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# THE DESIGN AND CONSTRUCTION OF A POWERED POGO-STICK

by

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Thesis Advisor

This thesis consists of the design and construction of a liquid fuel-air powered Pogo stick.

The end results are what I believe to be a properly powered Pogo stick, the drawings of which are included in this thesis.

This project is now under construction in the Sloan Laboratory.

The author is especially grateful to Professor A. R. Rogowski and J. Levingood for giving so much of their time in regard to this thesis. He is also indebted to them for their stimulating help in solving the various problems that were encountered.

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# INTRODUCTION

The analysis and complete design of a liquid fuel-air powered pogo stick.

**I. Analysis:** The analysis is divided into the following main topics:

1) Description of the operating cycle.
2) The investigation of the energy dissipated during the operation due to:
   a) internal friction of mechanism,
   b) air drag.
3) The determination of size requirements resolved through the preceding two studies.
4) The examination of combustion in this mechanism. This topic is further divided into:
   a) analysis of auto ignition through an energy approach,
   b) the complete analysis of N-heptane fuel in the pogo stick, with the necessary time-motion study of mechanism during the compression stroke.

**II. The Design:** Consists of complete and detailed drawings for the construction of this device.

Plus: 1) A description of auxillary and safety devices used in this mechanism.

2) List of all standard and supplement parts.

# ANALYSIS

## Descriptive Cycle Analysis

This device is essentially an Otto engine. The processes through which the charge pass are illustrated in Fig. 1 and Fig. 2 and may be described as follows:

1-2 Compression of charge until explosion occurs. Takes place in upper cylinder.

1-5 Charge is drawn into lower cylinder. Processes 1-2 and 1-5 occur simultaneously.

2-3 Combustion of whole charge takes place very quickly, so it may assume to explode at constant volume and the mixture of air and fuel become a mixture of combustion products at a higher pressure and temperature.

3-4 Expansion of products of combustion--pushing the piston and connecting rod outward. Takes place in upper cylinder.

5-6 A small compression of the new charge in the lower cylinder occur simultaneously with 3-4.

4-1 Exhaust of combustion products out exhaust port into the atmosphere. Takes place in the upper cylinder.

6-1 New charge expands into upper cylinder from the lower cylinder via bypass, pushing exhaust gases out through the exhaust port. Processes 4-1 and 6-1 occur in part simultaneously; 4-1 usually starts before 6-1.

## Fuel-Air Cycle Analysis*

The following was assumed:

1) Actual cycle = .85 of F/A cycle.

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* For complete description of this analysis, see, The Internal Combustion Engine, by C. F. Taylor and E. S. Taylor, 1950, Chapter IV.

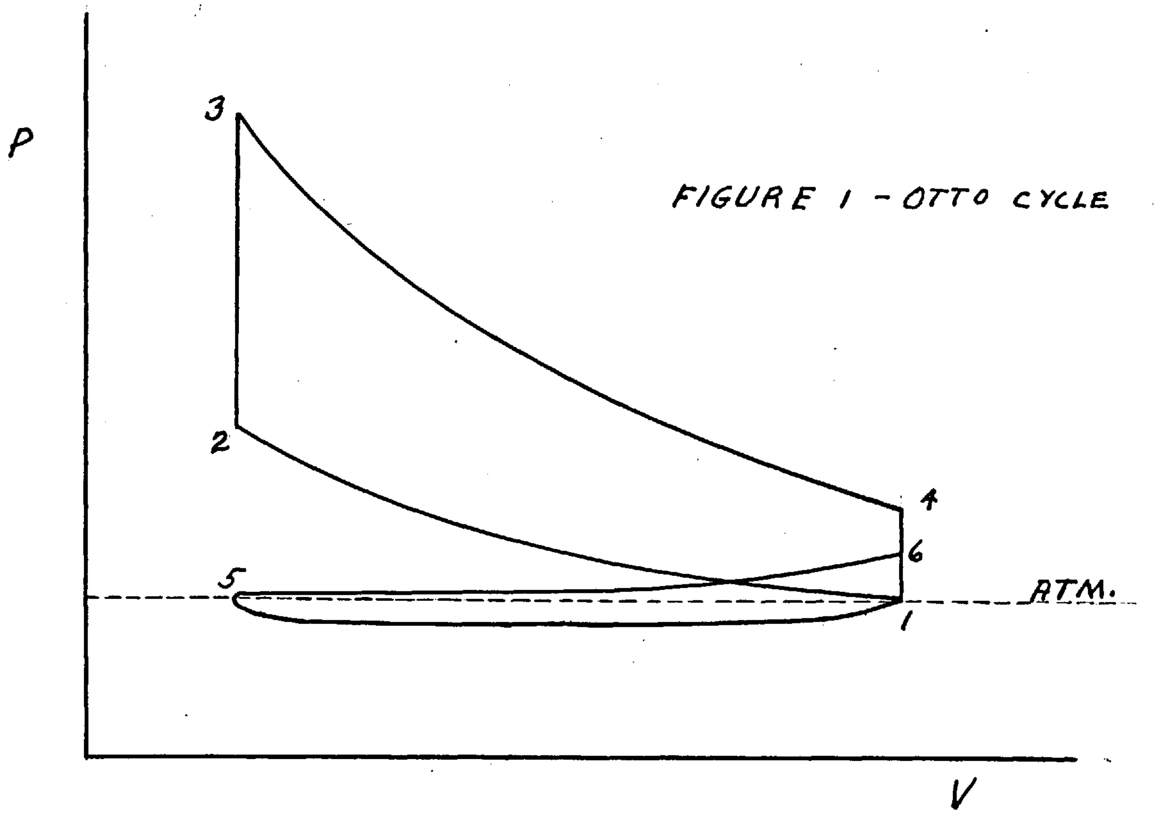


FIGURE 1 - OTTO CYCLE

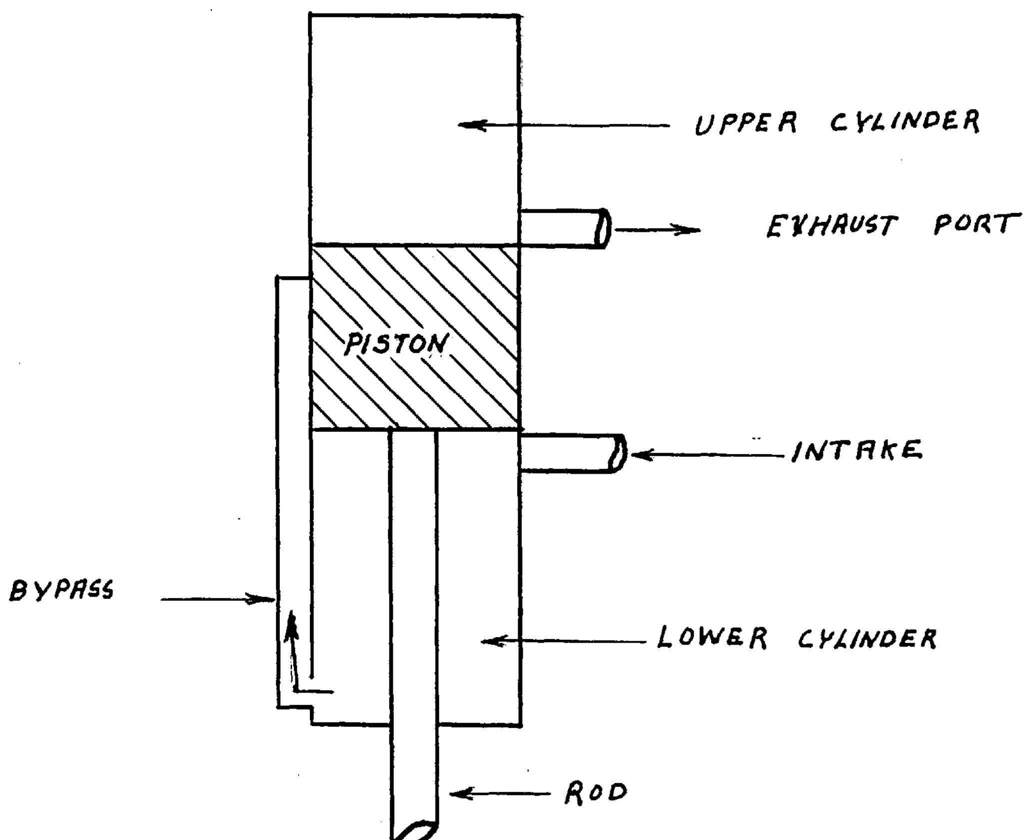


FIGURE 2 - SCHEMATIC

2) Intake pressure into cylinder = 14.7 psia

3) Exhaust pressure = 14.7 psia

4) Temperature of mixture at point 1, T1, (see Fig. 1) justified later = 520°R

5) Fraction of gas left in cylinder from the preceding cycle = .015 = f (explained on page 9)

6) Compression ratio of 14 (justified on page 30)

Information is obtained from the charts of "Thermodynamic Characteristics of Lean Fuel-Air Mixtures Before Combustion" ("Unburned charts"), F/A = .0605 and "Thermodynamic Characteristics of the Products of Combustion of "Lean" Mixture $C_8H_{18}$ and Air" ("Burned Charts"), F/A = .0605 (by Hershey, Eberhardt and Hottel).

Process 1-2 Isentropic Compression of Charge

$P_1 = 14.7 \quad T_1 = 520$

$E_{s1} = 0 \quad S_1 = .053 \quad U_1 = 12$ From above chart, (before combustion) $H_{s1} = 37$

$E_1 = 1165(1-f) = 1165 \times .985 = 1150$

Then $U_2 = \frac{U_1}{r} = \frac{12}{14} = .86$ and $S_2 = .053$

From "Unburned Charts"

$P_2 = 570$ psia $\quad T_2 = 1320°R \quad E_{s2} = 169 \quad H_{s2} = 262$

$\therefore E_2 = 169 + 1150 = 1319$

$W_{12} = E_1 - E_2 = E_{s1} - E_{s2} = -169$

Process 2-3 Constant-Volume Burning

$V_3 = V_2 = .86 \quad E_3 = E_2 = 1319$

From Combustion Products Chart:

$S_3 = .434 \quad P_3 = 1900 \quad T_3 = 5110$

Process 3-4 Isentropic Expansion

$U_4 = U_1 = 12 \quad S_4 = S_3 = .434$

From Combustion Products Chart:

$$P_4 = 95 \qquad T_4 = 2820 \qquad E_4 = 550 \qquad H_4 = 758$$

$$W_{34} = E_3 - E_4 = 1319 - 550 = 769$$

Process 4-1 Products of Combustion Expand to Atmospheric Pressure. From Combustion Products Chart:

C = combustion products

$$P_{1c} = 14.7 \qquad T_{1c} = 1890 \qquad E_{1c} = 300 \qquad V_{1c} = 50 \qquad H_{s1c} = 440$$

$$\text{or } H_{1c} = 140$$

f can now be determined

$$f = \frac{12 \times .2}{50} = .048$$

Does not warrent a re-calculation!

The .2 factor is used because of the scavenging $\eta(e_s)$ involved. It will be justified on page 11.

Process 6-1, where new charge expands into upper cylinder and mixes with the residual gas, at constant pressure (P = 14.7 psia).

This calculation is used as a measure for checking assumption 4. (Temperature of mixture at point 1)

$$H_{s1} = f H_{s1c} + (1-f) H_{sm}$$

$$= 45.9$$

where $H_{sm}$ = enthalpy of fresh charge

From "unburned chart"

$$\therefore T_1 = 530$$

does not warrent re-calculation.

Net work produced during above cycle:

$$W = W_{12} + W_{34}$$

$$= -169 + 769 = 600 \text{ Btu/cycle}$$

$$\text{or } \frac{600}{1.0605} = 565 \text{ Btu/lb. of charge.}$$

Calculations of work Required for Scavenging and Pumping:

Work required to get scavenging pressure $P_2$.

Assumptions:

1) $P_1 = 14.7$ psia

2) $P_2 = 38$ psia - required*

3) $T_1 = 520°R$

Process is an isentropic compression. From "unburned" charts (F = .0605).

$P_1 = 14.7$ $S_1 = .053$ $T_1 = 520°R$ $V_1 = 12$ $H_1 = 37$ $E_{s1} = 0$

$P_2 = 38$ $S_2 = .053$ $T_2 = 670°R$ $V_2 = 6.5$ $H_2 = 80$ $E_{s2} = 32$

$$H_2 - H_1 = 80 - 37 = \frac{43}{1.0605} \frac{\text{Btu}}{\text{lb. of CHARGE}} \text{ or } 40.5 \text{ Btu/lb. of CHARGE}$$

Work Required for Pumping Into Lower Cylinder:

This process is an isentropic expansion. Starting at the same conditions as the above process, since the ratio of $V_1/V_2$ in the above process is the exact reciprocal in this process, and since this process is an isentropic expansion (instead of isentropic compression) the above results, will be very nearly the same.

The very small difference (if any) will be due to a change in the properties of the charge during the expansion as compared with the properties during the compression and they will be assumed to remain constant during these two different cases.

Thus, the total work required for scavenging and pumping will be 91 Btu/lb charge used for scavenging.

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* Dimension of lower cylinder length is established by this required value of $P_2$ (scavenging) see page 19.

At this point it becomes necessary to fix some of the design criteria.

Since the diameter of the bore will be limited by the amount of acceleration a man can stand, the shape of the upper cylinder will have to be designed with this in mind. This in all probability will lead to a longer stroke than bore in this engine. This design is a relatively hard one to scavenge and therefore a scavenging ratio ($R_s$) of two will be chosen.

$$R_s = \frac{\text{mass of misture pumped/unit time}}{\text{mass of possible misture retained in cyl./unit time}}$$

From: Scavenging Efficiency vs Scavenging Ratio of Several Two-Stroke Engines, prepared by P. M. Ku, 4/6/51, (123.2 - PMK - 4-51)

for a $R_s$ of 2 , $e_s = .80$

$$\text{where } e_s = \frac{\text{mass of misture retained in cyl./unit time}}{\text{mass of possible mixture retained in cyl./unit time}}$$

Since, $R_s = 2$, the total work required for scavenging and pumping will be 182 Btu/[illegible] for [illegible] filling the upper cylinder.

Therefore:

$$565 - 182 = 383 \ \text{Btu/lb of CHARGE}$$

$$IMEP_{t/h} = \frac{W}{V_1 - V_2} \times \frac{778}{144} = \frac{383 \times 778}{\underbrace{(12 - .86)}_{11.14} \times 144} = 186 \text{ psi.}$$

Actual $IMEP = 186 \times .85 = 158$ psi.

From page 13 it has been calculated that $fMEP = 11$ psi

$$\therefore \ BMEP = 158 - 11 = 147 \text{ psi}$$

Actual work available = 144 x 11.14 x 147

$$= 236{,}000 \ \frac{\text{ft-lbs}}{\text{lbs of charge burned}}$$

<u>The Investigation of Energy Dissipated During the Operation Due to Internal Friction of Mechanism and Air Drag.</u>

1) Internal Friction of Mechanism

Usually piston speed (S) is defined by

$$S = \frac{2 \times \text{stroke} \times N}{12}$$

where S = piston speed - ft/min.
stroke = inches
N = rpm

but this formula is not particularly applicable to the pogo-stick. A better approach for the preliminary calculation of piston speed follows:

Preliminary dimensions:*

1) Bore = 1 inch in diameter

2) Stroke = 1.5 inches

3) Weight of man and pogo-stick = 160 lbs.

Assuming that the height of a hop will be 9 inches or .75 ft. from the ground. (On regular pogo-sticks this distance of .75 ft. off of the ground is a good figure!)

$$V_1 = \sqrt{2 g_o s}$$

where $V_1$ is velocity of pogo-stick when it hits the ground (ft/sec)

$g_o$ = acceleration of gravity 32.2 ft/sec$^2$

s = distance of fall .75 ft.

$$V_1 = \sqrt{2 \times 32.2 \times .75} = \sqrt{48.4} = 6.96 \text{ ft/sec.}$$

Since, the stroke is 1.5 inches, the acceleration during the stroke may be computed: $V^2 = 2as$, $a = \frac{V^2}{2s} = \frac{48.4}{2 \times \frac{1.5}{12}} = 193.5 \text{ ft/sec}^2$

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* These dimensions will be justified in a later section (page 17). They are proposed here, in order that a rough piston speed can be found, thereby enabling the prediction of F.M.E.P. (friction mean effective pressure).

From $S = \frac{1}{2} a t^2$, $t = \sqrt{\frac{2S}{a}} = \sqrt{\frac{2 \times 1.5}{12 \times 193.5}} = .039$ SEC.

$\bar{V}_{AVE.}$ during stroke $= \frac{S}{t} = \frac{1.5}{12 \times .039} = 3.2$ ft/sec.
$= 3.2 \times 60 = 193$ ft/min.

From interpolating Fig. 124, page 205, of The Internal Combustion Engine, by Taylor and Taylor (using curve 1)

FMEP = 11 psi

This value is an approximation, based on a limited amount of data.

