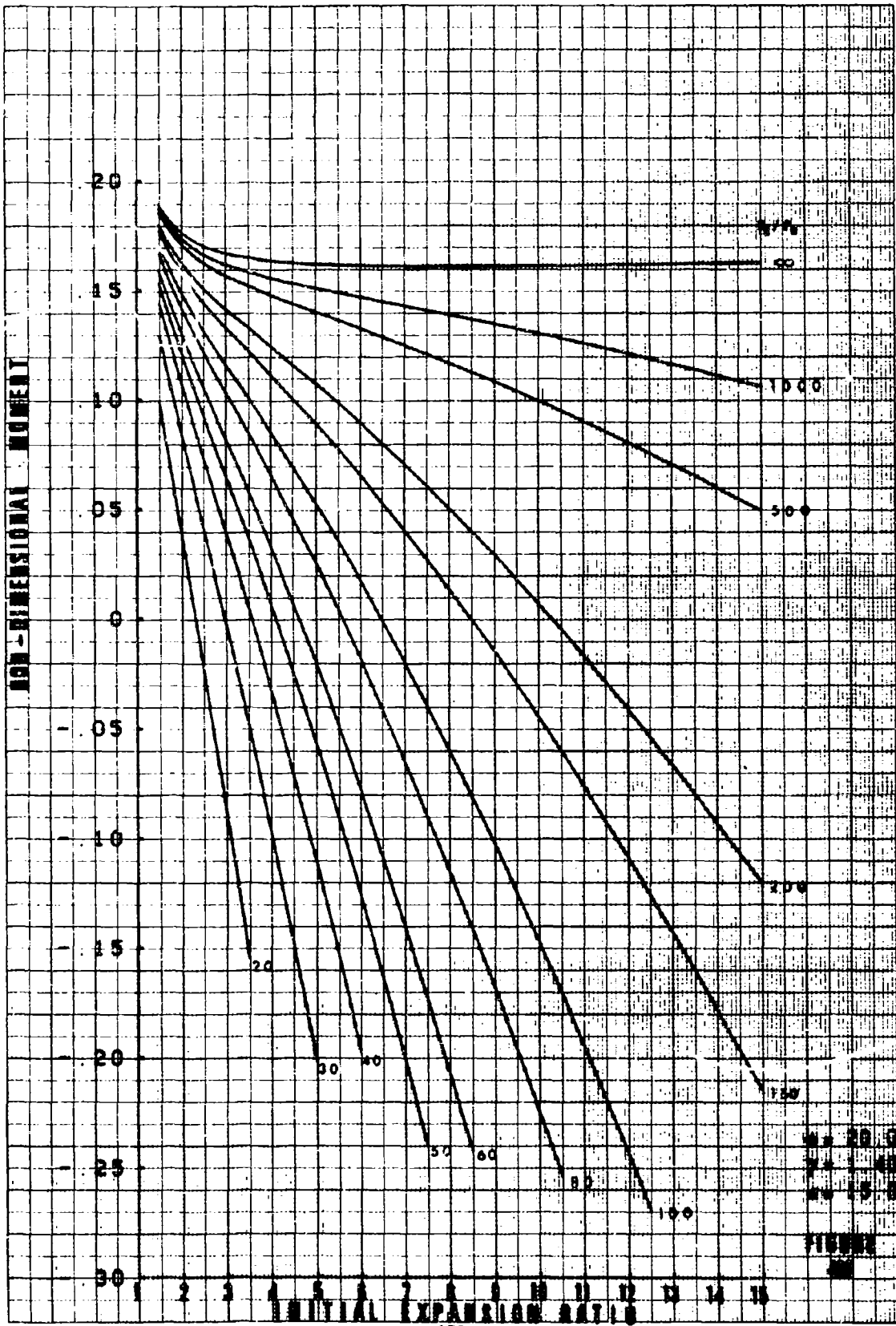
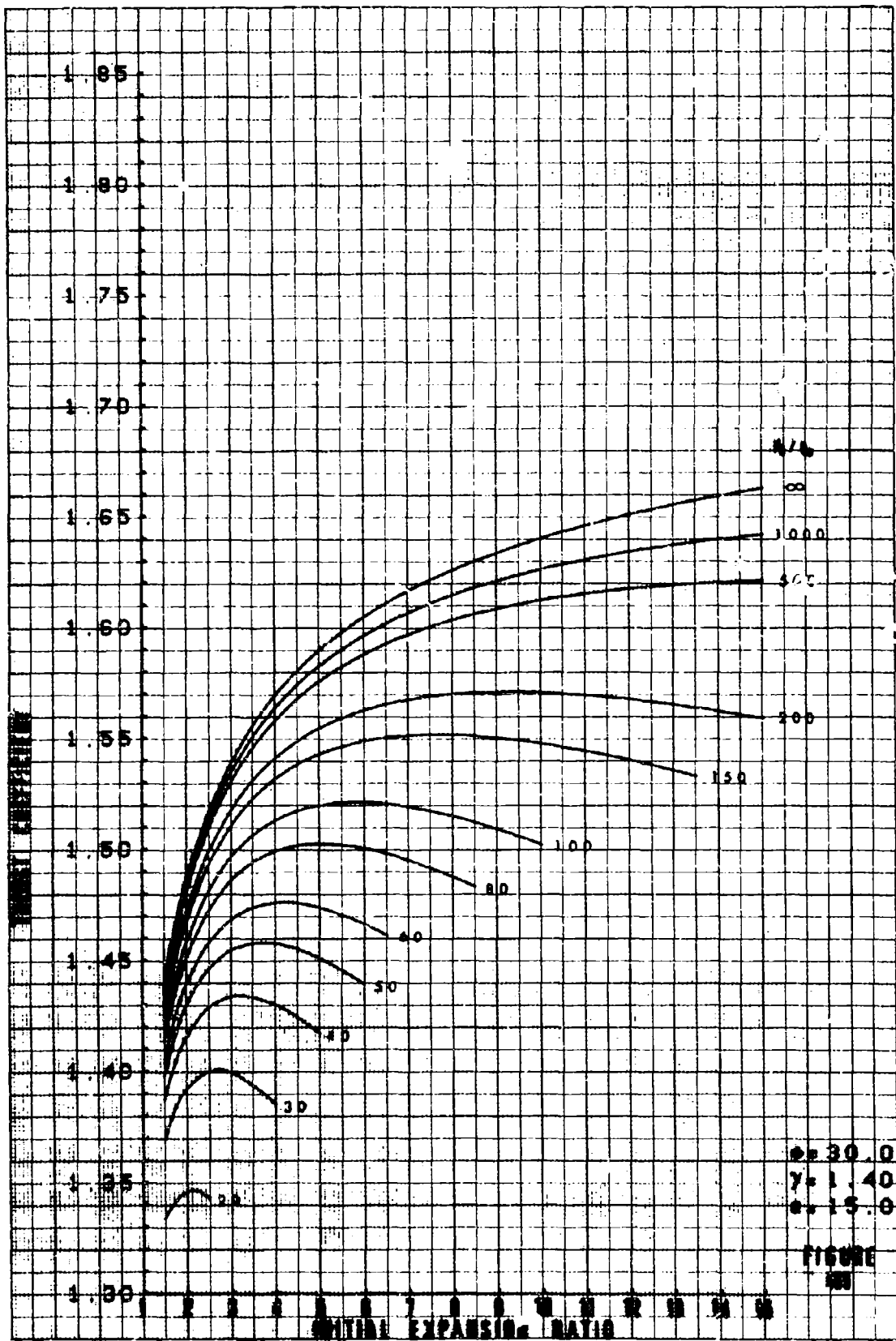
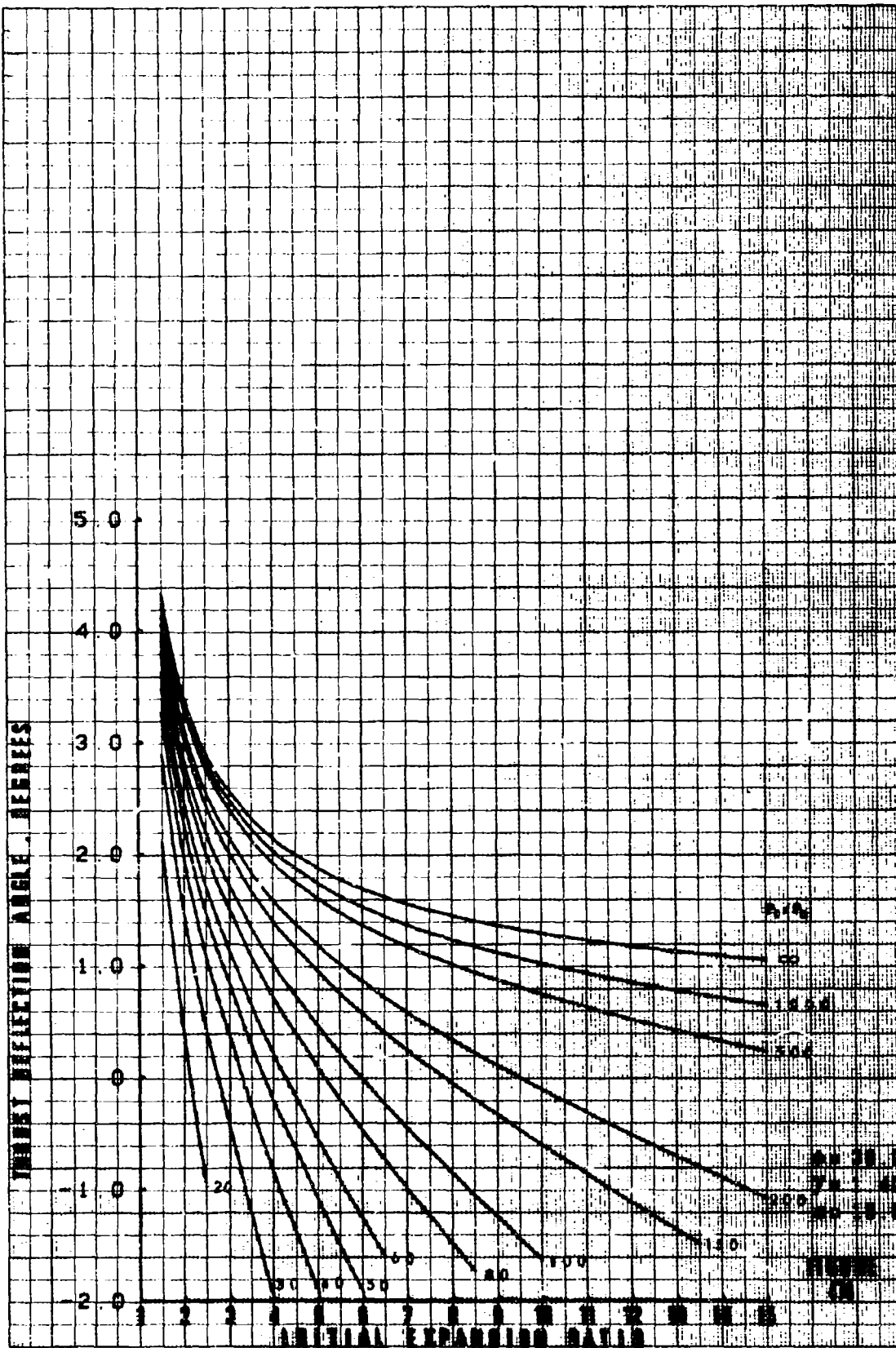


