APPLICATION OF THEORY TO EXTRUSION OF POLYETHYLENE

BY

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ABSTRACT

Application of Theory to Extrusion of Polyethylene

This thesis reviews the theory of isothermal melt extrusion beginning with the writings of early researchers up to its present state. The isothermal extrusion of a near-Newtonian liquid is compared to polyethylene, using five different extrusion screws, and calculated discharge rates are compared to the actual rates for both materials. A method of calculating forward flow was developed and this was shown to provide very good correlation with actual discharge rates.

Non-isothermal or plasticating extrusion of polyethylene was also studied and comparison is made to isothermal melt extrusion. The results obtained with the various types of screws studied are also discussed.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

Extrusion is a common method of forming thermoplastics and rubber and is an engineering unit operation which is beginning to receive much attention. The first screw extruder was built in 1880,[1] and with minor exceptions, the machine design has not changed appreciably since that time. The heart of an extruder is the screw and much remains to be done in the way of screw design. Unfortunately, there appears to be as many opinions regarding screw design as there are extruder operators, hence screw design has been largely empirical to date.

Lately, especially over the past four to five years, a number of papers have been published on the theory of screw extrusion which have shed much light on the subject. Unfortunately, all theory has its limitations and this is especially true of extrusion theory. One of the greatest limitations of extrusion theory to date is that it is based on the assumption of purely viscous or Newtonian liquid flow, while in the extrusion of most materials complex flow behavior takes place. This is especially true in the case of plasticating flow where the plastic in a granular solid state must be conveyed, compressed and melted by the rotation of the screw within a heated barrel.

Of all the materials presently being extruded, polyethylene is probably the most widely used and its use is expected to increase at a rapid rate owing to its increasing supply and its many extruded forms and uses. For this reason it is of interest to investigate the extrusion behavior of polyethylene in the light of present extrusion theory.

1. Numbers refer to references on page 82.

The purpose of this report is to present the state of extrusion theory and to investigate its application to the extrusion of a Newtonian-like viscous liquid in comparison to polyethylene.

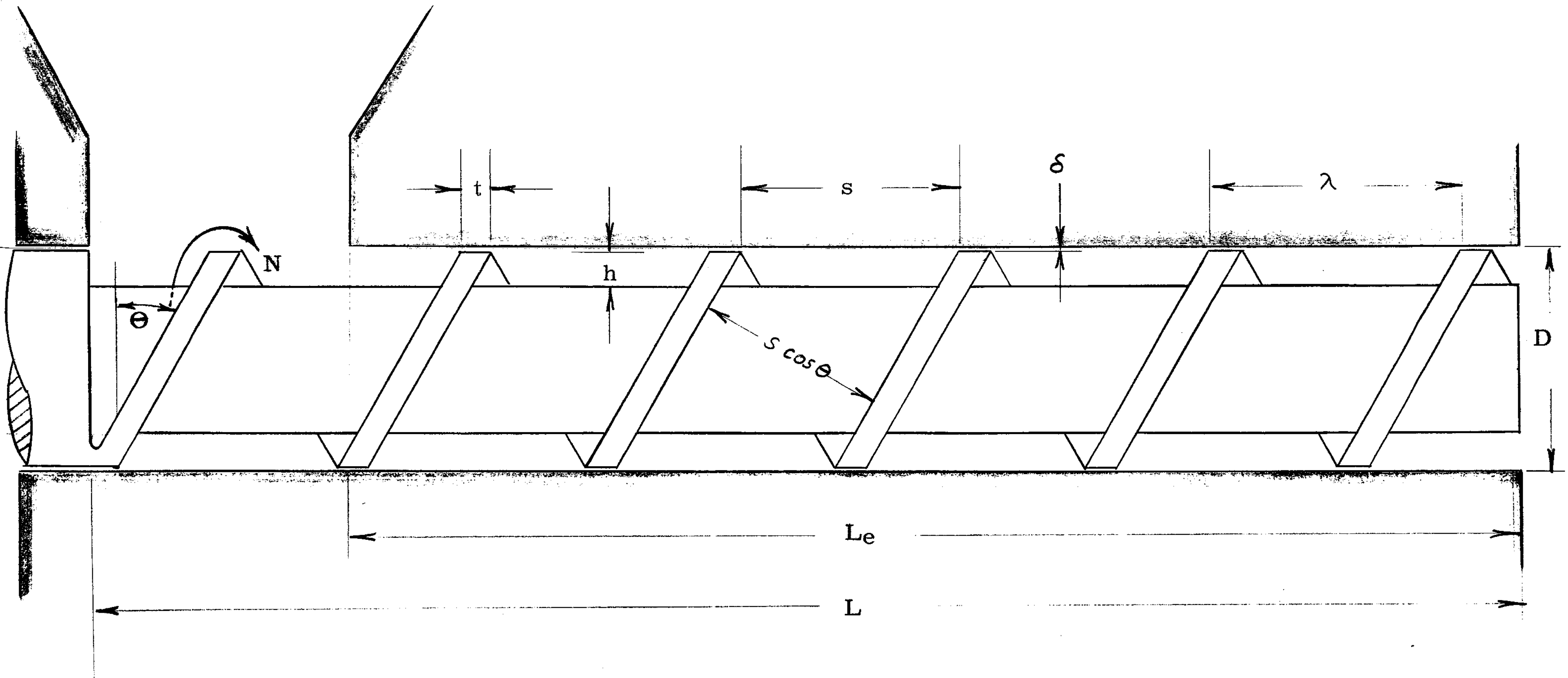
II. THEORY OF SCREW EXTRUSION

A. Introduction

An extruder consists of a driven screw which rotates within a tight fitting barrel and for purposes of comparison is analogous to a pump. A schematic diagram of an extruder is shown in Figure 1. In operation, granular plastic or strip rubber enters the screw at the feed section and is compacted and conveyed through the heated barrel by the rotation of the screw and forced through a die, held in a head at the end of the barrel. A screen-pack before the die is often used to filter foreign matter from the stock, and to break down unmelted granules.

As the screw rotates, the feed stock is conveyed forward at a rate which depends principally on the screw geometry and speed of rotation. The maximum forward rate at any given speed will be achieved when there is no resistance to forward flow. This condition is achieved when the head and screen-pack are removed. When a screen-pack and die are in place however, there is resistance to forward flow resulting in the generation of pressure which diverts a portion of the flow backward through the screw channel and backward through the clearance between the screw threads and barrel, if any. This will now be discussed in more detail.

Figure 1



SCHEMATIC DIAGRAM OF EXTRUDER

B. General Flow Relationship

There are four types or components of flow in screw extrusion.

The forward flow, Q_f, is caused by the rotating action of the screw which drags the material forward. This is sometimes referred to as "drag flow".

Backflow through the channel, Q_b, is caused by the pressure generated due to the resistance of the die, head, breaker plate, and screen pack.

Leakage flow, Q_l, backward over the screw threads is also caused by the pressure generated by dies, etc.

Transverse flow, Q_t, results from the inclination of the threads but does not have a forward or backward component, hence does not contribute to extrusion rate.

The net discharge rate, Q, at any instance is the sum of the forward flow, backflow through the channel and leakage flow between the threads and barrel and may be expressed:

$$Q = Q_f - Q_b - Q_l \tag{1}$$

The determination of each flow component will be discussed in more detail.

C. Forward Flow

The forward flow or gross forward rate in the direction of the screw channel rate Q_f, is caused by the shearing action of the liquid plastic between the rotating screw and the stationary barrel which drags the material forward. If the material stuck completely to the screw on entering the extruder and slipped completely on the barrel, no forward flow would result. If, on the other hand, the material stuck completely to the barrel and slipped on the screw in such a manner that no side slippage occurred, (as a nut prevented from rotating moves forward as the screw turns) the volume of material discharged would be equal to the volume of one complete flight for each revolution. Under these conditions, for a screw having uniform rectangular channel dimensions the output, Q_f, would be equal to the volume of the last flight times the screw speed.

$$Q_f = \pi D_m n s h N \qquad (2)$$

where:

D_m = mean diameter of screw = (D-h)

D = outside diameter of screw

s = channel width along screw axis

h = screw channel depth

N = screw speed

n = number of screw leads

In the case of a Newtonian liquid which sticks equally to both the barrel and the screw, the velocity distribution at any point is given by a differential equation. This equation was first solved by Rogowsky[2] and reported by Piggott[3] as follows.

$$Q_f = \frac{3\ n\ s^2}{\pi^2} D_m N \cos^3\Theta\ f(\ h/s \cos \Theta) \qquad (3)*$$

where: Θ = screw helix angle = arctan (lead/ πD_m)

* Equation 3 was expressed in terms of $\cos \Theta$ instead of $\cos^3 \Theta$, possibly a typographical error.

The function, $f(h/s \cos\Theta)$, is a correction factor containing the channel depth and a correction for the effect of the channel walls on the velocity distribution. This function was evaluated by Piggott[3] for various $h/s \cos\Theta$ values and was put into useful graphical form. This function is shown in Figure 2.

A similar equation was developed by Carley, and Strub.[4]

$$Q_f = n \pi D_m N s^2 \cos^3 \Theta F_d \tag{4}$$

where: F_d = shape factor for drag flow as $f(h/s \cos \Theta)$

They also evaluated the shape factor, F_d, for both rectangular and semi-elliptical profile channels as shown in Figure 3. This was obtained by taking into account the effect of channel walls on the velocity distribution of the liquid flowing in the channel.

Simplification of equation (4) can be made if the effect of channel walls on the velocity distribution is neglected, as is conceivable in the case of wide, shallow channels. It is then assumed that the liquid is being dragged forward between two infinite parallel plates by the forward motion of one over the other. Carley, Mallouk and McKelvey[5] presented such an equation.

$$Q_f = \frac{n}{2} \pi D_m h s \cos^2\Theta \tag{5}$$

Further simplification can be made if the effect of thread width is neglected.

A special case of equation (5) where the screw thread width is small compared to the pitch was also given.

Figure 2

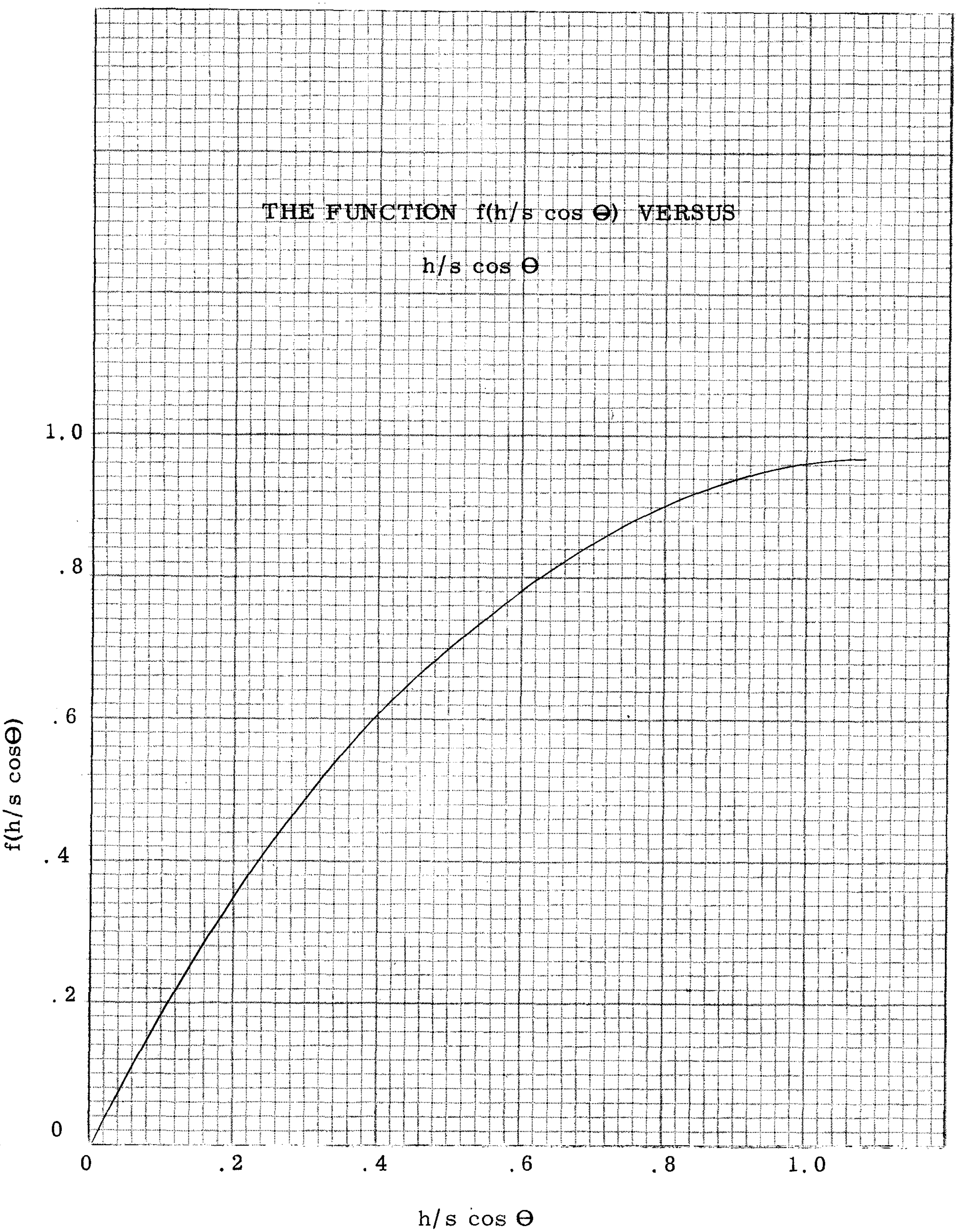
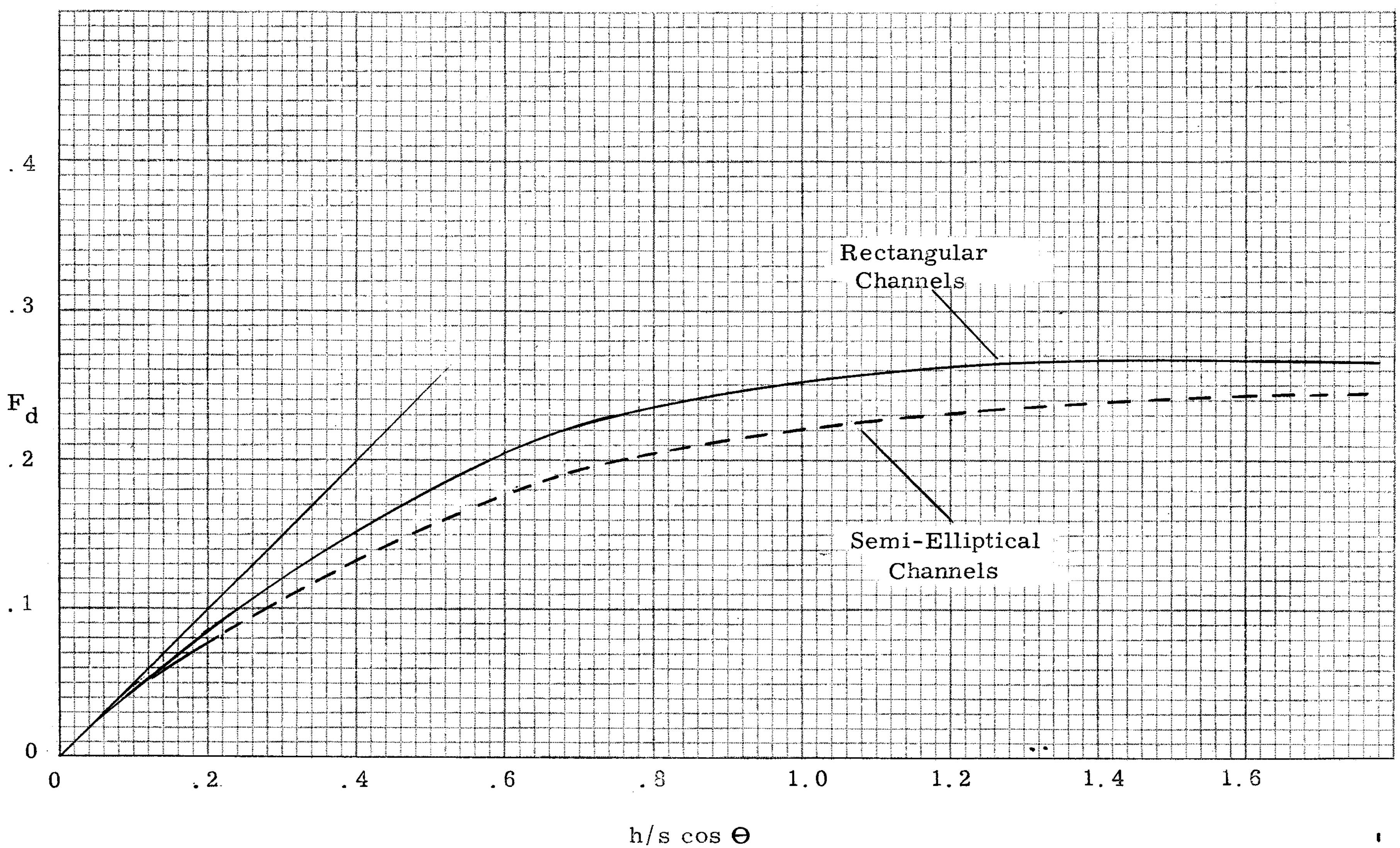

THE FUNCTION f(h/s cos Θ) VERSUS
h/s cos Θ
f(h/s cosΘ)
1.0
.8
.6
.4
.2
0
0
.2
.4
.6
.8
1.0
h/s cos Θ

Figure 3

SHAPE FACTOR FOR FORWARD FLOW



$$Q_f = \frac{n}{2} \pi^2 D_m^2 \; N\, h \sin \Theta \cos \Theta \qquad (6)$$

The major shortcoming of equations 2 to 6 is that they are suitable only for screws having uniform channel dimensions, while screws normally have decreasing thread volumes in progressing from the feed to the discharge end. The most common methods of achieving this decreasing volume or compression ration is to:

1. decrease the channel depth along the length
2. decrease the channel pitch along the length
3. decrease both

For screws having a constant compression ratio along their length, as in case 3 Carley, Mallouk and McKelvey[5] developed a general expression for Q_f where the thread width is neglected as in equation 6, and the ratio of channel width to depth is greater than 10.

$$Q_f = \frac{\dfrac{\pi^2 D_m^2 N}{2} \displaystyle\int_0^L \frac{\cot \Theta(\lambda)}{\left[h(\lambda)\right]^2}\, d\lambda}{\displaystyle\int_0^L \frac{\left[\csc \Theta(\lambda)\right]^2}{\left[h(\lambda)\right]^3}\, d\lambda} \qquad (7)$$

where: Θ is a function, $\Theta(\lambda)$ of length, λ

and h is a function, $h(\lambda)$ of length, λ

For variable pitch screws a graphical analysis of equation (6) is necessary.

For the case of a constant pitch, decreasing dept screw (case 2,) this reduces to:

$$Q_f = \frac{\dfrac{\pi^2 D_m^{\ 2} N \cot \Theta}{2} \left(\dfrac{L}{h_1 h_2} \right)}{\csc^2 \Theta \left[\dfrac{L(h_1 + h_2)}{2 h_1^{\ 2} h_2^{\ 2}} \right]} \qquad (8)$$

While for the case of a similar screw having a compression section, L_1, followed by a metering (uniform channel) section, L_2, this reduces to:

$$Q_f = \frac{\dfrac{\pi^2 D_m^{\ 2} N \cot \Theta}{2} \left(\dfrac{L_1}{h_1 h_2} + \dfrac{L_2}{h_2^{\ 2}} \right)}{\csc^2 \Theta \left[\dfrac{L_1(h_1 + h_2)}{2 h_1^{\ 2} h_2^{\ 2}} + \dfrac{L_2}{h_2^{\ 3}} \right]} \qquad (9)$$

D. Backflow Through Channel

Backflow through the channel is caused by the pressure developed along the screw resulting from the die and screen pack. As the die opening is reduced the resulting increased pressure increases the backflow. Although viscosity of the stock theroretically has no effect on forward flow, it does have an effect on the backflow which will increase, thus reducing output, as the viscosity decreases. Screw geometry also affects backflow, particularly channel depth. Deep channel screws allow considerably more backflow than shallow channel screws at high die resistances (small dies). Shallow channel screws therefore offer uniform extrusion rates which are affected by die size to a lesser degree than deep channel screws.

Backflow through a screw channel helix can be expressed in terms of flow of a liquid through a straight channel of rectangular cross section. Piggott[3] reports this flow equation was solved by Boussinesq giving rise to the following expression for backflow in screws of uniform channel dimensions for materials of constant viscosity.

$$Q_b = \frac{P s^2 h^2}{\mu \; l_t} \; g(s, h) \qquad (10)$$

where: μ = viscosity

l_t = uncoiled length of screw channel

The value of g (s, h) in terms of s and h are shown in Figure 4.

Carley and Strub[4] derived a similar equation also on the basis of Boussinesq's work.

$$Q_b = \frac{s h^3 \cos \Theta}{\mu \; F_p} \; \frac{dP}{d\lambda} \qquad (11)$$

where: F_p = a shape factor for backflow through the channel and is shown in Figure 5.