2) Air Drag

The forces due to air drag are calculated as a function of velocity. These forces are due to:

A) Air drag during the vertical motion. The energy loss/cycle due to this force remains constant, since it is assumed that the height of each hop(.75 ft) is constant.

when T = 0 the vertical velocity at the top of the hop = 0

when T = t the vertical velocity at the bottom = 6.96 ft/sec

(calculated on page 12)

Since $D_v$ (vertical drag force) is proportional to $V_v^2$, the average $\bar{V}_v^2$ should be used for drag force calculations.

$$\frac{(6.96)^2 - (0)^2}{2} = 24.2 \text{ ft}^2/\text{sec}^2$$

$$\text{or } \bar{V}_v = 4.9 \text{ ft/sec}$$

Reynolds No. $= \frac{\rho V l}{\mu}$

$\rho$ = density of air

$\mu$ = viscosity of air

$\mu/\rho$ = kinematic viscosity for air (ft²/sec)

$= 1.9 \times 10^{-4}$ at 14.7 psia. and 80°F

$l$ = characteristic length, taken to be 1.5 ft (width of person)

$$\text{Reynolds No.} = \frac{4.9 \times 1.5}{1.9 \times 10^{-4}} = 3.88 \times 10^4$$

Assumptions:

T - thickness of man - 9" or .75 ft.

W = width of man - 1.5 ft.

S = 2 x height of hop (2 x .75 ft) - 1.5 ft.

Therefore, area pertinent to vertical motion .75 x 1.5 = 1.13 $ft^2$

Coefficient of drag for flat rectangular plate:* WHERE $\frac{W}{T} = \frac{1.5}{.75} = 2$

$$C_D = 1.19$$

This $C_D$ is valid for Reynolds numbers greater than $10^3$ - so it is valid in the above case.

From shape considerations of the human body it appears that the above $C_D$ would be too large. The body is more streamline than a flat rectangular plate perpendicular to the direction of flow; but considering all of the odd projections and wind traps of clothes, the above figure is probably liberal.

$$C_D = \frac{D_V}{\rho/g \; \bar{V}^2/2 \; A}$$ $D_V$ = vertical drag force, lbs.

$$D_V = \frac{C_D \rho \bar{V}^2 A}{2g} = .00157 \bar{V}^2 \quad , \text{WHEN} \quad \bar{V}^2 = 24.2 \; ft^2/sec^2$$

$$D_V = \frac{1.19 \times .075 \times 1.13 \times 24.2}{32.2 \times 2} = .0378 \text{ lbs.}$$

Total up-down distance traveled during one cycle = 1.5 ft.

1.5 x .0378 = .0567 ft-lb expended during vertical motion.

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* From, Engineering Applications of Fluid Mechanics, Page 183. By J. C. Hunsaker and B. G. Rightmire, McGraw-Hill Book Company, Inc., 1947.

B) Air Drag during the horizontal motion as a function horizontal velocity.

Reynolds No. = $\frac{\rho V l}{\mu}$

$\rho$ = density of air

$\mu$ = viscosity of air

$\mu/\rho$ = kinematic viscosity for air ($ft^2/sec.$)

= $1.9 \times 10^{-4}$ at 14.7 psia and $T_1$ = 80°F

$l$ = characteristic length, taken to be 6 ft (average height of a person)

Reynolds No. = $\frac{14.7 \times 6}{1.9 \times 10^{-4}} = 46.4 \times 10^4$

Assumptions:

Length of man, $l$, = 6 ft.

Width of man, $w$, = 1.5 ft.

Therefore, man's area = 9 $ft^2$

Coefficient of drag for flat rectangular plate:* WHERE $\frac{l}{w} = 4$

$$C_D = 1.2$$

This $C_D$ is valid for Reynolds numbers greater than $10^3$--so it is valid in above case.

This value for the above $C_D$ is probably liberal since the resistance due to clothes has been neglected.

$$C_D = \frac{D_H}{\rho/g_c \; \bar{V}^2/2 \; A}$$

$D_H$ = horizontal drag force, lbs.

$$D_H = C_D \rho/g_c \times \frac{\bar{V}_H^2}{2} A$$

$$D_H = \frac{1.2 \times .075 \times 9 \; \bar{V}_H^2}{32.2 \times 2} = .0126 \; \bar{V}_H^2$$

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* From, Engineering Applications of Fluid Mechanics, page 183, by J. C. Hunsaker and B. G. Rightmire, McGraw-Hill Book Company, Inc., 1947.

3) The determination of size requirements (dimensions) resolved through the preceding two studies.

If Bore is set at 1" AND

Stroke is set at 1.5"

$R_s = 2 \quad e_s = .80$

Height of jump = 9" or .75 ft.

Vol. of cylinder $= \frac{\pi d^2 L}{4} = \frac{3.14 \times 1^2 \times 1.5}{4} = 1.18\ IN^3$

or $\frac{1.18}{1728} = .000682\ ft.^3$ (Displ.)

at initial conditions in cylinder of $T = 520°R$

$P = 14.7$ PSIA.

Vol. of charge/lb — $v = 12\ ft^3/lb$ ("unburned" charts)

$\therefore \frac{Displ.}{v} =$ lbs. of charge

$= \frac{.000682}{12} = .0000568$ lbs.

Since $e_s = .80$

$.80 \times .0000568 = .0000454$ lbs. burned per cycle

<u>Actual work available</u> = 236,000 $\frac{\text{ft-lbs}}{\text{lb of charge burned}}$

$\therefore 236000 \times .0000454 = 10.7$ ft-lbs/cycle available to overcome air friction.

Speed at which pogo-stick will travel at previous given dimensions:

Having a .75 ft. jump (vertical) the cycle time can be calculated.

$S = \frac{1}{2} g_o t^2, \quad t = \sqrt{\frac{2S}{g_o}} = \sqrt{\frac{1.5}{32.2}} = \sqrt{.0466}$

$= .216$ SEC.

Allowing for both "up and down" time

T cycle = .432

The time that the stick remains on the ground during combustion is small, and therefore neglected.

Distance between hops = $V_H T$, and energy dissipation due to vertical motion

= .0567 ft-lb/cycle

$$\therefore \quad .0126\, V_H^2 \times V_H T + .0567 = \text{ft-lbs/cycle (dissipated by air drag)}$$

$$.432 \times .0126\, V_H^3 + .0567 = 10.7$$

$$.00544\, V_H^3 = 10.64$$

$$V_H^3 = \frac{10.64}{.00544} = 1960$$

$$V_H = 12.4 \text{ ft/sec.}$$

$$\text{or} \quad \frac{12.4 \times 3600}{5280} = 8.5 \text{ M.P.H.}$$

8.5 M.P.H. is speed at which pogo-stick will travel with .75 ft. high hops.

The following is a calculation of how high the stick will go before the "up and down" energy dissipation due to air friction is equal to the energy output of the engine. The horizontal velocity is equal to zero.

From previous calculations

$$D_V = .00157\, \bar{V}_V^2$$

$V_V^2 = 2gS$, but the average velocity is used in the above case, and is:

$$\bar{V}_V^2 = gS \qquad \therefore D_V = .00157\, gS$$

Energy = $D_V \times S_T$ where $S_T$ (total distance) = $2S$ (up and down motion)

$$\text{Energy} = .00157 \times 32.2 \times 2 \times S^2$$

$$S^2 = \frac{10.64}{64.4 \times .00157}$$

$$S^2 = 105 \text{ ft}^2, \quad S = 10.25 \text{ ft. high.}$$

Determination of Scavenging pump piston diameter (see sheet 1A AND 9)

Requirements: $R_s = 2$

Vol. of upper cylinder = 1.18 cubic inches

2 x 1.18 = 2.36 cubic inches.

= amount of pumping volume needed.

Since diameter of connecting rod is 1" (same as piston diameter--see sheet 1) and the length of the stroke is 1.5", let $D_2$ = pumping piston diameter.

Pumping Vol. = $2.36 \text{ in}^3 = \frac{\pi}{4}\left(D_2^2 - (1)^2\right)1.5$

$$\frac{4 \times 2.36}{3.14 \times 1.5} = D_2^2 - 1$$

$$D_2^2 = 2 + 1 = 3$$

$D_2 = \sqrt{3} = 1.74$ inches

The actual design uses a $D_2$ = 1.75"

Determination of Vol. difference needed during pumping stroke of the scavenging piston in order to obtain a scavenging pressure of 38 psia. (This gives the dimension of x (Fig. 3) which is needed as design criterion).

Effective scavenging area $A_E = \frac{\pi}{4}\left((1.75)^2 - 1\right)$

(annular disk - see Fig. 3)

= 1.61 sq. inches.

Vol. of Bypass (see sheet 4 )

$= \frac{1}{8} \times 4.75 \times 10 \times 2$

$= 1.2 \text{ in}^3$ (Vol. of both bypasses)

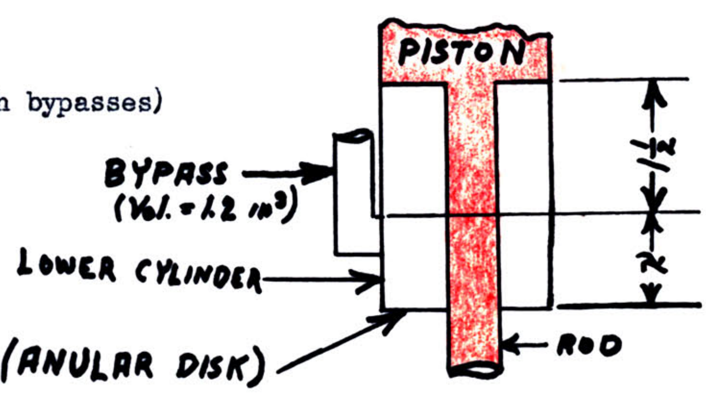


FIGURE -3

$P_1 = 14.7$ psia $\qquad V_1 = 12$

For $P_2 = 38$ psia $\qquad V_2 = 6.5$ $\qquad$ From unburned charts.

Therefore: $V_1 = 1.2 + A_E(1.5 + x) \qquad V_2 = 1.2 + A_E x \qquad$ (SEE FIGURE 3)

$$\frac{V_1}{V_2} = \frac{v_1}{v_2} \text{ or } \frac{1.2 + A_E(1.5 + x)}{1.2 + A_E x} = \frac{12}{6.5}$$

$$1.2 + A_E(1.5 + x) = 1.85(1.2 + A_E x)$$

$$1.2 + A_E 1.5 + A_E x = 2.22 + 1.85 A_E x$$

$$1.2 - 2.22 + 1.5 A_E = 1.85 A_E x - A_E x$$

$$A_E = 1.61$$

$$1.2 - 2.22 + 2.42 = x(2.98 - 1.61)$$

$$1.4/1.37 = x = 1.02 \text{ INCHES.}$$

The actual design uses x = 1.00 inch.

Summary of specifications used to give 10.7 ft-lbs of work per cycle, with $R_s = 2$, and a scavenging pressure of 38 psia.

Piston bore = 1 inch

Length of stroke = 1.5 inches

Scavenging piston bore = 1.75 inches

Distance between top of bypass port to bottom of lower cylinder = 1 inch.

(see detail drawings)

4) The Examination of Combustion in this Mechanism.

The complete charge is auto-ignited through the high compression obtained in this mechanism.* Therefore, no accessories are needed for ignition.

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* For a complete analysis of auto ignition see: M.I.T. - Ethyl Corporation, Annual Report No. 6, July 1952-July 1953; and M.I.T. - Ethyl Corporation Combustion Project Progress Report No. 17, covering the period June 15, 1953 to August 15, 1953.

As a first assumption, it was decided that a compression ratio of 11 was needed for auto-ignition of Benzene. Since all the information pertaining to the self-ignition of N-heptane fuel was available - this fuel was used instead. It was later found that for auto-ignition of N-heptane in the pogo-stick a compression ratio of 14 was necessary. (analyzed on page 30)

The preliminary approach to the auto-ignition problem was carried out with the assumption that the compression ratio of 11 was necessary, but this analysis did not include the effects of time. A later and more detailed study of the fuel properties of N-heptane showed that a compression ratio of 14 was required (included time effects).

This section will be divided into two sections:

a) Analysis of auto-ignition through an energy approach. (A compression ratio of 14 will be used, since it was later found to be necessary; even though the original energy approach used an r = 11.)

b) A complete analysis of auto-ignition of N-heptane--which determined the required compression ratio (14). This analysis included time effects on the fuel and therefore required a time-motion study of the pogo-stick during operation.

An Energy Approach Using a Compression Ratio of 14

At the initial state of the charge:

$$P_1 = 14.7 \text{ psia.} \qquad T_1 = 520\,°R$$

$$H_1 = 37 \qquad S_1 = .053 \qquad E_1 = 0 \qquad v_1 = 12$$

At a compression of 14, assuming an isentropic compression ("unburned charts", F/A = .0605)

$P_2 = 570$ $H_{S2} = 262$ $S_2 = S_1 = .053$ $E_{S2} = 169$ $U_2 = .86$ $T_2 = 1320°R$

$\Delta H = 262 - 37 = 225$

Btu/1.0605 lbs of charge

or $\frac{225}{1.0605} = 214$ Btu/lb of charge

Under the best possible scavenging conditions

.0000568 lbs. are compressed

therefore 214 x 778 x .0000568 = 9.45 ft-lbs needed are needed for compression. Under the above conditions $(e_s = 1)$ the amount of residual gases compressed is zero (f = 0).

The amount of energy required for pumping during the compression stroke is calculated and added to the above figure (7.5 ft-lbs), since the above sum of energies will be needed to reach the state required for auto-ignition. Pumping energy used during compression:

$\Delta H_p = 40.5$ Btu/lb. of CHARGE

calculated on page 10.

since $R_s = 2$

2 x .0000568 = .0001136 lbs. of charge pumped.

778 x 40.5 x .0001136 = 3.6 ft-lbs needed for pumping of charge during compression.

Total energy = 9.45 + 3.6 = 13.05 ft-lbs.

If the man and pogo-stick weight 160 lbs.

$160x = 13.05$ ft.-lbs. where x is height of jump needed to ignite the charge.

$x = \frac{13.05}{160} = .0816$ ft.

or $.0816 \times 12 = .99$ INCHES.

From this examination it appears that self-ignition will occur without excessive jumping - and that this type of ignition is "perfectly" suited for its present application.

B) A Complete Analysis of Auto-Ignition of N-Heptane Fuel in the Pogo-Stick.

For this analysis a time motion study of the compression stroke is needed, and follows:

Displacement of piston, $x$.

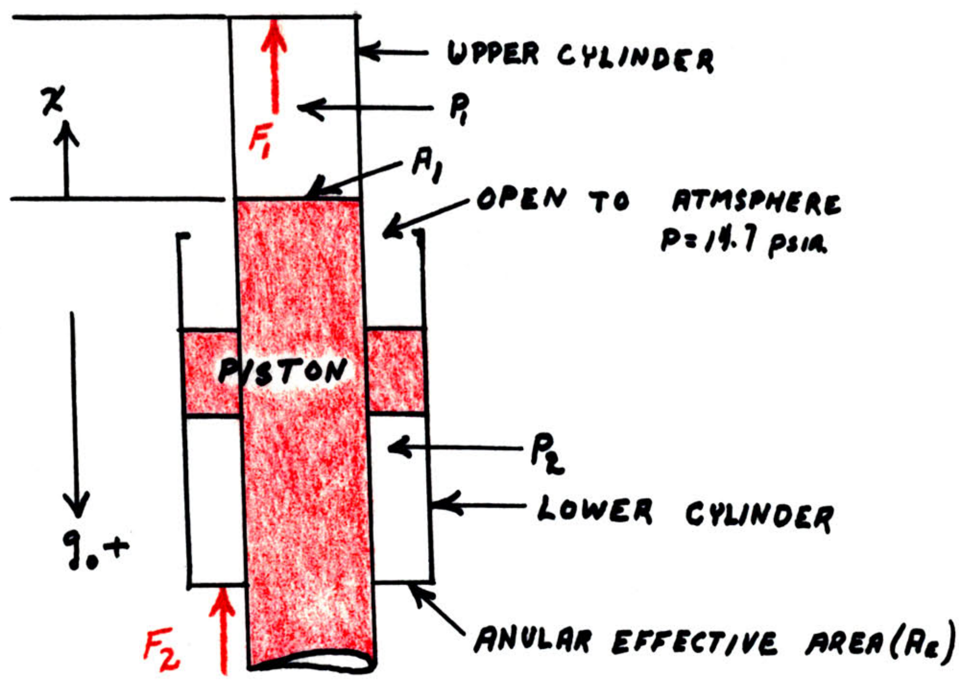



Figure 4

Mass of pogo-stick and man, $m = \frac{160}{32.2} = 5 \frac{lb - sec^2}{ft.}$

The calculation of the deceleration of pogo-stick due to the compression and pumping forces vs. piston displacement:

$$P_1 = f(x)$$

$$P_2 = f(x)$$

(1) $F_1 = (P_1 - 14.7)A$

(2) $F_2 = (14.7 - P_2)A_E$

Both forces act in the same direction and decelerate the pogo-stick (see Fig. 4).

The displacement is divided into 15-.1" increments and the average force ($F_1 + F_2$) occurring during each increment is used to calculate the average acceleration occurring during the displacement of one increment:

$$(3) \qquad a_p = g_0 - \frac{(F_1 + F_2)}{m}$$

where $g_0$ is gravitational acceleration of the earth.

AT Time = 0, when $x = 0$

$P_1 = 14.7 \quad \therefore F_1 = 0$

$P_2 = 14.7 \quad \therefore F_2 = 0$

then the piston is displaced upward .1" (see Fig. 4) $- x_1 = .1"$

From the formula $PV^N = K$ (4)

where n = 1.32 for N-heptane, the corresponding pressure $P_1$ can be calculated, by using the change in V due to the displacement of the piston.

Thus, the forces are found and it is possible to plot the acceleration vs piston displacement by using equations (1), (2), and (3).

This has been done and the corresponding calculations and data are in the appendix, page 52.