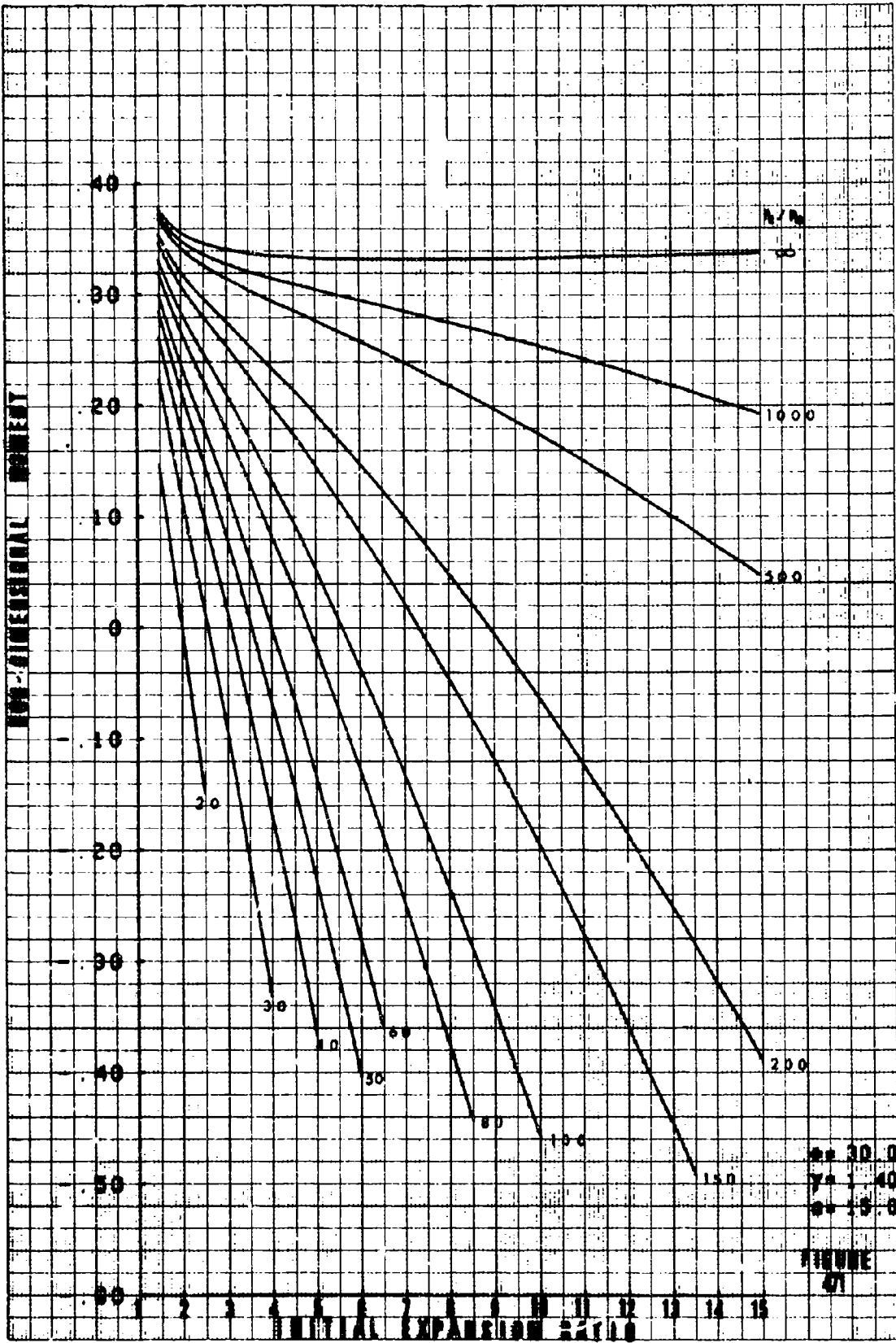
FIGURE 469







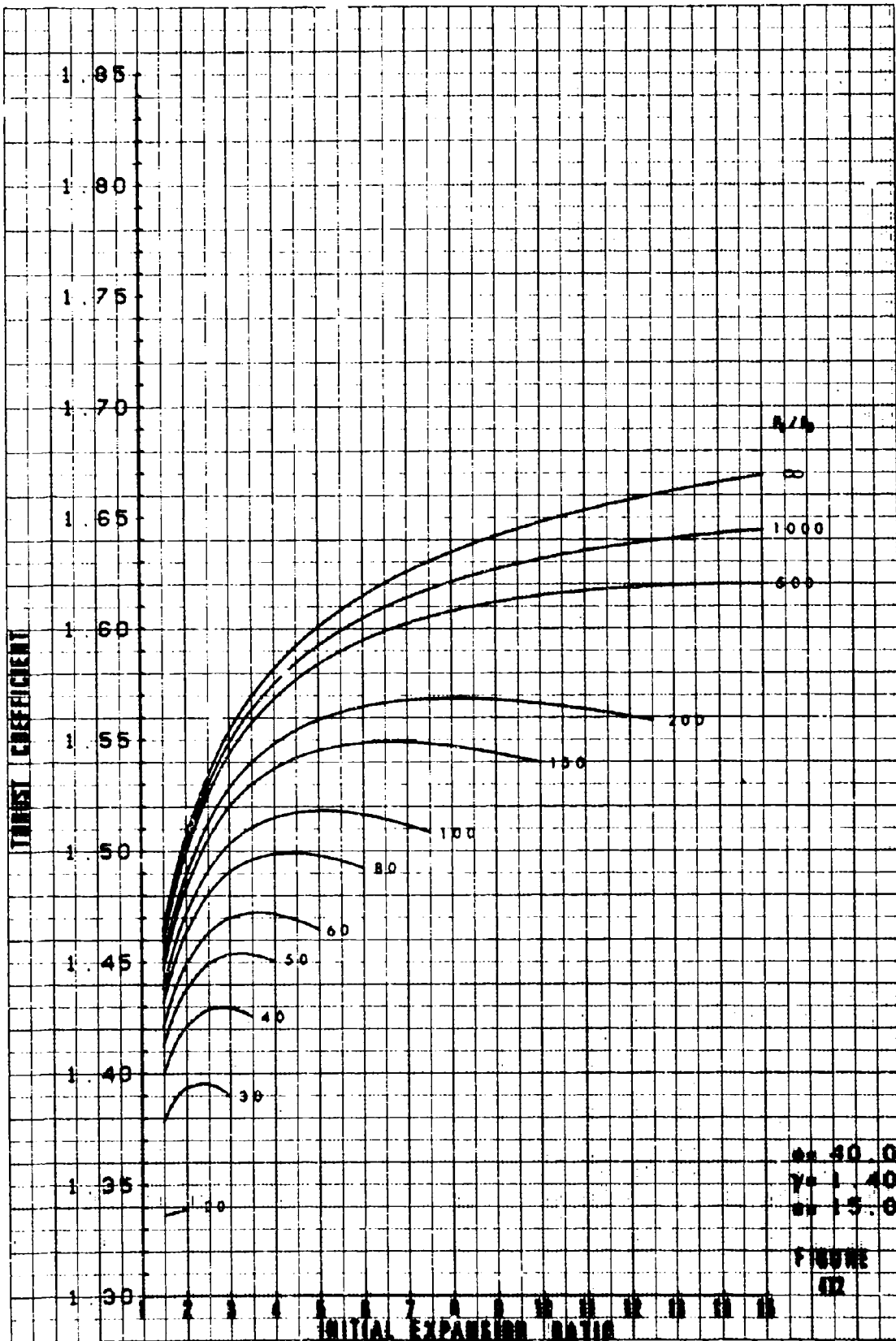


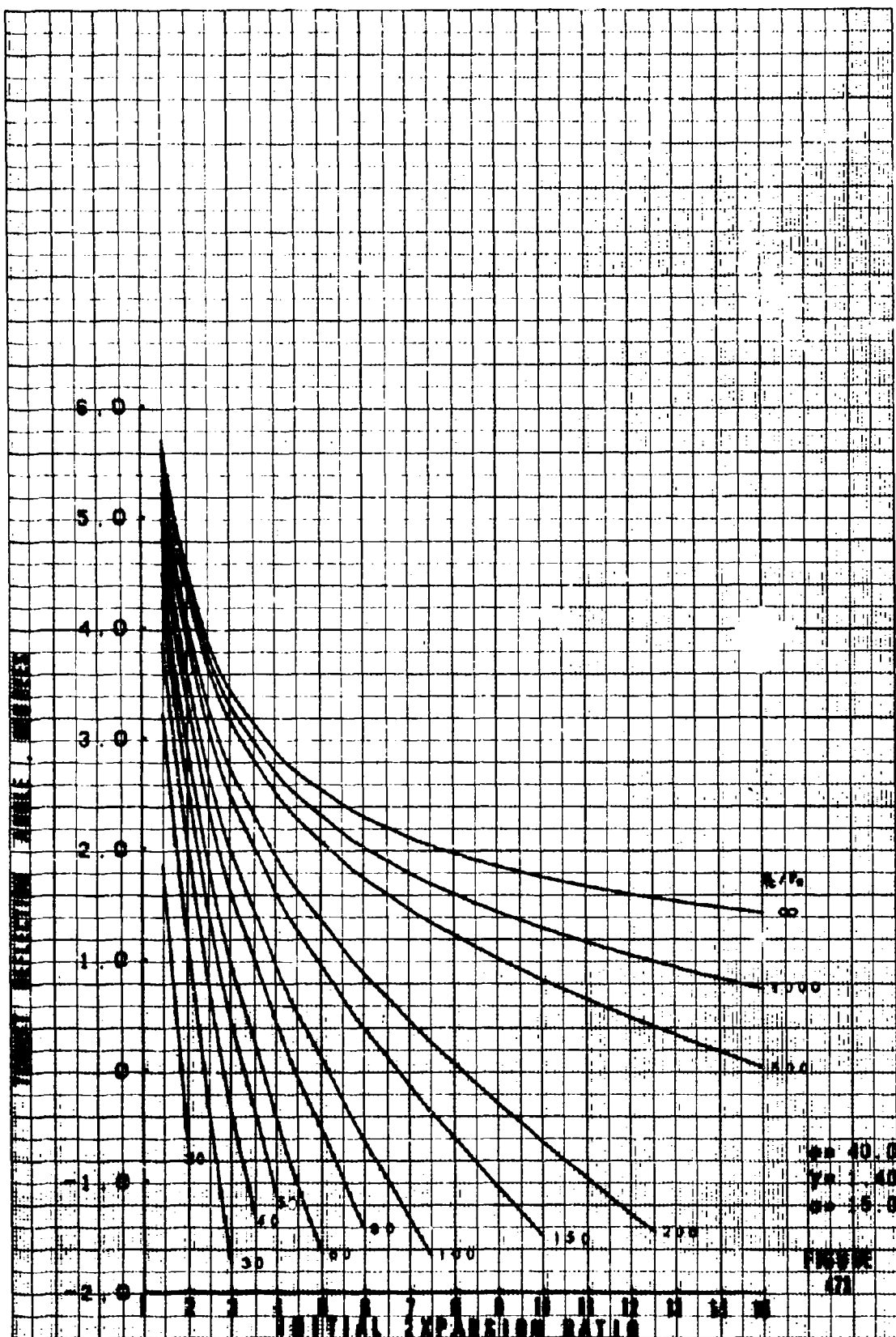


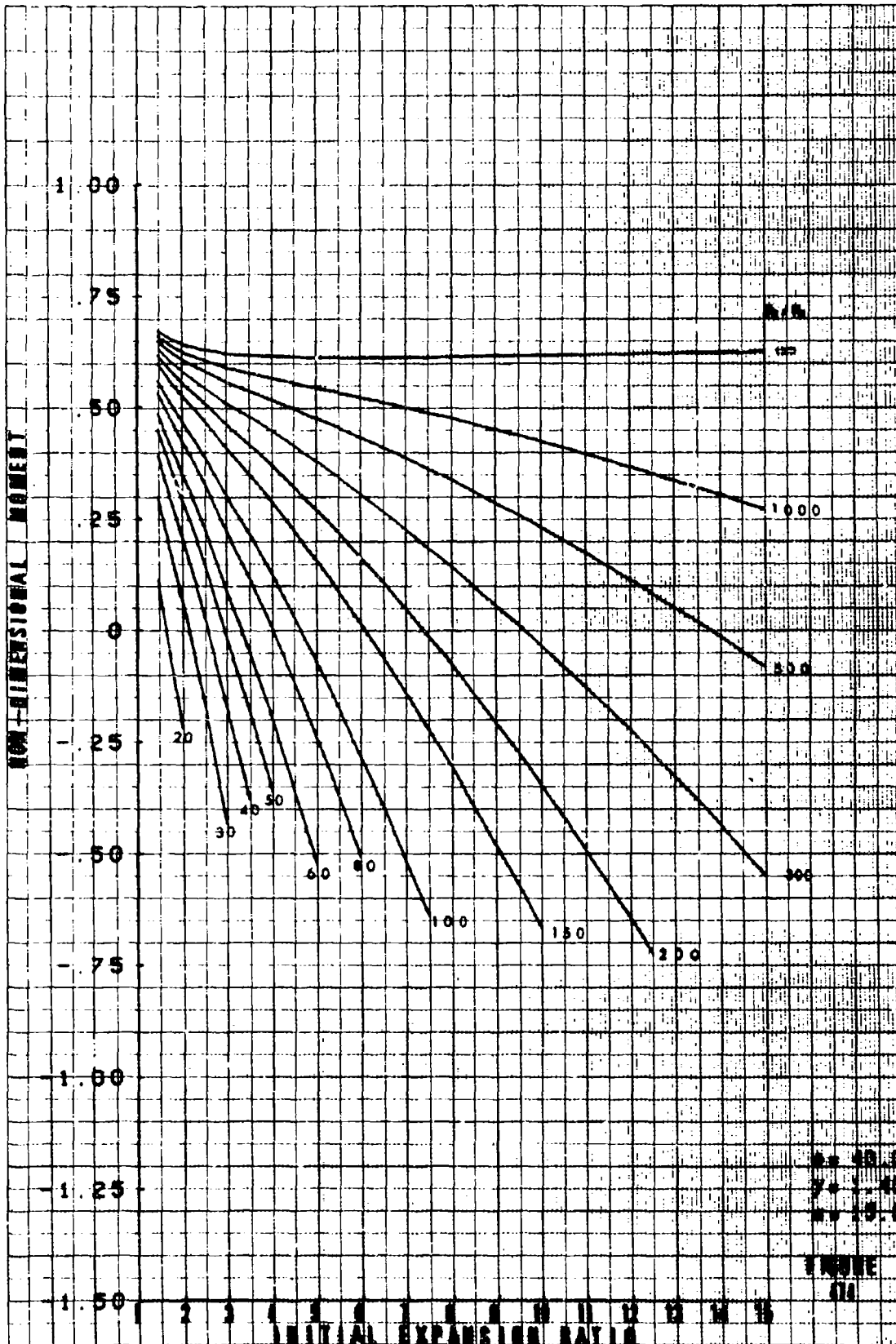
30.0  
 40  
 50.0

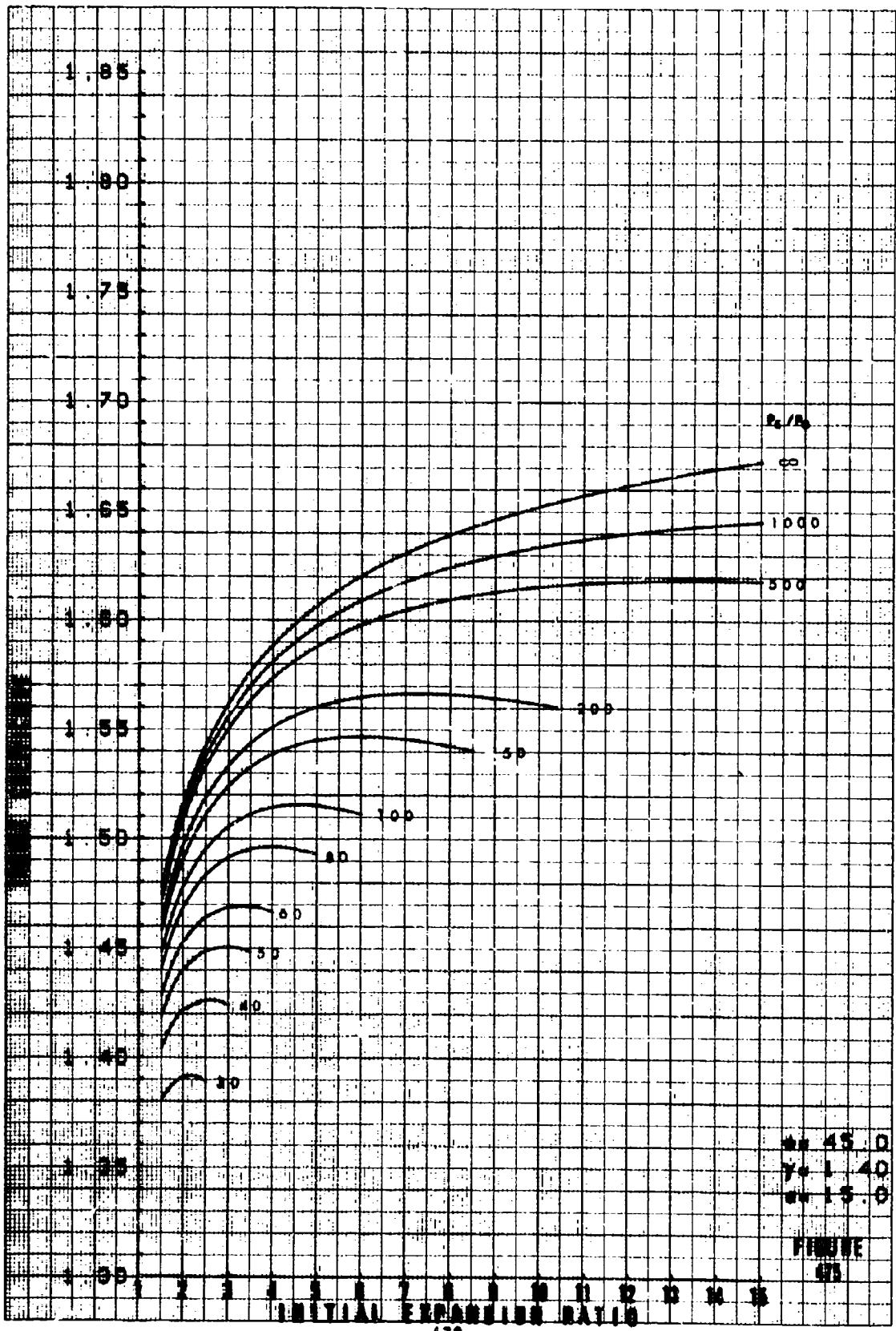
FIGURE 47

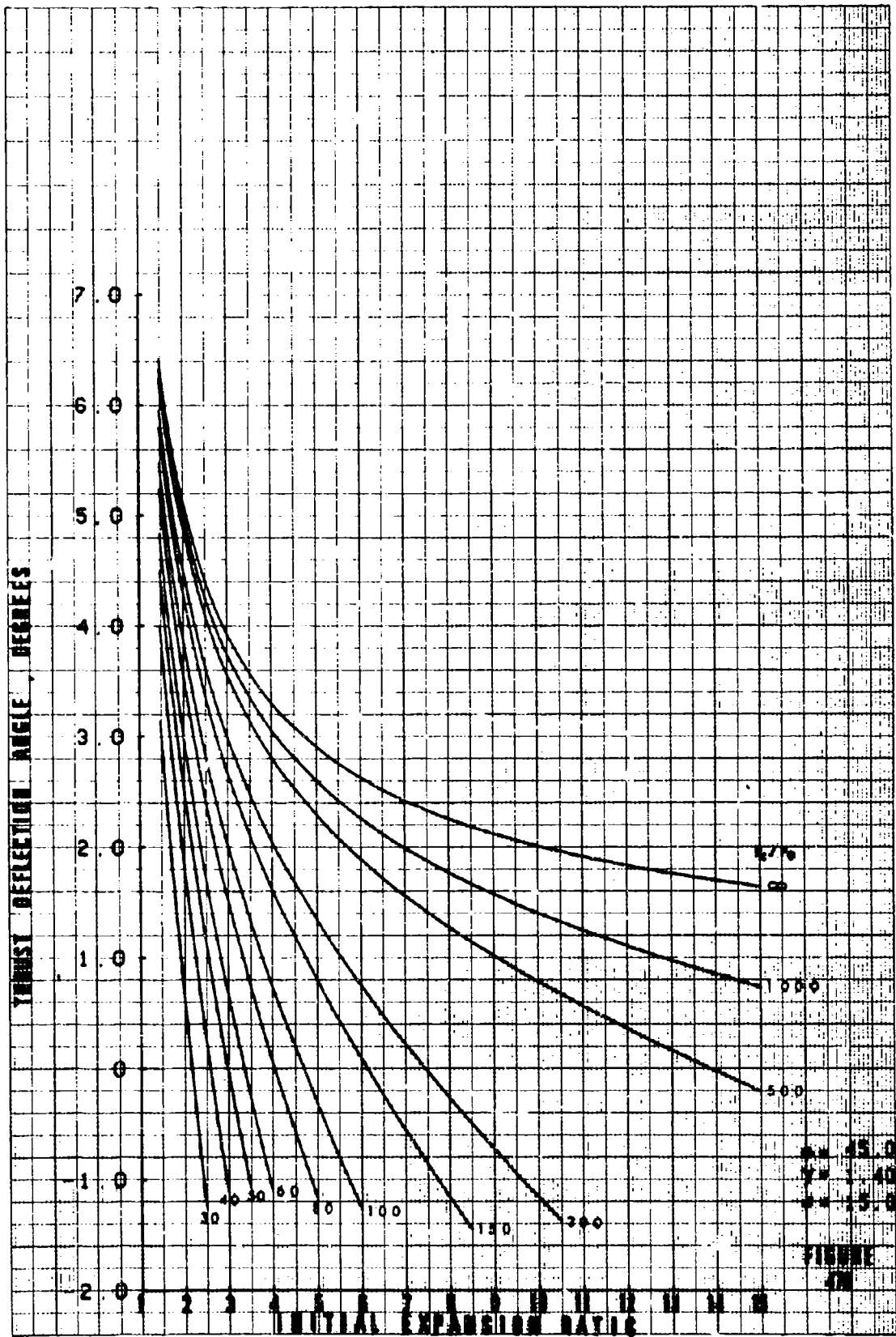




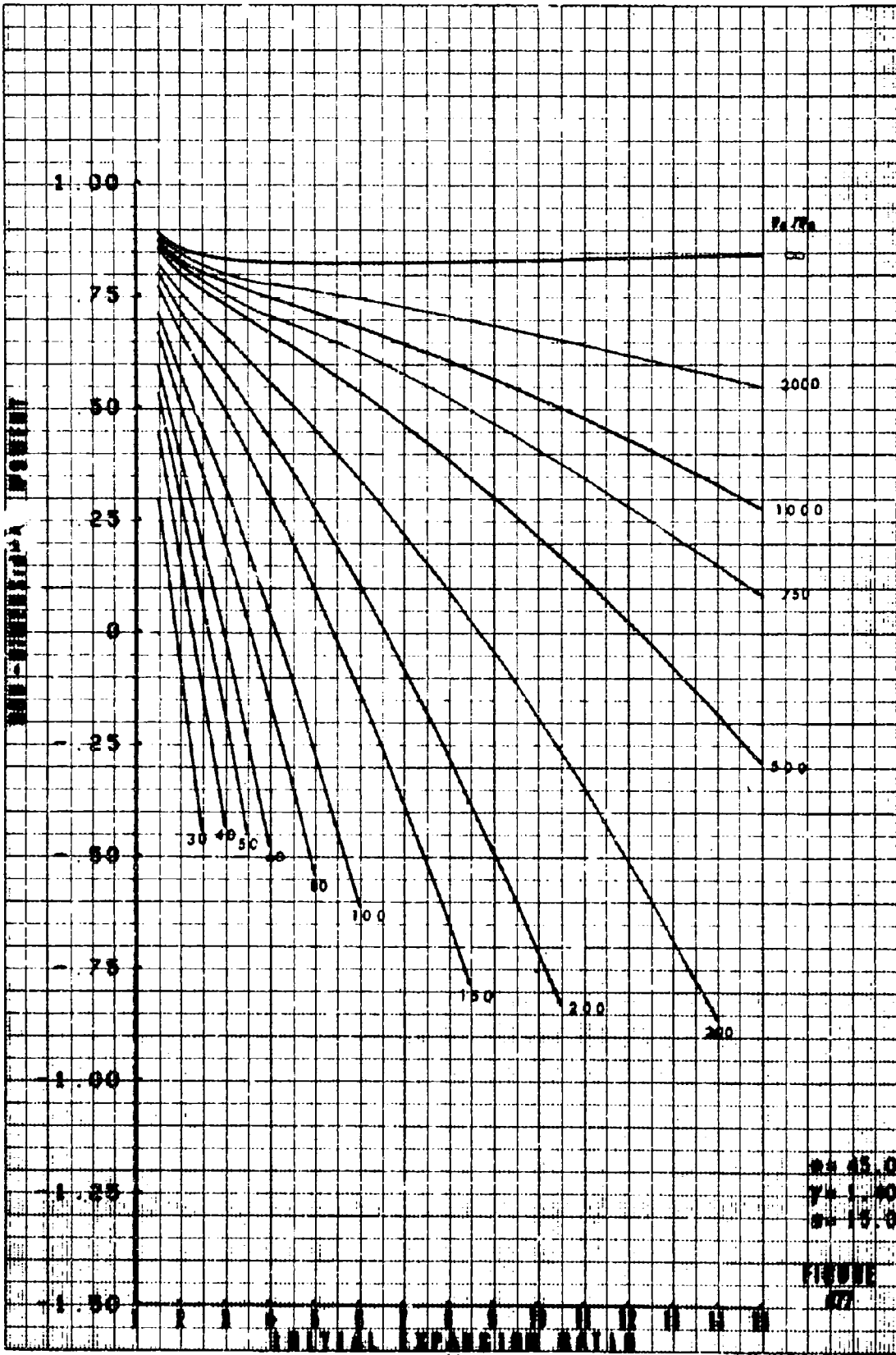








$\gamma = 1.4$   
 $\gamma = 1.67$   
 $\gamma = 1.33$   
 FIGURE 27



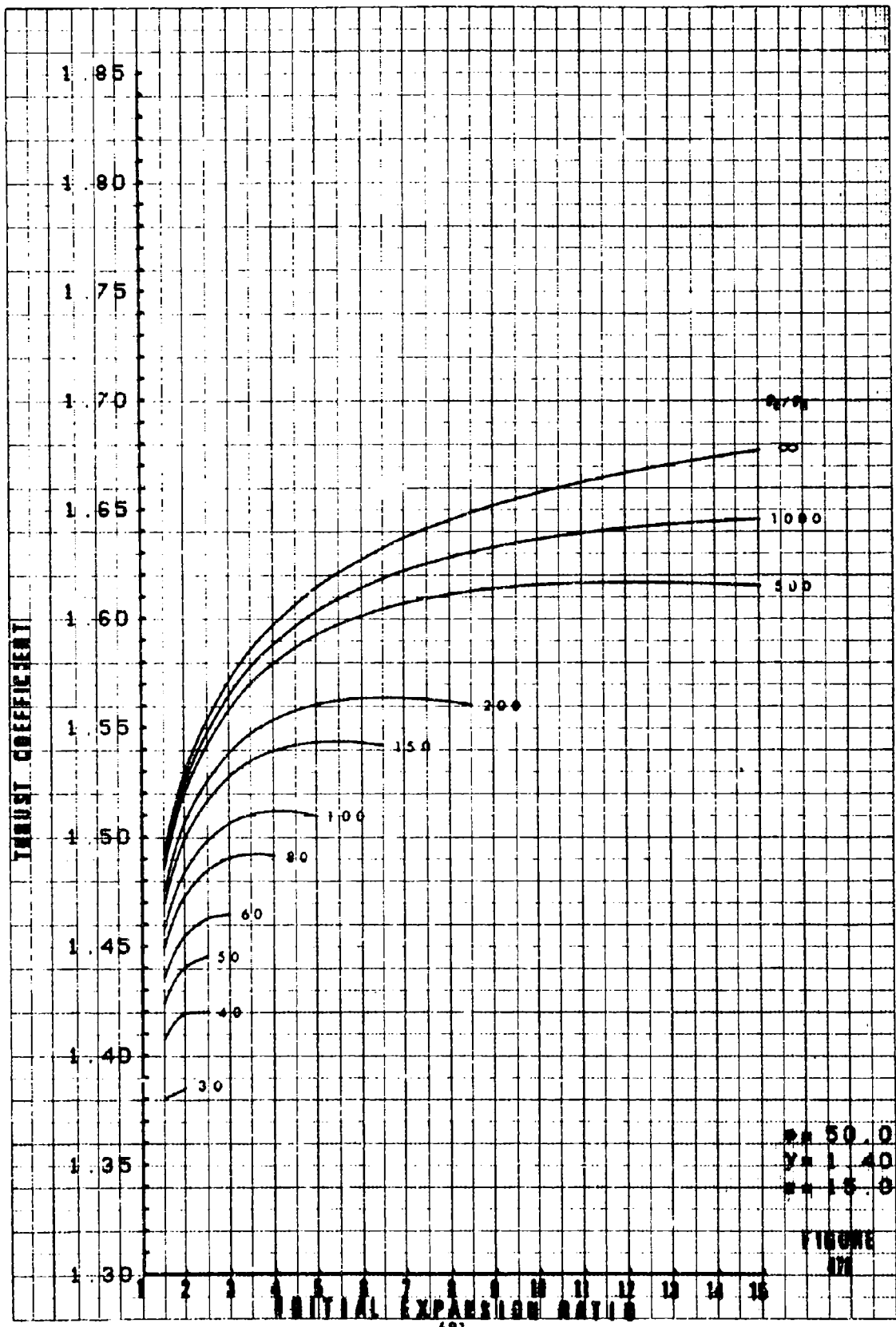


FIGURE 171

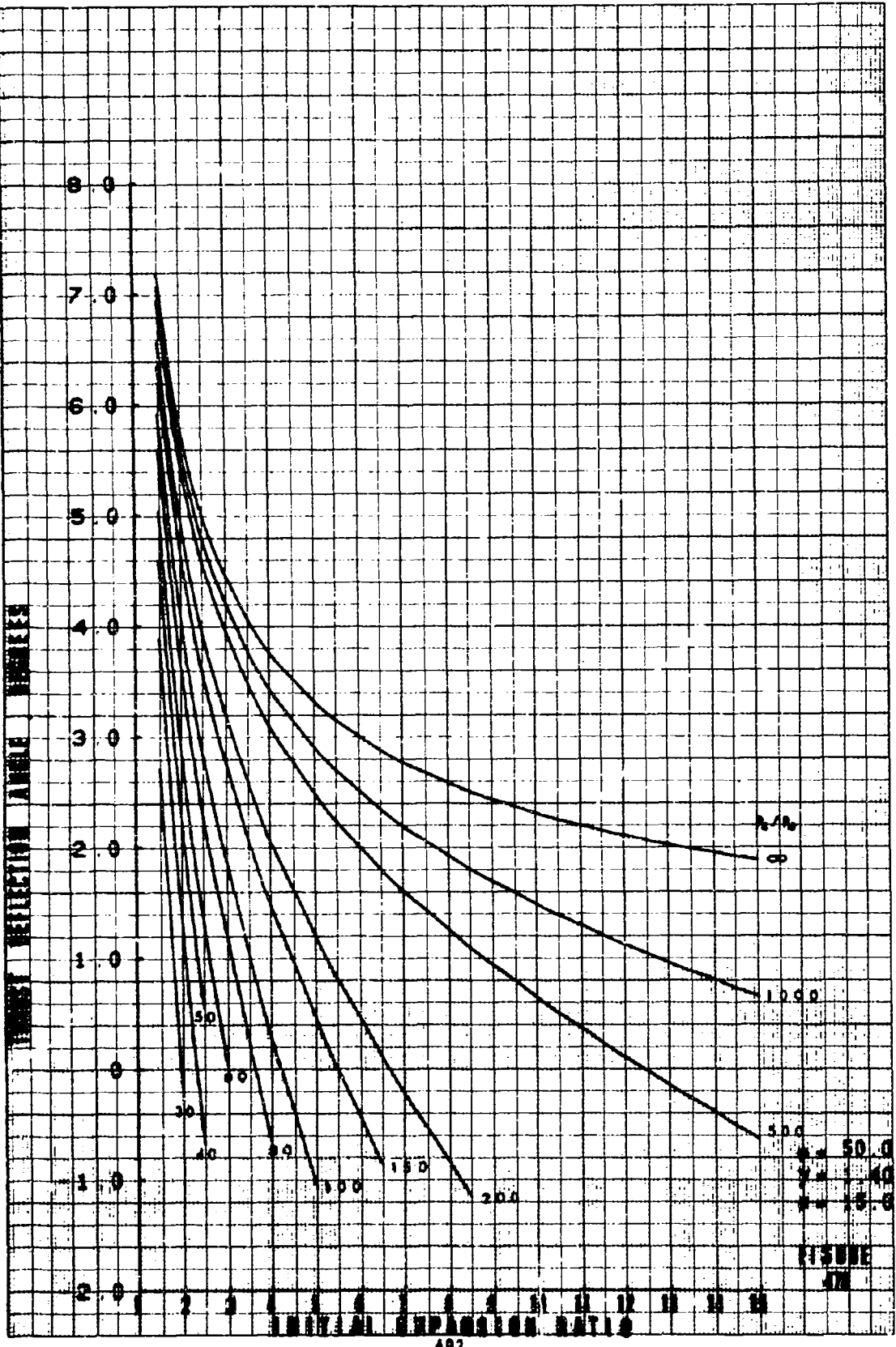


FIGURE 47



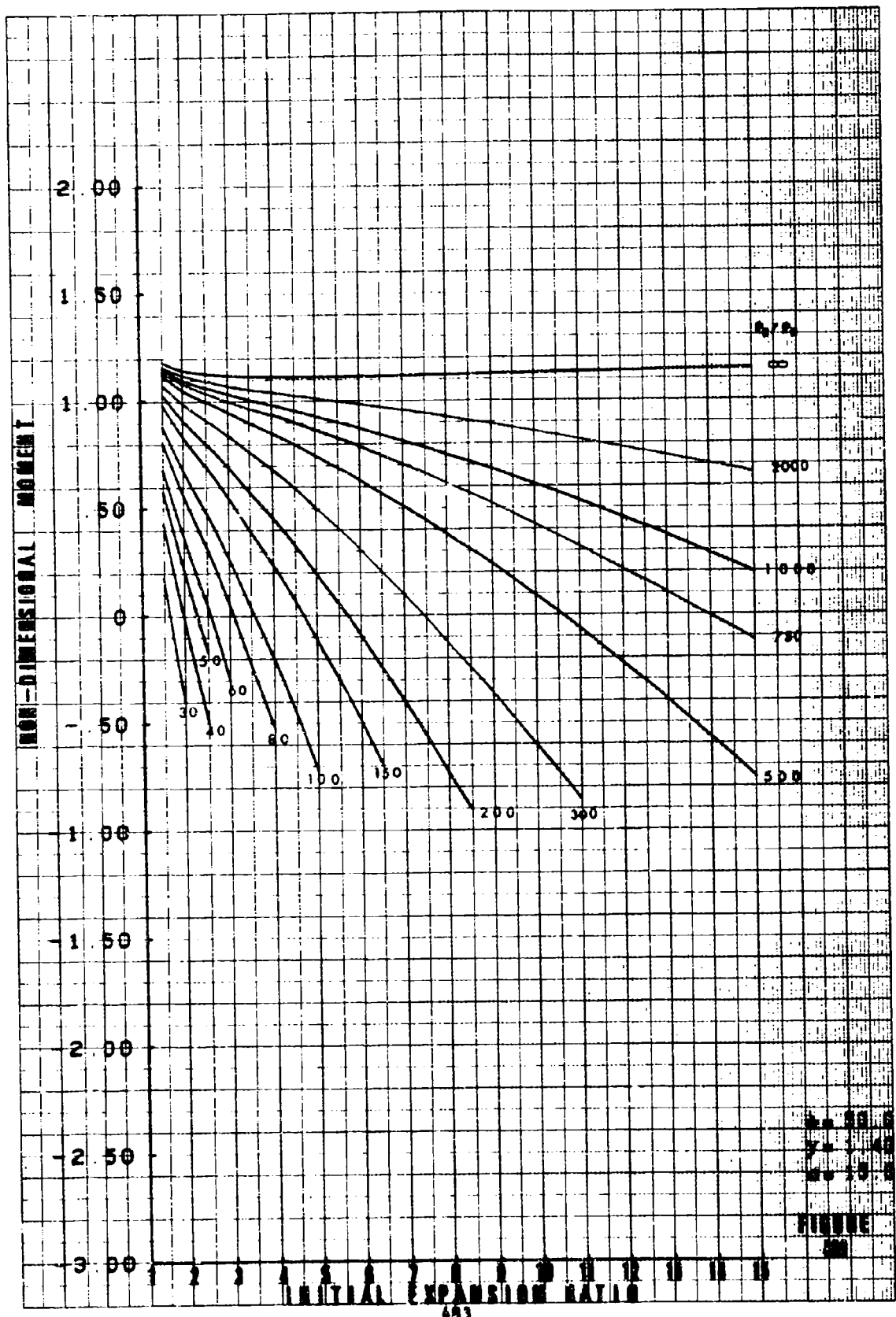
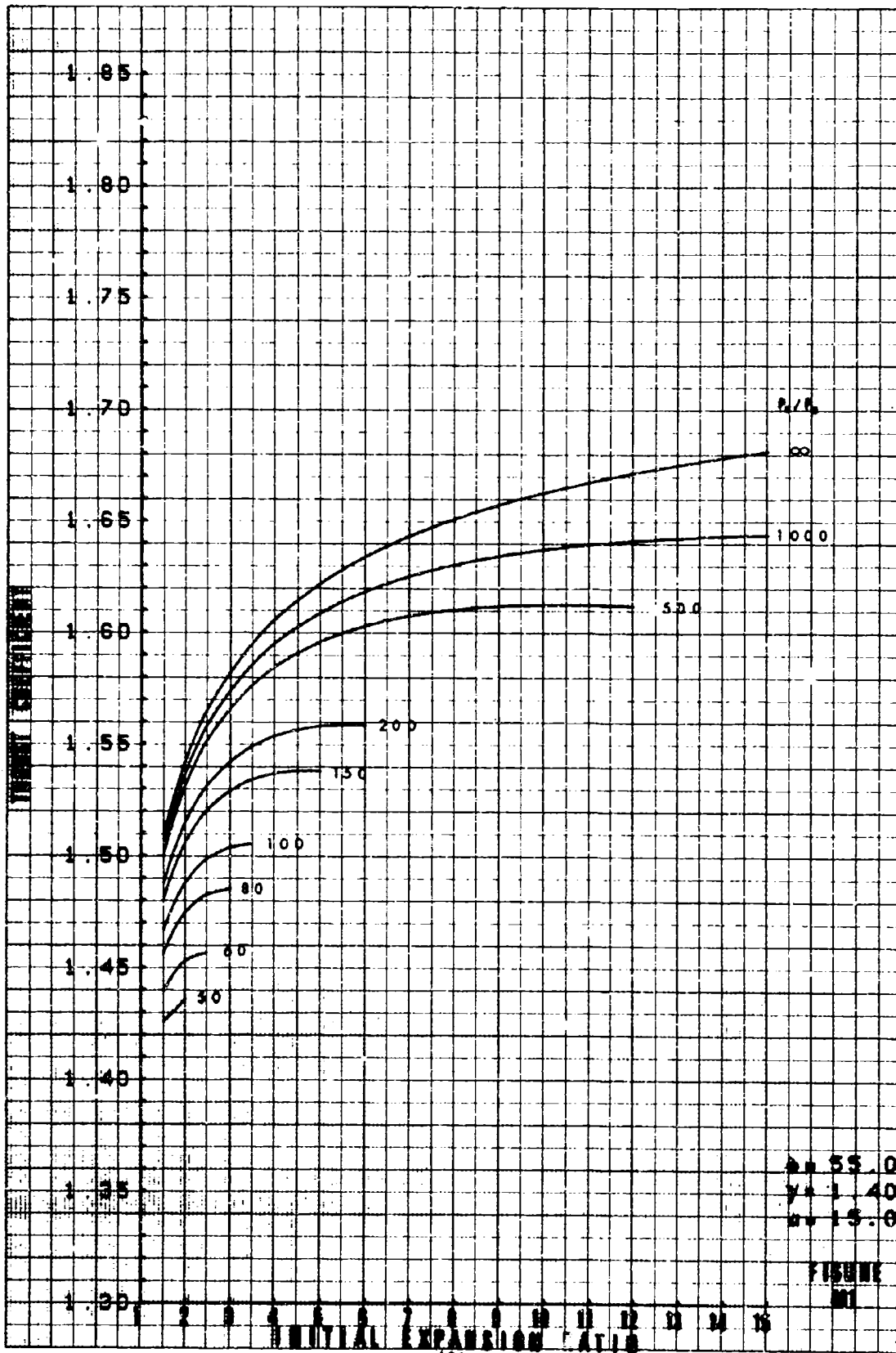
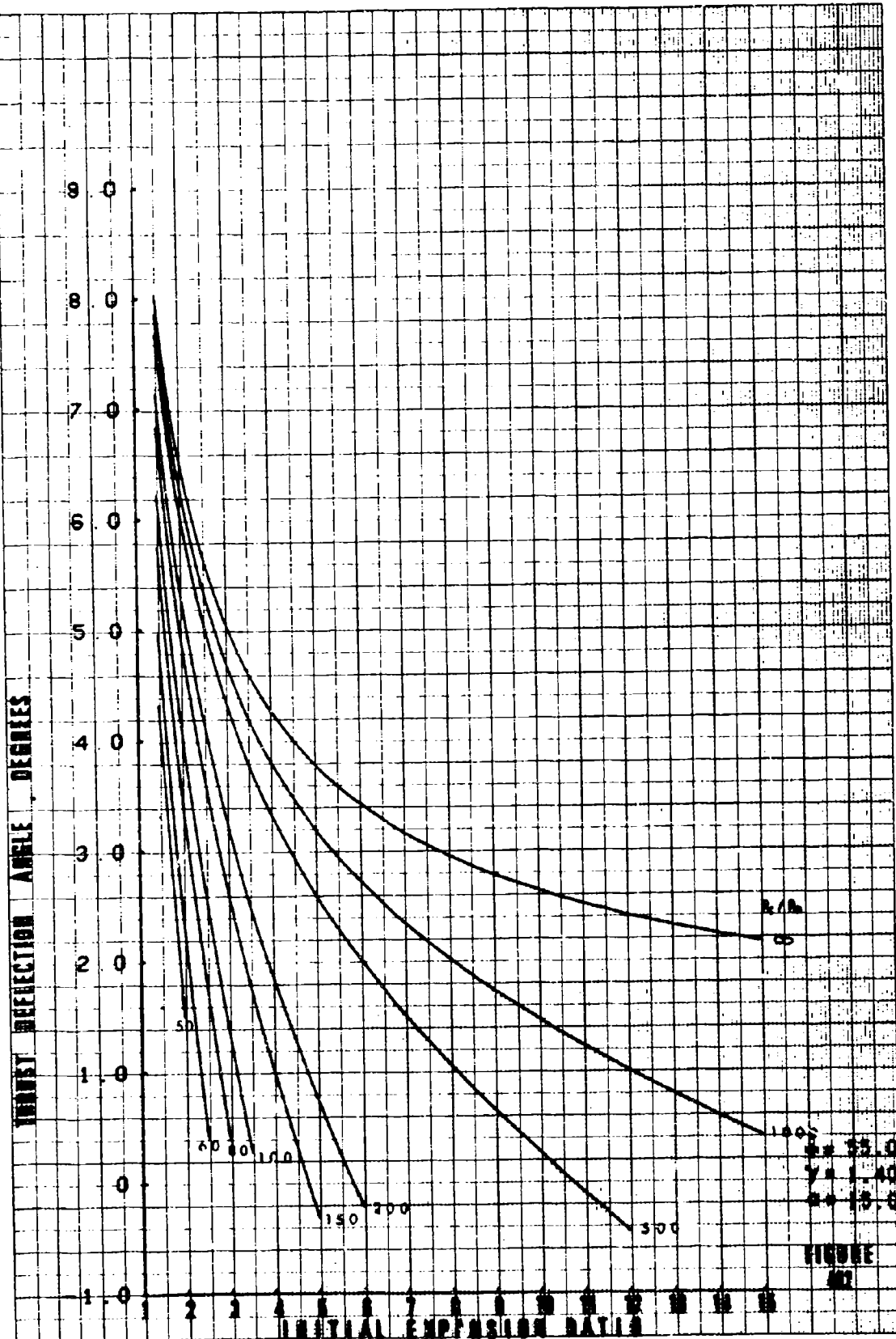