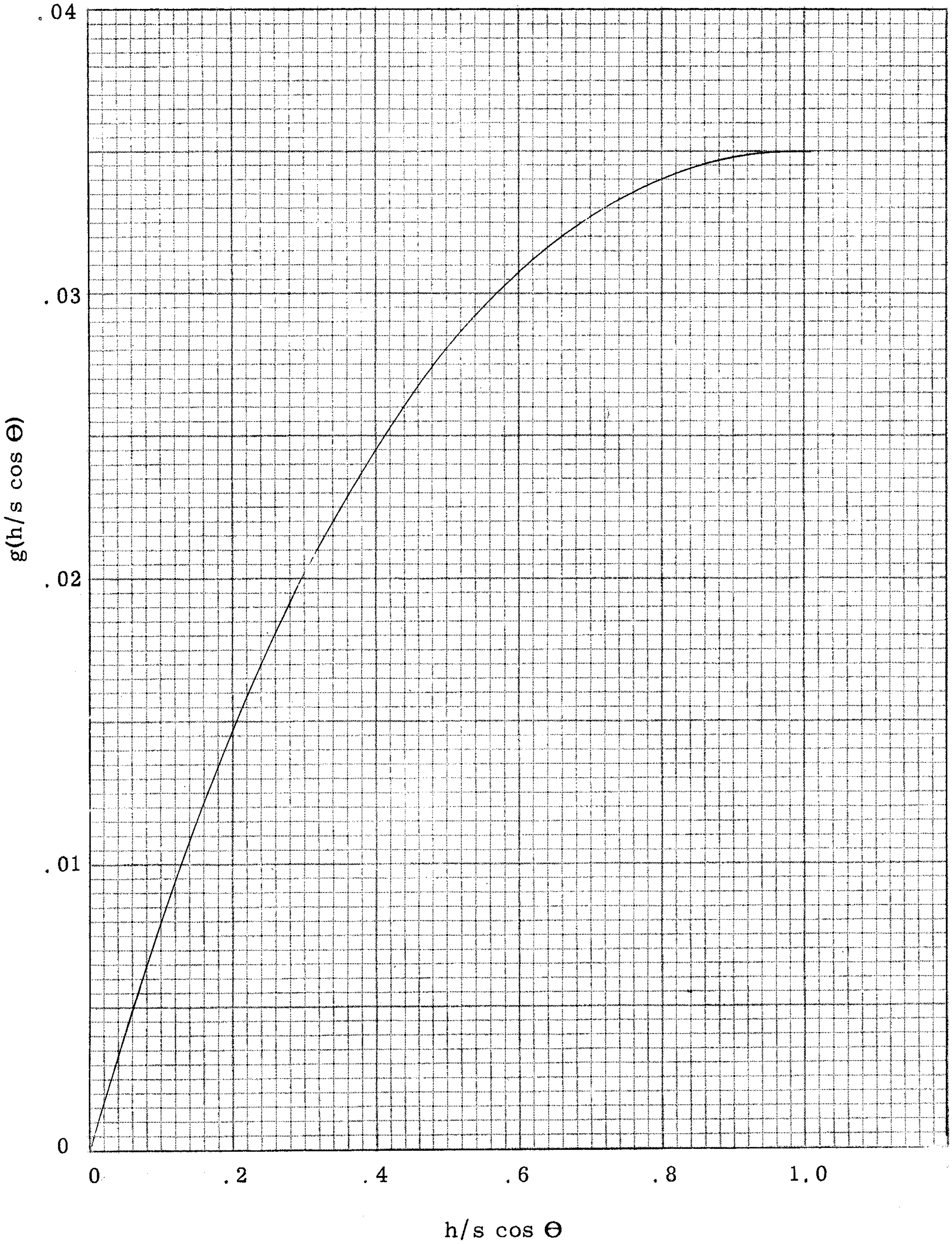
A special case of equation 11 is given by Gore[7] for screws in which the ratio of channel width to height is greather than 10.

$$Q_b = \pi \, \frac{D_m h^3 P \sin^2 \Theta}{12 \mu L_e} \qquad (12)$$

where: L_e = effective length of screw

Figure 4

THE FUNCTION g(h/s cos Θ) VERSUS h/s cos Θ



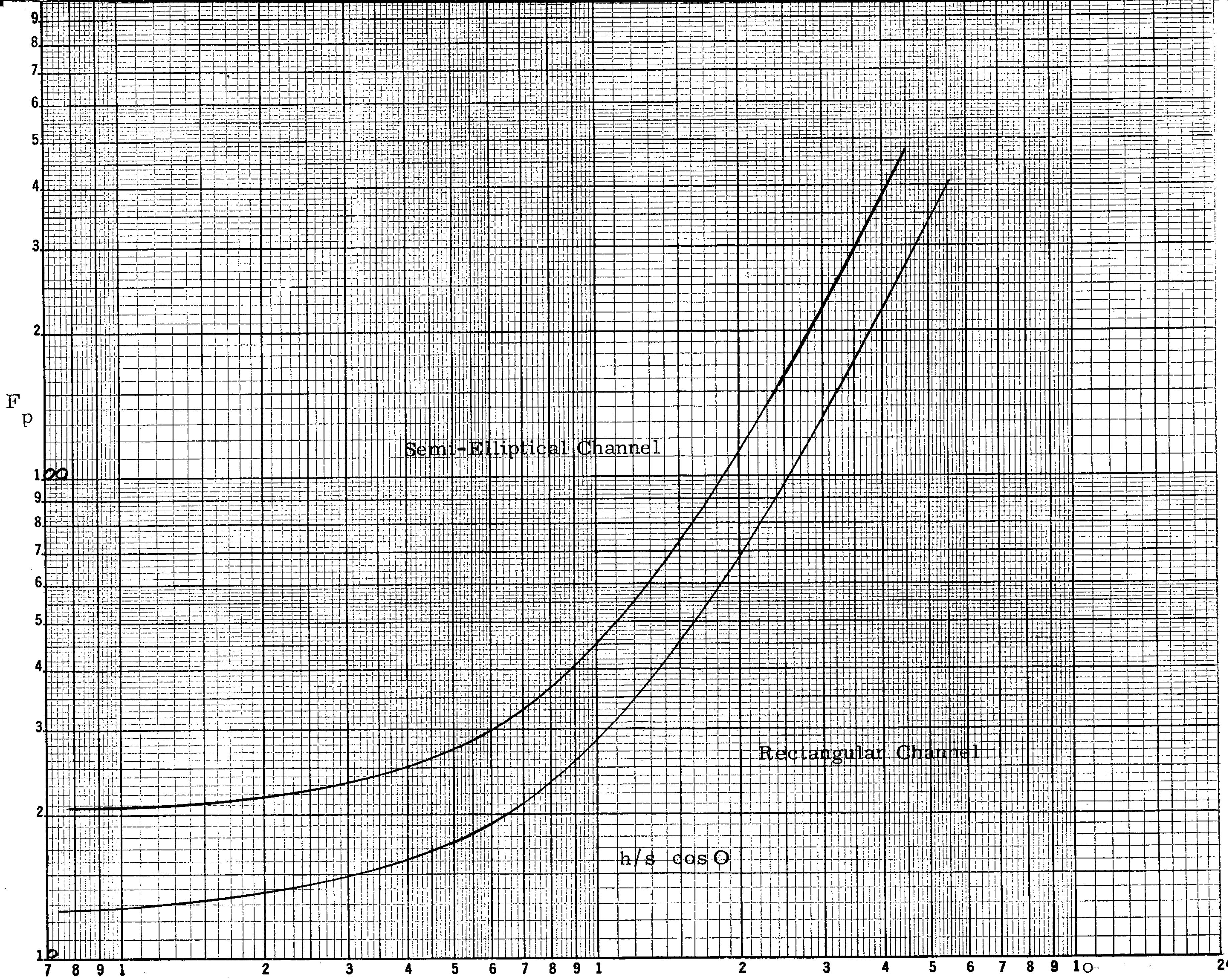


Figure 5

SHAPE FACTOR FOR PRESSURE FLOW

Other investigators have also given similar equations for pressure flow through rectangular channels, however these are even more complex and will not be considered. Notable among these is the work of Beyer and Towsley.[8]

E. Backflow Over Screw Threads

Leakage flow backwards over the screw threads is also caused by the pressure of die resistance. With proper fitting screws having small clearances the leakage flow can generally be neglected as only a small percentage of the backflow is diverted through the clearance. For estimating purposes, leakage flow can be expressed in terms of viscous liquid flow through annular orifices or long narrow slits. Rowell and Finlayson[9] derived an equation for leakage flow in 1928 in connection with screw lubricating pumps.

$$Q_l = \frac{\pi D \, \delta^3 \Delta P}{12 \mu t} \qquad (13)$$

where: δ = clearance between thread and barrel

t = thread width

ΔP = pressure drop

Carley and Strub[4] introduced a correction factor for screw eccentricity of 1.2 into this equation (13). Thus:

$$Q_l = \frac{\pi D_m \, \delta^3 \Delta P}{10 \mu t} \qquad (14)$$

Assuming a constant pressure rise along the screw length equation (14) can be shown to be equated to the following expression as shown by Carley, Mallouk and McKelvey.[5]

$$Q = \frac{\pi^2 D^2 \delta^3}{10 \mu} \frac{\tan \Theta}{t} \frac{\Delta P}{L_e} \qquad (15)$$

Piggott[3] also developed a similar equation for leakage flow as follows:

$$Q = \frac{P \lambda \delta^3}{12 \mu t L_e} \sqrt{\pi^2 D^2 + \lambda^2} \qquad (16)$$

where: λ = screw lead

F. Discharge Through Dies

In considering extruder discharge through dies, the screw is related to the die as a pressure developing device. Hence if two screws develop the same pressure under identical conditions of operation they will give the same output rate. Discharge rates through dies is also inversely proportional to the viscosity of the stock. For Newtonian liquids flowing through a die of any shape equation 17 applies.

$$Q = k \left(\frac{\Delta P}{\mu} \right) \qquad (17)$$

where: k = die constant

For circular dies having a length greater than ten times the diameter, the Poiseuille equation governing viscous flow in tubes and capilaries applies:

$$Q = \frac{\pi d^4}{128 l} \left(\frac{\Delta P}{\mu} \right) \qquad (18)$$

where: d = die diameter

l = die length

ΔP = pressure drop across die

Taking into consideration the general screw flow equation 1 which may be written:

$$Q = \alpha N - \beta \left(\frac{\Delta P}{\mu}\right) - \gamma \left(\frac{\Delta P}{\mu}\right) \tag{19}$$

where:

$$Q_f = \alpha N$$

$$Q_b = \beta \left(\frac{\Delta P}{\mu}\right)$$

$$Q_1 = \gamma \left(\frac{\Delta P}{\mu}\right)$$

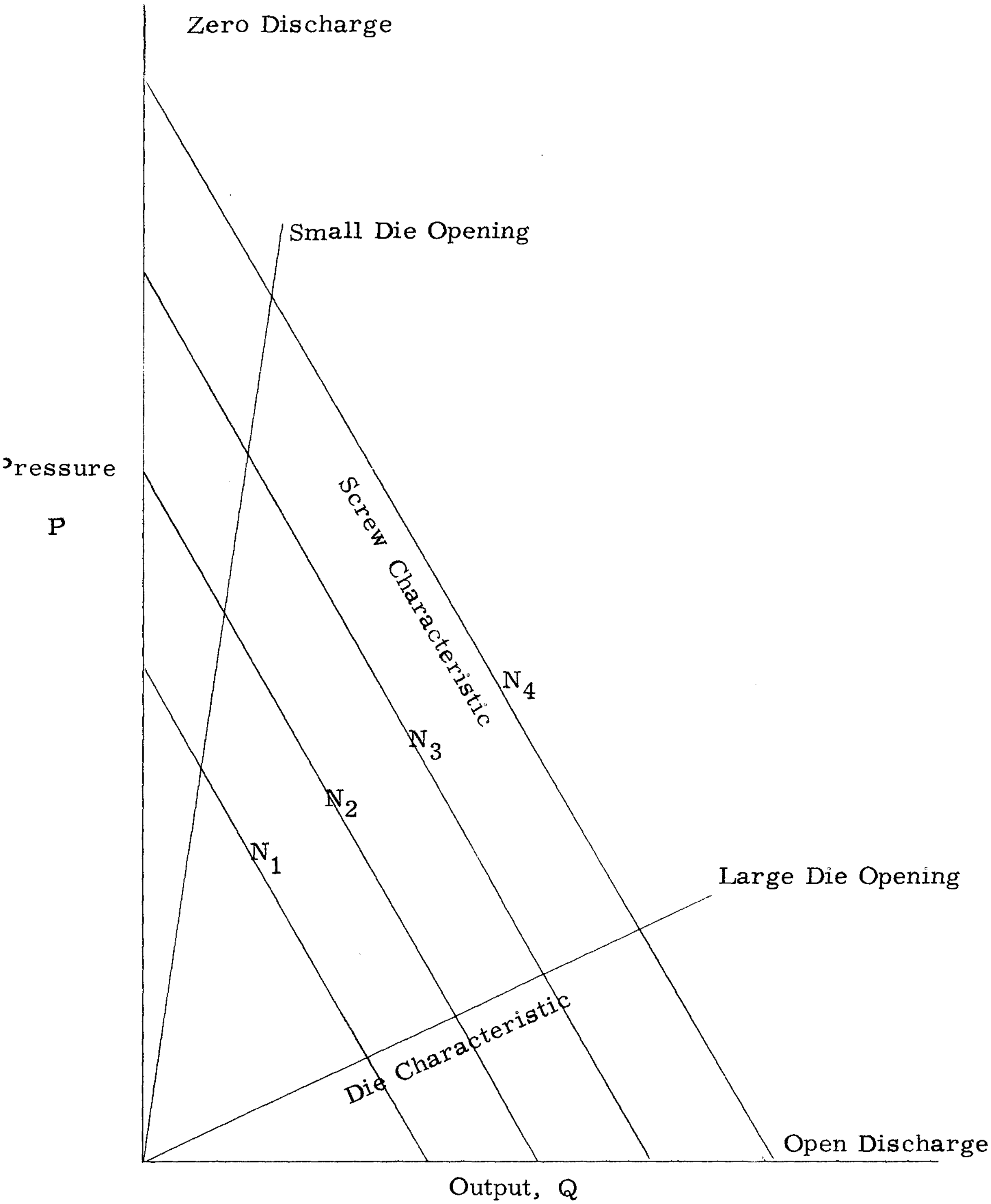
and combining equation 18 with the die flow equation, 17, it is possible to develop an expression relating the screw throughput with the die throughput in terms of constants as follows:

$$Q = \frac{\alpha N}{1 + \frac{(\beta + \gamma)}{k}} \tag{20}$$

Equation 19 may be better understood by considering an extruder in operation at speeds N_1, N_2, N_3 and N_4. Under conditions of open discharge (i. e. without die, head or screen pack in place), Q will be maximum (αN) as β and γ are O. As smaller dies are placed in front of the screw β and γ will become larger and k becomes smaller thus reducing Q. This is shown in Figure 6.

Figure 6

Theoretical Pressure - Discharge Relationship for Isothermal Melt Extrusion



With certain limitations it is possible to develop similar equations for variable channel screws. Carley, Mallouk and McKelvey[5] developed such an equation for the case where thread width and leakage flow are neglected for screws having channel widths greater than 10 times the channel height. This was done by combining equations 6 and 12, integrating over the length of the screw to obtain the total pressure rise, and substituting the resulting pressure expression into die flow equation 17.

$$Q = \frac{\dfrac{\pi^2 D_m^{\,2} N}{2} \displaystyle\int_0^L \frac{\cot \Theta(\lambda)}{[h(\lambda)]^2}\, d\lambda}{\dfrac{\pi D_m}{12\,k} \displaystyle\int_0^L \frac{[\csc \Theta(\lambda)]^2}{[h(\lambda)]^3}\, d\lambda} \qquad (21)$$

Equation 6 was obtained in the same manner, however under conditions of open discharge the $\frac{\pi D_m}{12\,k}$ term drops out.

For variable pitch screws equation 21 must be evaluated by graphical integration of portions of the numerator and denominator.

For screws having a constant pitch and tapering channel depth from feed section to discharge end, equation 21 reduces to:

$$Q = \frac{\dfrac{\pi^2 D_m^{\,2} N \cot \Theta}{2} \left(\dfrac{L}{h_1 h_2} \right)}{\dfrac{\pi D_m}{12\,k} + \csc^2 \Theta \left[\dfrac{L(h_1 + h_2)}{2\, h_1^{\,2}\, h_2^{\,2}} \right]} \qquad (22)$$

While for the case of a similar screw having a compression section, L_1, followed by a metering section, L_2, equation 21 becomes:

$$Q = \frac{\frac{\pi^2 D_m^2 N \cot\Theta}{2}\left(\frac{L_1}{h_1 h_2} + \frac{L_2}{h_2^2}\right)}{\frac{\pi D_m}{12 k} + \csc^2\Theta\left[\frac{L_1(h_1 + h_2)}{2 h_1^2 h_2^2} + \frac{L_2}{h_2^3}\right]} \qquad (23)$$

III. APPLICATION OF THEORY TO EXTRUSION OF VISCOUS LIQUID

Several investigators have confirmed various portions of the preceeding theoretical extrusion equations within certain limits Piggott[3] presented data obtained in the extrusion .5 and 1.1 poise oils in a 1 inch diameter extruder and gave evidence of excellent correlation with his equations. He also investigated the extrusion of several rubber stocks and found considerable deviation from theory which he attempted to correct by accounting for the effect of shear rate. McKelvey[6] investigated the extrusion of corn sirup in a 2 inch extruder and also gave evidence of excellent correlation with the equations developed by Carley, Mallouk and McKelvey. He investigated the melt extrusion of polyethylene terephthalate but presented insufficient data to fully support the conformance of this material to theoretical principles.

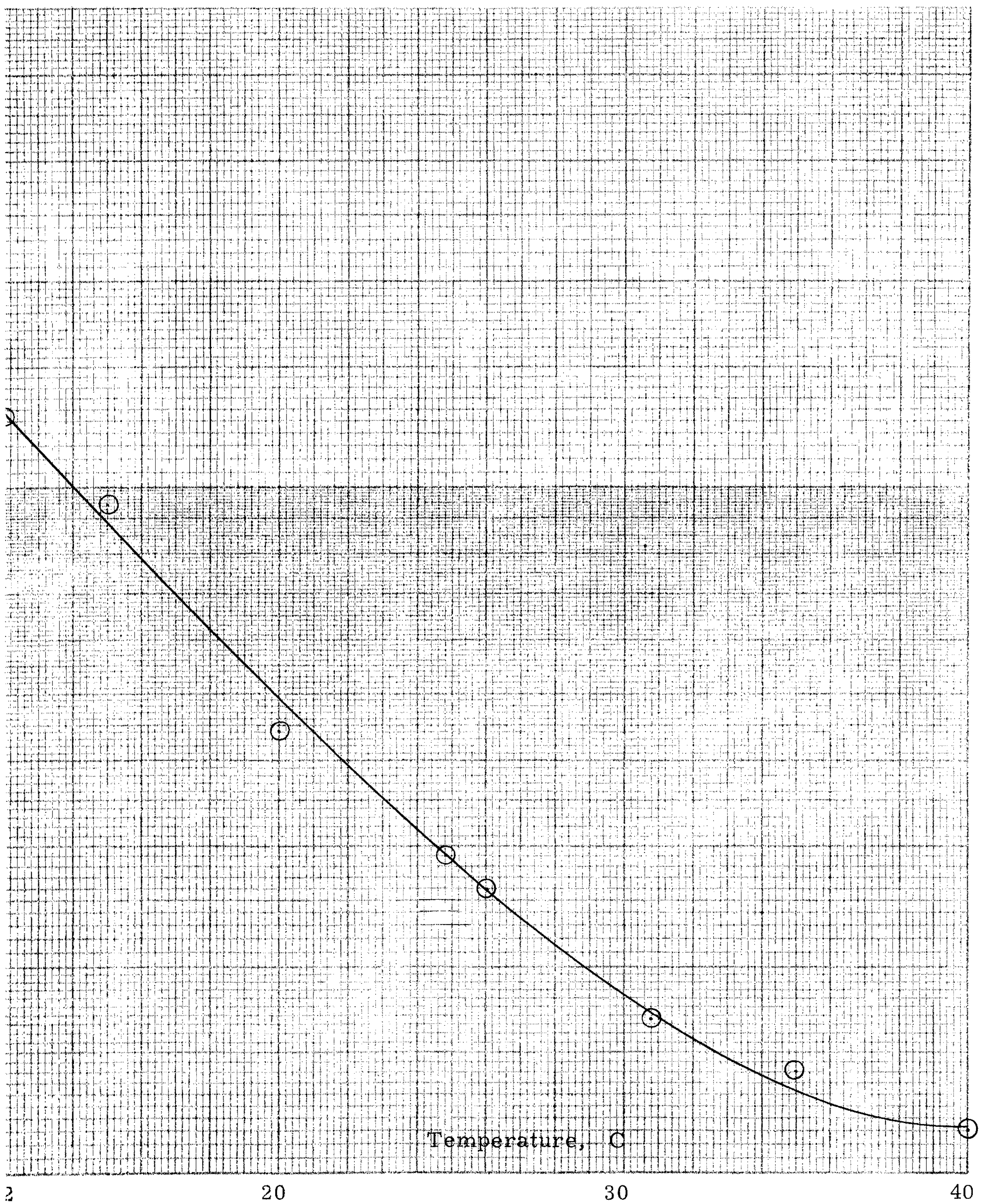
A. Procedure

In order to further investigate the validity of the foregoing extrusion theory, a viscous liquid, Oronite Polybutene #24 having a viscosity of 400 poises at room temperature,* was extruded in a No. 1 Royle (2 inch diameter) extruder using five different common screws and several different circular dies.

* Viscosity - Temp. curve is shown in Figure 7.

Figure 7

VISCOSITY VERSUS TEMPERATURE CURVE FOR POLYBUTENE #24



The extruder had an effective barrel length of 27 1/2 inches (excluding length in feed section) and was fitted with a breaker plate having 108, 1/8 inch diameter by .35 inch holes, and a screen pack consisting of a single 20, 40 and an 80 mesh screen. The extruder head was a crosshead type and was fitted with a calibrated Bourdon type pressure gage filled with silicone grease. Several gages having ranges of 0 to 200 psi, 0 to 600 psi and 0 to 3000 psi were employed in the course of the investigation. Extrusion rates were measured by weighing the extrudate over a given period of time. In the extrusion of Polybutene #24 the head, barrel and screw were maintained at a uniform temperature by circulating cold water through them. The temperature of the extrudate was measured at the die with a calibrated mercury thermometer.

Two of the screws employed were the constant depth, decreasing pitch type having relatively deep channels. The main difference between these two screws was their different compression rations of 3.9 and 2.7 to 1. The high compression screw had a double flighted feed section which did not alter its characteristics. The remaining screws were the constant pitch, decreasing depth type. Two of these screws had relatively shallow channels, one of which had a metering or constant dimension section at the discharge end, while the third had a deep channel also followed by a metering section. A summary of all the pertinent dimensions of the screws is shown in Table 1.

Table I

List of Screw Dimensions - Inches

	1A	1B	2	3A	3B
Total length, L of threaded section	30	30	30	30	30
Effective length, L_e	27 1/2	27 1/2	27 1/2	27 1/2	27 1/2
Length of metering section, L_2	8.60	6.00	none	none	none
Channel depth, h	.430-.180	.270-.125	.281-.126	.372	.395
Channel width, s	2.00	1.80	1.75	2.406-.500	2.080-.782
Diameter D	1.996	1.994	1.996	1.993	1.990
Radial clearance,	.004	.004	.004	.005	.007
Thread width, t	.145	.200	.250	.220	.36-.28
Fillet radius, r	1/16	1/8	1/8	1/4	1/4
Flights, n	2	1	1	1	1 (2 in feed section)
Lead, λ	4.29	2.00	2.00	2.30-1.00	2.73-.78
Compression ratio, R	2.0/1	2.0/1	2.0/1	2.7/1	3.9/1
Helix angle, Θ	36.9°	18.8°	18.8°	24.3° - 11.4°	29.1° - 8.9°
No. of flight turns	7 1/2 (double)	15	15	18	18
Vol. of discharge flight, in^3	4.10	1.29	1.27	1.38	.88
Vol. of threaded length, $in.^3$	40.5		27.2	43.7	45.7

Four circular orifice dies of various diameters ranging from .046 to .236 inches were employed in the course of the investigation. In all cases the length of the die surface was equal to the diameter and the approaching taper was 26.3 degrees from the axis. While these were typical plastic extrusion dies, they were too short to be treated according to the Poiseuille equation governing viscous flow in tubes. A description of the dies is shown in Table II.

