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PROGRAM: SRE

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STATEMENT OF PROBLEM: Develop a Preliminary Hydraulic Design for the SRE-PEP Core III Variable Orifice.

ABSTRACT: A single, wide range variable orifice design is developed which provides a maximum orifice flow area of 2.0 in^2 and a minimum orifice flow area of 0.2 in^2. The design is based on an overall operating core ΔP of 4.0 psi and provides for a sodium flow range of 2.45 #/sec to 10.0 #/sec. Bypass leakage arround the orifice is analyzed and accounted for in the design. It is shown that the use of piston rings is not necessary to reduce this leakage. The orifice plug profile is calculated for constant temperature sensitivity; the maximum average sensitivity being 451 ^oF/in. for a 1.5 in. plug length. Fuel channel pressure drop is recalculated for both special and standard elements using the latest proposed designs. Maximum ΔP including wide open variable orifice is 3.6 psi.

FORM 701-C REV. 10-62

I. Review of HNPF Variable Orifice Development

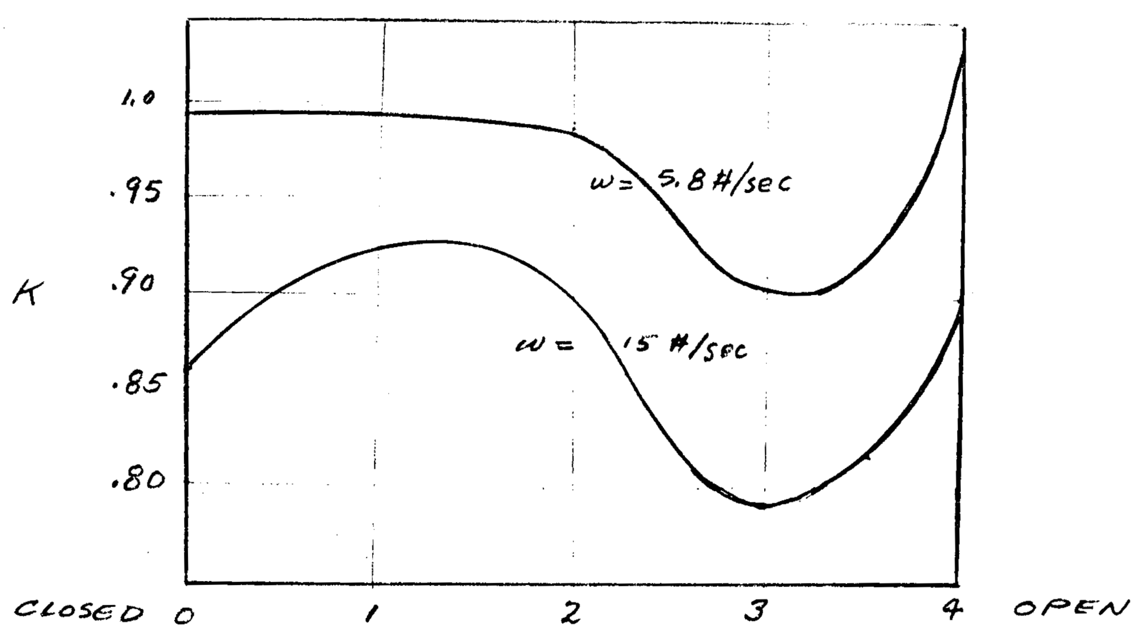
The development of the HNPF variable orifice is summarized in Reference 1. The first device tested ("Type I") had a tapered plug operating in a relatively streamlined throat section and was designed for uniform variation of flow with plug position. This arrangement proved to have an undesirably low pressure breakdown coefficient and an undesireably high "temperature sensitivity" when operating near the closed position. These faults were corrected in the "Type II" design by replacement of the smooth throat with a relatively sharp edged orifice and by reshaping the plug for constant temperature sensitivity instead of uniform flow variation. Several orifice shapes were tested; the final design selected is shown in Figure 1.[3]

Results of hydraulic tests on a production model HNPF variable orifice are shown in Figure 2.[2] The pressure breakdown coefficient, K, for this orifice has been calculated from these data after elimination of nonvariable pressure losses by the method described in Appendix I. Pressure breakdown coefficient, K, is defined by equation (1).

$$\Delta p_o = K \rho \frac{V_o^2}{2g} \qquad (1)$$

Calculated coefficients are shown in Figure 3 as a function of

FIG 3



plug position and flow rate. Approximate coefficients calculated from test data on other orifice designs reported in Reference 1 are given in Table I. Since the complete dimensions of the plugs used in these tests were not reported, it was possible to obtain only the closed position pressure breakdown coefficients for these designs.

TABLE I

Closed Position Pressure Breakdown Coefficients For Various HNPF Test Orificies

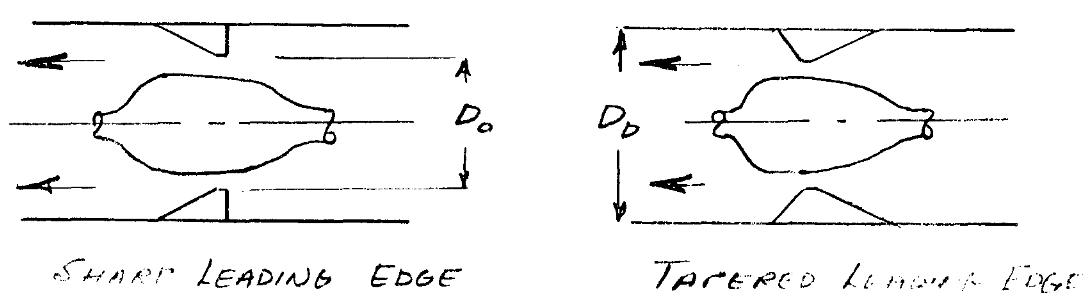
Type		Dia. Ratio D_D/D_o	Sodium Flow @ 945^oF (w) (#/sec)	K	Slope of log Δp vs log w
I	A	--	2.0	.480	1.80
	B	--	2.0	.418	1.66
	C	--	10.0	.372	1.985
II	A	1.48	10.0	1.44	1.93
	B	1.48	10.0	1.19	1.98
	C	1.16	10.0	.975	1.93
	D	1.59	10.0	1.25	1.91

The foregoing test results reveal several characteristics of the HNPF orifice which are of interest in design of similar devices.

1. K decreases with increasing Reynolds number; K $\approx\propto$ Re $^{-0.1}$

2. K increases as the ratio of downstream diameter to orifice diameter (D_D/D_o) increases. (Compare Type II A to C and B to D. These two pairs were similar except for the ratio D_D/D_o).

3. A sharp leading edge on the orifice yields a higher K than a tapered leading edge. (compare type II A to B)



4. The HNPF variable orifice, especially the tapered leading edge version (production model) behaves hydraulically more nearly like a nozzle than like a sharp edged orifice. (A nozzle has a K slightly less than 1.0 which decreases with increasing Reynolds Number at comparable Reynolds Number, whereas, an orifice typically has a K between 2.0 and 3.0 which increases slightly with increasing Reynolds Number).