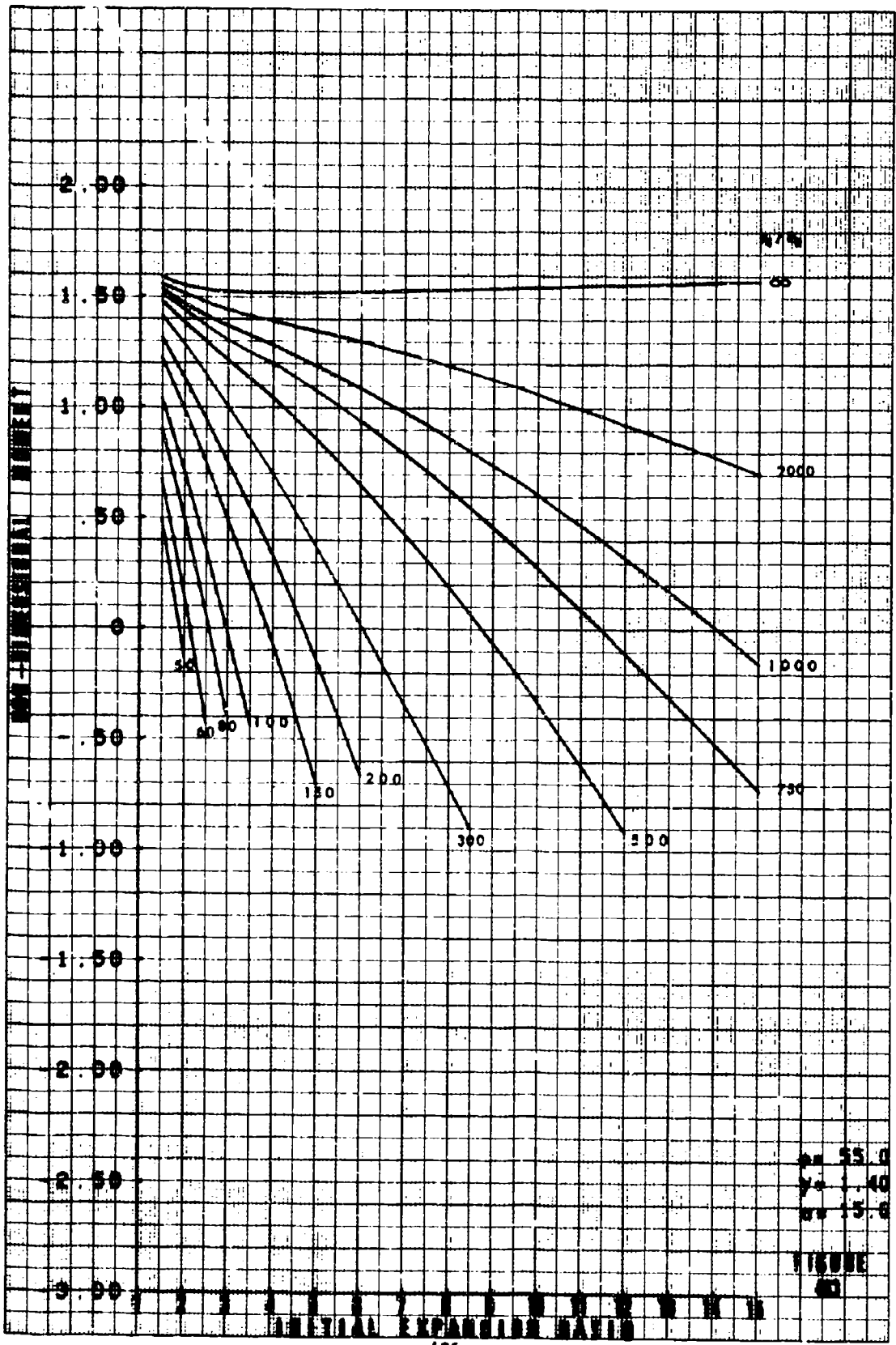
FIGURE 2



x = 55.0  
y = 1.40  
z = 15.0

FIGURE  
MI





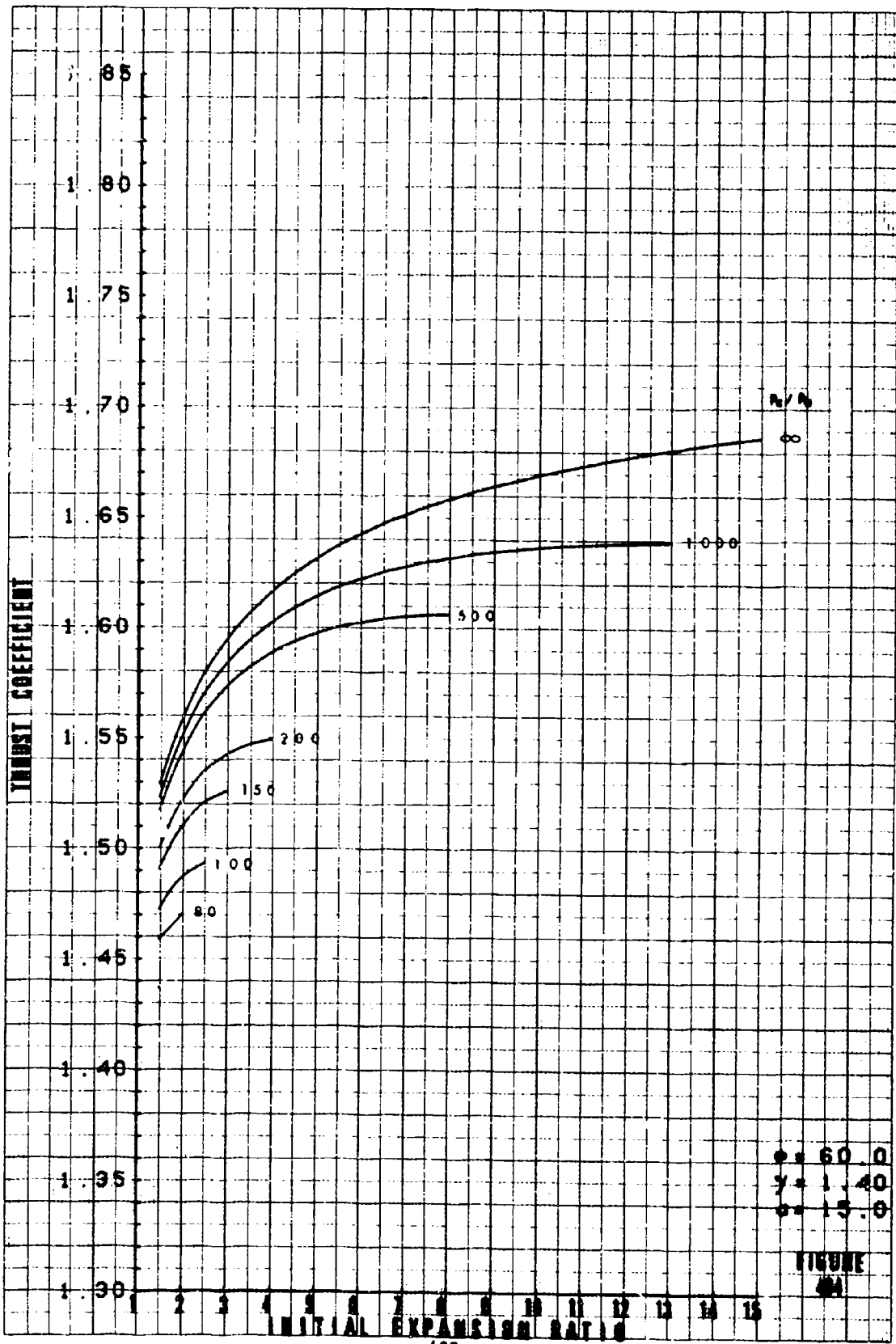
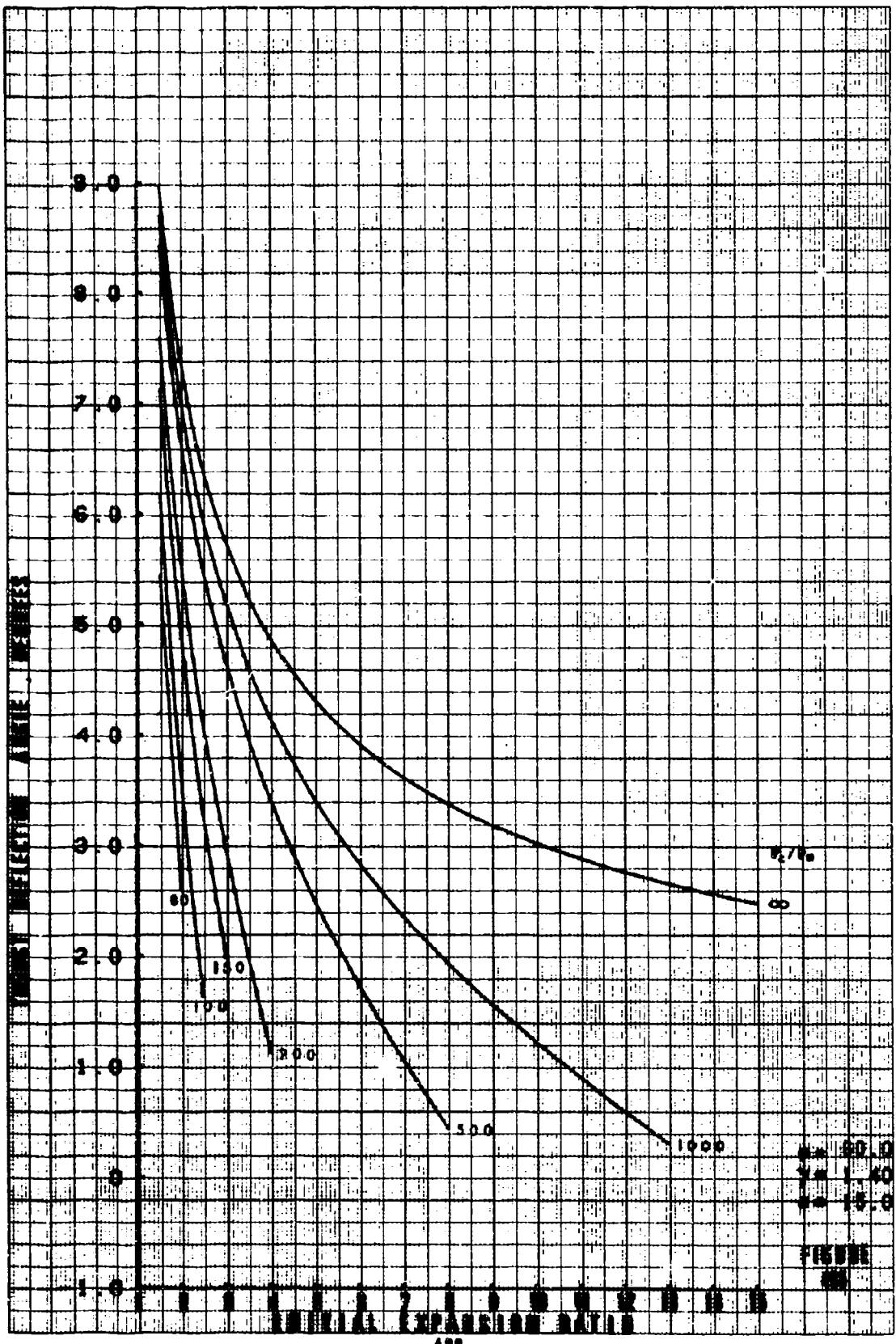
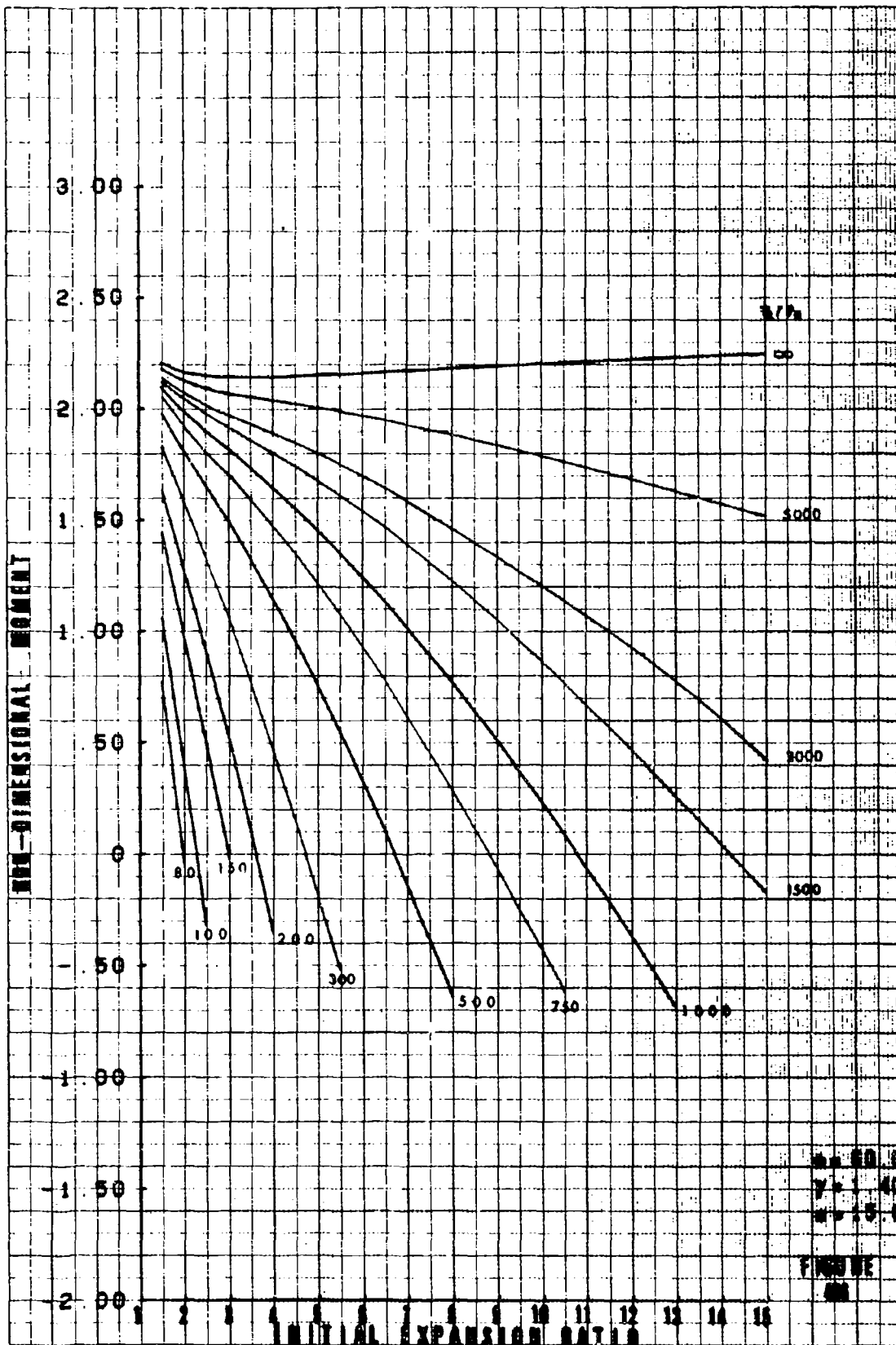
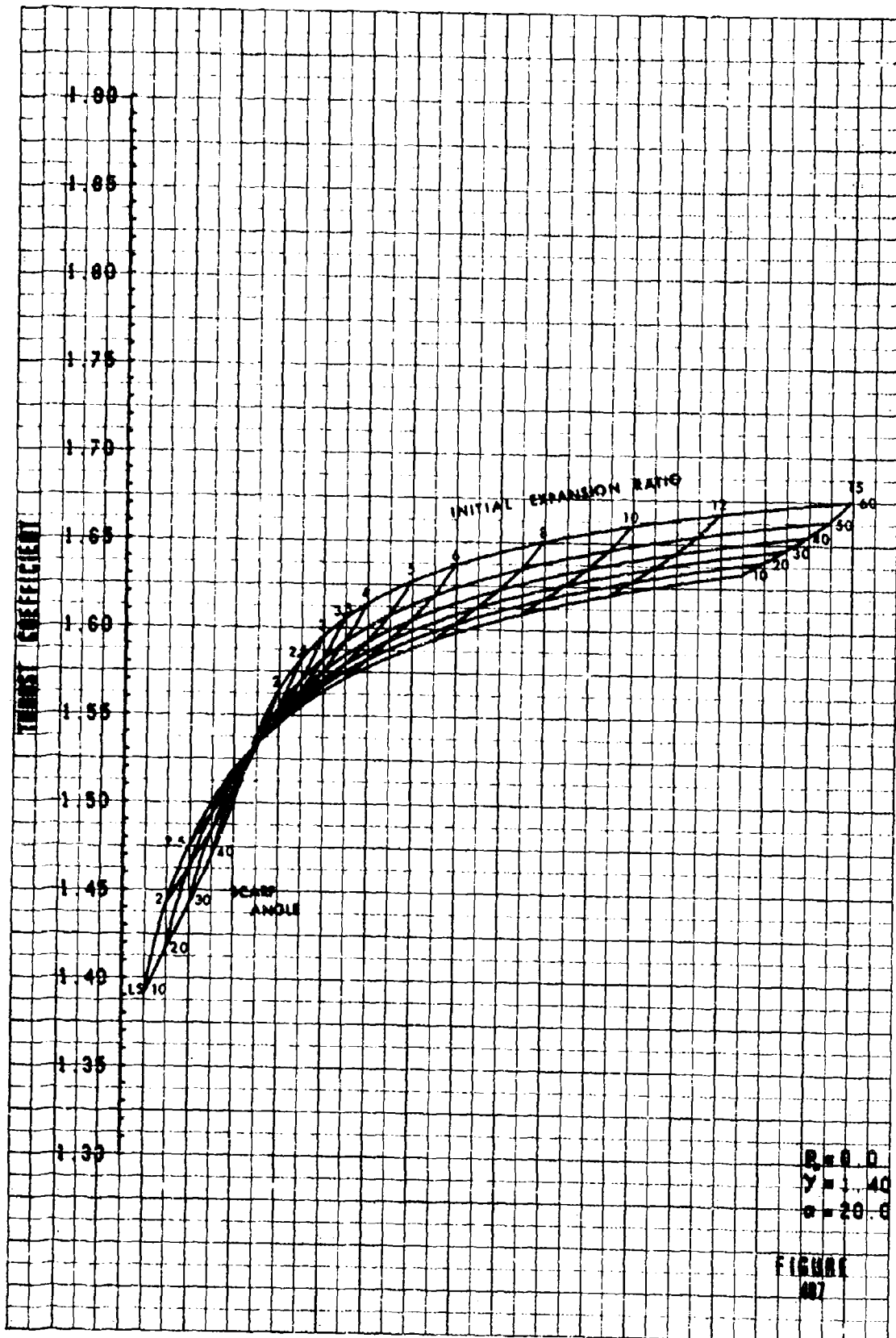


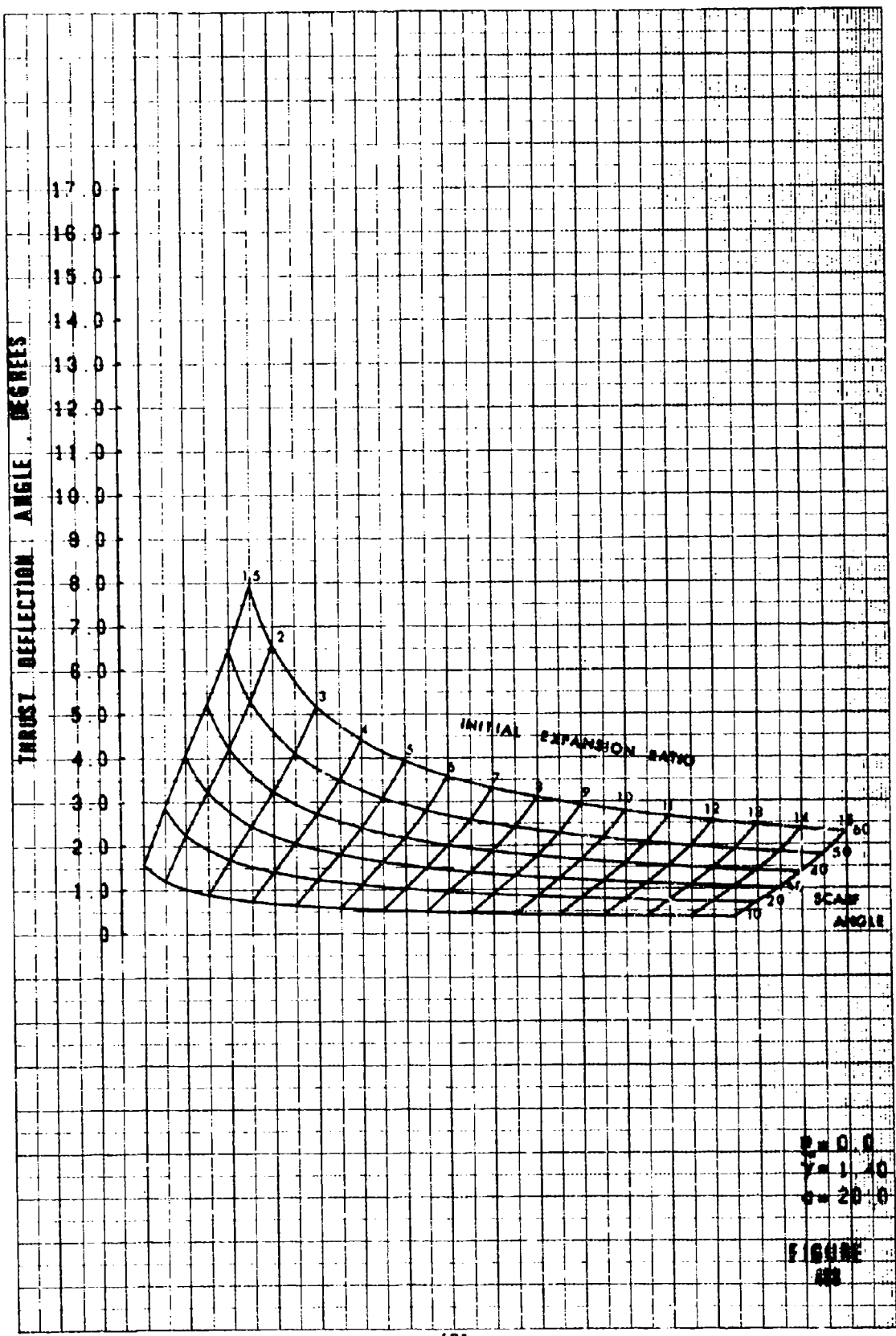
FIGURE 44

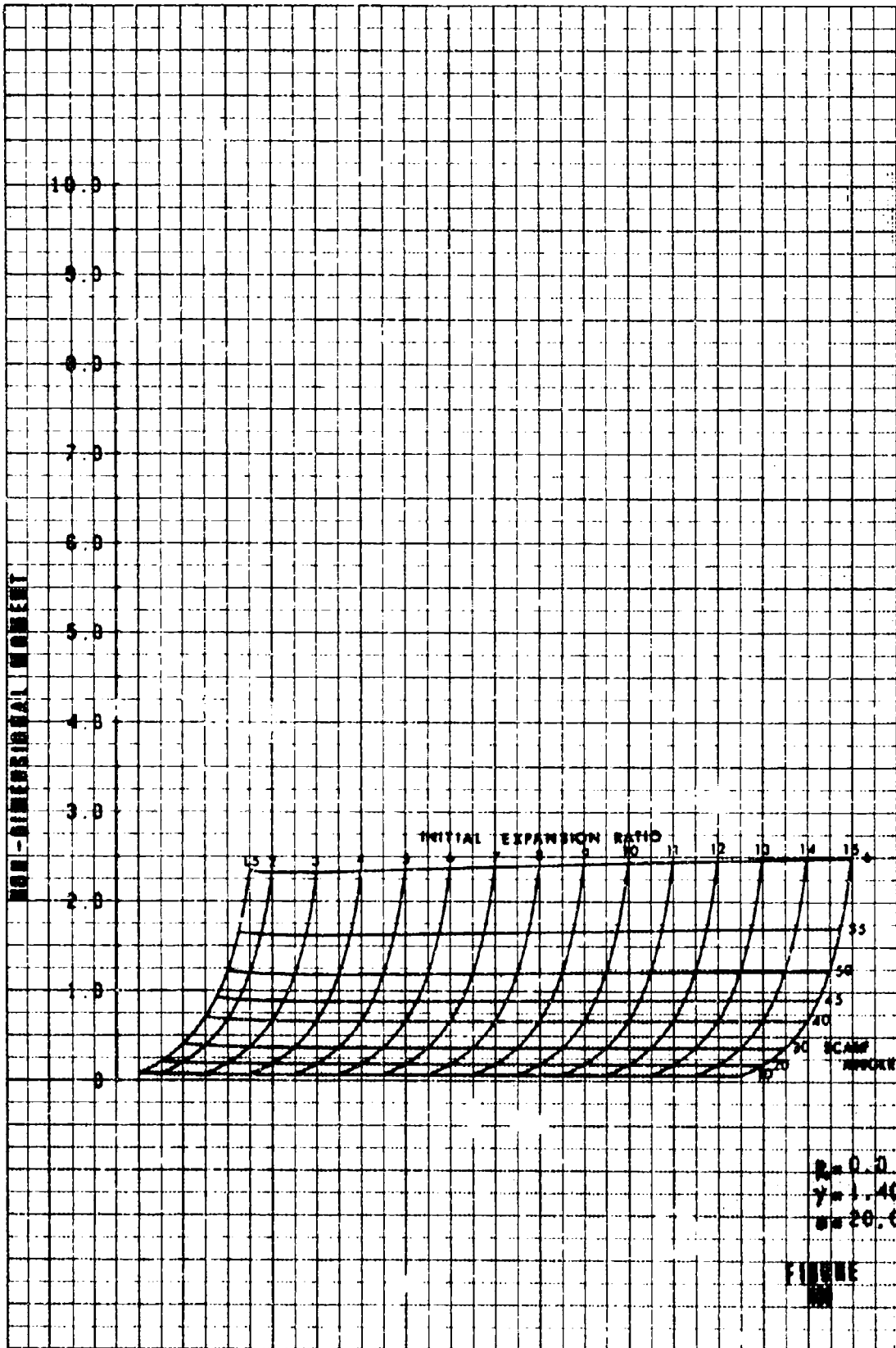


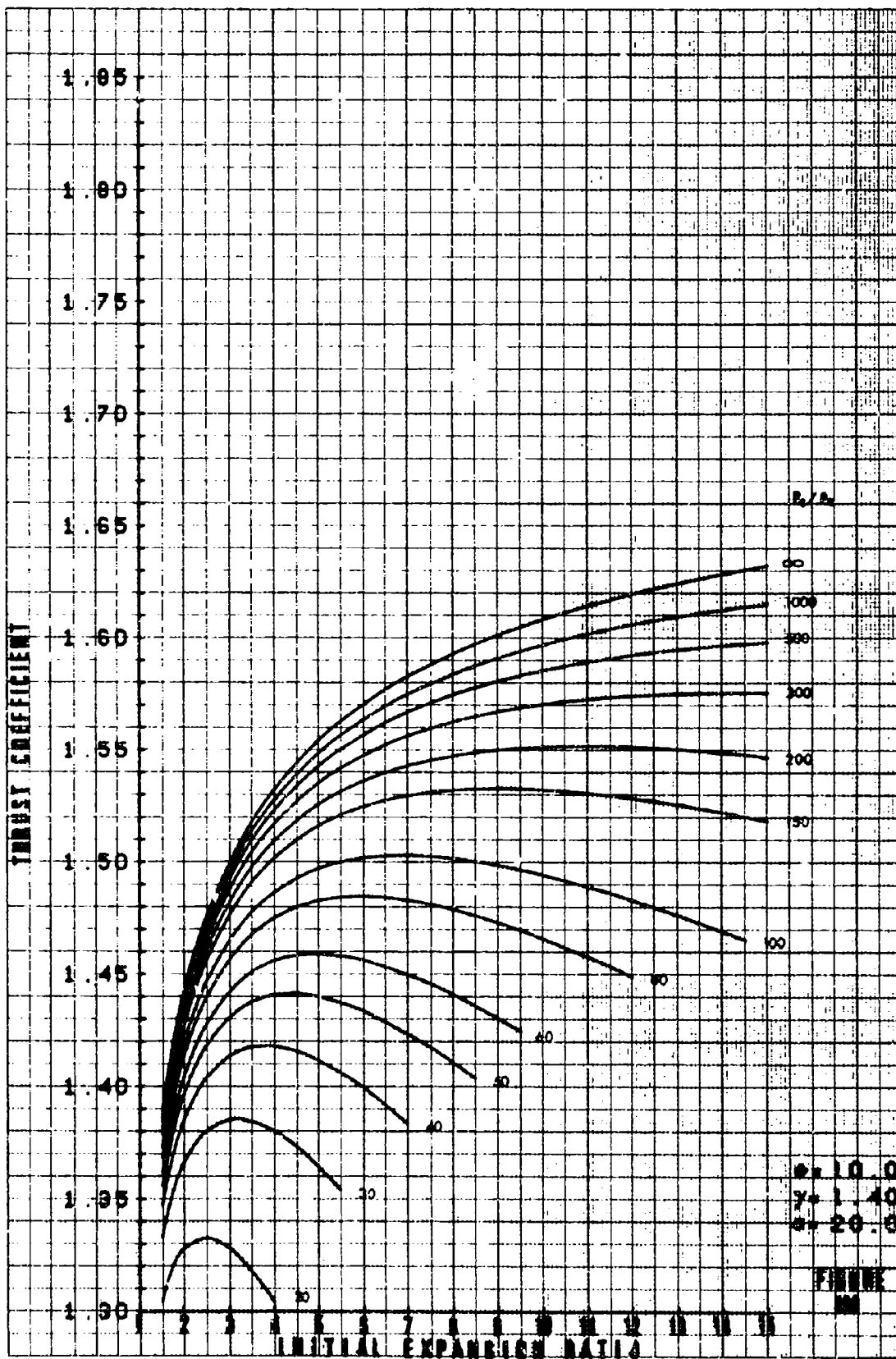


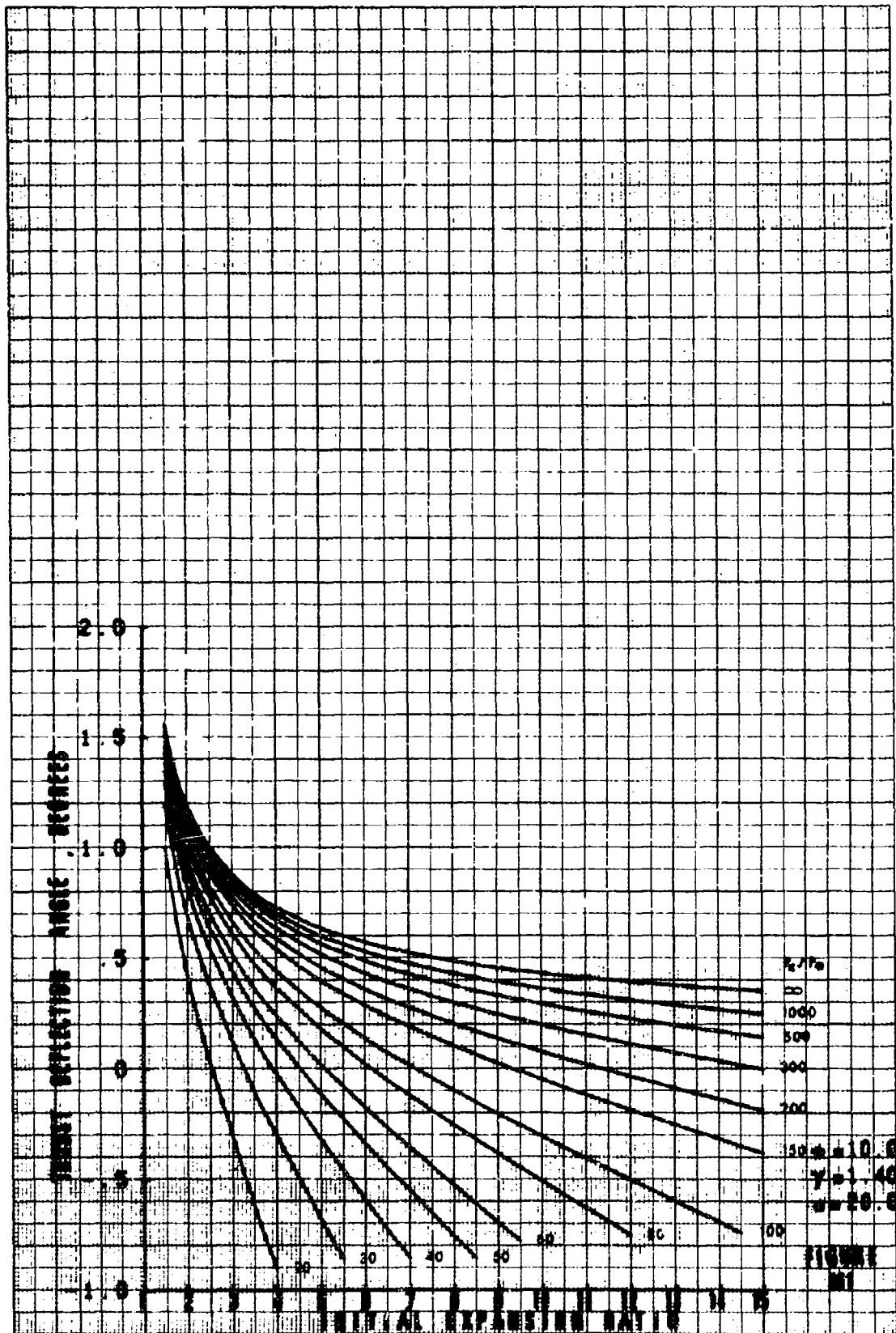


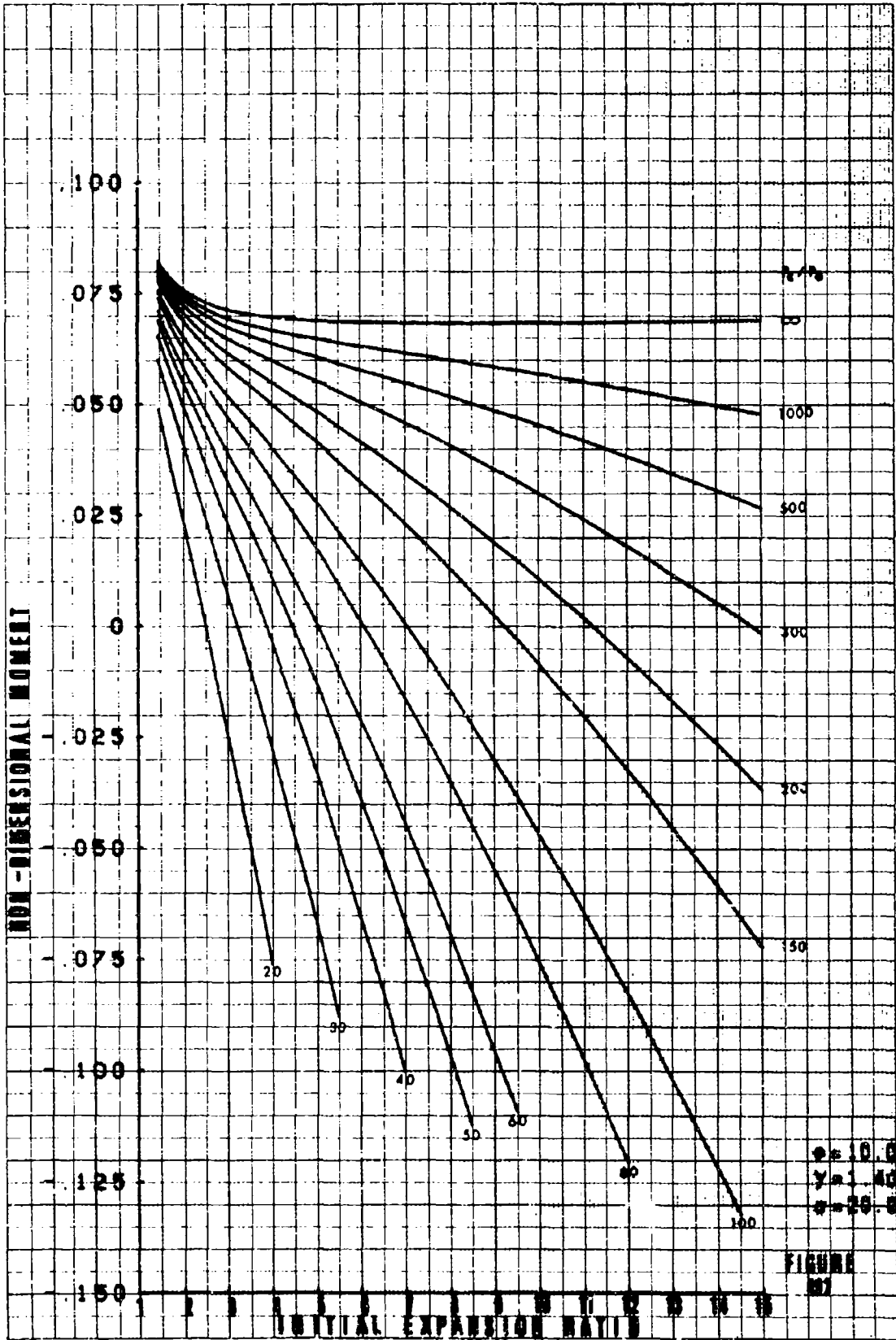












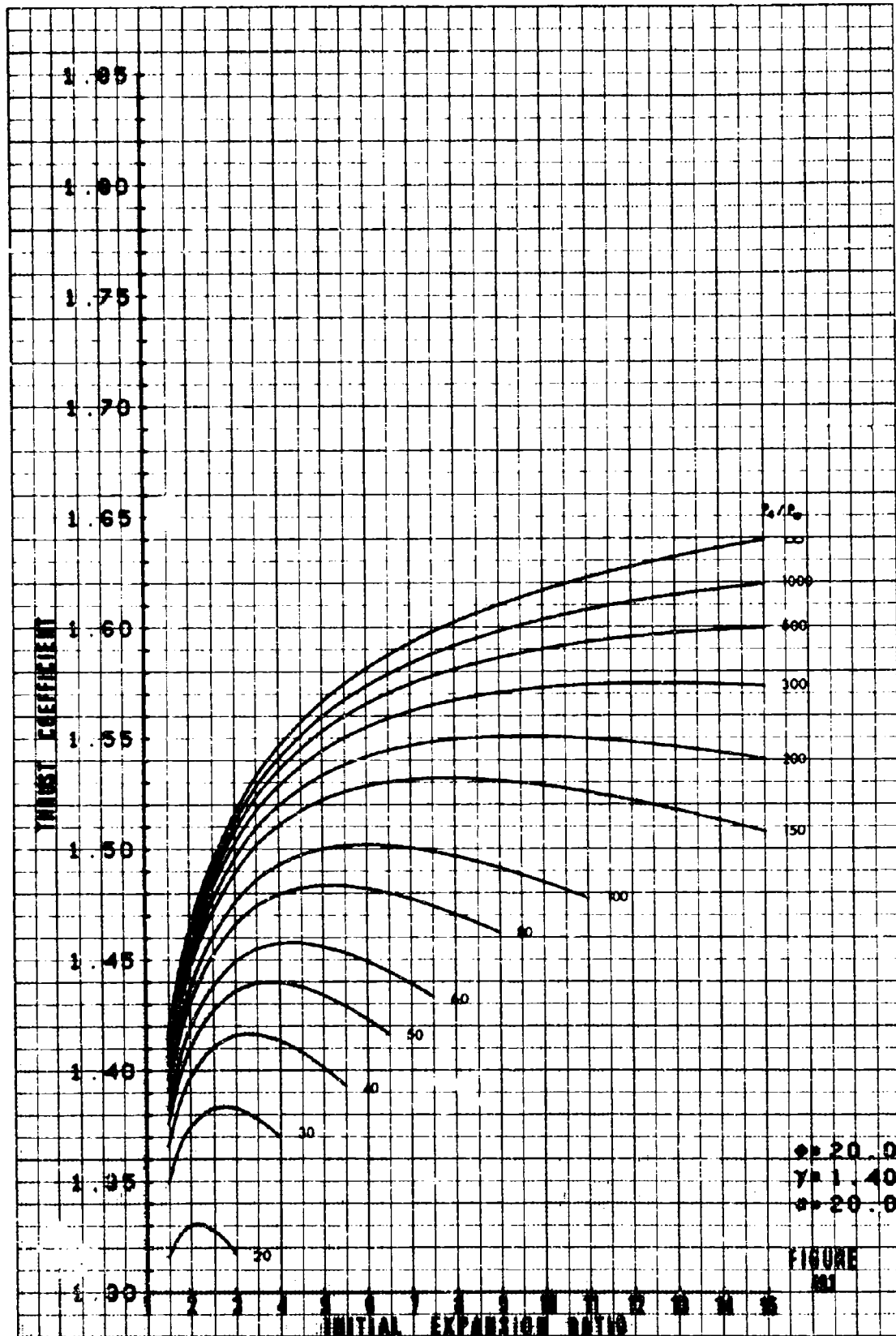
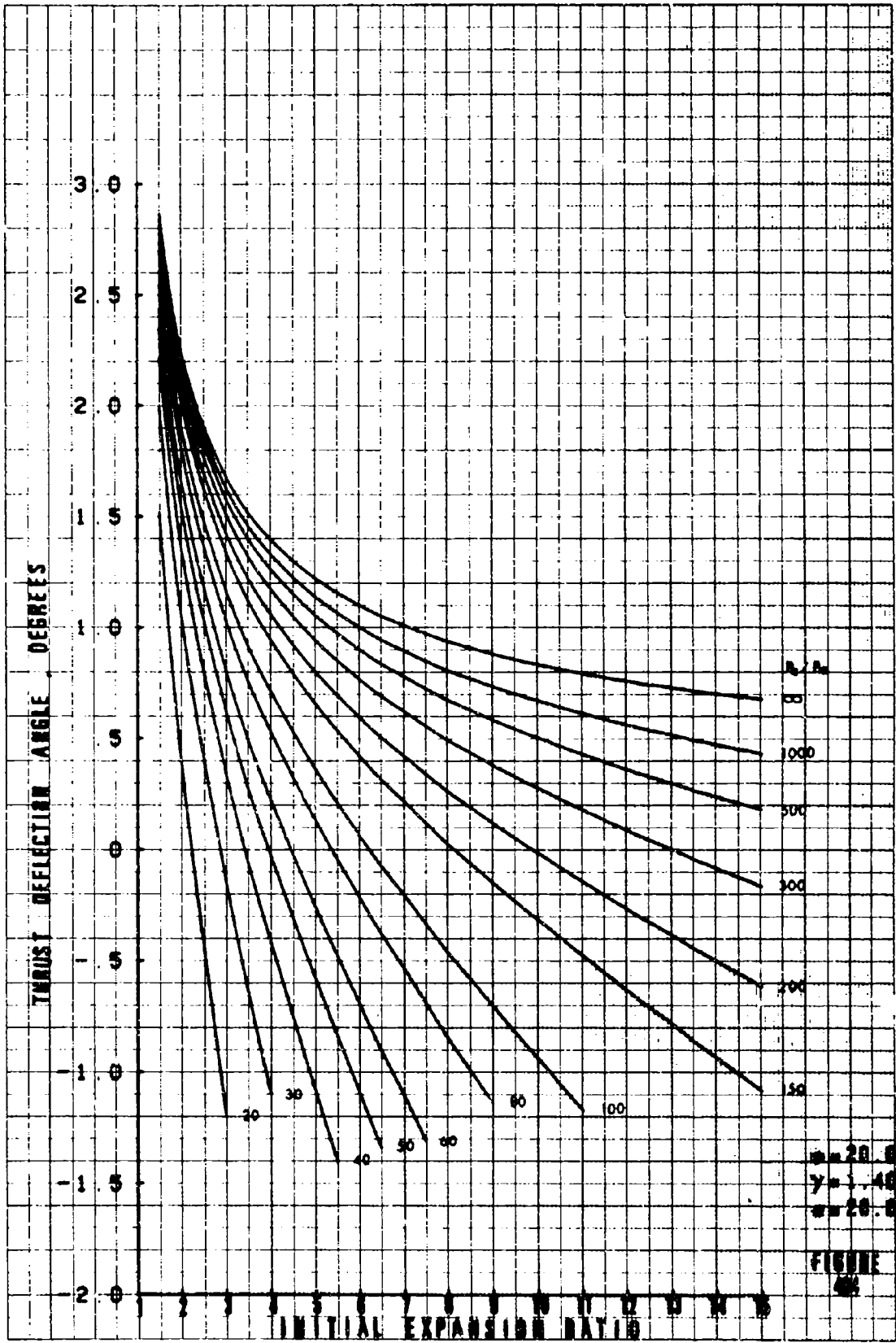
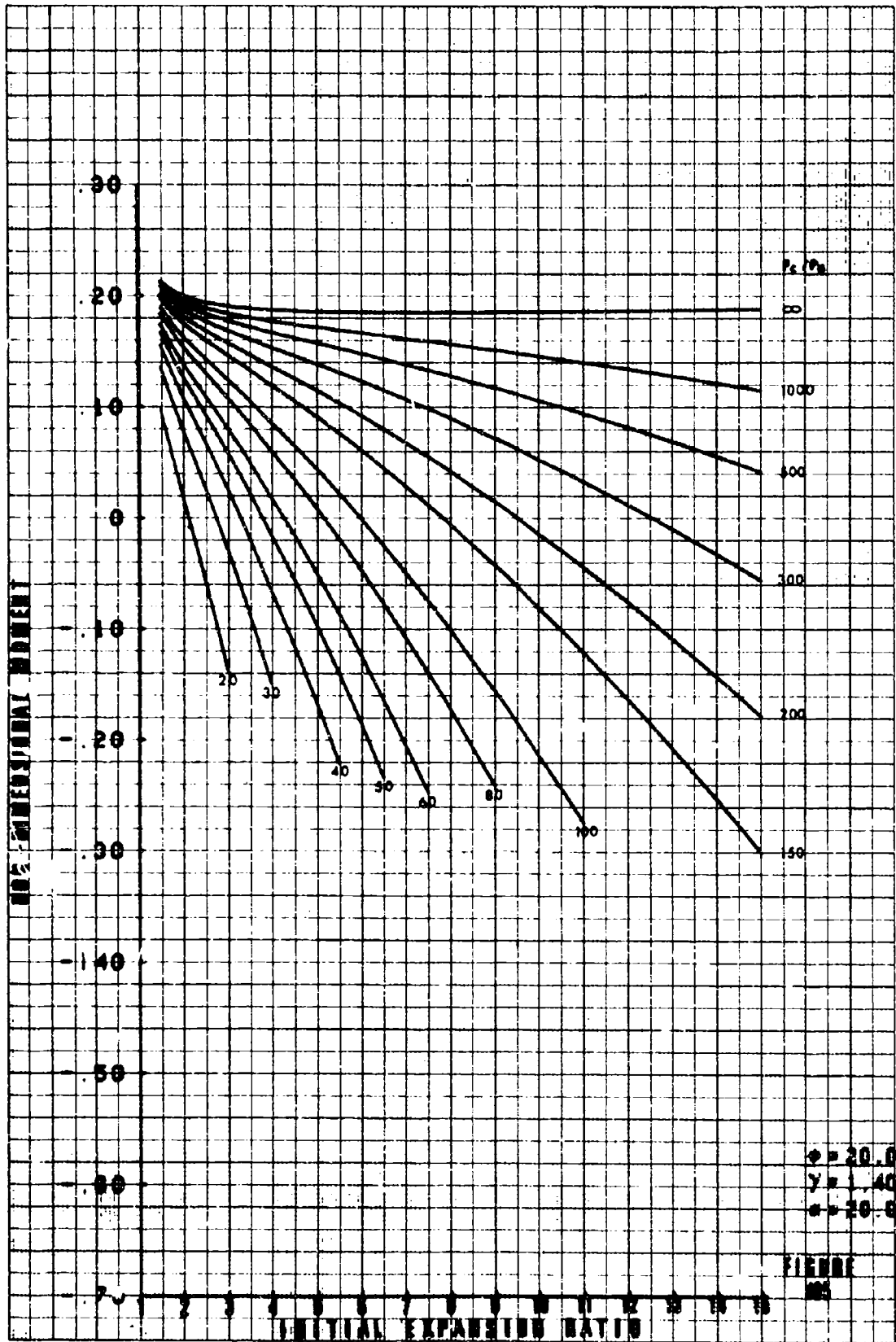