Table II

List of Die Dimensions

Nominal	Diameter, d inches	Length, l inches
.046	.0461	l = d
.096	.0957	"
.144	.1445	"
.236	.2360	"

B. Results

Using each of the screws described, a number of extrusion runs were made with four screw speeds of 25, 50, 75 and 100 rpm, measuring the discharge rates through various dies (Table II) and open discharge. Under these conditions it was found that the volumetric extrusion rate was linear with screw speed and could therefore be expressed in cubic inches per revolution. The discharge rates for each screw is shown in Figures 8a, b, c, d, and e. It was also found that the screw characteristic for each screw was linear with output rate and pressure as shown in Figures 9a, b, c, d, and e,

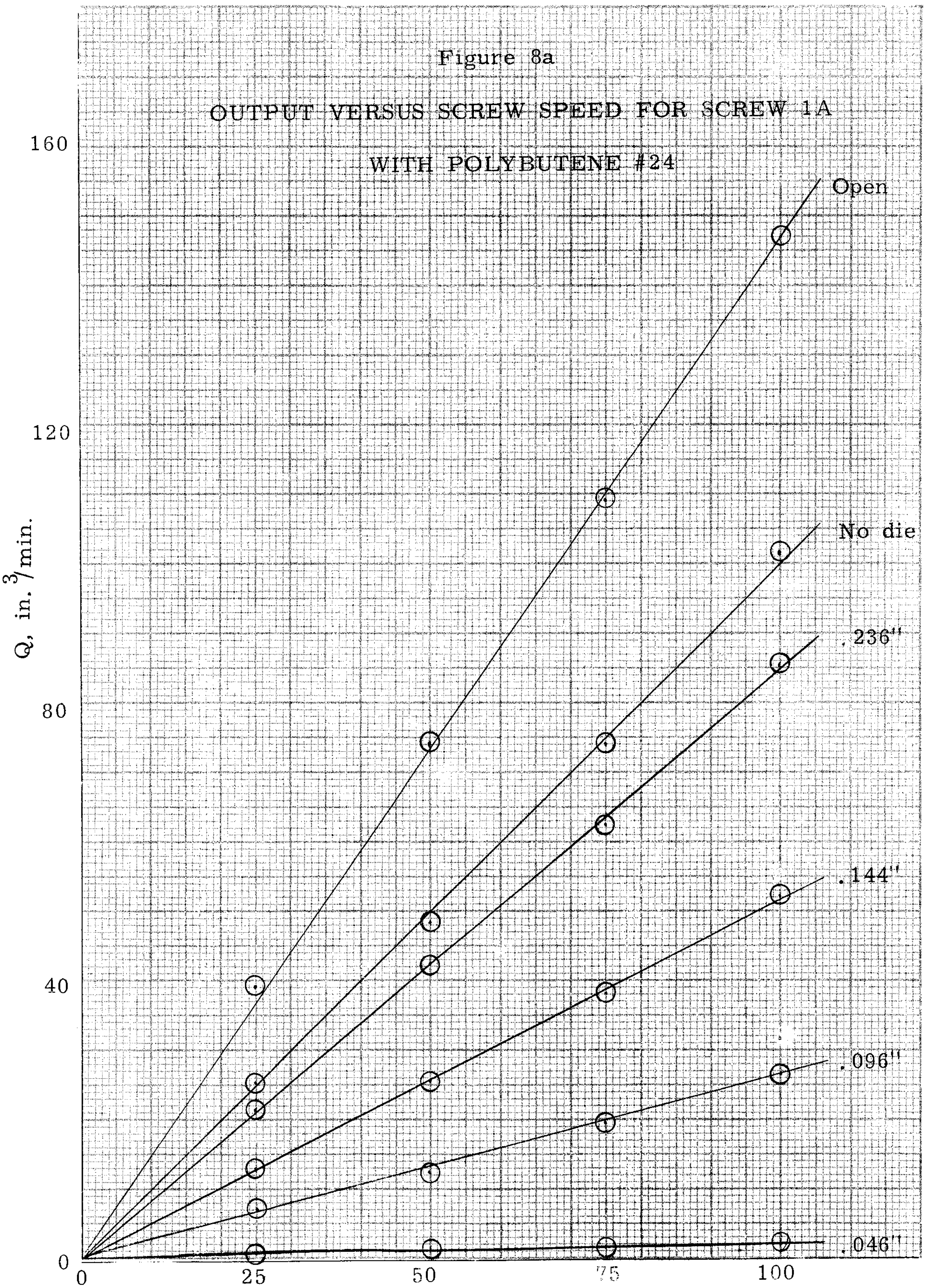


Figure 8a
OUTPUT VERSUS SCREW SPEED FOR SCREW 1A
WITH POLYBUTENE #24
Open
No die
.236"
.144"
.096"
.046"
160
120
80
40
0
Q, in.^{3}/min.
0
25
50
75
100
RPM

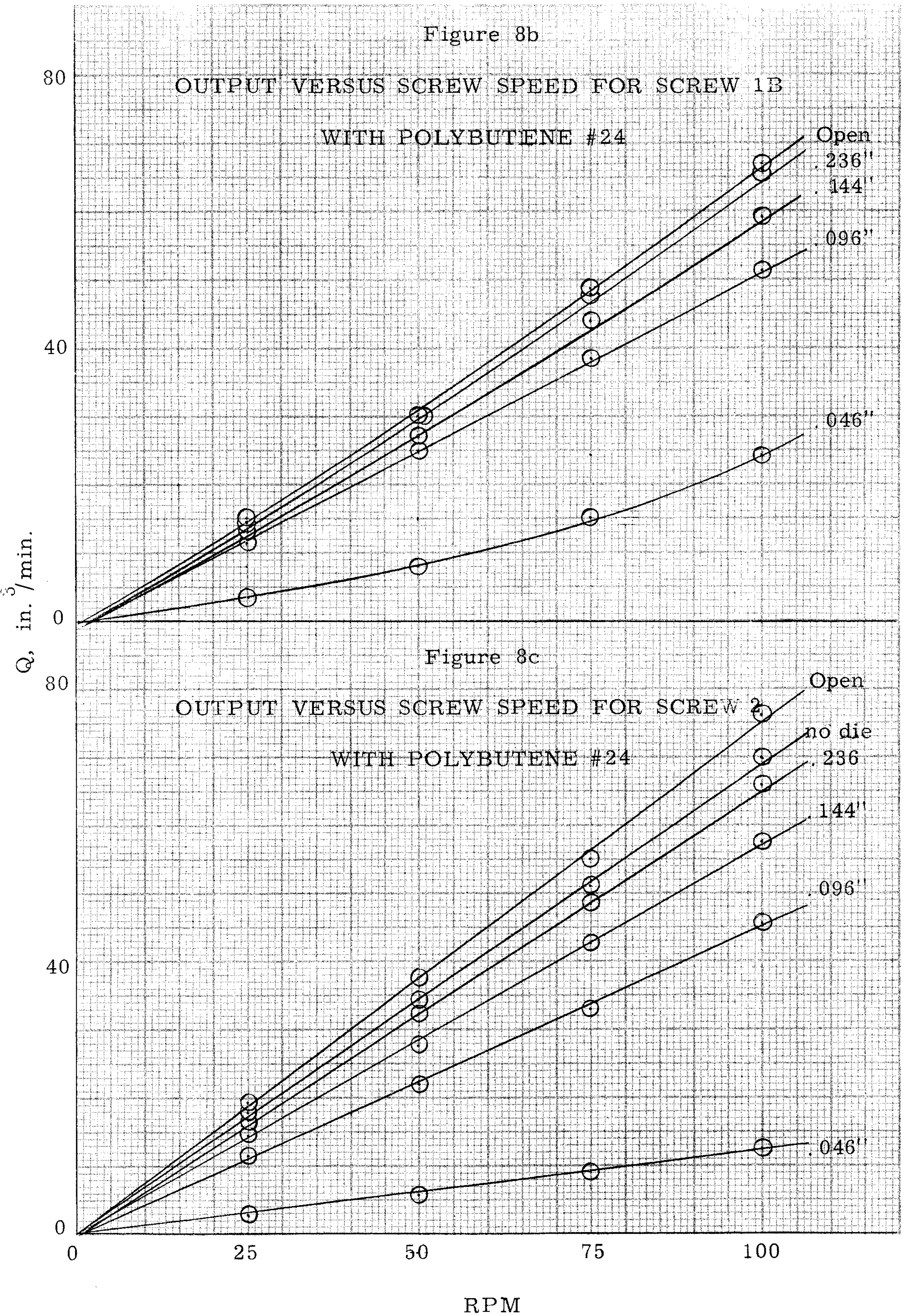


Figure 8b

OUTPUT VERSUS SCREW SPEED FOR SCREW 1B WITH POLYBUTENE #24

Figure 8c

OUTPUT VERSUS SCREW SPEED FOR SCREW 2 WITH POLYBUTENE #24

Figure 8d

OUTPUT VERSUS SCREW SPEED FOR SCREW 3A

WITH POLYBUTENE #24

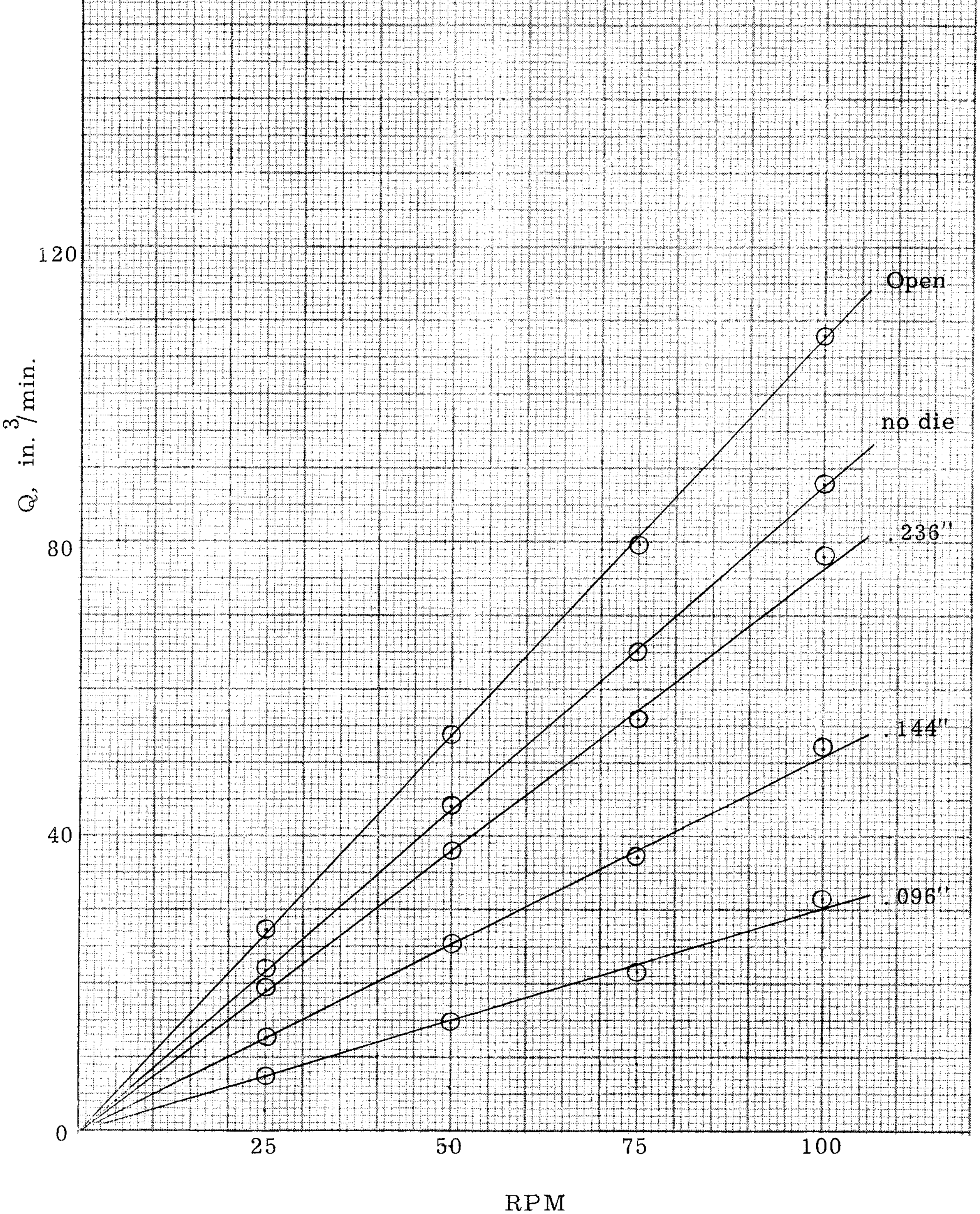


Figure 8e

OUTPUT VERSUS SCREW SPEED FOR SCREW 3B

WITH POLYBUTENE #24

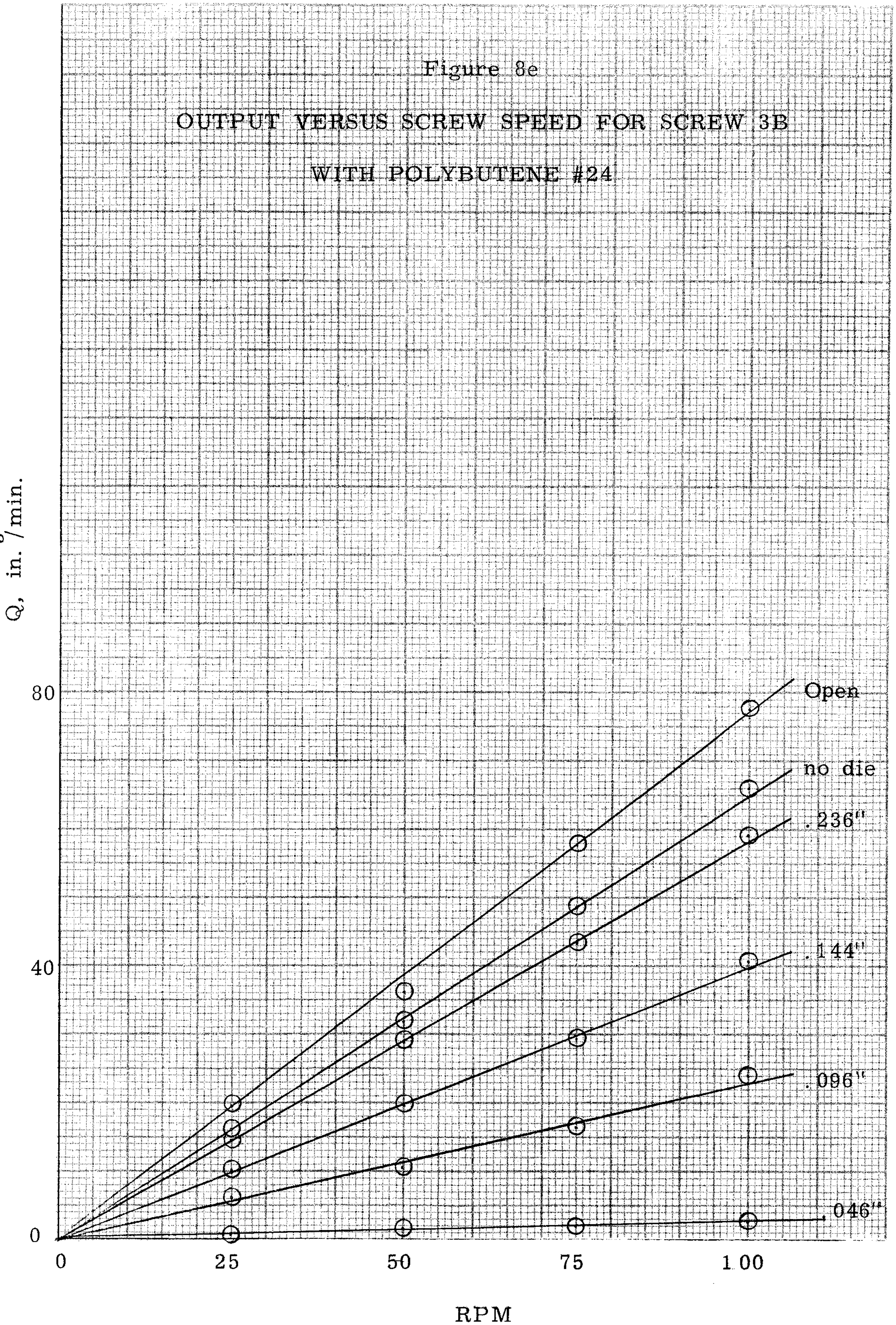


Figure 9a

PRESSURE-DISCHARGE RELATIONSHIP FOR SCREW 1A

WITH POLYBUTENE #24

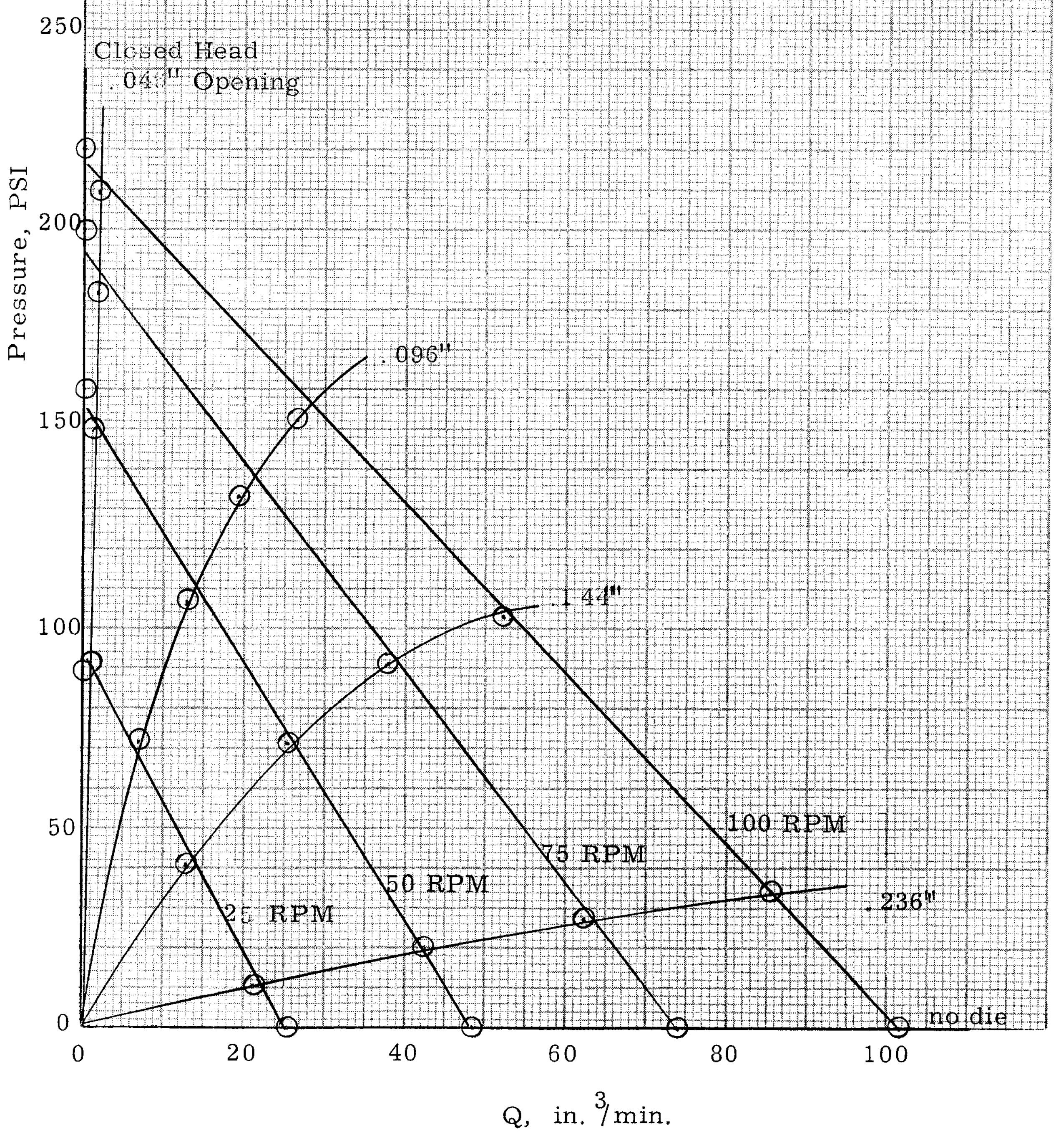
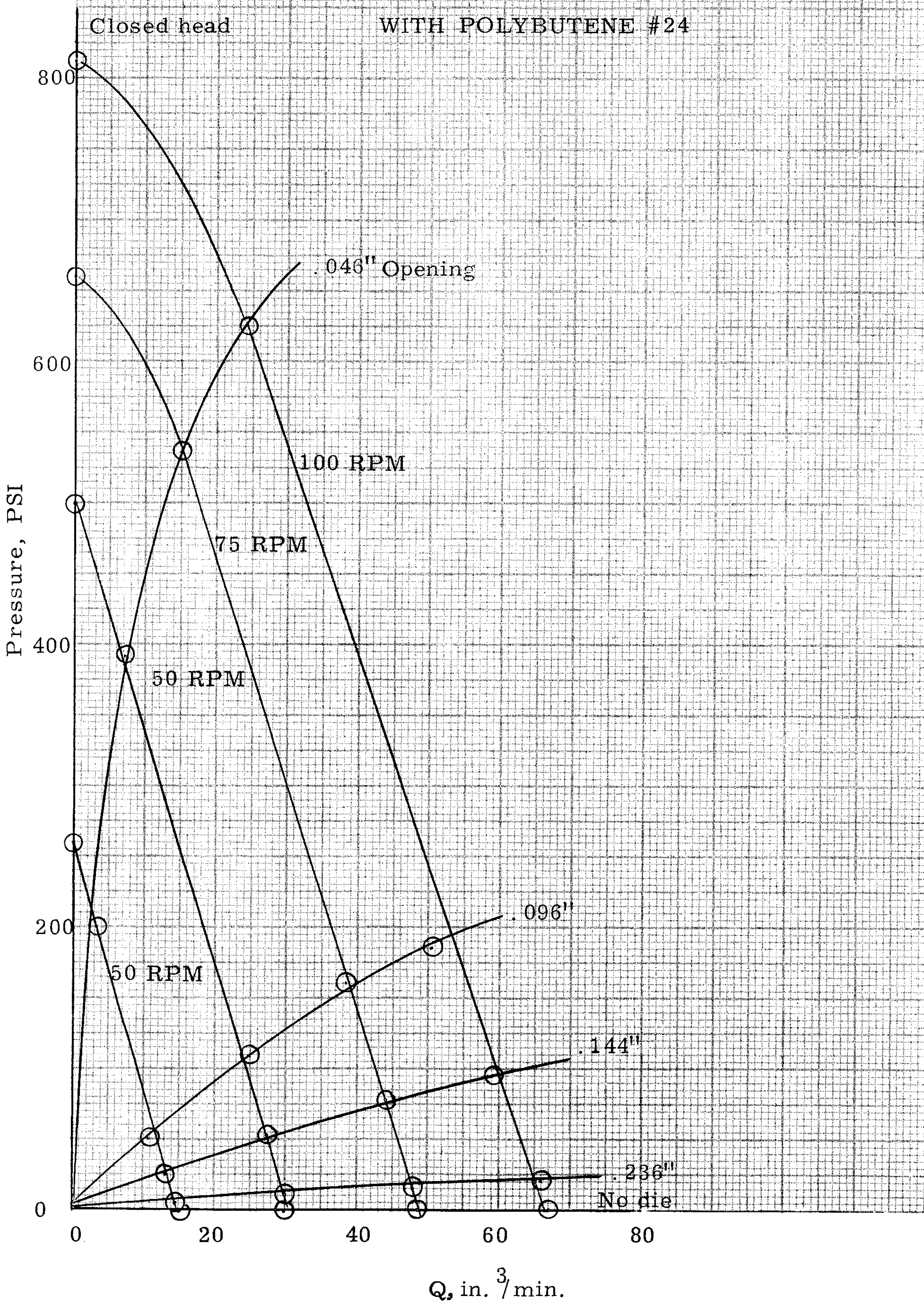
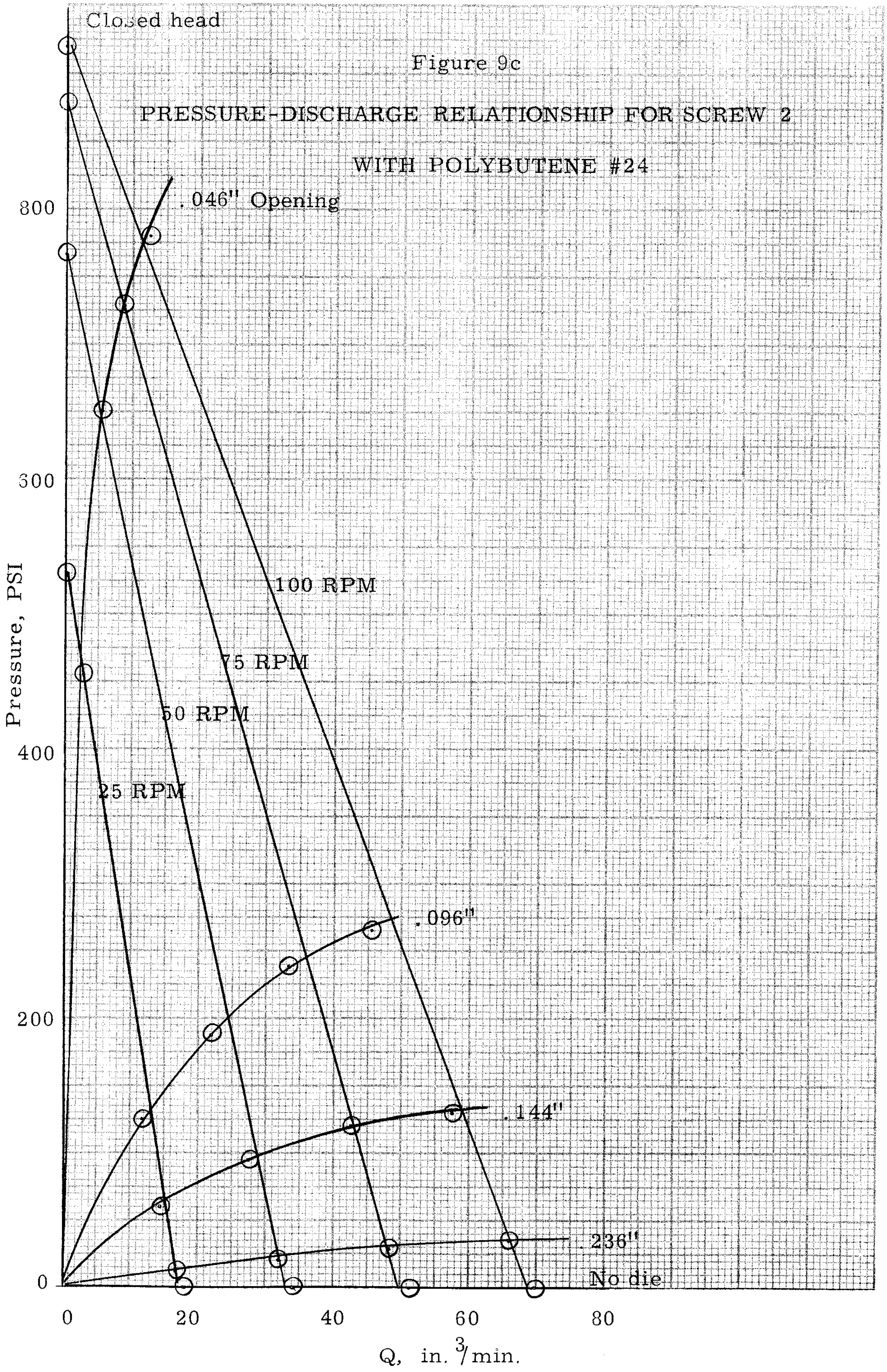