Analysis of the data from tests on the production model HNPF orifice shows K to be variable with plug position as well as flow rate (Figure 3). This variation does not follow a predictable trend, therefore, it is not practical at this time to account for it in the design of the SRE orifice. The mean value of K for the production model orifice as calculated from Reference 3 data can be represented as a function of the mean Reynolds number by equation (2).

$$\overline{K} = \frac{3.78}{(\overline{Re})^{.114}} \qquad (2)$$

where

$$\overline{Re} = \frac{4\, w_o}{\overline{P}\mu} \qquad (3)$$

$\overline{P}$ is the mean wetted perimeter of the orifice; the variation of P of the HNPF orifice from the mean value is $\pm$ 14% as the plug moves between its extreme positions.

The data of Reference 2 is most recent and most completely documented, therefore, equation (2) is used below for the SRE-PEP Core III preliminary orifice design. The uncertainty of equation (2) as applied to the new short plug orifice design for SRE is sufficiently large to require hydraulic tests before the final design can be established firmly.

II. Orifice Sensitivity

"Temperature Sensitivity", or merely "sensitivity" is a term coined during HNPF variable orifice development. It is defined as the incremental ratio of outlet temperature change to orifice plug position change when the orifice is adjusted in the operating reactor.

$$S \triangleq \frac{dT_o}{dx} \qquad (4)$$

From an operational viewpoint, it is desirable to minimize S so that undesirably large channel outlet temperature changes cannot occur during orifice adjustment. The average value of sensitivity, $\overline{S}$, is obviously inversly proportional to the total length of travel of the plug (X). Once X has been established from consideration of reasonable values of $\overline{S}$ and from consideration of mechanical limitations; only the shape of the plug remains to be established to keep S everywhere as low as possible. This requires that S be constant or

$$S = \frac{dT_o}{dx} = \text{constant} \qquad (4)$$

For convenience, write

$$T_o = T_{in} + \Delta T_{core} \qquad (5)$$

$$\Delta T_{core} = \frac{Q}{w_T\, C_p} \qquad (6)$$

$$S = \frac{d(\Delta T_{core})}{dx} = \frac{d}{dx}\left(\frac{Q}{w_T\, C_p}\right) = -\frac{Q}{w_T^2\, C_p}\,\frac{dw_T}{dx} \qquad (7)$$

On the right-hand side of equation (7), the factor $\left(\frac{Q}{w_T C_p}\right)$ is nearly constant with respect to large variations in x. Here we are considering the overall shape of the plug where large variations in x occur only because of variation in the location of the orifice in the core. That is, in the outer region of the core the orifice always operates nearly closed and in the inner region it always operates nearly open. Since ΔT_{core} is maintained nearly constant everywhere in the core, then from (6), $\left(\frac{Q}{w_T C_p}\right)$ is nearly constant. Then write (7)

$$S = -\frac{\Delta T_{core}}{w_T}\,\frac{dw_T}{dx} \qquad (8)$$

This requires that the change in flow with plug position, dw_T/dx, be everywhere proportional to the local flow, w_T. The local flow is, in turn, a function of the overall core pressure drop, the frictional resistance of the fuel element and hardware and the orifice bypass leakage as well as plug position. These relationships are summarized in the next section.

Integration of equation (8) yields expressions convenient for calculation of the plug shape and calculation of the average sensitivity, $\bar{S}$.

$$\int_0^x -\frac{S\,dx}{\Delta T_{core}} = \int_{w_{T_{min}}}^{w_T} \frac{dw_T}{w_T} \qquad (9)$$

$$-\frac{S\,x}{\Delta T_{core}} = \ln\left(\frac{w_T}{w_{T_{min}}}\right) \qquad (10)$$

$$\bar{S} = -\frac{\Delta T_{core}}{X} \ln\left(\frac{w_{T\,max}}{w_{T\,min}}\right) \tag{11}$$

From parameters developed below, the maximum average sensitivity for the proposed SRE-PEP Core III variable orifice is:

$$\bar{S}_{max} = \frac{550}{X} \ln\left(\frac{10}{2.45}\right) = \frac{773}{X} \;{}^{\circ}F/in.$$

The plug stroke proposed is 1.5 in., therefore

$$\bar{S}_{max} = 515\,{}^{\circ}F/in.$$

The HNPF production model orifice has a maximum sensitivity that ranges between 240°F/in and 90°F/in depending on plug position, the highest values being for the open position.

III. SRE-PEP Core III Preliminary Orifice Design

To find the appropriate design equation for the orifice, substitute $V = w/\rho A$ and Equation (2) in Equation (1).

$$\Delta P_o = \frac{3.78}{\left(\frac{4 w_o}{\bar{P}\mu}\right)^{.114}} \cdot \frac{\rho\left(\frac{w_o}{\rho A_o}\right)^2}{2g} \tag{12}$$

which reduces to

$$\Delta P_o\,(psi) = \frac{.0496\left[w_o\,(\#/sec)\right]^{1.886}}{\left[A_o\,(in.^2)\right]^2} \tag{13}$$

In Equation (13) we evaluated μ and ρ for sodium at 1200°F and assumed the mean diameter for the flow area of the orifice to be 1.75 inch yielding $\bar{P} = 2\pi(1.75) = 11.0$ in. When detailed design of the orifice is completed, $\bar{P}$ may turn out to be a little different than 11.0; however, the net effect on A_o will be small because of the power 0.114 on $\bar{P}$ makes its effect weak. Equation (13) is therefore, satisfactory for present preliminary design purposes. Equation (13) is plotted in Figure (4).

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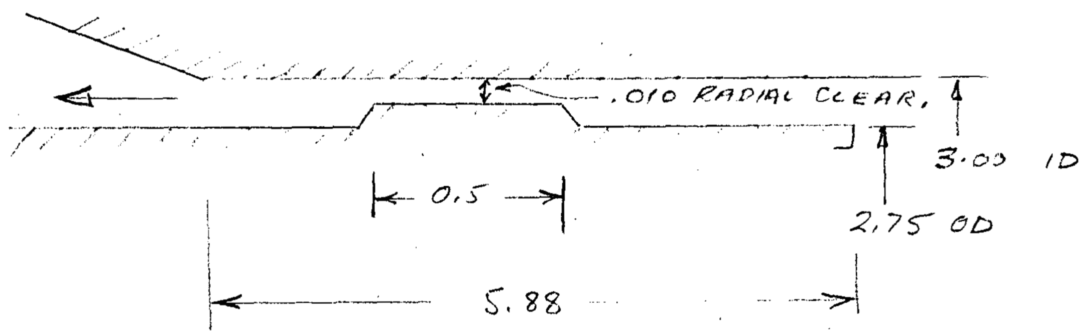
The arrangement of the SRE orifice assembly is such that a significant amount of bypass leakage will occur around the orifice. The orifice assembly slips into the top of the moderator can process tube. Partial sealing of the joint is accomplished by a flow restriction having a .020 diametrical clearance as indicated in the sketch below.



Bypass leakage flow calculated as a function of orifice ΔP_o for this geometry is plotted in Figure 5. As will be subsequently shown, a satisfactory orifice design can be made which will compensate for this leakage, therefore, it is not necessary to provide piston rings to improve sealing at this location.