FIGURE 81

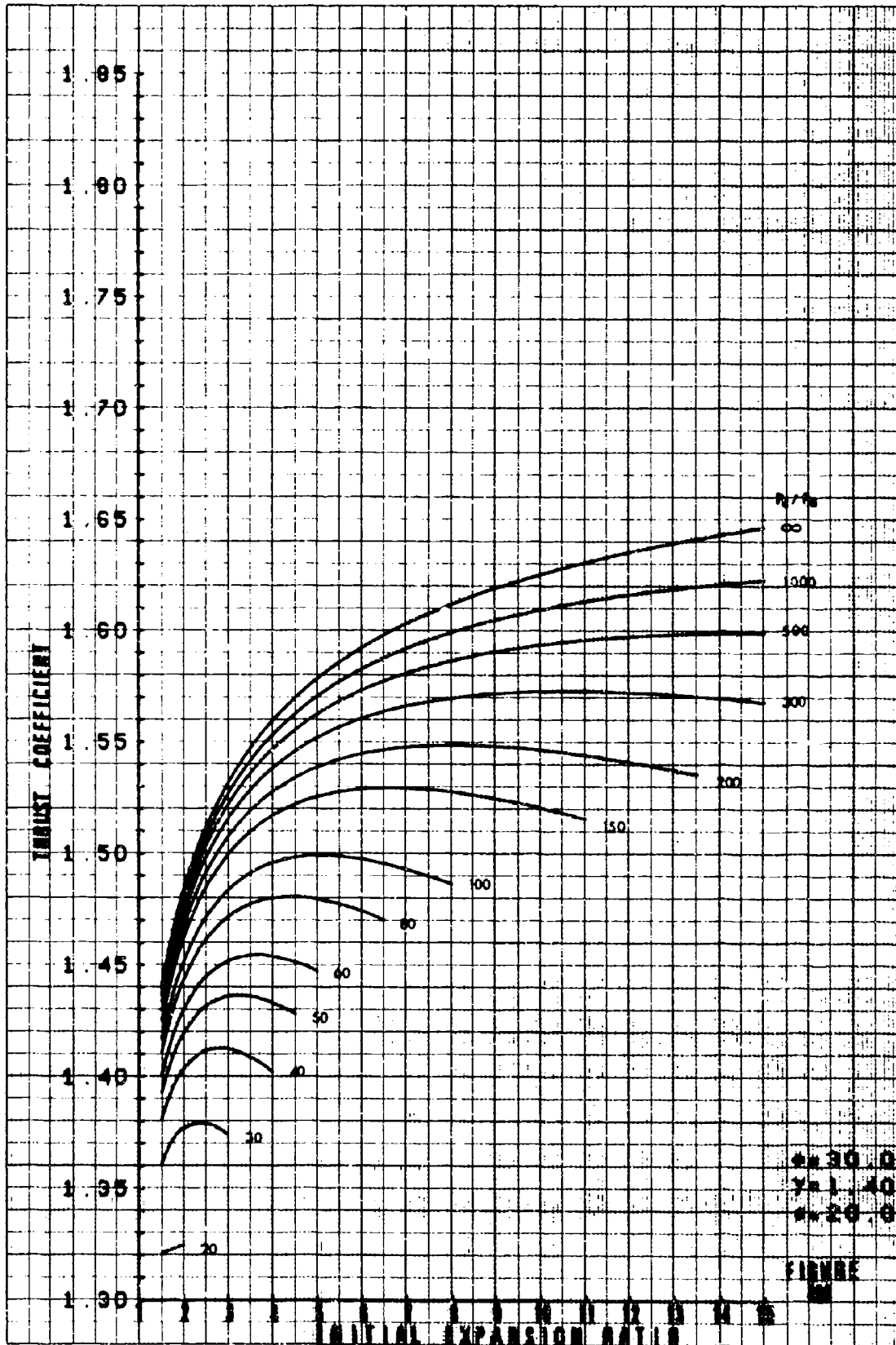


$\mu = 20.8$   
 $\gamma = 1.48$   
 $\mu = 20.8$

FIGURE 2







$\phi = 30.0$   
 $\gamma = 1.40$   
 $\sigma = 20.0$

FIGURE 1

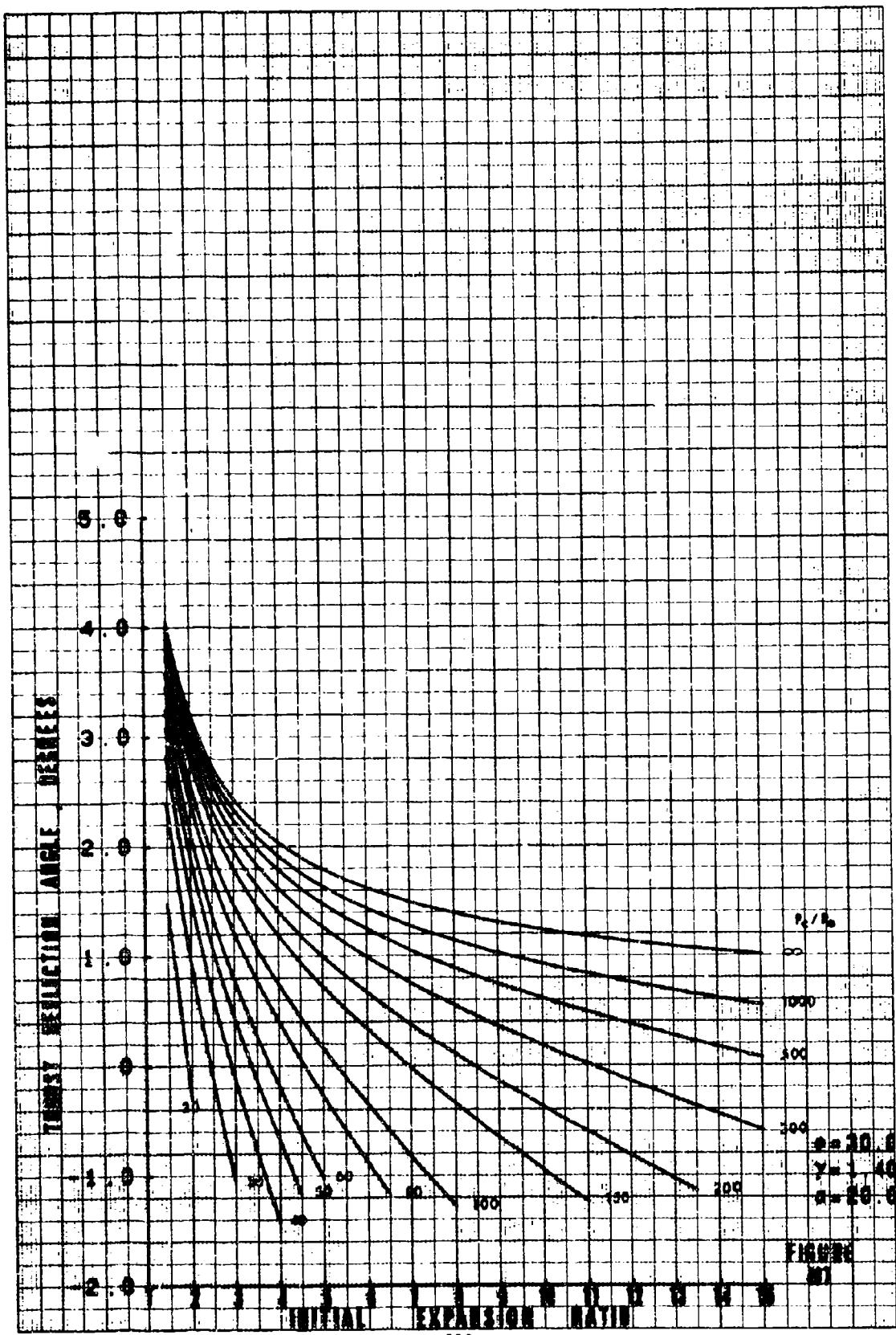
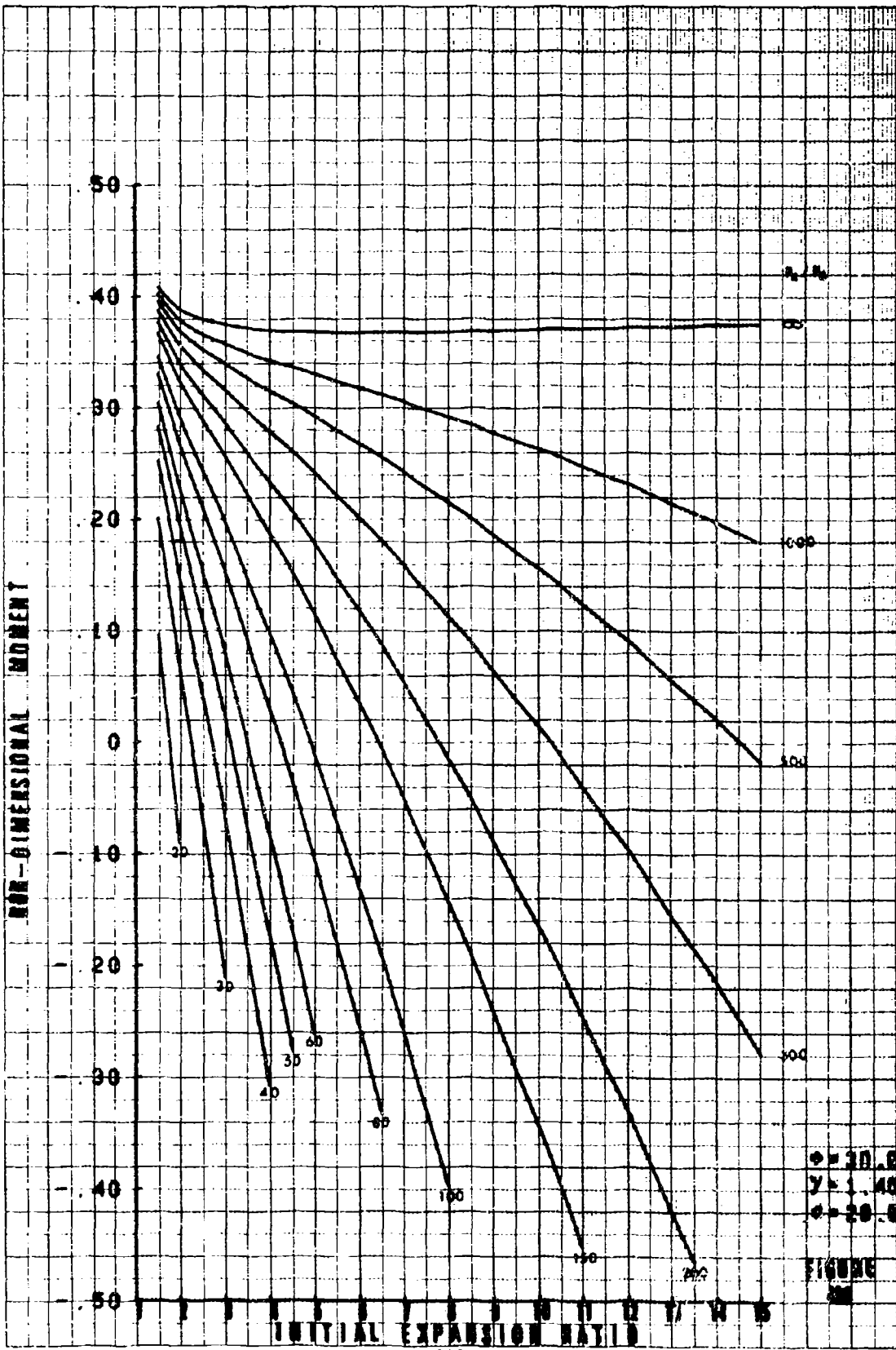


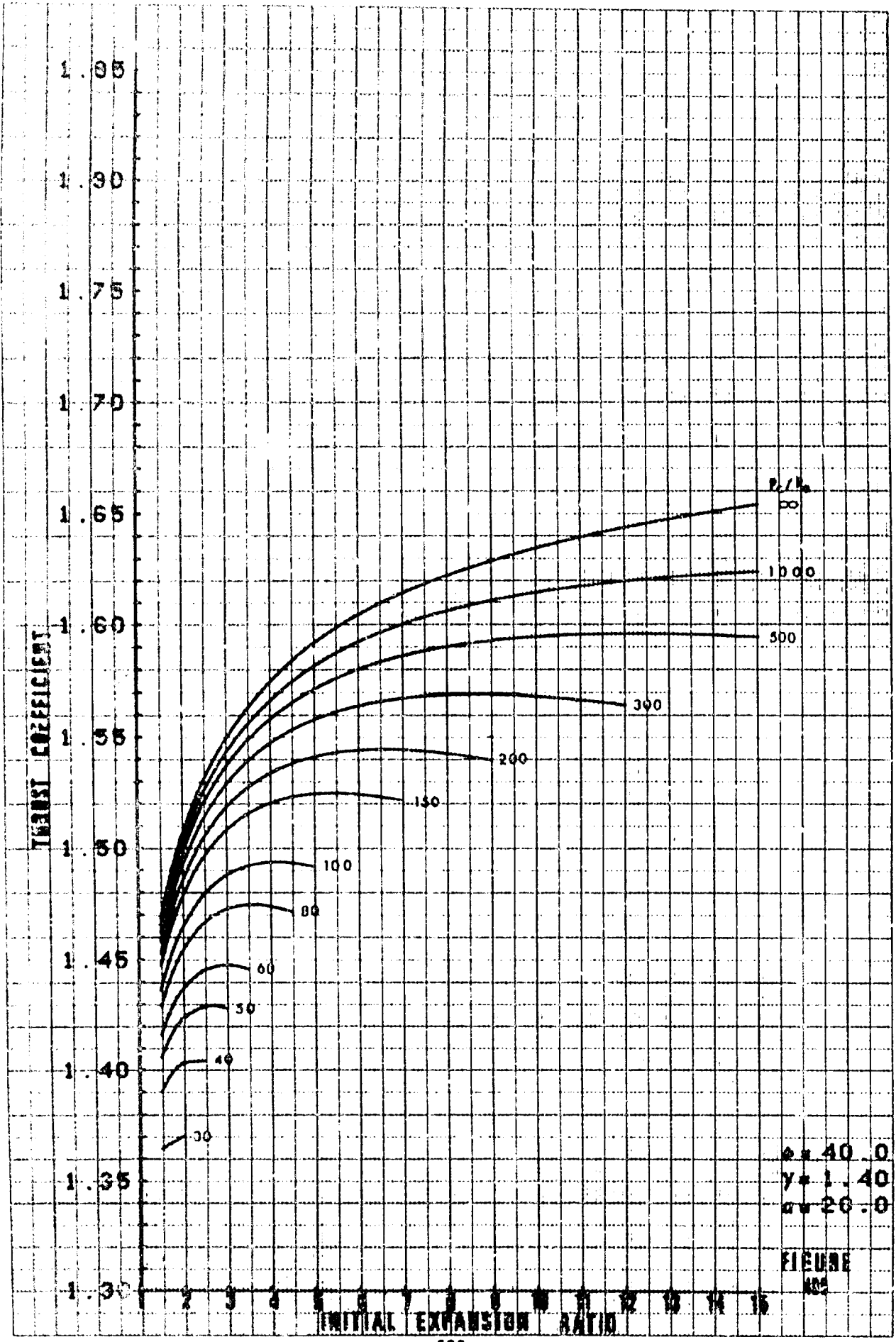
FIGURE  
M1

$\theta = 20.0$   
 $\gamma = 1.40$   
 $\alpha = 20.0$



$\phi = 30.6$   
 $\gamma = 1.40$   
 $\epsilon = 20.5$

FIGURE 2



$\alpha = 40.0$   
 $\gamma = 1.40$   
 $\alpha = 20.0$

FIGURE 405

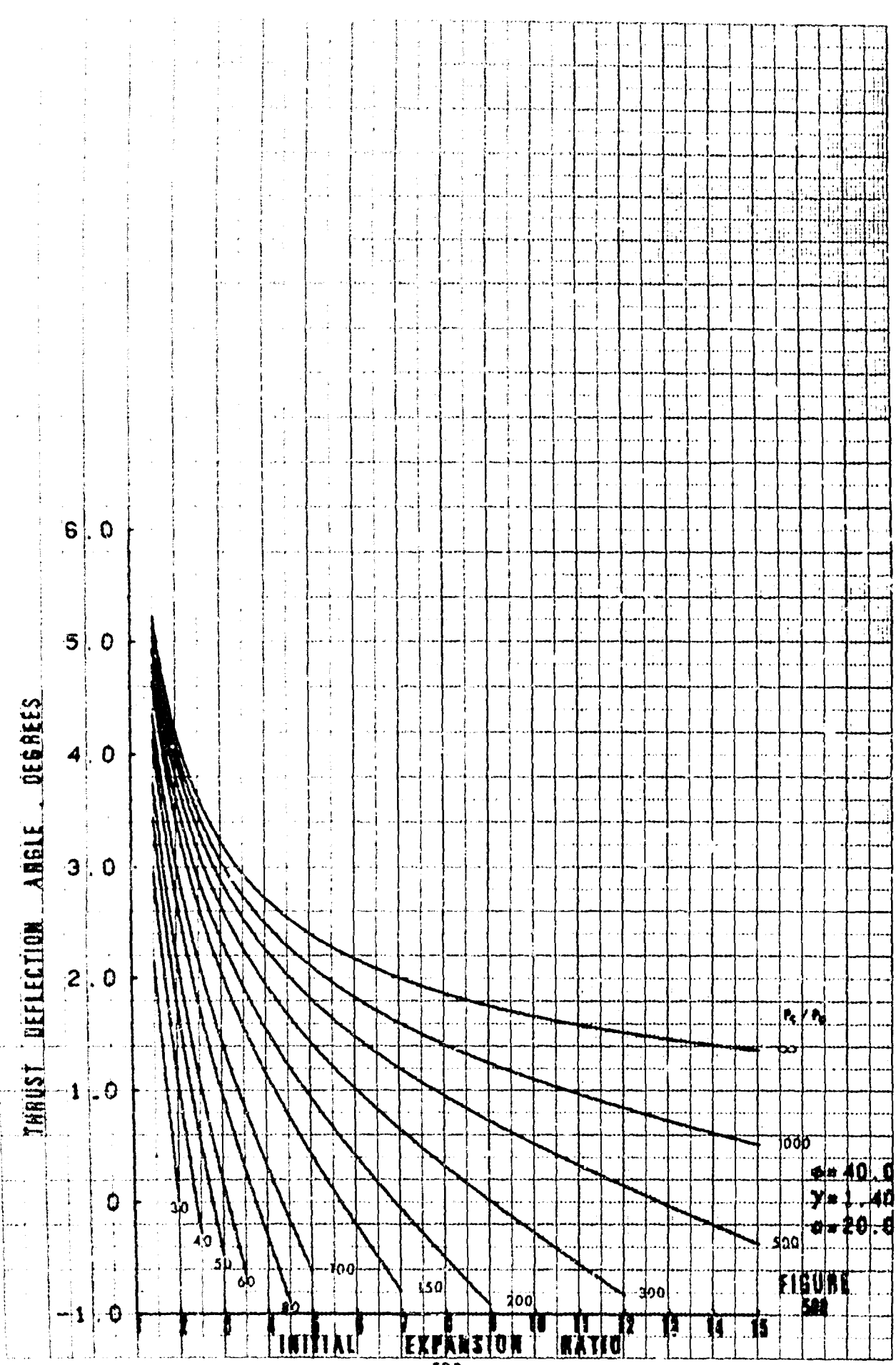


FIGURE 503

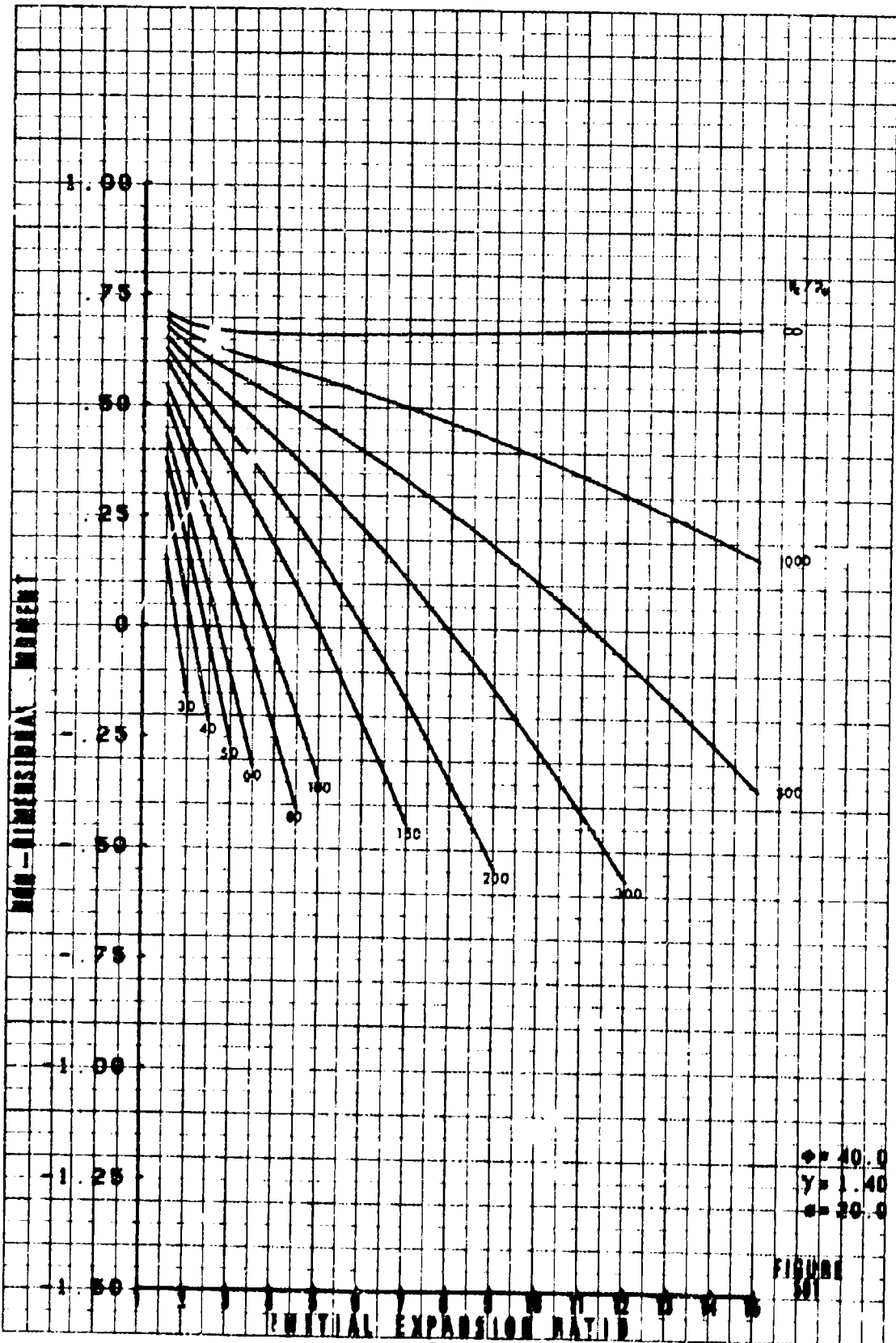
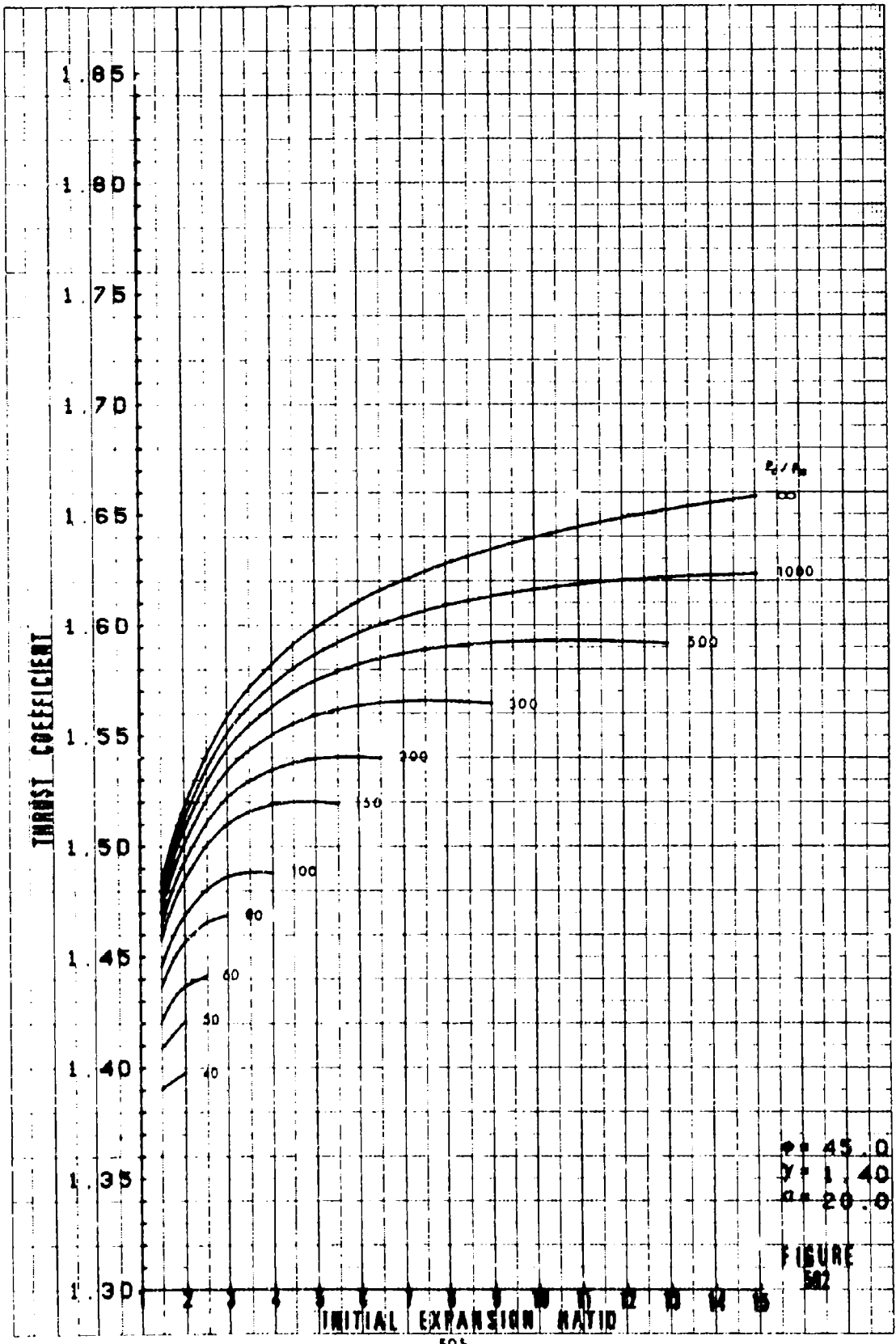
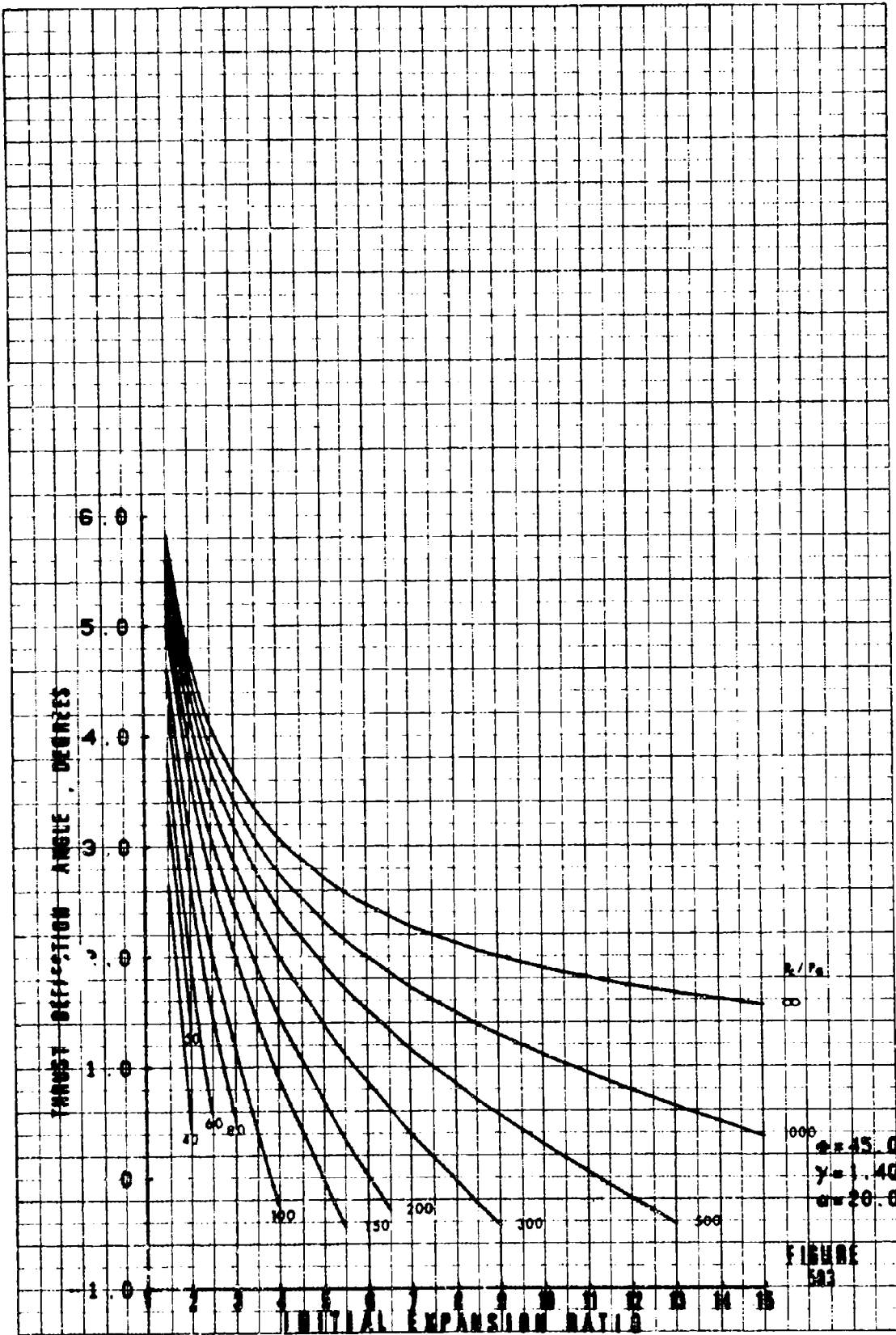
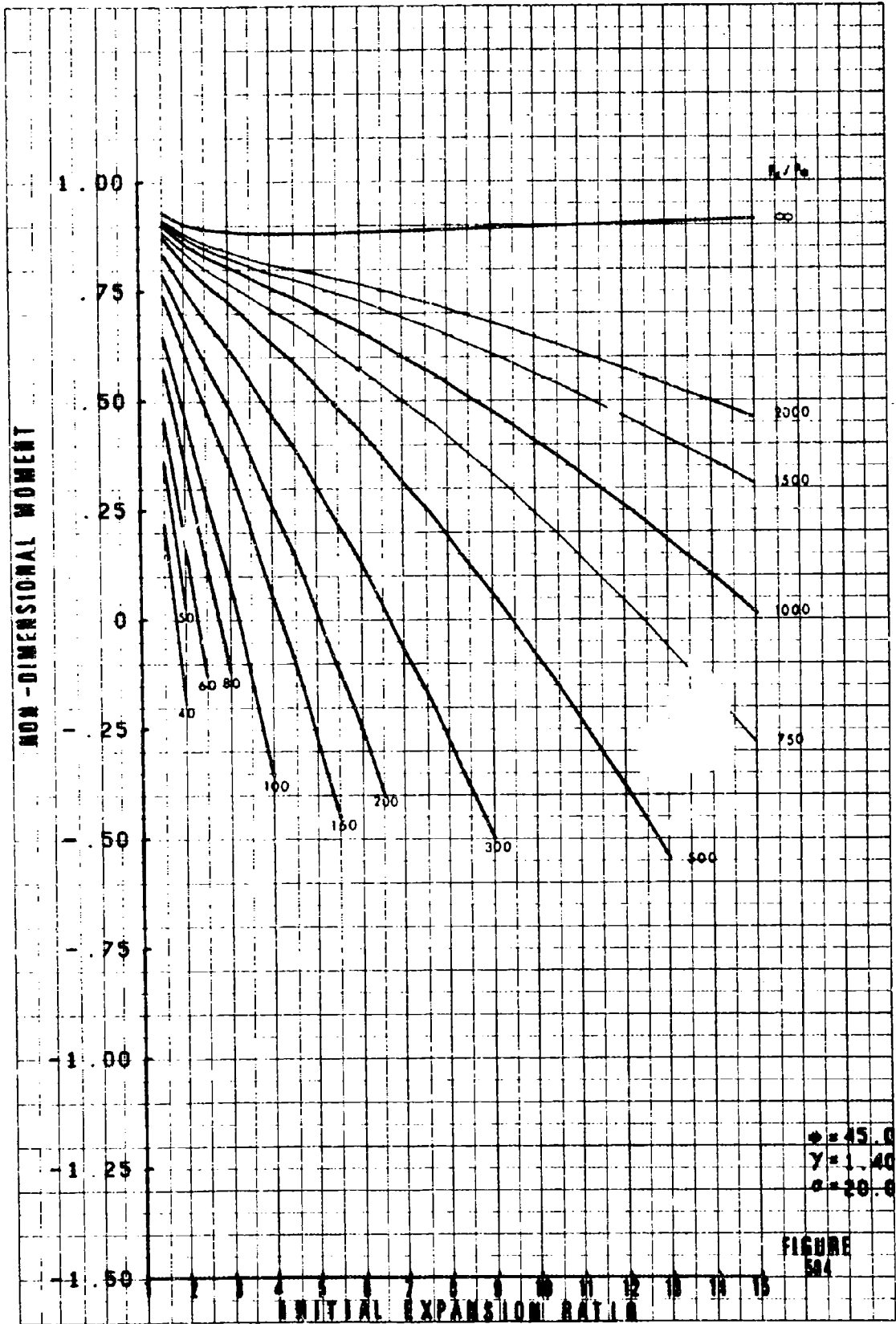