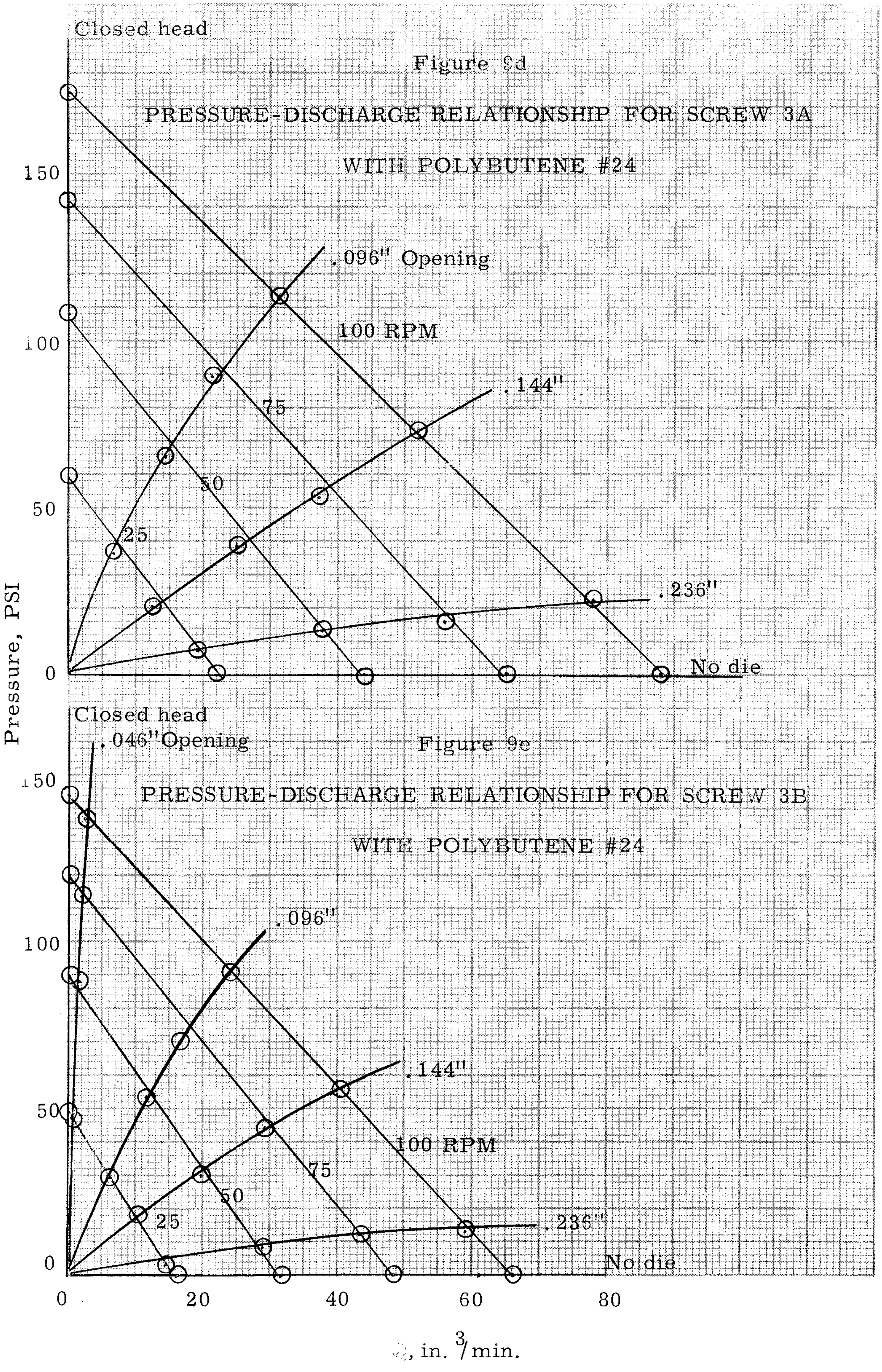
Figure 9b

PRESSURE-DISCHARGE RELATIONSHIP FOR SCREW 1B

WITH POLYBUTENE #24




Closed head
Figure 9c
PRESSURE-DISCHARGE RELATIONSHIP FOR SCREW 2
WITH POLYBUTENE #24
.046" Opening
100 RPM
75 RPM
50 RPM
25 RPM
.096"
.144"
.236"
No die
Pressure, PSI
0
200
400
600
800
0
20
40
60
80
Q, in.^{3}/min.


Closed head
Figure 9d
PRESSURE-DISCHARGE RELATIONSHIP FOR SCREW 3A
WITH POLYBUTENE #24
.096" Opening
100 RPM
.144"
75
50
25
.236"
No die
Closed head
.046" Opening
Figure 9e
PRESSURE-DISCHARGE RELATIONSHIP FOR SCREW 3B
WITH POLYBUTENE #24
.096"
.144"
100 RPM
75
50
25
.236"
No die
Pressure, PSI
150
100
50
0
0
20
40
60
80
Q, in.³/min.

while the die characteristic exhibited slight curvature due to the increase in temperature (hence decrease in viscosity) of the Polybutene with increasing screw speed. Had this change in temperature and viscosity, due to frictional working of the polybutene not taken place, it is believed that the die characteristic would have been a straight line.

It should be pointed out that some of the differences in pressures observed between the various screws are partly due to differences in the liquid viscosity due to the temperature imparted by the barrel head and screw. Screws 1B, 3A and 3B were run with a cooling water temperature of 19-20 C circulating through these parts while screws 2 and 1A were run with water temperatures of 12 and 13 C respectively. Since the viscosity of the extruded liquid was very much affected by small difference in temperature in this range, only qualitative comparison of pressures can be made. Although stock viscosity, due to temperature, theoretically has no effect on open discharge rates and probably has little effect on output through large dies, it does have considerable effect on output rates through small dies as backflow is dependent on viscosity which increases thus decreasing net output as viscosity decreases.

The individual output rates for each screw will be discussed shortly.

IV. APPLICATION OF THEORY TO POLYETHYLENE EXTRUSION

Polyethylene, like most plastics, is not usually extruded in the molten state. Inasmuch as the preceeding extrusion theory was based on isothermal liquid extrusion, it is desirable to compare the extrusion of both molten and granular polyethylene under various conditions, since relatively little detailed data on the application of theory to the extrusion of polyethylene has yet been published.

A. Molten Feed

In order to achieve as closely as possible the conditions of isothermal melt extrusion, which is the basic assumption of extrusion theory, molten polyethylene of the most common grade,* having an average feed temperature of 150 C, was extruded under similar conditions as the liquid polybutene. The major difference however, is that the head, barrel and screw temperatures were maintained at 190 C. Under these conditions molten polyethylene is extremely viscous and appears taffy-like.

Like the previous extrusion of liquid polybutene, the discharge rate of molten polyethylene was essentially linear with screw speed, except for screw 1B which was "slow starting". This is shown in Figures 10a, b, c, d, and e. In most cases the open discharge rates for the liquid polybutene and molten polyethylene were very nearly the same (within 5%) indicating the open discharge rate to be fairly independent of stock viscosity. In the case of screw 1A a significant reduction in rate occurred with molten polyethylene probably due to inadequate feeding as the screw lead was excessively long in

* Bakelite Polyethylene DE-2400, Melt Index 2.0.

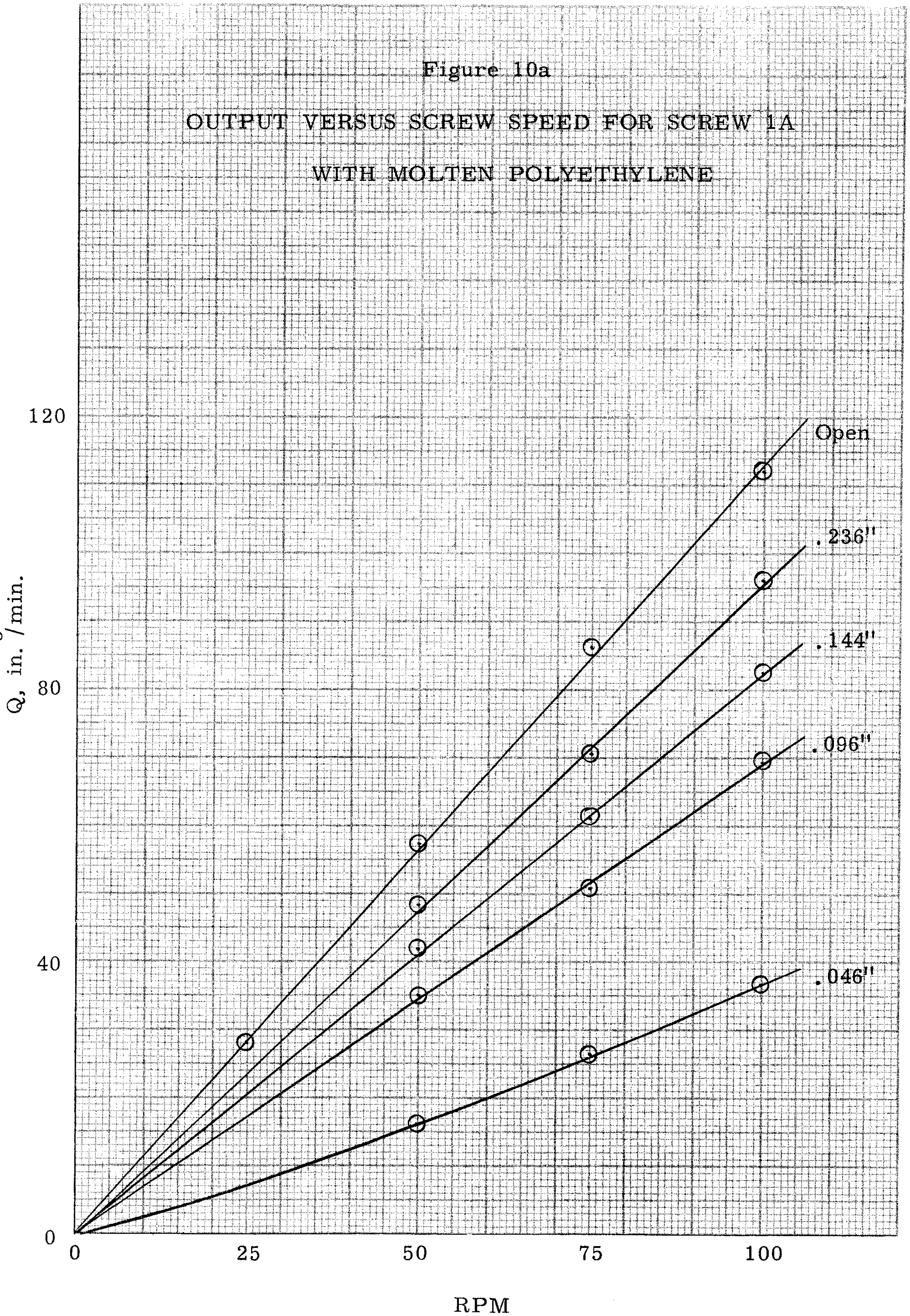


Figure 10a
OUTPUT VERSUS SCREW SPEED FOR SCREW 1A
WITH MOLTEN POLYETHYLENE
Q, in.^{3}/min.
120
80
40
0
0
25
50
75
100
RPM
Open
.236"
.144"
.096"
.046"

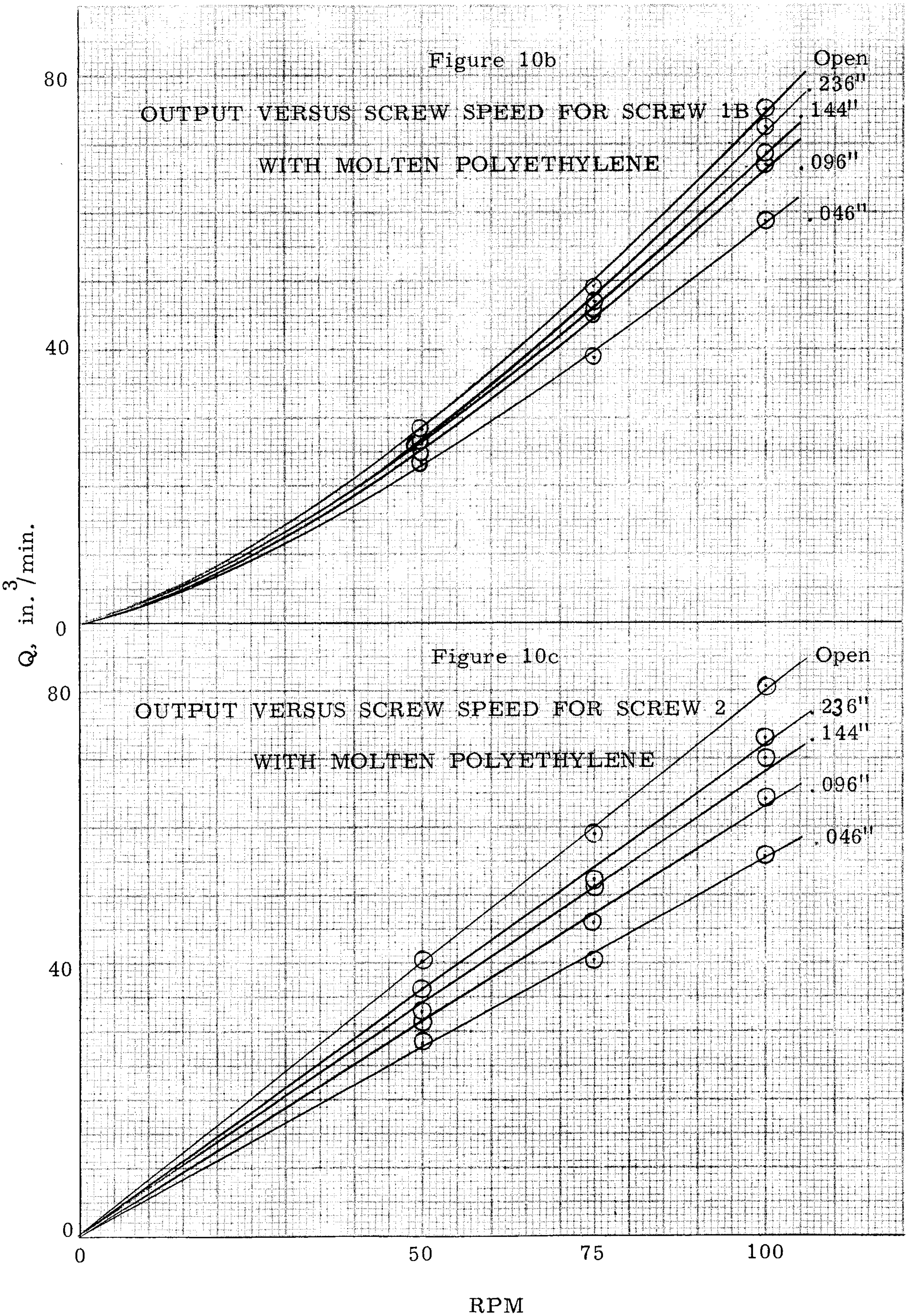


Figure 10b
OUTPUT VERSUS SCREW SPEED FOR SCREW 1B
WITH MOLTEN POLYETHYLENE
Open
.236"
.144"
.096"
.046"
Figure 10c
OUTPUT VERSUS SCREW SPEED FOR SCREW 2
WITH MOLTEN POLYETHYLENE
Open
.236"
.144"
.096"
.046"
80
40
0
80
40
0
Q, in.^{3}/min.
0
50
75
100
RPM

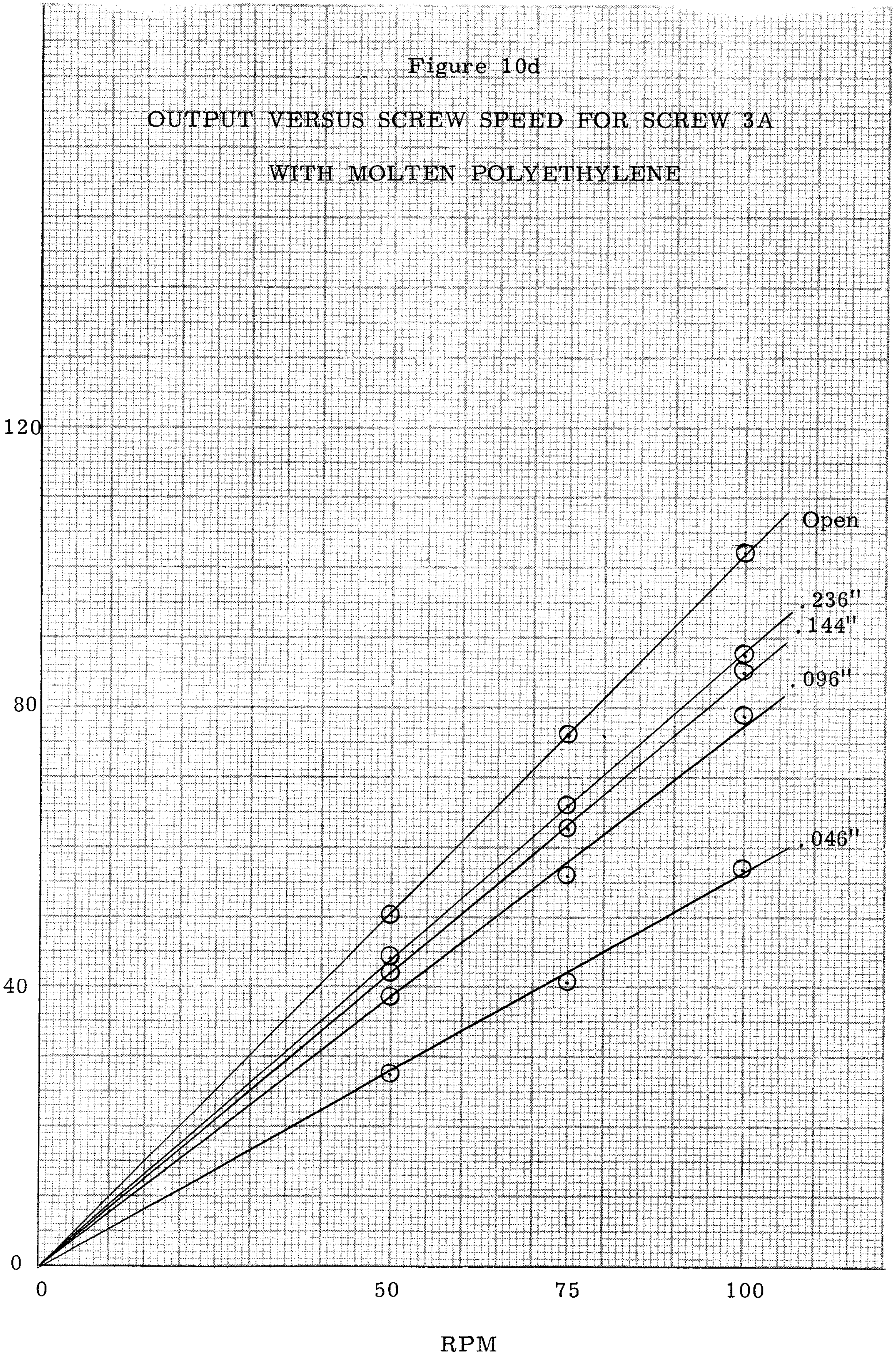
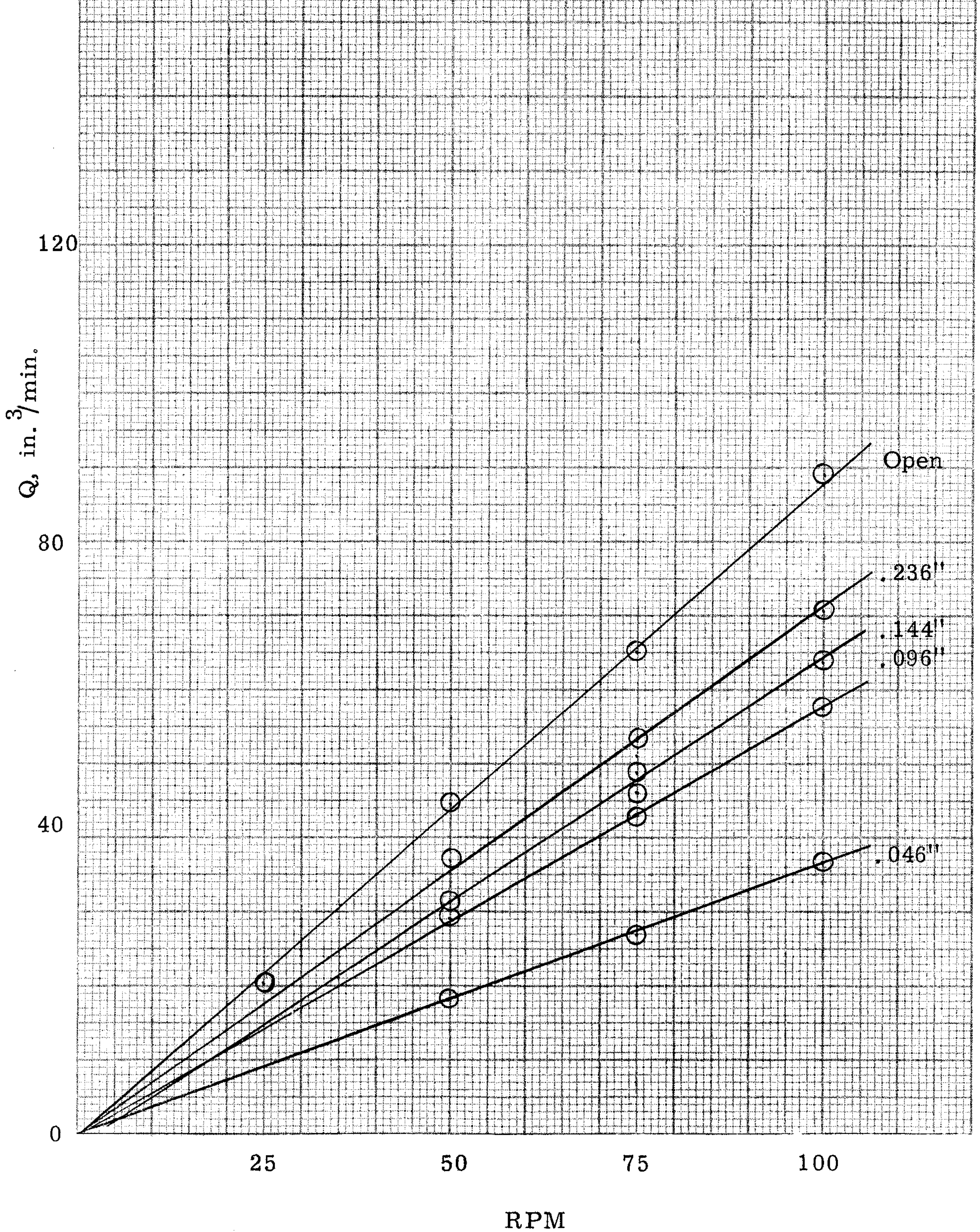


Figure 10d
OUTPUT VERSUS SCREW SPEED FOR SCREW 3A
WITH MOLTEN POLYETHYLENE
Open
.236"
.144"
.096"
.046"
120
80
40
0
0
50
75
100
RPM

Figure 10e

OUTPUT VERSUS SCREW SPEED FOR SCREW 3B

WITH MOLTEN POLYETHYLENE



comparison to the feed port. Similar results were reported by Piggott[3] with rubber stocks.

The output pressure relationship showing the screw and die characteristics for the molten polyethylene runs is shown in Figures 11a, b, c, d, and e. It will be observed that considerably more curvature is shown in the die characteristic curves with polyethylene than with liquid polybutene, especially in the high speed region with small die openings. This is the result of the non-Newtonian properties of polyethylene which causes viscosity to decrease with increasing shear rate in addition to the normal Newtonian effect of viscosity decreasing with increasing temperature, due to increasing frictional working at the high screw speeds.

It was also observed that considerably higher extrus on rates were obtained with small die openings using polyethylene as compared to liquid polybutene. This was caused by less backflow through the channel as a result of polyethylenes greater viscosity as compared to liquid polybutene.

Molten polyethylene was also extruded with a screw coolant temperature of 30 C, but otherwise identical conditions. In this case slightly lower open discharge rates were obtained which is believed due to a thin layer of solified polyethylene coating on the screw which reduced the channel dimensions slightly. This was especially noticeable in the case of screw 1B in which this coating was observed in the feed section. Extrusion results for the cold screw extrusion of molten polyethylene are shown in Figures 12a, b, c, d, and e and 13a, b, c, d, and e and may be compared to the results of hot screw extrusion previously discussed and shown in Figures 10a, b, c, d and e and 11a, b, c, d and e.

