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THE DETERMINATION OF PRESSURE DROP FACTORS THROUGH TYPICAL FUEL ELEMENT CHANNELS FOR HIGH TEMPERATURE GAS-COOLED THERMAL PILES

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BY: R. Morrison 2/8/57

The Determination of Pressure Drop Factors

Through Typical Fuel Element Channels for High

Temperature Gas-Cooled Thermal Piles

By

Chas. L. Segaser

July 9, 1948

[redacted]

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ABSTRACT

The initial phase of the pressure drop testing program on proposed fuel element design shapes for the high-temperature, gas-cooled power reactor as described in report MonN-383 has been completed with the compilation of pressure drop data for the flat-plate riveted-assembly type of unit, the ribbed cylinder type, the single bent-plate type both with and without rivets, the 13 hexagon - 6 pentagon type, and the 7 - hole graphite type. This phase of the program was conducted for the purpose of determining the equivalent skin-friction pressure drop factor for composite fuel element cross-sections, and for determining the joint loss factors for varying degrees of misalignment of the fuel units in the fuel channels of the pile.

The pressure drop through a gas cooled reactor, neglecting the change in elevation effect as negligible, may be computed from the equation,

$$\Delta P = \frac{G_s^2}{2g\rho}\left[\frac{4 f_c L}{D_e} + k_e(N-1) + k_b(N_b-1) + k_1\left(\frac{T_1}{T_{avg}}\right) + k_2\left(\frac{T_2}{T_{avg}}\right) + \left(\frac{T_2 - T_1}{T_{avg}}\right)\right]$$

where the meanings of the symbols are as described in the body of the report.

For a first approximation of pressure drop through a gas cooled reactor of 2-inch diameter fuel channels in which the exact shape of fuel element may not be initially known, the following average friction factors may be used.

a. Skin friction factor.

$$f_c = \frac{0.082}{R_e^{\,0.250}}$$

b. Fuel unit joint-loss factor. This factor varies with the cross section of the unit and the type of end construction used. For a unit similar to the type "C", the factor, k_e, is approximately 0.300 for Reynold's numbers from 3000 to 50,000. For the other units tested the average value of this factor for Reynold's numbers from 3000 to 50,000 is,

Type of Unit	k_e
F-28 unit	0.033
F-25-A unit	0.150
13-Hex, 6-Pent. unit	0.580

An average value of k_e for these four units for a range in Reynold's number from 3000 to 50,000 is, $k_e = 0.265$.

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c. Brick joint loss factor. This factor may be neglected in a first approximation of pressure drop since it is unlikely that there will be misalignment of the moderator bricks.

d. Entrance and exit loss factors. These factors may be determined with sufficient accuracy from the literature.

e. Acceleration loss. Since the exit and entrance gas temperatures will be known, this loss is readily computed.

The average gas flow area for a typical fuel element in a 2 inch diameter fuel channel may be taken as 0.0142 square feet, and the average equivalent diameter as 0.0309 feet. If a fuel element is contemplated in which rivets will be used for construction, a pressure drop per rivet equal to approximately one-tenth of a velocity head must be added.

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TABLE OF CONTENTS

Title	Page No.
Introduction	7
Pile Pressure Drop Equation	8
Pressure Drop Test Apparatus	10
Test data and results.	11
Type F-26-A Fuel Unit	17
Single Plate "Type C" Fuel Unit	22
Type F-28 Fuel Unit	31
Type F-25-D Fuel Unit...	37
13 Hexagon, 6 Pentagon Fuel Unit	43
Appendix A	46
Appendix B	56
References	58

[redacted]

[redacted]

LIST OF TABLES

Table No.	Title	Page No.
1	Effective Wall Friction Factor	13
2	Daniels Gas-Cooled Power Pile Data	49

[redacted]

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LIST OF FIGURES

Figure No.	Title	Dwg.No.	Page No.
1	Pressure Drop Test Apparatus	C-2987	14
2	Fanning Friction Factors for Clean Pipes	PPD-A-1189	15
3	Photograph		16
4	Fuel Element for BeO Pile	B-1926	19
5	Pressure Drop Vs Mass Flow Air	PPD-A-1190	20
6	Type F-26-A Fuel Unit	PPD-A-1191	21
7	Unit - Single Plate Type "C"	B-2656	23
8	Pressure Drop Vs Mass Flow of Air	PPD-A-1192	24
9	Type "C" Fuel Unit	PPD-A-1193	25
10	Equivalent Wall Friction Factor	PPD-A-1194	26
11	Fuel Unit Joint Loss Factor	PPD-A-1195	27
12	Pressure Drop Vs Mass Flow of Air	PPD-A-1196	28
13	Type "C" Fuel Unit	PPD-A-1197	29
14	Rivet Factor	PPD-A-1198	30
15	Unit Type F-28	B-2733	32
16	Pressure Drop Vs Mass Flow of Air	PPD-A-1199	33
17	Wall Friction Plus Joint Loss	PPD-A-1200	34
18	Equivalent Wall Friction Factor	PPD-A-1201	35
19	Fuel Unit Joint Loss Factor	PPD-A-1202	36
20	Type F-25-D Fuel Element	B-3381	38
21	Pressure Drop Vs Mass Flow of Air	PPD-A-1203	39
22	Type F-25-A Fuel Unit	PPD-A-1204	40
23	Equivalent Wall Friction Factor	PPD-A-1205	41
24	Fuel Unit Joint Loss Factor	PPD-A-1206	42
25	Unit - 13 Hex, 6 Pentagon	B-2257	44
26	13 Hex - 6 Pentagon Unit	PPD-A-1207	45
27	13 Hex - 6 Pentagon Unit	PPD-A-1208	46
28	Equivalent Wall Friction Factor	PPD-A-1209	47
29	Fuel Unit Joint Loss Factor	PPD-A-1210	48
30	Section Elevation of Pile Structure	E-2274	52
31	Fuel Channel Assembly	D-2957	53
32	Properties of Helium at 10 Atm.	PPD-A-1211	54
33	Pile Pressure Drop Vs Power Output	PPD-A-1212	55

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INTRODUCTION

The important factors which determine the optimum fuel element design for a gas cooled power pile are physics requirements such as escape of fission products, loading of fuel in the unit, heat transfer and the resultant problems due to thermal stresses, high temperature properties of the material, ease of fabrication of the unit, and pressure drop through the pile. Obviously, the design of a fuel unit which favors one factor may also adversely affect another. Therefore, the design of the fuel unit is a compromise among these various factors to obtain the optimum design shape and simultaneously minimize gas pumping power.

Briefly, (1) the heat of fission generated in the fuel unit must be transferred to the gas or coolant, and, hence, out of the pile. In order to transmit this heat there must be a difference in temperature between the interior and surface of the fuel unit, and the temperature gardients thus established will cause differential thermal expansion of the material. This differential expansion introduces thermal stresses which may cause fracture if not alleviated by plastic flow. Transfer of the heat from the fuel unit surface to the gas req uires a definite area for a given coolant flow and temperature in order to keep the surface temperature of the fuel element at a permissable level. One method of accomplishing these objectives and extracting greater power from the pile is by designing the fuel unit with a large surface to volume ratio. However, increasing the surface to volume ratio results, in general, in decreasing the hydraulic radius of the gas passage area with a consequent increase in pressure drop through the pile. It is desirable to keep this pressure drop to a minimum for two reasons. First, there is a definite percentage of total pile output which can be economically allocated to the blowers. Second, a single stage blower is limited in pressure rise which can be imparted to the gas by the maximum top speed at which the blower can operate.

Therefore, in order to obtain a fuel unit with a surface to volume ratio sufficient to generate and transmit the heat of fission, and at the same time minimize thermal stresses to a permissable value, various fuel units of more or less intricate cross sectional shapes have been proposed. A few of these

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shapes, selected as typical of the design proposals, are shown in Figure 3. Obviously, each cross section proposed will alter the gas flow area in a fixed two-inch diameter fuel channel hole, and, hence, the pressure drop through the pile, since for a given power output and entrance and exit gas temperature the total gas flow must remain the same.

The existing literature on pressure drop through pipes and tubes does not indicate methods of accurately calculating pressure drop through channels of such composite shapes as represented by the fuel units, although the well known Fanning equation is often used for approximating pressure drop through annular spaces using the equivalent diameter concept. Therefore, a laboratory pressure-drop test apparatus was constructed by which the pressure drop through a simulated reactor fuel channel using typical fuel element design shapes could be measured. Figure 31 in Appendix A shows a typical gas-cooled reactor fuel channel assembly and Figure 30 is a section elevation of the pile structure showing the relation of the fuel channels to the gas flow system.

Pile Pressure Drop Equation. (2) The Fanning equation is generally used for computing pressure drop through circular pipes, and may be used with caution for computing pressure drop in annular spaces. However, if the core of an annular space is not concentric with the larger pipe or is of intricate cross section, as in the fuel unit design shapes, substantial deviations in actual pressure drop with the computed value may occur. The usual form of the Fanning equation for pressure drop in circular pipes and annular spaces is, (3)

$$\Delta P = \frac{4 f_e L G_s^2}{2 g \rho D_e}$$

This component of the pile pressure drop equation is a measure of the channel wall friction, and in this equation the values of f_e for a given Reynolds number should correspond to the values from the literature as reproduced in Figure 2. The fuel channel in the pile will consist of short sections (five inch lengths) of fuel elements aligned at random in a two inch circular opening in the moderator bricks. Hence, to the Fanning equation for skin friction drop must be added factors to account for misalignment of the units and bricks, inlet and outlet shock losses and for loss in pressure due to acceleration of gas through the pile.

Because in most pile designs the length of each fuel element is only a fraction of the total length of the fuel channel, shock losses will occur at the junction of the elements. These losses will vary with the alignment of the fuel elements, warpage, design of the fuel element ends and the relative spacing maintained between the elements. The fuel element joint loss expression is

$$\Delta P = \frac{k_e G_s^2 (N-1)}{2 g \rho}$$

[redacted]

[redacted]

As in the case of the fuel elements, the moderator brick channel is made up also of many short lengths, more or less smoothly connected, and, hence, each joint will be a source of possible pressure drop due to eddy currents. However, the construction of the brick is such that this loss should be a minimum insofar that it is extremely unlikely that there will be misalignment as in the case of fuel elements. The expression for moderator brick joint loss is,

$$\Delta P = \frac{k_b G_s^2 (N_b - 1)}{2 g \rho}$$

The inlet and outlet shock loss factors are fairly accurately determinable from the literature, and this degree of accuracy is considered adequate for pile design. The inlet shock loss expression is,

$$\Delta P = \frac{k_1 G_s^2}{2 g \rho} \left(\frac{T_1}{T_{avg}} \right)$$

The outlet shock loss expression is,

$$\Delta P = \frac{k_2 G_s^2}{2 g \rho} \left(\frac{T_2}{T_{avg}} \right)$$

Since there is an increase in velocity of the gas through the pile due to absorption of heat energy, and the process takes place in a constant cross sectional area, there will be a corresponding drop in absolute pressure as given in the following expression,

$$\Delta P = \frac{G_s^2}{2 g \rho} \left(\frac{T_2 - T_1}{T_{avg}} \right)$$

Neglecting the change in elevation effect as being of negligible value in a gas-cooled pile and combining the previous expressions for individual pressure drops, the following equation is obtained,

$$\Delta P = \frac{G_s^2}{2 g \rho} \left[\frac{4 f_e L}{D_e} + k_e (N - 1) + k_b (N_b - 1) + k_1 \left(\frac{T_1}{T_{avg}} \right) + k_2 \left(\frac{T_2}{T_{avg}} \right) + \left(\frac{T_2 - T_1}{T_{avg}} \right) \right]$$

[redacted]

[redacted]

Where

ΔP = Pressure drop thru pile, Lb. per sq. ft.

G_s = Gas flow per channel, Lb. per sq. ft. per sec.

g = Acceleration due to gravity, 32.2 ft.per sec. per sec.

ρ = Average density of gas, Lb. per cu. ft.

f_e = Wall friction factor

L = Length of gas passage, Ft.

D_e = Equivalent diameter, Ft.

N = Number of fuel elements per channel

k_e = Fuel element joint loss factor

k_b = Moderator brick joint loss factor

k_1 = Fraction of inlet velocity head loss

k_2 = Fraction of outlet velocity head loss

T_1 = Gas inlet temperature, degrees Rankine

T_2 = Gas outlet temperature, degrees Rankine

T_{avg} = Average gas temperature, degrees Rankine

Pressure drop test apparatus. The pressure drop for various proposed fuel elements was measured in an apparatus as shown by Figure 1. In this apparatus air at constant temperature is delivered to the pressure drop testing section by means of a No. 55 Roots-Connerville positive displacement gas pump. Compressed air from the pump is first delivered to a surge tank to smooth out variations in air pressure. A 2 inch and a 3 inch standard pipe are connected to this tank such that by appropriate valves the air can be metered through either a 0.750 inch or a 1.4925 inch sharp edged orifice, depending on the volume of air flow, and hence to the pressure drop measuring section. Manometers are connected to the measuring section to measure the pressure drop through the fuel elements, and to the sharp edged orifices for measuring flow. Gas temperatures are obtained by standard Centigrade mercury thermometers inserted in wells in the gas stream. The method of calculating flow by use of the ASME code is outlined in Appendix B. An indicating flow meter was connected to the orifices, but was never calibrated and consequently was not used for these tests.

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Since air at constant temperature is used as the gas in the pressure drop test apparatus, the equation for pile pressure drop in this case reduces to,

$$\Delta P = \frac{G_s^2}{2g\rho}\left[\frac{4 f_e L}{D_e} + k_e(N-1) + k_b(N_b-1) + k_1 + k_2\right]$$

If the pressure drop measurements are made within the fuel element length and the pressure drop is expressed in lbs. per sq. in., this equation becomes

$$144\,\Delta p = \frac{G_s^2}{2g\rho}\left[\frac{4 f_e L}{D_e} + k_e(N-1)\right]$$

where

Δp = Pressure drop, lb. per sq. in.

The factors k_b, k_1 and k_2 are zero in this expression since the measuring section of the test apparatus is a smooth two inch inside diameter brass tube with no joints, and the pressure drop measurements are taken within the fuel element assembly length, hence entrance and exit losses are absent.

Dividing both sides of this equation by the length of the test section over which the pressure drop measurements are taken, the expression for pressure drop per foot of channel length is,

$$\frac{144\,\Delta p}{L} = \frac{G_s^2}{2g\rho}\left[\frac{4 f_e}{D_e} + \frac{k_e(N-1)}{L}\right]$$

Therefore,

$$\frac{144\,\Delta p}{L} \Big/ \frac{G_s^2}{2g\rho} = \frac{4 f_e}{D_e} + \frac{k_e(N-1)}{L}$$

Since all terms on the left hand side of this equation are determinable from test data, a plot of $\frac{144\,\Delta p}{L} \Big/ \frac{G_s^2}{2g\rho}$ versus Reynolds number, $\frac{D_e G_s}{\mu}$ may be constructed on logarithmic graph paper, and since this value equals the expression $\frac{4 f_e}{D_e} + \frac{k_e(N-1)}{L}$ values for f_e and k_e are readily obtained. The values for f_e were obtained by causing the units to remain aligned in the testing section by small dowel pins and assuming the joint loss factor, k_e, as zero. Values for k_e were calculated for 45° and 90° positions of misalignment by subtracting the values of $\frac{4 f_e}{D_e}$ from the sum as obtained from the graph and solving for k_e.

Test data and results. The data and results of the pressure drop tests are given in the following figures and tables from which the values of f_e and k_e may be obtained for any Reynolds number within the range of test data for a given shape of fuel unit. Whereas McAdams warns of the indiscriminate use of the Fanning equation for computing pressure drop in annular spaces in which the core is not concentric with the larger pipe, the results of these tests indicate that the

[redacted]

[redacted]

Fanning equation may be used for estimating skin friction drop through a gas cooled pile when using proper values for equivalent diameter and gas properties. In general, the Fanning friction factors as derived from friction factor curves for smooth tubes correlates fairly closely with the skin friction factor from the pressure drop test data. For purposes of comparison these values from the literature have been superimposed on the same curve sheets as the observed skin friction factor for the fuel units.

Four curve sheets in general are presented for each fuel unit tested. The first sheet of each series graphically depicts the data from the test run in terms of pressure drop in pounds per square inch per foot of length of fuel channel versus mass flow of air in pounds per second on ordinary graph paper. Each run of fuel unit pressure drop was made with the units aligned, 45 degrees misaligned and 90 degrees misaligned. On this curve sheet is also depicted a full size cross sectional drawing of the fuel element shape within the fuel channel. Directly below the drawing is the computed gas flow area and equivalent diameter. The equivalent diameter is defined as four times the hydraulic radius, the hydraulic radius being the gas flow area divided by the wetted perimeter.

The second sheet in each series is a logarithmic graph of the expression $\left[\frac{4f}{D_e} + k_e \frac{(N-1)}{L}\right]$ versus Reynolds number, $\frac{D_e G_s}{\mu}$ where each term is as previously defined, and μ is the viscosity of the gas in pounds per foot per second. From this graph the equivalent skin friction factor term in the pile pressure drop equation may be determined by assuming the joint loss factor as zero for the units aligned and substituting and solving for f in the previous equation. This value of f versus Reynolds number is plotted logarithmically on the third sheet of each series. For comparison the Fanning friction factor for smooth tubes is also plotted on this sheet. If desired, the equivalent skin friction factor may also be read versus the expression $\frac{W_c}{\mu}$ which is shown as an auxiliary scale at the top of sheet.

The final curve sheet of each series is a logarithmic plot of the fuel unit joint loss factor, k_e, versus Reynolds number for the misaligned units and is obtained from curve two of each series. This factor is obtained by obtaining values for the expression $\left[\frac{4f}{D_e} + \frac{k_e (N-1)}{L}\right]$ for a given Reynolds number and knowing the term $4f/D_e$ for the units aligned solving for the expression, k_e. This is also plotted for convenience with the auxiliary scale, $\frac{W_c}{\mu}$.

Over the limited range of Reynolds numbers from 3,000 to 50,000 the data for the effective wall friction factor may be fairly accurately given by the equation,

$$f_e = \frac{K}{Re^{n}}$$

where f_e = Wall friction factor

K = Constant

Re = Reynolds number

n = Exponent

[redacted]

[redacted]

For each unit the values of K and n are given in the following table.

Table 1.