See Fig. 5 for the plot of acceleration vs piston displacement. From Fig. 5 the average acceleration for each increment is found, and from:

$$V_2^2 - V_1^2 = 2as$$

$$\text{or } V_2 = \sqrt{2as + V_1^2}$$

where a = ave. accel. of each increment

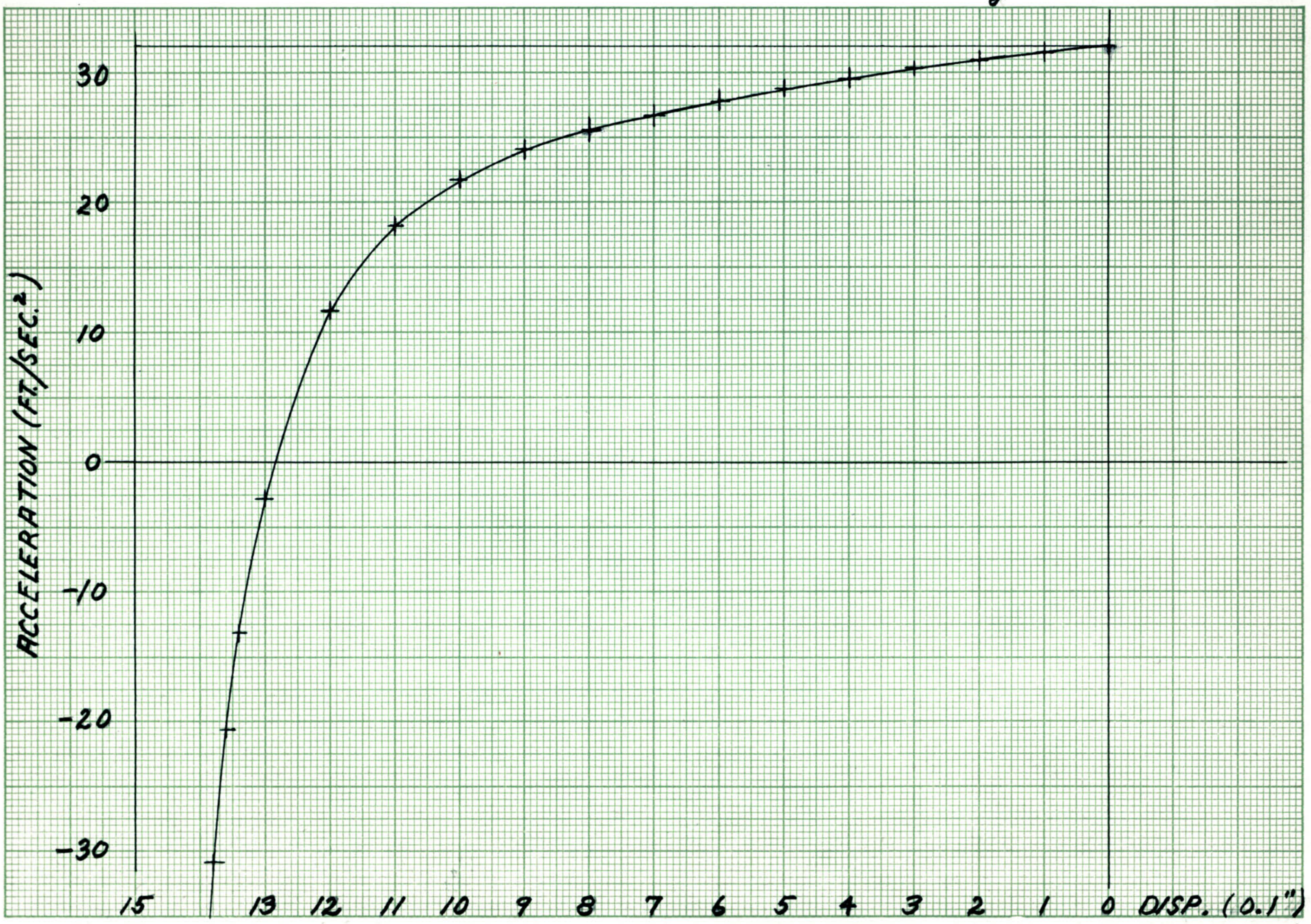
$V_2$ = vel. at the end of each "

$V_1$ = vel. of preceding increment

S = width of increment (.1")

initial velocity = 0

# ACCELERATION VS. PISTON DISPLACMENT during COMPRESSION



The velocity vs. piston displacement curve is obtained. See Fig. 6. The calculations are in the appendix on page 54.

From Fig. 6 the average velocity over each increment is found, and from:

$$\bar{V}t = S$$

$$t = \frac{S}{\bar{V}}$$

where t = time - secs.

$\bar{V}$ = average velocity over each increment.

S = width of each increment.

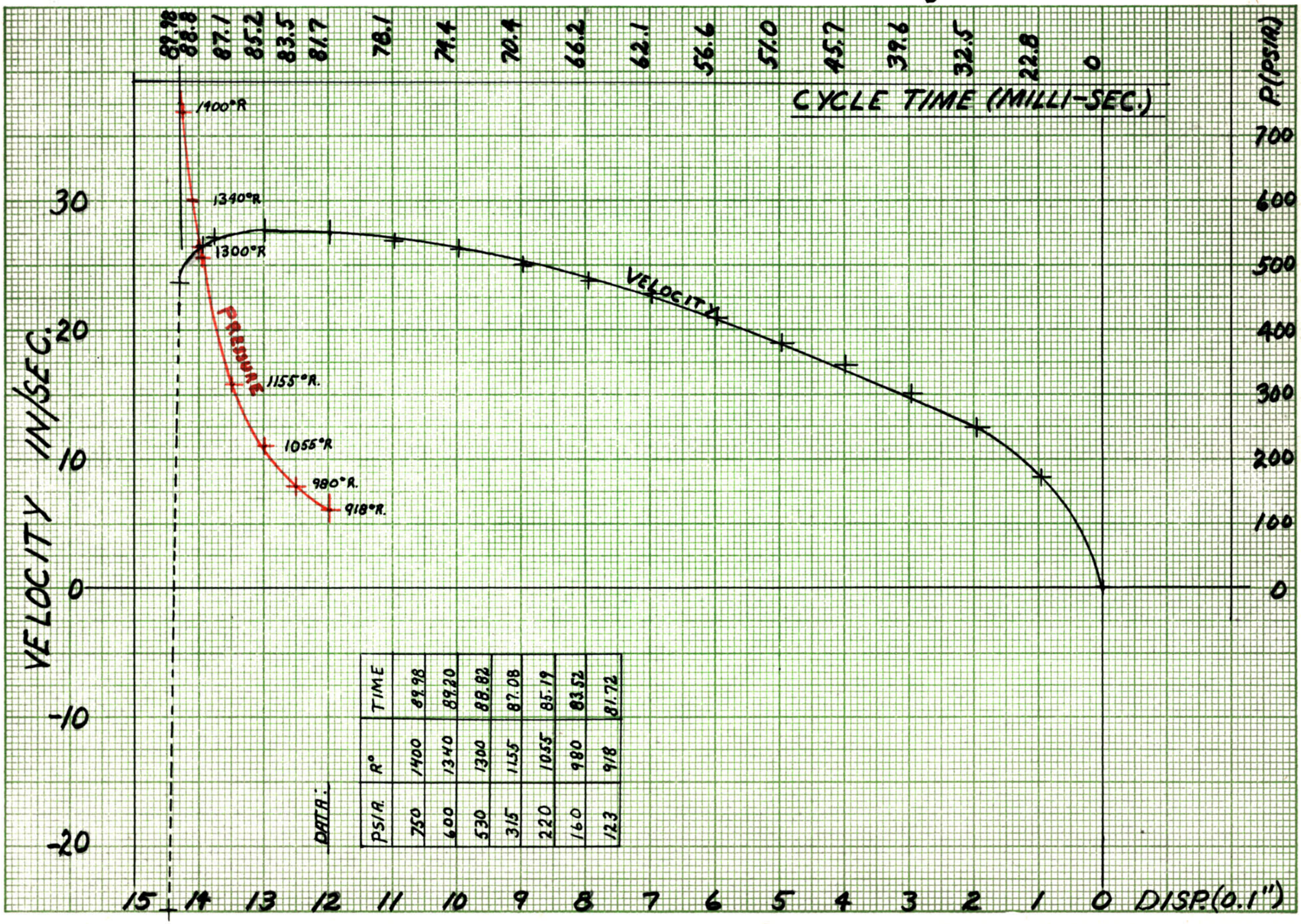
The time required for the piston to travel over each increment is found. Thus, the time required for the piston to travel to any displacement $x$, is the sum of the "times" of each increment through which the piston has travelled while getting to position $x$. These times are recorded on Fig. 6 (at the top of the graph) and correspond to the time required by the piston to reach the place where the time is recorded. (Time is in milli-seconds.)

A plot of pressure vs idsplacement is also recorded on the same graph, with their corresponding temperatures.

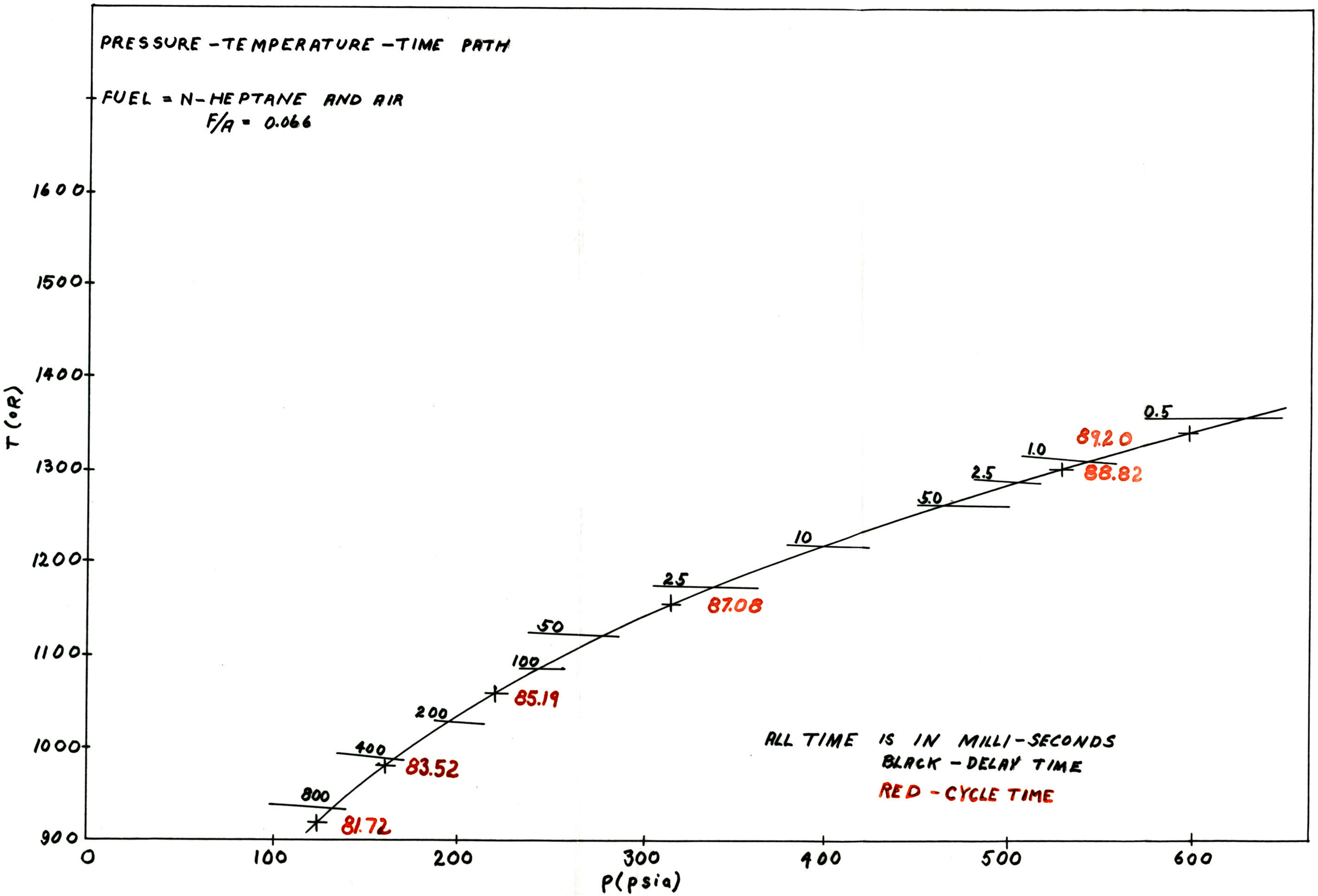
An auto-ignition-delay map for N-heptane and air, F/A = .066 is supplied in this report, Fig. 8. This "map" shows the time required for auto-ignition of the fuel-air mixture at different states of pressure and temperature. This above mentioned time is referred to as delay time.

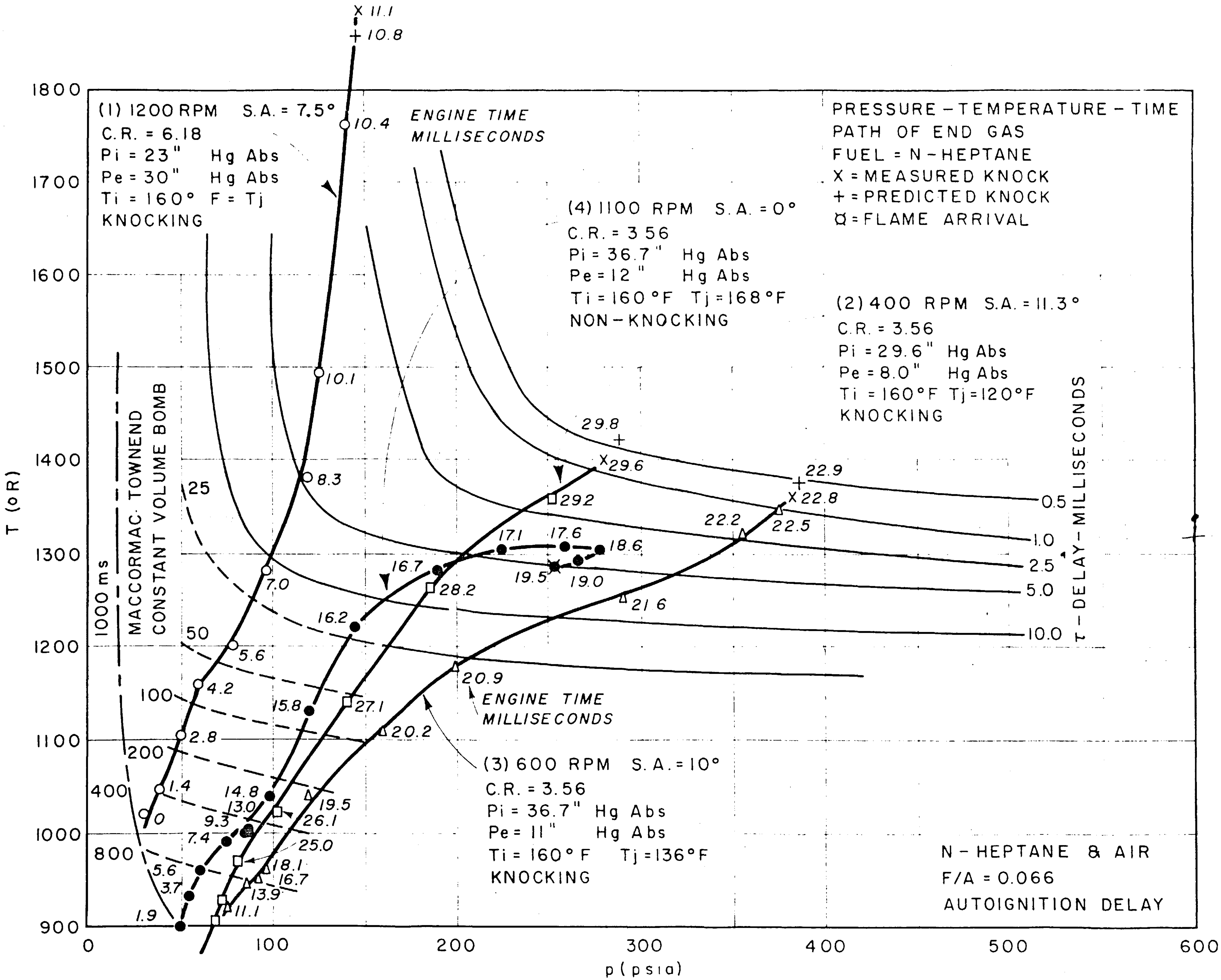
On an overlay of this map, Fig. 7, a plot is drawn of the temperature vs. pressure of the mixture which occurs in the pogo-stick. On this same plot the cycle times corresponding to the particular states are also shown. (Reference to Fig. 7 and Fig. 8, will elucidate the above description.) A corresponding delay time $\tau$, from Fig. 8 can be correlated with each cycle time $t$, recorded on Fig. 7. See chart on Fig. 9.

