COMPARISON OF ACTUAL TO THEORETICAL ENGINE CYCLES

By

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Submitted in Partial Fulfillment of the Requirements for
the Bachelor of Science Degree in Mechanical Engineering
from the
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Feb 14 1944

The MIT Graduate House
Cambridge, Massachusetts
12 February 1944

Professor George W. Swett
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir,

In accordance with the requirements for the degree of Bachelor of Science in Mechanical Engineering we herewith submit a thesis entitled "Comparison of Actual to Theoretical Engine Cycles".

We would like to express our appreciation for the help received from P.M. Ku in the Sloan Automotive Laboratory. Our thanks and appreciation are extended, also, to Professor Rogowski, our thesis adviser, who assisted us all through the term and whose aid was invaluable.

Sincerely yours,

Caesar A. Spero
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OBJECT

Theoretical engine cycles are valuable because they give a limit which could be reached theoretically in an actual engine and they are simple to compute. Before building an engine the maximum working pressures and temperatures can be approximated so that the designers will have some basis on which to work. After the engine has been built an indicator card can be made and compared to a theoretical cycle to determine the type and magnitude of losses; this information will aid in obtaining better results.

The Equivalent Fuel-Air Cycle has been selected because it most closely resembles the actual cycle since the charts are based on a mixture of fresh charge and residual gases containing "burned" fuel and air. Also, they take into account both variable specific heats and chemical equilibrium. The Standard Air Cycle was used because of its simplicity of calculation and because no charts are required. The Keenan and Kaye data, which includes the effect of variable specific heat only, is new and has never been used for comparison to actual gasoline engine cycles. Calculating the cycles with these tables is fairly simple, also.

In this thesis the values by the above three methods were determined, and plots of the results are included to show how each theoretical cycle approaches the actual cycle.

A visual comparison is shown for all Equivalent Fuel-Air Cycles and three of each of the other two theoretical cycles. The working basis for each of these cycles is also explained herein.

PROCEDURE

The first step was to run #1 C.F.R. engine in the Sloan Automotive Laboratory at M.I.T. The intake temperature was read off a thermometer inserted in the intake pipe. The air consumption was calculated from the pressure drop through an orifice. The fuel consumption was set by means of a rotameter but for each run the fuel was drawn from a burette and the time measured. If this time did not coincide with the calculated time the rotameter reading was changed and the run taken over. The intake and exhaust pressures were obtained from mercury manometers. The speed was held constant by adjusting the speed so that black lines on the flywheel appeared motionless under the illumination of a stroboscope. The desired compression ratio was obtained by setting a micrometer screw on the engine block and cranking the cylinder head to that point. Best power spark advance, which was used on all runs, was found by advancing or retarding the spark, while the speed was held constant, and observing the scale reading on the dynamometer brake. To prevent trouble from detonation 100 octane gas was used for all runs.

The indicator cards were taken on M.I.T. High Speed Indicator. All pressure pick-up units were constructed to give an accuracy within 1" Hg or about 0.5 psi. Top dead center was first set approximately. Then, by connecting the indicator spark to the light in the spark-advance indicator on the engine, so that the crank angle could be read every time the indicator would spark, dead center was set accurately by rotating the cam on the high speed indicator so that the light flashed at a crank angle of zero degrees. The resulting indicator cards of pressure versus crank angle were converted to P-V plots on the converting table in the laboratory. The area of the P-V plots was found by planimetering each cycle three times and taking the average.

Schematic diagrams of the C.F.R. engine set-up and P-V table are shown in Figures 1 and 2 respectively. Pictures of the M.I.T. High Speed Indicator and P-V Table are shown in Figures 3 and 4 respectively.

A total of twelve runs was taken as follows:

First set Runs 1-4

Fuel Air Ratio	Variable
Speed	1200 r.p.m.
Compression Ratio	7
Inlet Pressure	25 ins. Hg
Back Pressure	31 ins. Hg
Inlet Temperature	120°F.
Spark Advance	Best power

Second Set Runs 5-8

Inlet Pressure	Variable
Speed	1200 r.p.m.
Compression Ratio	7
Back Pressure	31 ins. Hg
Inlet Temperature	120°F.
Fuel-Air Ratio	.0782
Spark Advance	Best power

Third Set Runs 9-12

Compression Ratio	Variable
Speed	1200 r.p.m.
Inlet Pressure	25 ins. Hg
Back Pressure	31 ins. Hg
Inlet Temperature	120°F.
Fuel-Air Ratio	.0782
Spark Advance	Best Power

The actual data are shown in the Appendix.

BASES OF CYCLES

It was with considerable difficulty that the basis for each of the different cycles was chosen since the method of calculating the cycles must be simple in order to make them practical yet they must also have some meaning, for comparison.

Equivalent Fuel-Air Cycle

The Fuel-Air charts, Thermodynamic Characteristics of Mixtures of C_8H_{18} and Air (Hershey, Eberhardt, and Hottel), are constructed on the basis of the following:

of air gives only enough oxygen to burn 0.0665 lbs. of fuel. If the fuel air ratio is less than .0665 the available heat is F x 19,240 Btu.s per lb. but when F is greater than 0.0665 there is not sufficient oxygen in one pound of air and hence the available heat is only .0665 x 19,240 or 1280 Btu. per lb. and some of the fuel does not burn; however, in calculating the efficiency of a cycle the total heating value of the fuel is used as the heat input to put the results on the same basis as the actual and fuel-air cycles.

Equivalent Standard Air Cycle

For this cycle, calculated for runs 1, 7 and 12 and plotted in Figures 14, 20 and 25, the basis of one pound of air was still used but the initial pressure and volume were the same as in the actual cycle so that the plots would all start at the same initial conditions. The heat added for these cycles was (1-f) times the available heat where f was obtained from the equivalent fuel-air cycles. This was done to give a better approximation to the actual volumetric efficiency and thus allow the cycle to be called equivalent and make a better visual comparison when plotted.

Keenan and Kaye Air Cycle

These cycles were calculated on the basis of one pound of mixture as follows:

	(1-F) #	Air
	F #	Fuel
Total	1 #	Mixture

but the F pounds of fuel are assumed to act like air and hence all values are per pound of air. The heat of combustion is therefore $\frac{1}{1+F}$ times the heat of combustion discussed in the Standard Air Cycle.

Equivalent Keenan and Kaye Air Cycle

This cycle was calculated on the same basis as the Equivalent Standard Air Cycle in every respect.

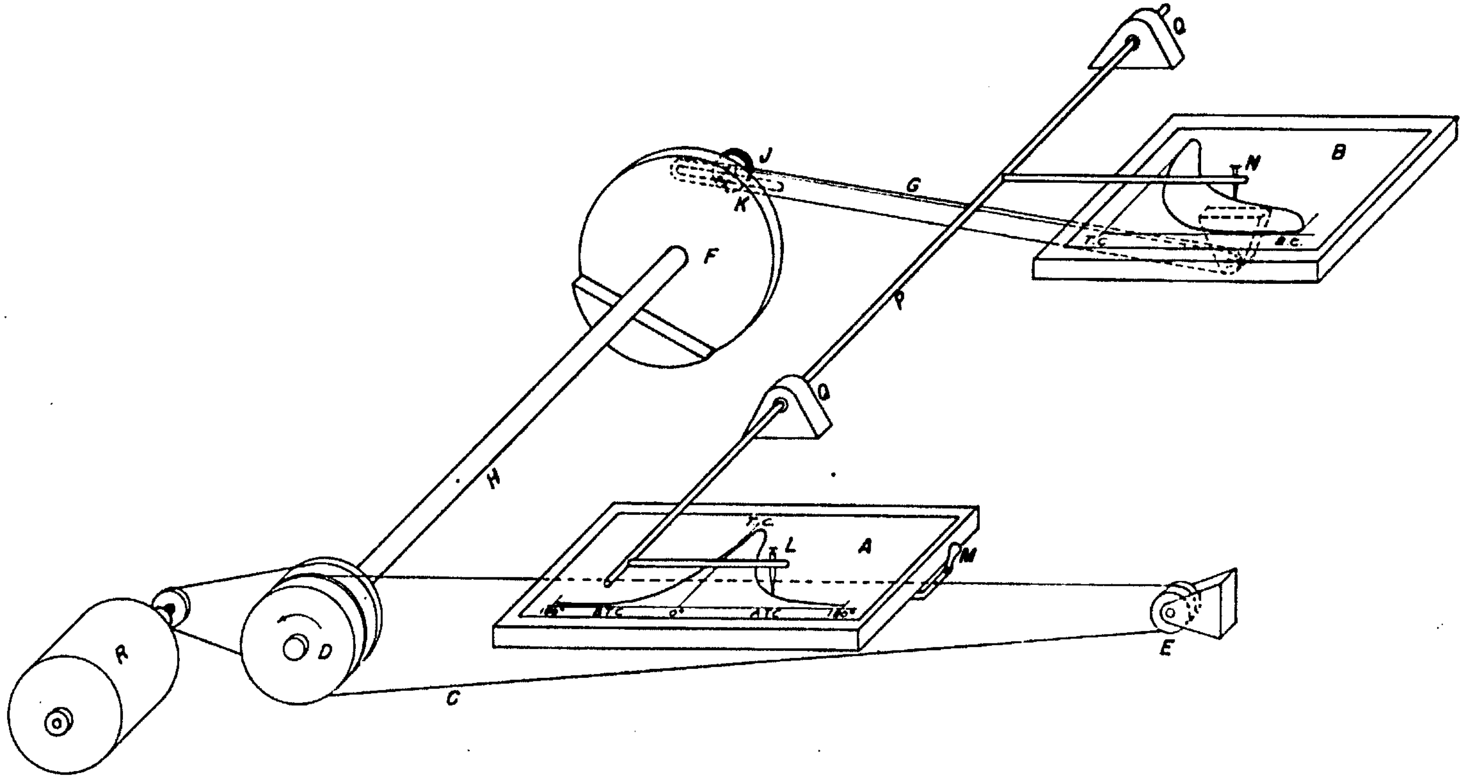


FIG. 2 Schematic diagram of d.T.T. transfer machine.