In addition to the above, it is of course necessary to have the pressure drop characteristics of the fuel channel. These were calculated and reported in Reference (4) for the standard element. Since that calculation was made, there has been a revision of the lower pedestal and screen arrangement. The results of revised pressure drop calculations for both the special and the standard fuel elements are shown in Figure 5. The method of calculation is given in detail in Reference (4) and the geometric parameters for the revised calculation are given in Figure 6.

The orifice area required to produce a given flow for a specified overall core pressure drop ΔP_T, can be obtained conveniently by the use of the curves in Figures 4 and 5. For instance, fix the core ΔP_T at 4.0 psi . Say the orifice flow, w_o, is 4.00 #/sec, then total flow, $w_o + w_1$, is about 4.6 #/sec and, for the standard element, $\Delta P_c \approx$ 0.9 psi from Figure 5. Then $\Delta P_o = \Delta P_T - \Delta P_c \sim 3.7$ psi and from Figure 5 the bypass leakage, w_1, is 0.60 #/sec, and soforth. By trial and error it is easy enough to find w_1, w_T and ΔP_c for a given ΔP_T and w_o. The corresponding A_o is read from Figure 4.

For total flows above 8.0 #/sec the pressure drop curve for the special element is used since, when operating in this flow range, the orifice will be attached to special elements. Results of calculations made in this manner are summarized in Table II below and plotted in Figure 7. The transition region around w_T = 8.0 #/sec is smoothed in to produce a single composite curve with a gradual transition between the characteristics required for the two types of elements. This allows the use of a single plug profile for all fuel elements. The exact profiles required for the two elements are not too different, therefore, errors resulting from this precedure are not large.

TABLE II

Calculation of Required Orifice Area for $\Delta P_T = 4.0$ psi

w_o (#/sec)	w_1 (#/sec)	w_T (#/sec)	ΔP_c (psi)	ΔP_o (psi)	A_o (in^2)
2.0	.640	2.64	.322	3.678	.222
4.0	.585	4.585	.930	3.07	.452
6.0	.495	6.495	1.78	2.22	.810
8.0	.440	8.44	2.25	1.75	1.18
10.0	.277	10.277	3.30	0.70	2.32

For each choice of ΔP_T, a different relation for A_o vs w_T exists and a different plug profile is required. It is necessary, therefore to choose ΔP_T near the expected operating condition for the reactor. Because of size limitations on the components involved, the maximum orifice flow area available is about 2.5 in^2. To allow for some freedom of design and margin of safety, we use 2.0 $in.^2$ as the maximum (wide open) design flow area for the orifice. Maximum expected flow rate in the center special element is $w_T = 9.45$ #/sec or $w_o \doteq 9.15$ #/sec. Referring to Figure 4 this flow would produce a wide open ($A_o = 2.0$) orifice pressure drop of 0.8 psi. Total core pressure drop for the center-channel wide-open condition is then, $\Delta P_T = 0.8 + 2.8 = 3.6$ psi. To minimize pumping power, it is desirable to operate at minimum ΔP_T, however, some degree of independent control on w_T for the center element would be desirable, therefore, $\Delta P_T = 4.0$ is selected as the design point for the orifice plug. So long as the reactor is operated near this point the orifice should function as intended.

Selection of a design range for w_T (or lower limit on A_o) is the next step in developing the plug profile design. A wide range orifice is desired to eliminate the need for fixed orificies or other complications. The top end of the range need not be much above the expected operating point for the center-channel since center-channel flow can always be increased by increasing the overall core pressure drop, ΔP_T. The low end, however, should be significantly below the expected minimum to allow for possible over-estimate of K and fuel channel ΔP_c and to allow for possible operation at ΔP_T greater than 4.0 psi.

The minimum expected flow rate for the outermost driver is 2.95 #/sec. According to Figure 7 the corresponding minimum orifice flow area required is 0.25 $in.^2$, however, if the plug is designed for $A_{o\ min} = 0.20\ in.^2$ then the flow in the outer element could be held down to 2.95 #/sec if the core is operated at $\Delta P_T = 6.0$ psi. This minimum area would also provide adequate margins in the other respects mentioned above. The selected range for orifice area is then 2.0 to 0.2 $in.^2$ which corresponds to a nominal flow range of 2.45 to 10.0 #/sec at $\Delta P_T = 4.0$ psi.

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The procedure outlined above yields the relation between orifice flow area and fuel channel flow rate and the desired operating range of the orifice. The last step is to combine this with equation (10), eliminate flow, and obtain a relation between plug position, x, and orifice flow area. This relation is used to design the plug profile.

Since the desired relationship between plug position and flow is ~~logarithinic~~ logarithmic equation (10) it is convenient to plot w_T vs x/X on semilog paper, the result being merely a straight line between w_{min} at $x/X = 0$ and w_{max} at $x/X = 1$ as indicated in Figure 8. The curve of Ao vs x is then obtained easily by reading points of the two curves (Ao vs w_T and w_T vs x/X). This is the final design curve for the plug plotted in Figure 8.

IV. Hydraulic Tests of Variable Orifice

Hydraulic tests of the variable orifice for SRE-PEP Core III are to be performed to establish its actual performance and to determine if changes are required to meet performance goals. These goals are:

1. Flow range of 2.45 #/sec to 10.0 #/sec at $\Delta P_T = 4.0$ psi when attached to appropriate fuel element.

2. Relatively constant sensitivity, i.e., dw_T/dx proportional to w_T over the full range of flows when attached to appropriate fuel element.

Measurements should be made to determine the following parameters:

1. Orifice pressure breakdown coefficient, K, as a function of plug position and Reynolds number.

2. Orifice bypass leakage rate, W_l, as a function of orifice pressure drop.

In addition to these factors, it may be necessary to investigate various plug shapes and orifice plate shapes if the variation of K with plug position turns out to be undesirably large. The SRE short plug design requires sharp curvature at the open end which may produce high sensitivity at certain positions. Modifications such as "shaving" the plug in the region of sharp curvature could be tried. Care should be taken to obtain accurate measurements of actual plug diameters and orifice plate dimensions prior to all tests.

Note: The analysis described above assumed that the only important leakage path which allows by-pass flow around the orifice is between the orifice assembly insert and the upper process tube as described on Page 7. Recently proposed moderator can design changes may introduce a significant additional by-pass leakage path in the region between the can head assembly and the graphite's zerconium skin. When final design of the orifice is made, this factor should be considered.

References

1. C. J. Baroczy, J. A. Hagel, W. D. Leonard, "Development of a Variable Orifice for HNPF Fuel Channels", NAA-SR- 5369, May 1961

2. C. P. Sutherland, "Hydraulic Characteristics of a Shield Plug Orifice", NAA-SR-TDR 7417, May 1962

3. AI Drawings 7518-D71815C, 7518-D71812F, 7518-D71817H

4. R. C. Noyes, "Hydraulic Analysis of SRE-PEP Core III Standard Fuel Element", NAA-SR-TDR 9029, September 1963

See also the following TDR's.