# VELOCITY VS. PISTON DISPLACMENT during COMPRESSION



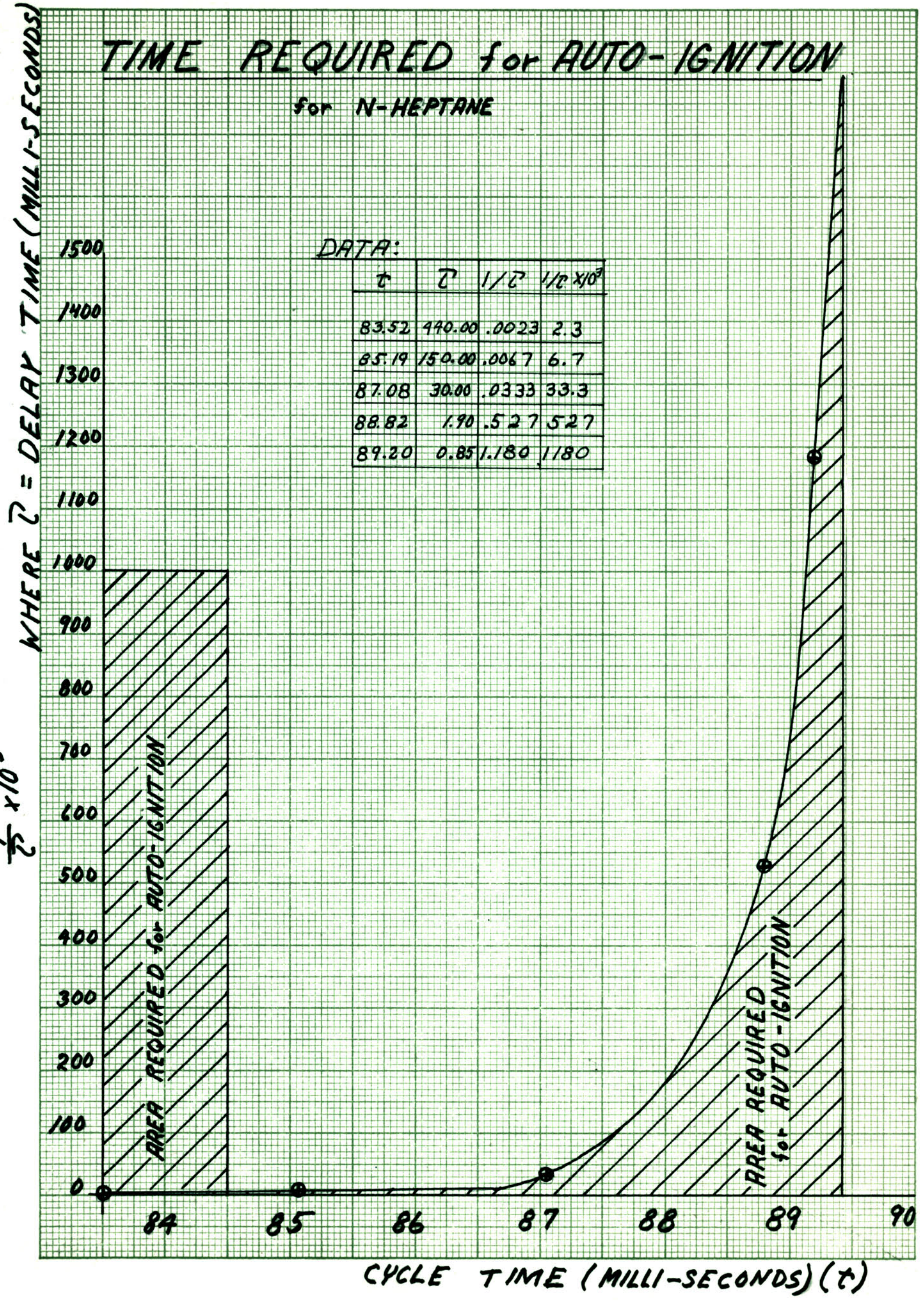

| TIME | R° | PSIA. |
|---|---|---|
| 89.98 | 1400 | 750 |
| 89.20 | 1340 | 600 |
| 88.82 | 1300 | 530 |
| 87.08 | 1155 | 315 |
| 85.19 | 1055 | 220 |
| 83.52 | 980 | 160 |
| 81.72 | 918 | 123 |


PRESSURE - TEMPERATURE - TIME PATH
FUEL = N-HEPTANE AND AIR
F/A = 0.066
T (°R)
P (psia)
1600
1500
1400
1300
1200
1100
1000
900
0
100
200
300
400
500
600
800
400
200
100
50
25
10
5.0
2.5
1.0
0.5
81.72
83.52
85.19
87.08
88.82
89.20
ALL TIME IS IN MILLI-SECONDS
BLACK - DELAY TIME
RED - CYCLE TIME



(1) 1200 RPM S.A. = 7.5°
C.R. = 6.18
Pi = 23" Hg Abs
Pe = 30" Hg Abs
Ti = 160° F = Tj
KNOCKING
ENGINE TIME MILLISECONDS
PRESSURE – TEMPERATURE – TIME
PATH OF END GAS
FUEL = N-HEPTANE
X = MEASURED KNOCK
+ = PREDICTED KNOCK
Ø = FLAME ARRIVAL
(4) 1100 RPM S.A. = 0°
C.R. = 3.56
Pi = 36.7" Hg Abs
Pe = 12" Hg Abs
Ti = 160°F Tj = 168°F
NON-KNOCKING
(2) 400 RPM S.A. = 11.3°
C.R. = 3.56
Pi = 29.6" Hg Abs
Pe = 8.0" Hg Abs
Ti = 160°F Tj = 120°F
KNOCKING
MACCORMAC · TOWNEND
CONSTANT VOLUME BOMB
1000 ms
τ – DELAY – MILLISECONDS
(3) 600 RPM S.A. = 10°
C.R. = 3.56
Pi = 36.7" Hg Abs
Pe = 11" Hg Abs
Ti = 160° F Tj = 136°F
KNOCKING
N-HEPTANE & AIR
F/A = 0.066
AUTOIGNITION DELAY
T (oR)
p (psia)


Figure 1.




| t | τ | 1/τ | 1/τ ×10³ |
|---|---|---|---|
| 83.52 | 440.00 | .0023 | 2.3 |
| 85.19 | 150.00 | .0067 | 6.7 |
| 87.08 | 30.00 | .0333 | 33.3 |
| 88.82 | 1.90 | .527 | 527 |
| 89.20 | 0.85 | 1.180 | 1180 |

With this information the cycle time at which auto-ignition occurs in the pogo-stick can be found.

Procedure:

a) First $1/\tau$ is plotted vs. t(Fig. 9).

b) Then, a unit area is defined as follows $t \times \frac{1}{\tau} = 1$ , this is seen by the shaded "square" area in Fig. 9.

c) A vertical line is drawn from the plot of $1/\tau$ vs t to the abscissa, so that the area encompassed by the plot, abscissa, and vertical line will equal the defined unit area. The above is recorded in Fig. 9.

The intersection of the vertical line with the abscissa gives the corresponding cycle time at which auto-ignition will occur*—89.45 milliseconds.

From Fig. 6 it is seen that when the cycle time is 89.45, the piston displacement is $\frac{14.2}{15}$ of the total stroke, or

$$\frac{14.2}{15} \times 1.5 = \underline{1.42 \text{ inches}}$$

as compared with .99 inches obtained from the energy analysis. Thus, the compression ratio required for auto-ignition is 14.2 All frictional effects are assumed to be small, and are, therefore, neglected in the time-motion study needed in the previous analysis.

---

* The complete theoretical analysis of this procedure is given in: M.I.T. - Ethyl Corporation, Annual Report No. 6, July 1952-July 1953; and M.I.T. - Ethyl Corporation Combustion Project Progress Report No. 17, covering the period June 15, 1953 to August 15, 1953.

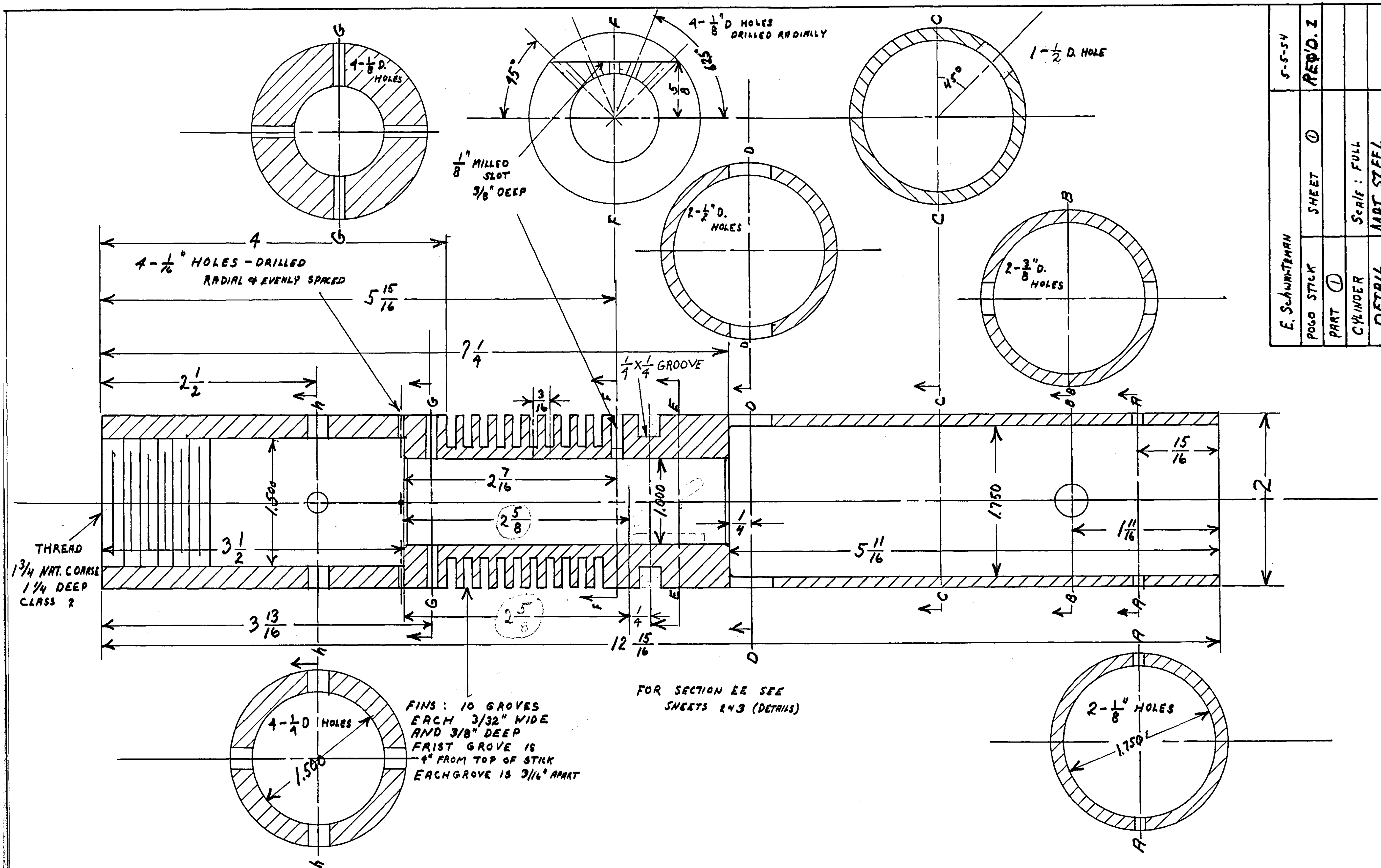
## II. Design

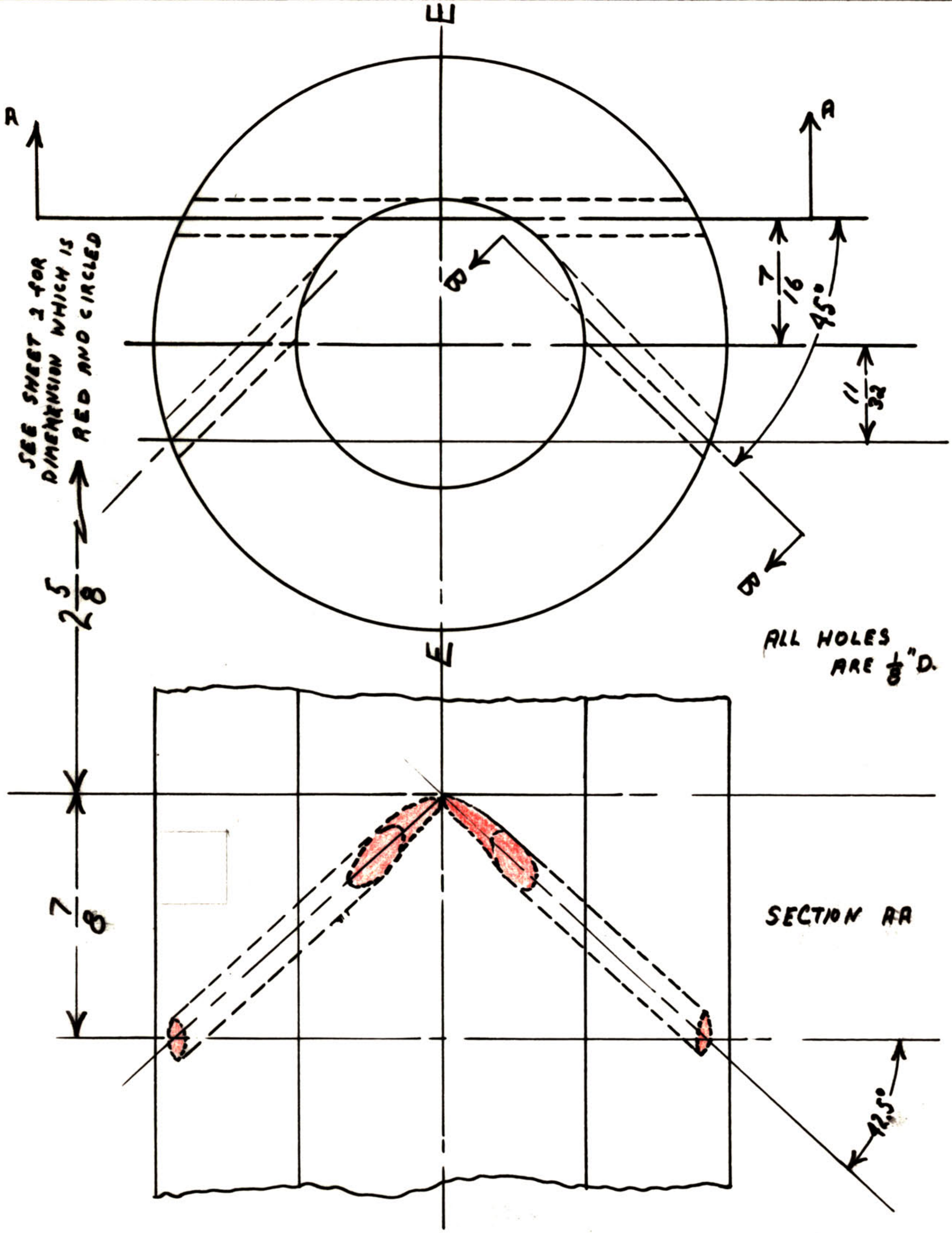
This section includes:

1) The complete and detailed drawings for the construction of this device.

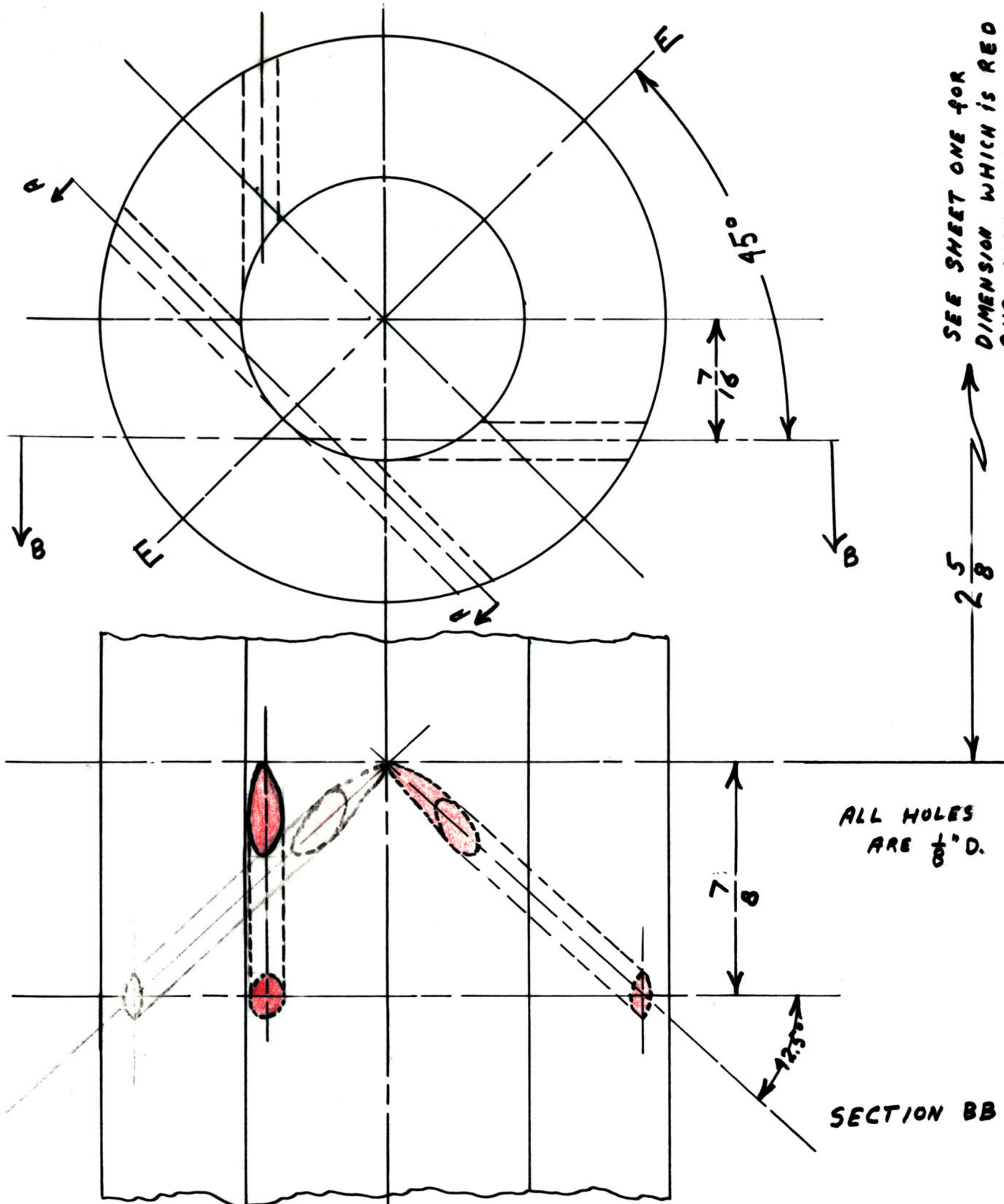
2) The description of auxillary and safety devices used in this mechanism.