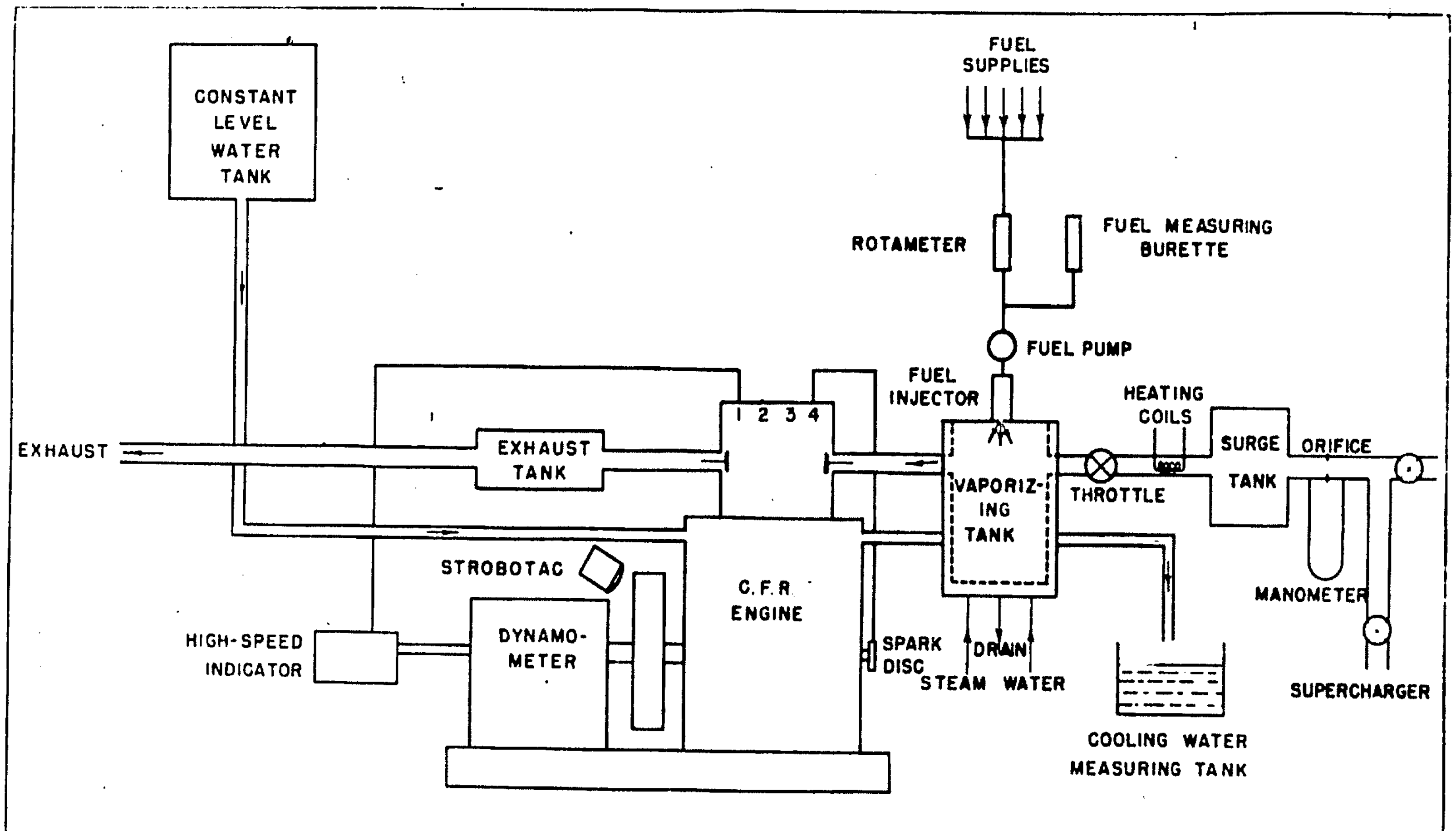


FIG. 1

SLOAN LABORATORY

EXPERIMENTAL C.F.R. ENGINE SETUP

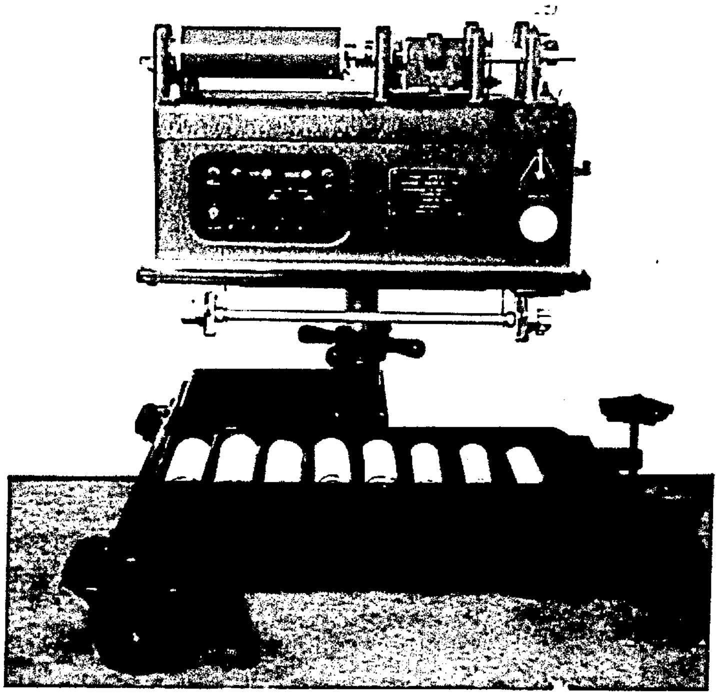


FIG. 3

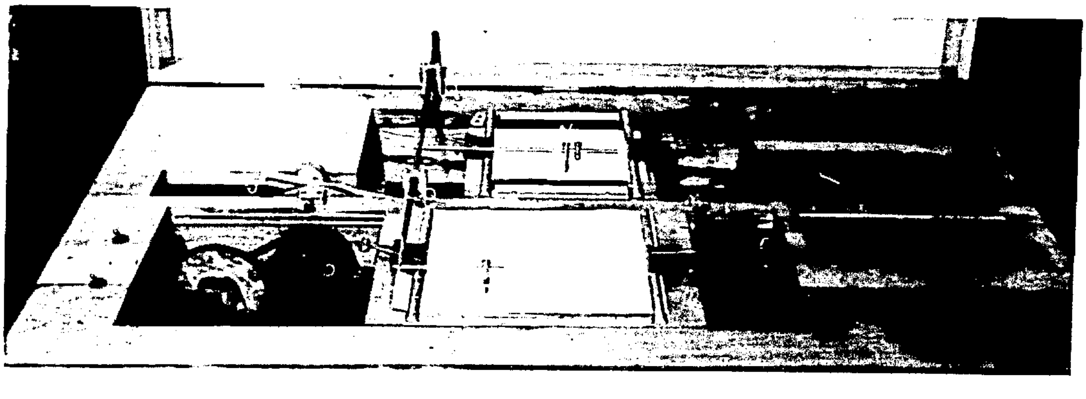


FIG. 4

DISCUSSION OF RESULTS AND CONCLUSIONS

The results are represented in graphical form by Figures 5-13 for the standard air, Keenan and Kaye, fuel-air, and actual engine cycles, showing variations in thermal efficiencies, maximum pressures, and ratio of IMEP to theoretical MEP with varying compression ratio, fuel-air ratio, and inlet pressure. The efficiencies of the standard air and Keenan and Kaye cycles follow the same trend, the lower efficiency and m.e.p. of the Keenan and Kaye occurring, since the variation of specific heats with temperature is accounted for. The specific heats increase with increasing temperatures, thus lowering k; all other assumptions are explained in the Basis of Cycles. The fuel-air cycle, which discards the assumption of a reversible cyclic process and contains heat from the chemical reaction of the working medium itself, most closely approximates the actual cycle. The lower efficiency of the actual cycle is caused by incomplete mixing of fuel and air, non-simultaneous burning of various parts of the charge, time required for chemical reaction, direct heat losses, and time required for escape of exhaust gases.

The actual indicated efficiency is not a constant with varying inlet pressure. The deviation is due to heat, time and blowdown losses. When plotted against fuel-air ratios, the air standard efficiency is a constant below chemically correct fuel-air ratio, and the efficiencies of the remaining cycles increase with decreasing fuel-air ratio tending toward air standard efficiency as a limit. The efficiencies decrease at fuel-air ratios greater than chemically correct instead of remaining a constant because the added heat was taken equal to the heat of chemically correct combustion and the heat value of the excess fuel is loss.

At fuel-air ratios greater than 120% chemically correct, the ratio of IMEP to theoretical MEP decreases with increasing fuel-air ratio. The lowering of the temperatures with an excess of fuel also lowers the mean effective pressures at these fuel-air ratios. The lower energy content and the slower combustion rate in the actual engine below chemically correct account for the positive slope due to the lesser IMEP. This ratio of IMEP to theoretical MEP follows the same trend when plotted against inlet pressure. The curves droop with inlet pressures higher than 12.8 psi due, perhaps, to undetected preignition. Versus compression ratio the trend is very similar, the discrepancy of the fuel-air cycle coming within the error of calculation.

The actual and fuel-air maximum pressures increase with increasing fuel-air ratio because of better combustion rates and an increase in the number of molecules, seemingly in a straight line function for the range covered. Below chemically correct fuel-air ratios the maximum pressures drop since the energy content in the smaller amount of fuel added is less. The constant maximum pressures after chemically correct follow from the basis of the cycles - i.e., the equivalent heat added was equal to that of chemically correct combustion.

Figures 5-13 show the actual indicator diagrams upon which the theoretical cycles have been superimposed. The fuel-air cycles are plotted for all runs. Figures 14, 20 and 25 also show the standard air cycle and Keenan and Kaye cycle. The compression lines of the above two cycles have been omitted because they are close enough to the other compression lines and would only be confusing. The comparison of fuel air and actual diagrams with low manifold air pressures is good since the densities and temperatures are lower and heat transfer less. A visual comparison of blow down, heat transfer and maximum pressures is obtained from these plots. The low compression line of Figure 20 probably occurs from an incorrect atmospheric line on the indicator card.

The feasibility of multiplying the theoretical efficiencies by a constant and getting the actual efficiency is not good. When the average value of the constant for each cycle was determined the following results with the maximum percent deviation from the mean value were obtained.

(1) Eff. (actual) = .834 x Eff. (fuel-air cycle)
Maximum error = 6.10%

(2) Eff. (actual) = .614 x Eff. (standard air cycle)
Maximum error = 5.36%

(3) Eff. (actual) = .723 x Eff. (Keenan and Kaye cycle)
Maximum error = 5.55%

It was necessary to extend the Keenan and Kaye Air Table to the higher temperature of the internal combustion engine. The extension which is included in this thesis was tabulated by using first order interpolation for internal energy and second order interpolation for the relative volume. The table has been checked against experimental results of Professor Kaye and u is accurate to the first decimal place, v_r accurate to the second decimal place. The use of this table should prove to be very interesting at extremely low fuel-air ratios as in the gas turbine where the Keenan and Kaye cycle should closely approach in its limit the actual cycle.