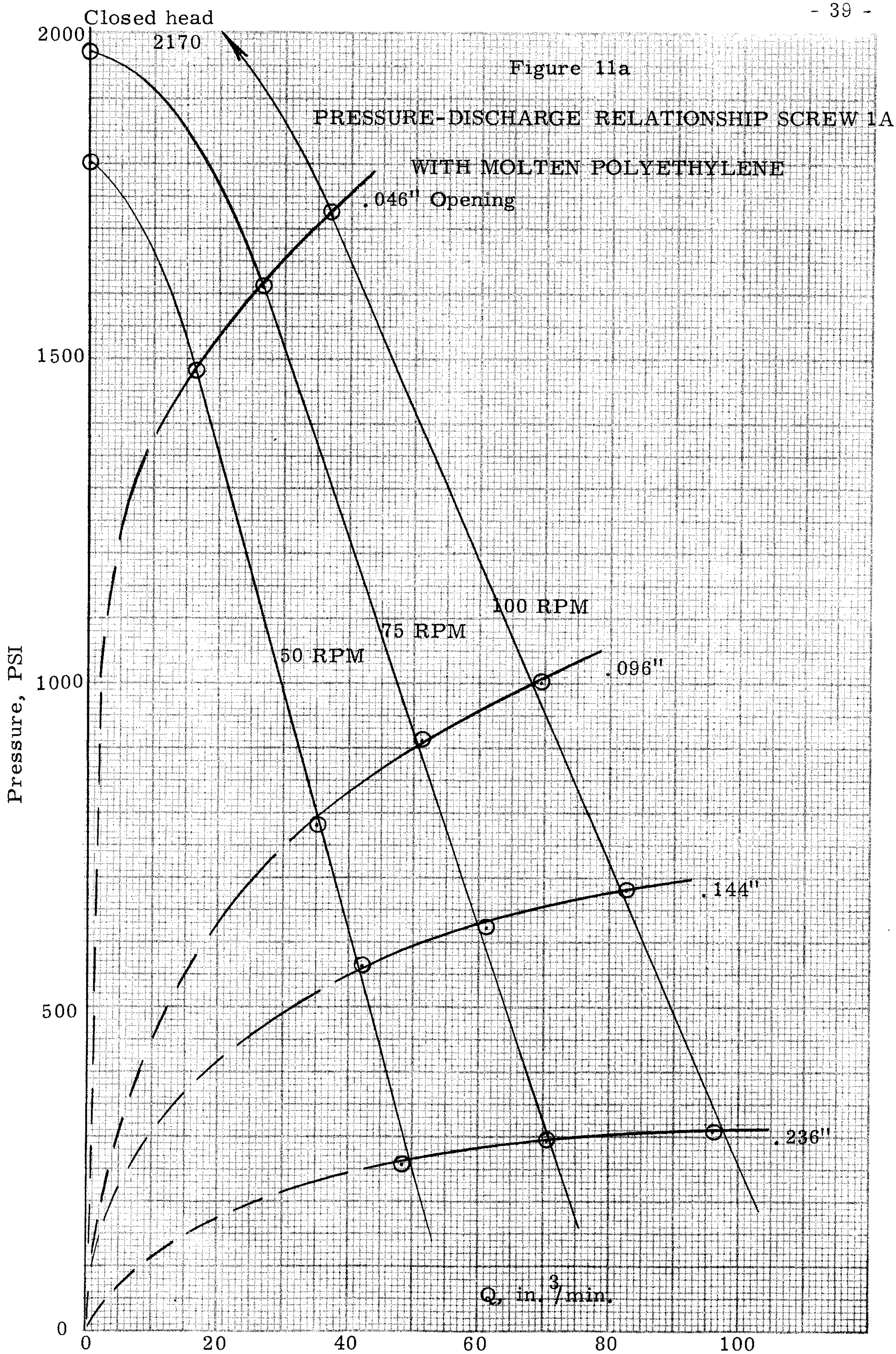


Figure 11a
PRESSURE-DISCHARGE RELATIONSHIP SCREW 1A
WITH MOLTEN POLYETHYLENE
Closed head
2170
.046" Opening
100 RPM
75 RPM
50 RPM
.096"
.144"
.236"
Pressure, PSI
2000
1500
1000
500
0
Q, in.3/min.
0
20
40
60
80
100

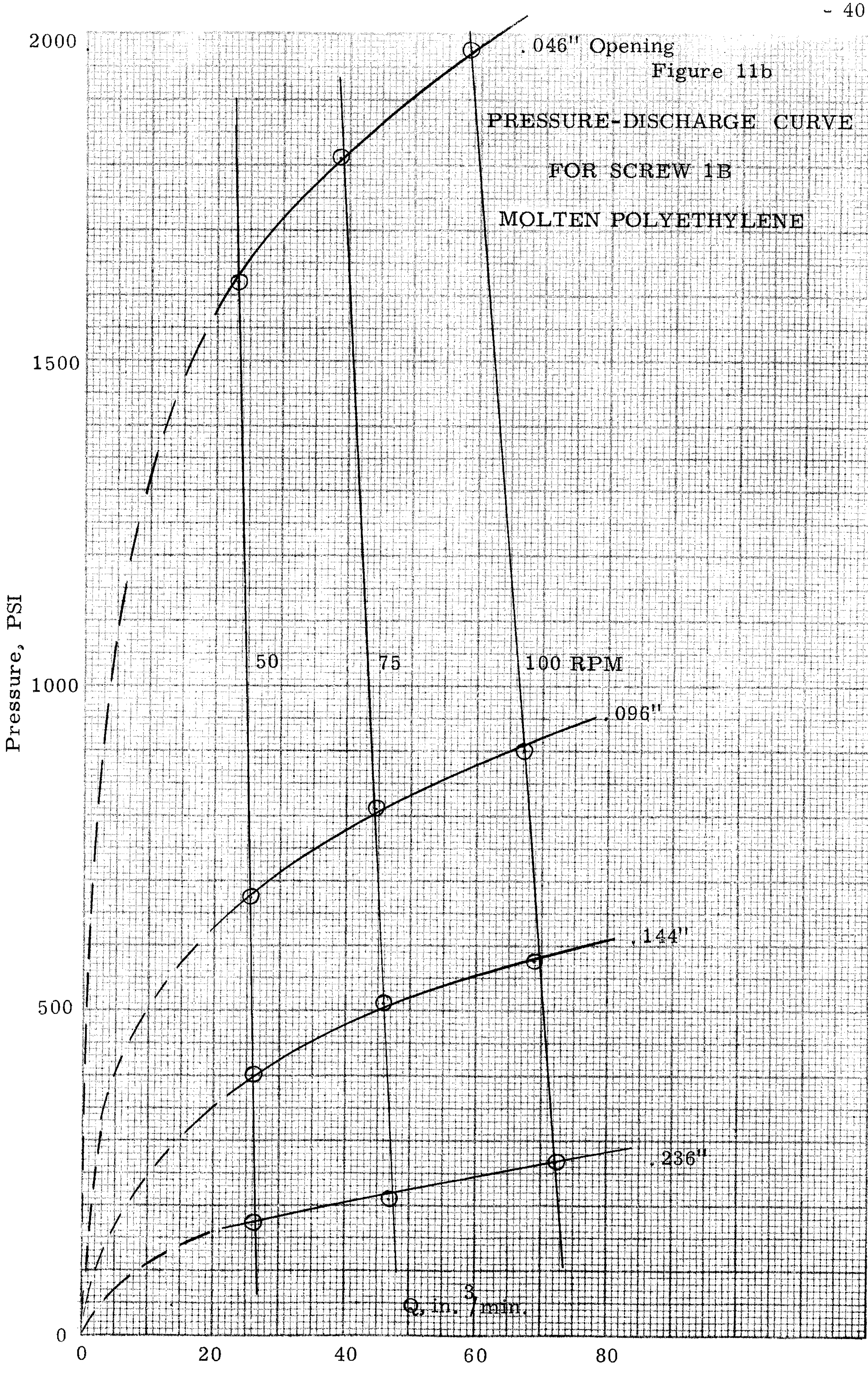
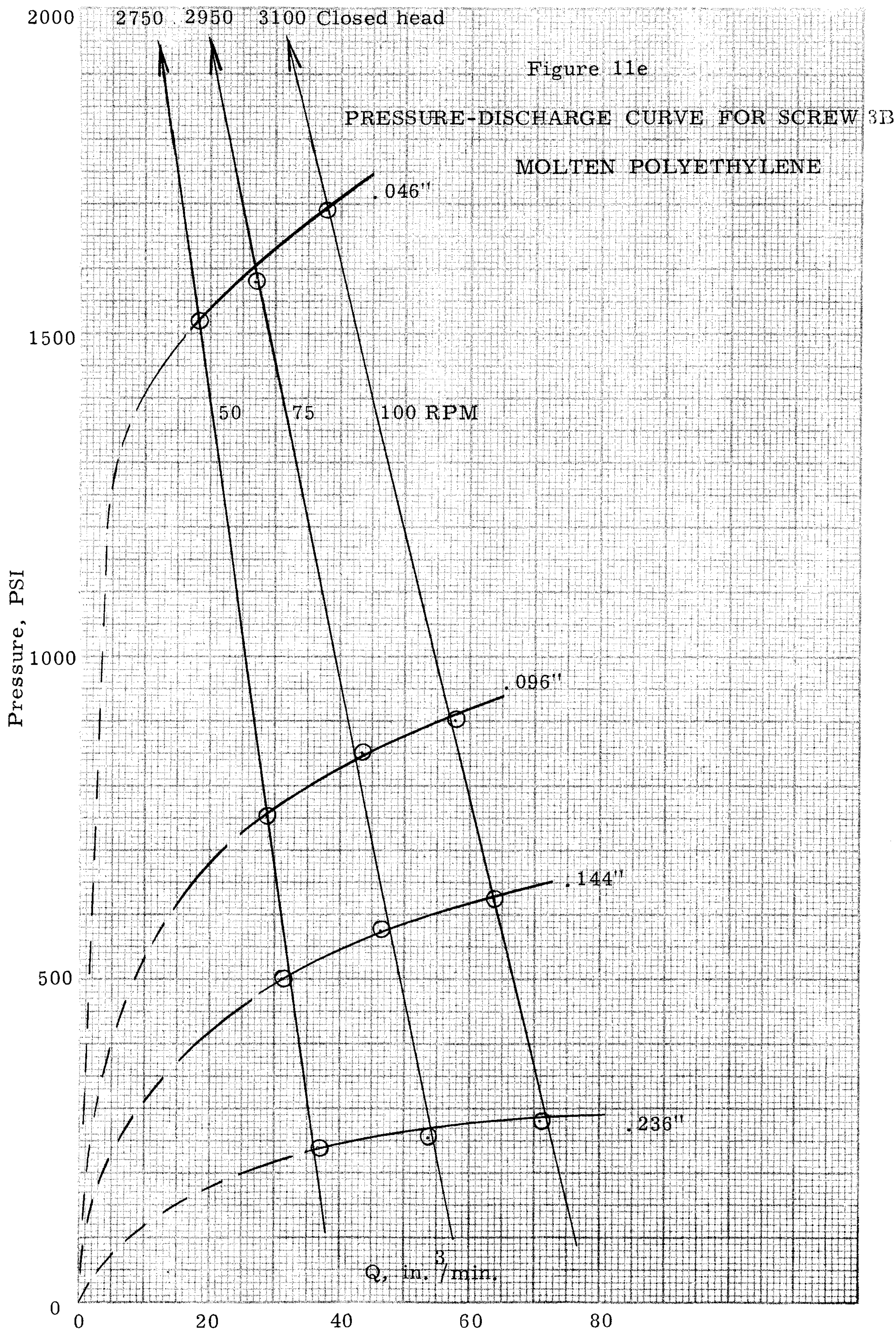


Figure 11b
PRESSURE-DISCHARGE CURVE
FOR SCREW 1B
MOLTEN POLYETHYLENE
.046" Opening
.096"
.144"
.236"
50
75
100 RPM
Pressure, PSI
2000
1500
1000
500
0
Q, in.3/min.
0
20
40
60
80


2750
2950
3100 Closed head
Figure 11e
PRESSURE-DISCHARGE CURVE FOR SCREW 3B
MOLTEN POLYETHYLENE
.046"
.096"
.144"
.236"
50
75
100 RPM
Pressure, PSI
Q, in.3/min.
2000
1500
1000
500
0
0
20
40
60
80

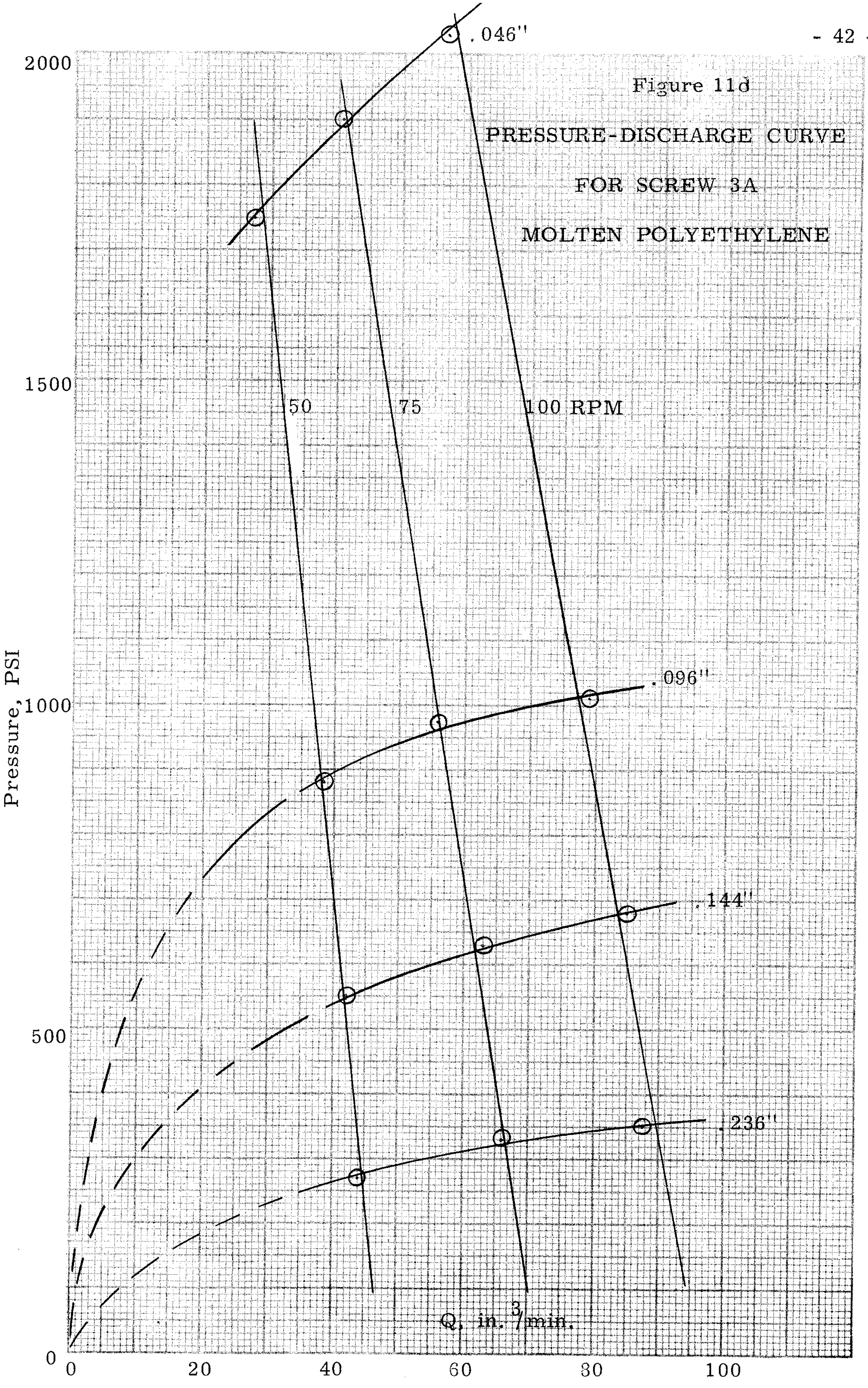


Figure 11d
PRESSURE-DISCHARGE CURVE
FOR SCREW 3A
MOLTEN POLYETHYLENE
.046"
.096"
.144"
.236"
50
75
100 RPM
Pressure, PSI
Q, in.3/min.
2000
1500
1000
500
0
0
20
40
60
80
100

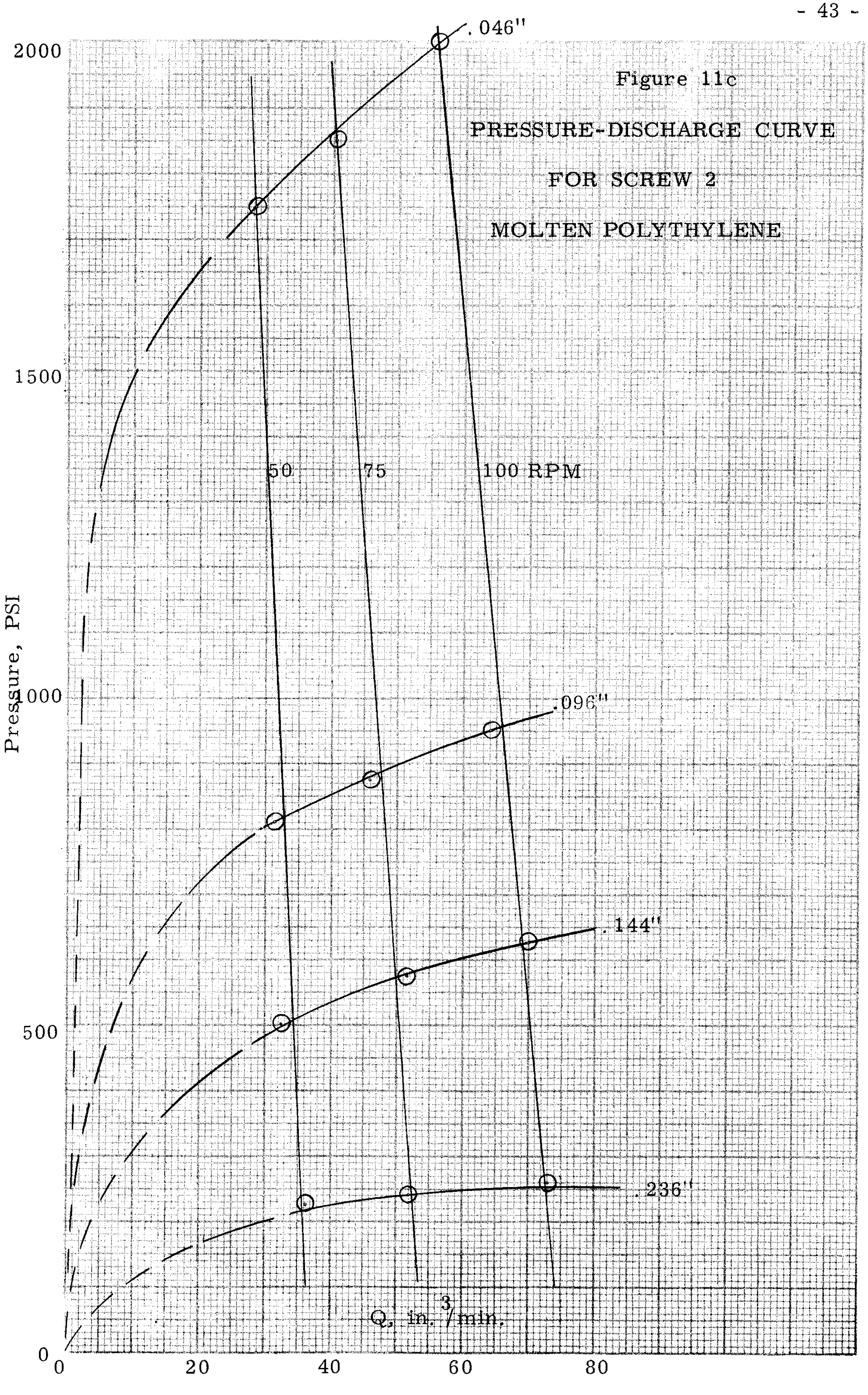


Figure 11c
PRESSURE-DISCHARGE CURVE
FOR SCREW 2
MOLTEN POLYTHYLENE
.046"
.096"
.144"
.236"
50
75
100 RPM
Pressure, PSI
2000
1500
1000
500
0
Q, in.³/min.
0
20
40
60
80

In the case of flow through small dies, several of the deep channel screws caused slightly higher rates as a result of less backflow due to the higher viscosity of polyethylene in the cold screw channel, as compared to hot screw extrusion, and possibly as a result of reduced channel dimensions due a built-up coating of solidified polyethylene.

B. Granular Feed

The extrusion of granular solid plastics is termed plasticating extrusion since the granular plastic must be melted in the extruder as compared to melt extrusion in which the molten stock is fed to the extruder. Inasmuch as the extrusion of polyethylene is usually plasticating extrusion, it is desirable to compare both methods in order to obtaine a better understanding of the process of plasticating extrusion as compared to melt extrusion.

The extrusion of granular polyethylene was investigated under the same conditions as molten feed except that the screw was operated at the more normal temperature of 30 C instead of 190 C.

Under these conditions the most important difference observed for granular feed is that extrusion rates were considerably lower than for melt feed. This is shown in Figures 12a, b, c, d, and e and may be compared to Figures 10a, b, c, d, and e for melt extrusion of polyethylene. In considering the feed condition with both materials, in one case the feed section of the screw is completely filled with molten stock while in the other a considerable amount of space is taken by voids between the granules. No doubt this effect of bulk density is responsible for a portion of this decrease with granular feed and

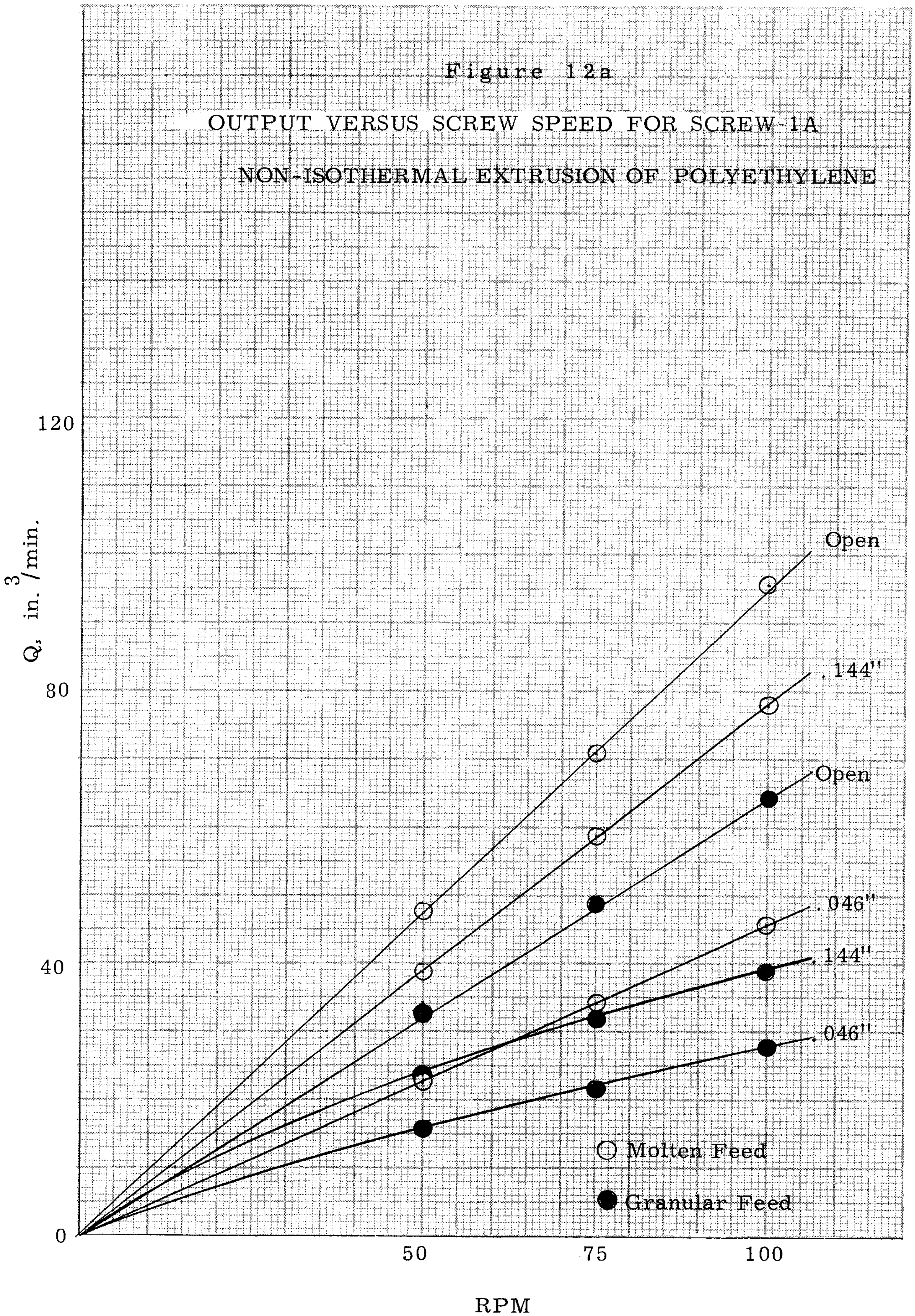


Figure 12a
OUTPUT VERSUS SCREW SPEED FOR SCREW-1A
NON-ISOTHERMAL EXTRUSION OF POLYETHYLENE
120
80
40
0
Q, in.3/min.
50
75
100
RPM
Open
.144"
Open
.046"
.144"
.046"
Molten Feed
Granular Feed