3) List of standard or supplement parts used in the pogo-stick.

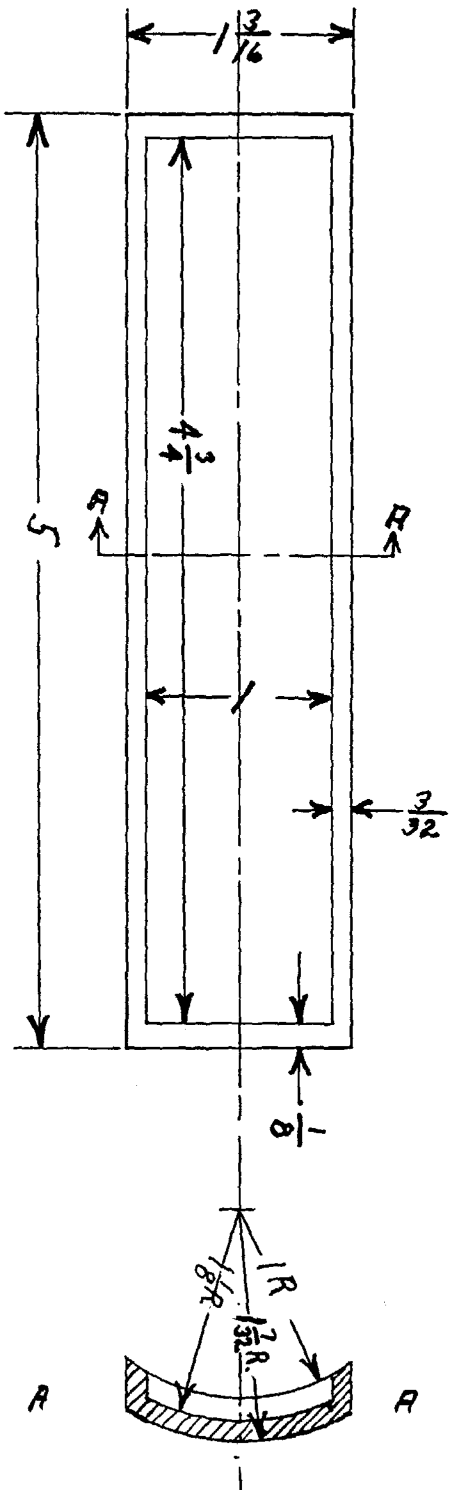

5-5-54
REQ'D. 1
E. Schwartzman
POGO STICK
SHEET ①
PART ①
CYLINDER
Scale : FULL
DETAIL
MAT. STEEL
4-1/8 D. HOLES
4-1/8" D HOLES DRILLED RADIALLY
45°
125°
5/8
1/8" MILLED SLOT 3/8" DEEP
1-1/2 D. HOLE
45°
2-1/2" D. HOLES
2-3/8" D. HOLES
4
4-1/16" HOLES - DRILLED RADIAL & EVENLY SPACED
5 15/16
7 1/4
2 1/2
1/4 X 1/4 GROOVE
3/16
2 7/16
2 5/8
1.500
1.000
1.750
1/4
5 11/16
15/16
1 11/16
2
THREAD 1 3/4 NAT. COARSE 1 1/4 DEEP CLASS 2
3 1/2
3 13/16
2 5/8
1/4
12 15/16
4-1/4 D HOLES
1.500
FINS : 10 GROVES EACH 3/32" WIDE AND 3/8" DEEP FRIST GROVE IS 4" FROM TOP OF STICK EACHGROVE IS 3/16" APART
FOR SECTION EE SEE SHEETS 2 & 3 (DETAILS)
2-1/8" HOLES
1.750



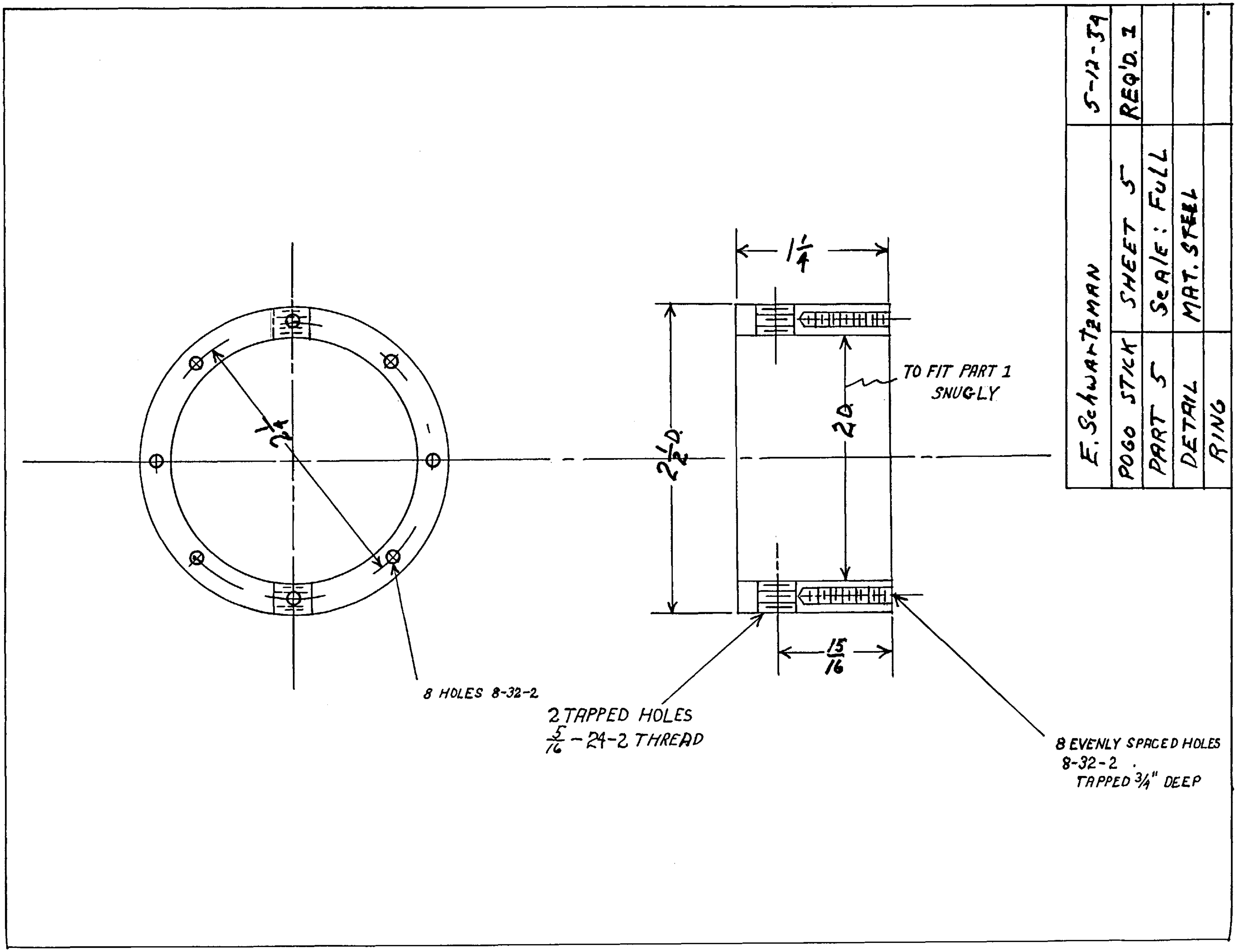

| | | |
|---|---|---|
| E. Schwartzman | | 5-4-54 |
| POGO STICK | SHEET 2 | |
| PART ① | 2"-1" (Scale : 2x) | |
| DETAIL | | |
| | | |



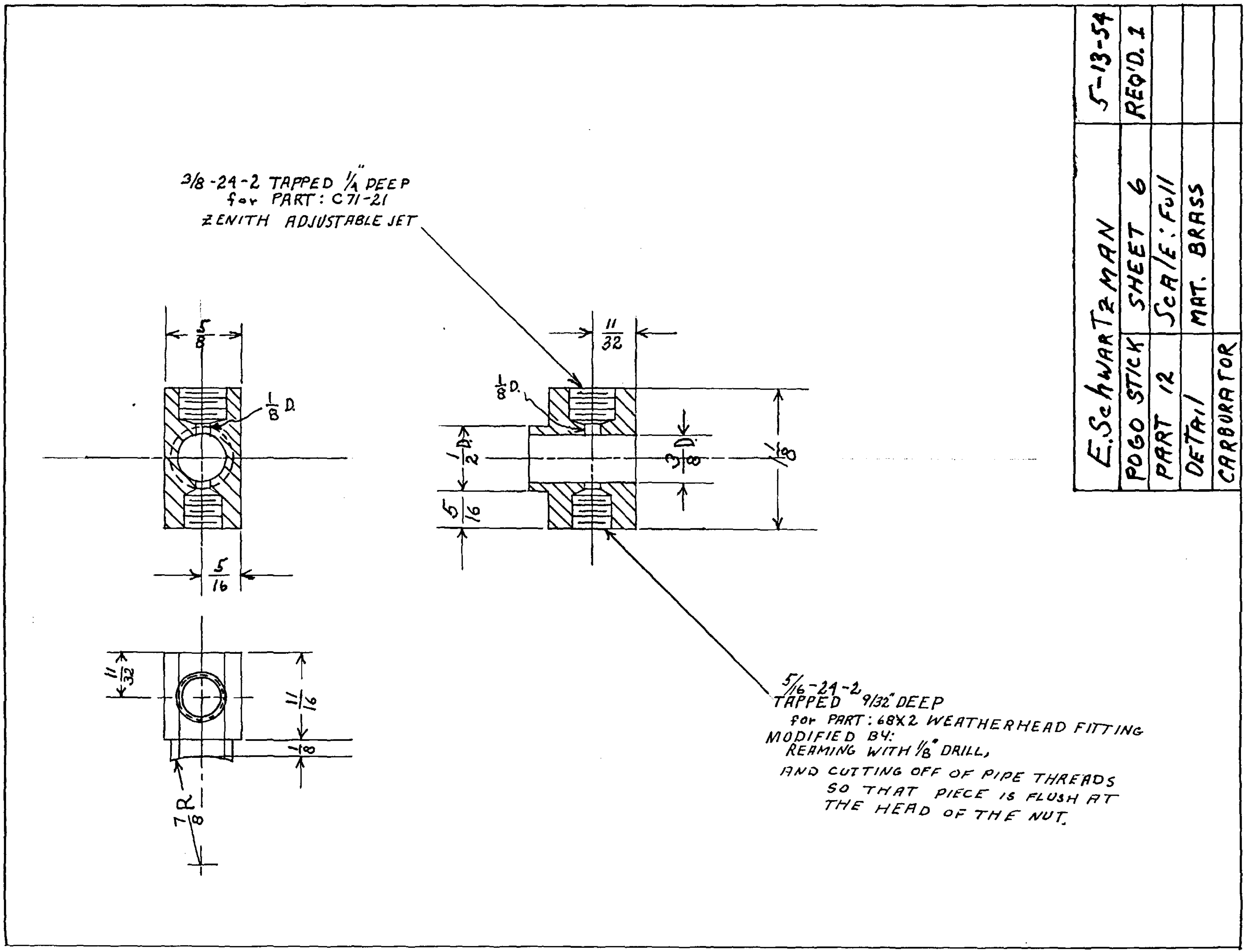

| | | |
|---|---|---|
| E. Schwartzman | | 5-4-54 |
| POGO STICK | SHEET 3 | |
| PART 1 | 2" = 1" (SCALE: 2X) | |
| DETAIL | | |
| | | |

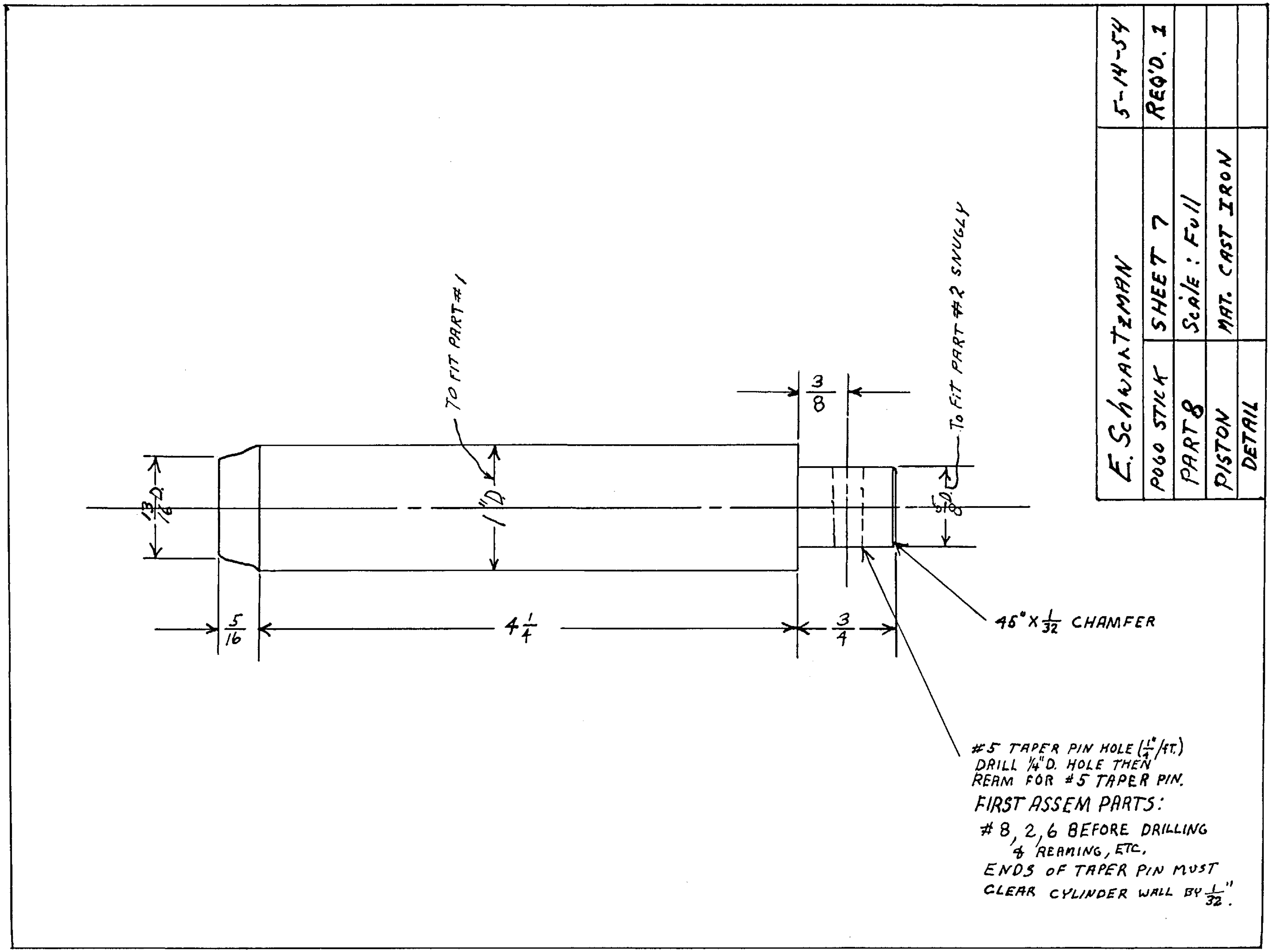



| | | |
|---|---|---|
| E. Schwartzman | | 5-12-54 |
| POGO STICK | SHEET 4 | REQ'D. 2 |
| PART 11 | Scale : Full | |
| DETAIL | BYPASS | |
| | MAT. BRASS | |