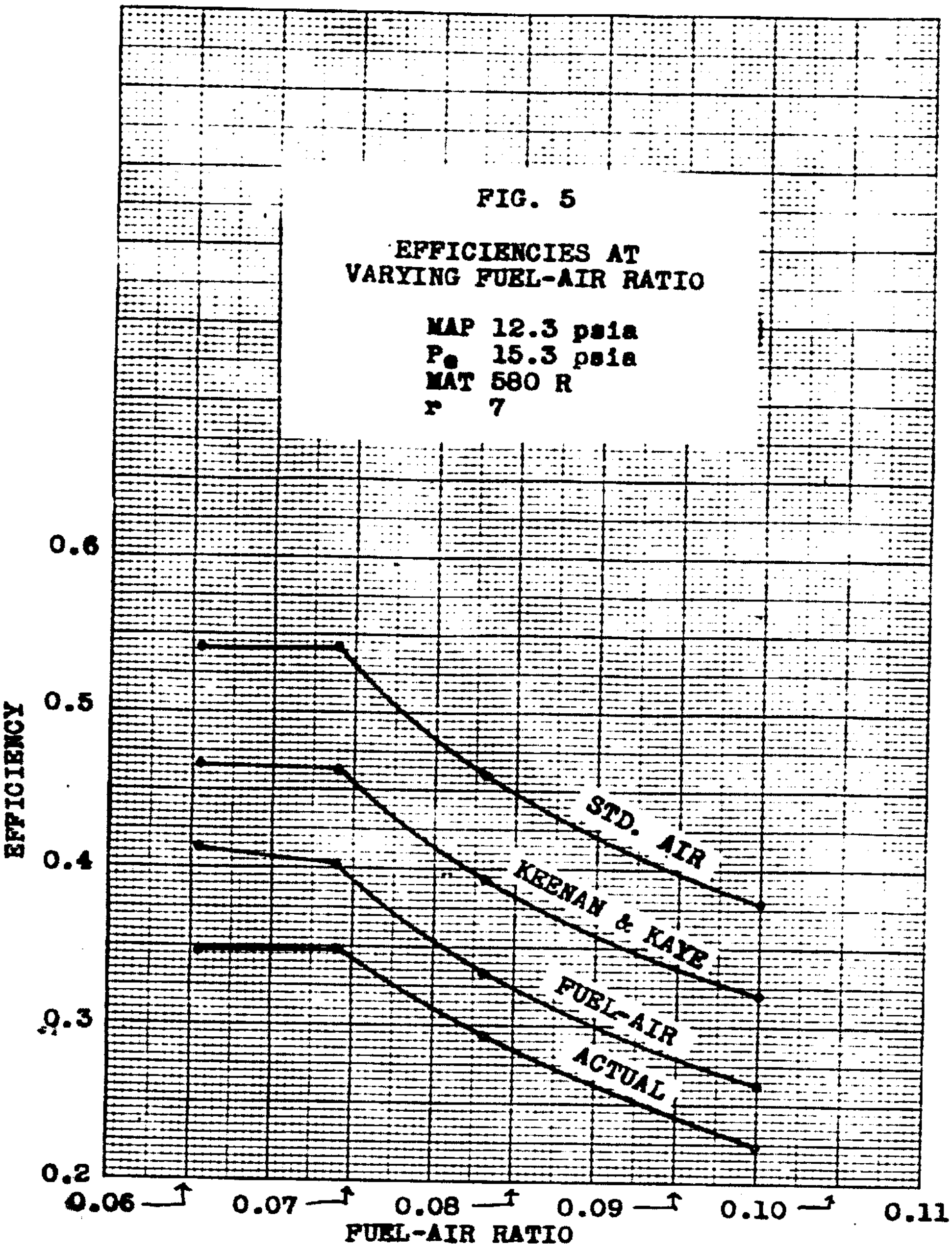


FIG. 5

EFFICIENCIES AT
VARYING FUEL-AIR RATIO

MAP 12.3 psia
P_e 15.3 psia
MAT 580 R
r 7

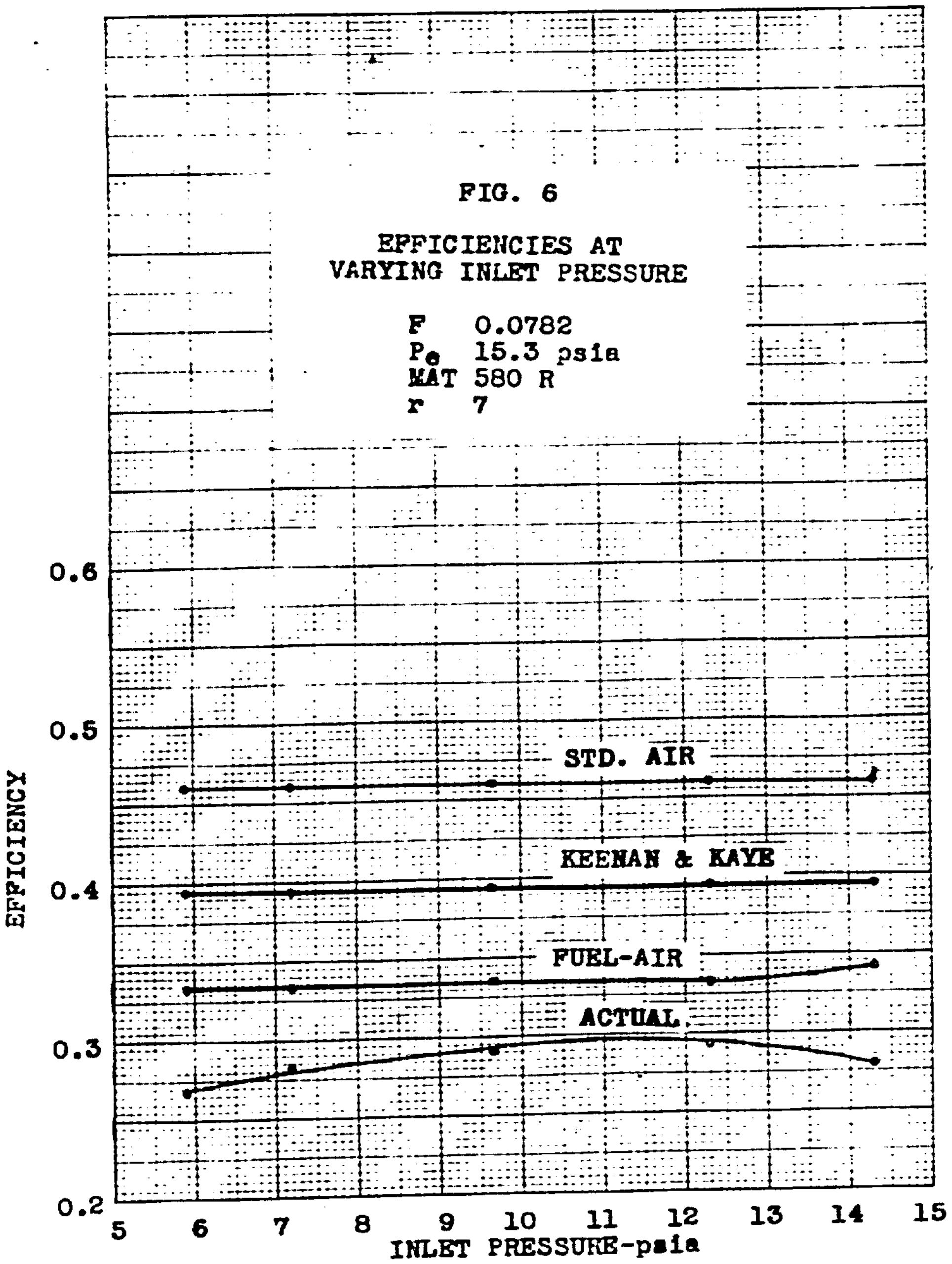


FIG. 6

EFFICIENCIES AT VARYING INLET PRESSURE

F 0.0782
P_e 15.3 psia
MAT 580 R
r 7

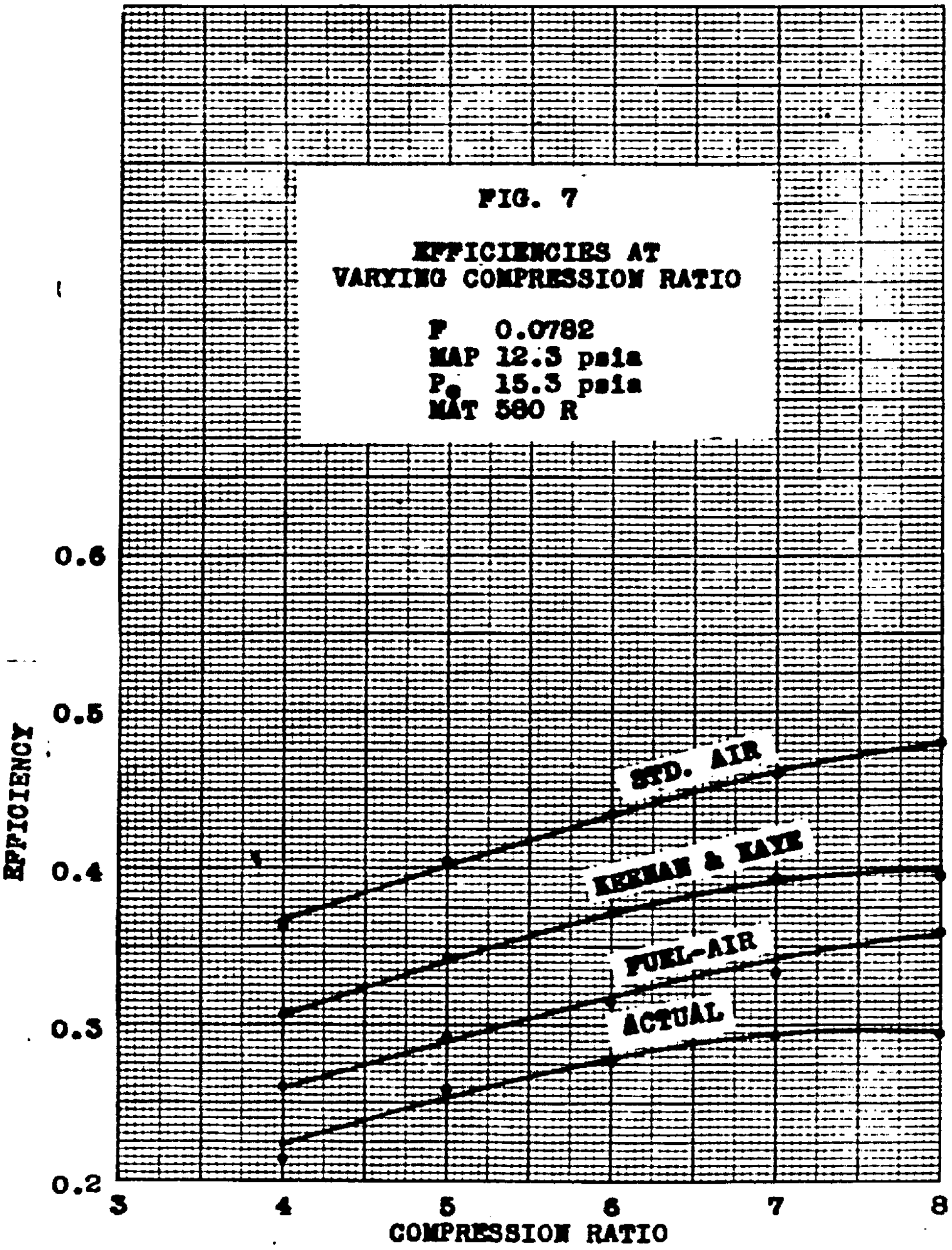


FIG. 7

EFFICIENCIES AT
VARYING COMPRESSION RATIO

F 0.0782
MAP 12.3 psia
P_e 15.3 psia
MAT 580 R

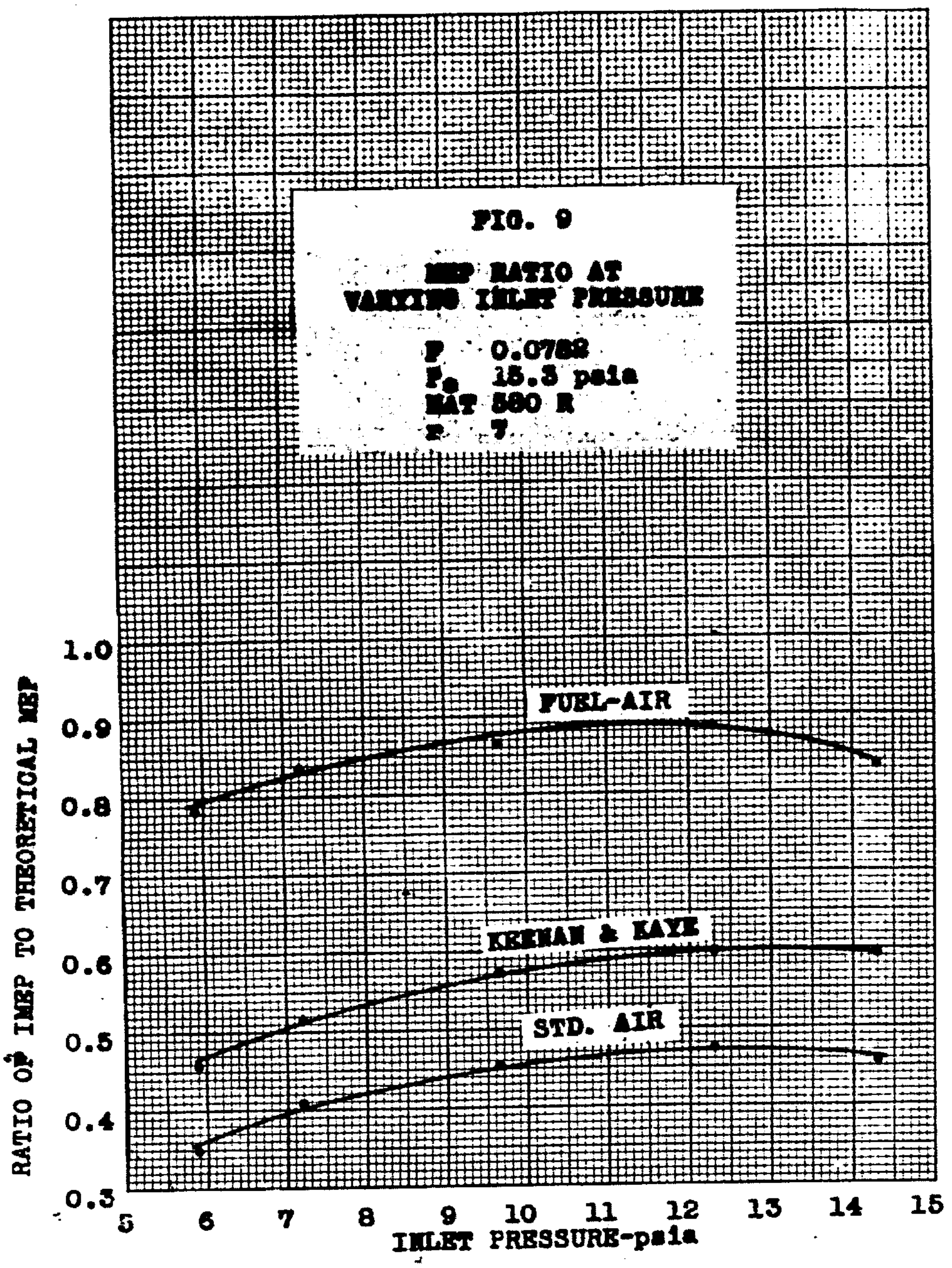


FIG. 9

MEP RATIO AT
VARYING INLET PRESSURE

F 0.0782
P_e 15.3 psia
MAT 580 R
r 7

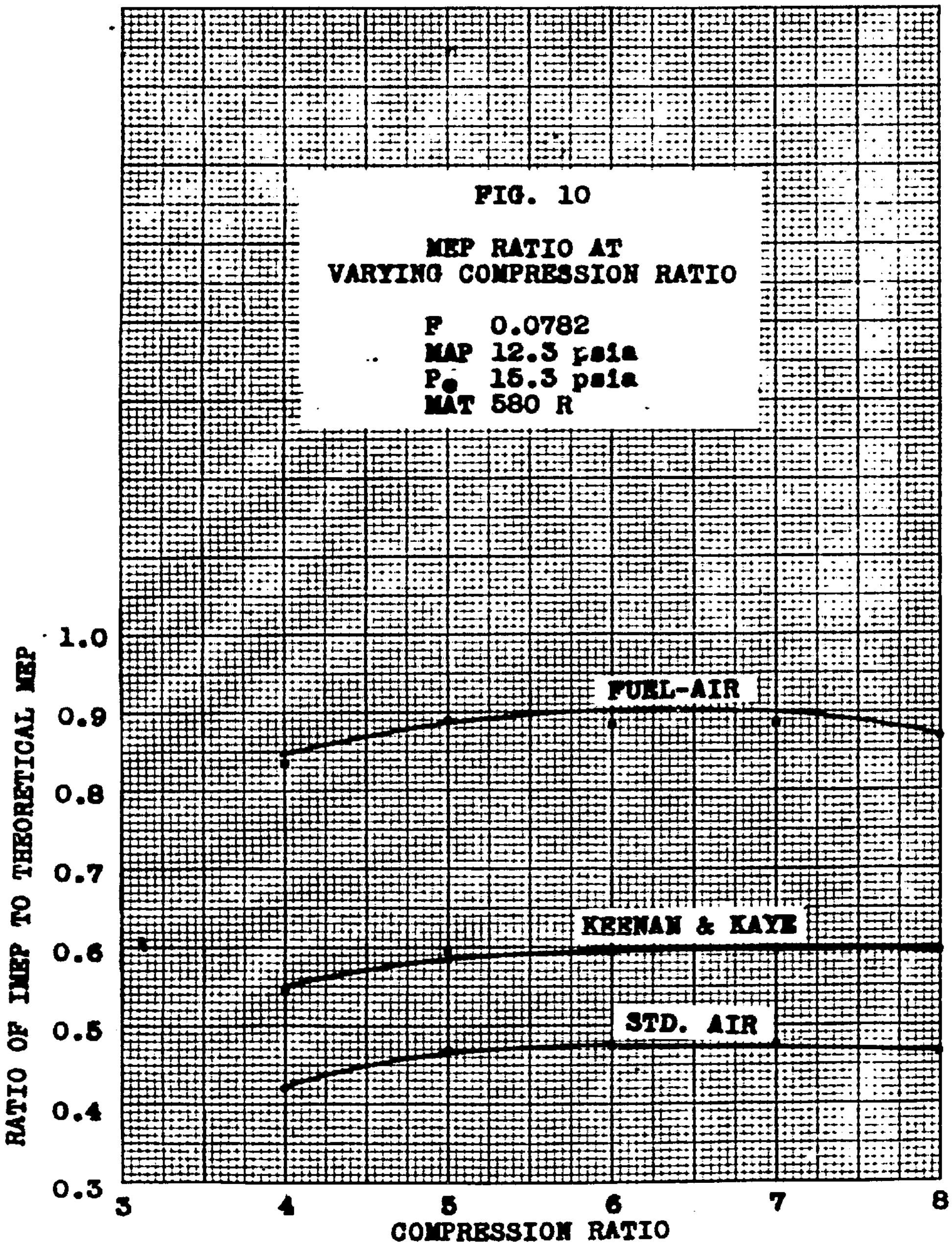


FIG. 10

MEP RATIO AT
VARYING COMPRESSION RATIO