Effective Wall Friction Factor

$$f_e = \frac{K}{R_e^{\,n}}$$

Shape of Assembly	DWG. No.	K	n
Flat plate ass'y (Type F-26-A)	B-1926	*	*
Ribbed cylinder (Type F-28)	B-2733	0.130	0.292
Single plate-Type "C"-No rivets	B-2656	0.060	0.239
Single plate - Type "C"-with rivets	B-2656	*	*
13 Hex: - 6 Pentagon	B-2257	0.062	0.222
7 hole graphite - (Type F-25-A)	B-1519	0.075	0.246

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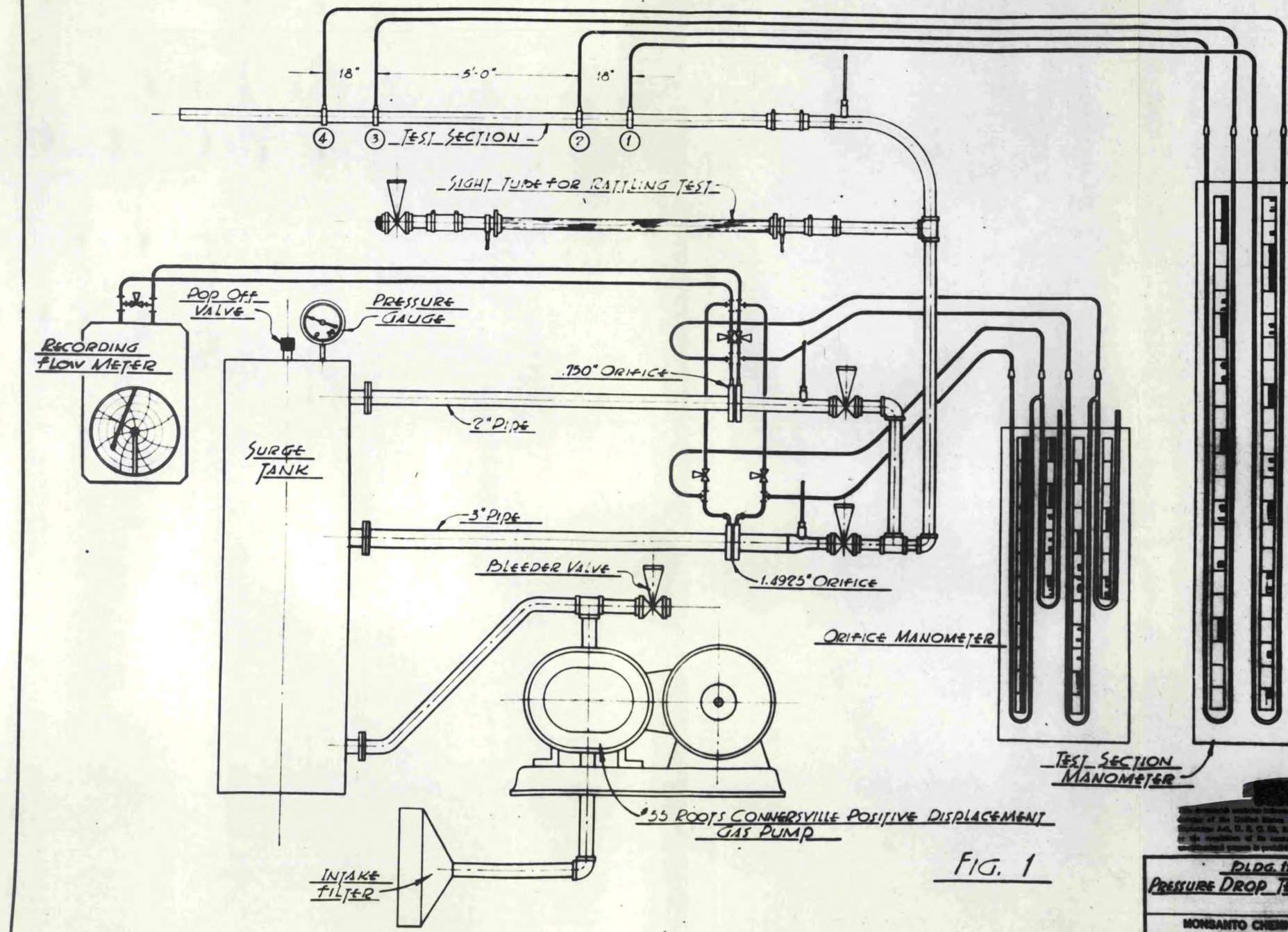

FIG. 1

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BLDG. 115 A.
PRESSURE DROP TEST APPARATUS

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. 10-1-47	F.L.S. C. 10/1/47	C.L. Sigmund A. 10-2-47	K. 10-3-47
Proj C-222 M			
SCALE: None			C-2907

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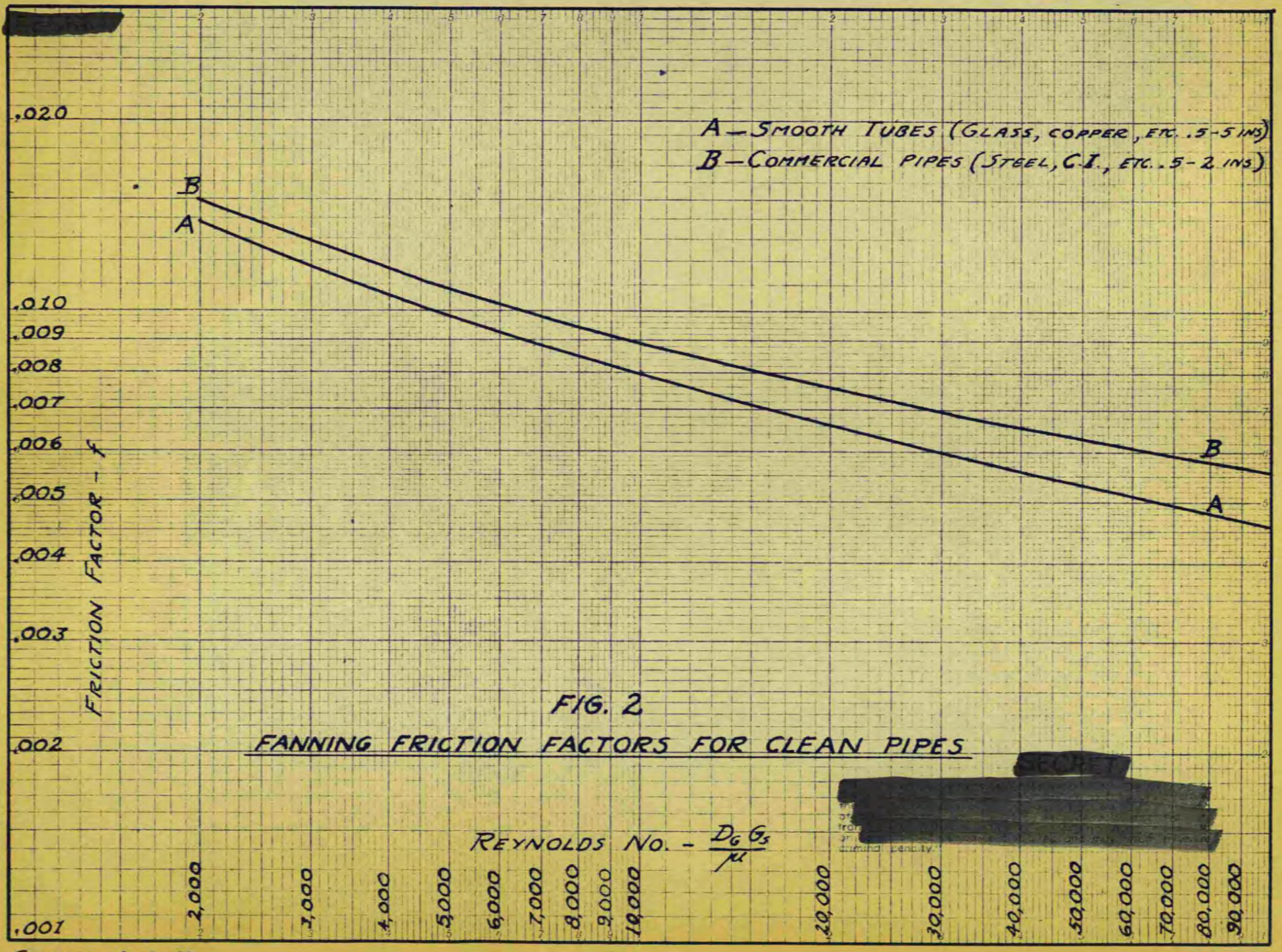

FIG. 2

FANNING FRICTION FACTORS FOR CLEAN PIPES

[redacted]

SEGASER 2-19-48

PPD-A-1189

FIG. 3

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TYPE F-26-A FUEL UNIT

This type of fuel unit is a design using six parallel plates of uranium - beryllium alloy fastened together by fourteen rivets, each having a maximum spacer diameter of 3/16 inch. The plates are 0.125 inches in thickness with a spacing of 0.200 inch between plates. The maximum overall diameter of the unit is 1-7/8 inch with a length of 8 inches. The ends of the plates are rounded to a radius of 1/16 inch to minimize reentrant pressure drop joint losses.

With this unit it was not possible to segregate the skin friction pressure drop factor and joint loss pressure drop factor because of the presence of the rivets. However, as expected, this unit has the largest pressure drop per foot of length of any of the units tested. From Figure 33 in Appendix A, the pressure drop through the Daniel's pile at 20,000 Kw pile output is 6.4 lb. per sq. in. At 12,000 Kw output, the pressure drop is 2.5 lb. per sq. in. Compared to the pressure drop through the single plate "Type C" type of bent plate unit without rivets, this is an increase of 225 percent at 20,000 Kw output, and 213 percent at 12,000 Kw output.

The friction for turbulent flow of a fluid normal to a bank of tubes in line is given by McAdams as,

$$F = 4 f''' N V_{max}^2 / 2 g_c$$

and,

$$f''' = \left(0.044 + \frac{0.08 x_\ell}{(x_t - 1)^n}\right)\left(\frac{D_o G_{max}}{\mu_f}\right)^{-0.15}$$

where,

F = Friction in feet x pounds force per pound of fluid.

N = Number of rows of tubes over which fluid flows

V_{max} = Maximum fluid velocity based on the minimum free area, ft. per second

g_c = Conversion factor in Newton's law of motion, equals 32.2 ft. x pounds matter/ (sec.)(sec.)(pounds force)

x_ℓ = Ratio of the longitudinal pitch to tube diameter

x_t = Ratio of the transverse pitch to tube diameter

n = $0.43 + (1.13/x_\ell)$

G_{max} = Mass velocity, lb. of fluid/(sec)(sq.ft. of cross section). In all cases G_{max} is based on the minimum free area.

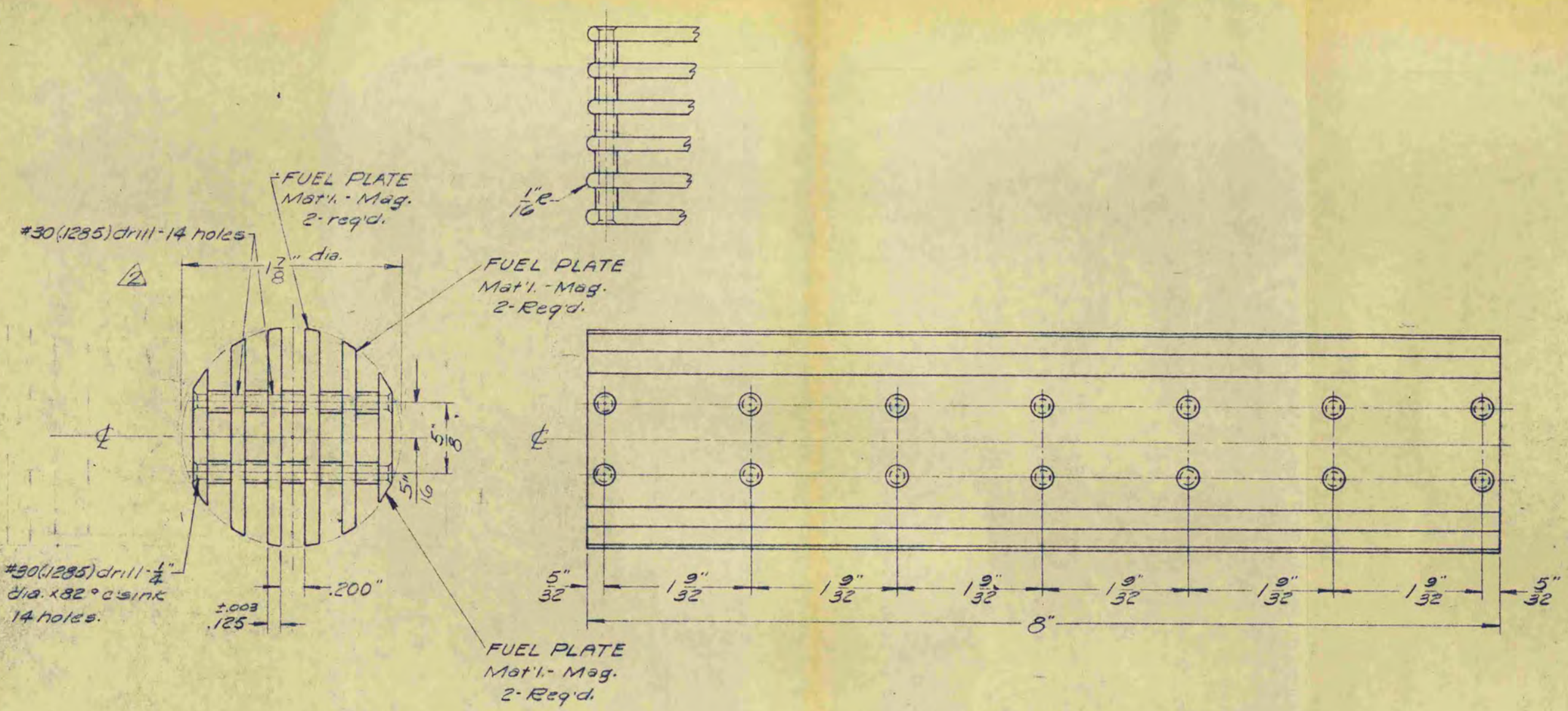
D_o = Outside diameter of tube, feet

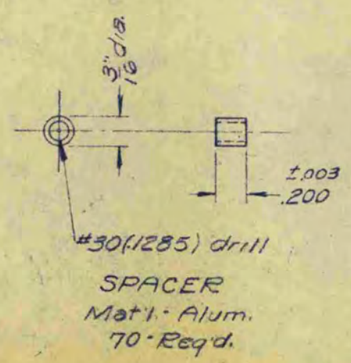
μ_f = Viscosity of Fluid, lb/(sec)(ft)

[redacted]

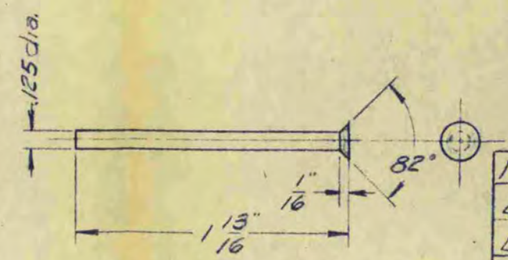
[redacted]

Using these equations and considering the rivets as tubes in line, one may estimate the effect of the rivets on pressure drop per foot of length. With these equations and using the method of computation as previously described, with the accompanying experimental data, the skin friction pressure drop factor and joint loss pressure drop factor may be estimated, if required, for this unit.





SPACER
Mat'l. - Alum.
70 - Req'd.



RIVET
Mat'l. - Alum. (3S)
14 - Req'd.

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FIG 4

19

No.	REVISION	DATE
1	TYPE ADDED	5/8/47
2	DIM. CHANGED	5/9/47

THE DANIELS EXPERIMENTAL POWER PILE
FUEL ELEMENT FOR BeO PILE
(6 PLATE)
1 TYPE F-26-A

MONSANTO CHEMICAL CO.
CLINTON LABORATORIES
KNOXVILLE, TENN.

3-4-47 D.	C. 5 Mar 47	A. 5 Mar 47			
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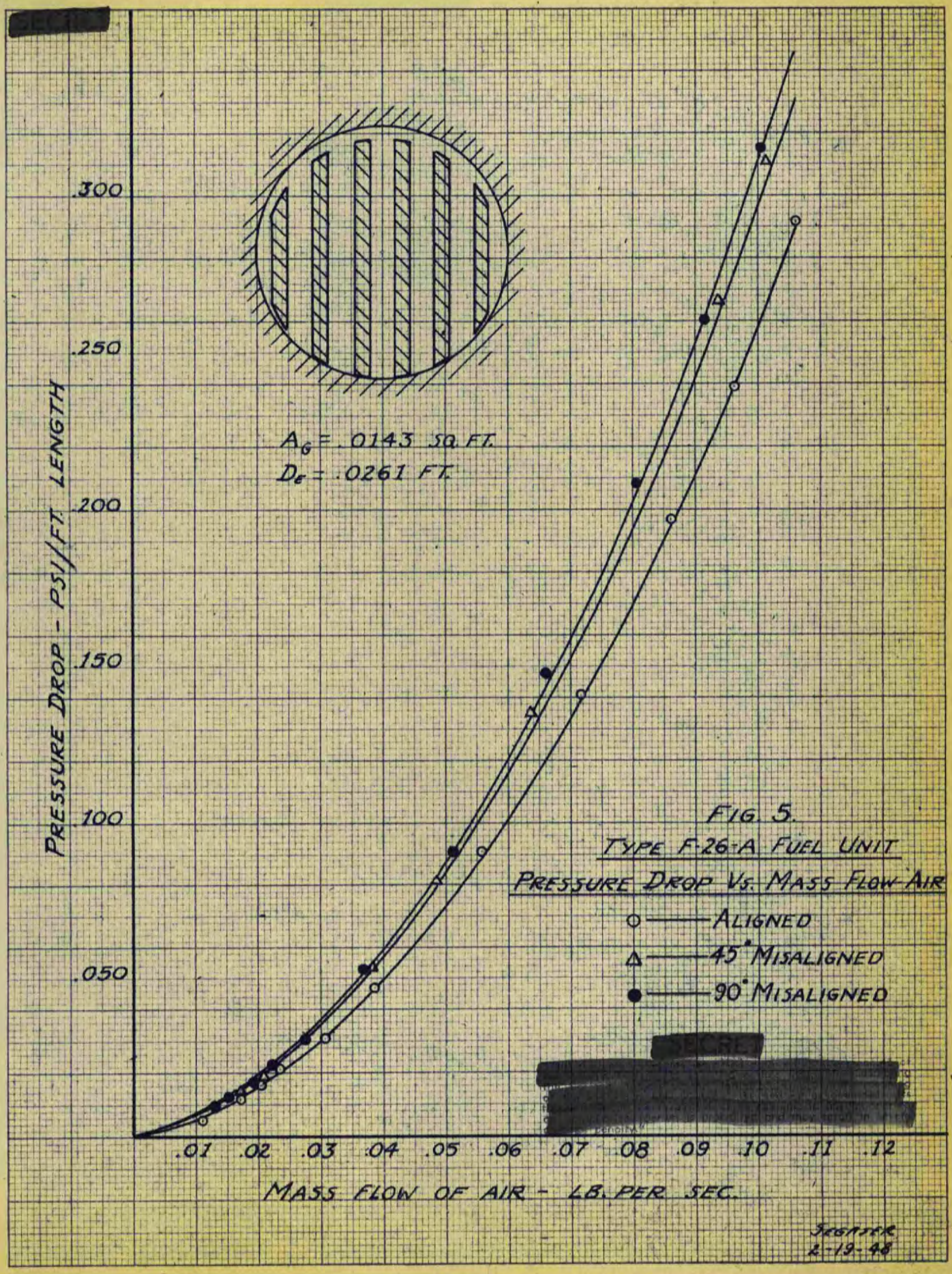


FIG. 5.
TYPE F-26-A FUEL UNIT
PRESSURE DROP VS. MASS FLOW AIR

[redacted]

NO. 31.257. LOGARITHMIC: 1-1.3 BY 2.5-INCH CYCLES. CODEX BOOK COMPANY, INC., NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

[redacted]

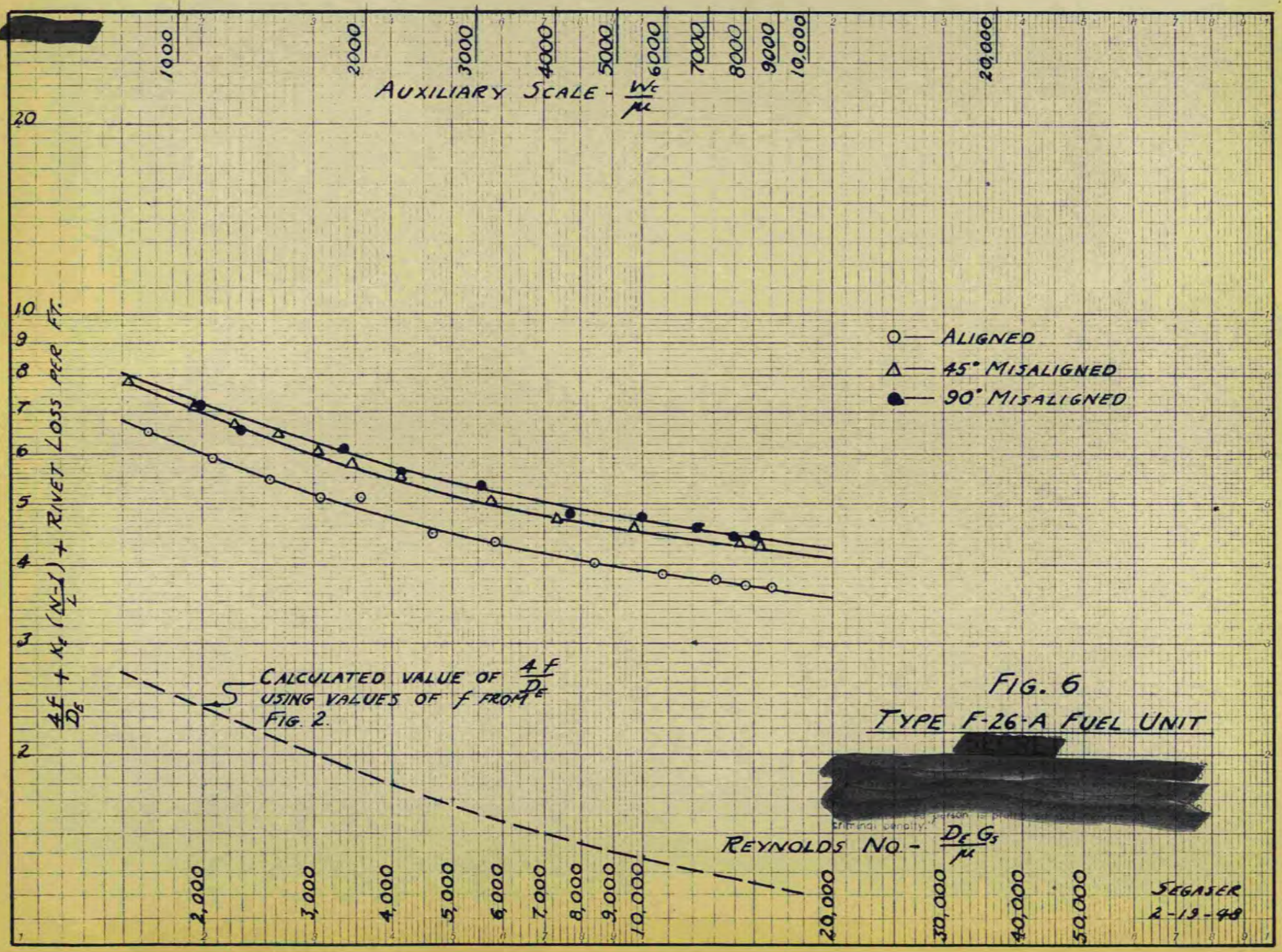


FIG. 6

TYPE F-26-A FUEL UNIT

[redacted]

[redacted]

Single Plate "Type C" Fuel Unit

This unit is essentially a parallel flat plate type, similar to the F-26-A design, with the exception that the unit is fabricated from one single uranium - beryllium alloy plate 1/8 inch thick bent longitudinally to the shape shown in Fig. 7. Structurally the unit is sufficiently strong to hold its shape at room temperature without the aid of the rivets. However, at operating pile temperatures it is feared that the unit may deform such as to cause the unit to jam in the fuel channel. Hence, five rivets are shown holding each plate rigidly at a spacing of 0.200 inch from its neighbor. The unit has a maximum overall diameter of 1-7/8 inch and a length of 8 inches.