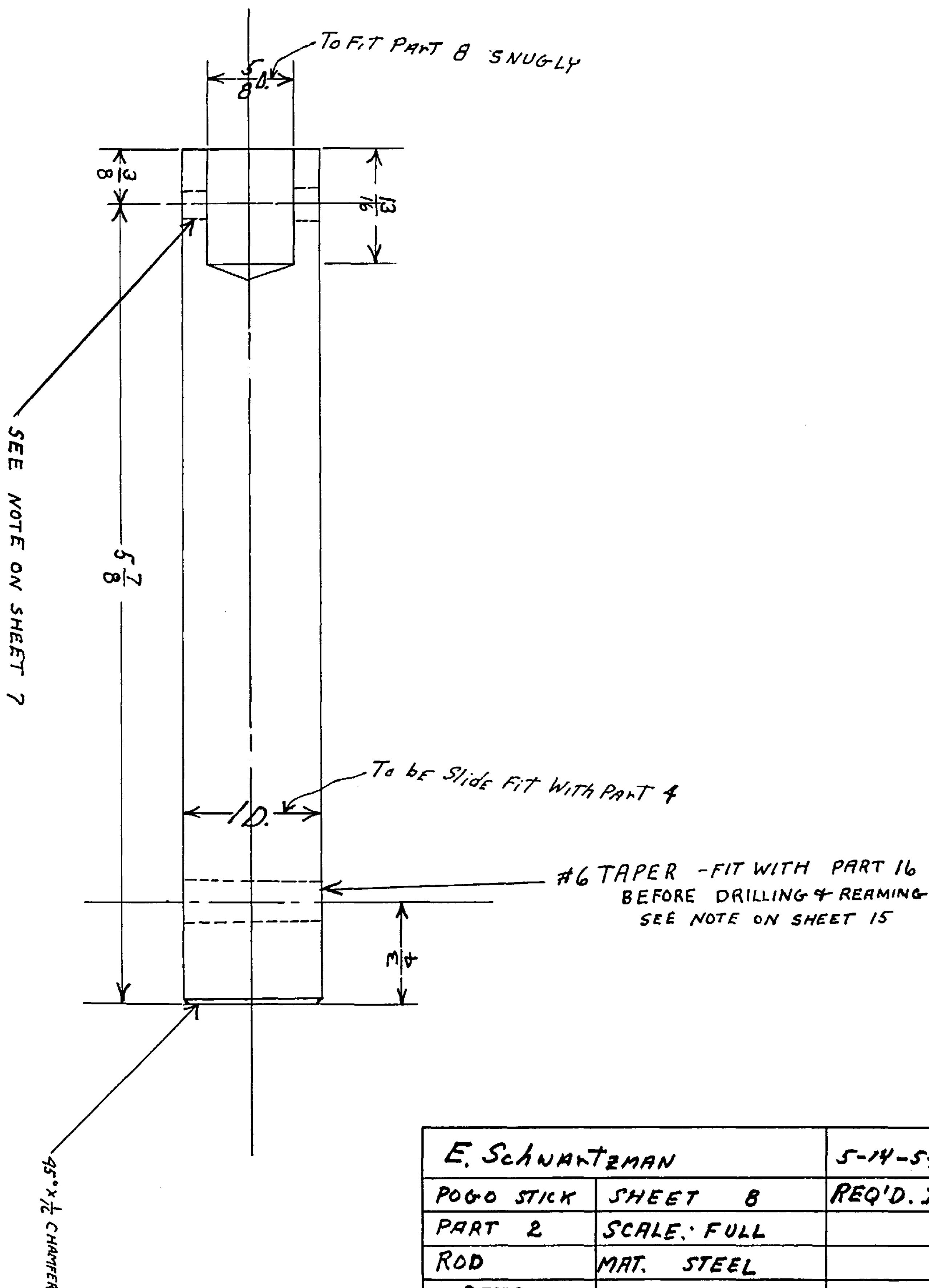


2 1/4
2 1/2 D.
1 1/4
2 D.
TO FIT PART 1 SNUGLY
15/16
8 HOLES 8-32-2
2 TAPPED HOLES 5/16 - 24-2 THREAD
8 EVENLY SPACED HOLES 8-32-2 TAPPED 3/4" DEEP
E. Schwartzman
5-12-59
POGO STICK SHEET 5
REQ'D. 1
PART 5
Scale: FULL
DETAIL
MAT. STEEL
RING

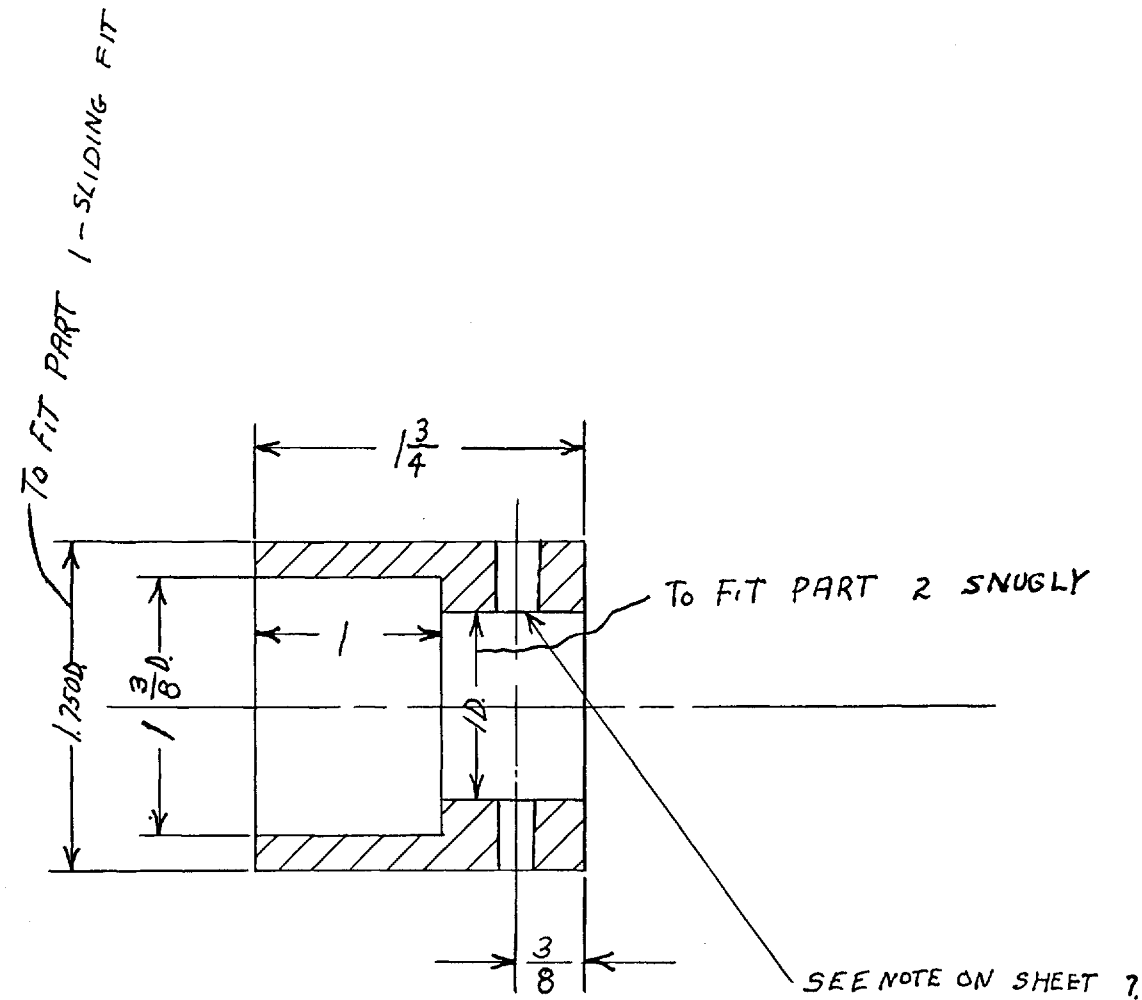

3/8-24-2 TAPPED 1/4" DEEP
for PART: C71-21
ZENITH ADJUSTABLE JET
5/16-24-2
TAPPED 9/32" DEEP
for PART: 68X2 WEATHERHEAD FITTING
MODIFIED BY:
REAMING WITH 1/8" DRILL,
AND CUTTING OFF OF PIPE THREADS
SO THAT PIECE IS FLUSH AT
THE HEAD OF THE NUT.
5/8
1/8 D.
5/16
11/32
1/2 D.
3/8 D.
1 1/8
11/16
7/8 R
E.SchwarTzMAN
5-13-54
POGO STICK SHEET 6
REQ'D. 1
PART 12
ScAlE: Full
DETAIl
MAT. BRASS
CARBURATOR



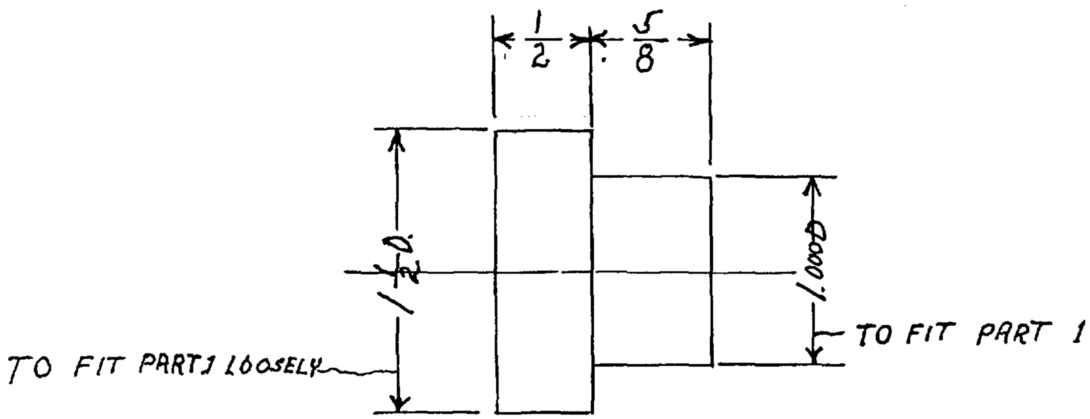
E. Schwartzman
5-14-54
POGO STICK
SHEET 7
REQ'D. 1
PART 8
Scale: Full
PISTON
MAT. CAST IRON
DETAIL
TO FIT PART #1
TO FIT PART #2 SNUGLY
13/16 D.
1" D.
5/8 D.
3/8
5/16
4 1/4
3/4
45° X 1/32 CHAMFER
#5 TAPER PIN HOLE (1"/4 FT.)
DRILL 1/4" D. HOLE THEN
REAM FOR #5 TAPER PIN.
FIRST ASSEM PARTS:
#8, 2, 6 BEFORE DRILLING
& REAMING, ETC.
ENDS OF TAPER PIN MUST
CLEAR CYLINDER WALL BY 1/32".



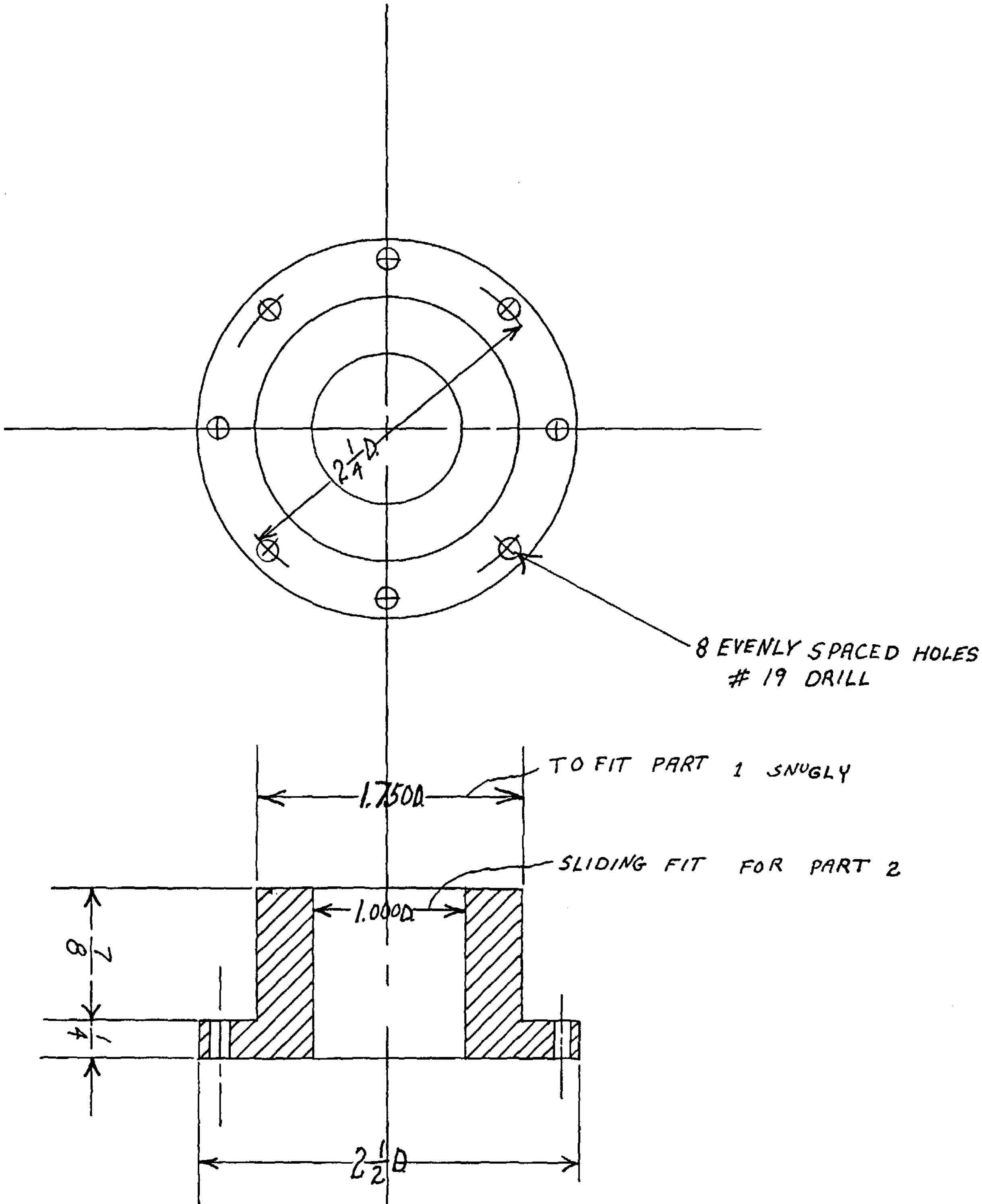

| | | |
|---|---|---|
| E. Schwartzman | | 5-14-54 |
| POGO STICK | SHEET 8 | REQ'D. 1 |
| PART 2 | SCALE: FULL | |
| ROD | MAT. STEEL | |
| DETAIL | | |