NAA-SR-TDR-4817, 7083, 5575, 4814, 3966, 3557, 4037, 4817, 5115, 4690, 3189

Nomenclature

ΔP_o Orifice pressure drop (psi or ft of Na)

ΔP_T Total pressure drop across core (psi)

K Orifice pressure breakdown coefficient (dimensionless)

ρ density ($\#/ft^3$)

V_o Maximum velocity through orifice (ft/sec)

g Constant in Newton's 2nd law (ft/sec^2)

D diameter (in.)

Re Reynolds number (dimensionless)

A_o Flow area of orifice ($in.^2$)

w_o Mass flow thru orifice (#/sec)

w_T total mass flow thru fuel channel (#/sec)

w_l bypass leakage flow around orifice (#/sec) $w_T = w_o + w_l$

μ Viscosity (#/hr-ft)

T_o Outlet temperature (°F)

S Orifice sensitivity (°F/in.)

x distance along plug (in.)

X length of plug (in.)

Q total heat released in fuel channel (Btu/sec)

C_p Specific heat (Btu/#-°F)

P wetted perimeter (in.)

Appendix I

The reduction of pressure drop data on the HNPF orifice to determine K requires determination of the non-variable portion of ΔP_o included between pressure taps used for measurement. This was done by the graphical procedure outlined here.

If orifice flow w_o is fixed, then the measured pressure drop can be represented,

$$\Delta P_o = \Delta P_F + \frac{K w_o^2}{2 g \rho A_o^2} = \Delta P_F + \frac{C_1(K)}{A_o^2}$$

ΔP_F is the fixed portion of ΔP_o (function of wo only). If K does not vary too much with variation of Ao, then a plot of ΔP_o vs $(1/A_o)^2$ for constant w_o will yield ΔP_F at the extrapolation to $(1/A_o)^2 = 0$.

Two such plots used in the calculation of K for the HNPF production model orifice are shown in Figure 9.