This unit was tested both with and without rivets and the results are shown by Figures 8 through 14 inclusive. Figure 8 is a graphical tabulation of the observed data for this unit without the rivets and shows the pressure drop in pounds per square inch per foot of length versus the mass flow of air through the channel in pounds per second. The gas flow area of this unit is 0.0145 sq. ft. and the equivalent diameter is 0.030 ft.

Figures 9, 10 and 11 are logarithmic plots of pressure drop factors versus Reynolds number for the unit without rivets. The curves of Figure 10 are calculated from data from Figure 9. The equivalent skin friction factor curve for this unit is below that of the Fanning friction factor for smooth tubes and roughly parallel. Figure 11 is a curve of the fuel unit joint loss factor for the "Type C" unit without rivets and is also derived from the data of Figure 9.

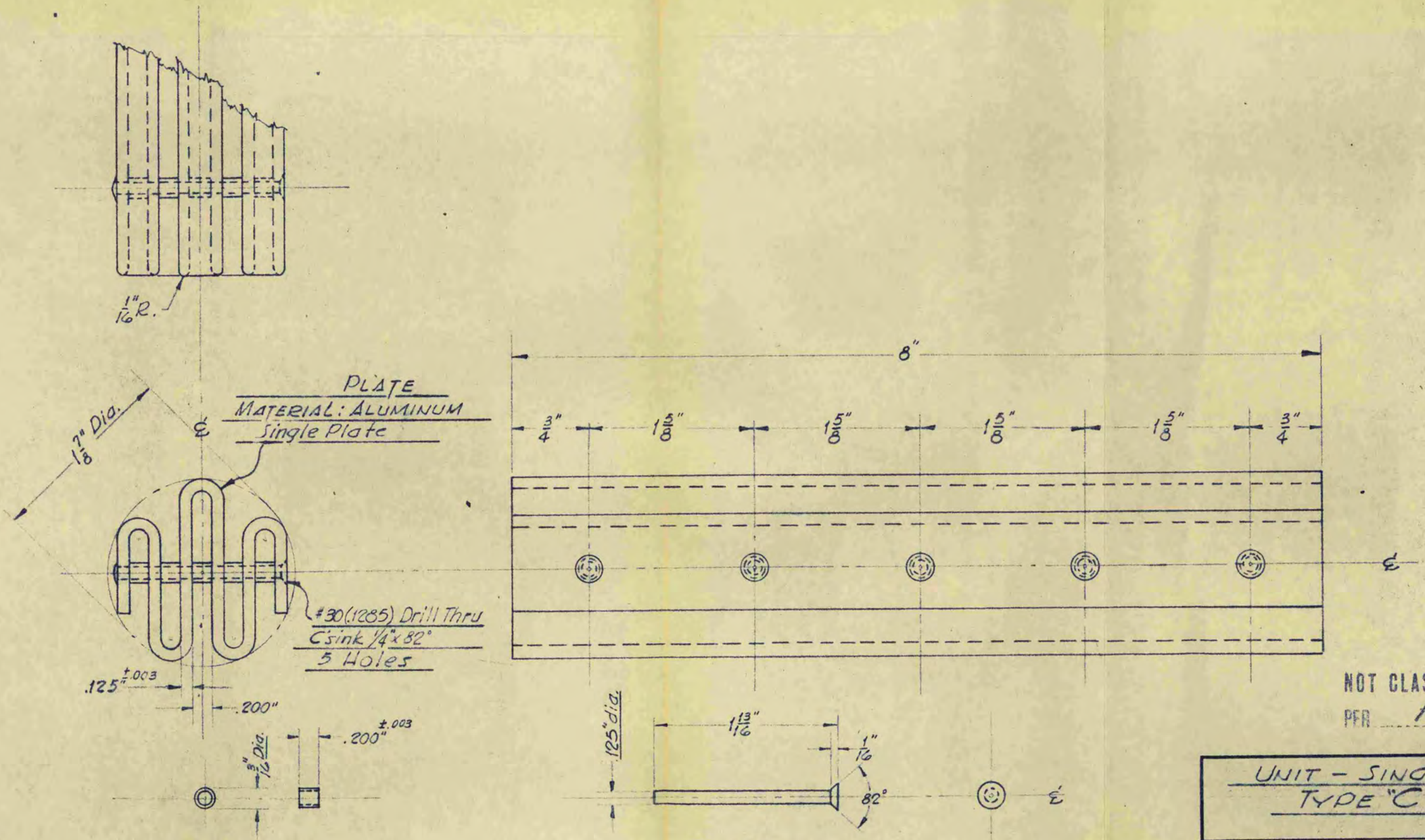
It is not expected that the pressure drop for a series of parallel plates should be less than the pressure drop as predicted by using the equivalent diameter concept with the Fanning friction factor for smooth tubes. The equivalent diameter was therefore recalculated assuming that the fuel element consisted of 9 channels in parallel. By this method the equivalent diameter was

$$D_e^{.667} = \frac{\sum A_n D_{en}^{.667}}{\sum A_n} = .0296 \text{ ft.}$$

Only actual surface area was charged to each channel, that is, imaginary boundary lines were not charged as "wetted" perimeter. This method should have made the predicted pressure drop more nearly coincide with test results but as can be seen produced no better agreement. A careful check was made of all dimensions of the fuel elements. The flow was checked by both the .750 in. diameter orifice and the 1.4925" diameter orifice without discrepancy. The pressure drop readings were checked with pressure taps located before and after the fuel elements and suitably corrected for entrance and exit losses. Since no explanation can be found for this discrepancy, the test results are herein presented but it is advised that the more conservative data available from the literature be used.

Figure 12 shows the pressure drop in pounds per square inch per foot of length versus mass flow of air in lbs. per second for the single plate "Type C" unit with rivets inserted in the two end holes. The effect of the rivets is to increase the pile pressure drop by 32.5 percent at a pile output of 20,000 Kw compared to pressure drop through the unit with no rivets. Fig. 13 and 14 are logarithmic graphs constructed to show graphically the effect of the rivet addition. On Fig. 14 is plotted the rivet factor for the units aligned and misaligned. Each rivet may be considered to add an increment of pressure drop equivalent to approximately one-tenth of the velocity head.

[redacted]



NOT CLASSIFIED
PER M

FIG 7

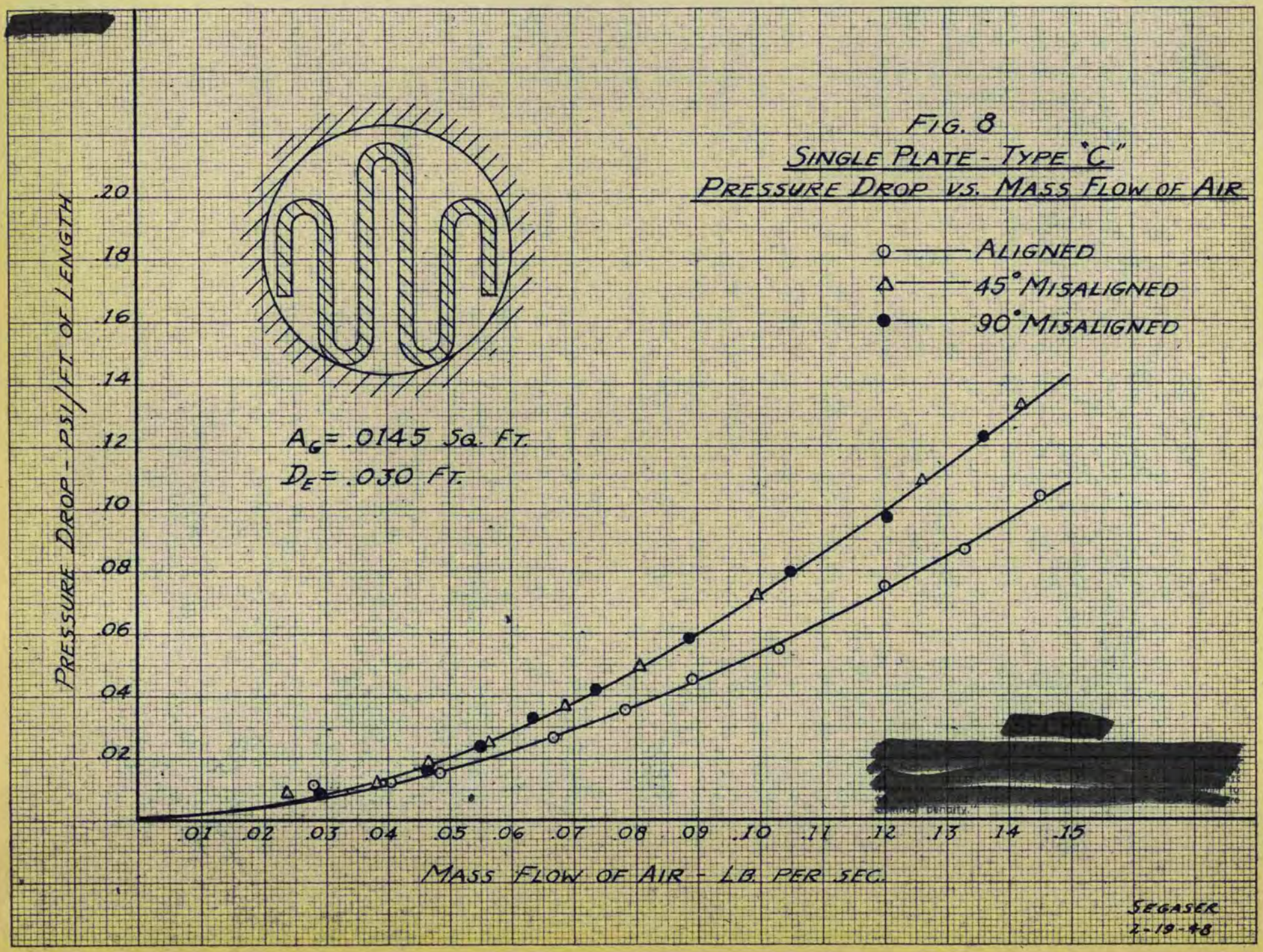
UNIT – SINGLE PLATE
TYPE "C"

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

Strauchman D. 6-2-47	A.L.S. C. 6-2-47	A. 6-3-47	6/3/47			
Proj. C-222 M			A.E.C.	B-2656		
SCALE: Full						

NO. 318. 20 DIVISIONS PER INCH BOTH WAYS. 150 BY 200 DIVISIONS. CODEX BOOK COMPANY, INC. NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

[redacted]



[redacted]

[redacted]

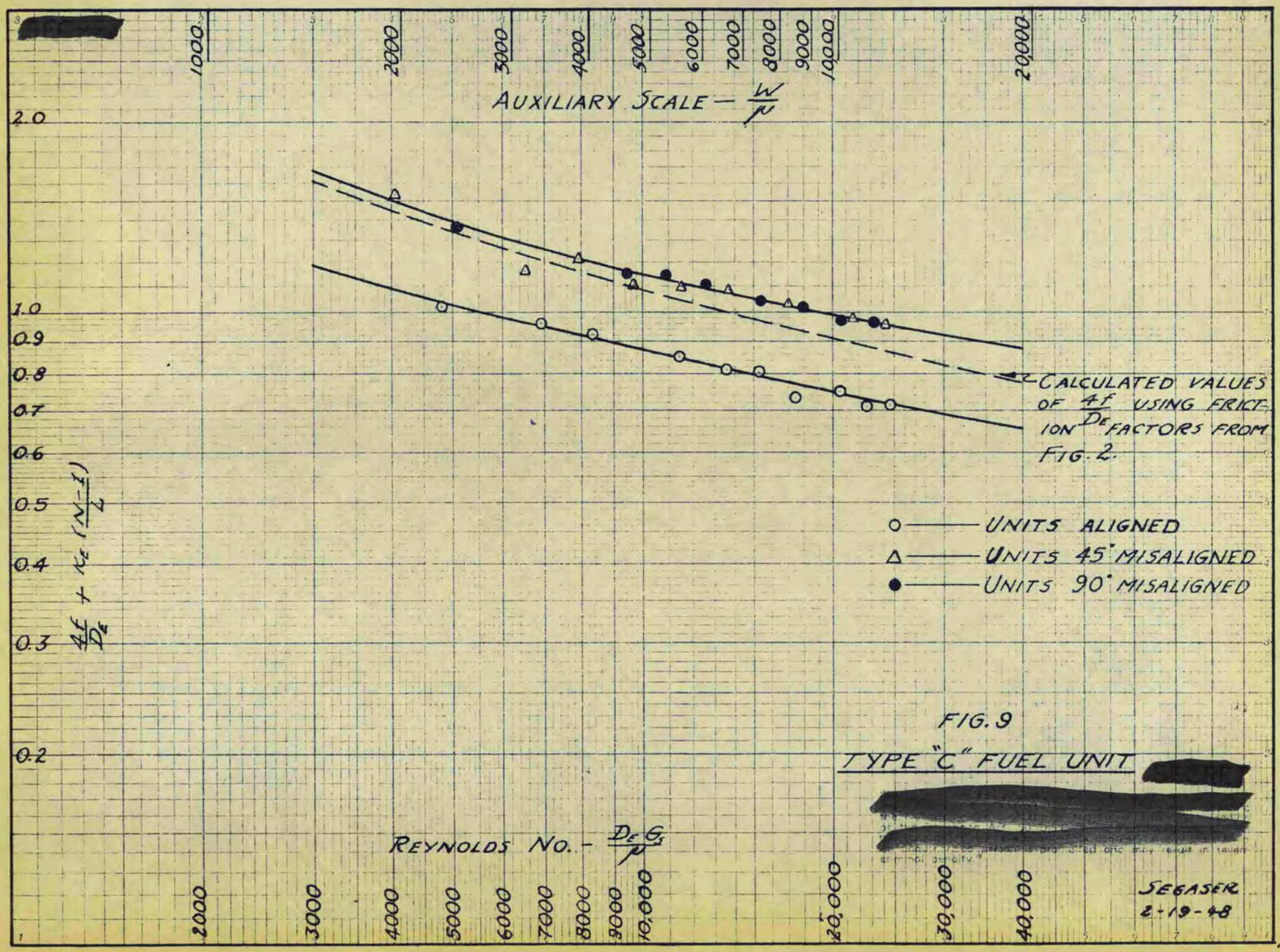


FIG. 9

TYPE "C" FUEL UNIT

[redacted]

PPD-A-1193

NO. 31,257. LOGARITHMIC: 1-1/3 BY 2 5-INC. 1 CYCLES. CODEX BOOK COMPANY, INC., NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

[redacted]

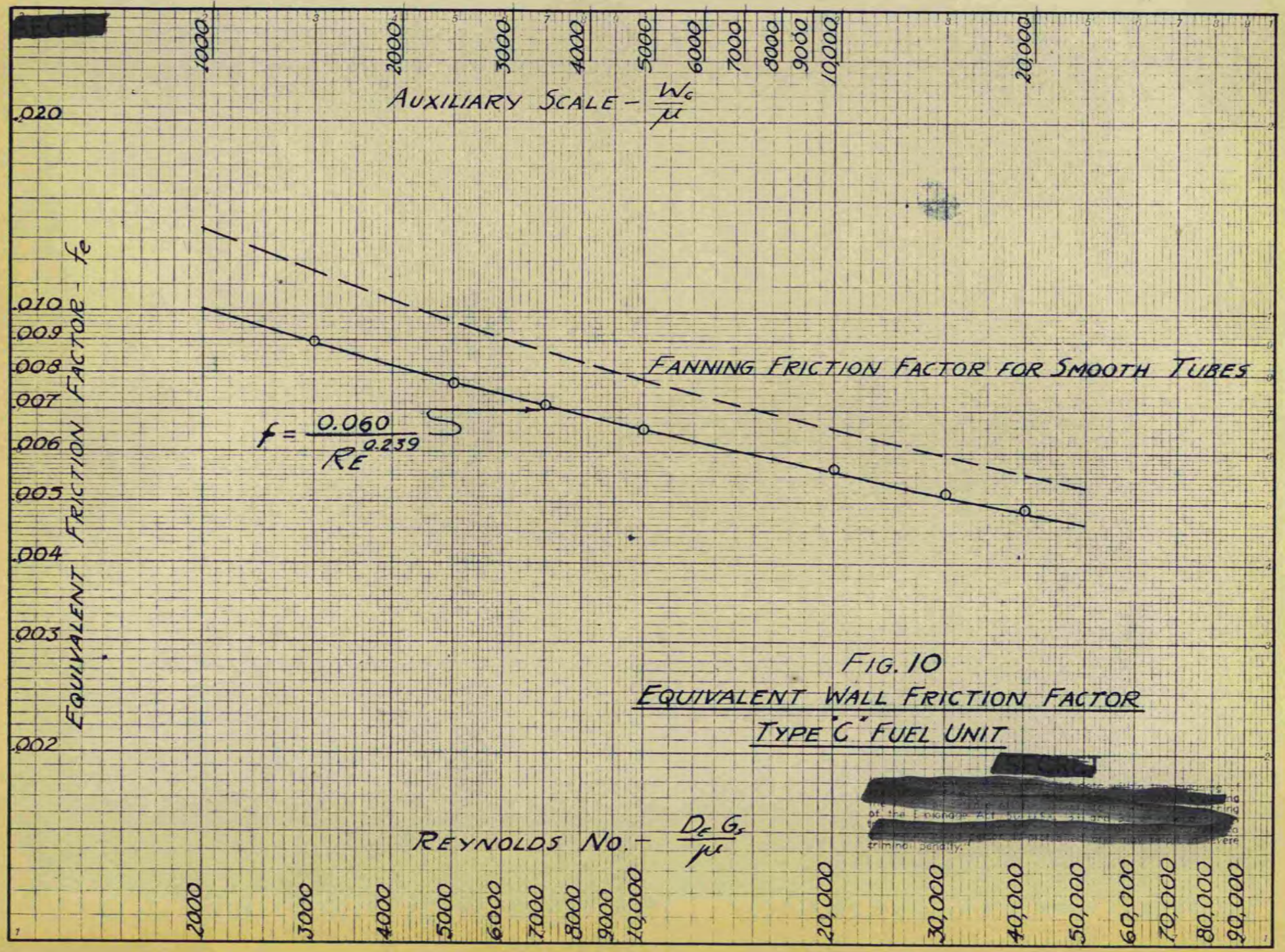


FIG. 10

EQUIVALENT WALL FRICTION FACTOR

TYPE "C" FUEL UNIT

[redacted]

SEGASER 2-19-48

PPD A-1194

NO. 31.257. LOGARITHMIC: 1-1/3 BY 2 5-INCH CYCLES. CODEX BOOK COMPANY, INC., NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

[redacted]