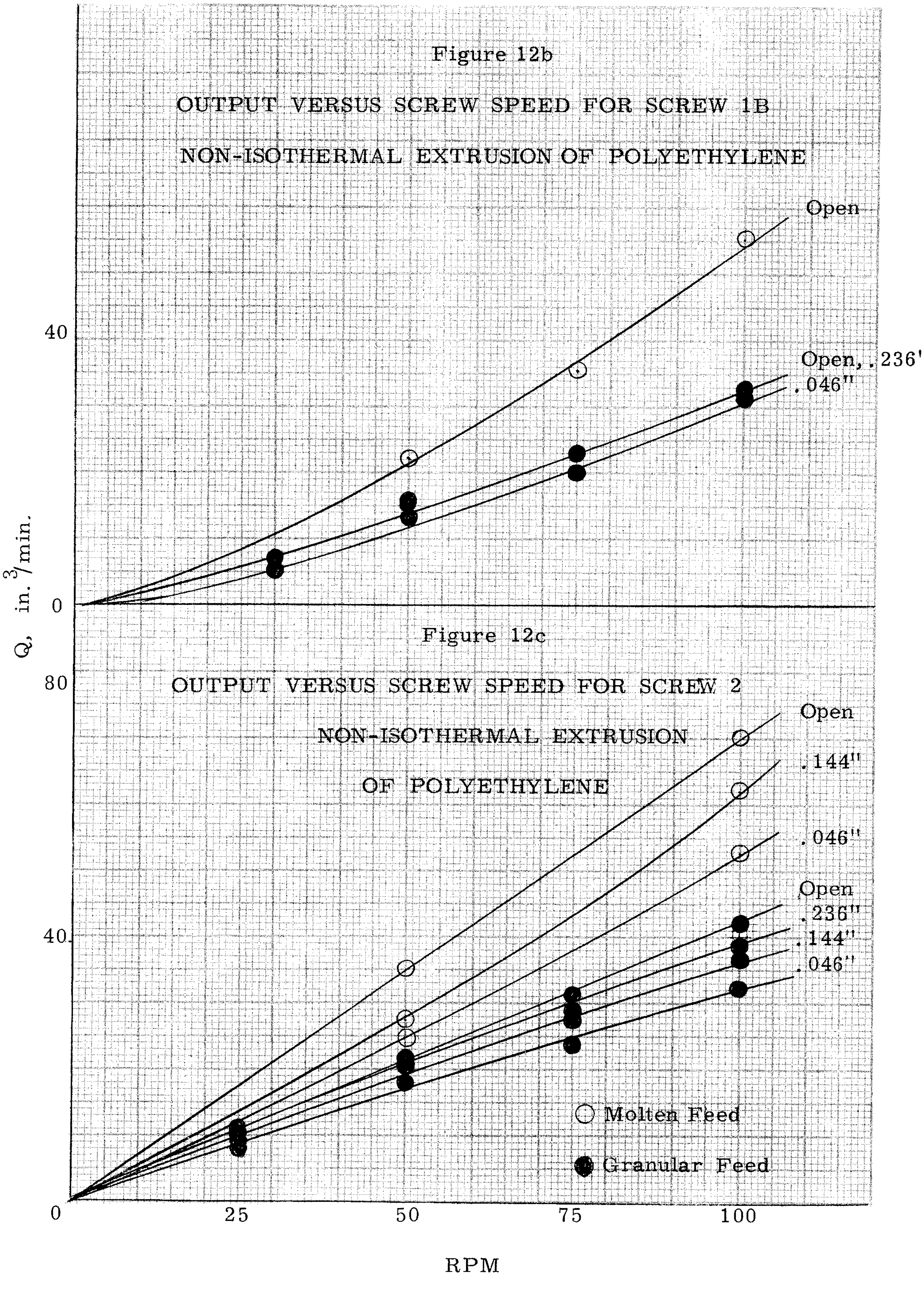


Figure 12b
OUTPUT VERSUS SCREW SPEED FOR SCREW 1B
NON-ISOTHERMAL EXTRUSION OF POLYETHYLENE
Open
Open, .236"
.046"
40
0
Q, in.³/min.
Figure 12c
OUTPUT VERSUS SCREW SPEED FOR SCREW 2
NON-ISOTHERMAL EXTRUSION
OF POLYETHYLENE
80
Open
.144"
.046"
Open
.236"
.144"
.046"
40
Molten Feed
Granular Feed
0
25
50
75
100
RPM

Figure 12d

OUTPUT VERSUS SCREW SPEED FOR SCREW 3A

NON-ISOTHERMAL EXTRUSION OF POLYETHYLENE

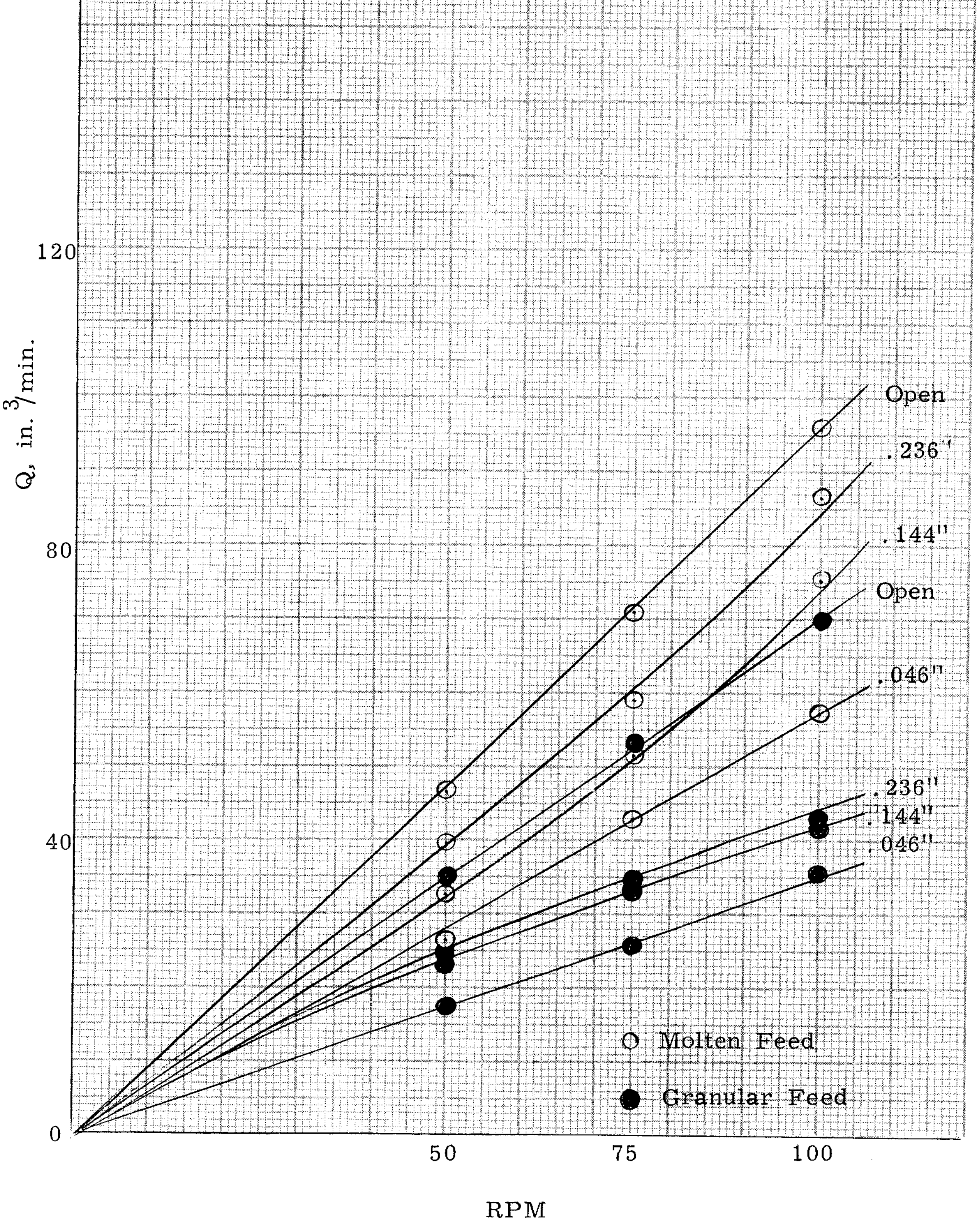
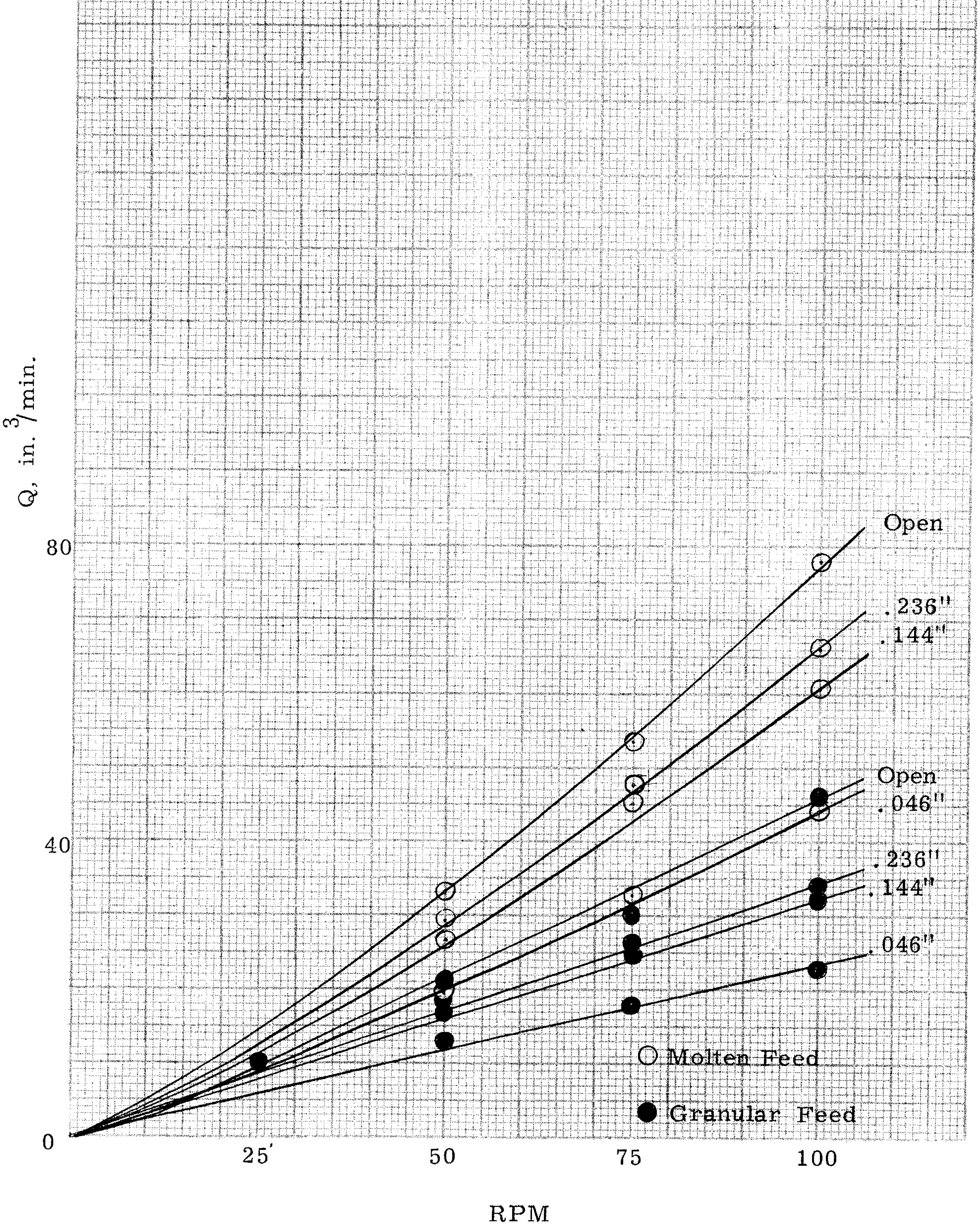


Figure 12e

OUTPUT VERSUS SCREW SPEED FOR SCREW 3B

NON-ISOTHERMAL EXTRUSION OF POLYETHYLENE



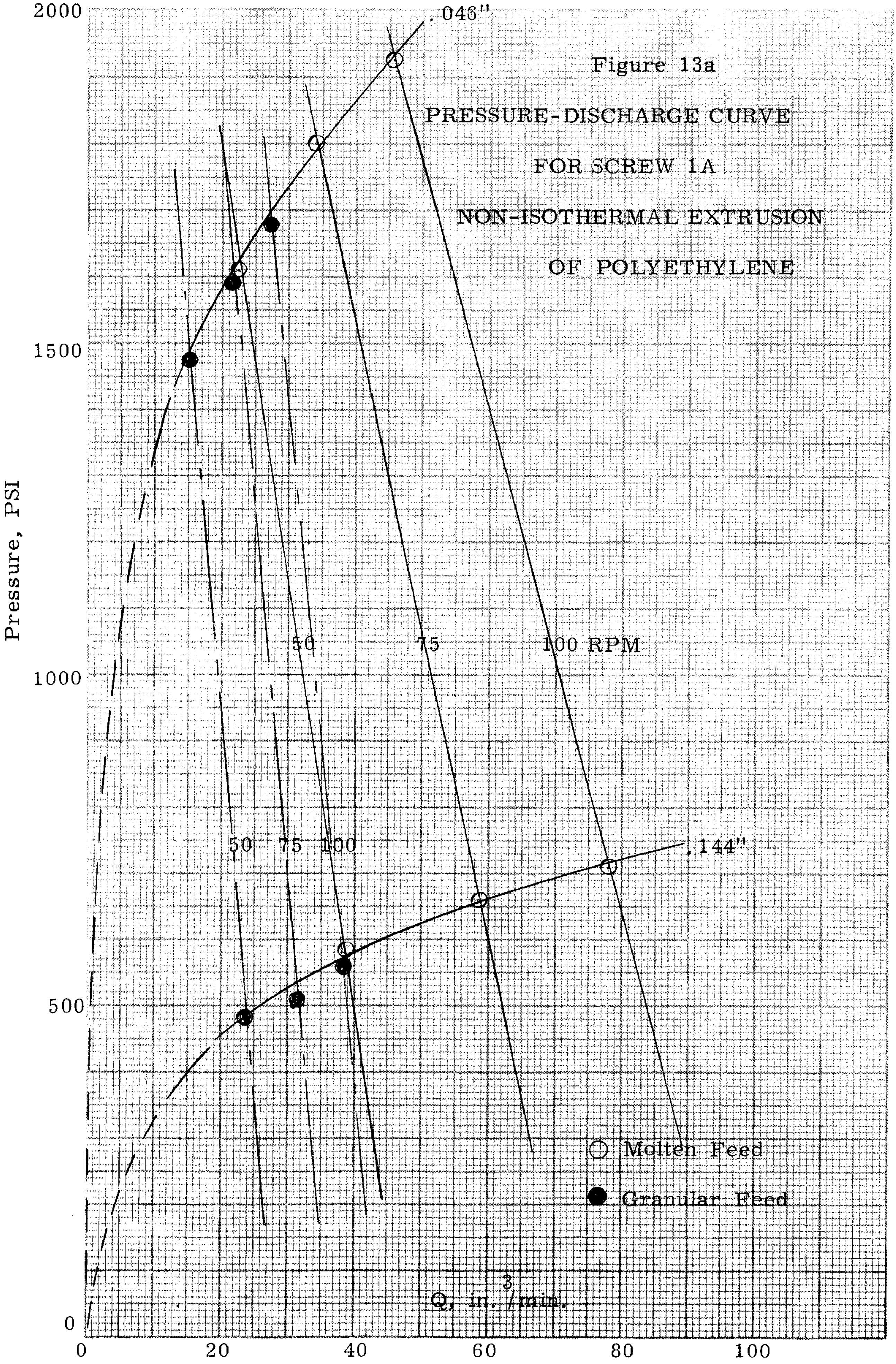


Figure 13a
PRESSURE-DISCHARGE CURVE
FOR SCREW 1A
NON-ISOTHERMAL EXTRUSION
OF POLYETHYLENE
.046"
.144"
50
75
100 RPM
50
75
100
Molten Feed
Granular Feed
Pressure, PSI
2000
1500
1000
500
0
Q, in.3/min.
0
20
40
60
80
100

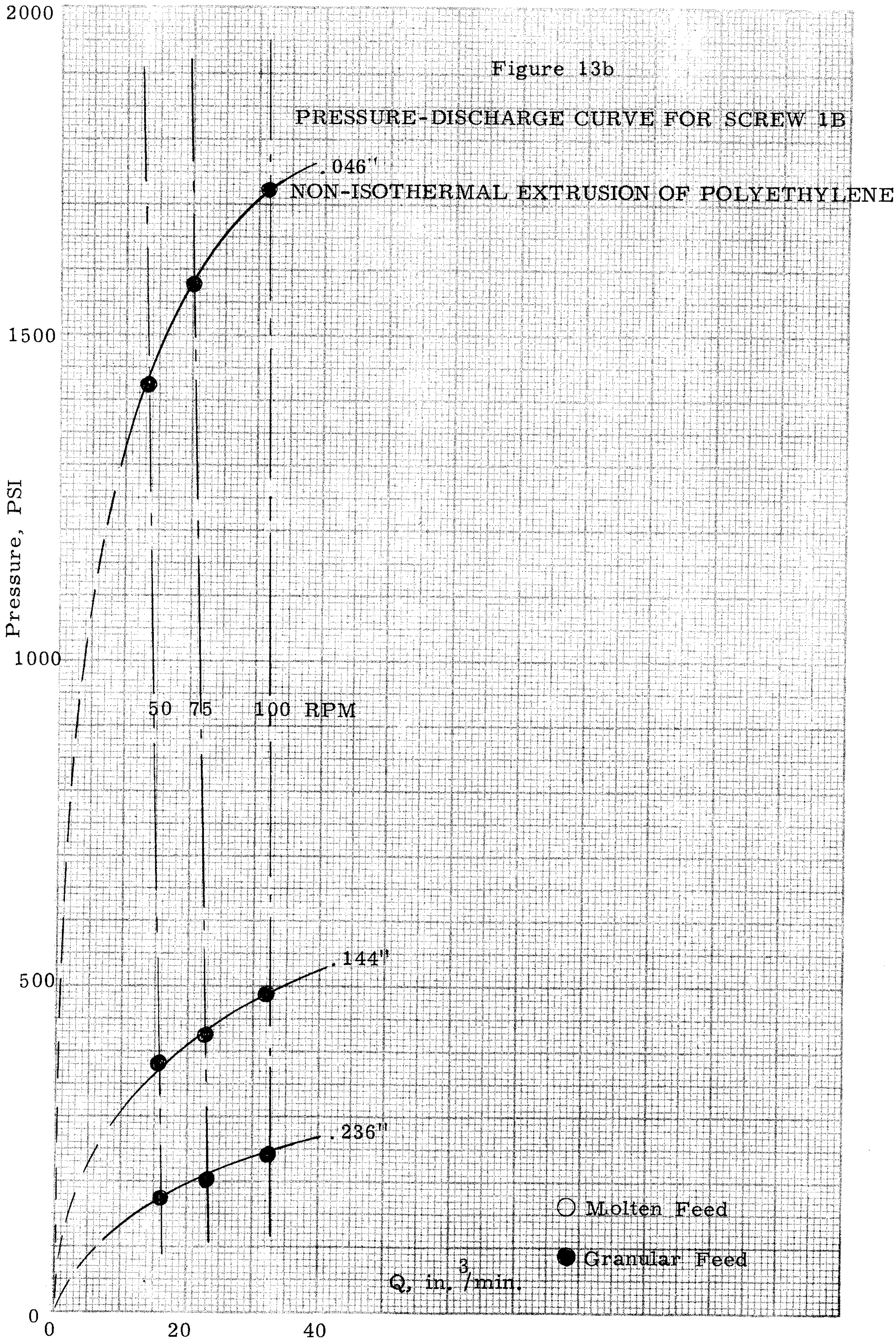


Figure 13b
PRESSURE-DISCHARGE CURVE FOR SCREW 1B
NON-ISOTHERMAL EXTRUSION OF POLYETHYLENE
2000
1500
1000
500
0
Pressure, PSI
.046"
.144"
.236"
50
75
100 RPM
Molten Feed
Granular Feed
Q, in.3/min.
0
20
40