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HNPF VARIABLE ORIFICE

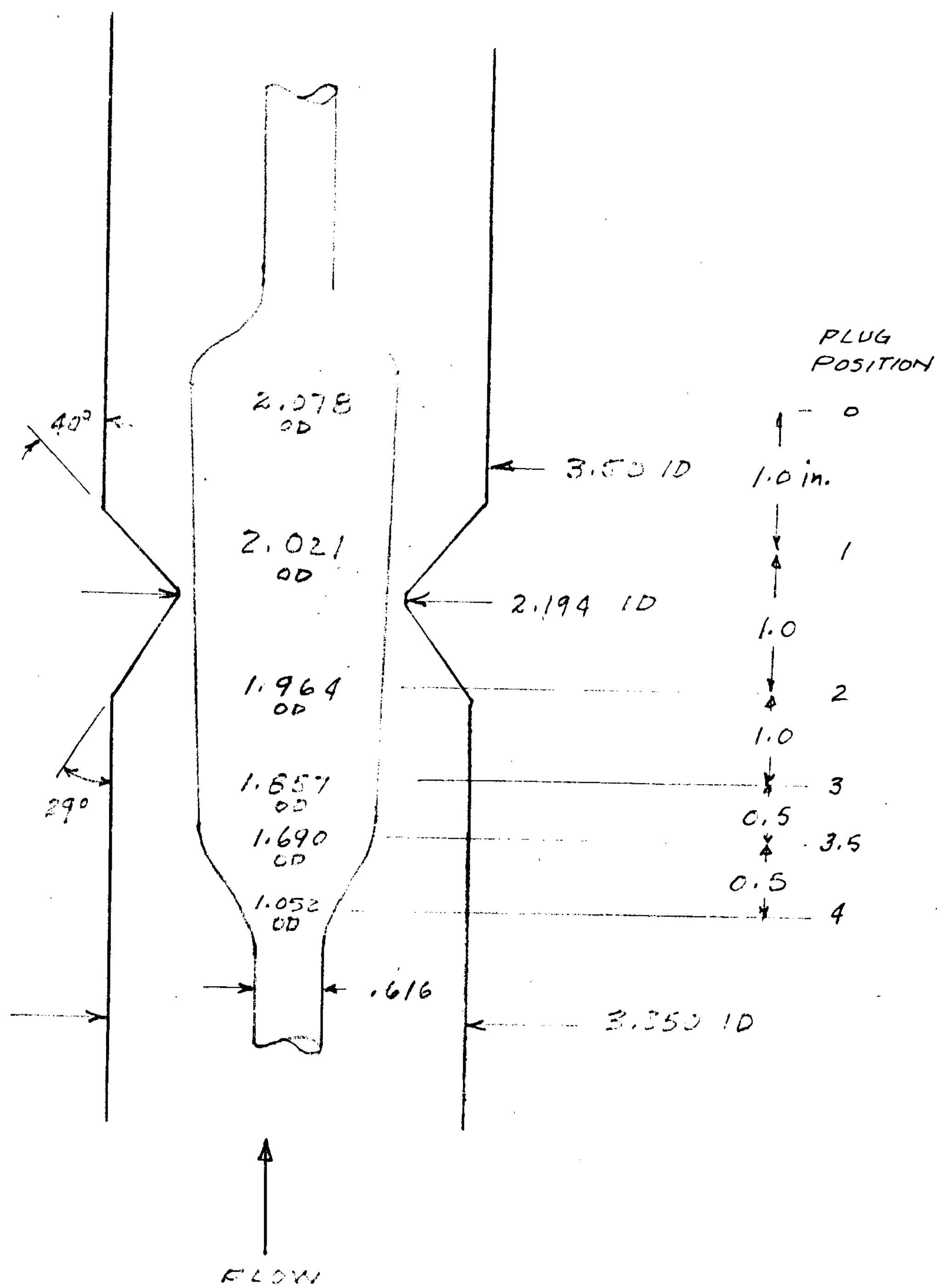


Figure 1

HNPF PRODUCTION MODEL VARIABLE ORIFICE PRESSURE DROP

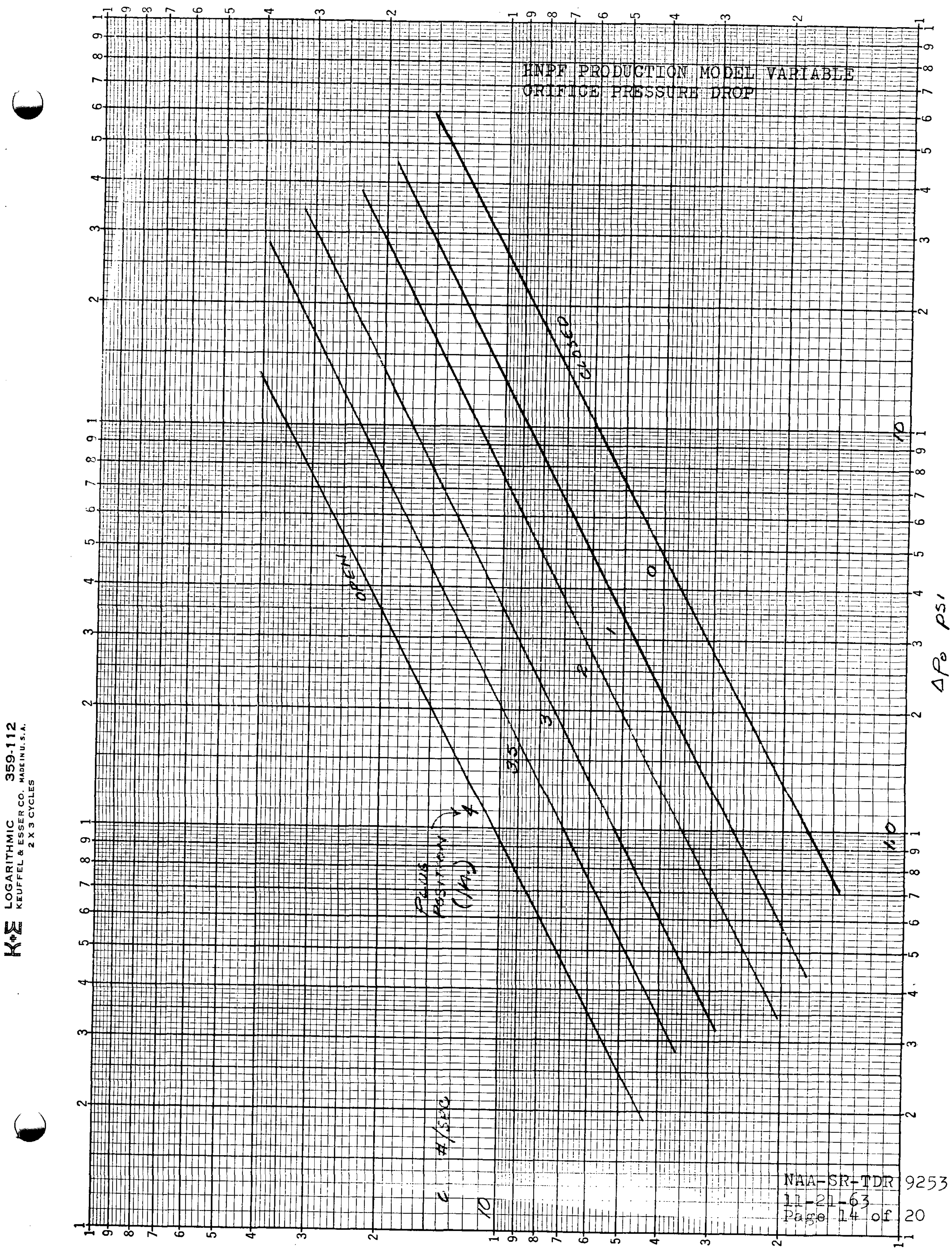


Figure 2

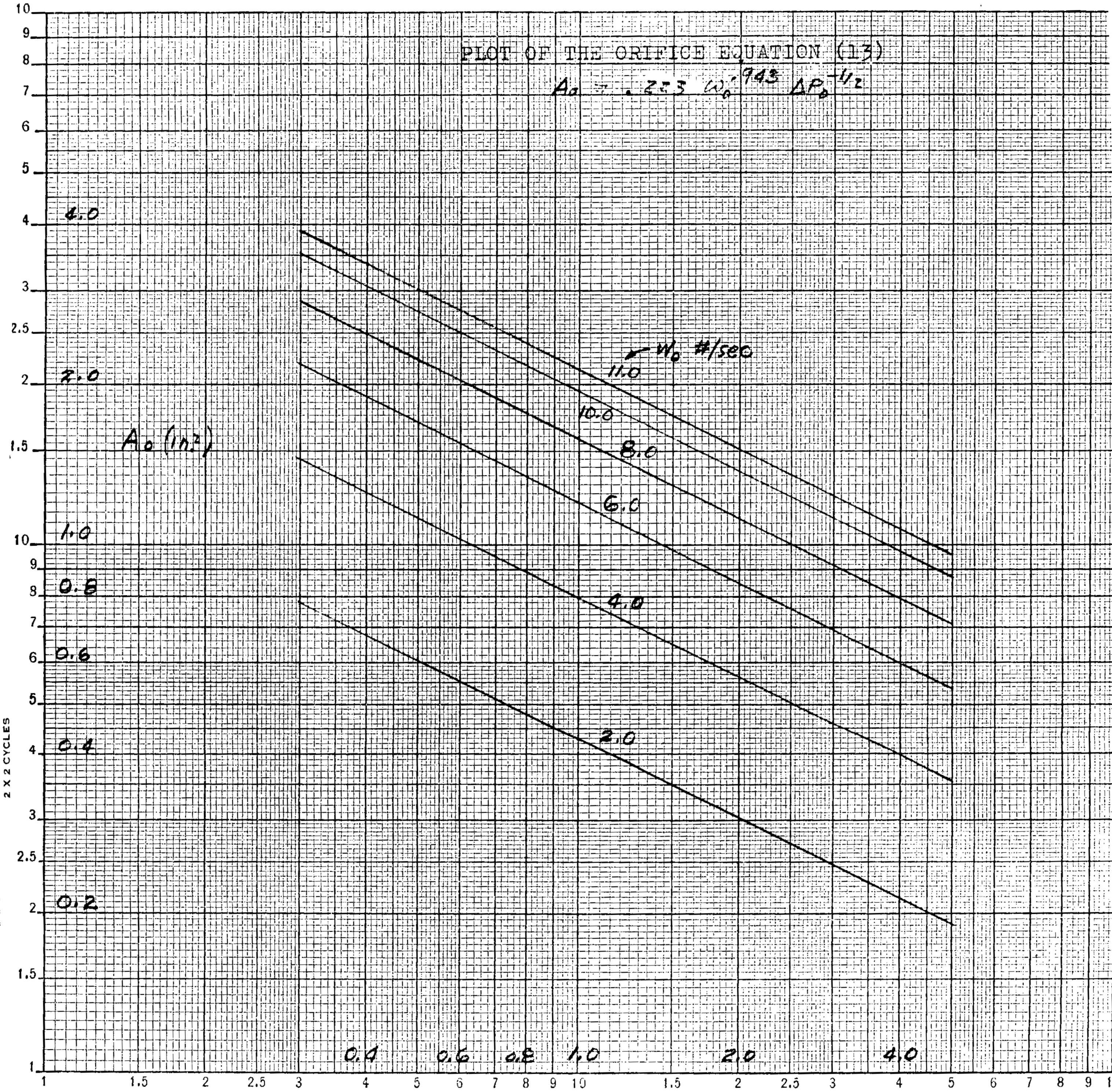


Figure 4

ΔP_o (psi)