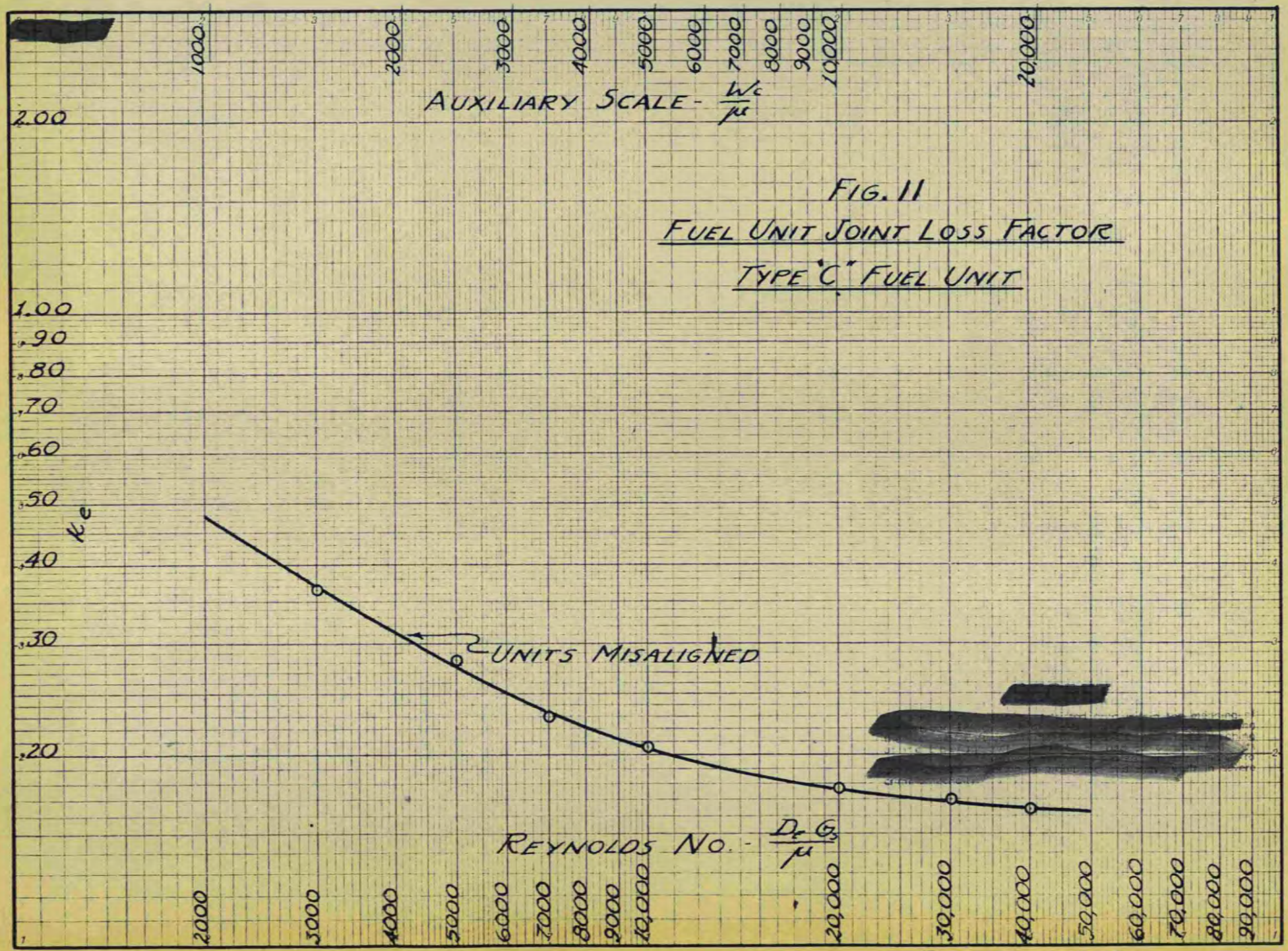


FIG. 11

FUEL UNIT JOINT LOSS FACTOR

TYPE "C" FUEL UNIT

[redacted]

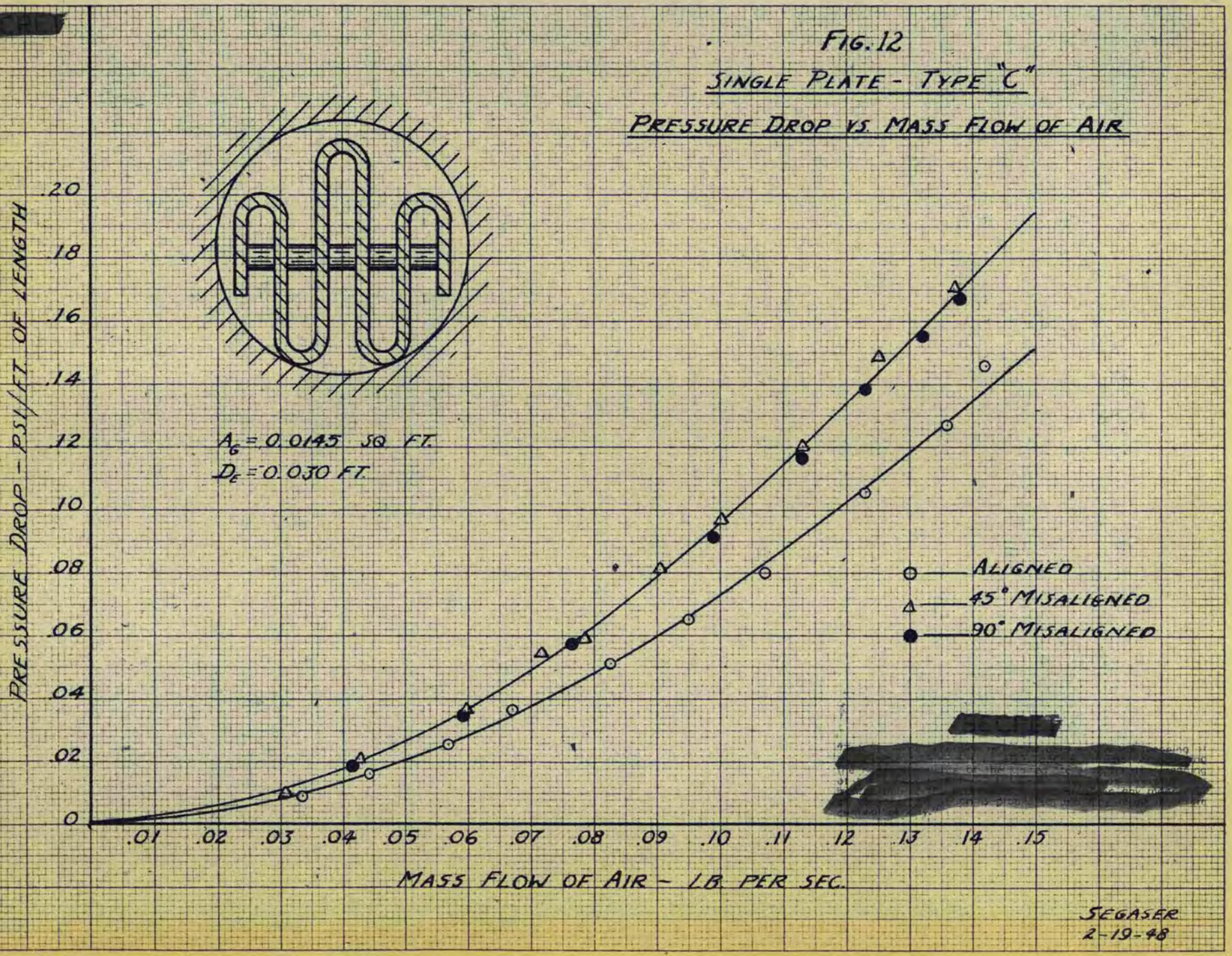
NO. 318. 20 DIVISIONS PER INCH BOTH WAYS. 150 BY 200 DIVISIONS. CODEX BOOK COMPANY, INC. NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

[redacted]

FIG. 12

SINGLE PLATE - TYPE "C"

PRESSURE DROP VS. MASS FLOW OF AIR

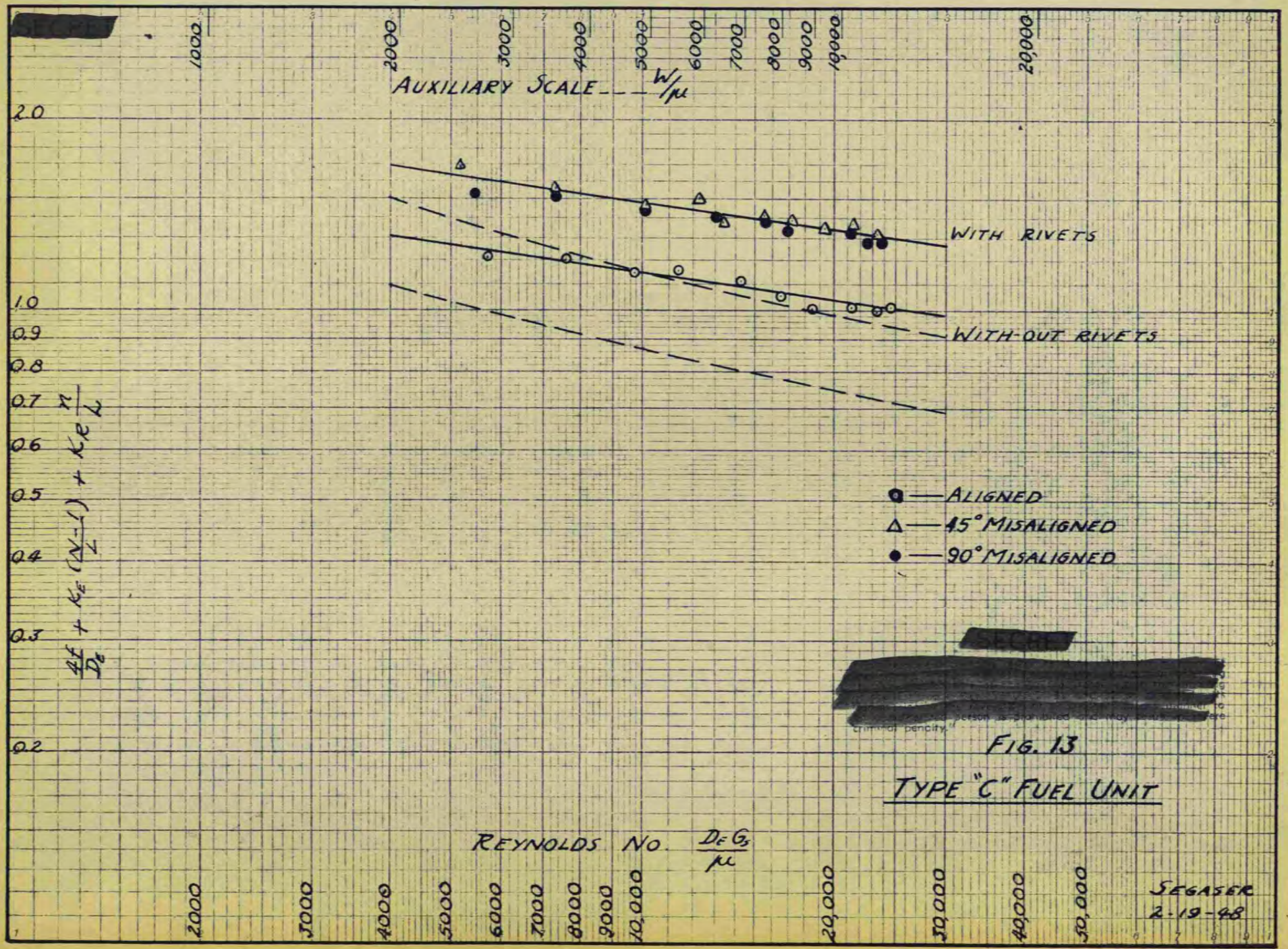


[redacted]

SEGASER
2-19-48

NO. 31.257. LOGARITHMIC: 1-1/3 BY 2 5-INCH CYCLES. CODEX BOOK COMPANY, INC., NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

[redacted]



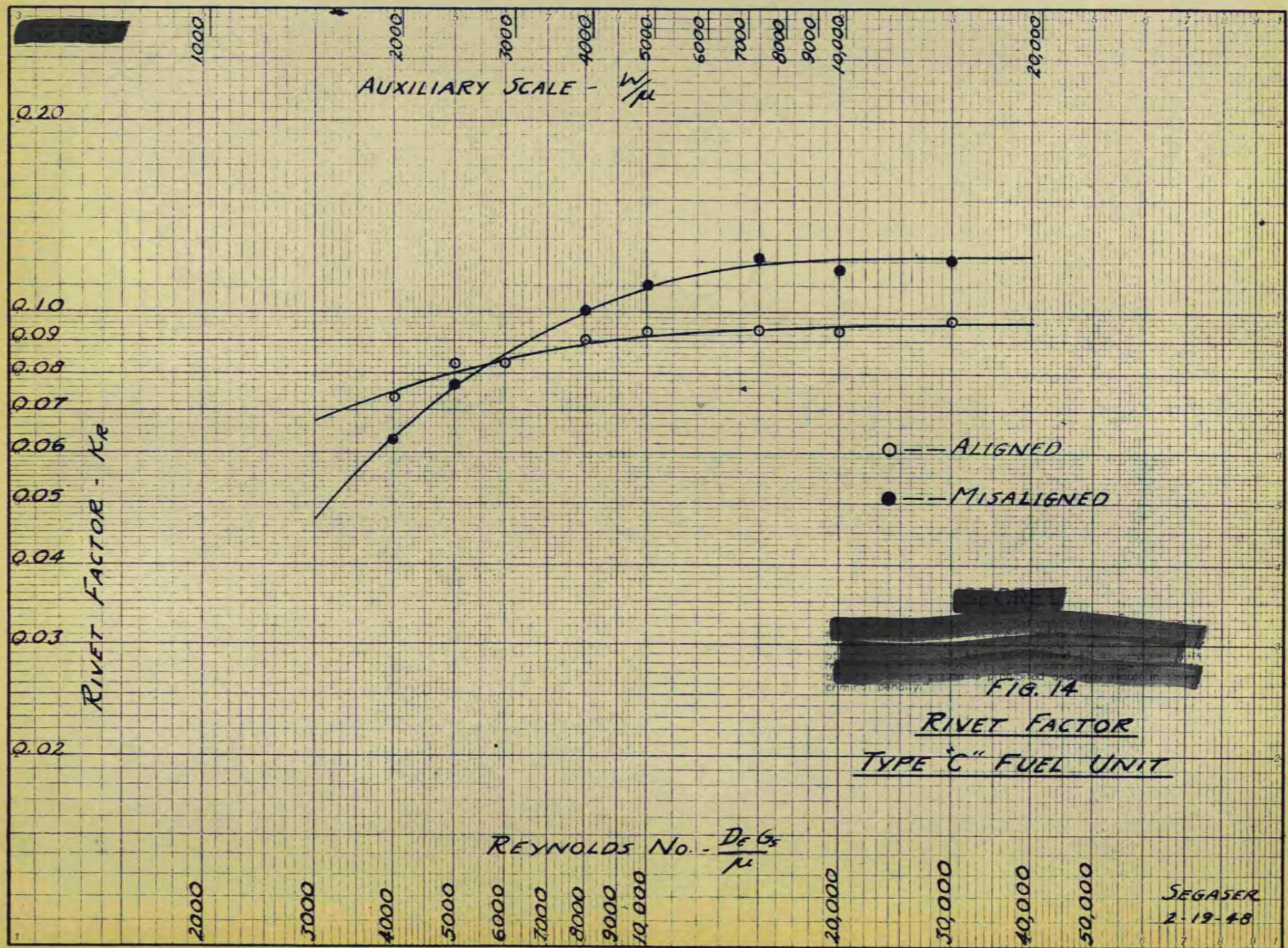
[redacted]

FIG. 13

TYPE "C" FUEL UNIT

NO. 21,257 LOGARITHMIC: 1-1 3 BY 2 5-INCH CYCLES.
CODEX BOOK COMPANY, INC., NORWOOD, MASSACHUSETTS.
PRINTED IN U.S.A.

[redacted]



[redacted]

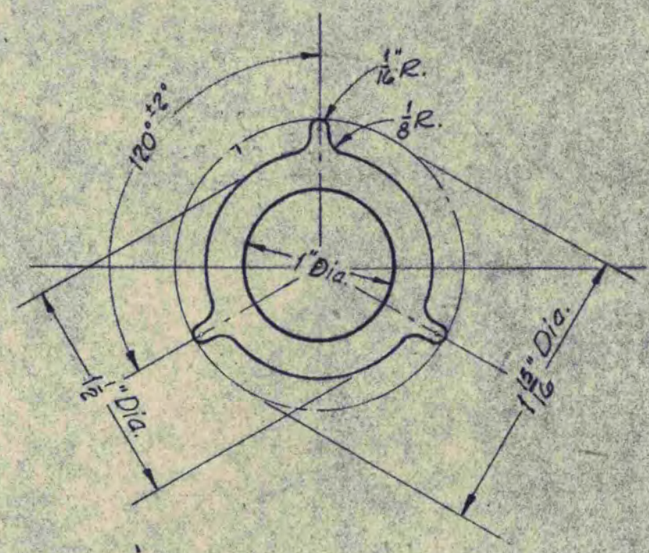
FIG. 14
RIVET FACTOR
TYPE "C" FUEL UNIT

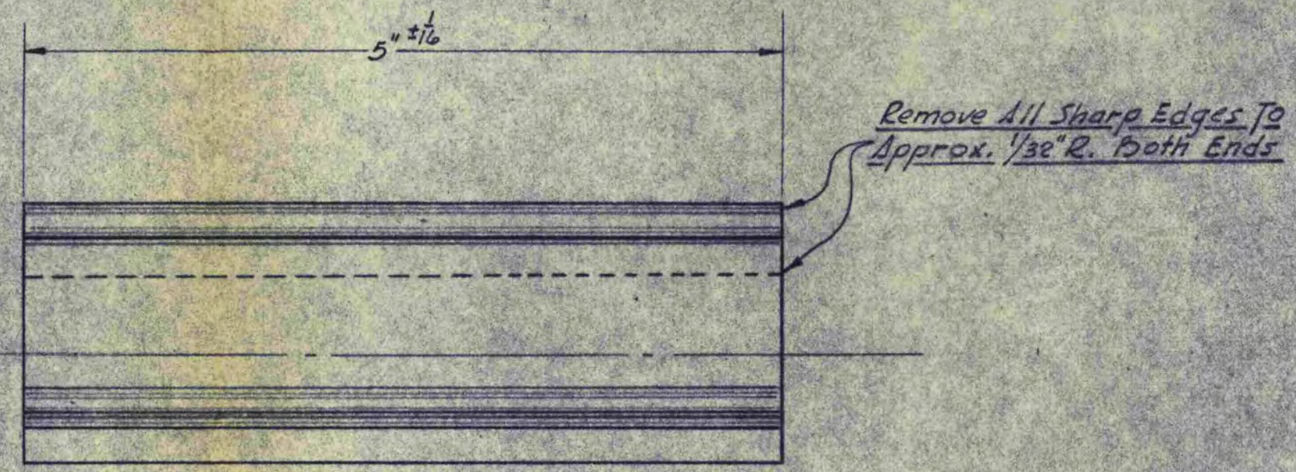
[redacted]

Type F-28 Fuel Unit

These units were fabricated especially for the pressure drop tests from aluminum billets. The F-28 type of unit is the simplest conceivable type, being essentially a cylinder 5 inches long with an inside diameter of one inch and an outside diameter of 1-1/2 in. Three ribs, spaced equally around the periphery, with an overall diameter of 1-15/16 in. are used for centering the unit in the fuel channel. Presumably, the unit as designed for power extraction would be fabricated from uranium impregnated graphite or beryllium oxide.

Figure 16 is a graphical presentation of the pressure drop data. The fuel element cross section depicts the function of the centering ribs. Each loaded fuel element channel has a gas flow area of 0.0143 sq. ft. and an equivalent diameter of 0.0456 ft. Figures 17 through 19 inclusively are logarithmic graphs of pressure drop factors for this unit versus Reynolds number. Figure 18 shows the equivalent skin friction factor and agrees fairly closely with the Fanning friction factor for smooth tubes. Figure 19 shows the fuel unit joint loss factor. This factor is shown to decrease from a value of about 0.054 at a Reynolds number of 2000 to a value of about 0.022 at a Reynolds number from 20,000 to 50,000. As might be expected, these curves indicate that the pressure drop through the pile is lower than for the other units. Actually, compared to the single plate "Type C" unit with no rivets, the pressure drop is 35 percent lower at 20,000 Kw output.





NOT CLASSIFIED
PER AA

NOTE:
For Pressure Drop Tests Only

Tolerance ±1/64" On All Dimensions
Except As Noted.