F 0.0782
MAP 12.3 psia
P_e 15.3 psia
MAT 580 R

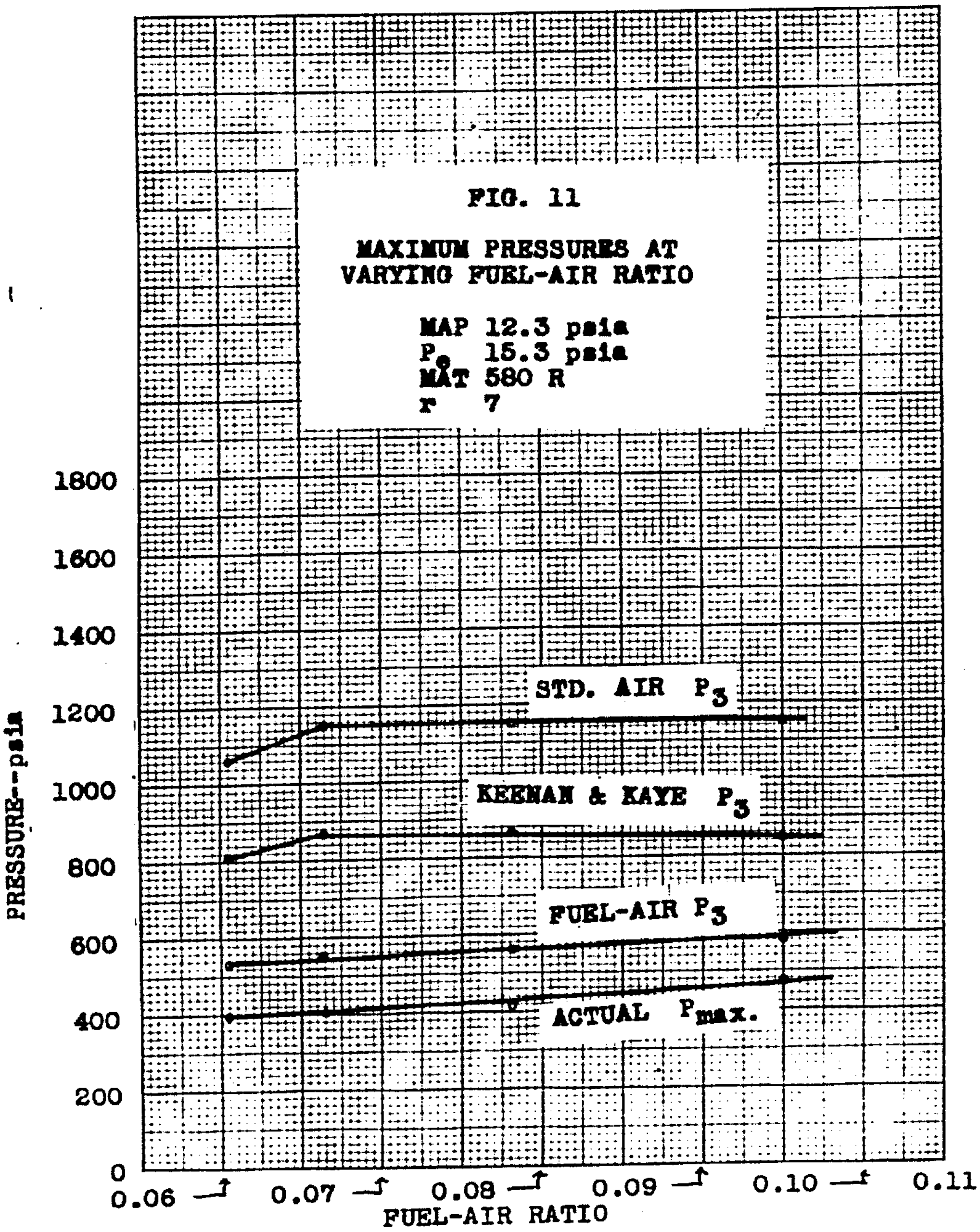


FIG. 11

MAXIMUM PRESSURES AT VARYING FUEL-AIR RATIO

MAP 12.3 psia
P_e 15.3 psia
MAT 580 R
r 7

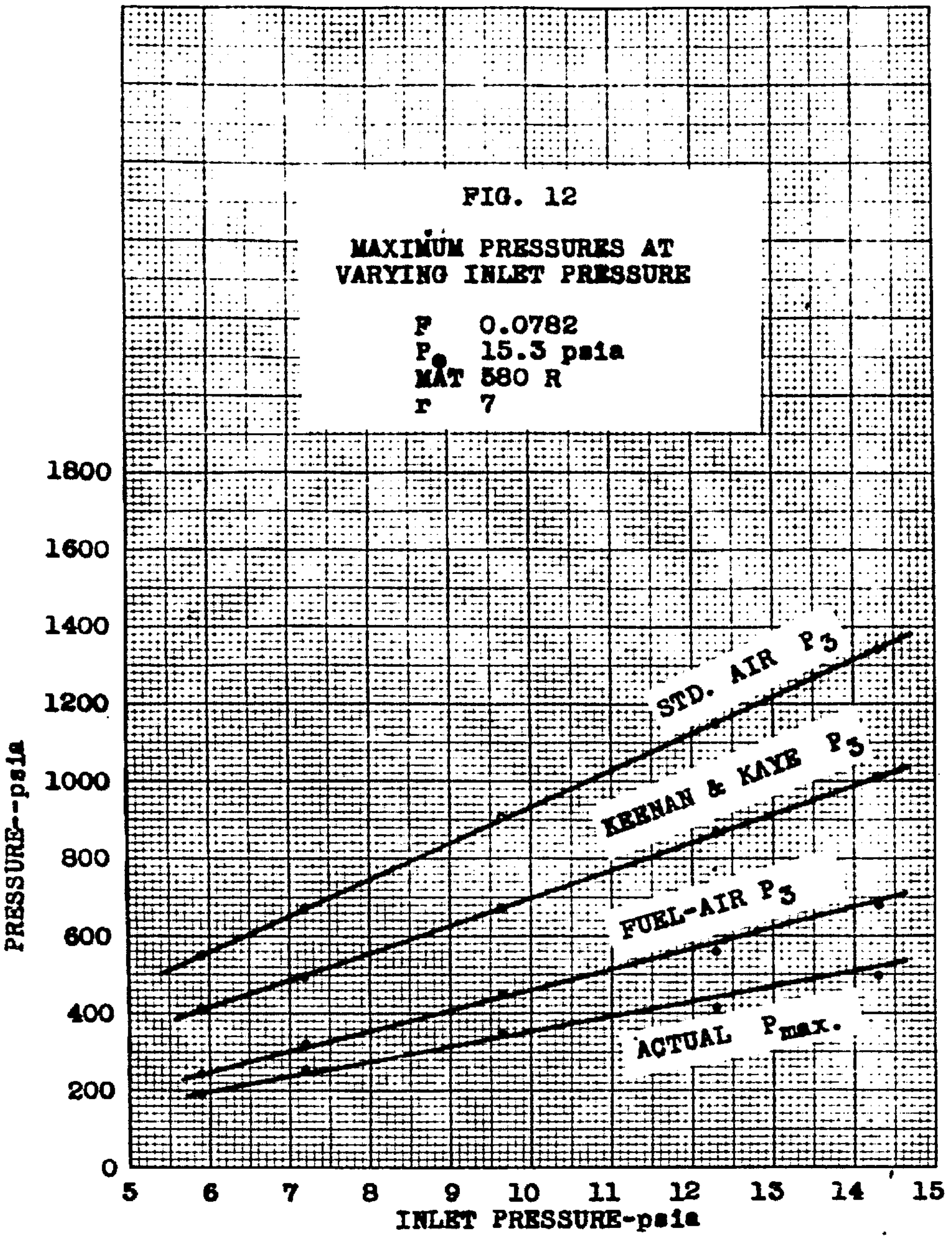


FIG. 12

MAXIMUM PRESSURES AT VARYING INLET PRESSURE

F 0.0782
P_e 15.3 psia
MAT 580 R
r 7

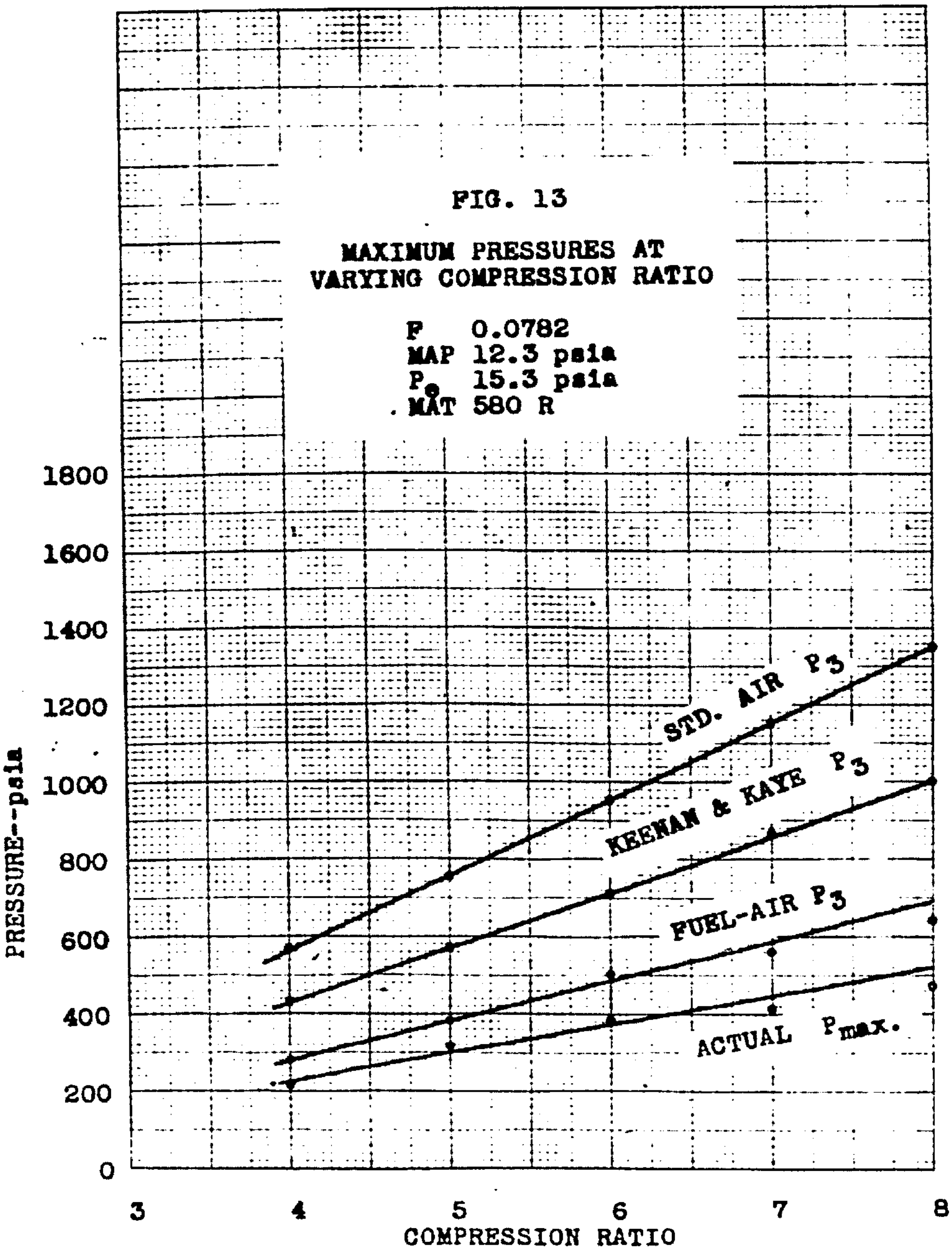


FIG. 13

MAXIMUM PRESSURES AT VARYING COMPRESSION RATIO

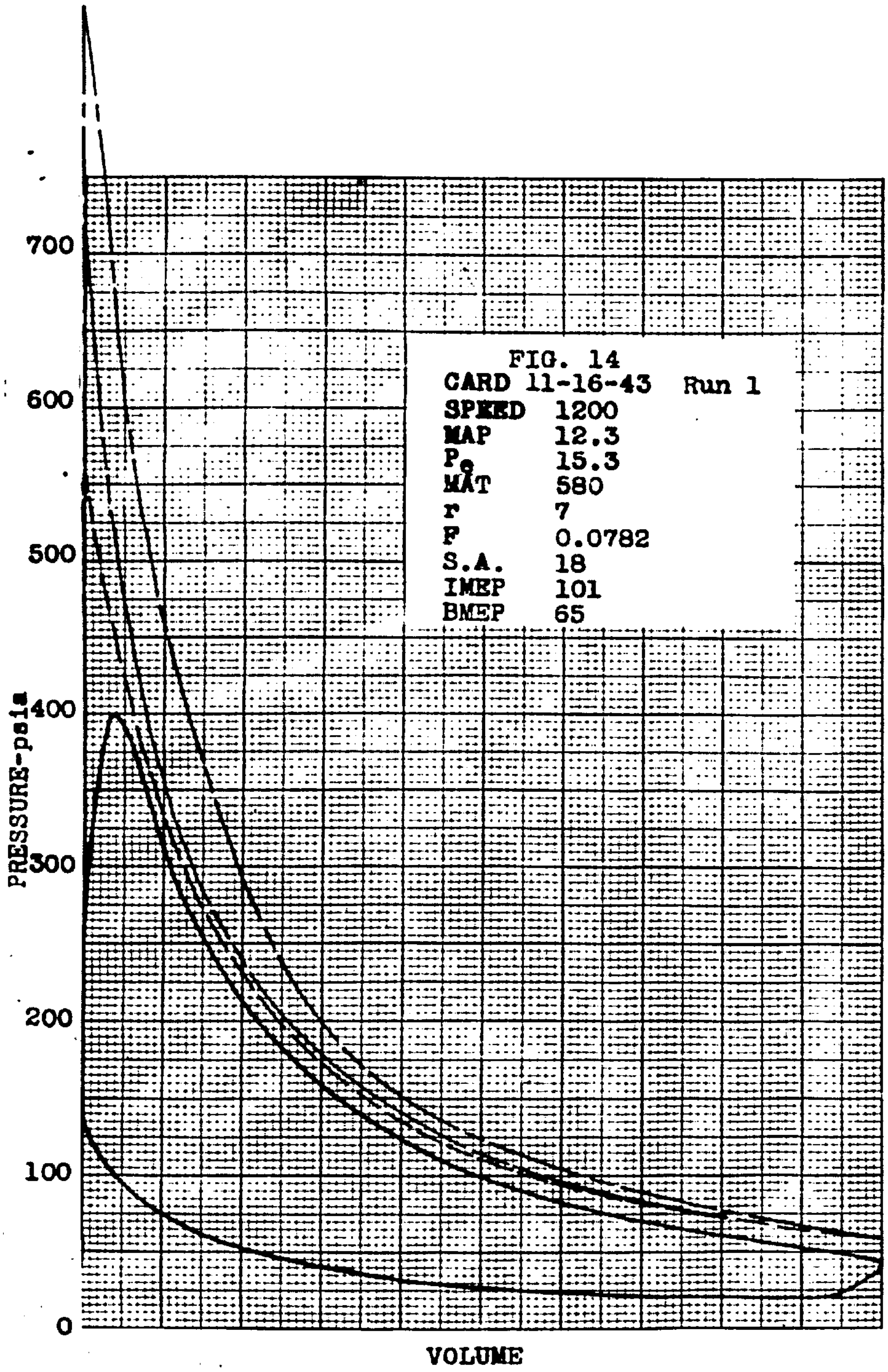


FIG. 14

CARD 11-16-43 Run 1
SPEED 1200
MAP 12.3
P_e 15.3
MAT 580
r 7
F 0.0782
S.A. 18
IMEP 101
BMEP 65
PRESSURE-psia
700
600
500
400
300
200
100
0
VOLUME