SRE-PEP CORE III FUEL ELEMENT
PRESSURE DROP AND ORIFICE BYPASS
LEAKAGE

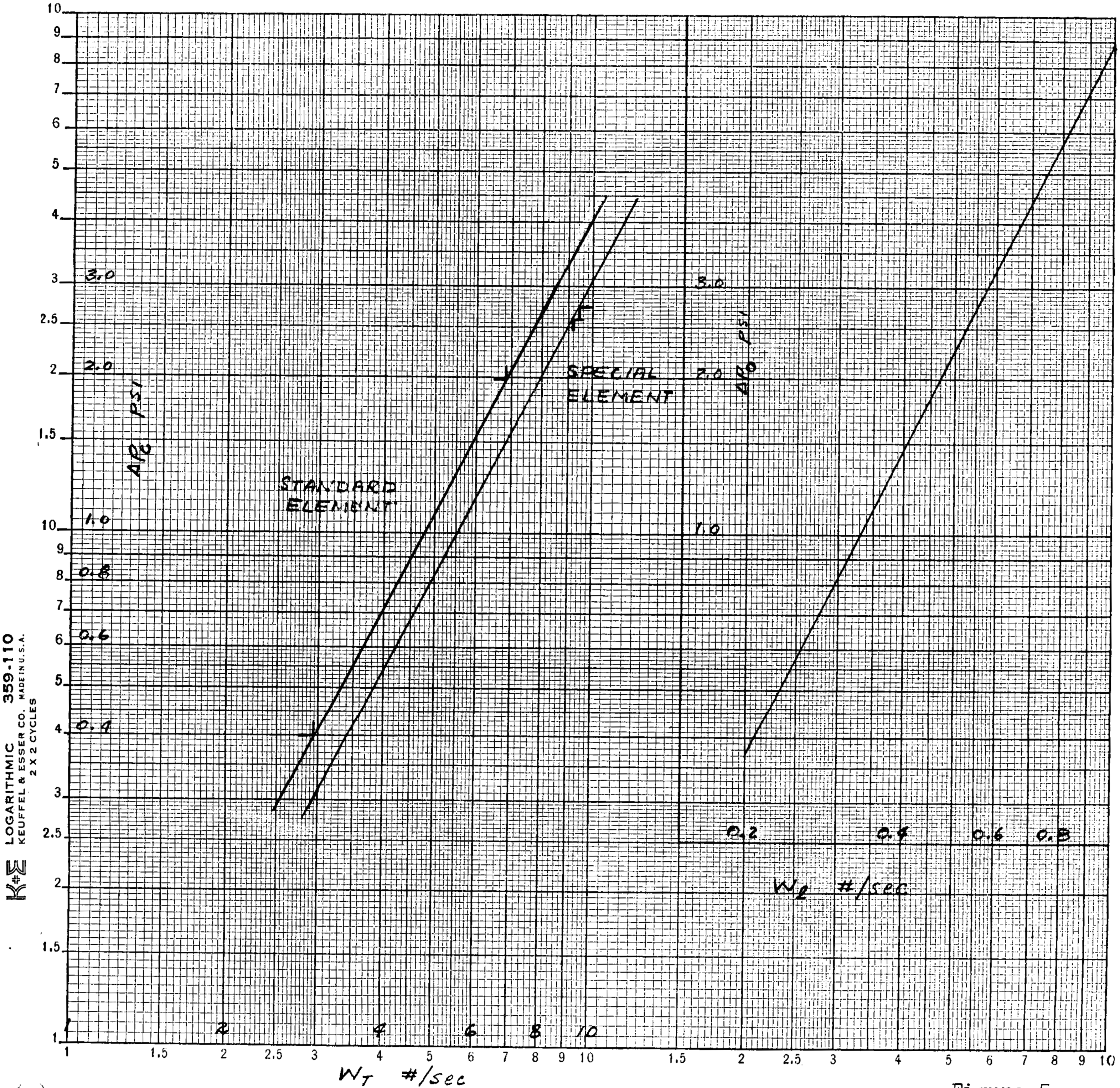


Figure 5

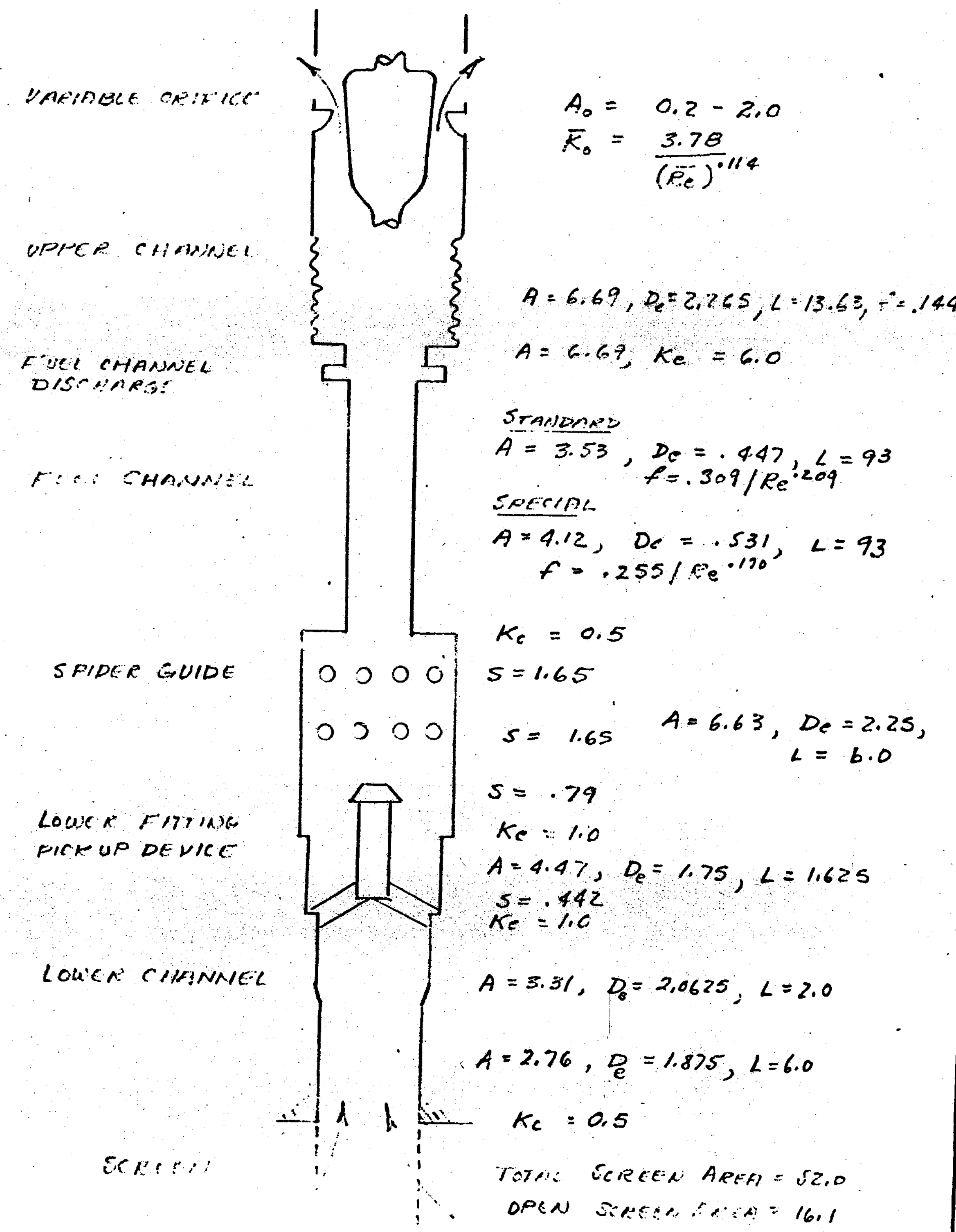

VARIABLE ORIFICE
A_o = 0.2 - 2.0
$\bar{K}_o = \frac{3.78}{(\bar{Re})^{.114}}$
UPPER CHANNEL
A = 6.69, D_e = 2.265, L = 13.63, f = .144
FUEL CHANNEL DISCHARGE
A = 6.69, Ke = 6.0
STANDARD
A = 3.53, De = .447, L = 93
$f = .309/Re^{.209}$
SPECIAL