FIG 15

[redacted]

UNIT-TYPE F-28

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

Streuchman D. 6-18-47	A.L.S. C. 6-18-47	H.B.F. A. 6-18-47	R.E.P. 6-19-47			
Proj: C-222-M						
SCALE: Full				B-2733		

NO. 318 20 DIVISIONS PER INCH BOTH WAYS. 150 BY 200 DIVISIONS. CODEX BOOK COMPANY, INC. NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

[redacted]

FIG. 16

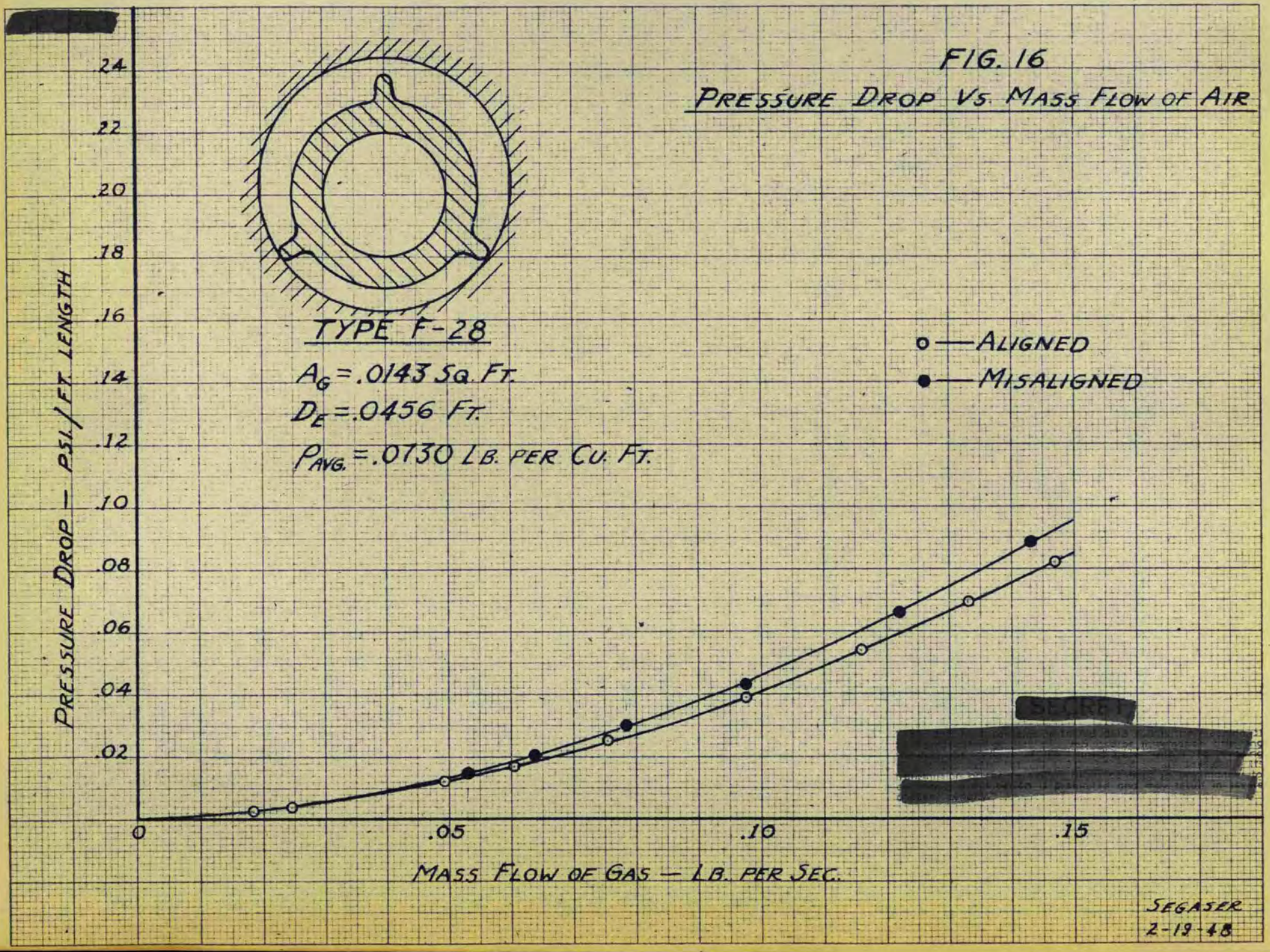
PRESSURE DROP VS. MASS FLOW OF AIR

TYPE F-28

$A_G = .0143$ SQ. FT.

$D_E = .0456$ FT.

$P_{AVG.} = .0730$ LB. PER CU. FT.

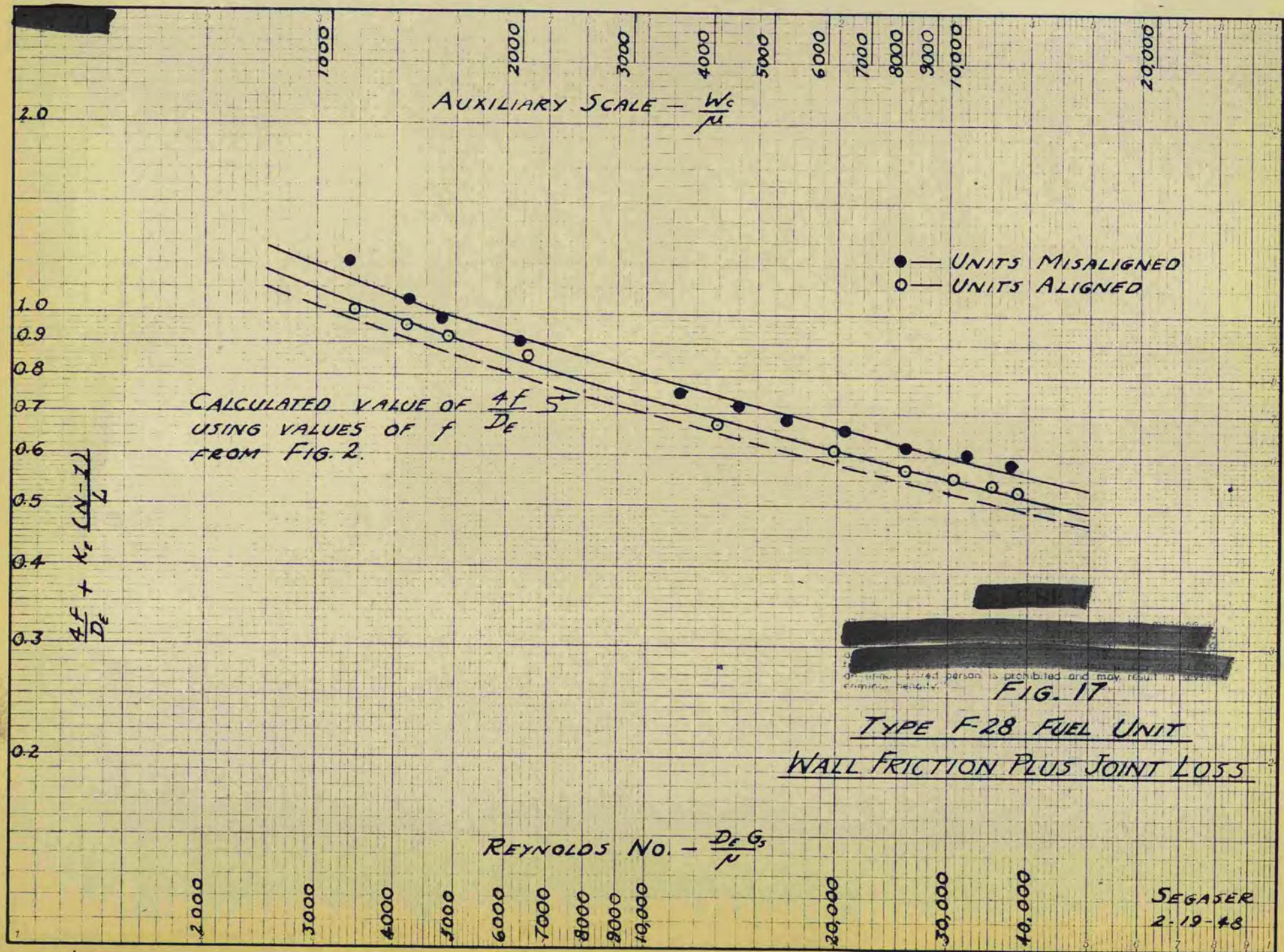


[redacted]

SEGASER
2-19-48

NO. 31 257 LOGARITHMIC 1-1 3 BY 2-5 INCH CYCLES.
CODEX BOOK COMPANY, INC., NORWOOD, MASSACHUSETTS.
PRINTED IN U.S.A.

[redacted]



[redacted]

FIG. 17

TYPE F-28 FUEL UNIT

WALL FRICTION PLUS JOINT LOSS

NO. 31,257. LOGARITHMIC: 1-1/3 BY 2 5-INCH CYCLES. CODEX BOOK COMPANY, INC., NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

[redacted]

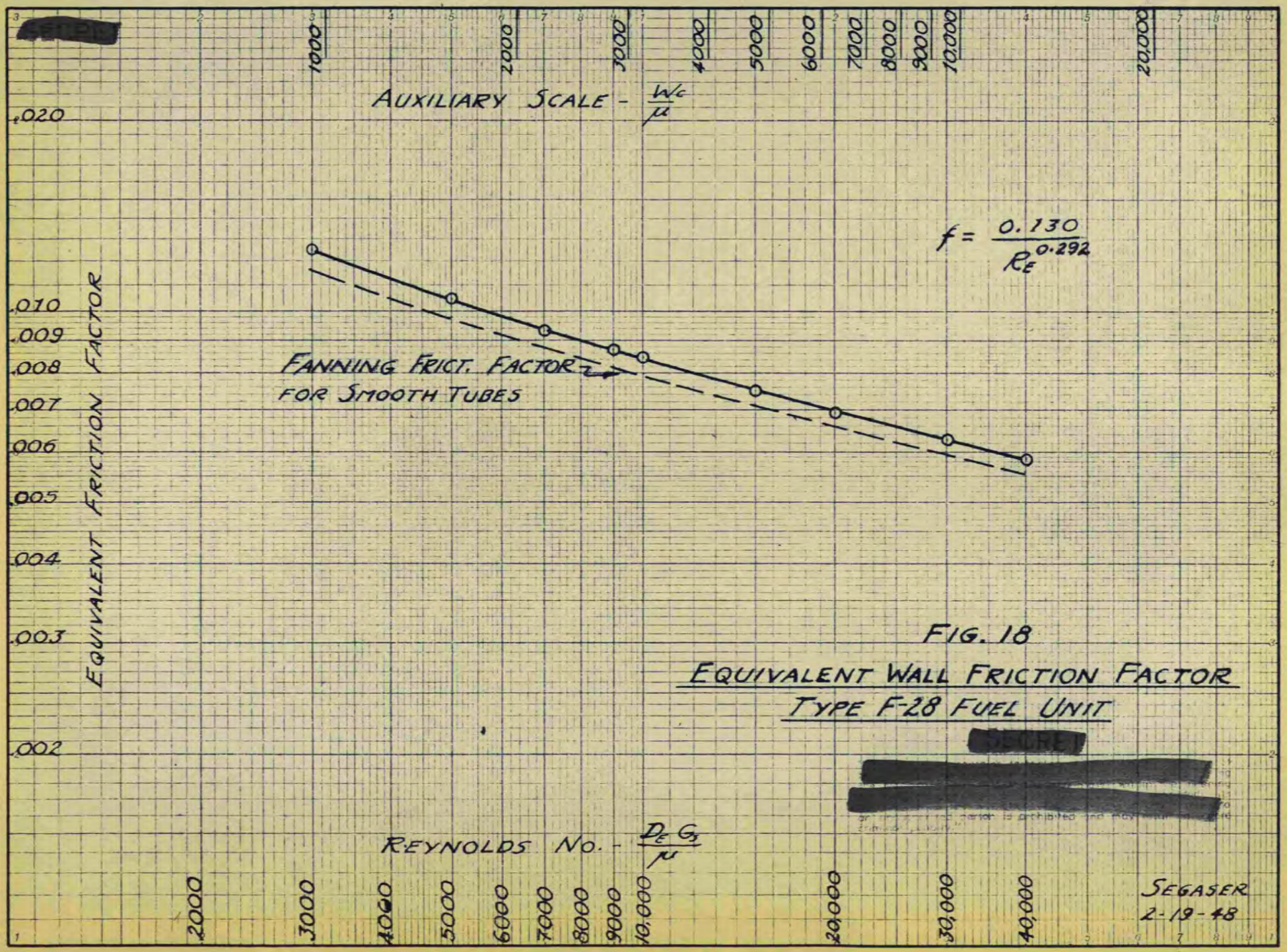


FIG. 18

EQUIVALENT WALL FRICTION FACTOR

TYPE F-28 FUEL UNIT

[redacted]

NO. 31 257 LOGARITHMIC 1-1 3 BY 2 5-INCH CYCLES
CODEX BOOK COMPANY, INC., NORWOOD, MASSACHUSETTS.
PRINTED IN U.S.A.

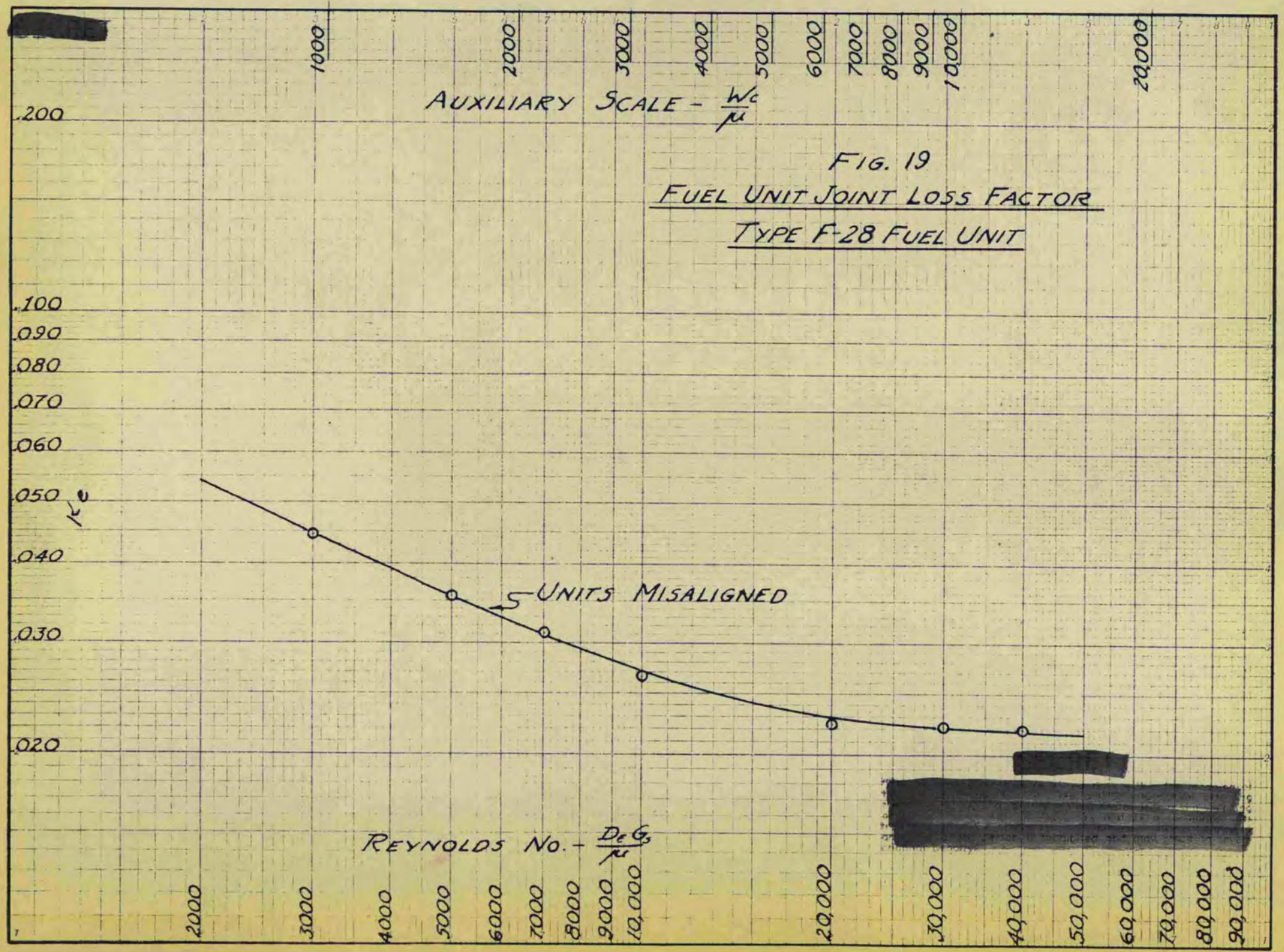


FIG. 19
FUEL UNIT JOINT LOSS FACTOR
TYPE F-28 FUEL UNIT

SEGASER 2-19-48

[redacted]

Type F-25-D Fuel Unit

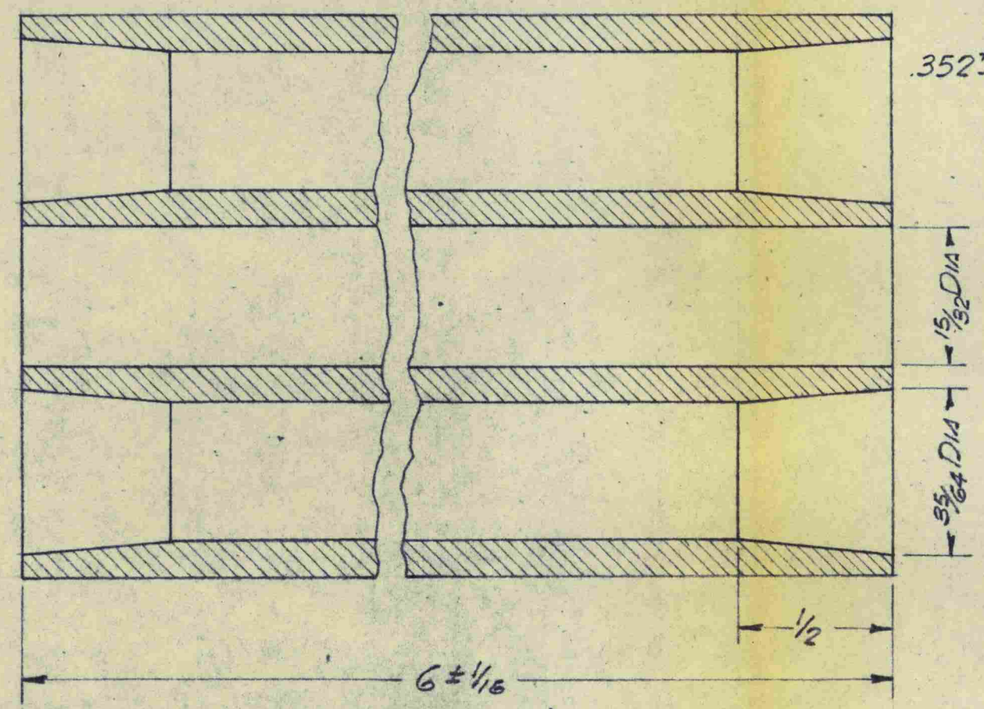
These units are fabricated either of graphite or beryllium oxide and are the nearest design approach to the simple cylindrical shape for a unit with the greatest surface-to-volume ratio and a wall thickness thin enough to minimize thermal stresses. Each unit is 6 inches long with seven holes each 15/32 in. diameter drilled longitudinally. Six of the holes are spaced equally around the central hole and all holes, with the exception of the central hole, which will always remain aligned, are beveled to minimize the reentrant pressure drop joint losses. The overall diameter of the unit is 1.875 in.