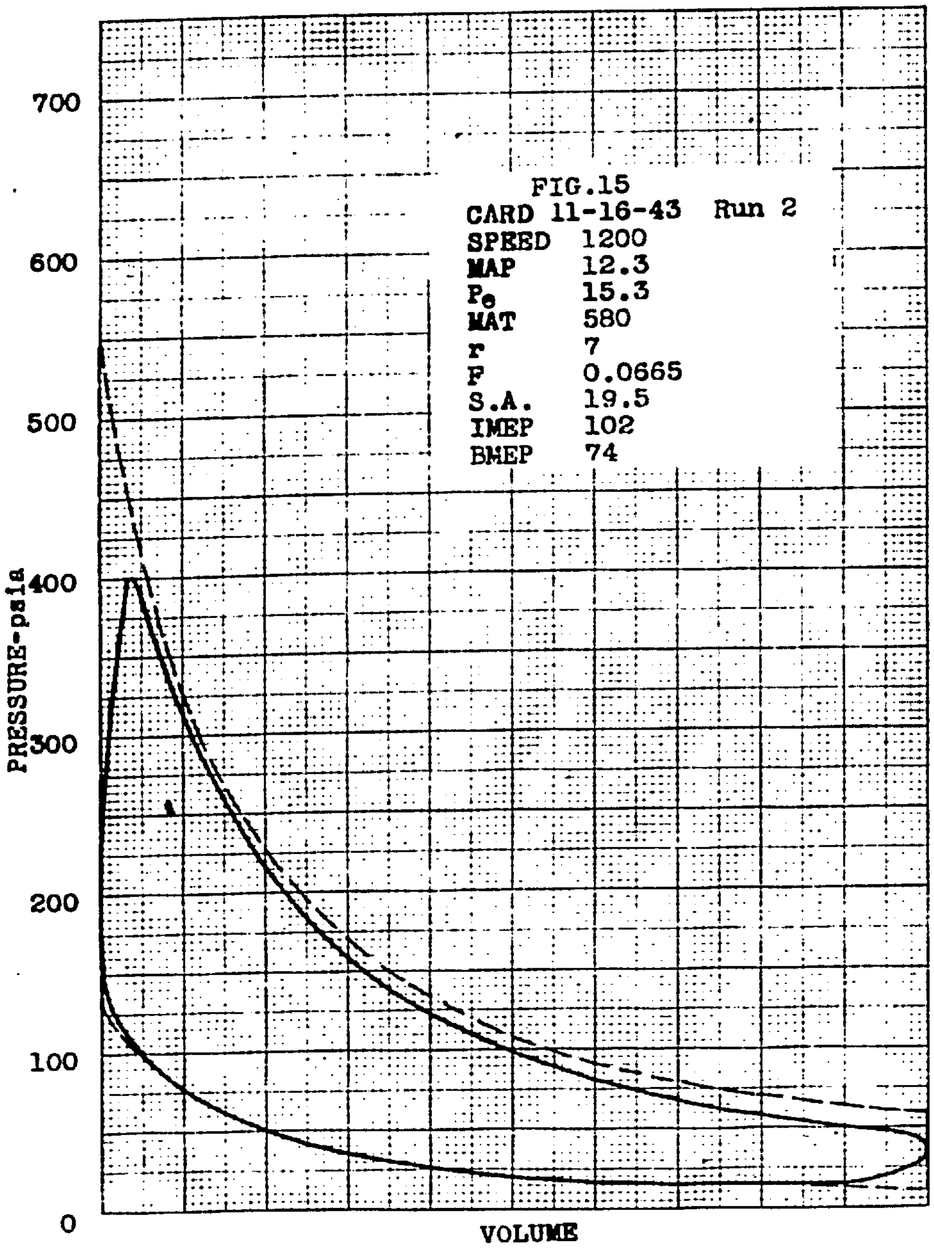


FIG.15

CARD 11-16-43 Run 2
SPEED 1200
MAP 12.3
P_e 15.3
MAT 580
r 7
F 0.0665
S.A. 19.5
IMEP 102
BMEP 74

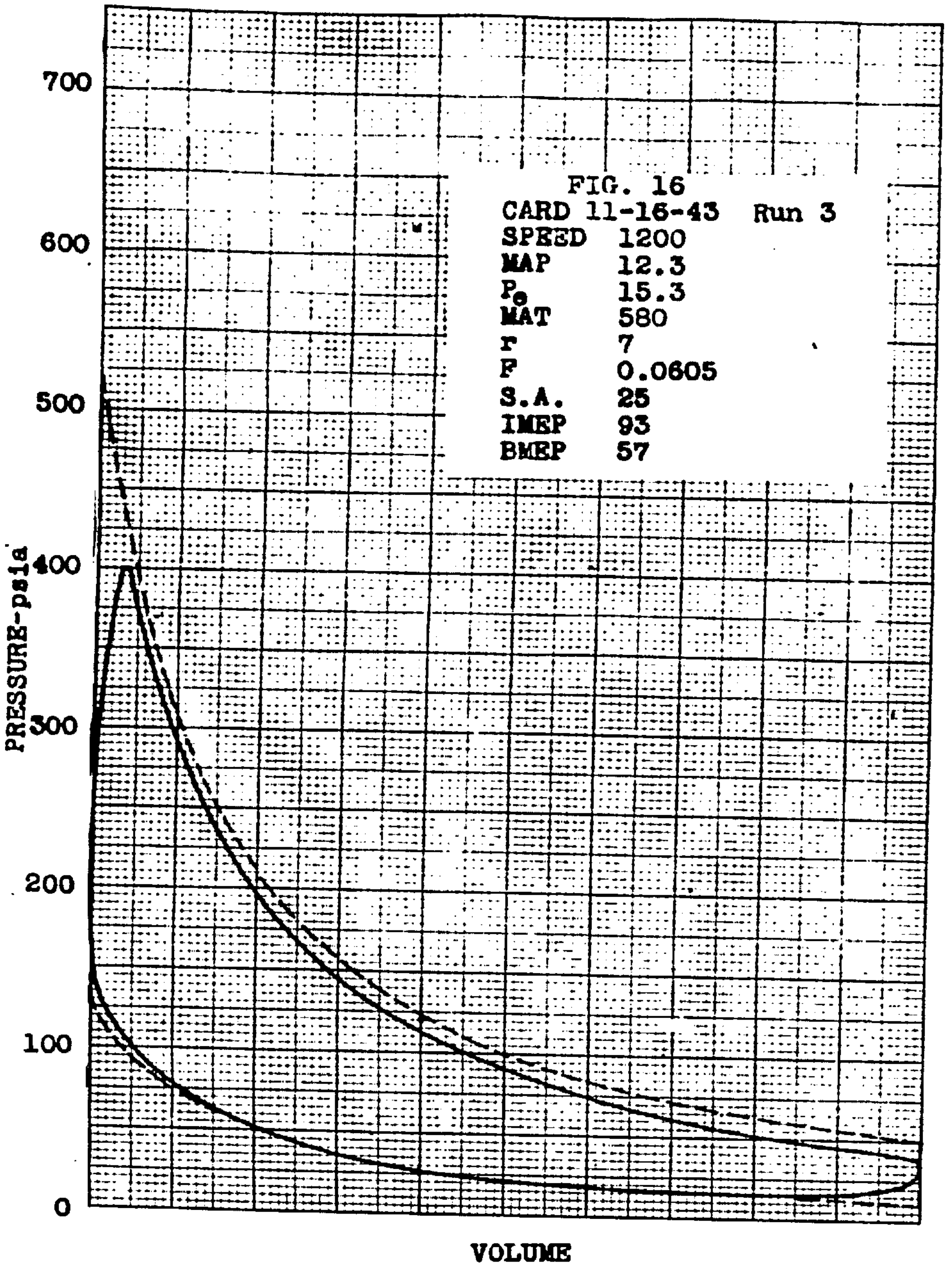


FIG. 16

CARD 11-16-43 Run 3

SPEED	1200
MAP	12.3
P_e	15.3
MAT	580
r	7
F	0.0605
S.A.	25
IMEP	93
BMEP	57

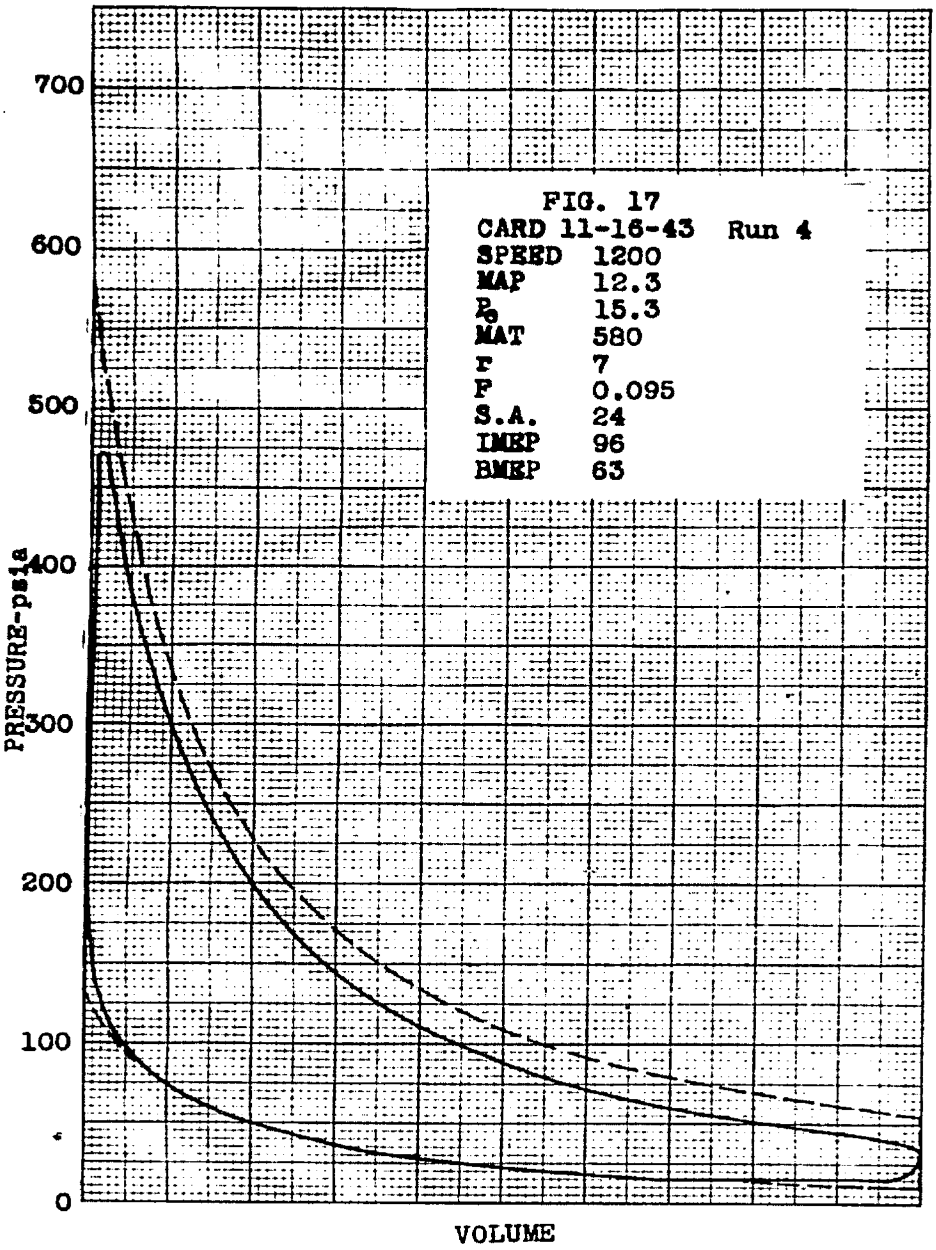


FIG. 17

CARD 11-16-43 Run 4

SPEED	1200
MAP	12.3
P_e	15.3
MAT	580
r	7
F	0.095
S.A.	24
IMEP	96
BMEP	63

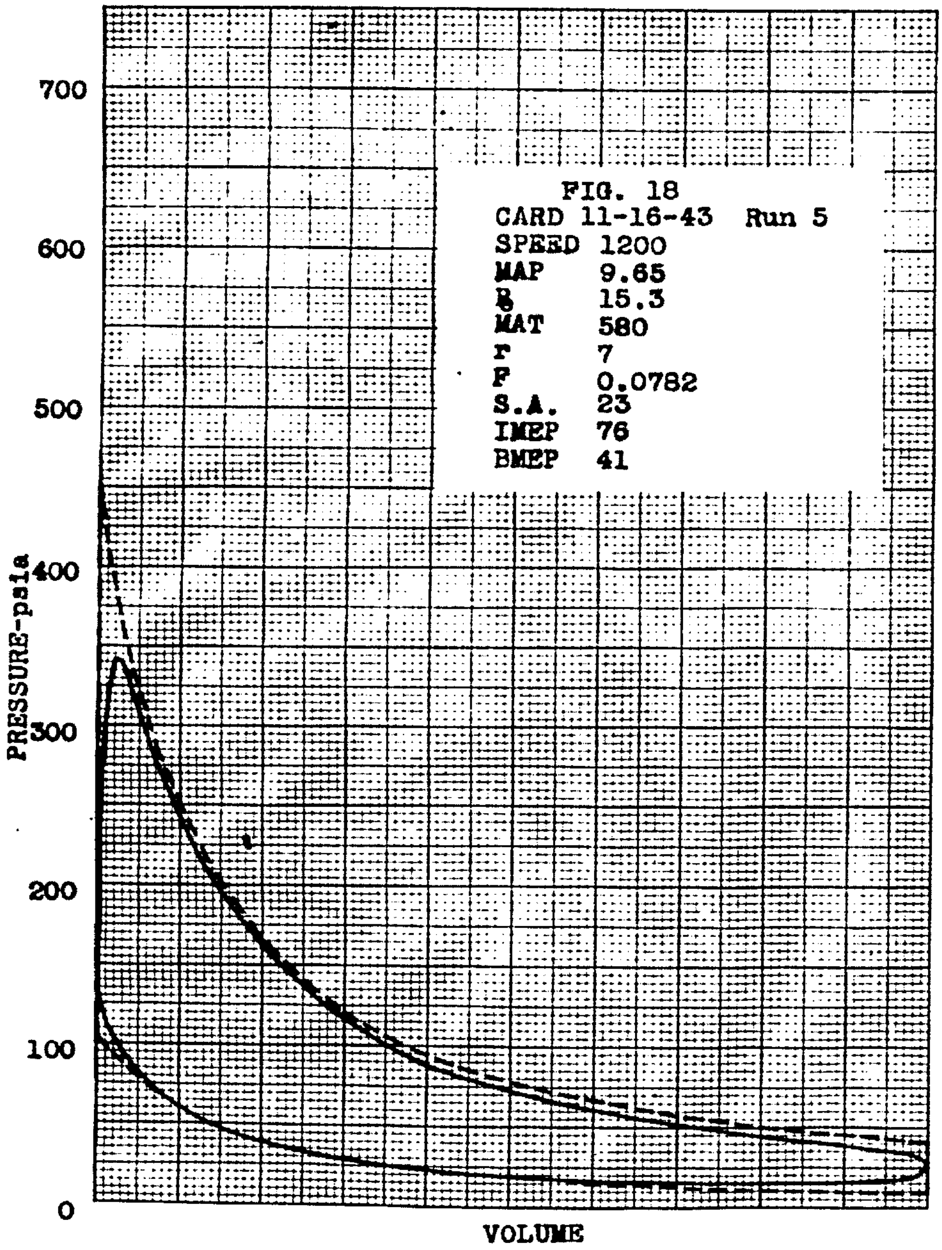


FIG. 18

CARD 11-16-43 Run 5
SPEED 1200
MAP 9.65
P_e 15.3
MAT 580
r 7
F 0.0782
S.A. 23
IMEP 76
BMEP 41
700
600
500
400
300
200
100
0
PRESSURE-psia
VOLUME