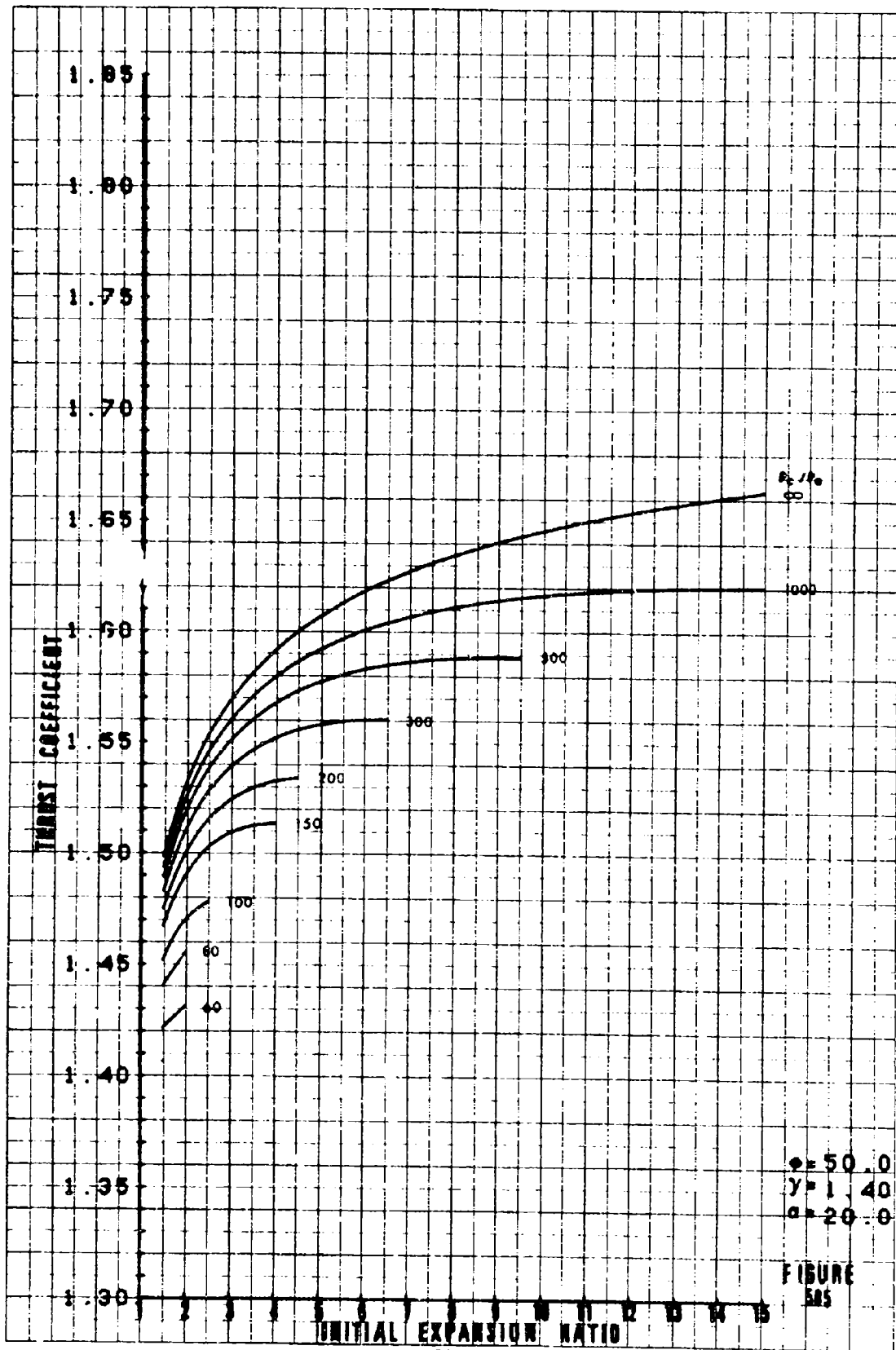
FIGURE 501











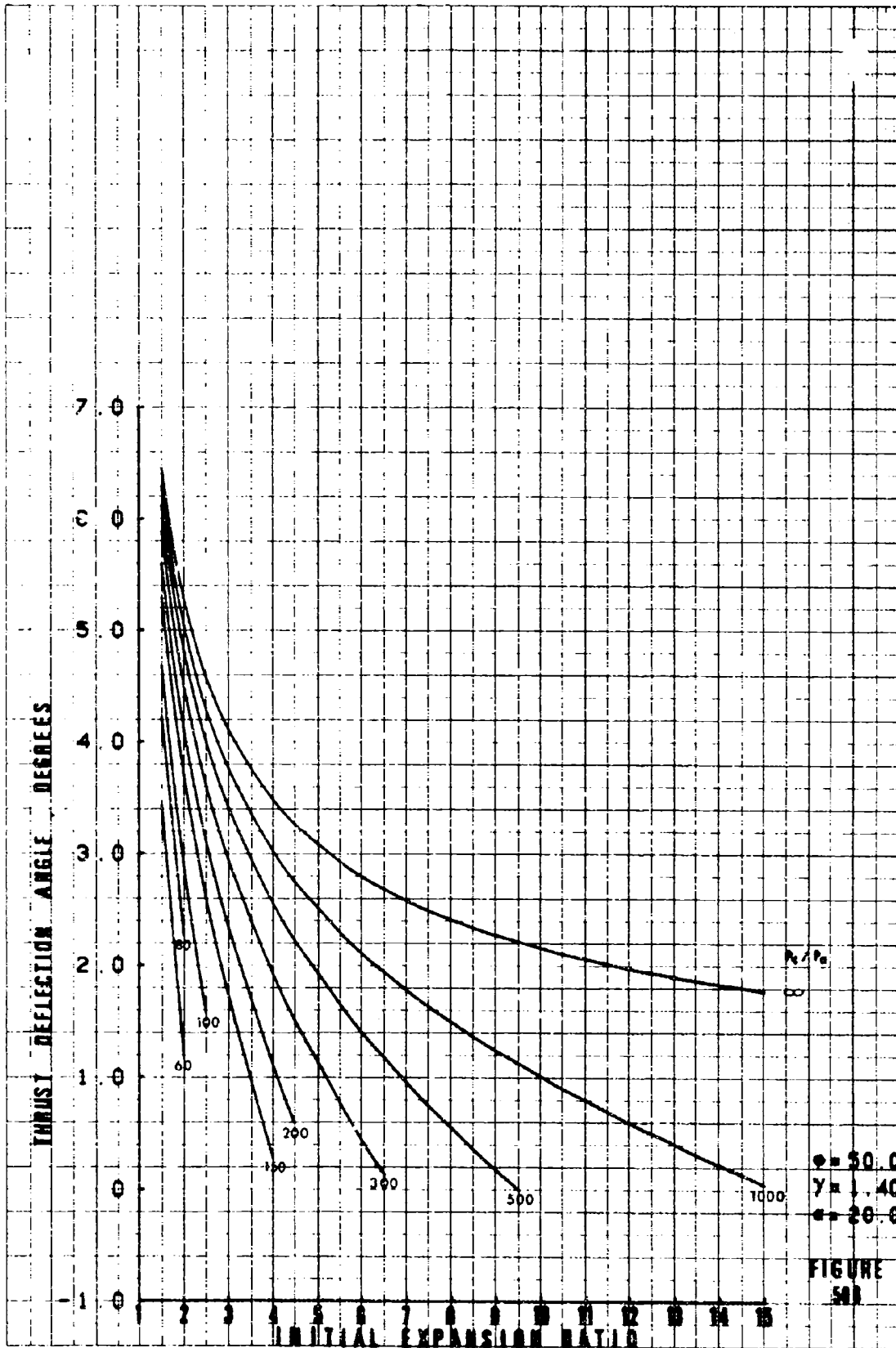
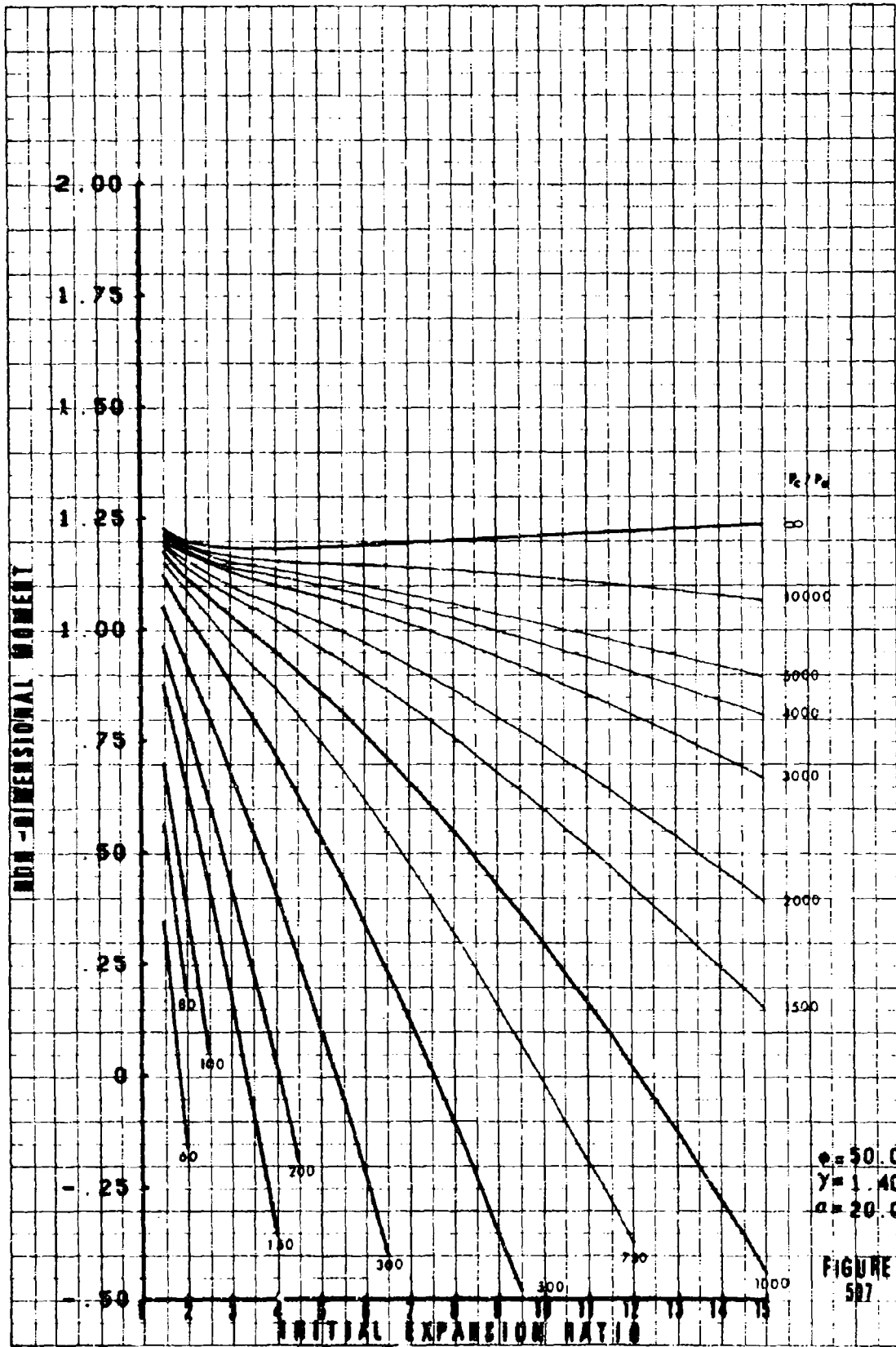


FIGURE 50



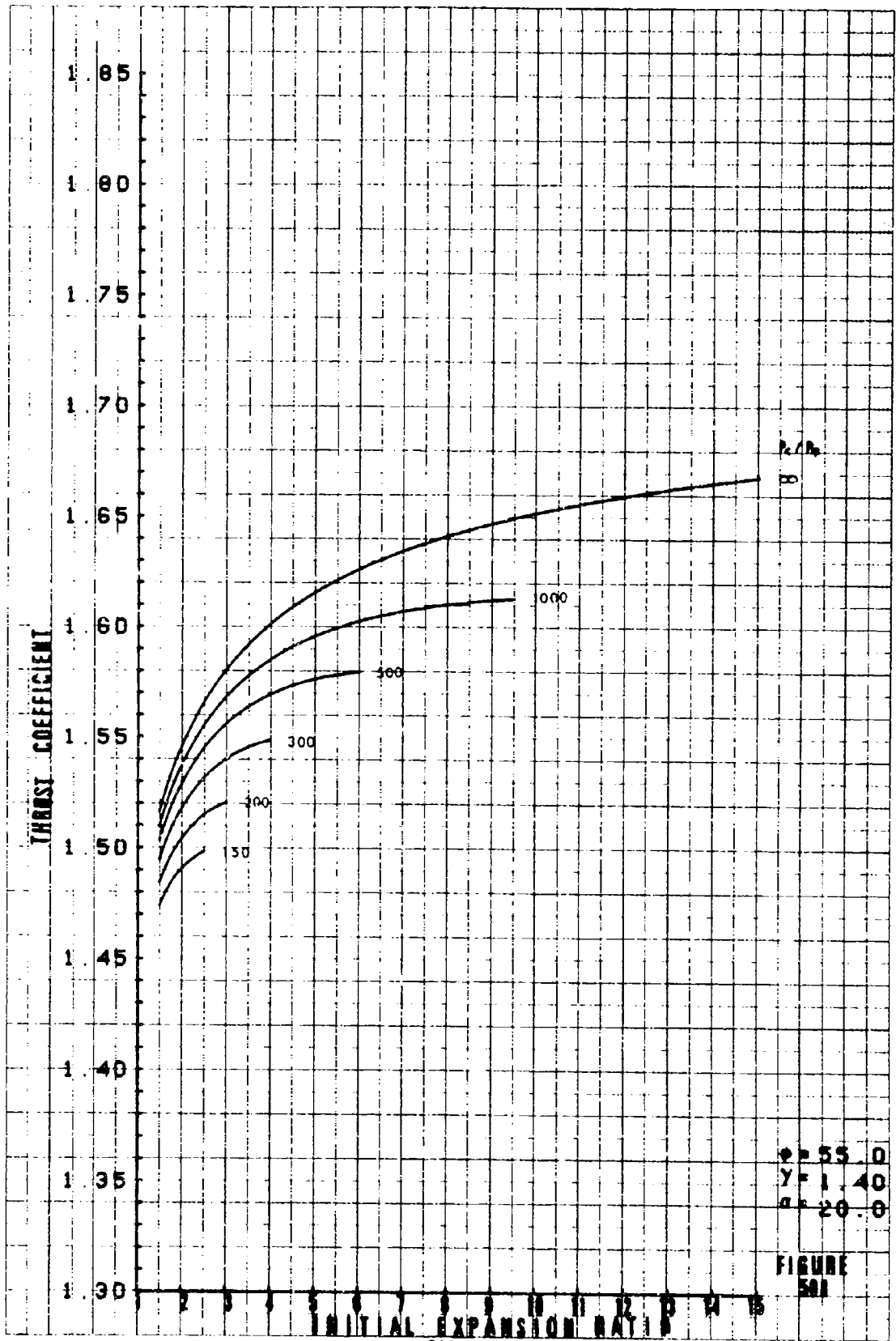


FIGURE 501

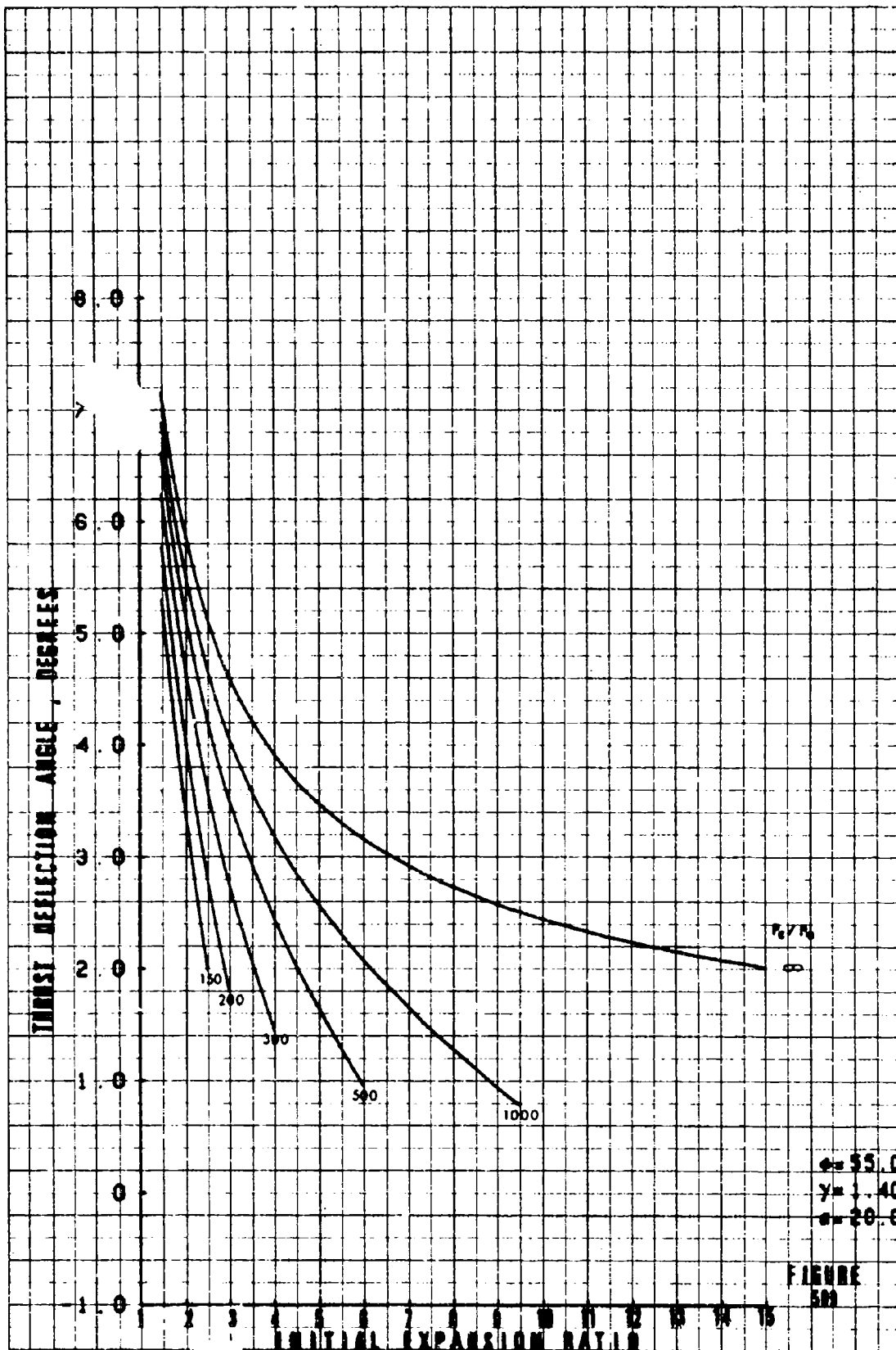
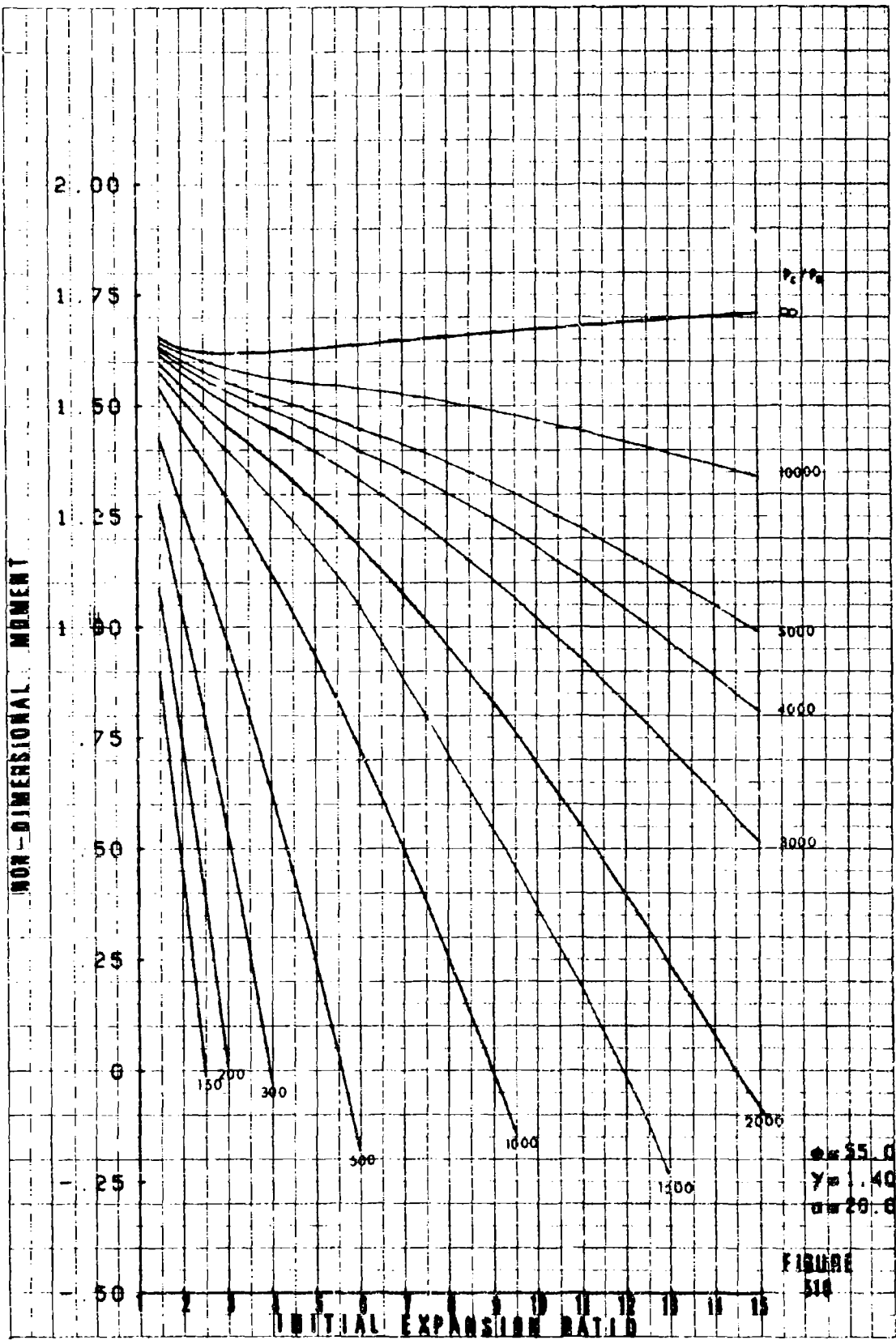
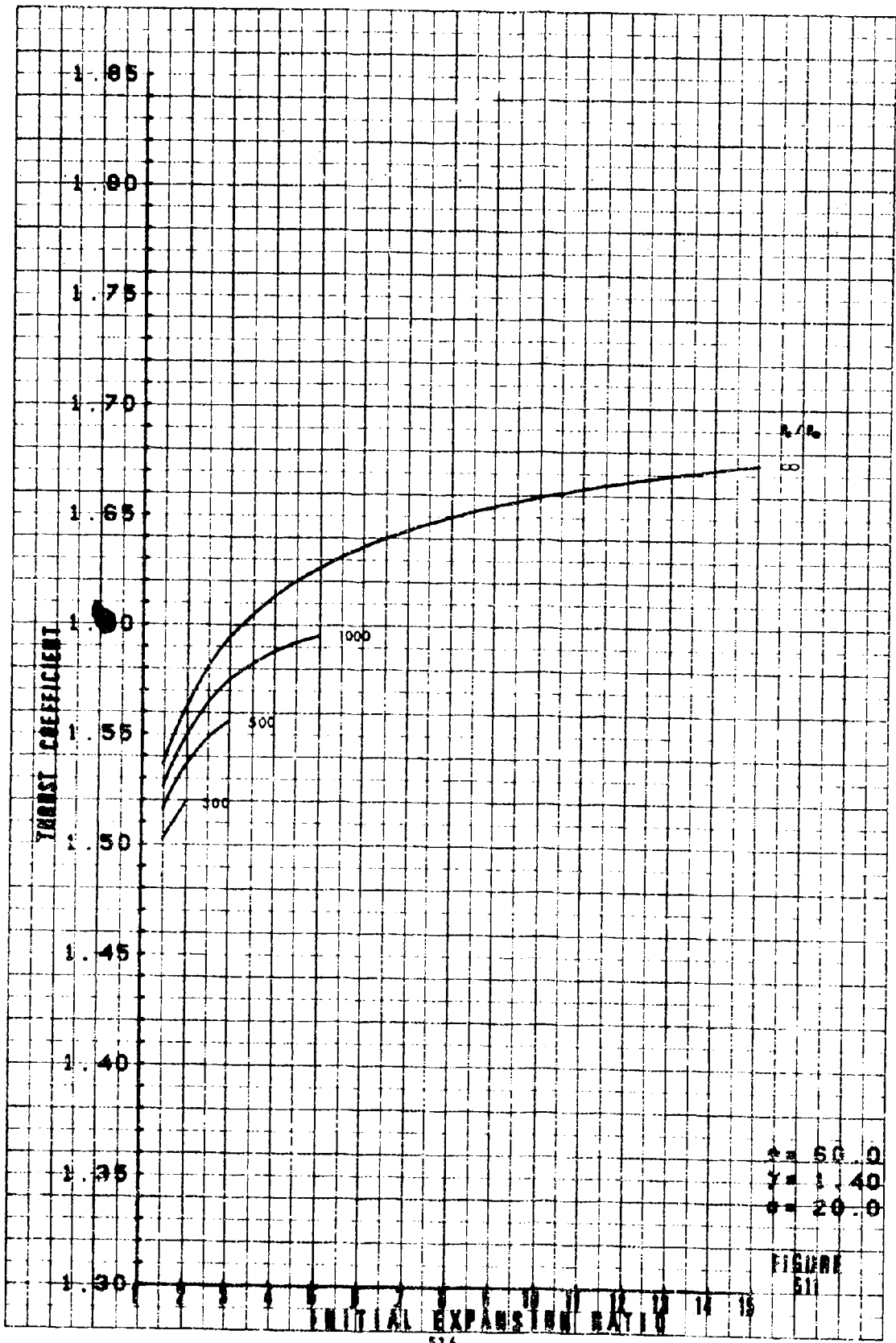