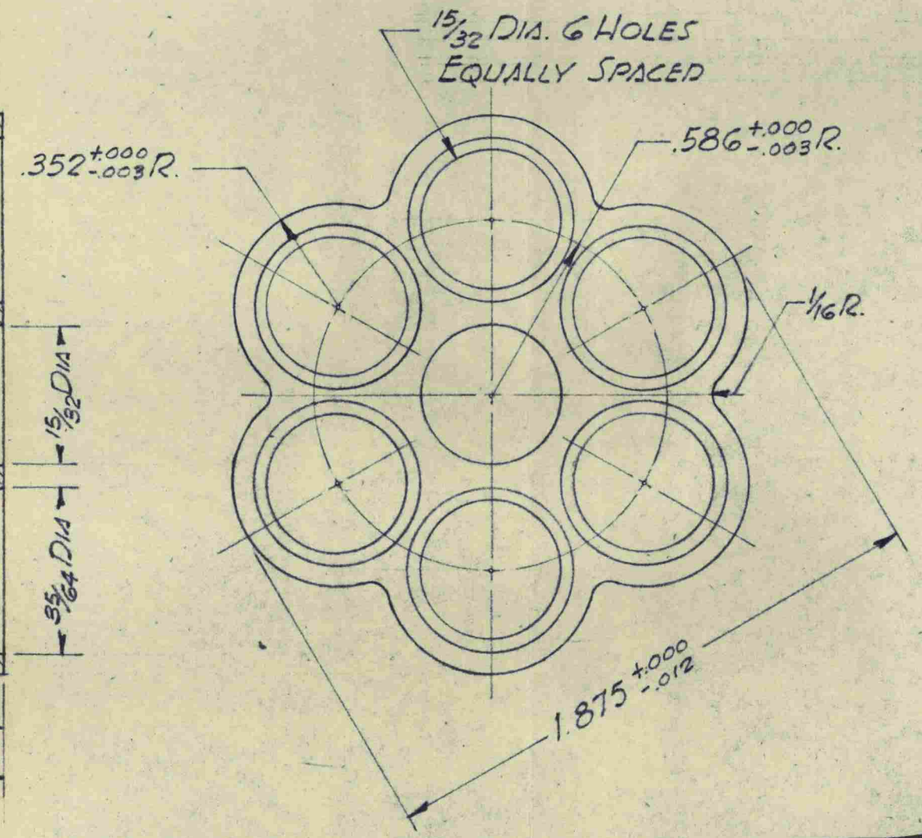
These units result in slightly higher pressure drops than the "Type C" unit without rivets. At 20,000 Kw pile output, the pressure drop through the F-25-D unit is 2.35 psi and for the "Type-C" unit is 2.00 psi or an increase of 17.5 percent. Figure 21 shows the pressure drop through the pressure drop apparatus versus air flow and the cross sectional shape, gas flow area and equivalent diameter. The agreement in equivalent wall friction factor with the Fanning friction factor is very close for this unit as shown by Figure 23.

Figure 24 indicates that the joint loss factor with the units misaligned remains constant at 0.150 through the Reynolds number range from 2000 to 40,000. As mentioned above, the reason that this factor is considerably less than that for fuel elements "C" and the 13 - hex, 6 pentagon unit is because the holes are beveled at the inlet and outlet. No attempt was made to reduce the joint losses in the other mentioned fuel element designs.

[redacted]

[redacted]





[redacted]

FIG 20

[redacted]

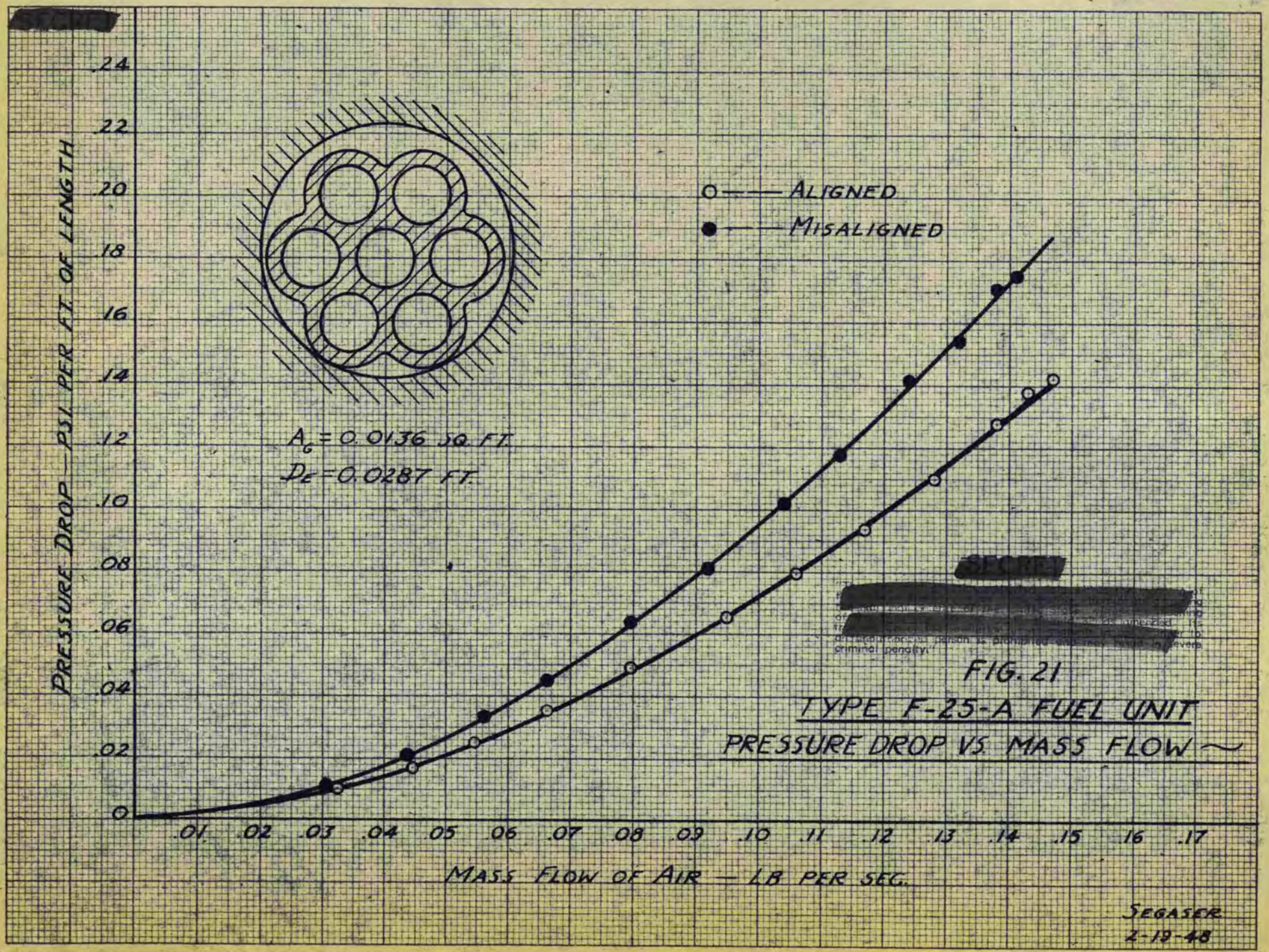
TYPE F-25-D
FUEL ELEMENT

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

LEDGERWOOD D. 2-20-48	SEGASER C. 2-20-48	A. G.L.S. 3-1-48				
C-222-M-81						
SCALE 2"=1"						B-3381

NO. 318. 20 DIVISIONS PER INCH BOTH WAYS. 150 BY 200 DIVISIONS. CODEX BOOK COMPANY, INC. NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

[redacted]



[redacted]

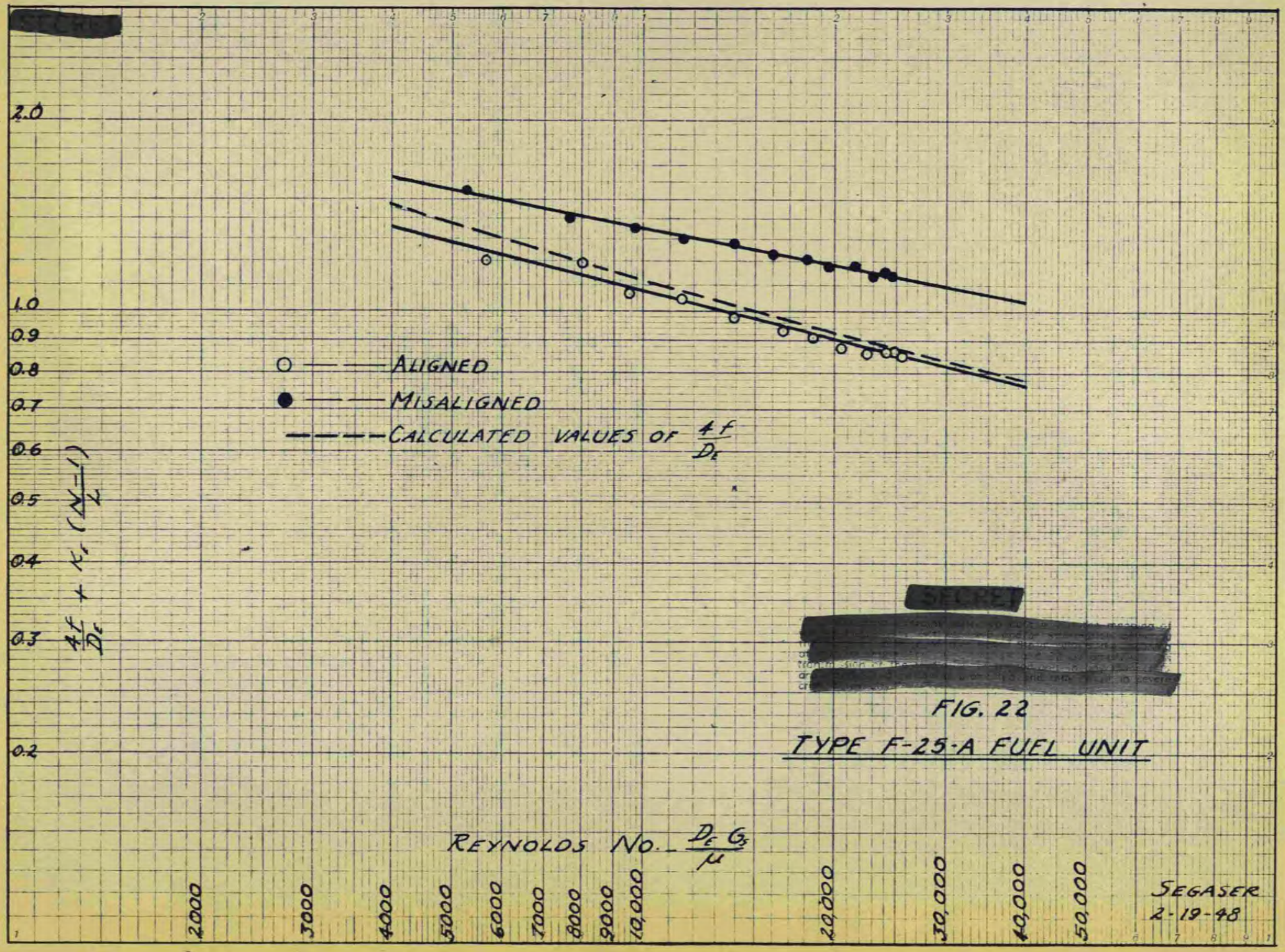
FIG. 21

TYPE F-25-A FUEL UNIT

PRESSURE DROP VS. MASS FLOW

NO. 31,257. LOGARITHMIC: 1-1/3 BY 2 5-INCH CYCLES. CODEX BOOK COMPANY, INC., NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

[redacted]



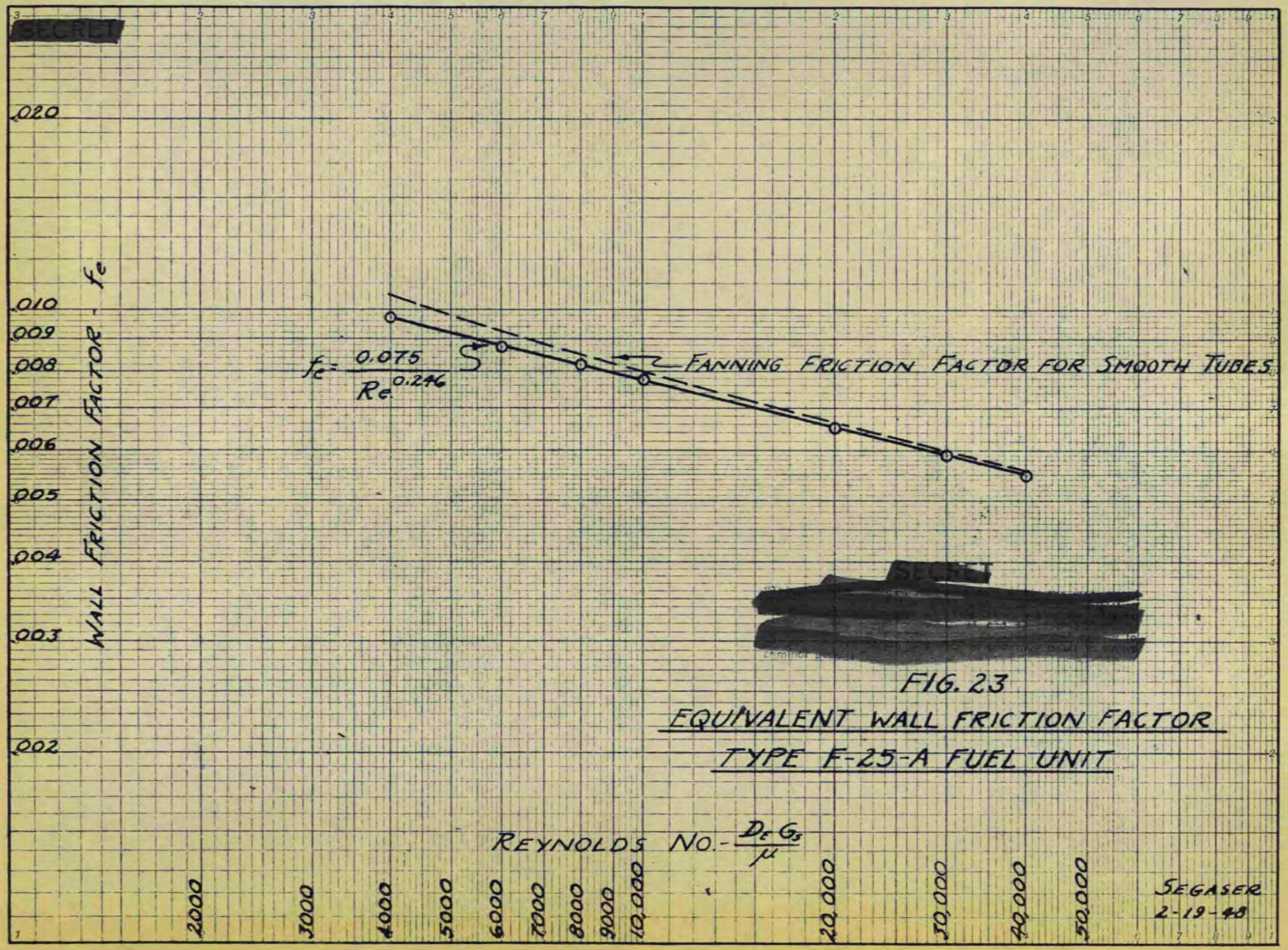
[redacted]

FIG. 22

TYPE F-25-A FUEL UNIT

NO. 31,257. LOGARITHMIC: 1-1/3 BY 2 5-INCH CYCLES. CODEX BOOK COMPANY, INC., NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

[redacted]



[redacted]

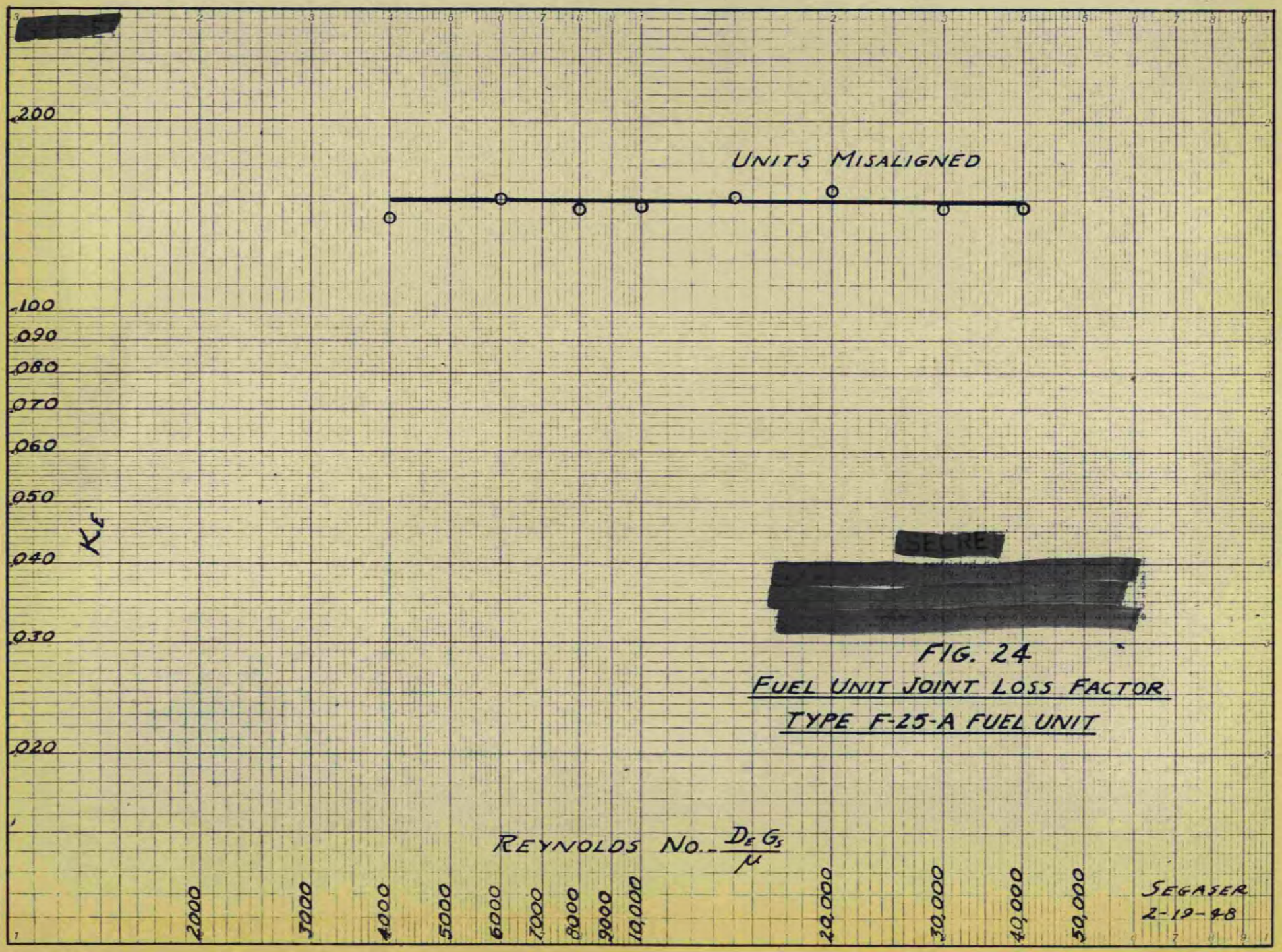
FIG. 23

EQUIVALENT WALL FRICTION FACTOR

TYPE F-25-A FUEL UNIT

NO. 31,257. LOGARITHMIC: 1-1/3 BY 2 5-INCH CYCLES.
CODEX BOOK COMPANY, INC., NORWOOD, MASSACHUSETTS.
PRINTED IN U.S.A.

[redacted]



[redacted]

FIG. 24

FUEL UNIT JOINT LOSS FACTOR

TYPE F-25-A FUEL UNIT

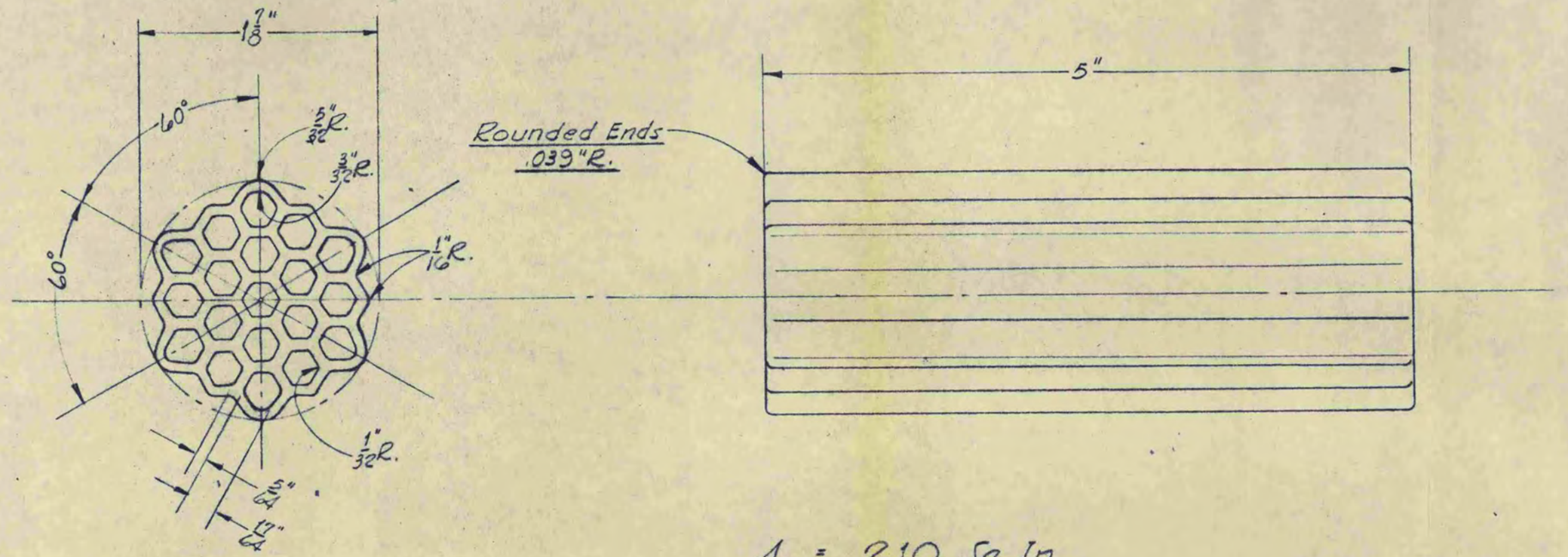
[redacted]

13 Hexagon, 6 Pentagon Fuel Unit

This unit is the nearest approach to the optimum design of large surface-to-volume ratio and thin walls of any of the units tested. However, as a consequence the pressure drop is relatively high. Compared to the single plate "Type C" unit without rivets the pressure drop at 20,000 Kw output of the pile is 75 percent higher, and 170 percent higher than the type F-28 unit.