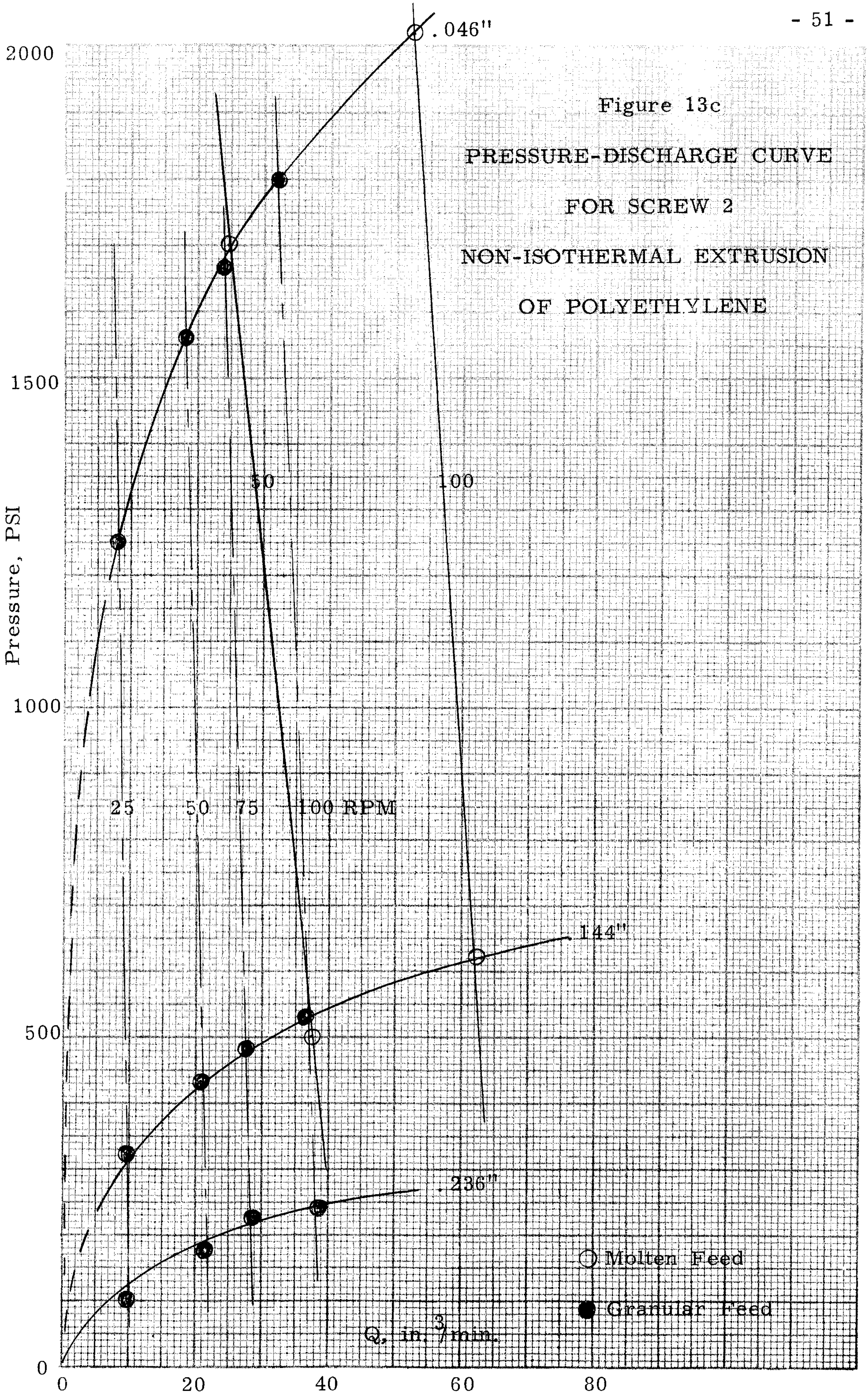


Figure 13c

PRESSURE-DISCHARGE CURVE

FOR SCREW 2

NON-ISOTHERMAL EXTRUSION

OF POLYETHYLENE

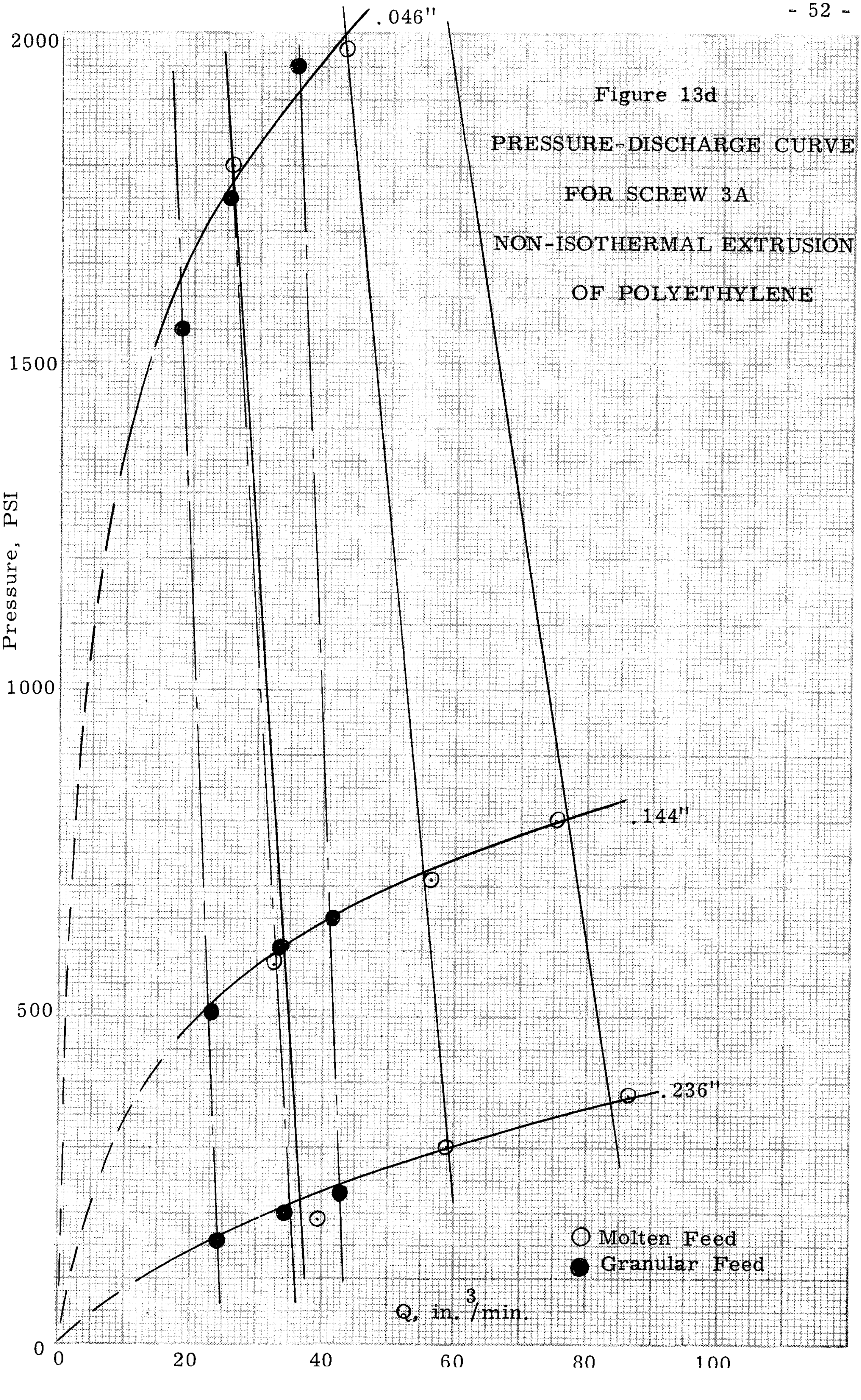


Figure 13d
PRESSURE-DISCHARGE CURVE
FOR SCREW 3A
NON-ISOTHERMAL EXTRUSION
OF POLYETHYLENE
Pressure, PSI
2000
1500
1000
500
0
0
20
40
60
80
100
Q, in.3/min.
.046"
.144"
.236"
Molten Feed
Granular Feed

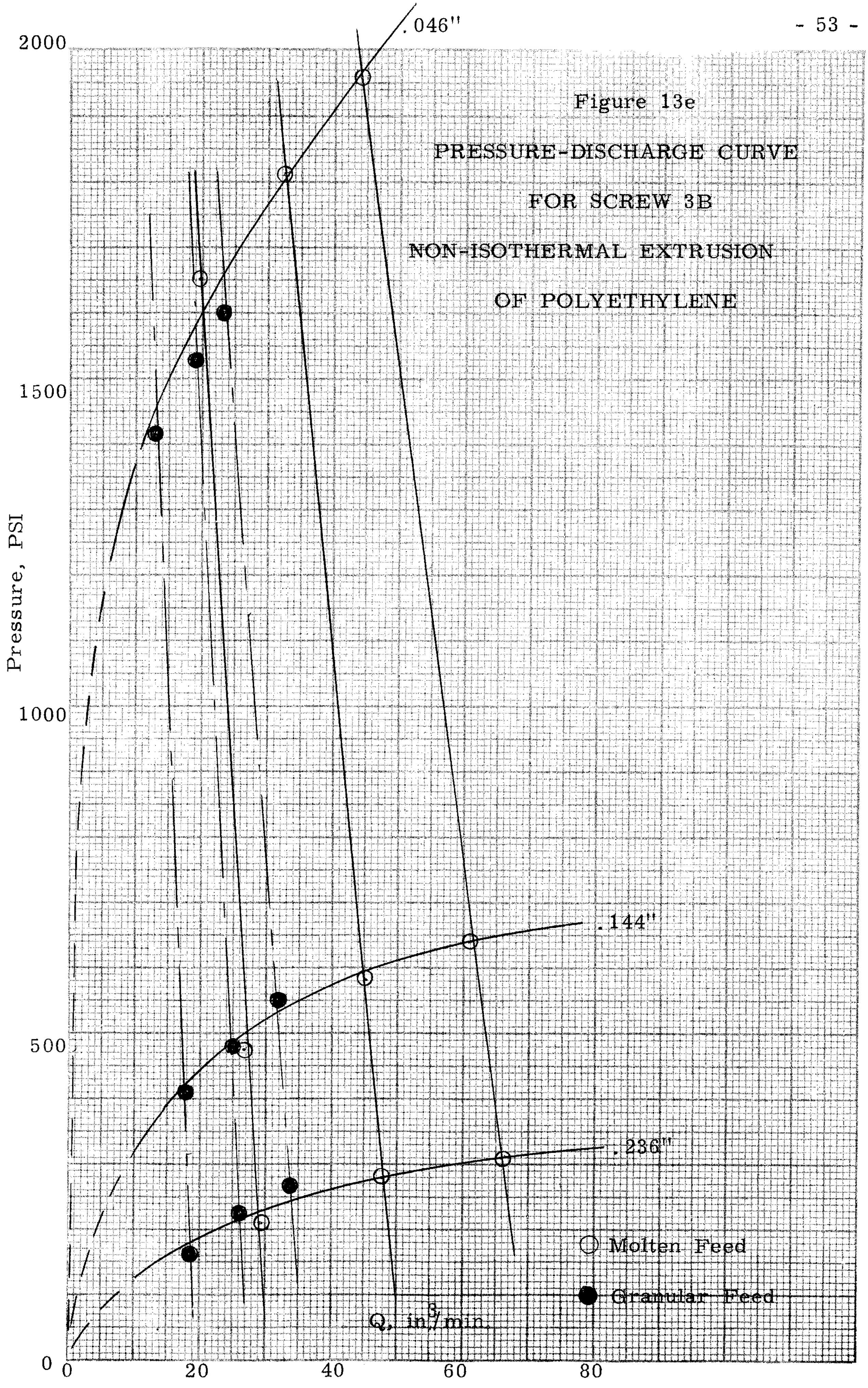


Figure 13e
PRESSURE-DISCHARGE CURVE
FOR SCREW 3B
NON-ISOTHERMAL EXTRUSION
OF POLYETHYLENE
.046"
.144"
.236"
Molten Feed
Granular Feed
Pressure, PSI
Q, in³/min.
2000
1500
1000
500
0
0
20
40
60
80

other experiments have shown this to be true. Another reason for this difference is probably due to lower drag flow rates with granular materials due to slippage of the granules over one another when sheared between the rotating screw and stationery barrel. It was also shown by Darnell and Mol[10] that screw conditions which favor extrusion of liquids are less favorable to the conveying of granular solids.

It has been observed that preheating of thermoplastic granules has a beneficial effect on extrusion rate, particularly with polyethylene. This increase in rate due to preheating is believed to be due to faster fluxing of the stock resulting in increased length of molten stock in the screw channel which increases forward drag flow. This relationship between output rate and length of molten stock in the screw channel has also been observed by other investigators [2, 9] and could be the reason why one progressive extruder manufacturer claims up to 50% increased extrusion rates with new 20/1 length to diameter ratio extruders as compared to conventional 15/1 models as employed in these experiments.

It has also been observed that extrusion rate for granular polyethylene increases with increasing screw temperature up to the melting point of the stock. Above this temperature the polyethylene granules apparently stick selectively to the screw in the feed section thus reducing extrusion rates to abnormally low values. This was investigated by feeding granular polyethylene to the extruder while all parts, including the screw, were heated to 190 C. The effect of these extrusion conditions on the open discharge rate for three screws is shown in Figure 14. Only the shallow channel screw, 1A, had the ability to extrude granular polyethylene satisfactorily with a hot screw. The wide variation in extrusion rate obtained under these conditions with the deep channel screws, 3A and 3B, is shown in these figures by the upper and lower limits of rates measured over the period of ten minutes. The "pulsing" in extrusion rate which was encountered was so severe that no two adjacent rate measurements were duplicated. This pulsing condition is believed to be due to the stock alternately sticking to and releasing from the screw, and was also recognized by Rogowsky.[2] Apparently this condition is minimized in shallow channel screws due to the increased effectiveness of forward drag flow motion between closer surfaces of the screw and barrel.

V. COMPARISON OF THEORETICAL AND ACTUAL DISCHARGE RATES

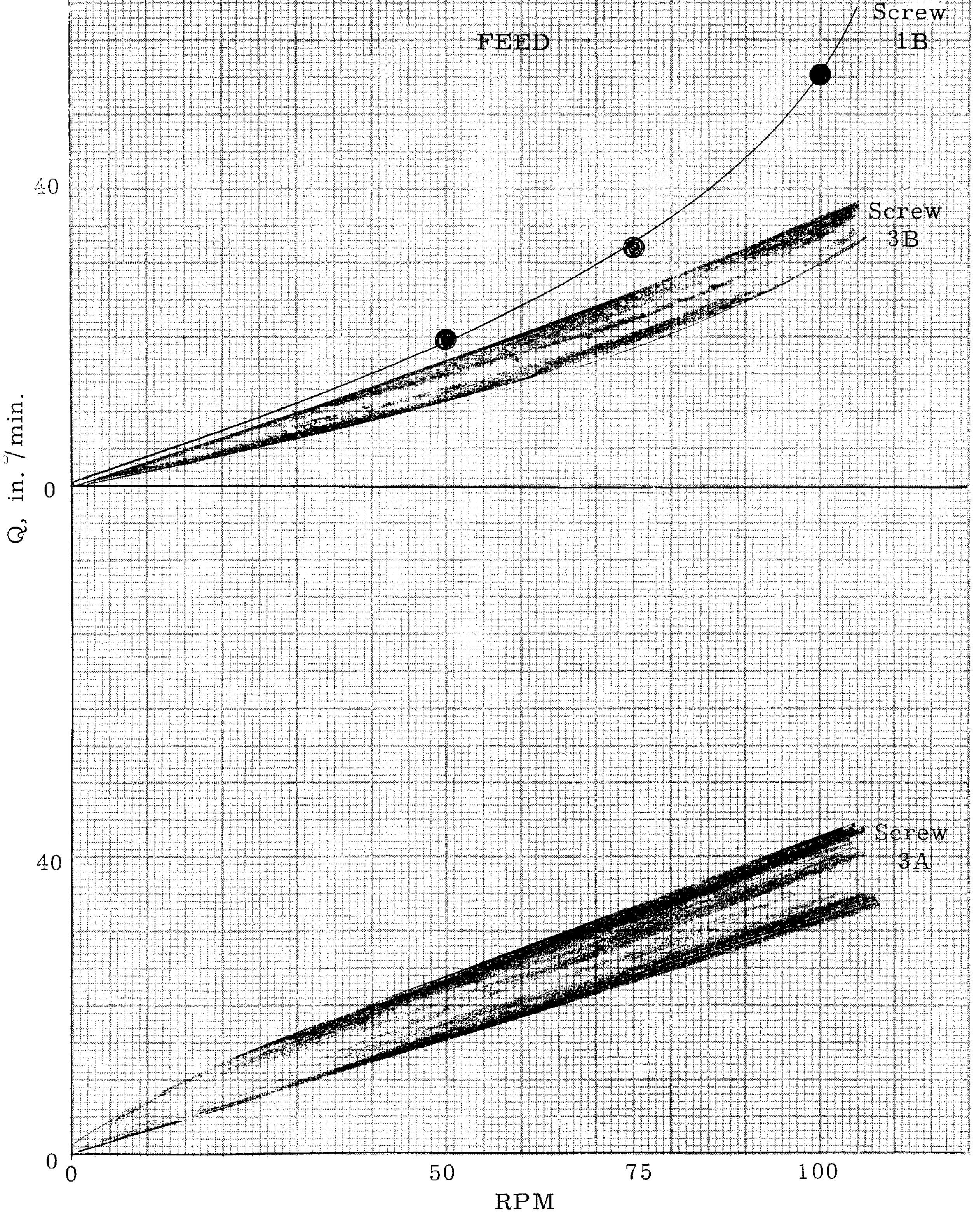
In order to obtain a better understanding of the comparison between the extrusion of liquid polybutene, molten polyethylene and theory, it is desirable to compare actual results with calculated results.

A. Open Discharge

The forward flow, Q_f, of an extruder screw can be readily measured by measuring the "open discharge" rate with head, die, and screen pack removed. Thus a comparison can be made with calculated values of Q_f. Most of the equations for Q_f are based on the assumption of uniform channel dimensions over the entire screw length. While plastic extrusion screws have compression ratios in order to compress granular feed, these equations when

Figure 14

COMPARISON OF OPEN DISCHARGE RATES FOR THREE SCREWS AT 190° C WITH GRANULAR POLYETHYLENE FEED



based on discharge end dimensions, yield low values for Q_f. The reason for this is due to pressure developed in the compression section which provides additional forward thrust. Screws having metering (uniform channel) sections at the delivery end most nearly approximate the assumption of uniform channel dimensions. The two such screws which were evaluated showed better agreement between actual and calculated values based on this assumption, than continuous compression screws.

Table 3 shows a comparison of calculated values of Q_f in cubic inches per revolution for each screw using eight different methods, compared to actual open discharge rates for liquid polybutene and molten polyethylene. In the case of equations 3, 4, 5 and 6 the calculations were based on the dimensions of the last (discharge end) flight only while in the case of the remaining four equations the calculations were based on the entire effective screw geometry. In all cases the assumption of liquid extrusion under isothermal (hence isoviscosity) conditions with equal adhesion of the liquid to the screw and barrel is made. Since all of the equations are based on rectangular channel dimensions, a correction factor to correct for the volume occupied by the fillets is also given. This was calculated by determing the ratio of volumes with and without fillets. The calculations for each screw are further discussed.

Table III

Comparison of Actual and Calculated Open Discharge Rates

Method	1A	1B	2	3A	3B
	Calculated Q_f - in.^{3}/rev.				
Equation 3*	1.21	.67	.63	.54	.31
" 4*	1.16	.60	.58	.48	.24
" 5*	1.32	.60	.58	.74	.48
" 6*	1.40	.66	.66	.92	.74
" 7, 8 or 9	1.27	.75	.83	1.19	1.31
Equation 5d	1.81	.84	.88	1.21	.86
Equation 3d	1.64	.77	.84	1.15	1.48
Equation 4d	1.53	.72	.77	.97	1.13
Fillet Correction	.99	.98	.98	.95	.91
	Measured Open Discharge - in.^{3}/rev.				
Polybutene	1.47	.68	.75	1.07	.78
Molten Polyethylene	1.13**	.75***	.80	1.02	.88

(Columns 1A–3B are under the heading "Screw".)

* Based on dimensions of last flight only.

** Inadequate feeding suspected.

*** Based on 100 rpm only - lower values were obtained at lower speeds.

Equations 3 and 4 are the most highly developed forward flow (Q_f) equations, as the effect of the channel walls on flow is considered. The assumption of uniform channel dimensions however, reduces their usefulness to a great extent. The similarity between these two equations can be seen by comparing calculated results in Table III which are very nearly equal, particularly for those screws having wide, shallow channels. Since the calculations with equations 3 and 4 were based on the dimensions of the discharge flight only, it would be expected that calculated values would be lower than measured values. This was experimentally verified as can also be seen in Table III. The variability of the calculations based on these equations compared to actual results was such that they cannot be recommended for screws having compression sections.

Equation 5, like the previous equations for Q_f, was calculated using the discharge dimensions only. This equation is a simplification of equation 4 which ignores the effect of channel walls on the liquid flow thus yielding somewhat higher values of Q_f, particularly in the case of deep channels. This has the effect of compensating, to some extent, for the error caused by neglecting the effect of forward thrust due to compression except for screws having relatively wide and shallow channels. While this equation offers some improvement by virtue of compensating errors its application is also not recommended.

Equation 6 is a further simplification of equation 5 in which the thread width is assumed to be negligible. This introduces further compensating errors when based on discharge flight dimensions, yielding calculated values of Q_f only 5 to 17% lower than actual open discharge rates. This equation therefore appears suitable for applications where fair accuracy is required.

In equation 7, variable channel dimensions are accounted for by integrating equation 6 over the length of the screw to obtain Q_f for the special case of wide, shallow channels. Equations 8 and 9 are derivations of equation 7 applicable to constant pitch, decreasing depth screw with and without metering sections, respectively. Since the effect of channel walls on flow in the channel, and the effect of the presence of thread width is neglected in this equation, calculated results are expected to be higher than actual. This was especially true in the case of the two variable pitch screws where channels were approaching squareness. Fairly good correlation was obtained for the three constant pitch screws, however.

Further attempts were made to consider variable channel dimensions by integrating several of the previous equations over the effective length of the screws. Equation 5 was one such equation integrated in order to eliminate the limitation of uniform channel dimensions. Naturally the previous limitation (i. e. neglecting the effect of channel walls of liquid flow in the channel) still applies, hence calculated values of Q_f would now be expected to be somewhat larger than actual values, which was found to be the case. The integration of equation 5 was accomplished differently depending on screw type. For constant pitch screws the mean diameter, $D_m = D-h$, and the channel depth, h, were integrated over the effective length mathematically, by expressing both terms as a function of length. For the decreasing pitch screws graphical integration was the only method that could be employed.

It was reasoned that if equations 3 and 4 were the most highly developed equations for forward flow in uniform channel screws, this should also be the case for variable channels if the equations could be integrated over the effective screw length. This introduces complications since the shape factors f ($h/s \cos\Theta$), and F_b change with channel dimensions and must also be integrated. This must be done graphically by determining the area under the shape factor-length curve which necessitates finding the shape factor for each turn or flight of the screw. The balance of the equation is integrated mathematically in the case of constant pitch screws and graphically for variable pitch screws, as discussed previously. As would be expected with the elimination of all previous limitations, good correlation was obtained, especially by means of integrating equation 3. Calculations based on the integration of equation 4 gave somewhat higher than actual values while equation 3 gave values of Q_f which varied by only 2 to 10% except in the case of screw 3A. This screw had the peculiarity of having a double flighted feed section which tapered to a single flight (increasing in volume), followed by a decrease in volume. The compression ratio in the feed section of this screw was 3.9:1 while this increased to 4.7:1 at the end of the double flight. This increase in compression ratio was sufficient to account for the difference between actual and calculated values of Q_f. It is therefore concluded that the best means of calculating open discharge rates for isothermal melt extrusion is by the integration of equation 3, including graphical integration of the shape factor, over the effective length of the screw.

B. Discharge Through Dies

Unlike open discharge, discharge rates through dies are not independent of viscosity of the extruded stock, hence the extrusion rates of liquid polybutene and molten polyethylene cannot be directly compared. Polyethylene being considerably more viscous than polybutene was therefore more resistant to backflow resulting in higher output rates for the same die and screw. The influence of viscosity can be seen by examination of the equations for backflow through the screw channel and over the screw threads.

Another factor affecting backflow is the pressure on the stock in the screw channel. The higher the pressure, the greater the backflow. Unfortunately pressure taps along the barrel were not available, as the machine was an unmodified standard wire coating extruder.

The only place where a pressure measurement could be made was in the head, by connecting a pressure gage to the bleeder tap. Since the breaker plate and screens were located between the pressure gage and the end of the screw, resulting in a pressure drop, no reliable estimate of screw pressure could be made. For this reason theoretical backflow rates could not be determined and net discharge rates could not be calculated for comparison to actual rates.

Inasmuch as considerable data was obtained in the course of this investigation it is desirable to present this information by comparing the actual results obtained with the extrusion of liquid polybutene and molten polyethylene. A tabulation of this data for the five screws investigated using four circular orifice dies is shown in Table IV.

Table IV

Comparison of Discharge Rates of Liquid Polybutene and Molten Polyethylene

Screw	1A	1B	2	3A	3B
Die Opening	Liquid Polybutene Q, in.^{3}/rev.				
Open Discharge	1.47	.68**	.75	1.07	.78
No Die	1.11	.68	.69	.87	.65
.236" dia.	.85	.65	.65	.77	.59
.144 "	.52	.58	.57	.51	.40
.096 "	.26	.51	.45	.30	.23
.046 "	.02	.24	.12	-	.02
	Molten Polyethylene Q, in.^{3}/rev.				
Open Discharge	1.13*	.75**	.80	1.02	.88
No Die ***	1.10	.74	.77	.96	.75
.236" dia.	.95	.72	.72	.88	.71
.144 "	.82	.69	.68	.84	.64
.096 "	.69	.67	.63	.77	.58
.046 "	.36	.59	.56	.56	.36

* Inadequate feeding suspected.

** All values for screw 1B based on 100 rpm - somewhat lower values were obtained at lower speeds.

*** Extrapolated from Figure 11.

The major difference between isothermal extrusion of liquid polybutene at room temperature and melt extrusion of polyethylene at 190 C is the difference in viscosity between the two stocks. Hence in comparing extrusion rates in Table IV, the differences observed between the stocks are due to the great difference in their viscosities. For comparative purposes, the viscosity of liquid polybutene was similar to molasses while molten polyethylene was more like bread dough or taffy. In addition, the viscosity of liquid polybutene was virtually unaffected by shear rate while the viscosity of polyethylene is known to decrease considerably with increasing shear rate.

From examination of Table IV it can be seen that discharge rates diminish at a greater rate with decreasing die opening for the liquid than for polyethylene. This is due to increased backflow rates with the less viscous stock. It is also evident that considerably lower discharge rates are obtained with small dies using deep channel screws than with shallow channel screws. This is especially true of liquid polybutene, however it is probable that the same effect would have been more pronounced with polyethylene using smaller dies.

The large differences in discharge rates through dies with the two materials and the five screws serves to emphasize the importance of selecting the proper screw design to suit to stock being extruded.

VI. COMPARISON OF RESULTS OF MELT AND PLASTICATING EXTRUSION OF POLYETHYLENE

For all practical purposes, the present state of extrusion theory is limited to melt extrusion practices while the bulk of product fabrication of polyethylene is by means of plasticating extrusion. As an aid in understanding plasticating extrusion for the eventual purpose of formulating suitable theory, it is desirable to compare the results of both methods. Since extruder screw design has been largely empirical and is highly contraversial, each screw investigated will be examined individually.

A. Screw 1A

Screw 1A (2:1 compression ratio) was a double flighted constant pitch screw having a long lead (4.28")and avery deep channel in feed section, tapering to .180 inches, followed by a metering section the length of two double flights. After extrusion of the liquid and prior to the extrusion of polyethylene this screw was modified by removing the double flight in the feed section so that the channel width was excessively long in comparison to the feed opening (2 1/2 inches). This prevented complete filling of the feed section with all but liquid feed, resulting in 20% lower than theoretical open discharge rate with molten polyethylene feed. Even under these conditions this screw produced the highest open discharge rate with molten feed, although with the highest resistance die it produced the lowest rate under the same conditions. The low discharge rate with high die resistance is attributed to the deep channel which allowed high backflow rates. A summary of results is shown in Table V.