FIGURE 509





\* = 50.0  
 Y = 1.40  
 • = 20.0

FIGURE 511



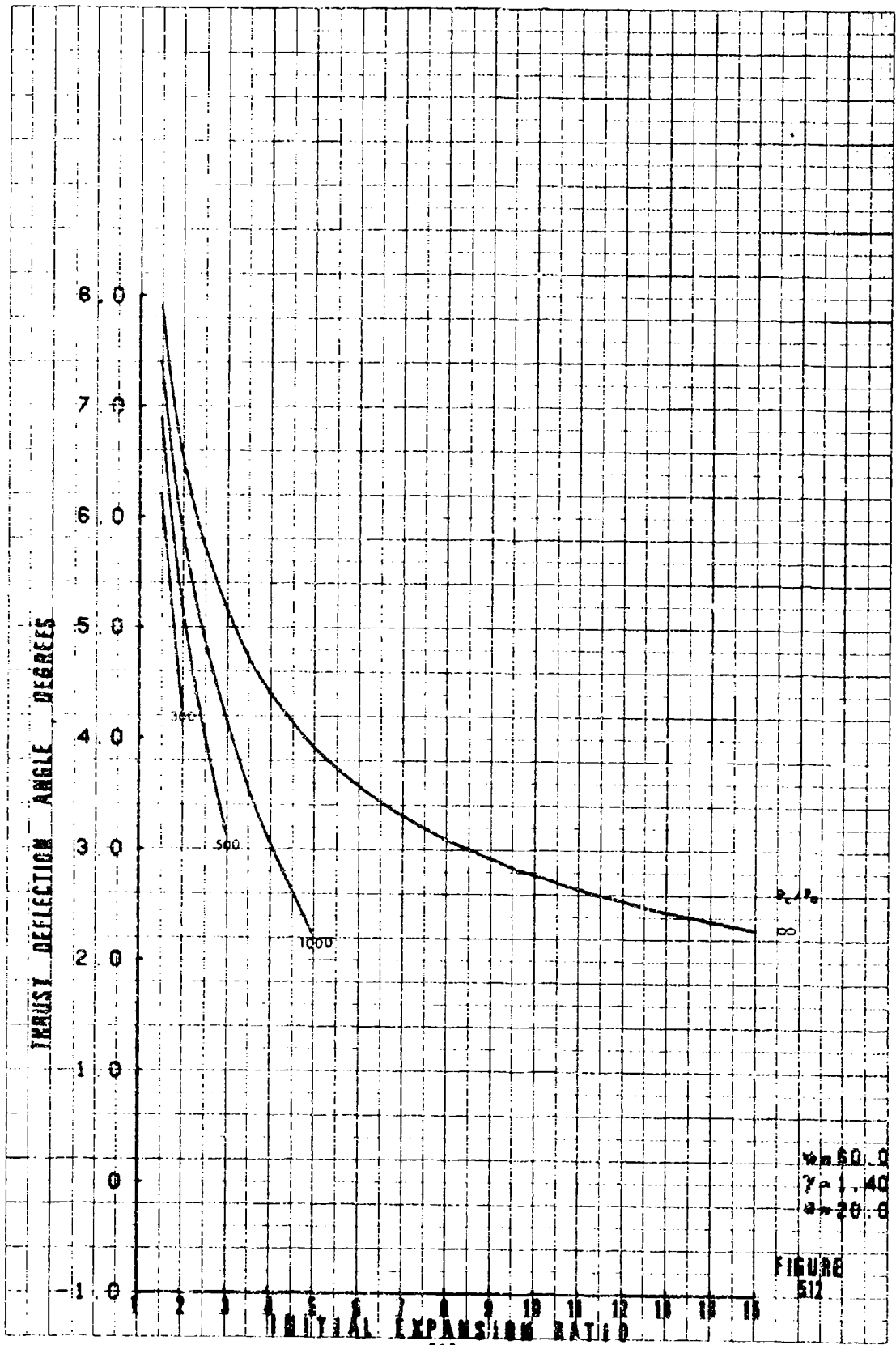
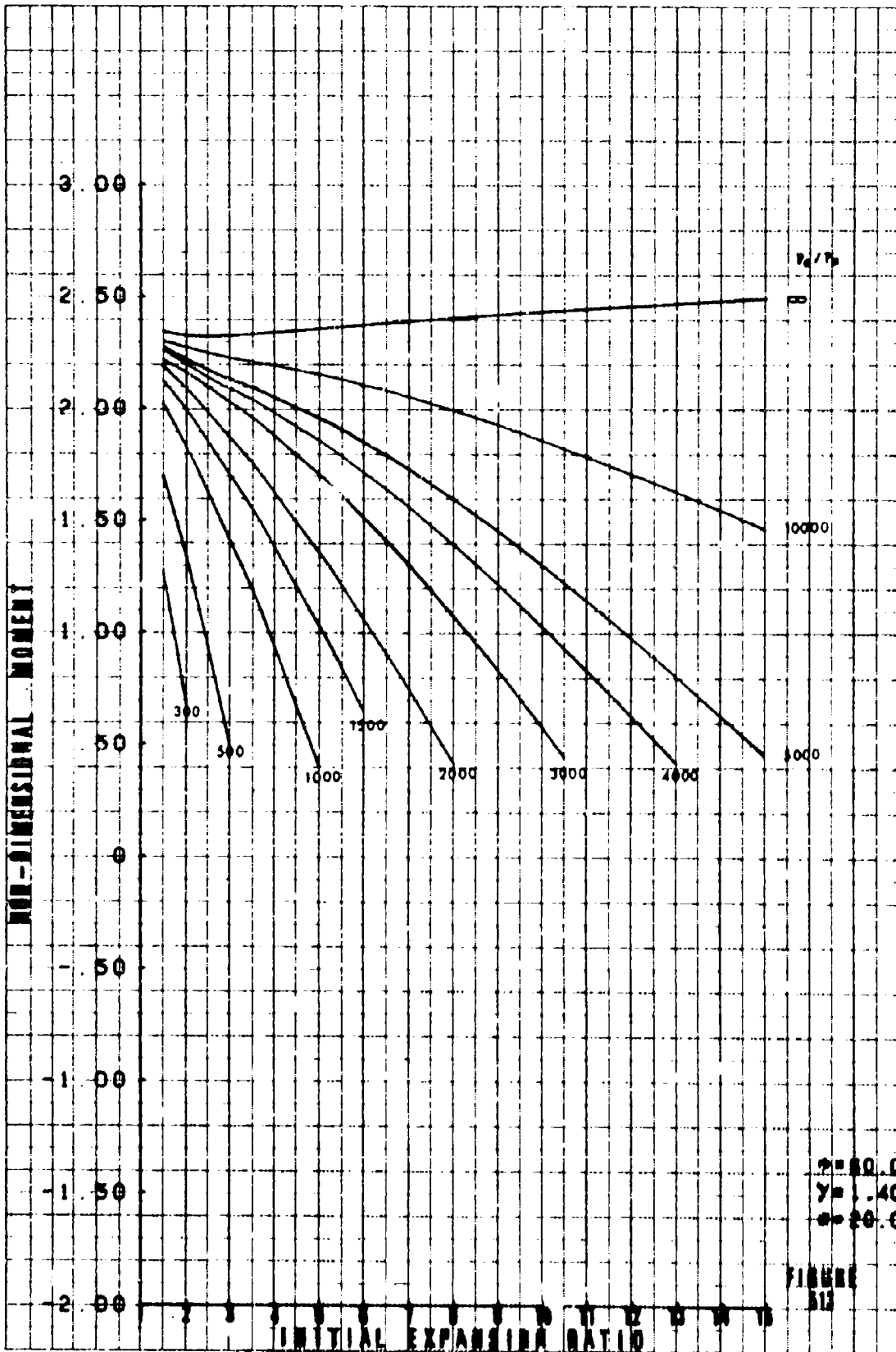
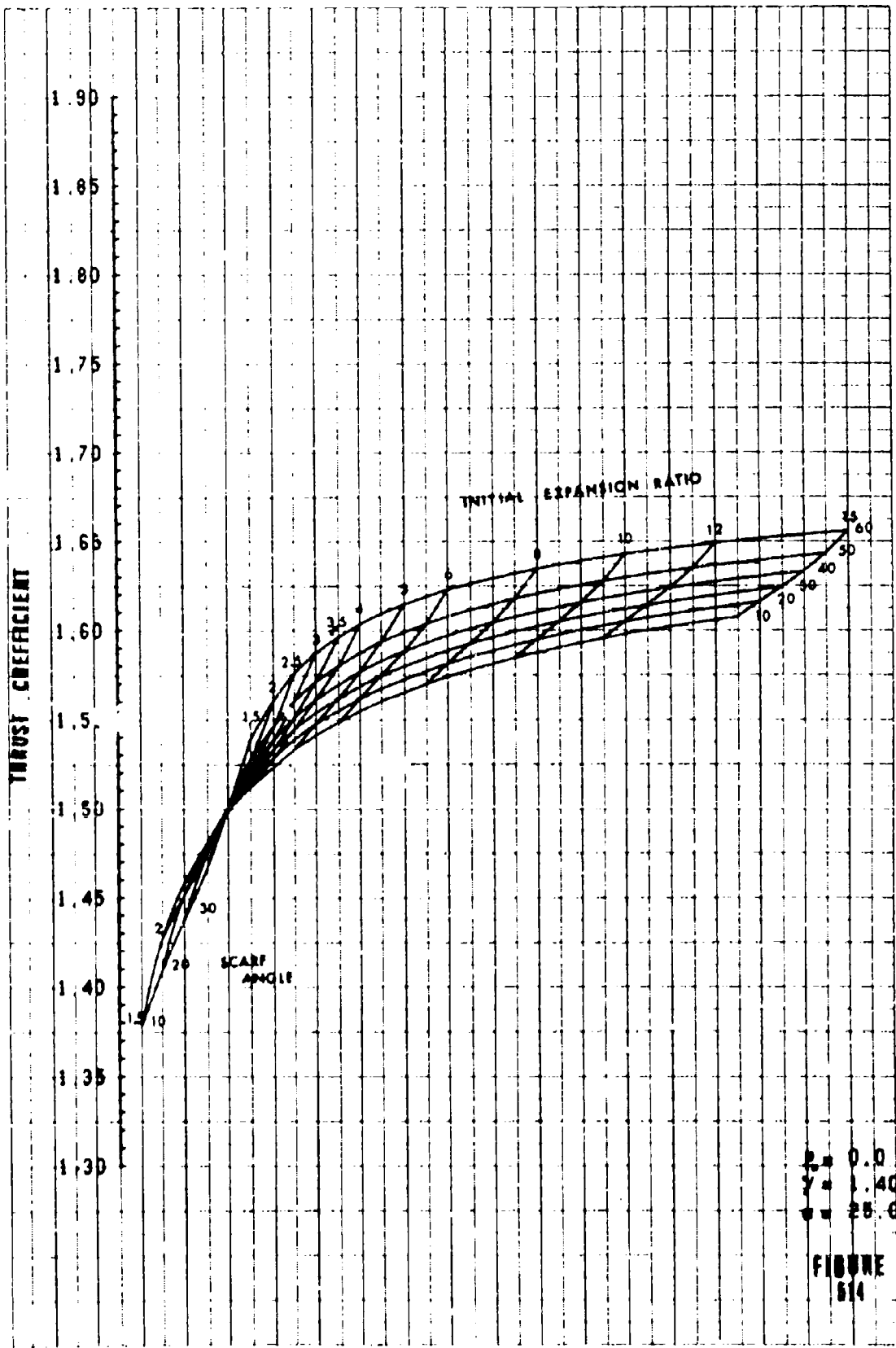


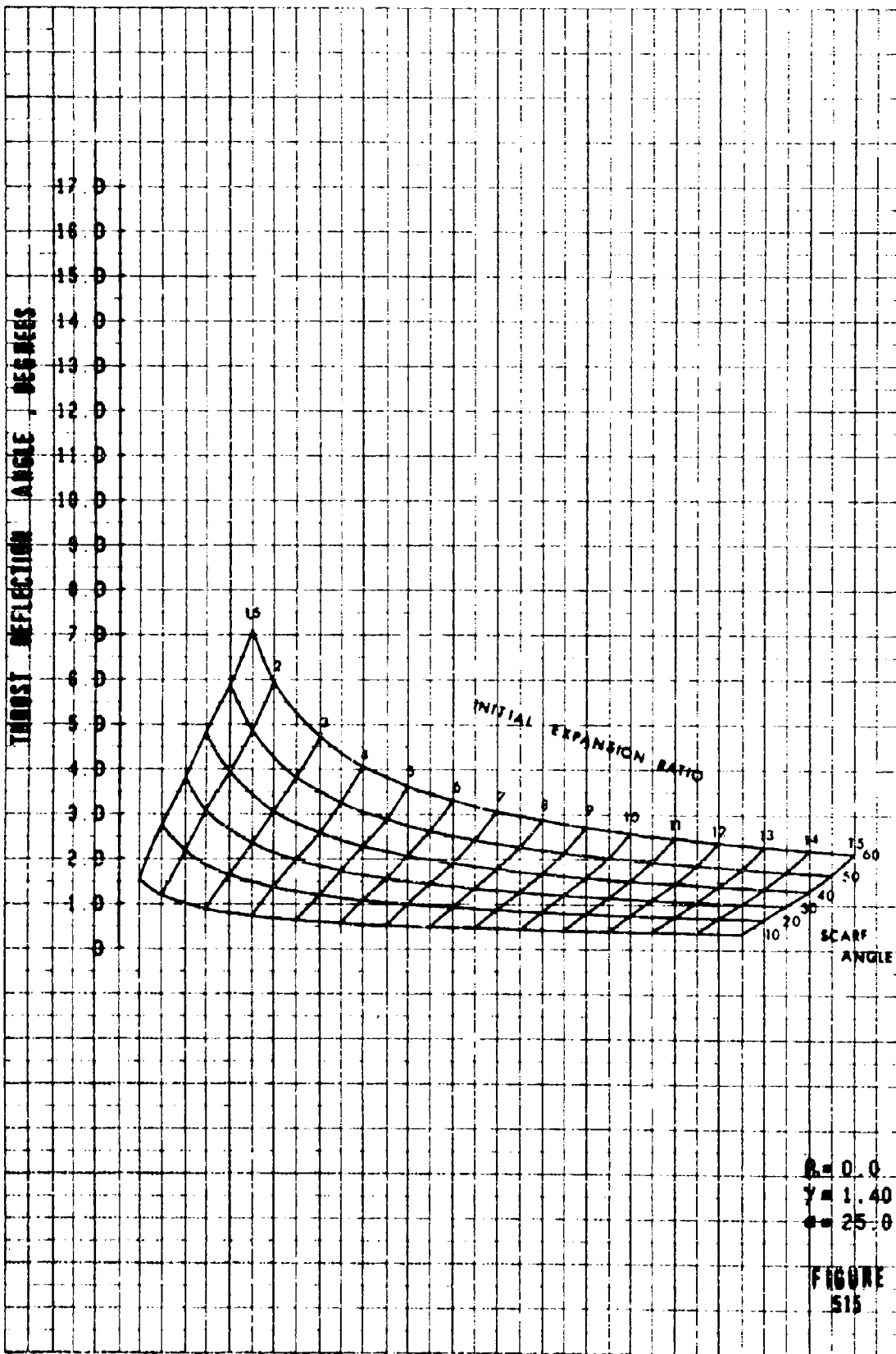
FIGURE 512

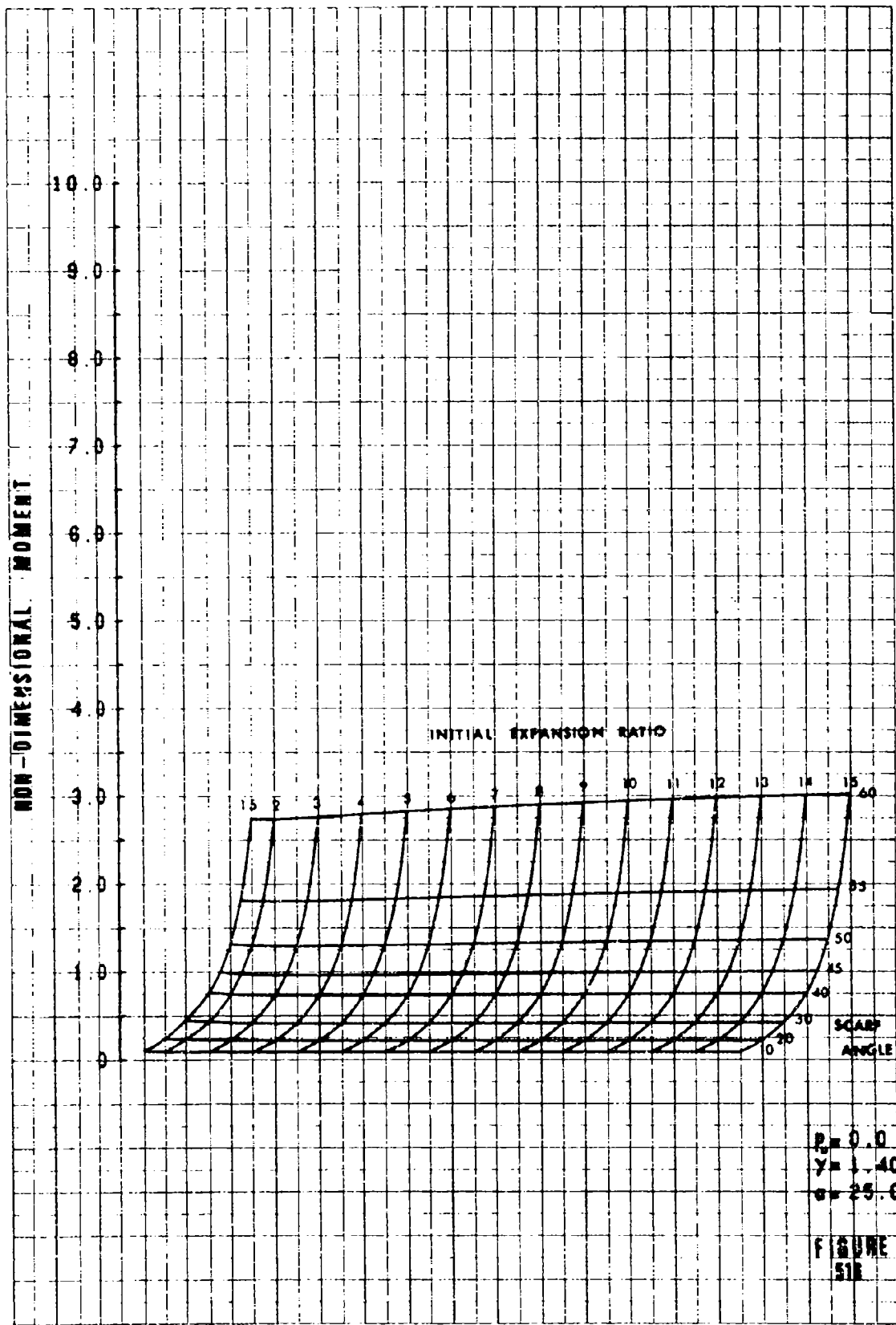


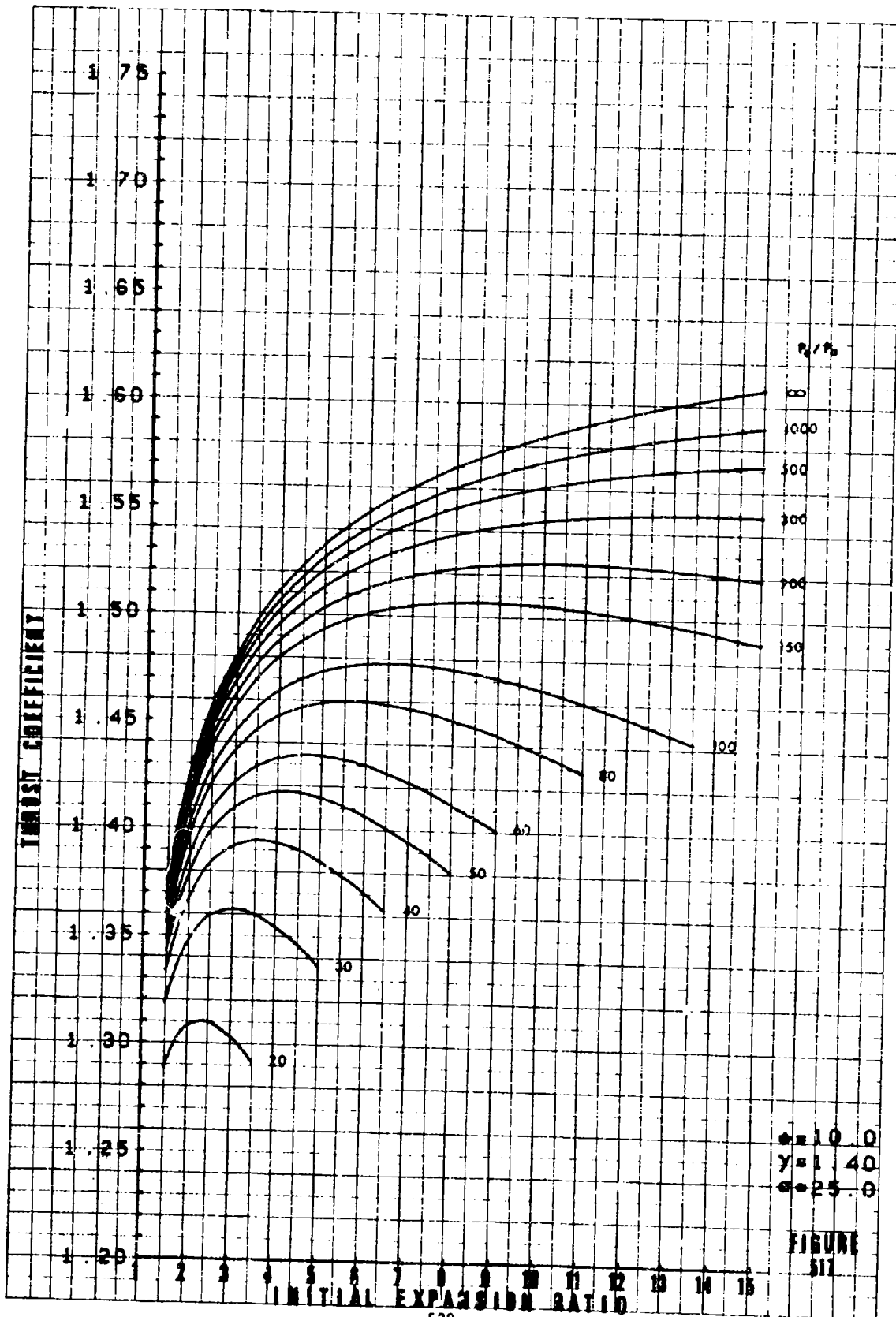


$P_0 = 0.0$   
 $\gamma = 1.40$   
 $\mu = 25.0$

FIGURE 514







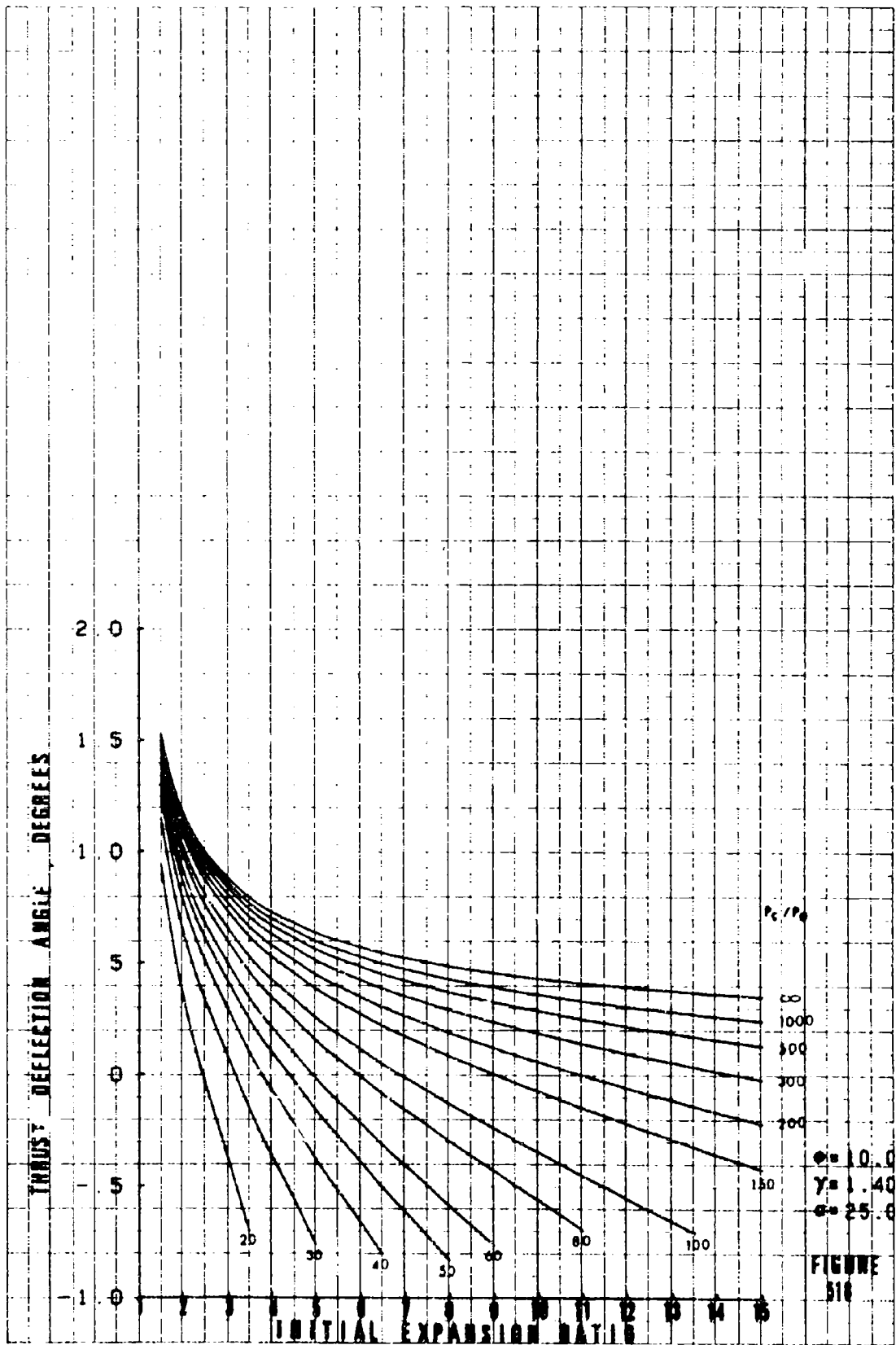
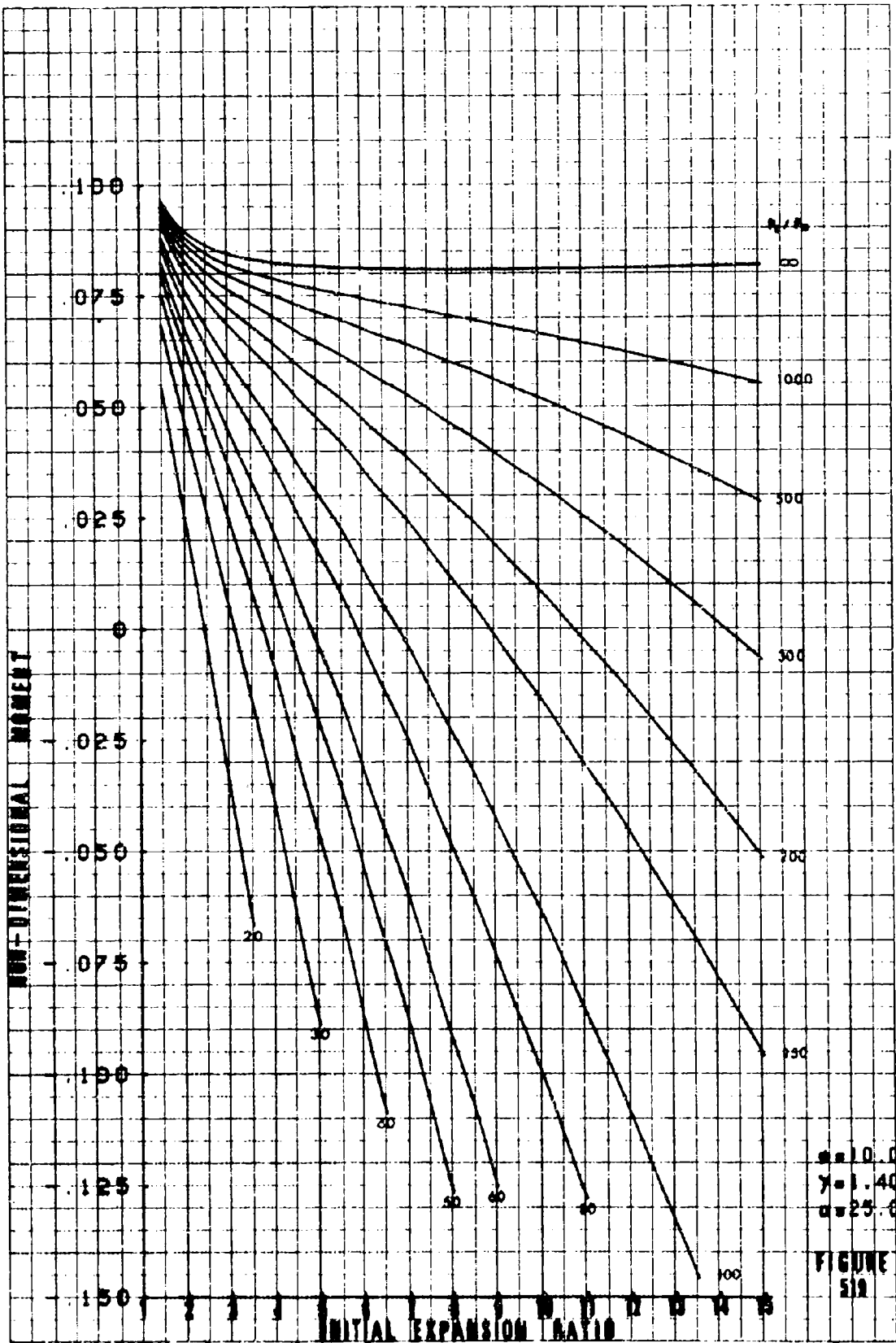
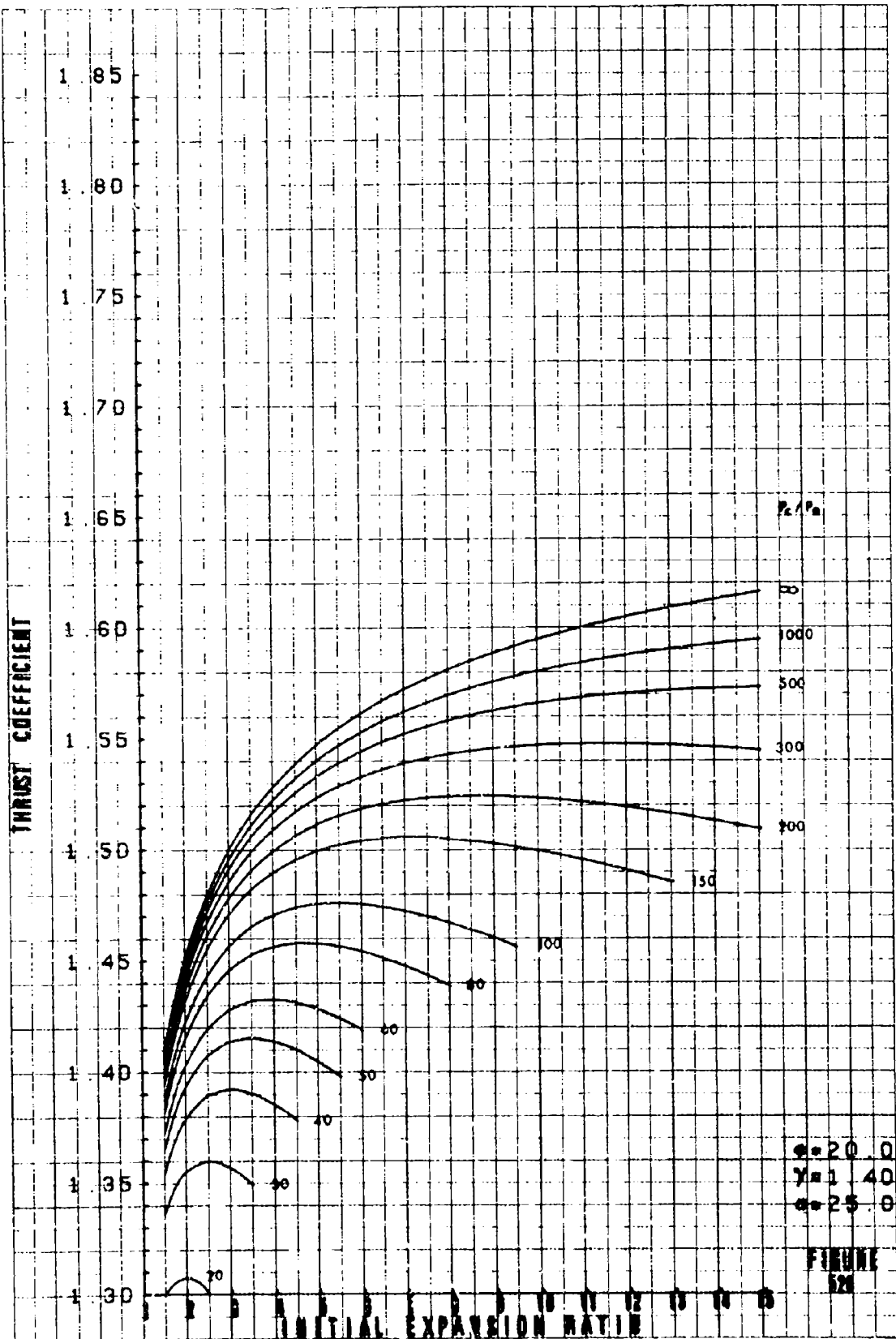