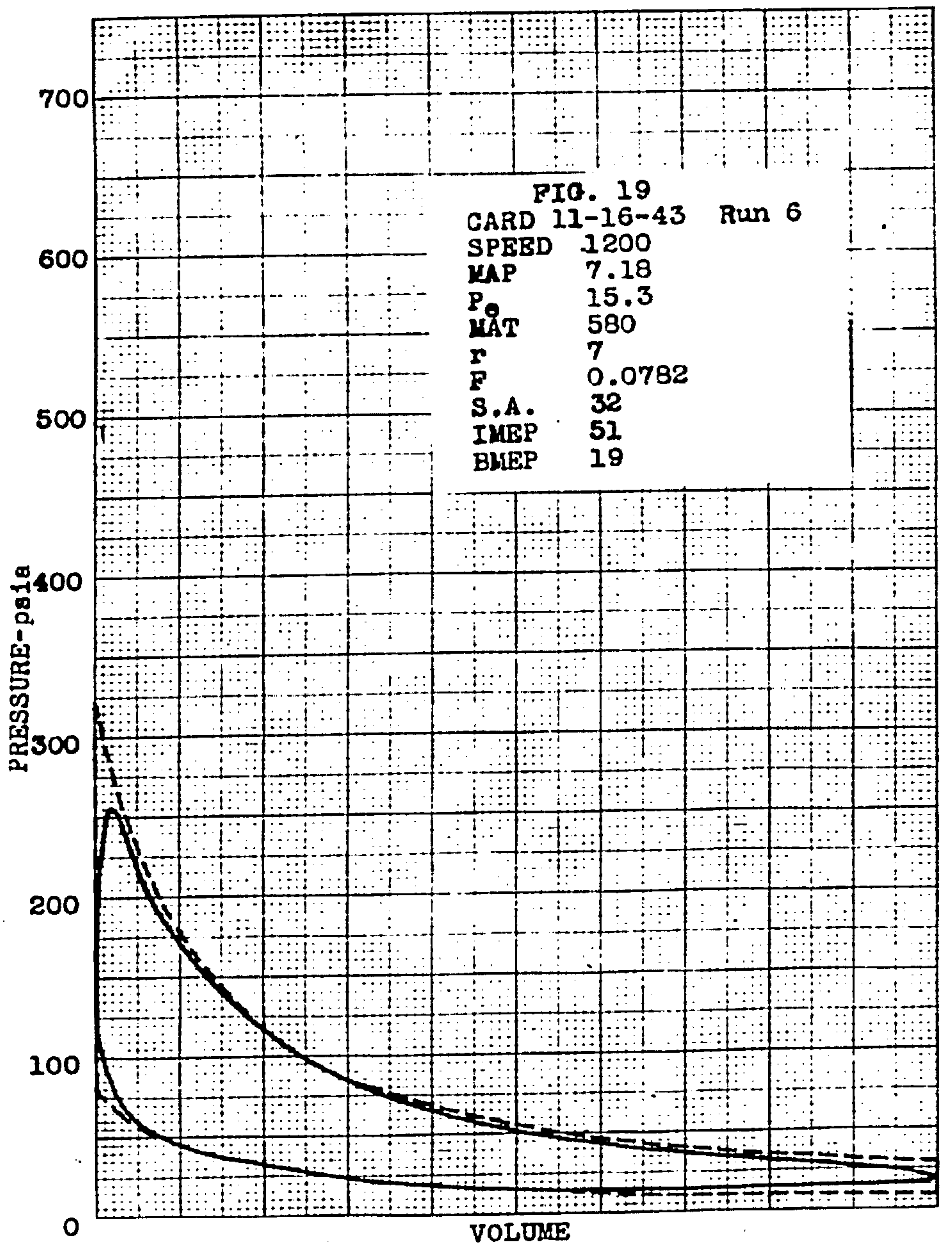


FIG. 19

CARD 11-16-43 Run 6

SPEED	1200
MAP	7.18
P_e	15.3
MAT	580
r	7
F	0.0782
S.A.	32
IMEP	51
BMEP	19

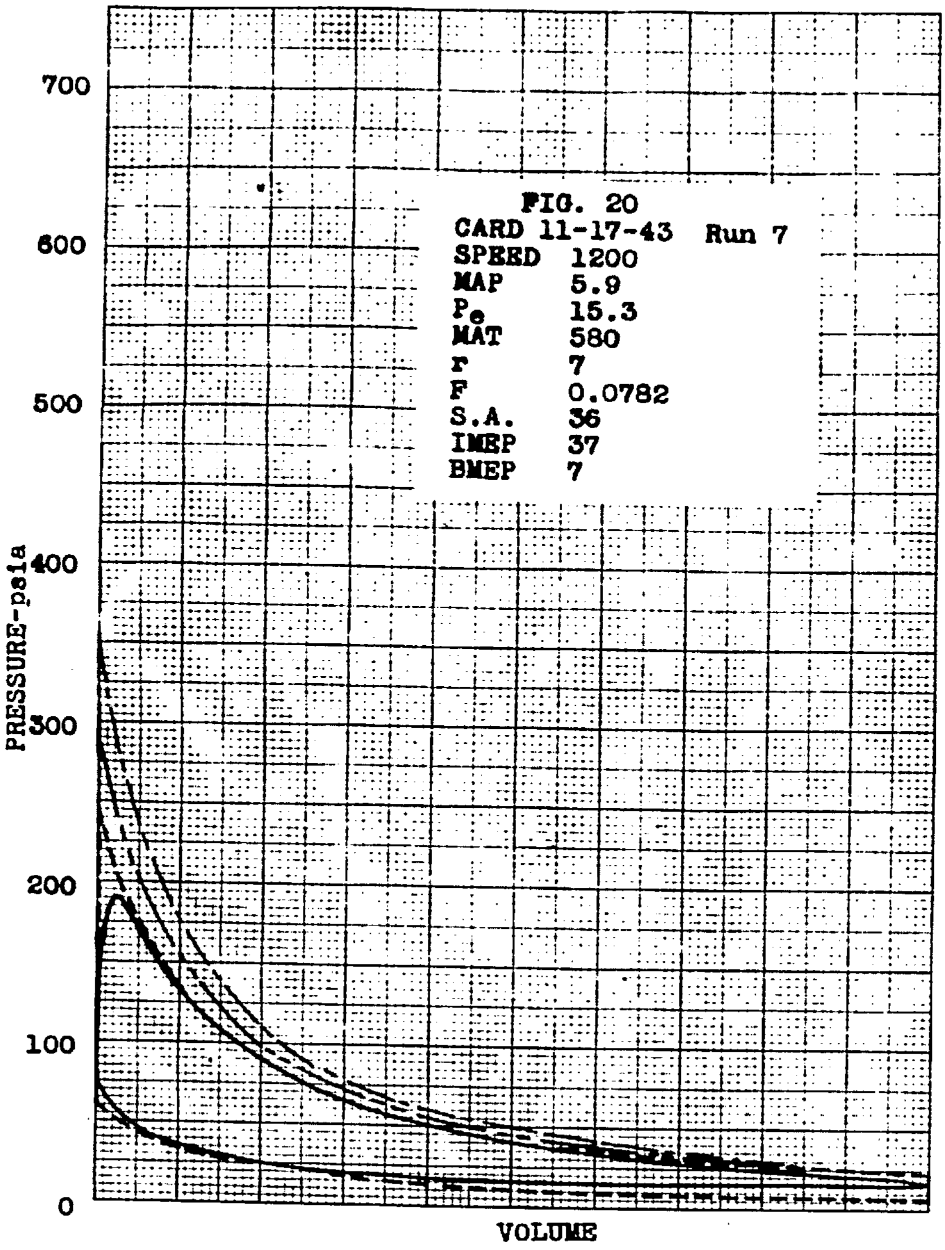


FIG. 20

CARD 11-17-43 Run 7

SPEED	1200
MAP	5.9
P_e	15.3
MAT	580
r	7
F	0.0782
S.A.	36
IMEP	37
BMEP	7

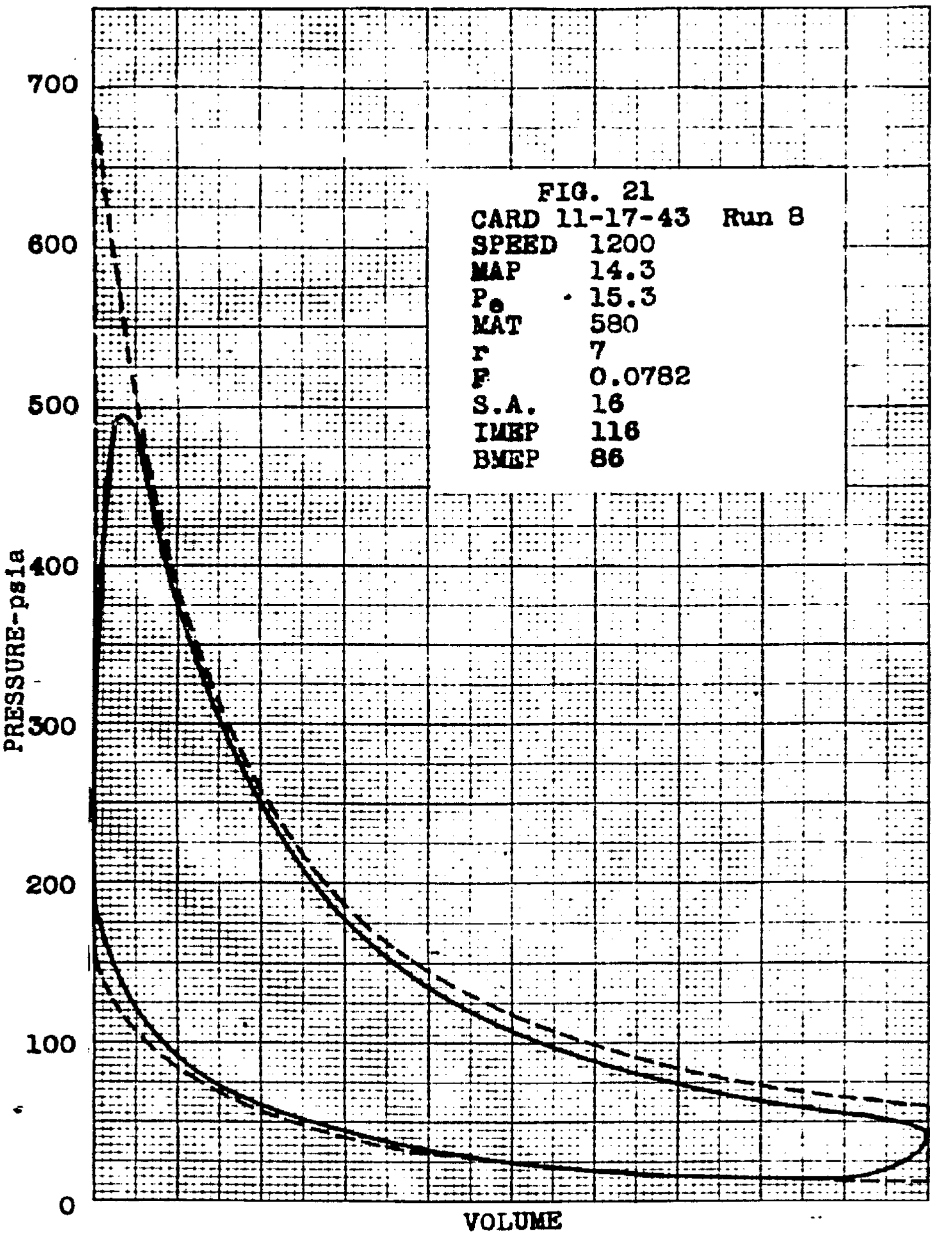


FIG. 21

CARD 11-17-43 Run 8

SPEED	1200
MAP	14.3
P_e	15.3
MAT	580
r	7
F	0.0782
S.A.	16
IMEP	116
BMEP	86

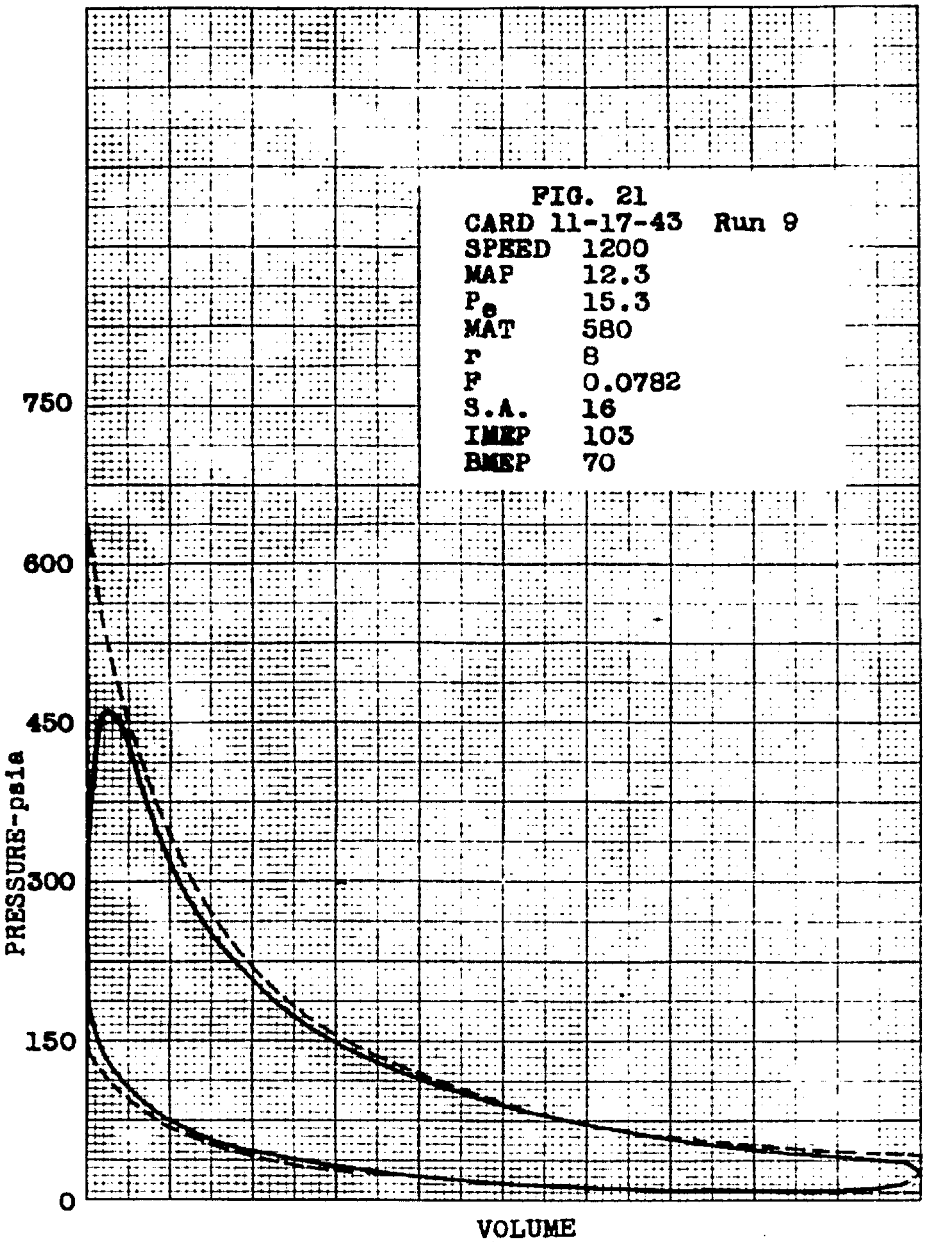