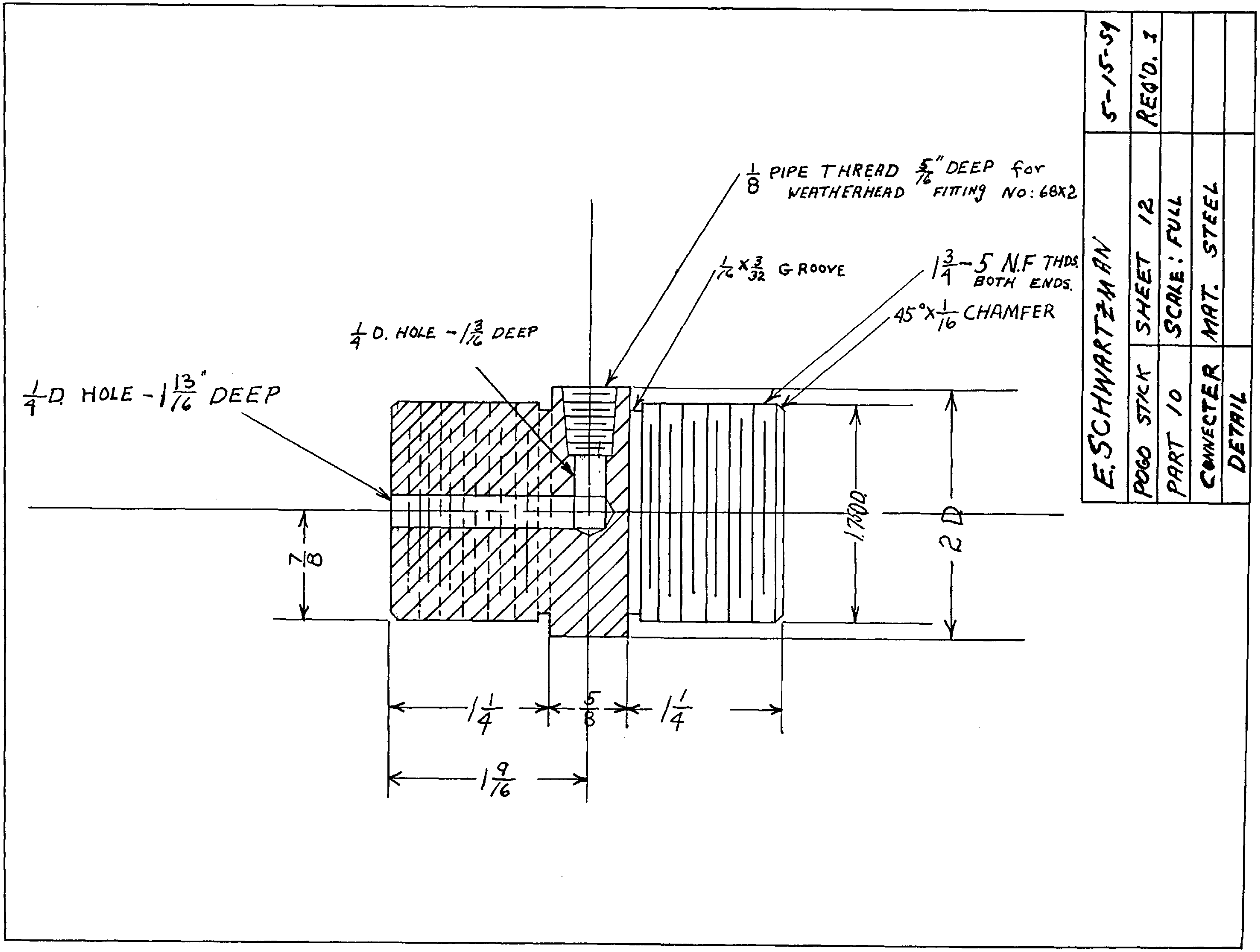

E. SCHWARTZMAN | 5-14-54
P.Go STICK | SHEET 9 | REQ'D. 1
PART 6 | Scale : Full
PUMP-PISTON | MAT. CAST IRON
DETAIL



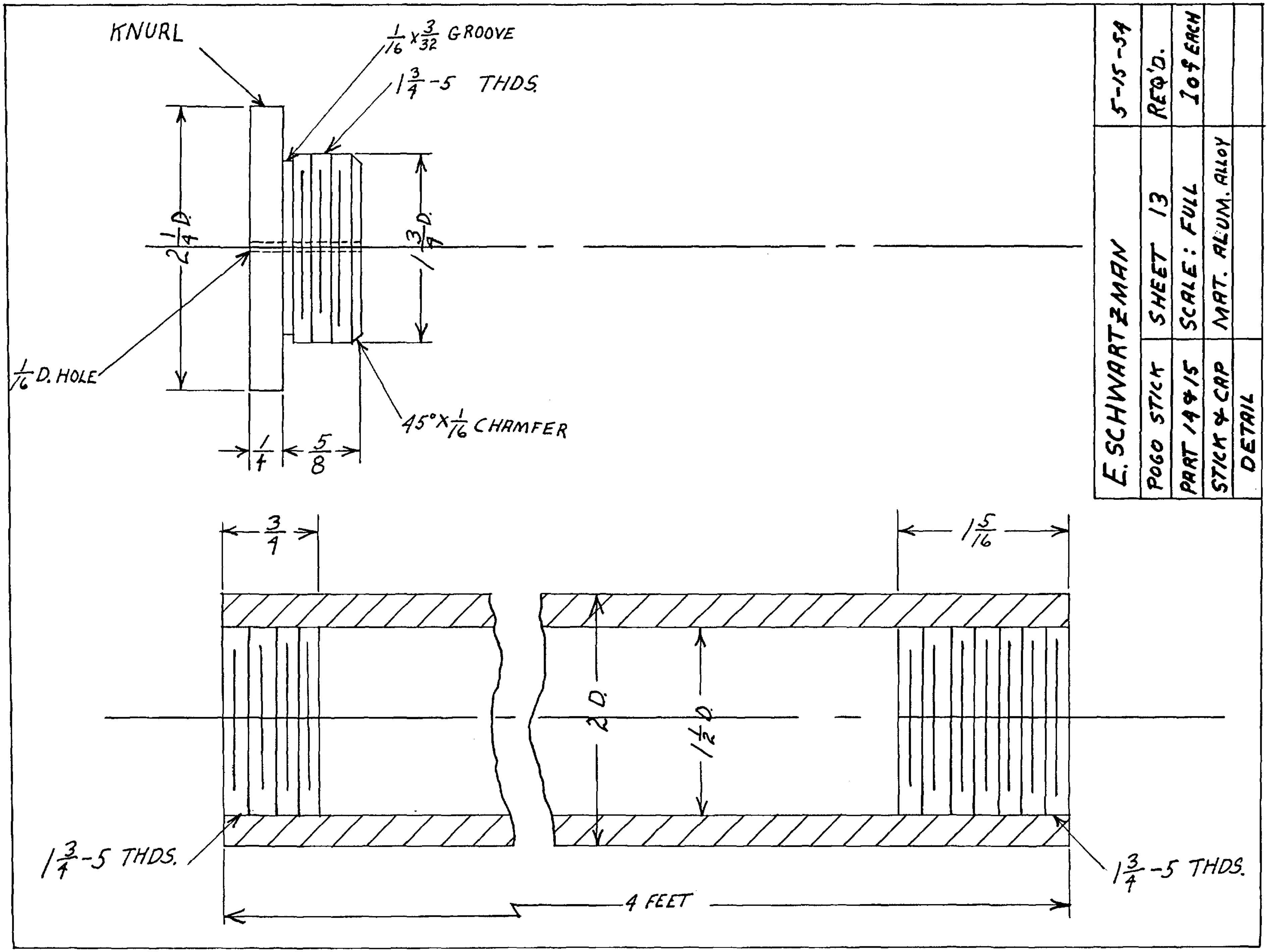

| | |
|---|---|
| E. SCHWARTZMAN | 5-14-59 |
| POGO STICK SHEET 10 | REQ'D. 1 |
| PART 9 | SCALE: FULL |
| UPPER PISTON DETAIL | MAT. CAST IRON |



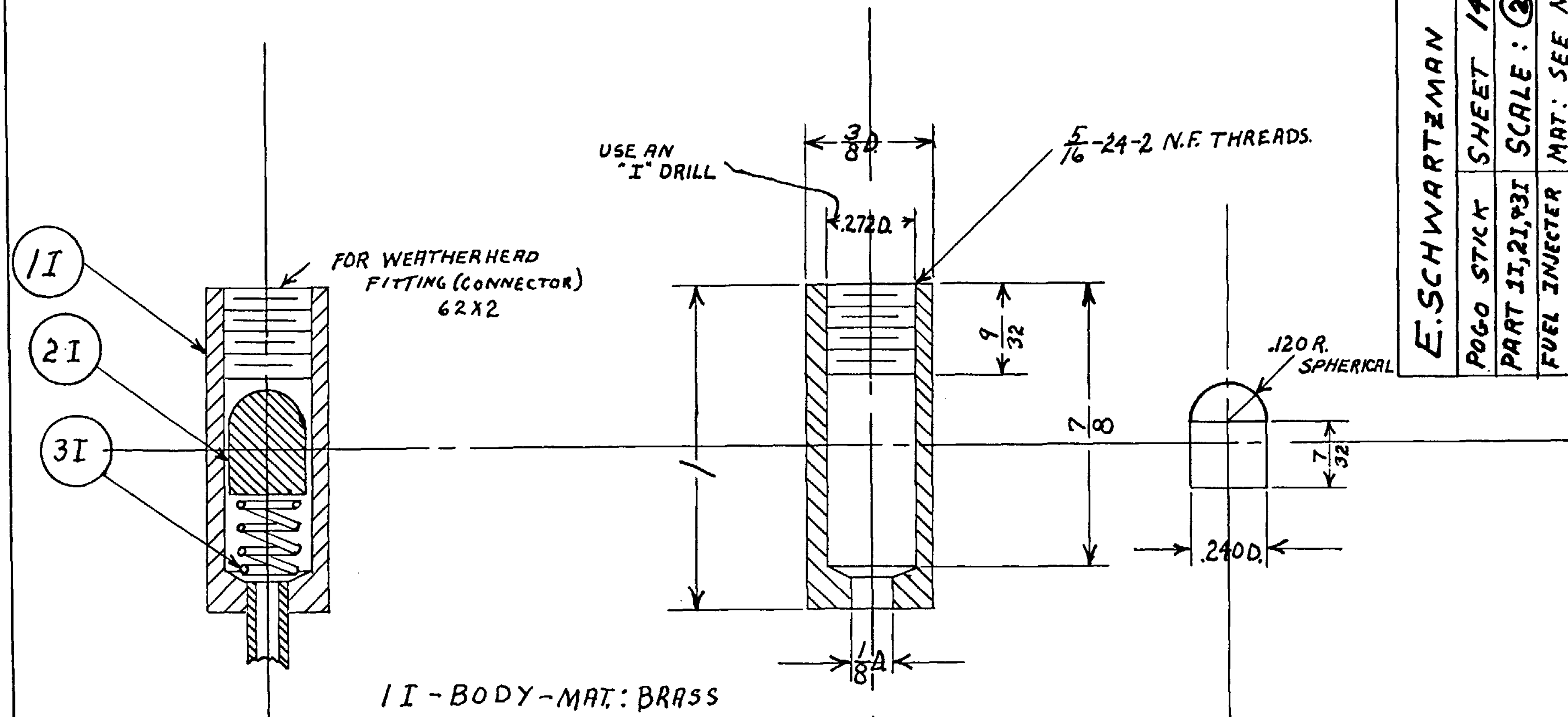

| | | |
|---|---|---|
| E. Schwartzman | | 5-15-54 |
| POGO STICK | SHEET 11 | REQ'D. 1 |
| PART 4 | SCALE: FULL | |
| BEARING | "OIL LIGHT" BEARING MATERIAL | |
| DETAIL | or Phos. Bronze | |



1/8 PIPE THREAD 5/16" DEEP for WEATHERHEAD FITTING NO: 68X2
1/16 X 3/32 GROOVE
1 3/4 - 5 N.F THDS. BOTH ENDS.
45° X 1/16 CHAMFER
1/4 D. HOLE - 1 3/16 DEEP
1/4 D. HOLE - 1 13/16" DEEP
7/8
1.780D.
2 D
1 1/4
5/8
1 1/4
1 9/16
E. SCHWARTZMAN
5-15-51
POGO STICK
SHEET 12
REQ'D. 1
PART 10
SCALE: FULL
CONNECTER
MAT. STEEL
DETAIL


KNURL
1/16 x 3/32 GROOVE
1 3/4 -5 THDS.
2 1/4 D.
1 3/4 D.
1/16 D. HOLE
45° x 1/16 CHAMFER
1/4
5/8
3/4
1 5/16
2 D.
1 1/2 D.
1 3/4 -5 THDS.
1 3/4 -5 THDS.
4 FEET
E. SCHWARTZMAN
5-15-54
POGO STICK
SHEET 13
REQ'D.
PART 14 & 15
SCALE : FULL
1 of EACH
STICK & CAP
MAT. ALUM. ALLOY
DETAIL

TO BE PLACED ON FUEL LINE
NEAR THE CARBORATOR



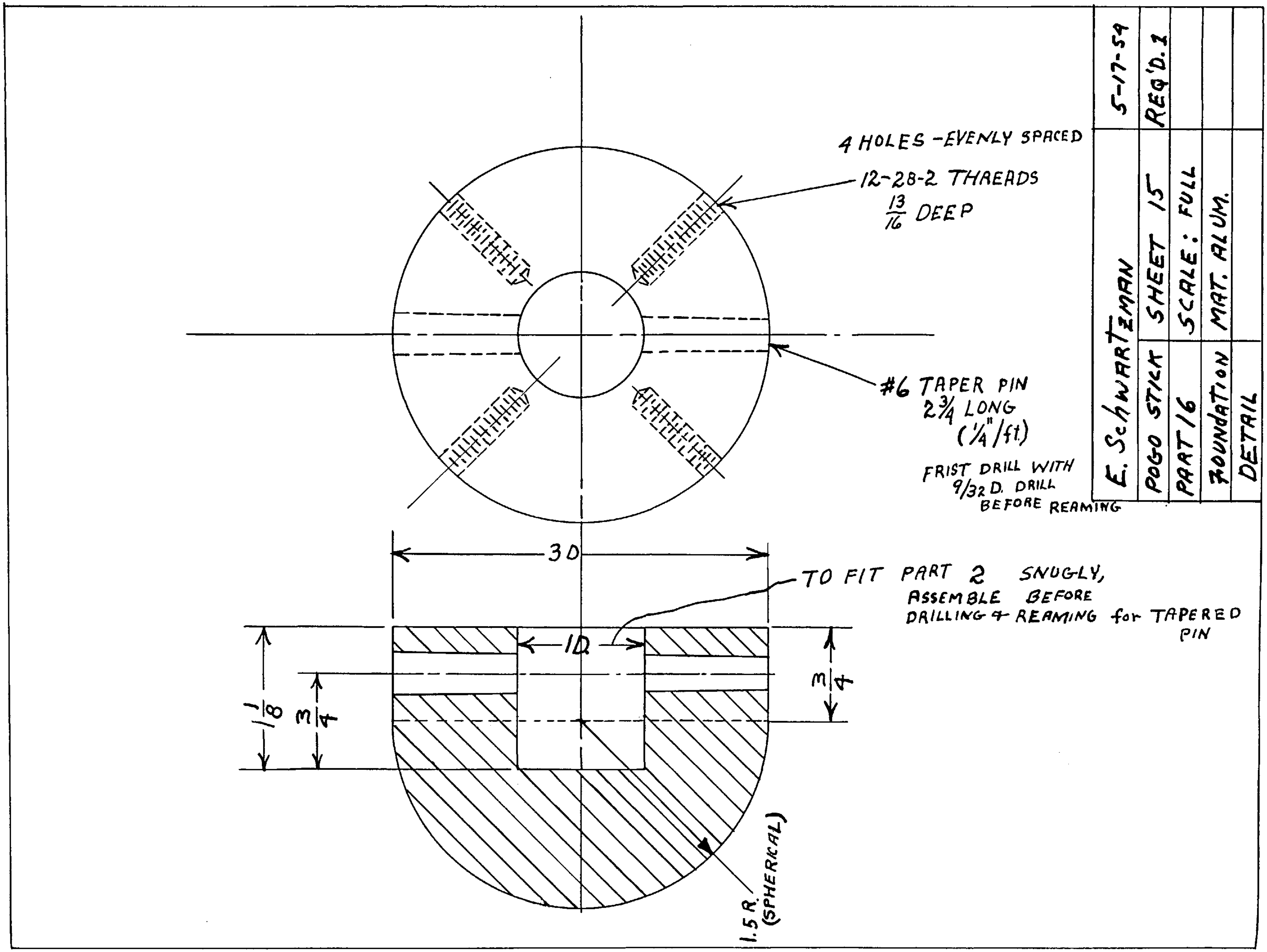

1I - BODY - MAT.: BRASS

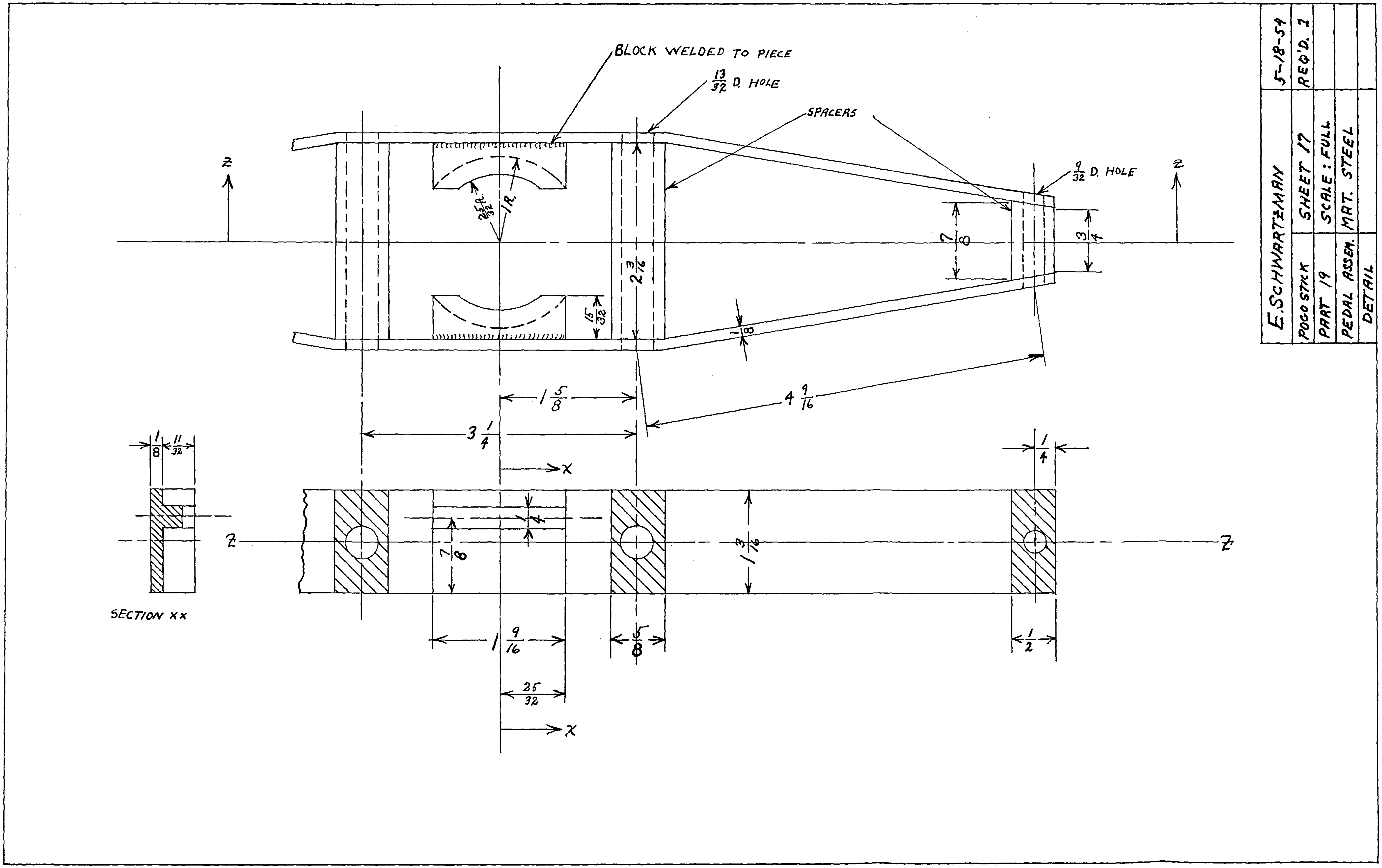
2I - VALVE - MAT. : BRASS

3I - SPRING - MAT. : STEEL

SCALE : 2

| | | |
|---|---|---|
| E. SCHWARTZMAN | | 5-17-51 |
| POGO STICK | SHEET 14 | REQ'D. |
| PART 1I, 2I, & 3I | SCALE : (2) | 1 of EACH |
| FUEL INJECTER | MAT.: SEE NOTE | |
| LAYOUT & DETAIL | | |


4 HOLES - EVENLY SPACED
12-28-2 THREADS
13/16 DEEP
#6 TAPER PIN
2 3/4 LONG
(1/4"/ft.)
FRIST DRILL WITH
9/32 D. DRILL
BEFORE REAMING
3 D
TO FIT PART 2 SNUGLY,
ASSEMBLE BEFORE
DRILLING & REAMING for TAPERED
PIN
1 D
3/4
1 1/8
3/4
1.5 R.
(SPHERICAL)
5-17-54
REQ'D. 1
E. Schwartzman
POGO STICK SHEET 15
PART 16 SCALE: FULL
FOUNDATION MAT. ALUM.
DETAIL


BLOCK WELDED TO PIECE
13/32 D. HOLE
SPACERS
9/32 D. HOLE
SECTION XX
E. SCHWARTZMAN
5-18-59
POGO STICK
SHEET 17
REQ'D. 1
PART 19
SCALE: FULL
PEDAL ASSEM.
MAT. STEEL
DETAIL

2) The description of auxillary and safety devices used in this mechanism.