FIGURE 518







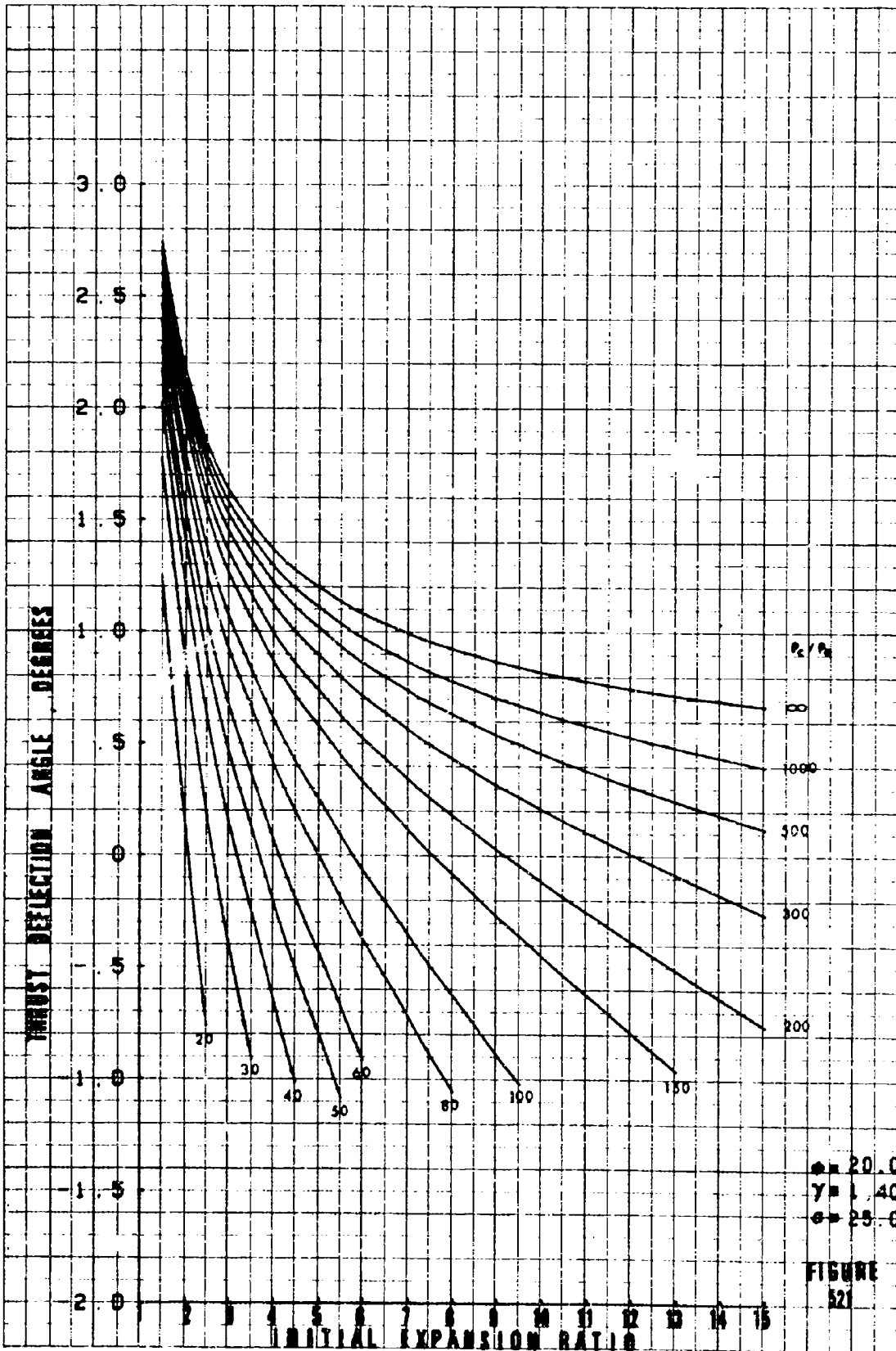
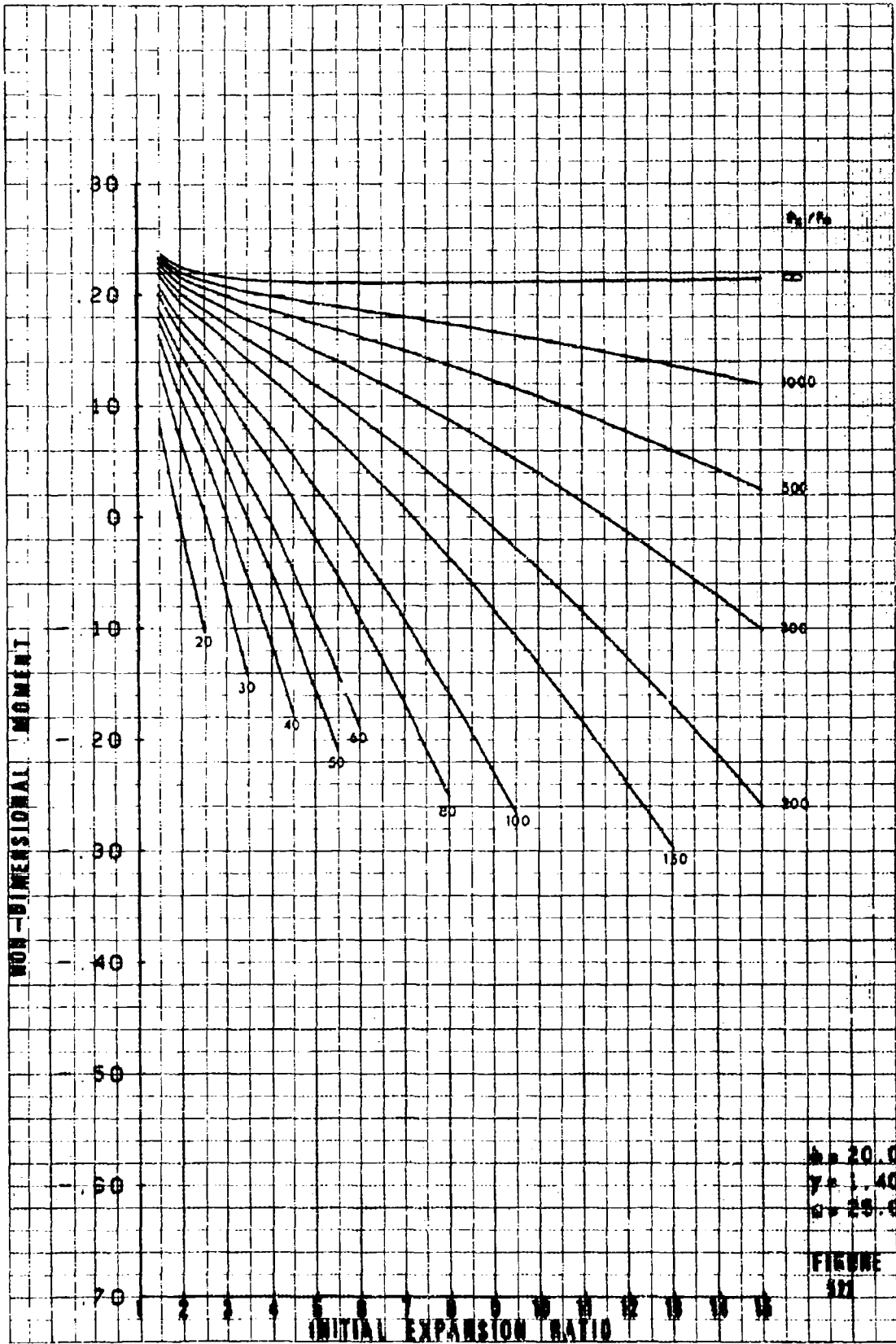


FIGURE 521



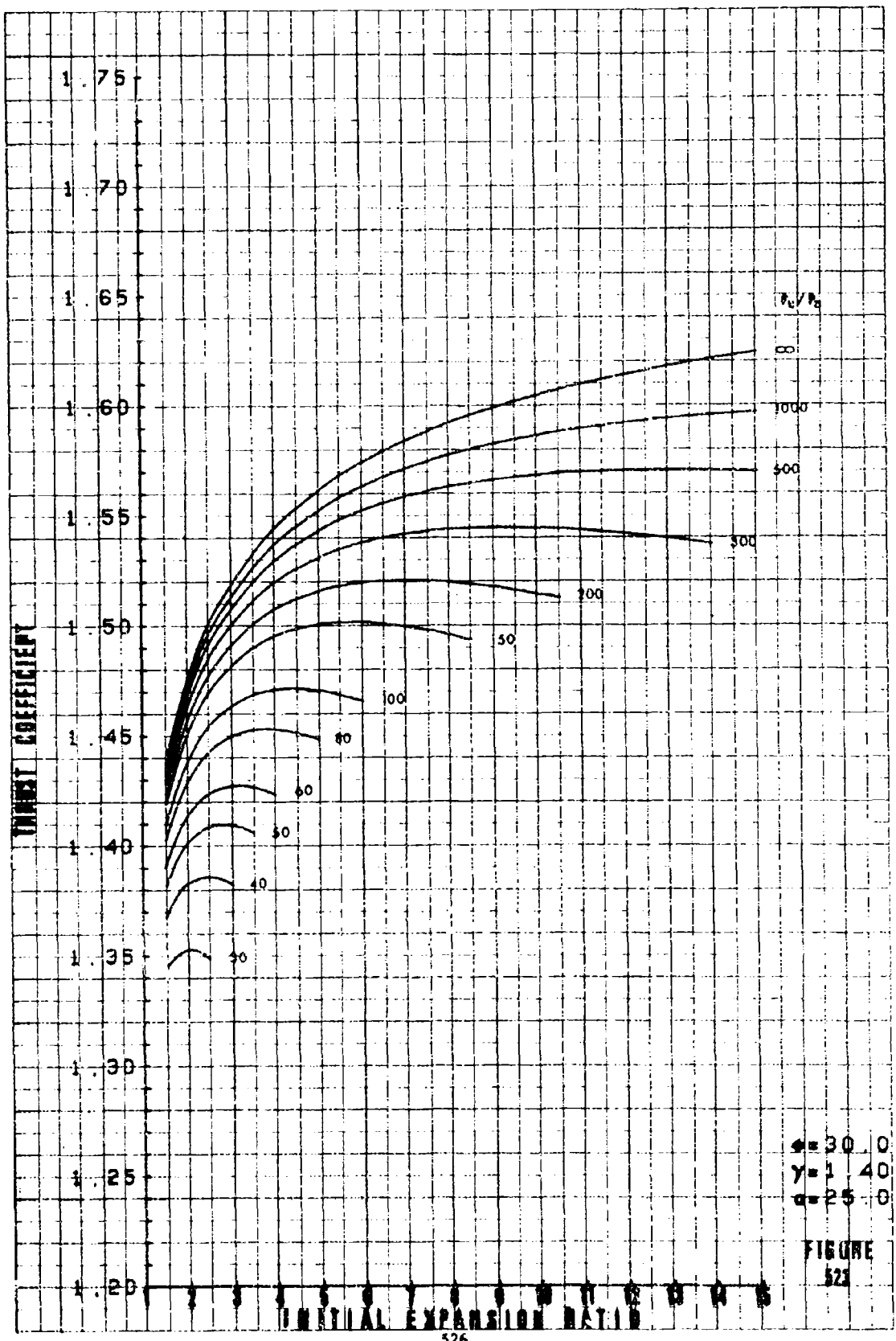
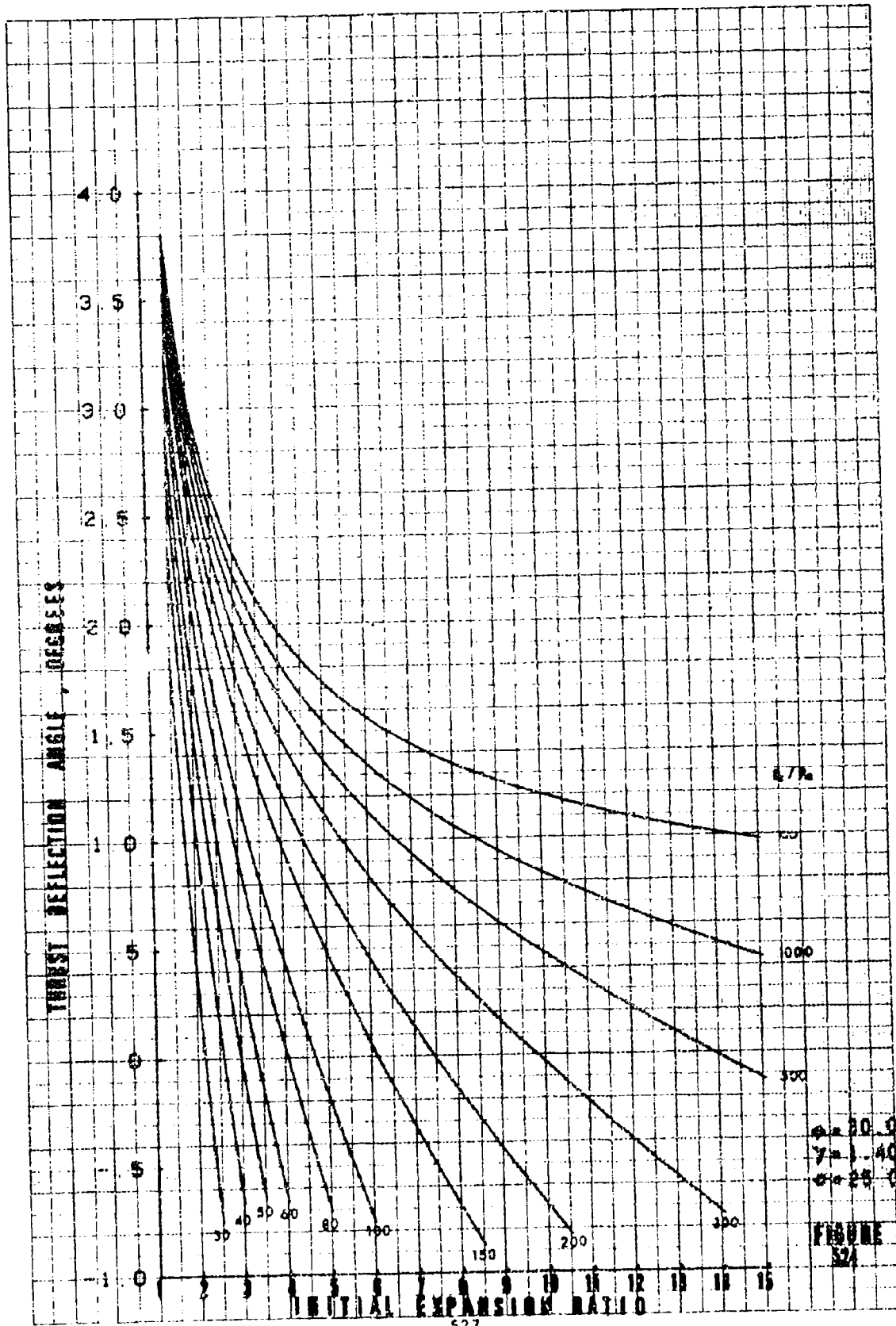
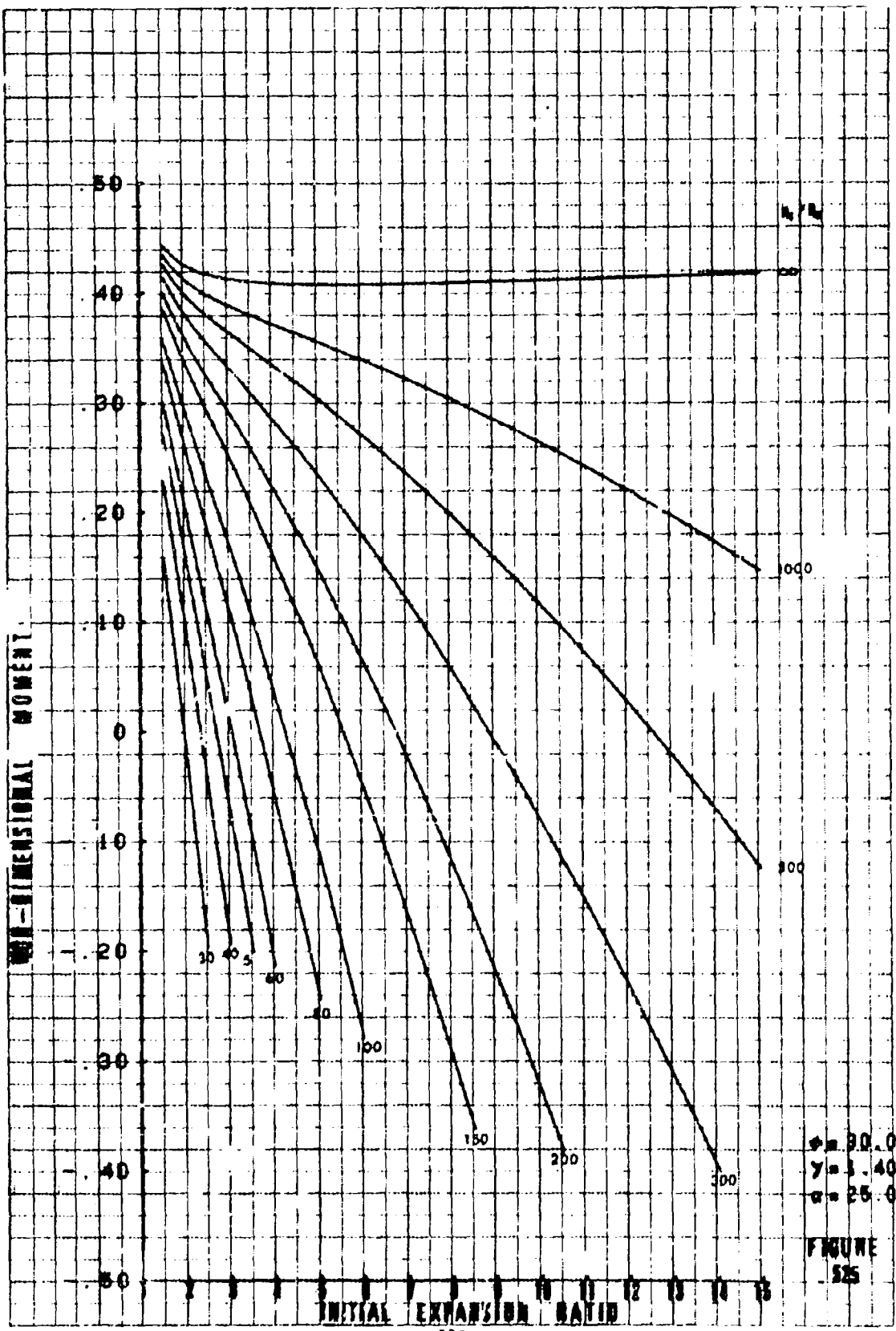
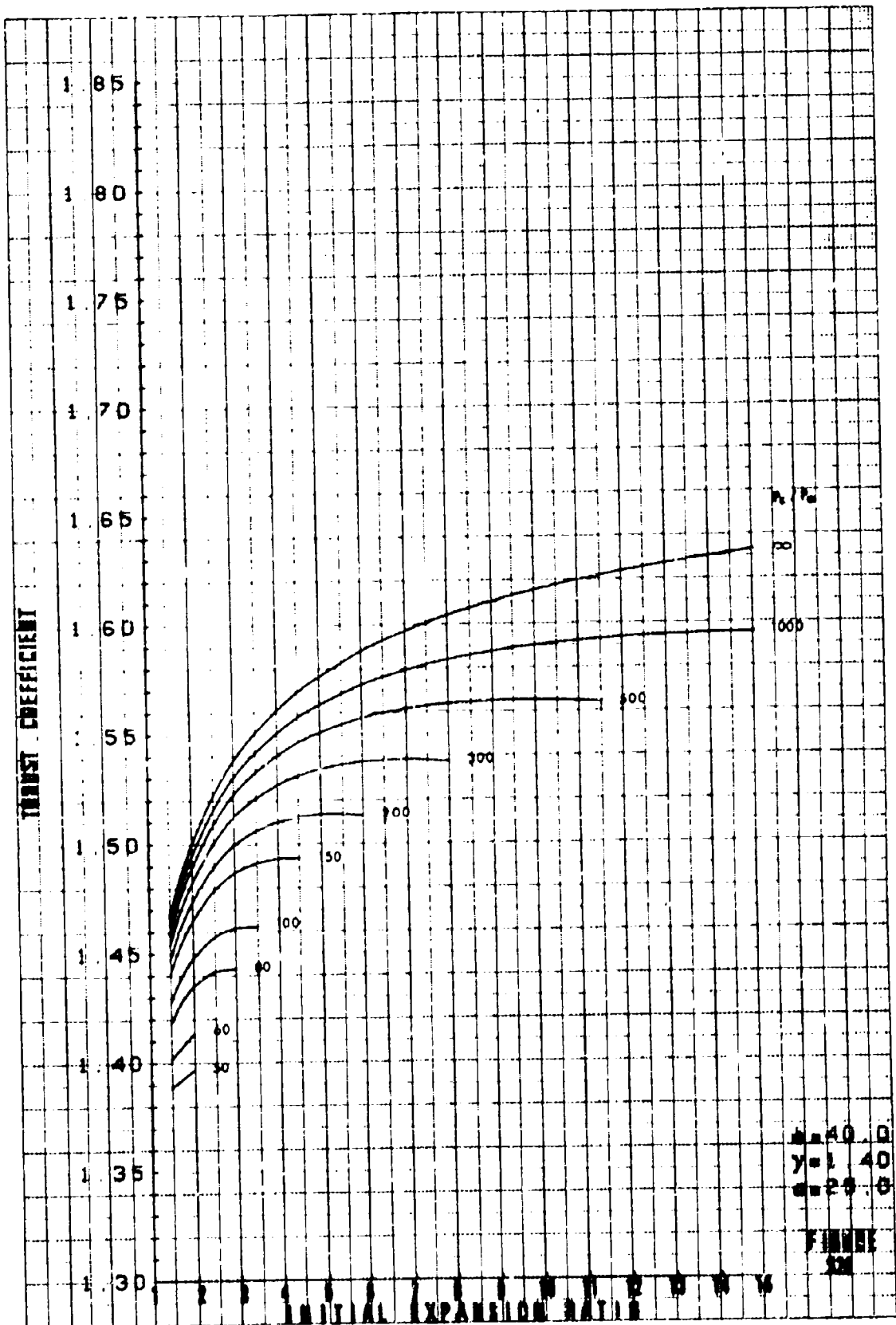
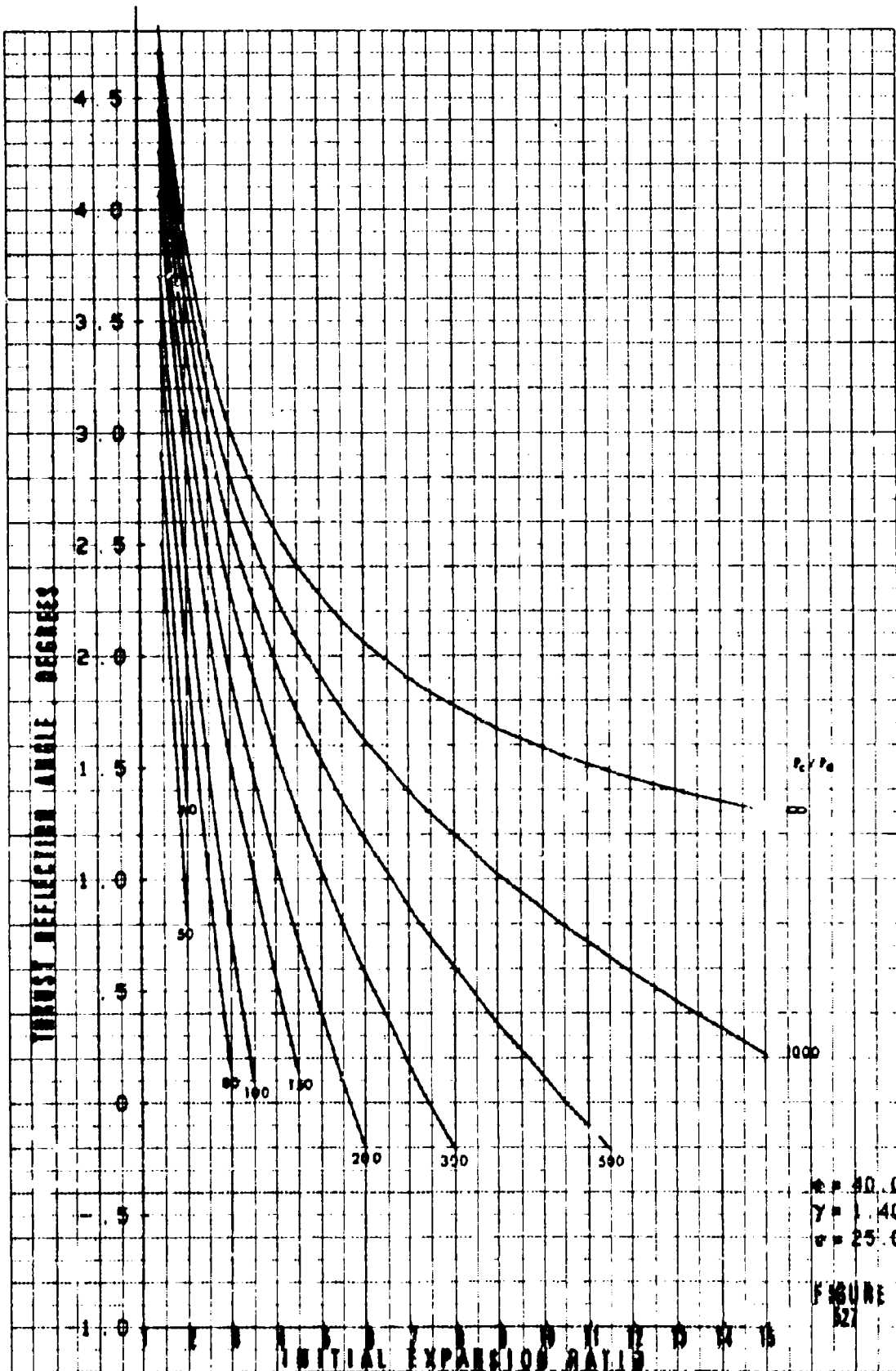


FIGURE 523











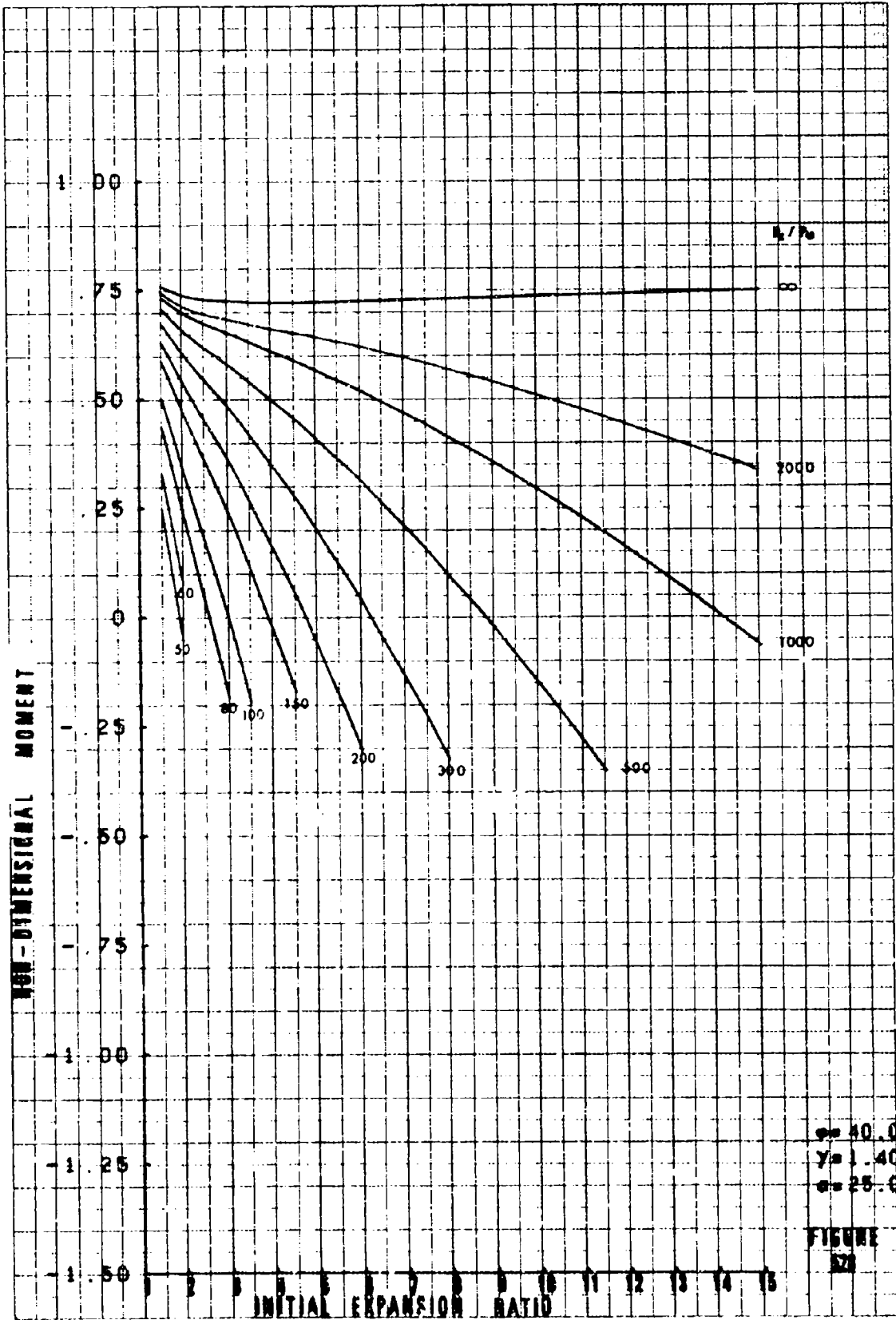
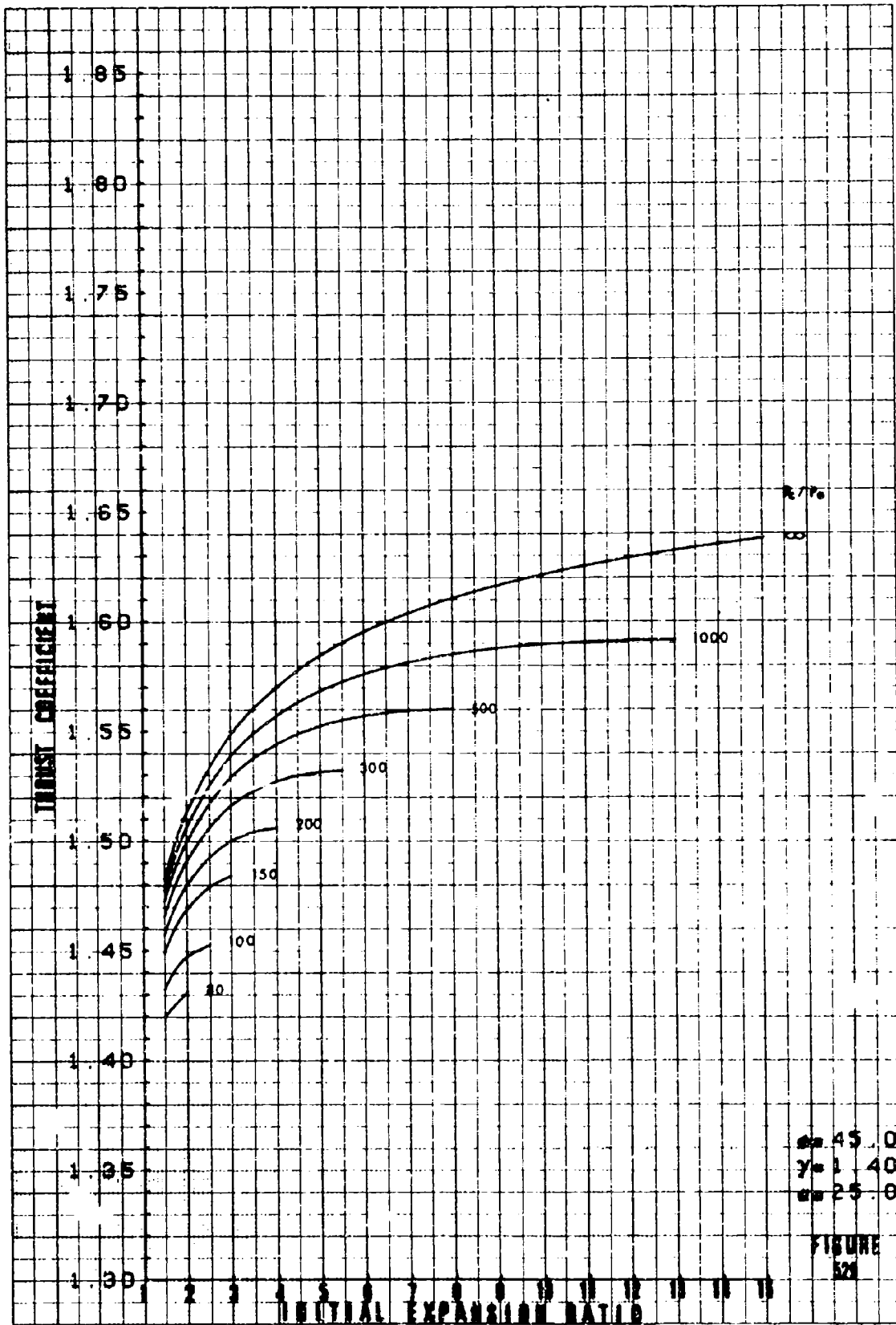
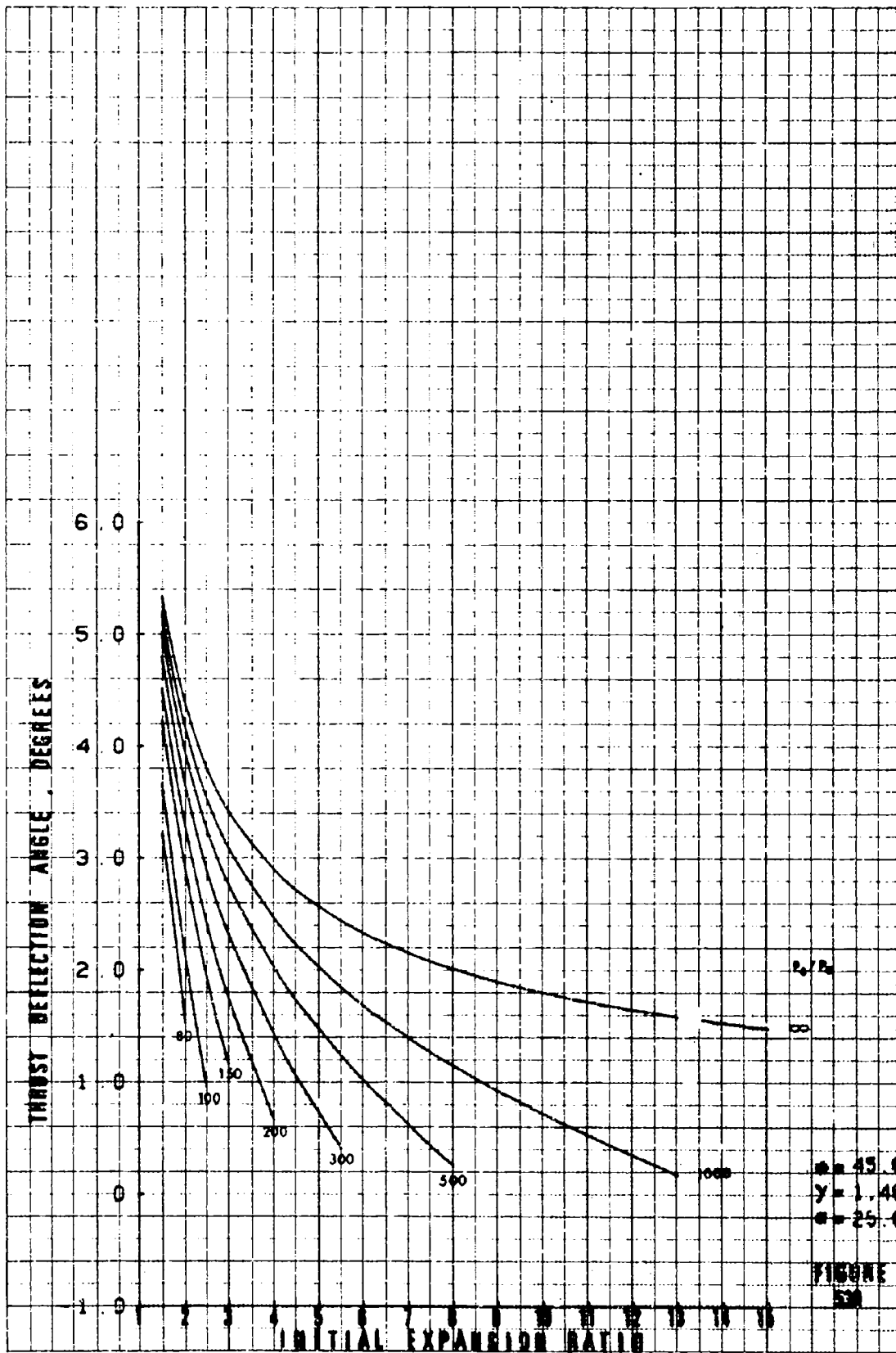