Table V

Comparison of Polyethylene Discharge Rates With Molten And Granular Feed

Die Opening	Screw 1A	1B	2	3A	3B
Molten Feed-190 C	Average Q, in.^{3}/rev.				
Open Discharge	1.13	.75*	.80	1.02	.88
.236" Diameter	.95	.72	.72	.88	.71
.144 "	.82	.69	.68	.84	.64
.096 "	.69	.67	.63	.77	.58
.046 "	.36	.59	.56	.56	.36
Molten Feed -30 C					
Open Discharge	.95	.55*	.70	.95	.78*
.236" Diameter	-	-	-	.82	.66
.144 "	.78	-	.58	.70	.61
.046 "	.46	-	.51	.57	.44
Granular Feed -30 C					
Open Discharge	.64	.32	.42	.70	.44
.236" Diameter	-	.32	.39	.46	.34
.144 "	.43	.32	.36	.44	.32
.046 "	.28	.30	.35	.35	.24

Table V (continued)

Granular Feed -190 C	Screw 1A	1B	2	3A	3B
Open Discharge	-	.55*	-	.39 ± .09	.29 ± .09

* Based on 100 rpm only - somewhat lower values obtained at slower speeds.

Using a cool (30 C) screw temperature instead of the isothermal condition previously discussed, the open discharge rate was reduced 17%. This is believed due to the formation of a solidified layer of polyethylene deposit on the screw. This reduction in channel size coupled with the increased viscosity of the stock due to the cooling effect by the screw resulted in a significant increase in extrusion rate through small dies compared to isothermal melt extrusion conditions.

With granular feed and operating at the cool screw temperature the open discharge rate dropped to 43% below that obtained under isothermal melt conditions, and unfluxed granules were discharged. With high resistance dies the extrusion rate was decreased excessively as in the case of melt extrusion, but to a lesser extent, due to the beneficial effect of higher viscosity resulting from the lower stock temperatures. The lower extrusion rates with granular polyethylene feed has been previously discussed and is believed to be due to the lower bulk density and reduced drag flow with granular feed.

The advantage of screw 1A appeared to be its very high discharge rate under conditions of open discharge and with large dies. This was especially pronounced with melt feed. Since the metering section has the effect of reducing open discharge rates, a similar screw without the metering section would give even higher throughput rates for applications requiring low die resistances. Still higher output rates would be expected if the double flight were extended into the feed section, enabling improved feeding.

B. Screw 1B

Screw 1B (2:1 compression ratio) was similar in design to 1A in that it was a decreasing depth, constant pitch screw having a metering section. It differed considerably however, in that it was a single flight screw with a 2.0 inch lead having a shallow channel of .125 inches at the discharge end. This screw had entirely different characteristics than screw 1A as it developed very high pressures with small dies thus having the tendency to yield very nearly the same discharge rate regardless of die resistance. This screw had the peculiar tendency of being considerably less efficient at low speeds than at high speeds with melt feed, although output was linear with screw speed with granular feed.

In operation with melt feed under isothermal conditions, screw 1B gave the lowest open discharge rate of the screws evaluated, its theoretical output being half that of screw 1A. In discharge through dies however, this screw showed little reduction in output with increasing die resistance so that with the smallest die opening it gave a slightly higher output than the remaining other screws. In comparison to screw 1A, which exhibited 70% reduction in rate with the smallest die, this screw showed only 21% reduction. Like screw 1A, 1B also showed a 17% reduction in open discharge rate when the screw temperature was reduced to 30 C.

In the case of granular feed with the cool screw temperature, screw 1B gave a 58% lower open discharge rate compared to isothermal melt conditions, but discharged completely molten product which is considered by some authorities to be the test of a good screw. This rate remained virtually constant regardless of die resistance. It was also found that this screw was suitable for extruding granular polyethylene with high screw temperatures with a 70% increase in output, compared to cool screw operation presumably due to the shallow channel which allowed appreciably faster melting of the stock in the channel. Of the three screws operated at 190 C with granular feed, only screw 1B produced satisfactory uniform extrusion rates. The remaining screws had relatively deep channels and when operated hot produced extremely variable rates.

It is concluded that screw 1B is a screw most suitable for operations requiring high die resistances and for developing high pressures. Also, that this screw is suitable for operation at high screw temperatures with granular feed thus affording a large increase in output without degrading quality.

C. Screw 2

Screw 2 (2:1 compression ratio) was very similar to screw 1B except that it did not have a metering section. The compression ratio, pitch and depth were the same.

As would be expected, the absence of the metering section produced slightly higher open discharge rates and slightly lower die discharge rates with small dies under isothermal melt conditions. A reduction of 30% in output rate compared to open discharge occurred with the smallest die, compared to a 21% reduction with screw 1B.

The operation with granular feed, screw 2 also produced higher rates than screw 1B, but tended to reach the same rate with high resistance dies. Completely molten polyethylene was discharged under open head conditions. Operation of this screw at high temperatures with granular feed was not carried out, however results similar to those obtained with screw 1B might be expected.

Although not the type of screw designed for maximum output, screw 2 is a good general purpose screw gaining in favor for extruding polyethylene. It is suitable for both high and low resistance dies and is capable of developing high product temperatures with granular polyethylene using large die openings. It is believed that this screw, like screw 1B, may be operated hot resulting in increased output rates without undue sacrifice in product quality.

D. Screw 3A

Screw 3A (2.7:1 compression ratio) was radically different from the preceeding screws. This screw had a deep (.372 inch) channel and a pitch of 2.08" which decreased to .78" at the discharge end. The channel shape at the discharge end was elliptical rather than rectangular.

In operation under isothermal melt conditions, screw 3A produced high discharge rates. The open discharge rate was exceeded only by screw 1A. In operation with the smallest die a 45% decrease in rate occurred compared to open discharge. Still further reduction in output would be expected with higher die resistances owing to the deep channel. Reducing the screw temperature to 30 C reduced open and low die resistance rates by 10% but had no effect on the highest resistance die.

With granular feed and a cool screw, discharge rates exceeded all other screws operated under the same conditions. Under open discharge conditions, unfluxed granules were discharged. The polyethylene temperature at the die with screw 3A was lower than screws 1B and 2, as in the case 1A, which may be a disadvantage for certain types of extrusion where high product temperatures are required. Increasing the screw temperature to 190 C caused a decrease in open discharge rate and extreme surging presumably due to polyethylene alternately sticking and releasing to the screw.

On the whole, screw 3A was a high output screw but suffered from the limitations of somewhat lower product temperatures, and surging at high screw temperatures.

E. <u>Screw 3B</u>

Screw 3B (3.9:1 compression ratio) was similar to 3A in that it was a constant depth, decreasing pitch screw with a deep (.395") eliptical channel. The feed section of this screw was double flighted and the lead decreased from 2.4 to .50 inches. This screw is representative of early plastic extrusion screws which were modified (extended) rubber extrusion screws.

Under isothermal melt extrusion conditions an intermediate open discharge rate was obtained with screw 3B which decreased 59% with the highest resistance die to the same low rate as screw 1A. As in the case of screw 1A, reducing the screw temperature to 30 C caused an 18% reduction in open discharge rate and a slight increase in output through the smallest die.

In the case of granular feed, this screw produced an intermediate discharge rate compared to the other screws investigated, while product temperatures were also generally intermediate. Increasing the screw temperature to 190 C caused a decrease in open discharge rate with considerable surging.

It is concluded that screw 3B offered no advantages over any of the preceeding screws and is therefore not recommended for any application.

VII. SUMMARY AND CONCLUSIONS

The theory of isothermal melt extrusion was reviewed beginning with the results of early researches up to those of the present day. Using this theory, open discharge rates were calculated by eight different methods and compared to results obtained with a Newtonian-like liquid and polyethylene using five different extrusion screws. It was shown that open discharge rates for Newtonian liquids and molten polyethylene under isothermal melt extrusion conditions can be calculated by one method with good accuracy, provided that unaccounted-for design limitations do not affect output. For plastic extrusion screws having compression sections, the preferred method of calculation is by integration of equation 4 from the feed section to the discharge end of the screw in order to account for varying channel dimensions. This was done for five different screws with good agreement between calculated and measured results.

It was found that the near-isothermal extrusion of a liquid polybutene through dies nearly approximated the general behavior of a Newtonian liquid. Slight curvature of the die characteristic appeared to be the sole deviation from the theoretical relationship, and this was attributed to the change in viscosity of the liquid due to heat developed by friction at high screw speeds. Although liquids such as polybutene are not normally extruded, it provides an excellent method of evaluating the extrusion characteristics of extruder screws.

The near-isothermal extrusion of molten polyethylene through dies exhibited considerable deviation from isothermal melt theory. Slight deviation occurred in the screw characteristic curves while severe deviation occurred in the die characteristic curves. Both phenomena are attributed to the decrease in viscosity of polyethylene due to heat developed by frictional working, and the complex behavior of polyethylene which causes viscosity to decrease with increasing shear rate due to frictional working.

Under these conditions it is doubtful that isothermal melt extrusion theory can be applied to the melt extrusion of polyethylene with good accuracy, except in the case of open discharge.

In the case of melt extrusion of polyethylene under non-isothermal conditions using a cool screw, reductions in open discharge rates of 7 to 23% occurred compared to isothermal conditions, while discharge rates through dies exhibited less differences, and in the case of small dies gave the same or slightly increased rates. This phenomenon was attributed to the build-up of a layer of solidified polyethylene on the screw and/or the increase in viscosity, decreasing backflow. Under these conditions even poorer correlation with isothermal melt extrusion is obtained, which also extends to open discharge rates. Thus even open discharge rates cannot be calculated with even fair accuracy in the extrusion of molten polyethylene using normally cool screws.

In the case of plasticating extrusion of granular polyethylene with cold screws, as is the common practice, open discharge rates decreased by 31 to 58% thus making the application of isothermal flow theory even more impractical. This condition may be caused by the decrease in bulk density of granular polyethylene compared to molten polyethylene resulting in incomplete filling of the screw channel, the increased slippage of granules over one another, and possibly the limited capacity of the screw to melt the polyethylene granules. There appears to be no simple and direct correction factor which may be applied to theoretical open discharge rates to estimate plasticating extrusion rates. It was observed however, that the die characteristic curves were essentially independent of screw temperature and feed temperature or form, while the screw characteristics were displaced by both these conditions. It is apparent therefore, that die operating characteristic curves in pressure-output performance diagrams, as shown in Figure 6, amy be determined experimentally, and that operating points for any feed condition or screw temperature will lie within the limits established for a given die. It will not be until the screw characteristic curves for various screw temperatures and feed conditions can be estimated, that operating points can be successfully predicted.

The effect of isothermal extruder conditions on the extrusion of granular polyethylene was also investigated with three of the screws. In the case of two deep channel screws this resulted in surging and a large reduction in output due to fouling. In the case of a shallow channel screw having a metering section the output rate increased considerably with no evidence of surging. This indicates that increased output can be obtained with shallow channel screws by operating these screws hot. This benefit is believed due to increased melting capacity of such screws when operated hot, owing to the closer heated surfaces of the screw and barrel.

In comparing the performance of five extruder screws with polyethylene it was found that this same shallow channel screw with a metering section exhibited very little change in throughput regardless of die opening and developed extremely high pressures with high resistance (small opening) dies due to low backflow rates. A similar screw without the metering section produced slightly higher discharge rates under conditions of open discharge and with large dies while rates with small dies were little affected. Several deep channel screws exhibited high open discharge rates but due to their deep channels allowed excessive backflow resulting in low discharge rates through small die openings.

Since the heart of an extruder is the screw, the importance of screw design cannot be overemphasized. A screw which yields optimum performance with a given plastic material may not be suitable for other materials, hence there can be no universal screw design for all materials and all types of operations. From the experimental work conducted with the five screw investigated it is possible to reach several generalized conclusions regarding screw design for polyethylene.

1. Shallow channel screws develop better heat transfer and better mixing (due to higher shear rates), higher pressures and tend to give more nearly the same extrusion rate regardless of die opening than deep channel screws. A disadvantage is that lower extrusion rates are obtained than with deep channel screws. There is an indication that shallow channel screws will give increased extrusion rates with satisfactory results when operated hot with granular polyethylene feed compared to normal cool screw operation. This may result in equal or higher extrusion rates in comparison to deep channel screws operated cool with granular feed.

2. Deep channel screws develop higher discharge rates than shallow channel screws under conditions of open discharge and with large dies although lower rates are likely to be encountered with small dies. Extrusion rates are known to increase with increasing screw temperature, however deep channel screws are subject to fouling with granular polyethylene feed when operated hot thus preventing the use of this output increasing technique.

3. Metering sections at the discharge end of screws reduce open discharge rates somewhat but may increase rates with small dies. No advantage was found with a shallow channel having a metering section compared to the same screw without a metering section.

This investigation was conducted with the hope that it would contribute to the present state of isothermal melt extrusion theory and to promote a better understanding of the differences between melt and plasticating extrusion of polyethylene.

VIII. APPENDIX

Nomenclature for Extrusion Theory

Table VI

d	=	die diameter
D	=	screw diameter
D_m	=	mean screw diameter = D-h
F_b	=	channel shape factor for backflow through channel
F_d	=	channel shape factor for forward flow
h	=	channel depth
k	=	die constant
l	=	die length
l_t	=	uncoilded length of screw channel
L	=	axial length of screw (threaded section)
L_e	=	effective length of screw = L - length of feed section
n	=	number of parallel flights in multi-threaded screw
N	=	screw speed rpm
P	=	pressure
P	=	pressure drop across thread
Q	=	net volumetric rate of discharge
Q_b	=	volumetric backflow through channel
Q_f	=	volumetric forward flow
Q_l	=	volumetric leakage flow over threads
s	=	axial channel width
t	=	thread width
T	=	temperature

VIII. APPENDIX (continued)

α	=	forward flow constant = Q_f/N
β	=	constant for backflow through channel
γ	=	constant for backflow over threads
δ	=	radial clearance between screw thread and barrel
λ	=	lead of screw thread or variable axial length along screw
θ	=	helix angle = arctan $\lambda/\pi D_m$
μ	=	viscosity of extrudate.

TABULATION OF LIQUID POLYBUTENE EXTRUSION DATA

SCREW		1A			1B			2			3A			3B		
R.P.M.	DIE DIAM.	RATE in³/min	PRESS. PSIG	TEMP. °C	RATE in³/min	PRESS. PSIG	TEMP. °C	RATE in³/min	PRESS. PSIG	TEMP. °C	RATE in³/min	PRESS. PSIG	TEMP. °C	RATE in³/min	PRESS. PSIG	TEMP. °C
25	0	0	88.5		0	260		0	530		0	59.0		0	49.0	
50		0	159		0	500		0	765		0	107.5		0	89.5	
75		0	198		0	660		0	880		0	142		0	120.0	
100		0	220		0	810		0	920		0	174		0	144.0	
25	.046"	.74	91.0	13.0	3.46	198	19.5	2.79	455	12.5				.75	48.0	21.5
50		1.29	149	13.8	8.05	390	20.0	5.75	650	14.5				1.41	88.0	21.5
75		1.63	184	15.0	14.9	535	22.7	7.05	730	18.0				1.98	113.5	21.5
100		1.98	209	15.5	24.2	625	24.0	12.5	880	19.2				2.55	137	21.5
25	.096"	7.05	72.0	14.0	11.4	51	19.4	11.7	125	13.0	7.36	36.0	21.5	6.15	29.5	21.5
50		12.8	107	16.0	24.8	108	20.0	22.0	187	15.1	14.6	65.5	22.0	11.4	53.5	21.5
75		19.3	133	18.0	38.5	160	21.0	33.3	239	18.0	21.4	89.0	23.0	16.4	70.0	23.0
100		26.7	152	20.0	51.1	185	22.4	45.5	265	19.5	31.4	113.0	24.7	24.0	91.0	24.5
25	.144"	12.9	40.5	14.0	13.2	25.5	19.5	14.4	60	13.0	12.5	20.5	22.0	10.2	18.0	21.5
50		25.4	71.0	16.0	27.3	52	20	27.6	94	15.5	24.9	38.0	22.4	19.4	30.0	22.5
75		38.0	91.0	18.2	44.0	77	21.6	42.7	121	18.0	37.1	53.0	23.0	29.2	44.5	23.4
100		52.2	103	20.5	59.0	95	22.0	57.6	130	19.5	52.0	73.0	24.0	40.5	56.0	24.6
25	.236"	21.3	10.0	14.5	14.4	4.0	19.4	16.9	12.0	13.0	19.2	7.0	21.5	14.5	3.0	21.5
50		42.5	20.0	16.5	29.7	11.0	20	32.2	21.0	15.8	37.7	13.0	22.0	28.8	8.0	22.6
75		62.5	27.0	18.2	47.8	15.0	21.0	48.6	28.0	18.2	56.0	16.0	23.0	43.3	12.0	23.0
100		85.5	34.0	20.0	66.0	21.0	21.6	66.0	34.0	20.0	78.0	22.0	24.0	59.0	16.5	
25	NO	25.4	0	14.5	14.8	0	20.2	17.9	0	13.5	21.9	0	22.0	16.2	0	22.0
50	DIE	48.5	0	16.0	30.0	0	22.0	34.3	0	16.0	44.0	0	22.0	31.8	0	
75		74.0	0	18.0	48.0	0	22.0	51.2	0	18.5	65.1	0	23.0	48.5	0	23.0
100		101.5	0	19.0	66.6	0	22.6	69.7	0	20.0	87.8	0	24.0	65.9	0	
25	OPEN	39.0	0		15.0	0		19.2	0		27.3	0		19.5	0	
50	HEAD	74.0	0		30.0	0		37.6	0		53.7	0		36.1	0	
75		109	0		48.7	0		55.0	0		79.5	0		57.8	0	
100		147	0		67.0	0		76.0	0		108	0		77.5	0	
HEAD TEMP, °C				13.0			19.2			12.0			20.0			20.0
BARREL "				13.0			19.2			12.0			20.0			20.0
SCREW "				13.0			19.2			12.0			20.0			20.0

Table VIII

TABULATION OF MOLTEN POLYETHYLENE EXTRUSION DATA

SCREW R.P.M.	DIE DIAM.	1A RATE in.³/min	1A PRESS. PSIG	1A TEMP. °C	1B RATE in.³/min	1B PRESS. PSIG	1B TEMP. °C	2 RATE in.³/min	2 PRESS. PSIG	2 TEMP. °C	3A RATE in.³/min	3A PRESS. PSIG	3A TEMP. °C	3B RATE in.³/min	3B PRESS. PSIG	3B TEMP. °C
MOLTEN FEED AT 150°C																
25	0	0	1380		0	>3000		0	>3000		0	>3000		0	2100	
50	|	0	1800		0	>3000		0	>3000		0	>3000		0	2750	
75	|	0	1970		0	>3000		0	>3000		0	>3000		0	2950	
100	|	0	2170		0	>3000		0	>3000		0	>3000		0	>3000	
50	.046"	16.1	1480	206	23.3	1620	205	28.3	1750	205	27.6	1750	198	18.2	1520	204
75	|	26.4	1610	214	38.8	1810	208	40.3	1850	210	40.7	1900	199	27.0	1580	210
100	|	36.7	1725	216	58.6	1975	216	55.8	2000	215	57.0	2025	210	36.7	1690	215
50	.096"	35.0	780	202	25.5	675	200	31.3	810	204	38.6	880	198	28.9	750	194
75	|	51.0	910	204	44.5	810	204	46.0	875	204	56.0	975	200	43.3	850	195
100	|	69.3	1000	208	67.2	900	208	64.0	950	206	78.8	1010	204	57.7	900	204
50	.144"	42.0	560	195	26.0	400	198	32.8	500	200	42.0	550	190	31.2	500	194
75	|	61.1	620	200	46.0	510	196	51.5	575	204	62.8	630	192	46.2	575	194
100	|	82.5	680	204	68.8	575	206	70.0	625	204	85.0	680	194	63.7	625	198
50	.236"	48.5	255	190	26.2	175	199	36.3	225	196	44.0	270	190	36.9	240	190
75	|	70.4	290	194	46.7	210	202	52.3	240	200	66.0	330	196	53.4	255	194
100	|	96.0	305	202	72.5	270	208	73.0	260	206	87.4	350	202	70.7	280	198
25	OPEN	28.0	0	186	12.3	0	192							20.2	0	190
50	HEAD	57.5	0	185	28.3	0	195	40.2	0		50.3	0	184	44.5	0	182
75	|	86.3	0	186	47.0	0	198	59.0	0		76.2	0	186	65.0	0	188
100	|	112.0	0	190	75.0	0	200	80.3	0		102.0	0	190	89.0	0	186
GRANULAR FEED AT ROOM TEMP.																
25	OPEN															
50	HEAD				19.5	0	192				15-24	0	184	12-19	0	184
75	|				32.3	0	180				24-34	0	156	20-27	0	166
100	|				55.5	0	158				31-43	0	130	30-36	0	146
HEAD TEMP, °C				190			190			190			190			190
BARREL "				190			190			190			190			190
SCREW "				190			190			190			190			190

Table IX
TABULATION OF GRANULAR POLYETHYLENE EXTRUSION DATA

SCREW		1A			1B			2			3A			3B		
R.P.M.	DIE DIAM.	RATE in^3/min	PRESS. PSIG	TEMP. °C	RATE in^3/min	PRESS. PSIG	TEMP. °C	RATE in^3/min	PRESS. PSIG	TEMP. °C	RATE in^3/min	PRESS. PSIG	TEMP. °C	RATE in^3/min	PRESS. PSIG	TEMP. °C
					MOLTEN FEED AT 150°C											
50	.046"	22.4	1610	188				24.6	1700	188	26.2	1800	186	19.4	1650	188
75	|	34.0	1800	196							43.0	1975	186	32.4	1810	188
100	|	45.8	1925	198				52.5	2020	200	57.2	2125	190	44.0	1960	190
50	.144"	38.6	580	178				27.2	500	182	32.4	580	178	26.4	475	174
75	|	58.7	660	184							51.5	710	180	45.1	580	180
100	|	78.0	710	188				62.1	620	192	75.2	800	182	60.7	640	184
50	.236"										39.4	290	174	29.3	210	170
75	|										59.0	350	174	47.7	280	174
100	|										86.5	380	178	66.0	310	182
50	OPEN	47.6	0	165	22.1	0	174	34.9	0	174	46.6	0	166	33.0	0	160
75	HEAD	71.0	[illegible]	168	35.4	0	176				71.0	0	166	53.3	0	172
100	|	95.4	0	172	55.0	0	180	70.1	0	179	95.8	0	170	78.0	0	168
					GRANULAR FEED AT ROOM TEMP.											
25	.046"				5.7	1100	186	8.1	1250	184						
50	|	15.2	1475	190	13.3	1420	188	18.0	1560	186	17.5	1550	194	12.9	1415	188
75	|	21.7	1590	192	20.2	1575	190	23.8	1665	190	25.7	1750	190	18.1	1525	192
100	|	27.6	1680	198	31.2	1720	195	32.0	1790	198	35.2	1950	192	23.2	1600	195
25	.144"							9.5	325	180						
50	|	23.5	480	178	15.4	380	183	20.8	435	180	23.5	510	165	17.8	440	176
75	|	31.6	510	182	22.7	425	185	27.2	480	182	33.5	610	175	25.0	480	175
100	|	38.7	555	182	32.0	485	186	36.7	530	186	41.8	650	178	31.7	550	168
25	.236"							10.0	100	172						
50	|				15.8	175	180	21.3	175	175	24.7	260	150	18.5	160	176
75	|				22.9	205	177	28.6	225	180	34.4	300	156	26.1	225	165
100	|				32.2	240	175	38.5	240	186	43.0	330	156	33.7	265	162
25	OPEN				6.7	0	165	11.5	0	166				10.6	0	168
50	HEAD	32.7	0	138	16.3	0	170	21.8	0	168	35.3	0	145	21.3	0	168
75	|	48.3	0	135	22.9	0	156	31.6	0	155	53.9	0	135	29.2	0	154
100	|	64.0	0	130	31.3	0	145	42.2	0	146	69.4	0	110	40.1	0	145
HEAD TEMP. °C				190			190			190			190			190
BARREL "				190			190			190			190			190
SCREW "				30			30			30			30			30

IX. REFERENCES

1. "The Rubber Extruder", Rubber World 131, 379, Dec. 1954.
2. Rogowsky, Z., Engineering, 162, 358, Oct. 11, 1946.
3. Piggott, W. T., Trans. ASME, 73, 947, Oct. 1951.
4. Carley, J. F. and Strub, R. A., Ind. and Eng. Chem., 45, 970, May 1953.
5. Carley, J. F., Mallouk, R. S., and McKelvey, J. M., Ind. Eng. Chem., 45, 974, May 1953.
6. McKelvey, J. M., Ind. and Eng. Chem., 45, 978, May, 1953.
7. Gore, W. L., S. P. E. Journal, 6, Mar., 1953.
8. Beyer, C. E., and Towsley, F. E., J. Coll. Sci., 7, 236, 1952.
9. Rowell, H. S., and Finlayson, D., Engineering, 114, 249, Aug. 31, 1928.
10. Darnell, W. H., and Mol, E. A. J., "Solids Conveying in Extruders," Paper presented at 11th S. P. E. Conference, Mar. 1955.