For the purpose of conducting the pressure drop tests, sixteen of the units were fabricated from lead by pouring into especially constructed steel molds. The units were 5 in. long by 1-7/8 in. overall diameter. Each unit consisted of a honeycomb of hexagonal holes 17/64 in. across flats separated by a 5/64 in. thick wall. Six of the outer holes were shaped as shown for the purpose of centering the units in the fuel channel.

Agreement of the effective wall friction factor with the Fanning friction factor for smooth tubes was very good as shown by Fig. 28. The fuel unit joint loss factor for misaligned units was substantially constant, as shown by Fig. 29, varying from a factor of 0.60 at a Reynolds number of 4000 to a factor of 0.50 at a Reynolds number of 50,000.



A_G = 2.10 Sq. In.
W.P. = 28.7 In.
D_e = .29 In.

NOT CLASSIFIED
PER TTT

FIG 25

[redacted]

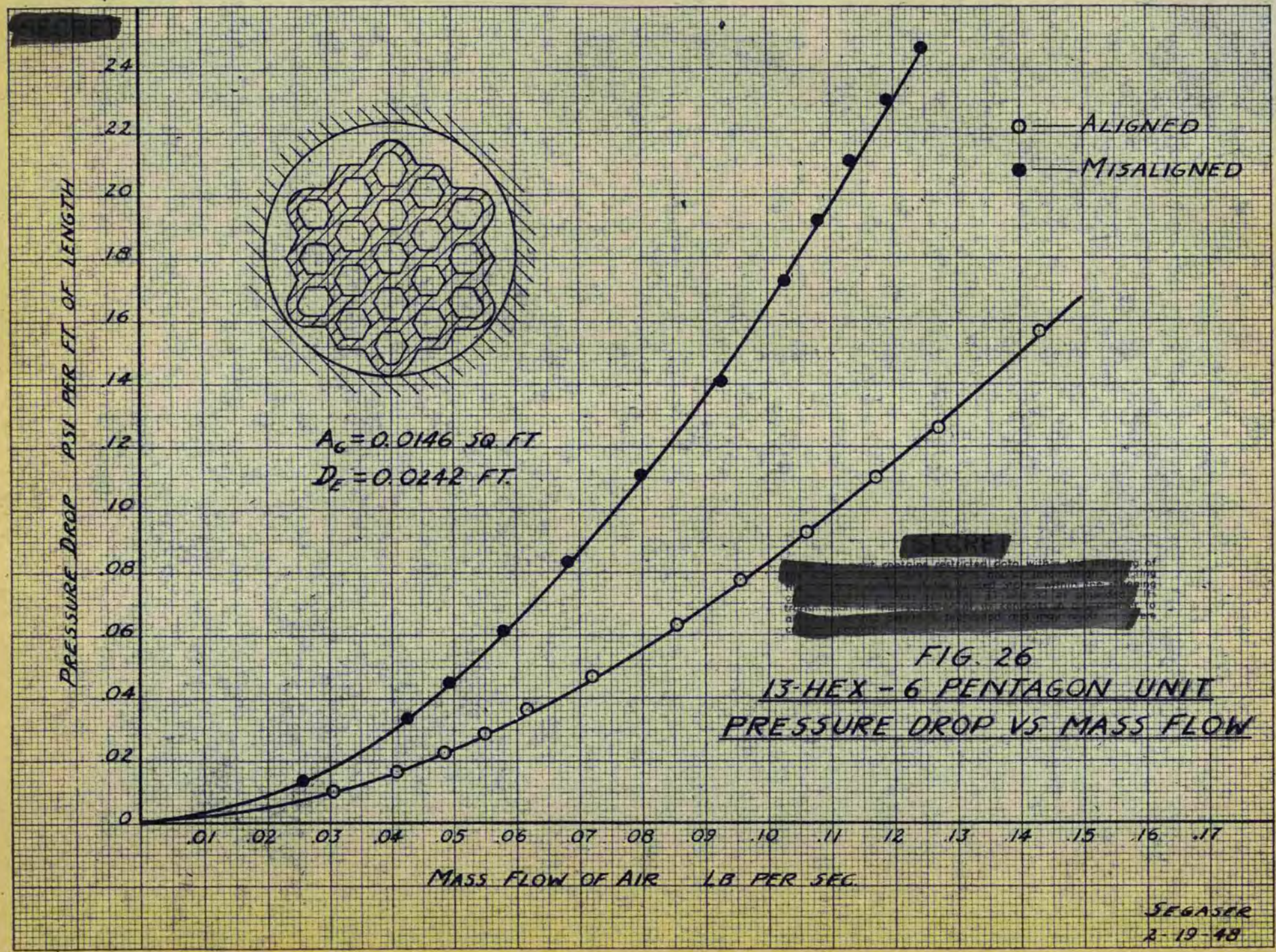
UNIT - 13 HEX.
6 PENTAGON

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. Strauchman 7-25-47	C. 7-30-47	A. 8-13-47			
Proj: C-222 M					
SCALE: Full			B-2257		

NO. 318. 20 DIVISIONS PER INCH BOTH WAYS. 150 BY 200 DIVISIONS. CODEX BOOK COMPANY, INC. NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

[redacted]

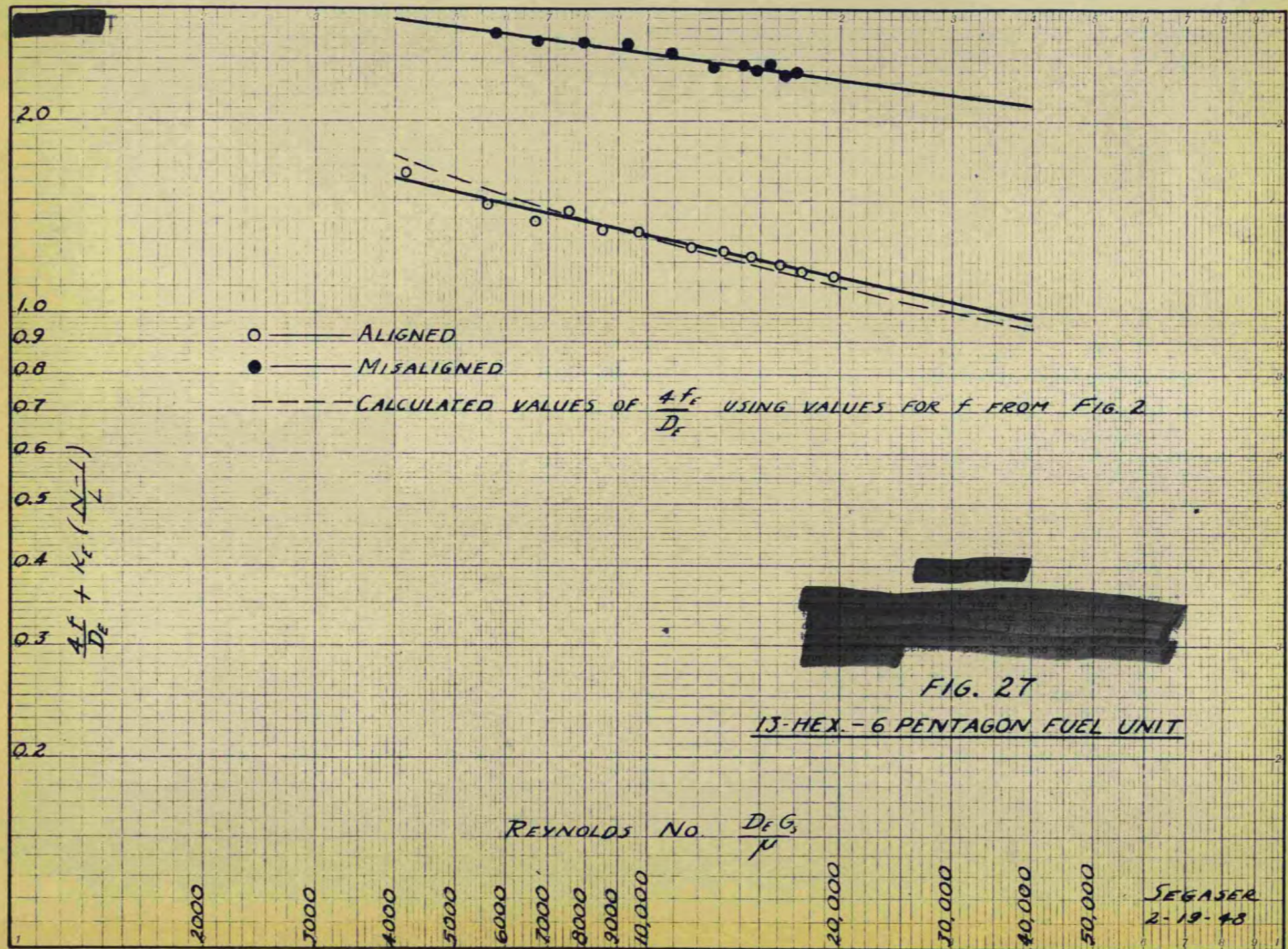


[redacted]

FIG. 26
13-HEX - 6 PENTAGON UNIT
PRESSURE DROP VS. MASS FLOW

NO. 31,237. LOGARITHMIC: 1-1 3 BY 2 5-INCH CYCLES. CODEX BOOK COMPANY, INC., NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

[redacted]



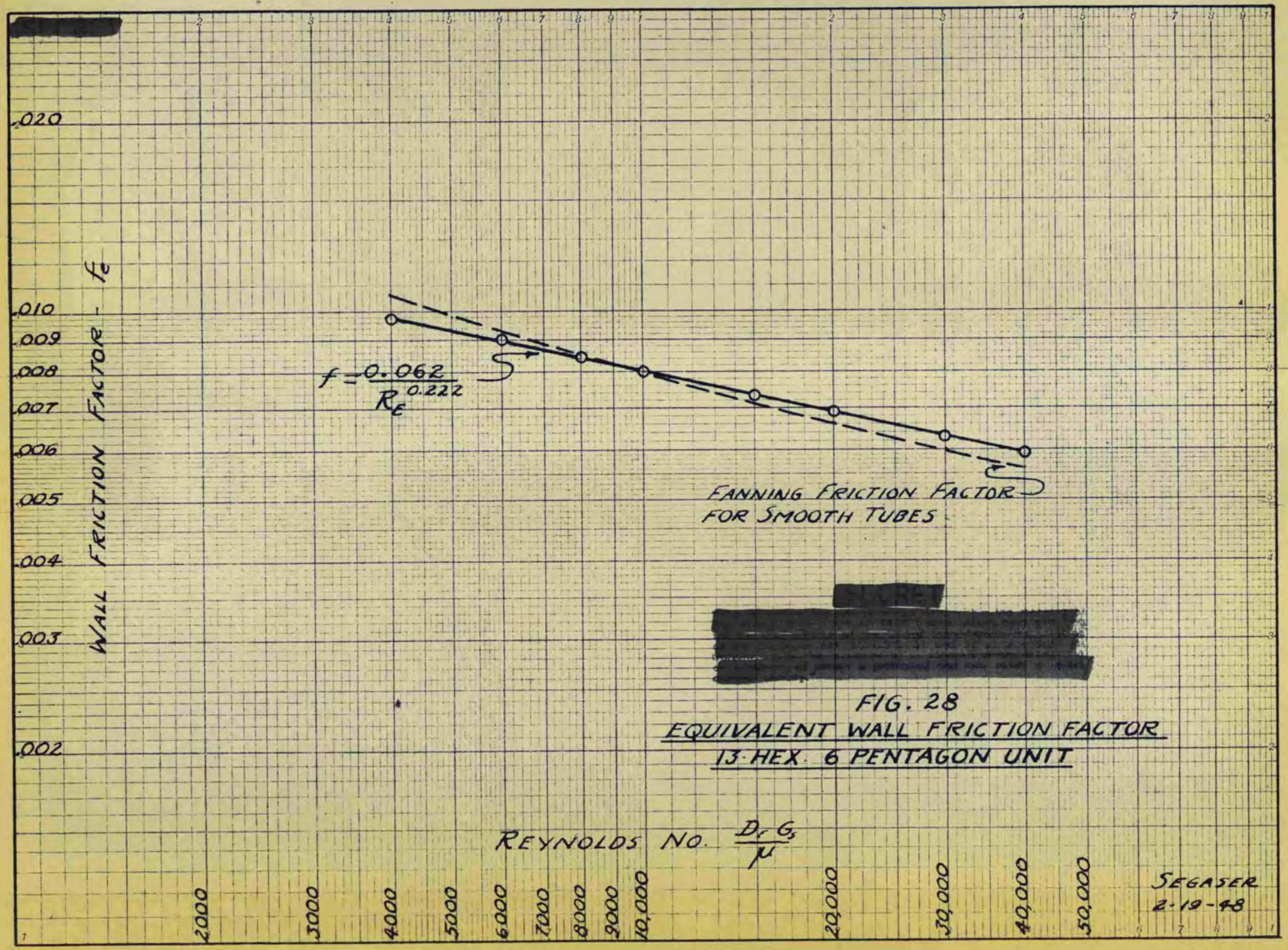
[redacted]

FIG. 27

13-HEX. - 6 PENTAGON FUEL UNIT

NO. 31,257. LOGARITHMIC: 1-1/3 BY 2 5-INCH CYCLES. CODEX BOOK COMPANY, INC., NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

[redacted]



[redacted]

FIG. 28
EQUIVALENT WALL FRICTION FACTOR
13-HEX. 6 PENTAGON UNIT

NO. 31,257 LOGARITHMIC: 1-1/3 BY 2 5-INCH CYCLES.
CODEX BOOK COMPANY, INC., NORWOOD, MASSACHUSETTS.
PRINTED IN U.S.A.

[redacted]

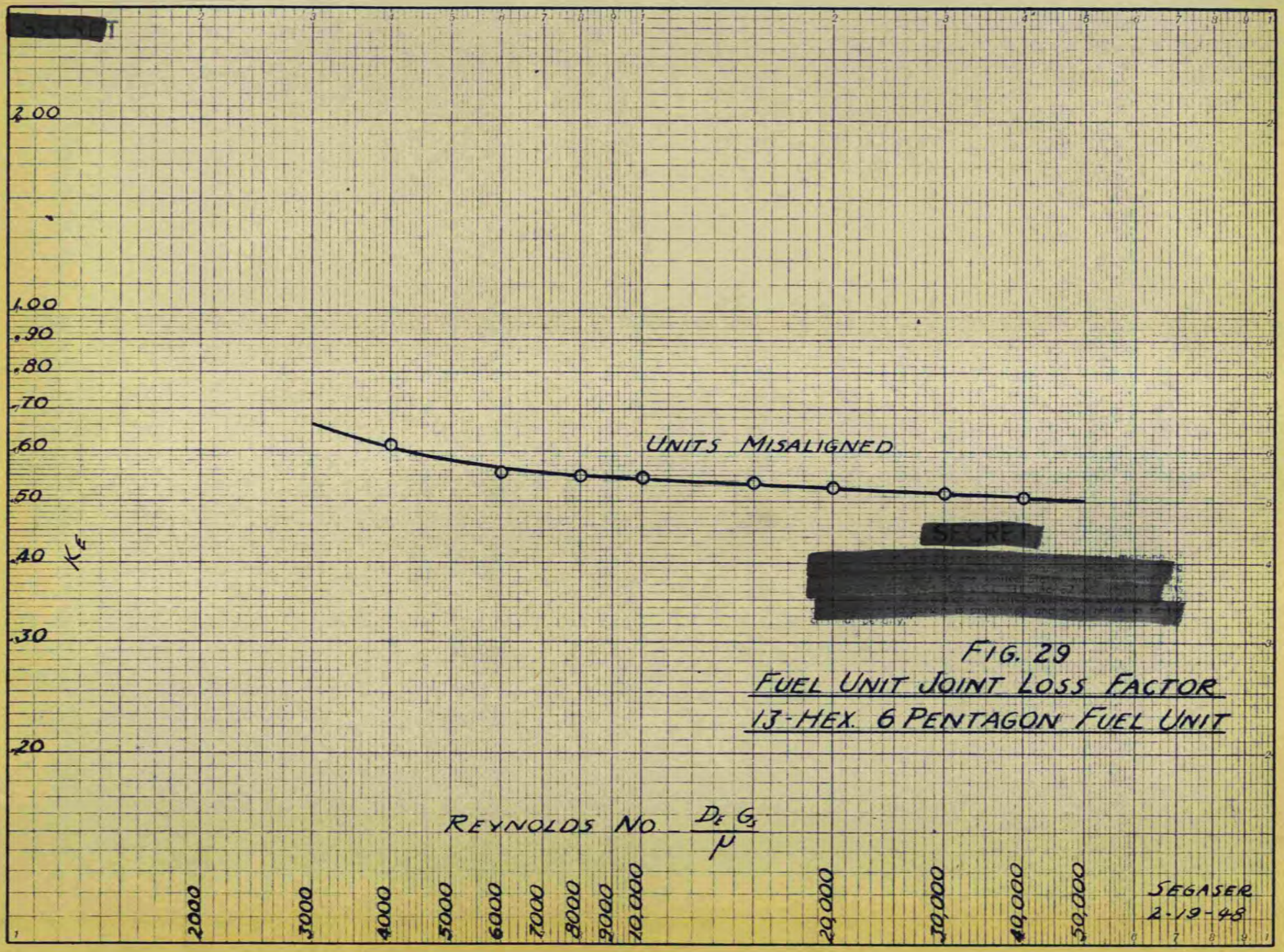


FIG. 29
FUEL UNIT JOINT LOSS FACTOR
13-HEX. 6 PENTAGON FUEL UNIT

[redacted]

APPENDIX A

Pile Pressure Drop. Although the primary objectives in conducting the pressure drop tests were to obtain data on equivalent skin friction and joint loss factors, the actual pressure drops through the Daniel's gas cooled power pile using the type fuel units tested have been computed, and the results are presented as follows such that a comparison of the relative merits of each fuel unit design may be made from the point of view of pressure drop and, therefore, gas pumping power involved.

Data was taken as the basis of calculation from the Design 3 version of the Daniel's pile and from the results of the pressure drop tests. Figure 30 shows the cross sectional elevation of the pile and depicts the flow of gas through the connecting duct work and fuel channels. Figure 31 is a cross section through a typical fuel channel and shows the relation between the latch retaining device, the spring element take-up, the fuel units and the hold down weights.

Table 2

Daniels Gas-Cooled Power Pile Data

Number of active channels	228
Length of channel (reflector and reactor)	76 in.
Length of fuel element	5 in.
Thickness of bottom support plate	6 in.
Thickness of top retainer weight	10 in.
Pile Output	12,000 Kw. continuous, 20,000 Kw. maximum
Helium coolant pressure	10 atm. abs.
Entrance gas temperature	500° F.
Exit gas temperature	1400° F.
Radial peak to average heat release ratio	1.56
Axial peak to average heat release ratio	1.26

The assumption was made that the latch retaining device and spring element take up introduces a drop in pressure equivalent to two additional fuel elements. The elements are all assumed to be 5 inches in length to conform to limitations imposed by the loading mechanism, hence, the number of fuel elements required is sixteen, and the pressure drop through the pile is, therefore, based on a fuel channel length of 80 inches or 6.667 feet. With this data and the properties of Helium at 10 atm., taken from Figure 32, the following graph, Figure 33, was obtained.