FIG. 21

CARD 11-17-43 Run 9

SPEED	1200
MAP	12.3
P_e	15.3
MAT	580
r	8
F	0.0782
S.A.	16
IMEP	103
BMEP	70

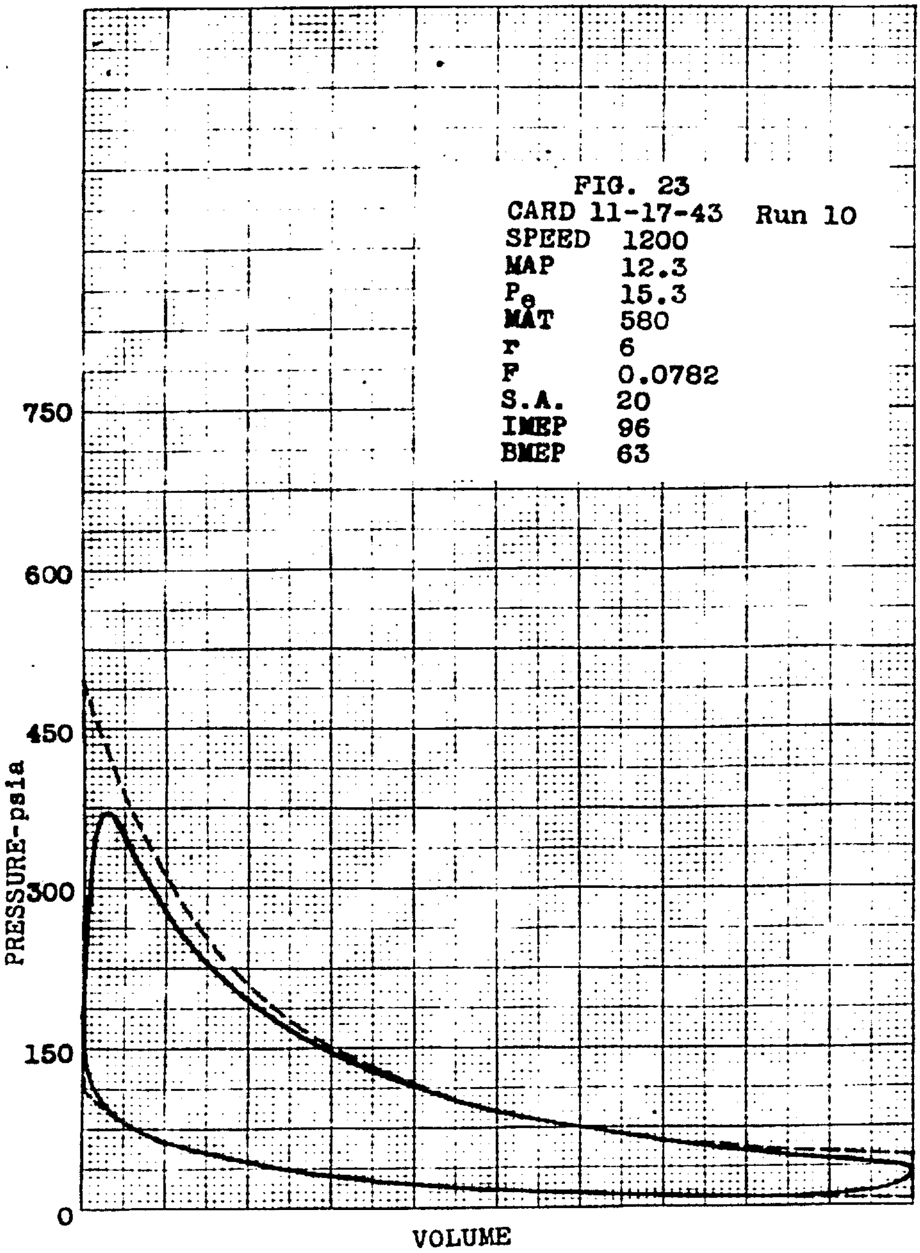


FIG. 23

CARD 11-17-43 Run 10
SPEED 1200
MAP 12.3
P_e 15.3
MAT 580
r 6
F 0.0782
S.A. 20
IMEP 96
BMEP 63

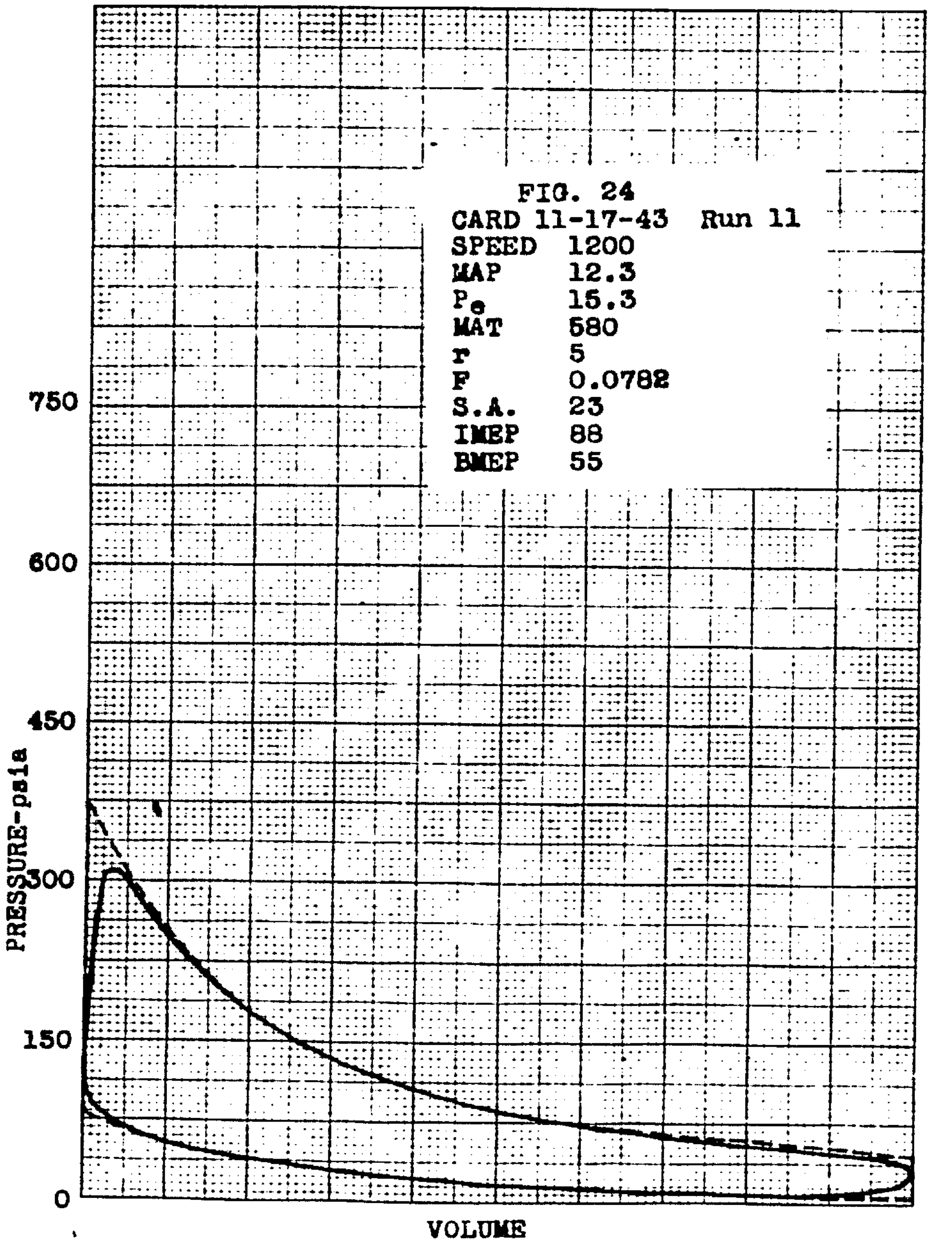


FIG. 24

CARD 11-17-43 Run 11
SPEED 1200
MAP 12.3
P_e 15.3
MAT 580
r 5
F 0.0782
S.A. 23
IMEP 88
BMEP 55
750
600
450
300
150
0
PRESSURE-psia
VOLUME