A = 4.12, De = .531, L = 93
$f = .255/Re^{.170}$
Kc = 0.5
SPIDER GUIDE
S = 1.65
S = 1.65
A = 6.63, De = 2.25, L = 6.0
S = .79
LOWER FITTING PICK UP DEVICE
Ke = 1.0
A = 4.47, D_e = 1.75, L = 1.625
S = .442
Ke = 1.0
LOWER CHANNEL
A = 3.31, D_e = 2.0625, L = 2.0
A = 2.76, D_e = 1.875, L = 6.0
Kc = 0.5
TOTAL SCREEN AREA = 52.0

Figure 6

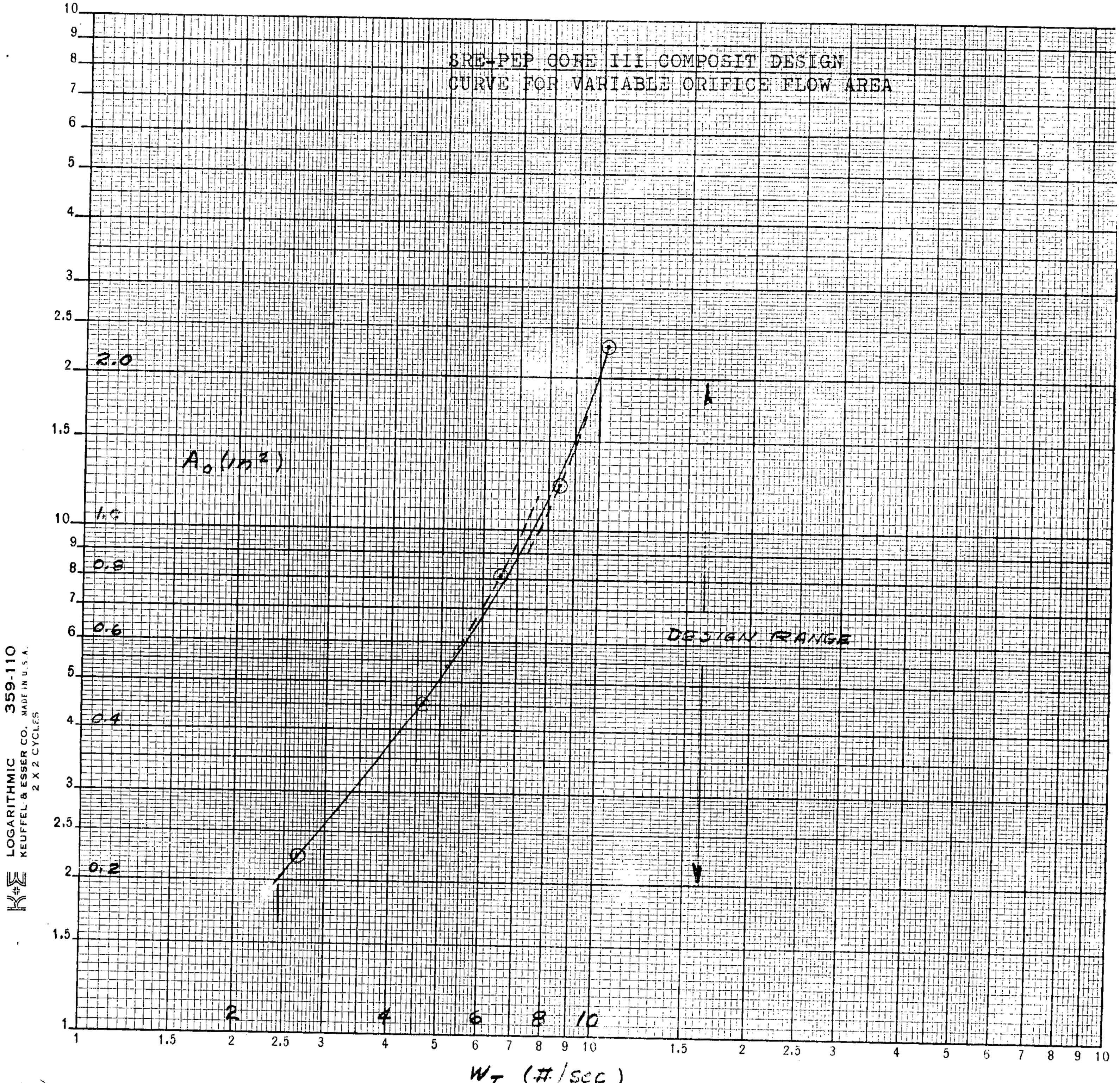
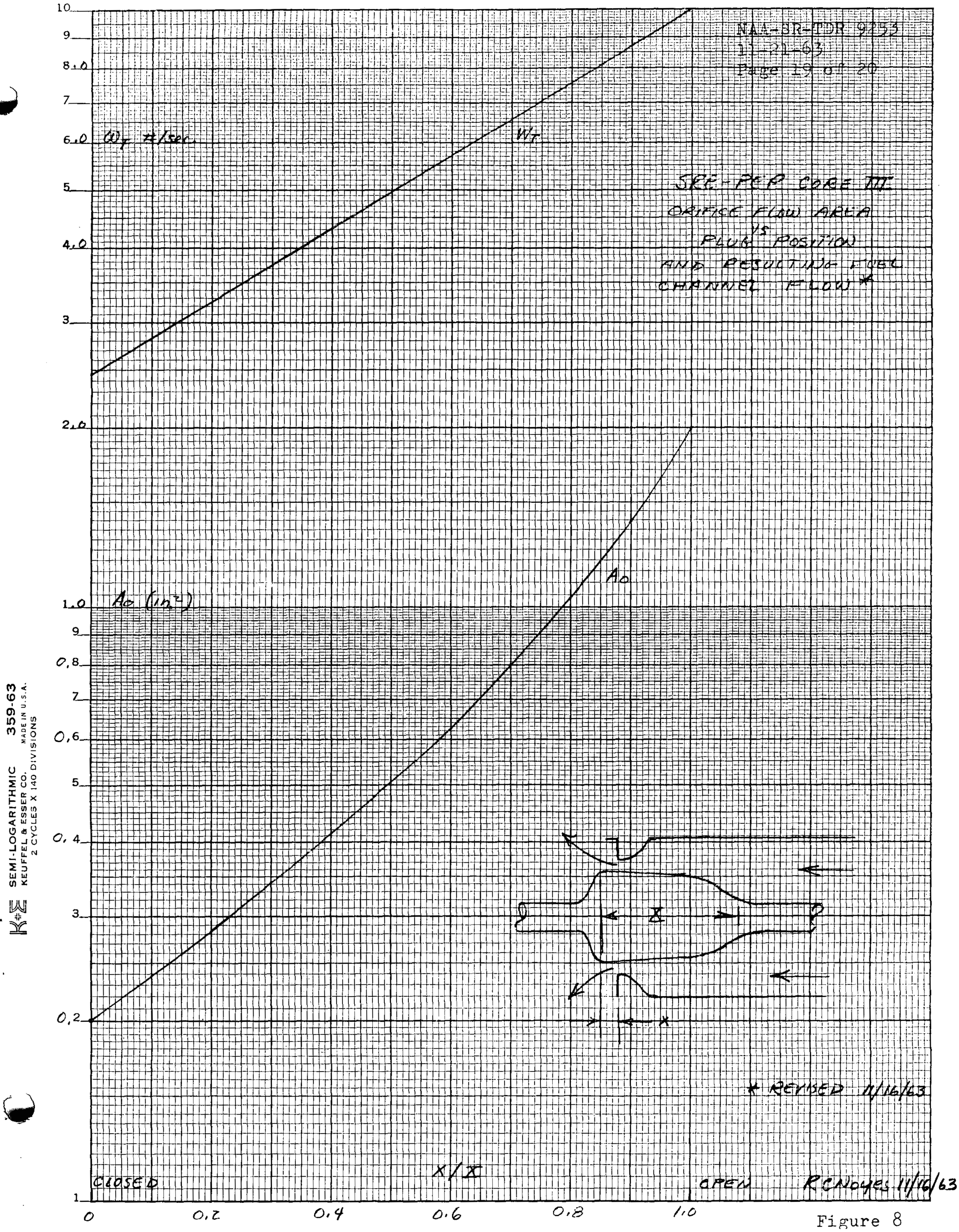