[redacted]

The average mass flow of gas through the pile is obtained from the heat balance,

$$3415\ KW = 3600\ W\ C_p\ N\ (T_2 - T_1)$$

where,

KW = Pile power output, KW

W = Mass flow of gas, lb. per sec. per channel

N = Number of channels

C_p = Average specific heat of gas at const. press. btu/lb-°F.

T_2 = Exit gas temperature, °F.

T_1 = Entrance gas temperature, °F.

Since the energy release at the center of the reactor is 1.56 times the average and the coolant Helium is metered through the reactor in proportion to the heat release, the flow through the central channel is,

$$W_c = \frac{(1.56)\ (KW)\ (3415)}{(3600)(W)(C_p)(N)(T_2-T_1)}$$

substituting values,

$$W_c = KW/172{,}000 \text{ lb. per sec. per center channel}$$

Therefore, the mass velocity, G_s, in the central channel is,

$$G_s = \frac{W_c}{A_G} = \frac{KW}{172{,}000\ A_G} \text{ lb. per sec. per sq. ft.}$$

From which the corresponding Reynolds number, $\frac{D_e G_s}{\mu}$ may be computed for any fuel element design, where,

D_e = Equivalent diameter = 4 x hydraulic radius = 4 x

$$\frac{\text{Gas Flow Area, sq. ft.}}{\text{Wetted perimeter, ft.}} = \text{ft.}$$

μ = Gas viscosity at average gas temperature, lb/sec-ft.

[redacted]

Determining the corresponding equivalent skin friction factor and joint loss factor from the appropriate curve, substituting in the pile friction drop equation, and using a value of 0.2 for K_1 and 1.0 for K_2, the pressure drops through the pile as shown by Figure 33 for the various fuel units were determined. These computations were simplified by substituting of the proper constant values and reducing the pressure drop equation to the following form,

$$P = \frac{G_s^2}{352} \left[26.7 \frac{fe}{D_e} + 15 K_e + 2.1 \right] \text{Psi}$$

[redacted]

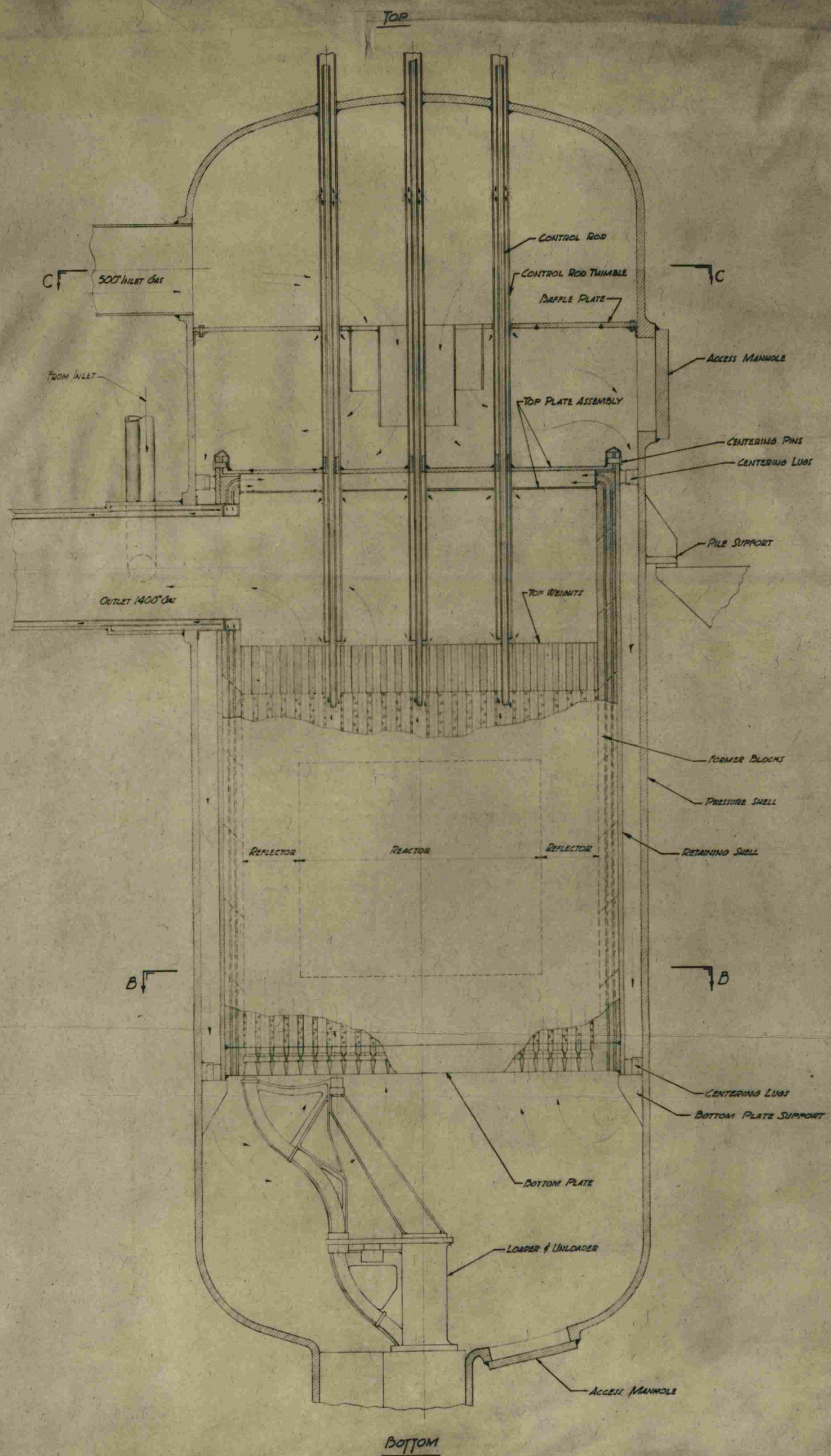


FIG 30

SECTION ELEVATION OF PILE STRUCTURE
WITH TEMPERATURE GAS COOLED FORMER PILE
MONSANTO CHEMICAL CO.
E-2274

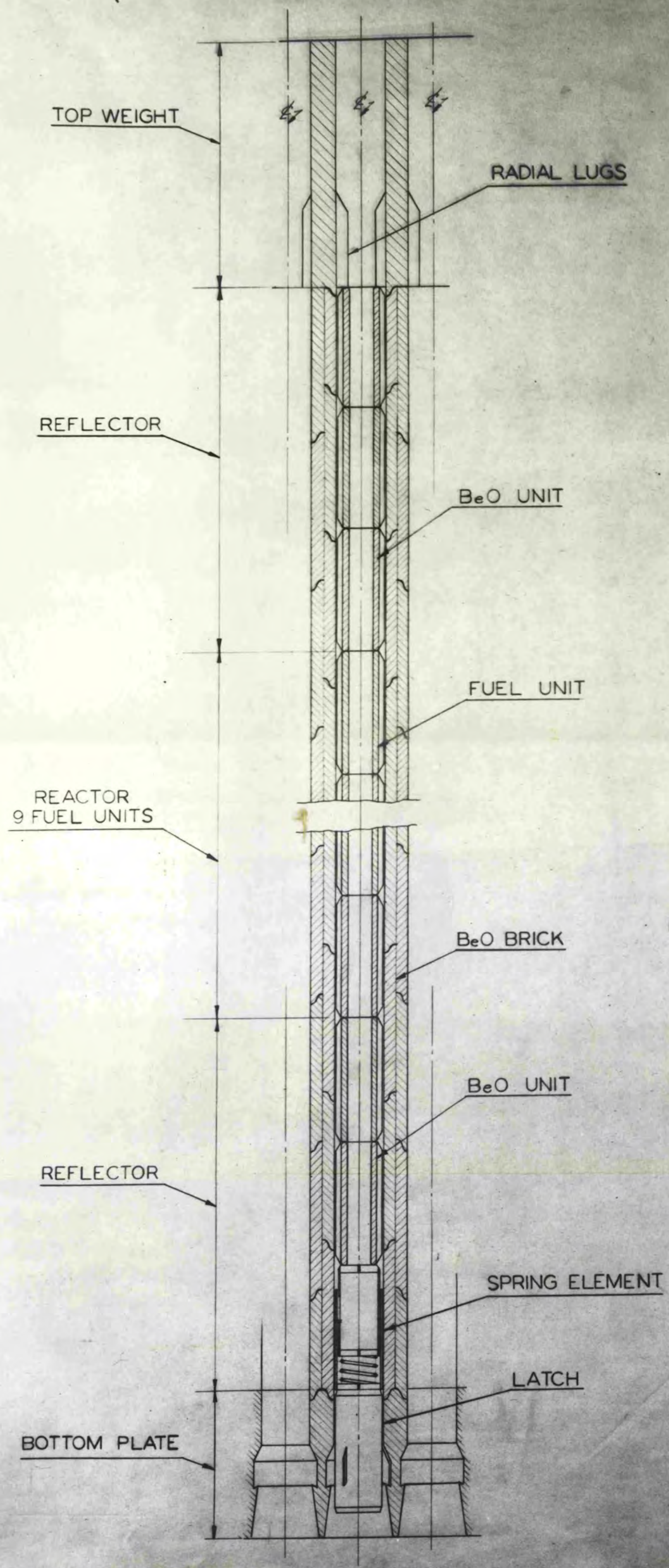


FIG 31

[redacted]

FUEL CHANNEL ASSEMBLY

HIGH TEMPERATURE GAS COOLED POWER PILE

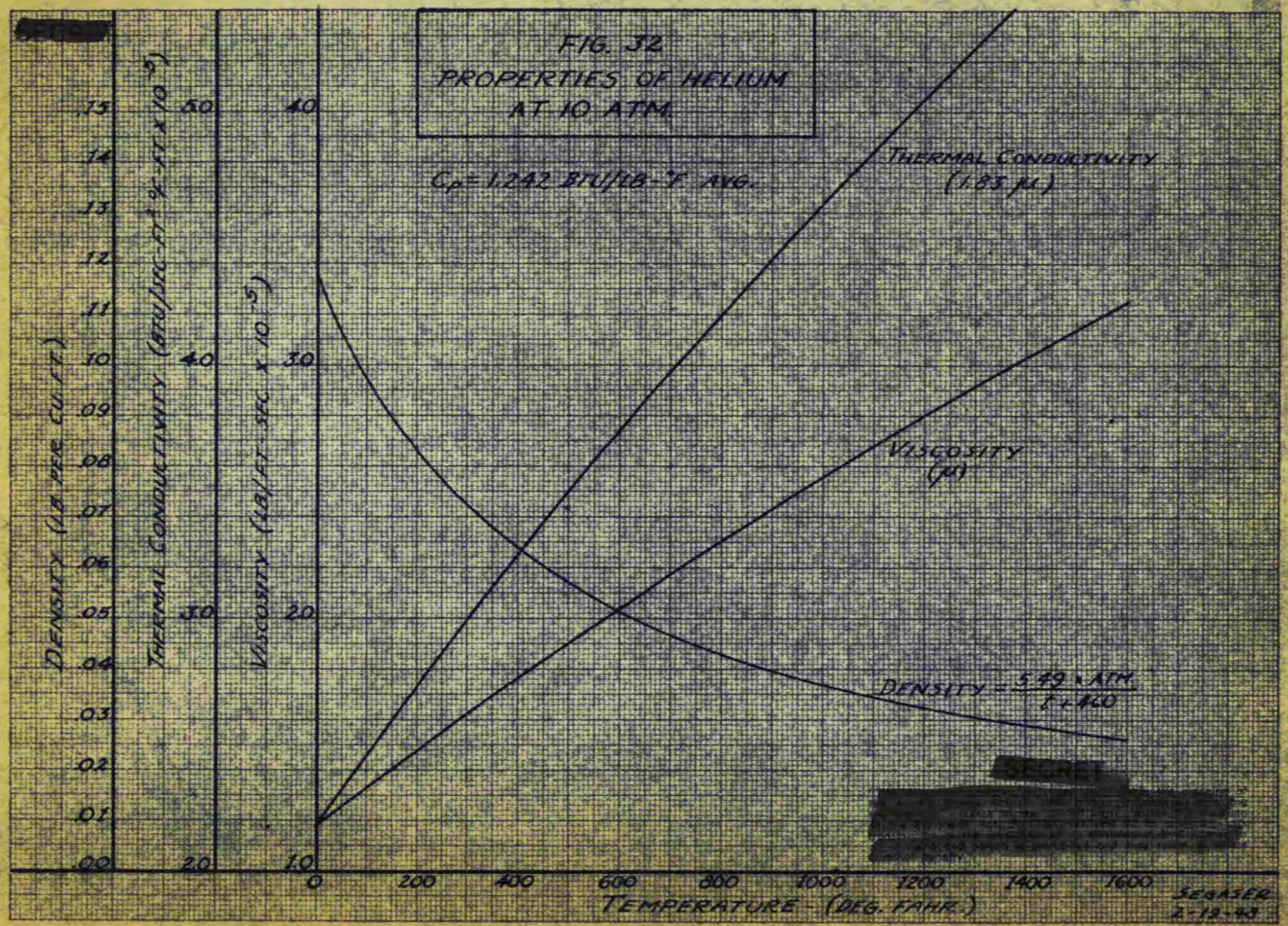
MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

SCALE 1/2"

D-2957

KEUFFEL & ESSER CO., N. Y. NO. 359H-14
Millimeters, 5 mm. lines accented, cm. lines heavy.
MADE IN U. S. A.

[redacted]



[redacted]

NO. 318. 20 DIVISIONS PER INCH BOTH WAYS. 150 BY 200 DIVISIONS. CODEX BOOK COMPANY, INC. NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

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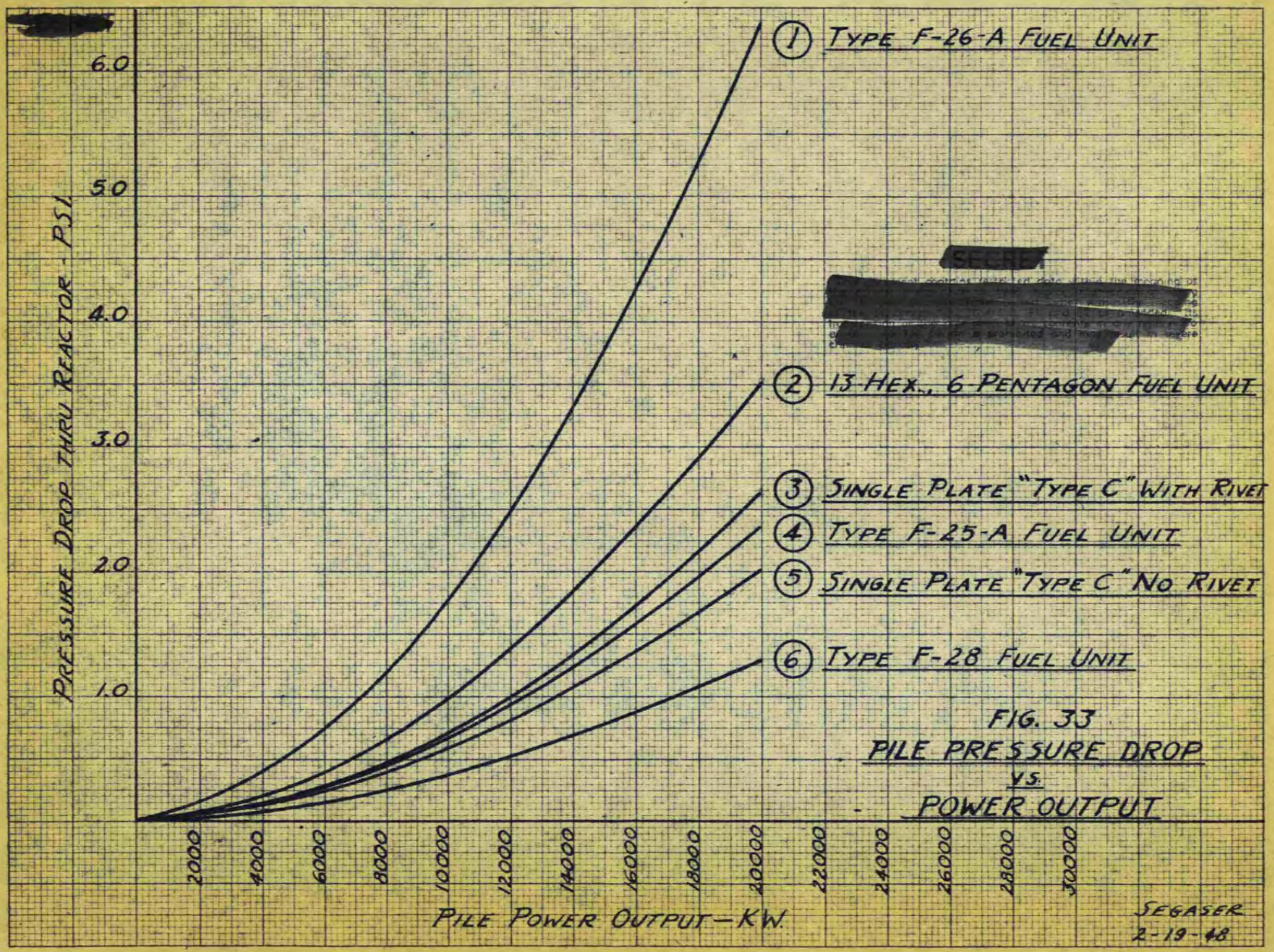

[redacted]

FIG. 33
PILE PRESSURE DROP
VS.
POWER OUTPUT

PPD-A-R12

[redacted]

APPENDIX B

Calibration of Flow Measurement Orifices.[4] The flow of air through the measuring section of the pressure drop apparatus was determined by metering the air through a 0.750 inch diameter sharp edged orifice inserted in a standard 2 inch pipe for low rates of flow, and through a 1.4925 inch diameter sharp edged orifice in a standard 3 inch pipe for higher rates of flow. The rate of flow through the apparatus was controlled by means of a bleed-valve discharging to atmosphere, as shown by Figure 1.

Equation 98 (a), page 49 of "Fluid Meters - Their Theory and Application" was used as the basis of computing the calibration curves for the orifices. This equation is

$$W = 0.0997\, Y_1 \left(\frac{C\, D_2^2}{\sqrt{1-\beta^4}} \right) \sqrt{\rho_1 h_w}$$

where

W = Weight flow, lb. per sec.

Y_1 = Expansion factor

C = Discharge coefficient

D_1 = Inside pipe diameter, inches

D_2 = Orifice diameter, inches

β = Ratio D_2/D_1

ρ_1 = Gas Density, lb. per cu. ft.

h = Monometer displacement, inches water

Since the flow coefficient, $K = \frac{C}{\sqrt{1-\beta^4}}$, this equation becomes,

$$W = 0.0997\, Y_1\, K\, D_2^2 \sqrt{\rho_1 h_w}$$

The density of air, ρ_1 is,

$$\rho_1 = 0.0390 \frac{P}{T}$$

And,

$$h_w = \frac{0.33}{25.4} h_{mm} = 0.0327\, h_{mm}$$

[redacted]

[redacted]

Where,

P = Orifice absolute pressure, mm. Hg

T = Absolute air temperature, °R.

h_{mm} = Manometer displacement, mm. oil

Substituting, assuming $T = 30°C = 303°R$, and simplifying;

$$W = 0.000176\ Y_1 K D_2^2 \sqrt{P h_{mm}}$$

For the 1.4925 in. orifice, this equation becomes,

$$W = 0.000392\ Y_1 K \sqrt{P h}$$

For the 0.750 in. orifice, the equation is,

$$W = 0.0000990\ Y_1 K \sqrt{P h}$$

Values for Y_1 are obtained from page 124, Fig. 72, Ref. 1, and values for K from p. 111, Ref. 1 of "Fluid Meters - Their Theory and Application". Using the two equations above, values of W, the weight flow in lb. per sec. were calculated for various values of manometer readings in mm. of oil with absolute gas pressure at the orifice as parameters and plotted on calibration curve sheets. Using these curves, the weight rate of flow of air can be readily determined. However, since a temperature of $T = 30°C = 303°K$ was assumed for calibration, a temperature correction factor must be applied for gas temperatures other than the above. Therefore since, $W \propto \frac{1}{\sqrt{T}}$ the values of W as obtained should be multiplied by a factor equal to $\sqrt{\frac{303°K}{T°K}}$ to correct for temperature variations.

[redacted]

[redacted]

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1. MonN-383 - "Summary Report on Design and Development of High Temperature Gas Cooled Power Piles" by C. R. McCullough. September 15, 1947.

2. MonN-299 - "Heat Transfer in Gas-Cooled Piles" by A. Amorosi. May 29, 1947.

3. "Heat Transmission" by W. H. McAdams, 1st Edition, McGraw-Hill Book Co., 1933.

4. "Fluid Meters - Their Theory and Application", A.S.M.E. Research Publication. Fourth edition, 1937.

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