A) The upper piston (Part 9):

In reference to sheet 1A the position of the upper piston is seen. A heavy spring (Part 18) keeps a back pressure on this piston (Part 9) during the operation of this mechanism.

By changing the compression in this spring (accomplished by placing spacers between Part 10 and the spring (Part 18), the amount of energy utilization during the operation of this mechanism can be controlled.

During combustion in the upper cylinder high gas pressures are reached (order of 2000 psia). This pressure exerts a force on the upper piston, which in turn displaces it upward and compresses the spring (Part 18).

If the upper piston is displaced high enough, exhaust ports will be uncovered (see Part 2 for details), thus allowing some of the high pressure gases to expand into the atmosphere and thereby accomplishing less useful work in respect to driving the mechanism as compared with the case when the upper exhaust ports are not uncovered during the operation of the mechanism.

In this manner the device can be adjusted to suit people of different weights.

B) Bleed values (Part 13):

In reference to sheet 1A the position of these values (Parts 13) is seen.

During operation of the pogo-stick a high downward velocity of the piston occurs while combustion is taking place in the upper piston.

Upon completion of the power stroke, the piston motion has to be stopped. This is accomplished by compressing gas in the lower part of the power cylinder. In order to keep the piston in the downward or cocked position after the power stroke, it becomes necessary to bleed some of this gas into the atmosphere--to prevent the upward "bouncing" of the piston caused by the compressed air in the lower part of the lower cylinder. This is accomplished and controlled by the needle values (Part 13).

C) Spring (Part 17):

In reference to sheet 1A, the position of this spring (Part 17) is seen.

This spring keeps the piston in the cocked position so that the compression and power stroke will occur at the desired time--when the operator and pogo-stick hit the ground.

Because of the position of the spring in the mechanism it enables the implement to be operated as a normal pogo-stick when the fuel supply is cut-off.

3) List of standard or supplement parts used in the pogo-stick.

| Part No. | No. Required | Description and Part No. |
|---|---|---|
| 13 | 2 | Stromberg Adj. Jet P12802 |
| | 1 | For carburetor - |
| | | Zenith Adj. Jet C71-21 |
| | 2 | Compression male connector |
| | | Weatherhead 68-2 |
| | 1 | For injector - compression union |
| | | Weatherhead 62-2 |
| 7 | 1 | Taper pin #5 1 3/4" long |
| | 1 | Taper pin #6 2 3/4" long |
| 17 | 1 | Spring-size will be determined by |
| | | Experiment upon Completion of Pogo-stick |
| 18 | 1 | Spring-size will be determined by |
| | | Experiment upon Completion of Pogo-stick |

## III. Appendix

1) Data and calculations used for the Motion-time graphs.

2) An analysis of the stresses encountered in the cylinder during combustion--which leads to its design dimensions.

# CALCULATIONS for $F_1$

$A_1 = .783$ "$^2$

$PV^N = K$ where $N = 1.32$ for N-HEPTANE (STOICHIOMETRIC)

when $P = 14.7$, $V = 1$, $K = 14.7$

$V_1 = 1 - \frac{1}{15} = 1 - .0667 = .9333$

$V_2 = 1 - 2/15 = 1 - .1334 = .8666$, etc.

| INCREMENTS | V | $V^N$ | $P = K/V^N$ PSI | $F_1 = (P_1 - 14.7)A_1$ lbs | T° R |
|---|---|---|---|---|---|
| 0 | 1 | 1 | 14.7 | 0 | 520 |
| 1 | .9333 | .885 | 16.6 | 1.49 | 560 |
| 2 | .8666 | .823 | 17.9 | 2.51 | 565 |
| 3 | .8000 | .741 | 19.8 | 4.00 | 570 |
| 4 | .733 | .643 | 22.9 | 6.45 | 580 |
| 5 | .666 | .58 | 25.4 | 8.46 | 600 |
| 6 | .600 | .51 | 28.9 | 11.15 | 620 |
| 7 | .534 | .447 | 33.0 | 14.35 | 650 |
| 8 | .466 | .362 | 40.6 | 20.3 | 685 |
| 9 | .400 | .297 | 49.6 | 27.4 | 718 |
| 10 | .333 | .236 | 62.3 | 37.4 | 770 |
| 11 | .267 | .174 | 84.5 | 54.8 | 830 |
| 12 | .200 | .119 | 123.5 | 85.4 | 920 |
| 12.5 | .166 | .093 | 158.0 | — | 978 |
| 13.0 | .133 | .069 | 216.0 | 158.00 | 1040 |
| 13.5 | .098 | .0463 | 318.0 | — | 1150 |
| 14 | .067 | .0284 | 518.0 | 394.00 | 1280 |
| 15 | 0 | 0 | ∞ | ∞ | ∞ |

# CALCULATIONS for $A_p$.

$PV^N = K$, $N = 1.32$ for N-HEPTANE (STOICHIOMETRIC)

WHEN $P = 14.7$, $V_0 = 1$ $\therefore K = 14.7$

$A_E = 1.63''^2$ $V_1 = V_0 + .1 = 1.1$, $V_2 = V_0 + .2 = 1.2$, etc.

| INCREMENTS | $V$ | $V^N$ | $P_2 = 14.7/V^N$ | $(14.7 - P_2)$ | $F_2 = (14.7 - P_2)A_E$ | $F_1 + F_2 = F_T$ | $F_T/S$ | $a_p$ |
|---|---|---|---|---|---|---|---|---|
| | | | PSI. | PSI. | lbs. | lbs. | $\frac{lbs-SEC^2}{FT.}$ | FT/SEC |
| 0 | 1 | 1.00 | 14.7 | 0 | 0 | 0 | 0 | 32.2 |
| 1 | 1.1 | 1.14 | 12.85 | 1.85 | 2.98 | 4.47 | .894 | 31.31 |
| 2 | 1.2 | 1.27 | 11.55 | 3.15 | 5.08 | 9.59 | 1.52 | 30.68 |
| 3 | 1.3 | 1.41 | 10.40 | 4.30 | 6.93 | 10.93 | 2.20 | 30.00 |
| 4 | 1.4 | 1.56 | 9.40 | 5.3 | 8.54 | 14.99 | 3.00 | 29.20 |
| 5 | 1.5 | 1.71 | 8.60 | 6.1 | 9.82 | 18.28 | 3.66 | 28.54 |
| 6 | 1.6 | 1.86 | 7.92 | 6.78 | 10.9 | 22.05 | 4.42 | 27.78 |
| 7 | 1.7 | 2.03 | 7.24 | 7.46 | 12.0 | 26.35 | 5.28 | 26.92 |
| 8 | 1.8 | 2.17 | 6.78 | 7.92 | 12.77 | 33.07 | 6.64 | 25.56 |
| 9 | 1.9 | 2.34 | 6.29 | 8.41 | 13.55 | 40.95 | 8.20 | 24.00 |
| 10 | 2.0 | 2.50 | 5.89 | 8.81 | 14.20 | 51.60 | 10.30 | 21.9 |
| 11 | 2.1 | 2.67 | 5.50 | 9.2 | 14.80 | 69.6 | 13.94 | 18.26 |
| 12 | 2.2 | 2.84 | 5.18 | 9.5 | 15.35 | 100.75 | 20.34 | 11.86 |
| 13 | 2.3 | 3.00 | 4.90 | 9.8 | 15.80 | 173.80 | 34.80 | -2.6 |
| 14 | 2.4 | 3.18 | 4.62 | 10.1 | 16.28 | 410.28 | 82.20 | -50.0 |
| 15 | 2.5 | 3.36 | 4.38 | 10.3 | 16.63 | ∞ | ∞ | -∞ |

CALCULATIONS for THE VELOCITY VS. DISPLACEMENT CURVE, WITH THE CORRESPONDING TIMES.

$$\frac{dv}{dt} = \bar{a}$$

$$\frac{ds}{dt} = v$$

$$\frac{dt}{ds} = \frac{1}{v}, \quad dt = \frac{ds}{v}$$

$$\frac{v\,dv}{ds} = \bar{a}, \quad \int_1^2 v\,dv = \bar{a}\int_1^2 ds \quad \text{——} \quad V_2^2 - V_1^2 = 2\bar{a}s$$

$$V_2^2 = 2\bar{a}s + V_1^2$$

| INCREMENTS | $\bar{a}_p$ IN/SEC² | $2\bar{a}s$ IN²/SEC² | $V_2^2$ IN²/SEC² | $V_2$ IN/SEC | $\Delta T \times 10^3$ MILLI-SECS. | $t_2 \times 10^3$ MILLI-SECS. |
|---|---|---|---|---|---|---|
| 0 | 386 | — | 0 | 0 | 0 | 0 |
| 1 | 382 | 76.4 | 76.4 | 8.75 | 22.8 | 22.8 |
| 2 | 376 | 75.0 | 151.4 | 12.30 | 9.7 | 32.5 |
| 3 | 367 | 73.2 | 224.6 | 15.00 | 7.1 | 39.6 |
| 4 | 360 | 71.9 | 296.5 | 17.20 | 6.1 | 45.7 |
| 5 | 350 | 69.9 | 366.4 | 19.10 | 5.8 | 51.0 |
| 6 | 341 | 68.1 | 434.5 | 20.8 | 5.58 | 56.6 |
| 7 | 328 | 65.6 | 500.1 | 22.7 | 5.48 | 62.1 |
| 8 | 313 | 62.5 | 562.6 | 23.7 | 4.17 | 66.2 |
| 9 | 297 | 59.4 | 622.0 | 25.0 | 4.16 | 70.4 |
| 10 | 276 | 55.1 | 677.1 | 26.0 | 3.99 | 74.38 |
| 11 | 240 | 47.9 | 725.0 | 26.9 | 3.76 | 78.14 |
| 12 | 182 | 36.4 | 761.4 | 27.6 | 3.58 | 81.72 |
| 13 | 72 | 14.4 | 775.8 | 27.8 | 3.47 | 85.19 |
| 13.2 | -60 | -2.40 | 773.4 | 27.7 | | |
| 13.4 | -120 | -4.80 | 768.6 | 27.6 | | |
| 13.6 | -204 | -8.07 | 760.5 | 27.55 | | |
| 13.8 | -300 | -12.00 | 748.5 | 27.30 | | |
| 14.0 | -480 | -19.20 | 728.- | 26.90 | | |
| 14.2 | -840 | -33.6 | 694.- | 26.40 | | |

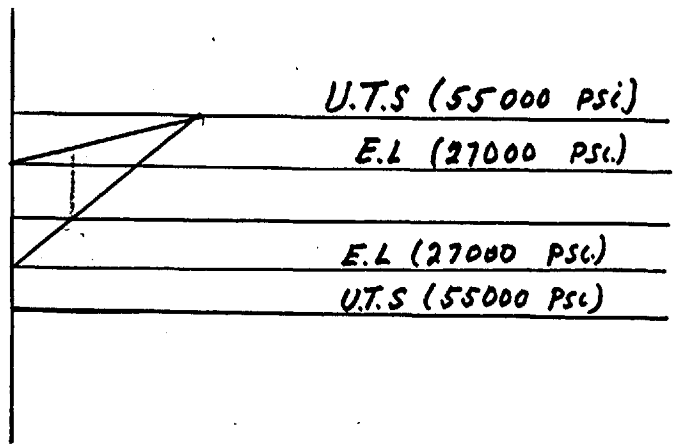
SEE FIG. 6 for these FIGURES.

2) Calculations for determining the cylinder wall thickness.

Material: 1020 cold rolled steel.

Ultimate tensile strength -55,000 psi (U.T.S)

Endurance limit in reverse bending 27,000 psi (E.L)




Goodman Diagram

Useful endurance limit = 34,000

Since cylinder wall stresses will be only in tension, from Goodman's diagram an effective endurance limit of 34000 psia will be used.

axial stress = 0

hoop stress = $S_t = \frac{FPr}{2t}$

$$34000 = \frac{4 \times 2000 \times 1}{t}$$

$$t = \frac{8000}{34000 \times 2} = .118''$$

P = cylinder pressure (psi)

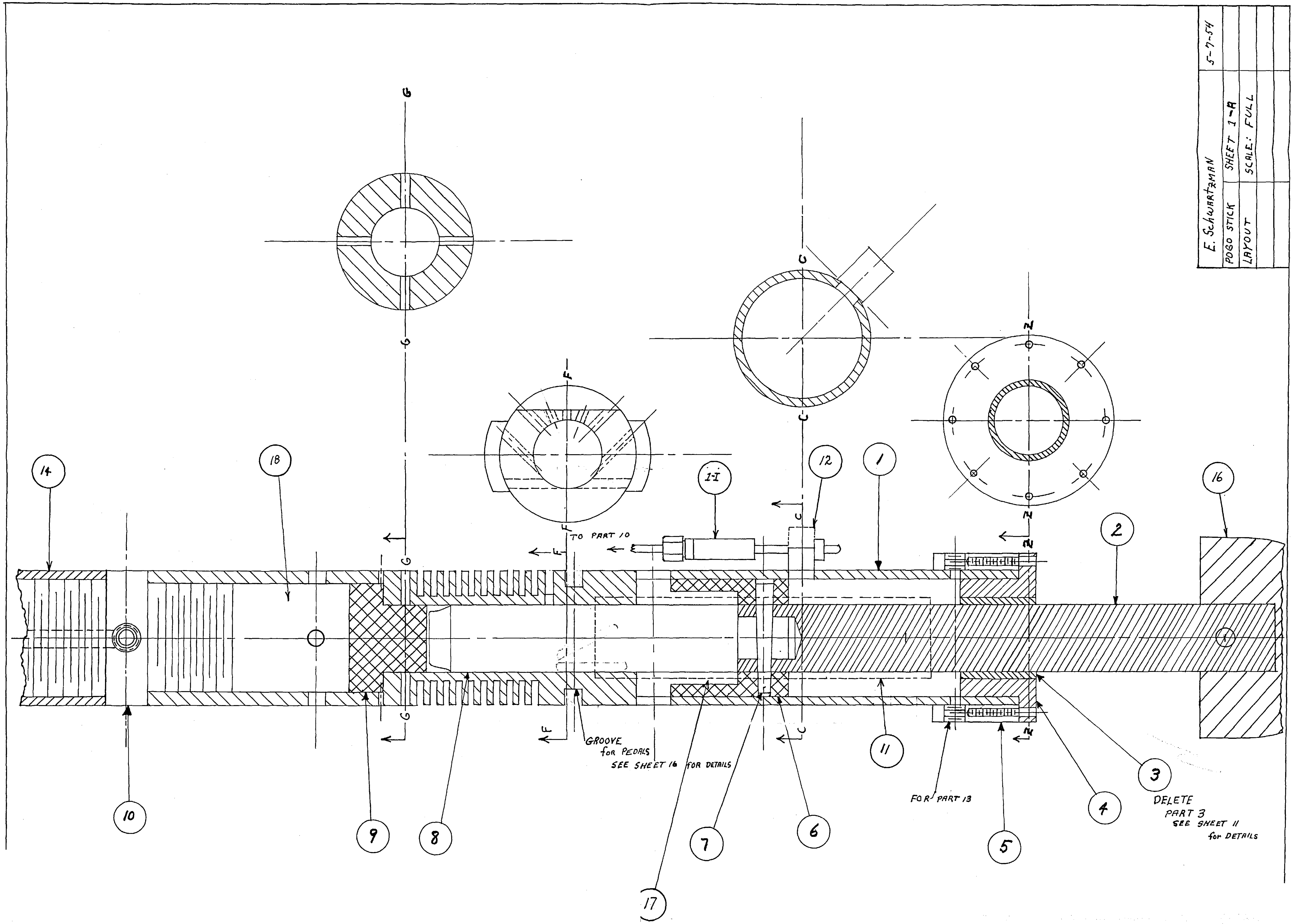
r = cylinder radius (inch)

t = cylinder wall thickness (inch)

F = safety factor (4)

$S_t$ = endurance limit (psi)

A cylinder wall thickness of .125" is actually used.


E. Schwartzman
5-7-54
POGO STICK
SHEET 1-A
LAYOUT
SCALE: FULL
G
G
F
F
C
C
N
N
1-I
12
1
16
2
14
18
TO PART 10
GROOVE for PEDALS
SEE SHEET 16 for DETAILS
11
FOR PART 13
3
4
5
6
7
8
9
10
17
DELETE PART 3
SEE SHEET 11 for DETAILS