SRE-PEP CORE III COMPOSIT DESIGN
CURVE FOR VARIABLE ORIFICE FLOW AREA
A_o (in²)
2.0
1.0
0.8
0.6
0.4
0.2
DESIGN RANGE
2
4
6
8
10
W_T (#/sec)
LOGARITHMIC 359-110
KEUFFEL & ESSER CO. MADE IN U.S.A.
2 X 2 CYCLES

Figure 7


SRE-PEP CORE III
ORIFICE FLOW AREA
VS
PLUG POSITION
AND RESULTING FUEL
CHANNEL FLOW *
W_T #/sec.
W_T
A_o (in^2)
A_o
X / X̄
CLOSED
OPEN
* REVISED 11/16/63
RCNoyes 11/16/63
10
9
8.0
7
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K&E SEMI-LOGARITHMIC 359-63
KEUFFEL & ESSER CO. MADE IN U.S.A.
2 CYCLES X 140 DIVISIONS

Figure 8

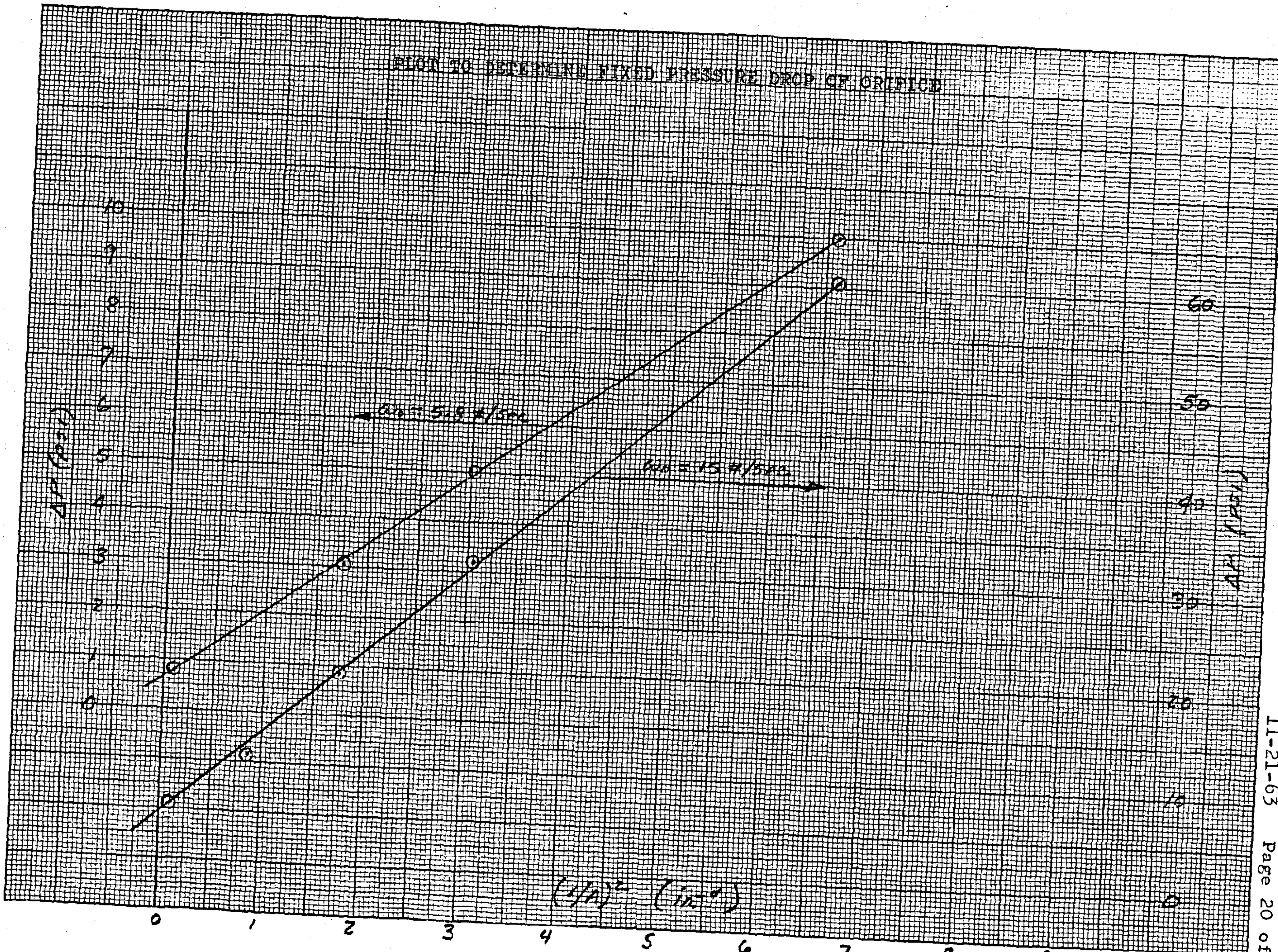
PLOT TO DETERMINE FIXED PRESSURE DROP OF ORIFICE
ΔP (psi)
ΔP (psi)
ẇ = 5.9 #/sec
ẇ = 15 #/sec
(1/A)² (in⁻⁴)
0
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60

Figure 9