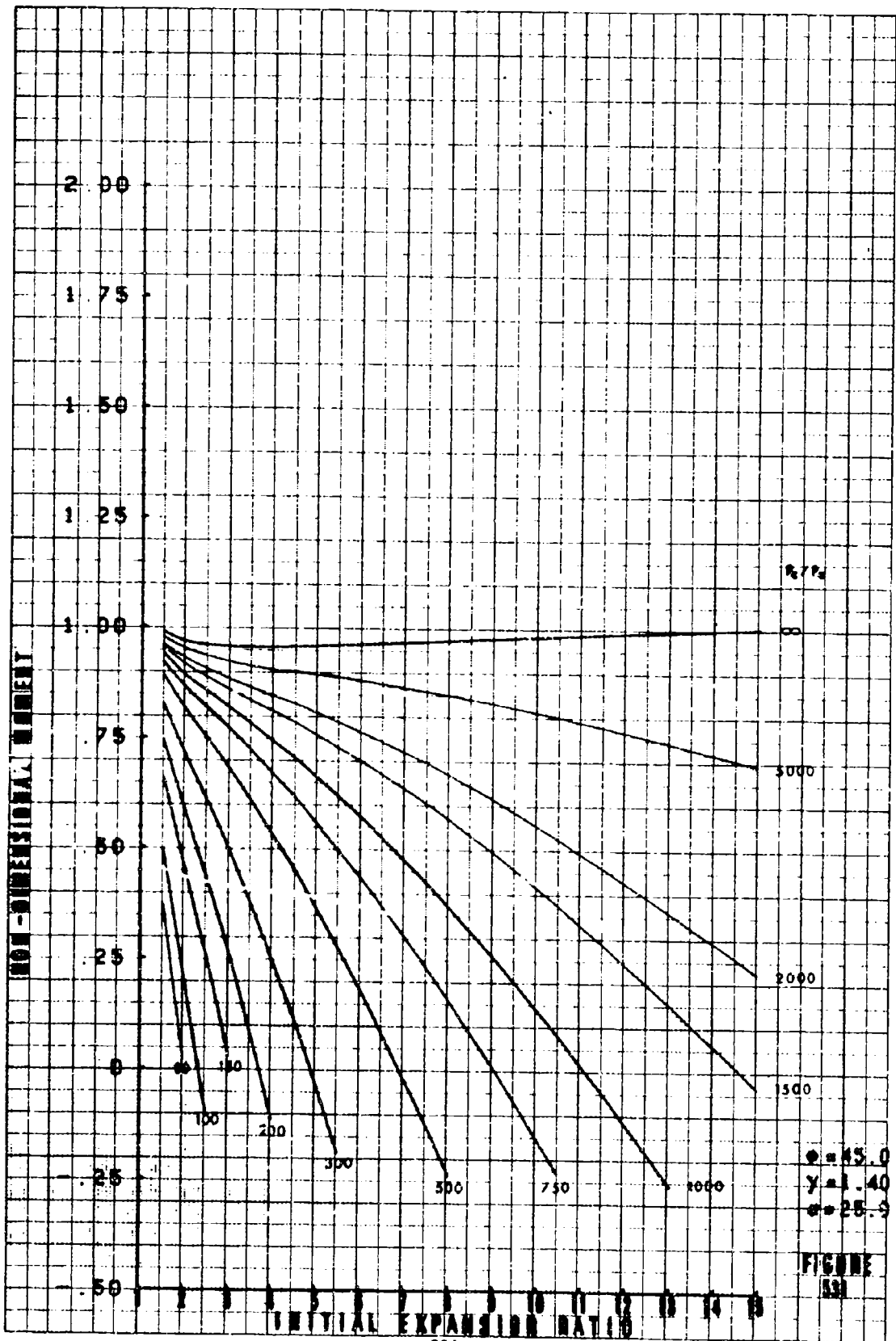
FIGURE 52





$\gamma = 45.0$   
 $\gamma = 1.40$   
 $\gamma = 25.6$

FIGURE 529



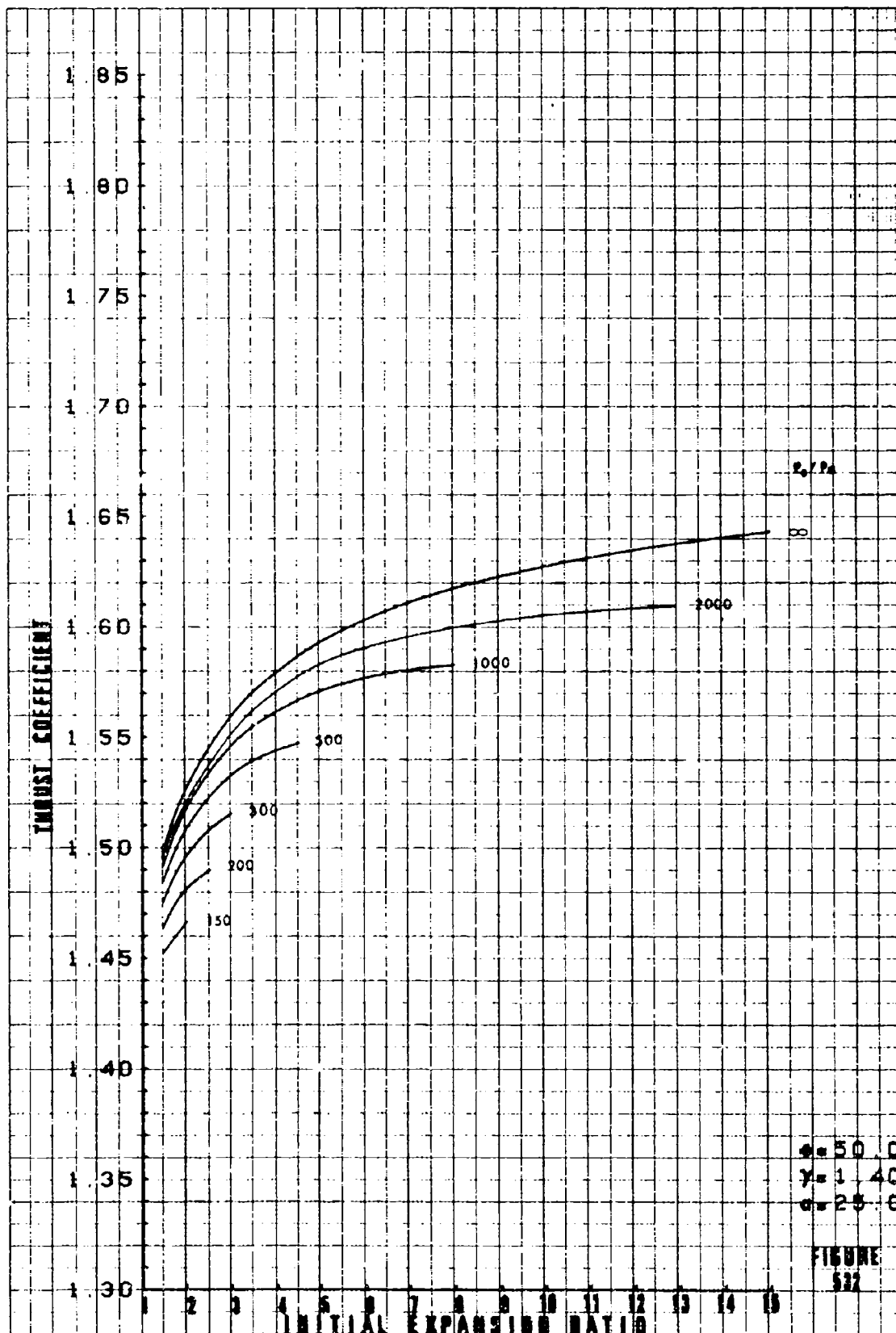
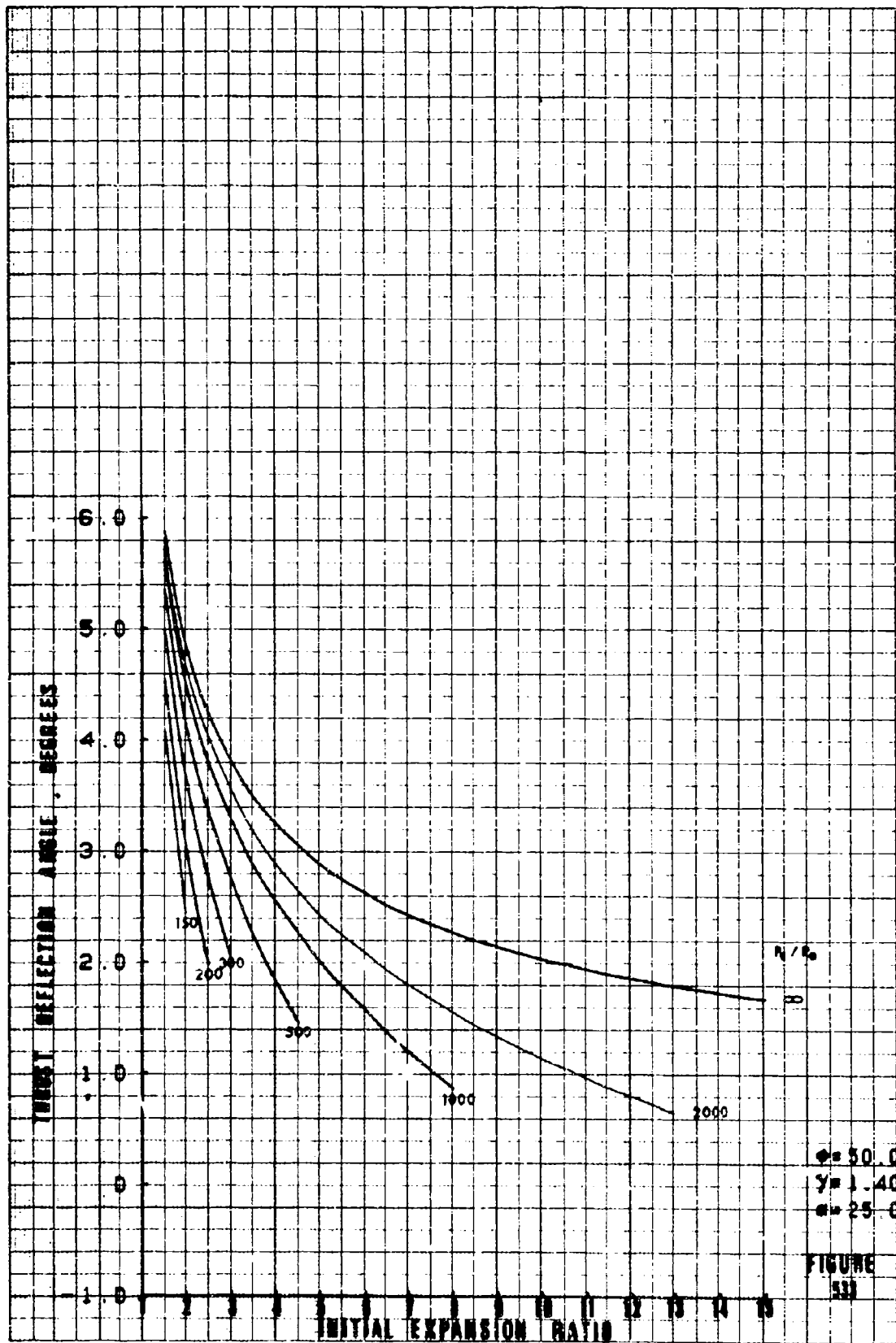


FIGURE 532



$\phi = 50.0$   
 $\gamma = 1.40$   
 $\sigma = 25.0$

FIGURE 533

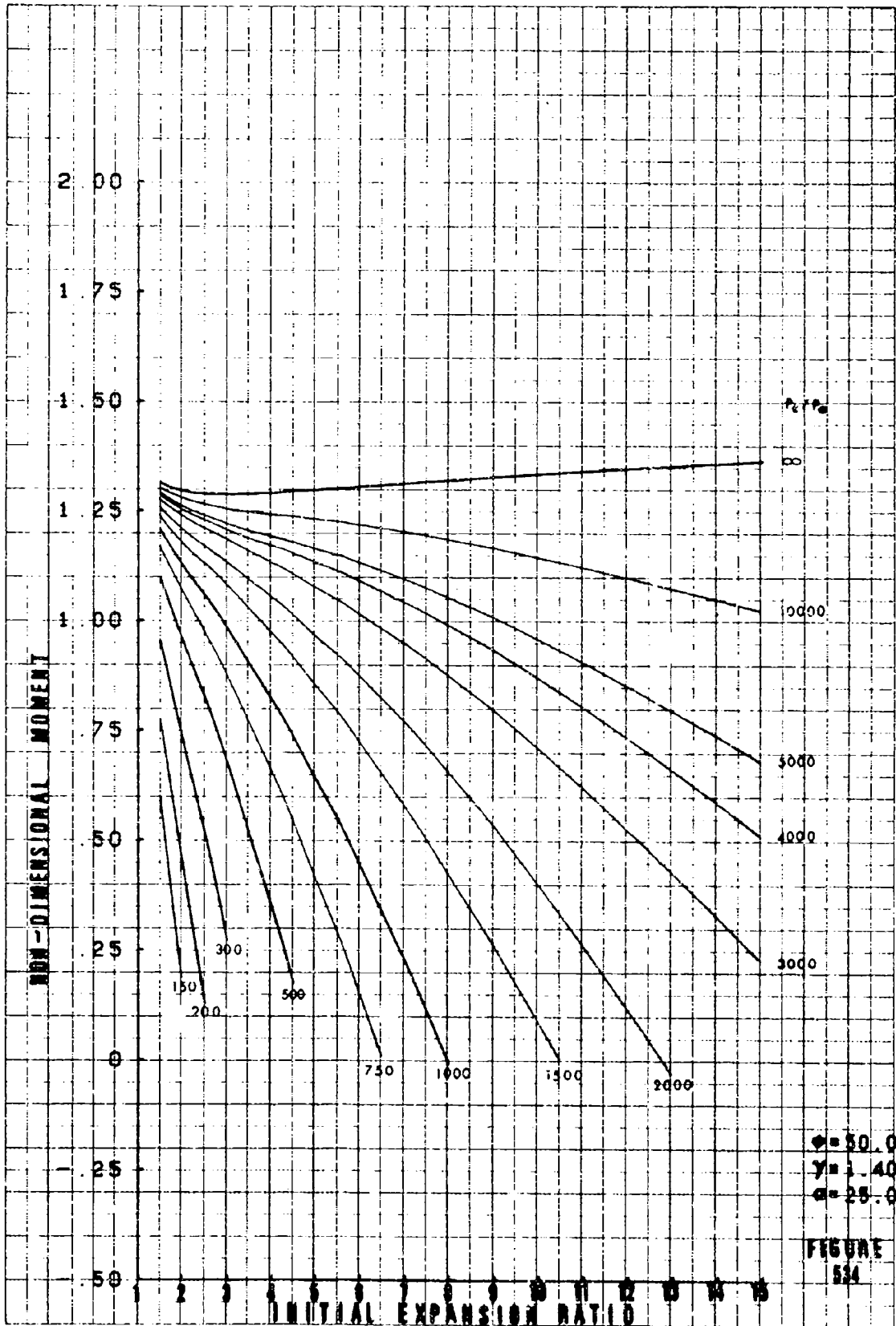
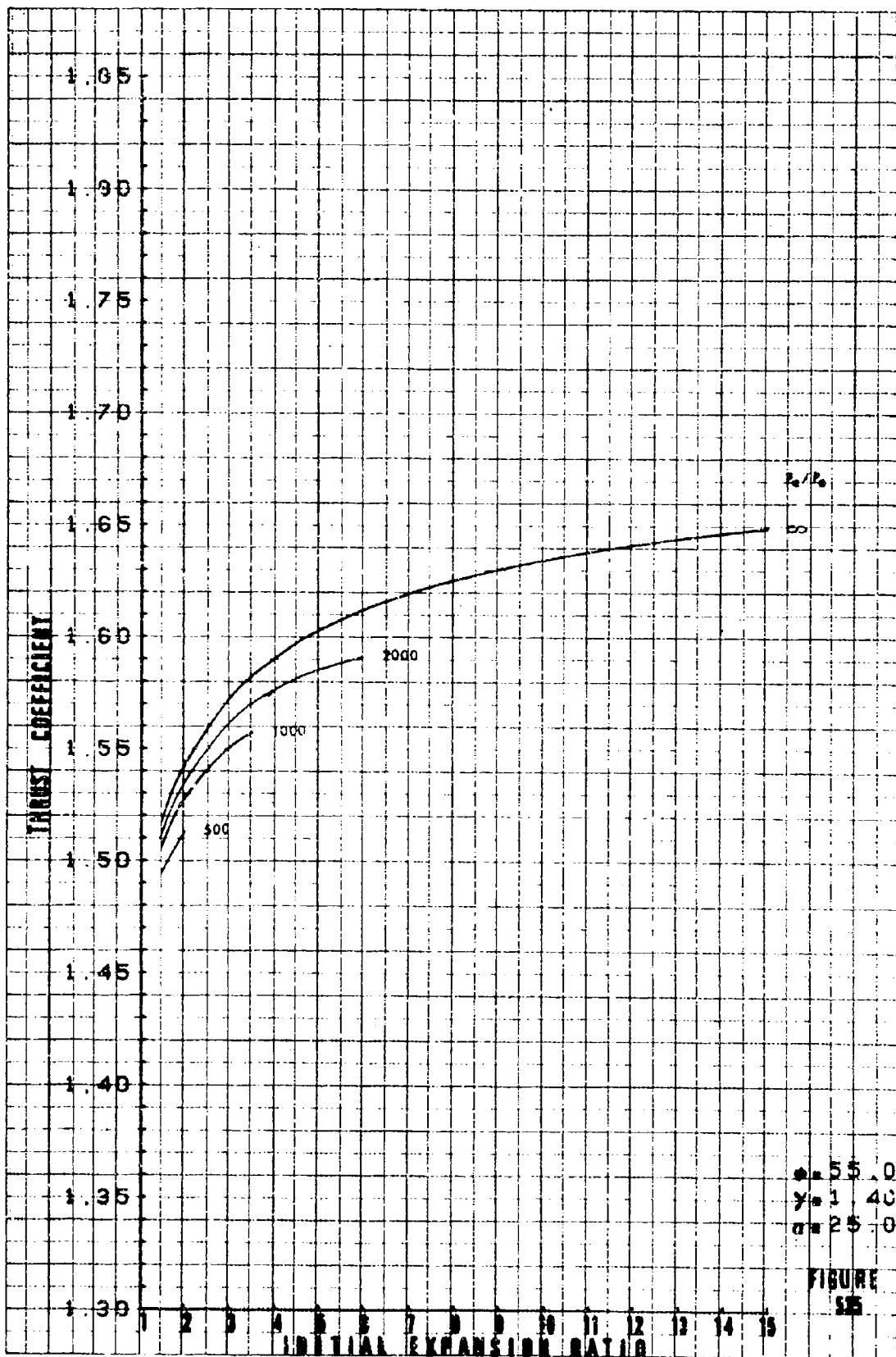


FIGURE 534





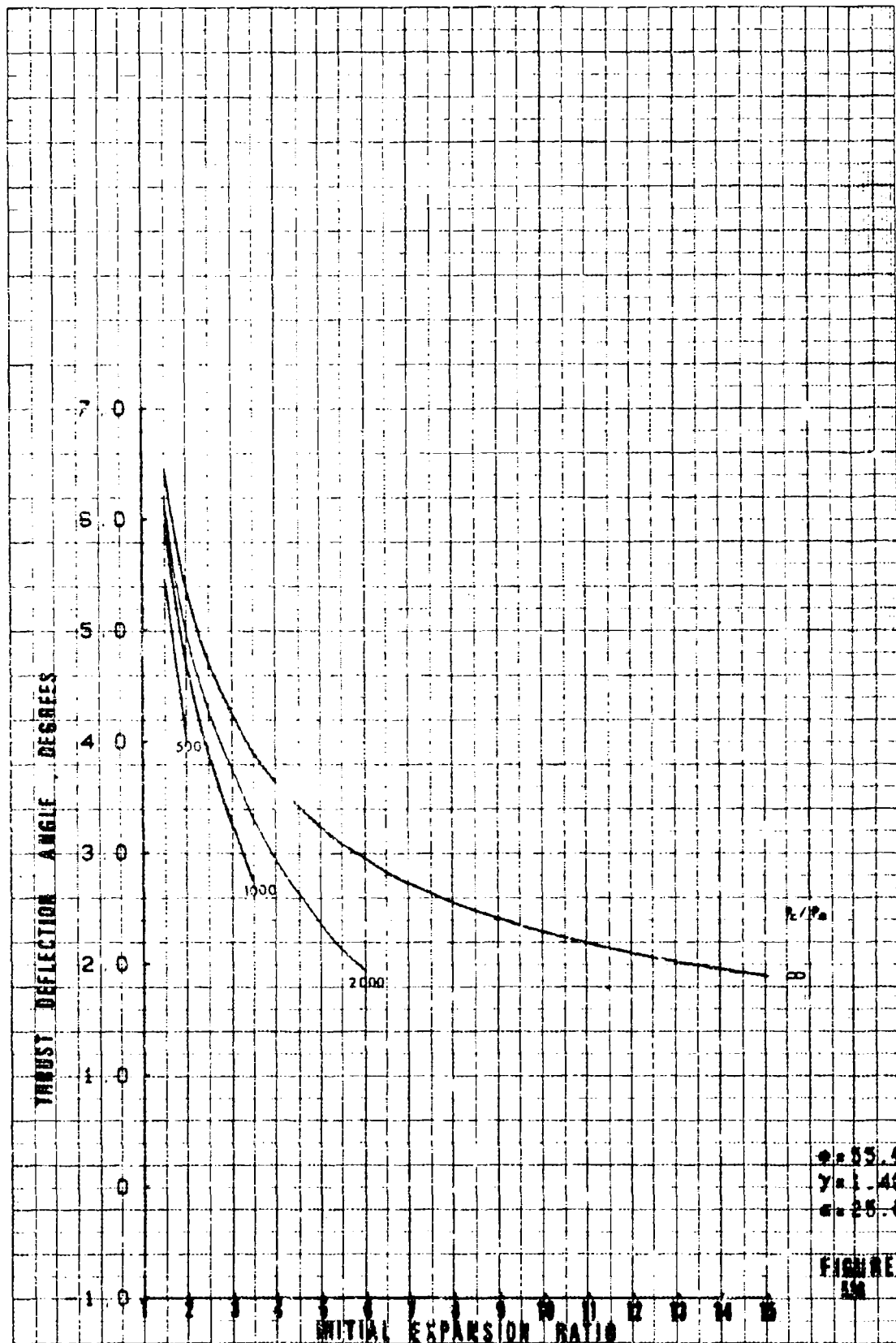
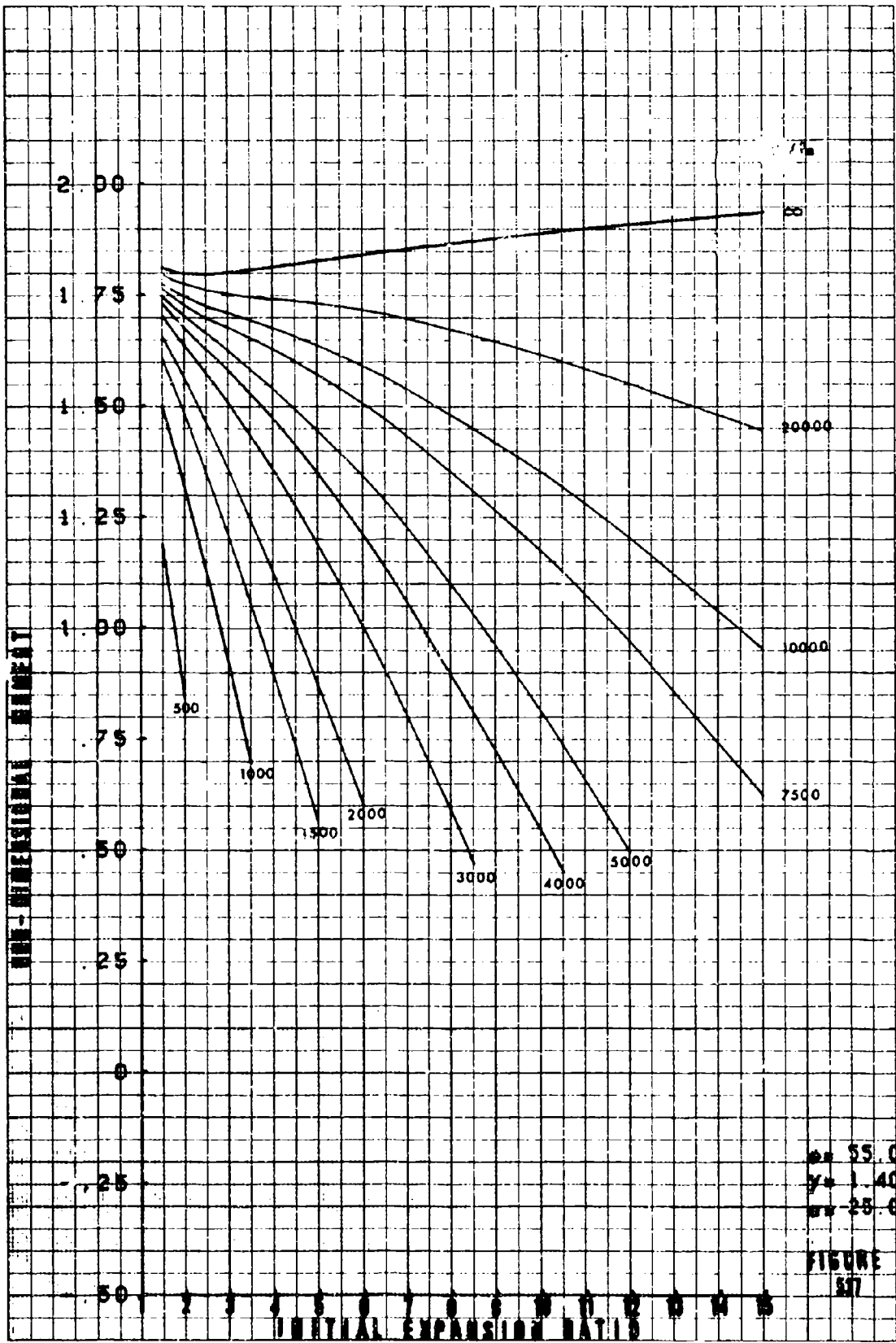
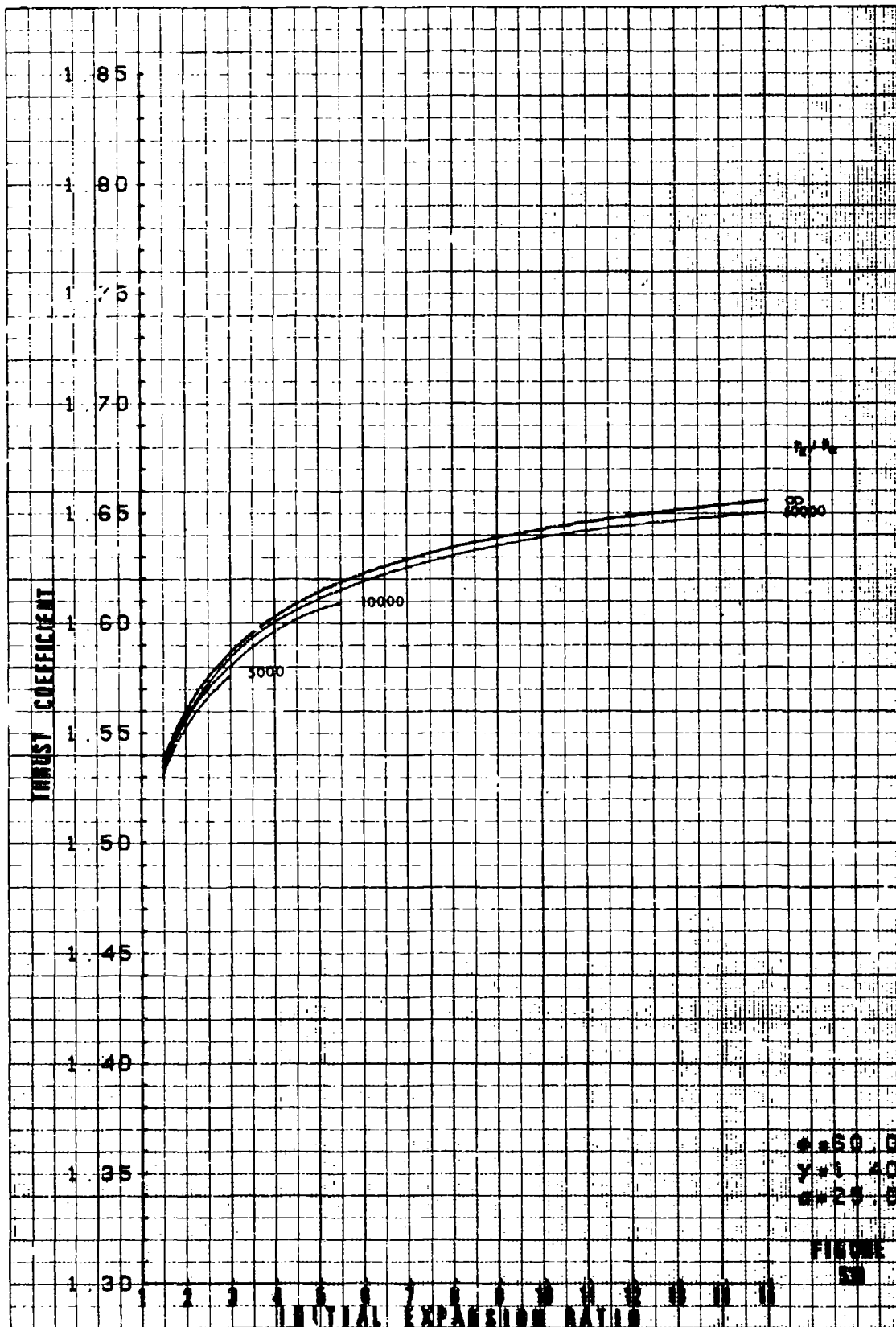


FIGURE 15



$\mu = 55.0$   
 $\gamma = 1.40$   
 $\sigma = 25.0$

FIGURE 87



$\gamma = 1.4$   
 $\beta = 0.0$   
 $\alpha = 0.0$

FIGURE 5