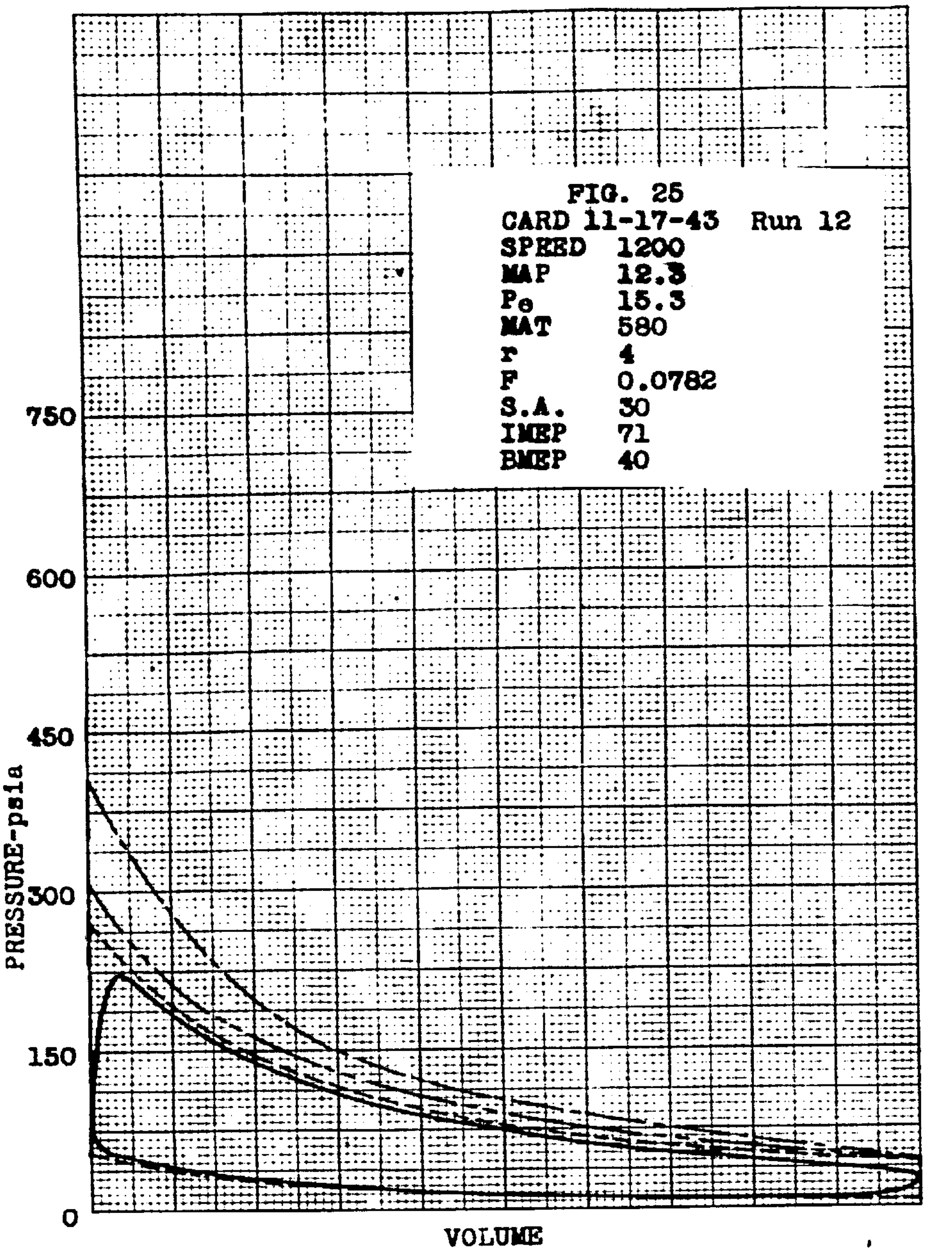
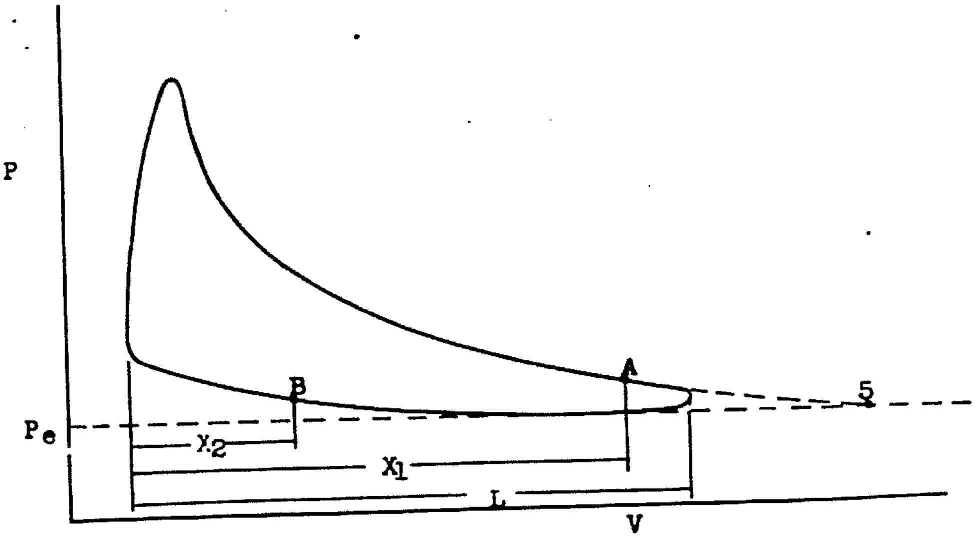


FIG. 25

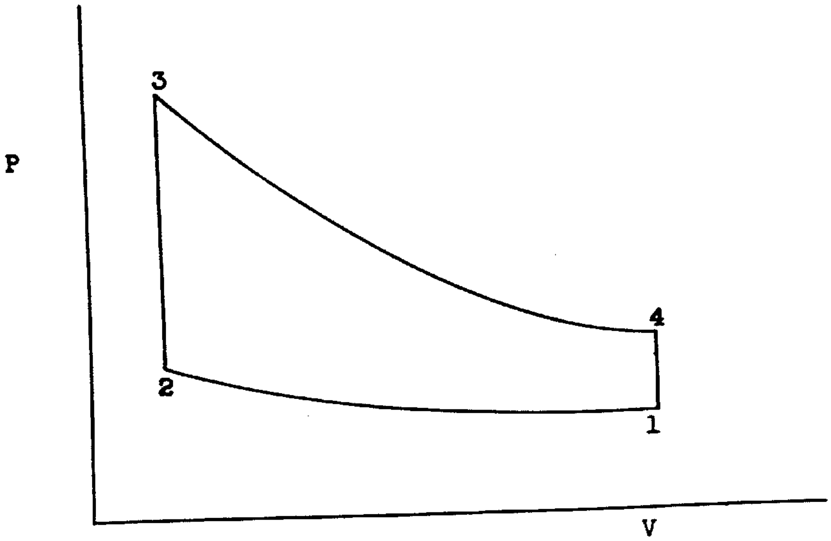
CARD 11-17-43 Run 12
SPEED 1200
MAP 12.3
P_e 15.3
MAT 580
r 4
F 0.0782
S.A. 30
IMEP 71
BMEP 40

APPENDIX



Actual Cycle

FIG 14



Theoretical Cycle

FIG 15

TABLE OF SYMBOLS

BMEP	brake mean effective pressure
E	total internal energy
E_c	energy of combustion
E_s	internal energy exclusive of energy of combustion
F	fuel-air ratio
IMEP	indicated mean effective pressure (from indicator cards)
MAP	manifold absolute pressure
MAT	manifold absolute temperature
MEP	mean effective pressure
P	pressure
P_e	exhaust or back pressure
r	compression ratio
S.A.	spark advance
u	internal energy
V	volume
v_r	relative volume

Computation of Actual Cycle for Run #1

The mean effective pressure from the P-V cards is calculated from the equation

$$IMEP = \frac{A_c K}{L_c} \quad psi$$

where A_c = area of P-V plot, sq. ins.

L_c = length of P-V plot, ins.

K = spring constant, lbs. per in.

$$IMEP = \frac{(5.06)(100)}{5} = 101 \quad psi$$

The efficiency is the ratio of work output to the heat input

$$Work = \frac{PLAN}{778 \quad W_A} \quad \text{Btu per lb. of raw air}$$

P = IMEP, lbs. per sq. ft.

L = length of stroke, ft.

A = area of piston, sq.ft.

N = no. of intake strokes per sec.

W_A = air consumption, lbs. per sec.

$$Work = \frac{(101)(4.5)(3.25)^2(10)(3.14)}{(12)(778)(4)(.00915)} = 442 \text{ Btu per lb. of air}$$

For each lb. of air F lbs. of fuel are also added. The heating value of F lbs. of fuel is F(19,240) Btu.

Heat input = (.0782)(19,240) = 1507 Btu

Efficiency = $\frac{442}{1507}$ = .293

Computation of Equivalent Fuel-Air Cycle for Run #1

To find the initial conditions a point low on the expansion line such as A, Figure 14, is selected and the pressure and volume measured with a scale.

Piston displacement = 37.4 sq.in. = V_{PD}

Clearance volume = 6.23 sq. in. = V_{cl}

Cylinder volume of A = $\frac{r}{L} V_{PD} + V_{CL}$

$$V_{CA} = \frac{4.44}{5}(37.4) + 6.23 = 39.4 \text{ in}^2$$

The volume on the fuel-air chart at this point,

$$V_A = \frac{\text{cylinder volume, ft.}^3}{\text{lb. of air in cylinder}} = \frac{V_c\,(1-f)}{B}$$

B = weight of air taken in per stroke

f = fraction of residual gas

V_C = cylinder volume at point in question

V_A = chart volume at point A

A guess is made as to f and the chart volume computed. f = .065

$$V_A = \frac{(39.4)(.935)}{(1728)\ 9.15 \times 10^{-4}} = 23.3 \text{ cu.ft.}$$

P_A from diagram $= 48.6$ psi.

Then this point is found on the burned fuel-air chart and a line of constant entropy is followed to P_E to find V_5.

$P_E = 15.3$ psi

$V_5 = 55$ cu.ft.

$$\frac{V_2}{V_{c2}} = \frac{V_A}{V_{cA}} = \frac{V_1}{V_{c1}}$$

$$V_2 = \frac{(23.3)}{(39.4} (6.23) = 3.69 \text{ cu.ft.}$$

$$\frac{V_2}{V_5} = \frac{3.69}{56} = .0647$$

Since $f = \frac{V_2}{V_5}$ the assumption of $f = .065$ is good.

$$V_1 = \frac{(23.3)}{39.4} (43.63) = 25.83 \text{ cu.ft.}$$

Another point, B, is then selected on the compression line of the diagram such that the pressure can easily be read.

$$V_{CB} = \frac{1.44}{5} (37.4) + 6.23 = 20.7$$

$$V_B = \frac{(23.3)}{(39.4)} (20.7) = 12.3 \text{ cu.ft.}$$

$P_B = 27.6$ psi

This point is found on the unburned chart and a line of constant entropy is followed to V_1 to find the initial pressure P_1. At the point , P_1 V_1, the initial temperature, T_1, and sensible internal energy or internal energy exclusive of energy of combustion is found.

P_1 = 10 psi
V_1 = 25.83 cu.ft.
T_1 = 670°R
E_{s1} = 30 Btu

Then a line of constant entropy is followed on the same unburned chart to point 2 (Figure 15) and where V_2 is already known.

V_2 = 3.59 cu.ft.
P_2 = 130 psi
T_2 = 1265°R
E_{s2} = 165 Btu

Combustion takes place from point 2 to point 3 and the energy of combustion, E_c, is calculated from the formula on the fuel-air chart.

$$E_c = (1507)(1-f) + 300f$$
$$= (1507)(.935) + (300)(.065) = 1429 \text{ Btu}$$
$$E_3 = E_{s2} + E_c = 1429 + 165 = 1594 \text{ Btu}$$
$$V_3 = V_2 = 3.69 \text{ cu.ft.}$$

Point E_3, V_3 is then found on the burned chart where the P_3 and T_3 are read

$$P_3 = 560 \text{ psi}$$
$$T_3 = 5000^\circ R$$

From this point a line of constant entropy is again followed to $V_4 = V_1$ and the values again read directly

$$V_4 = 25.83 \text{ cu.ft.}$$
$$P_4 = 53 \text{ psi}$$
$$T_4 = 3230$$
$$E_4 = 990$$

The work of the cycle W, the mean effective pressure, MEP, and the efficiency are then calculated by the following equations:-

$$W = (E_3 - E_4) - (E_{s2} - E_{s1})$$
$$= (1594 - 990) - (165 - 30) = 469 \text{ Btu}$$

$$MEP = \frac{W}{V_1 - V_2}$$
$$= \frac{(469)(778)}{(22.14)(144)} = 114 \text{ psi}$$

$$Eff = \frac{W}{(1-f)1507}$$
$$= \frac{469}{(.935)(1507)} = .333$$

Computation of Standard Air Cycle for Run #1

A reversible adiabatic process is assumed from 1 to 2 (Figure 15) and from 3-4 and a constant volume process is assumed from 2 to 3 and from 4 to 1. As explained in the Bases of Cycles the conditions at point 1 are assumed to be those in the manifold where temperature T_1 and pressure P_1 were measured.

$$v_1 = \frac{WR\,T_1}{p_1}$$

R = universal gas constant for air

R = 53.35 ft. lbs. per degree Rankine per lb.

W = weight of air = 1 lb.

$$v_1 = \frac{(53.35)(580)}{(12.3)\ (144)} = 17.46 \text{ ft}^3$$

From 1 to 2

$$v_2 = \frac{1}{r}\ v_1 = \frac{17.46}{7} = 2.49 \text{ ft}^3$$

$p_1\, v_1^{\,k} = p_2\, v_2^{\,k}$ for a reversible adiabatic process.

k = 1.4 for air

$$p_2 = \left(\frac{v_1}{v_2}\right)^k p_1 = (12.3)(7)^{1.4} = 187 \text{ psi}$$

$$T_2 = \frac{p_2 v_2}{R} = \frac{(187)(2.49)(144)}{(53.35)} = 1260^\circ\text{R}$$

From 2 to 3

Heat, Q, is added at constant volume and since we assume a volumetric efficiency of 100%

$$Q = (\text{Available heat})\left(\frac{r-1}{r}\right) = 1280\ \frac{6}{7} = 1098 \text{ Btu}$$

$Q = WC_v\ (T_3 - T_2)$ where C_v = specific heat of air at constant volume

C_v = .169 Btu per lb. per degree Rankine

$$T_3 = \frac{Q}{C_v} + T_2 = \frac{1098}{.169} + 1260 = 7760^\circ R$$

$$v_3 = v_2 = 2.49 \text{ ft}^3$$

$$P_3 = \frac{RT_3}{v_3} = \frac{(53.35)(7760)}{(2.49)(144)} = 1152 \text{ psi.}$$

From 3 to 4

$$p_3 v_3^{\,k} = p_4 v_4^{\,k}$$

$$p_4 = p_3\left(\frac{v_3}{v_4}\right)^k = 1152\ \left(\frac{1}{7}\right)^{1.4} = 75.9 \text{ psi}$$

$$v_4 = 17.46 \text{ ft}^3$$

$$T_4 = \frac{p_4 v_4}{R} = \frac{(75.9)(17.46)(144)}{(53.35)} = 3580^\circ R$$

$$\text{Work} = M\ C_v\ \ (T_3 - T_2) - (T_4 - T_1)$$

$$= .169\ \ (7760 - 1260) - (3580 - 300) = 594 \text{ Btu}$$

$$MEP = \frac{W}{v_1 - v_2} = \frac{(594)(778)}{(14.97)(144)} = 214 \text{ psi}$$

The efficiency based on the amount of available heat is

$$Eff = \frac{594}{1098} = .541$$

This efficiency can be checked by the following:

$$Eff. = 1 - \left(\frac{1}{r}\right)^{k-1} = 1 - \left(\frac{1}{7}\right)^{.4} = .541$$

In order to base the efficiency on the amount of potential heat when F = .0782 instead of the heat added in the cycle which is that for a chemically correct mixture containing one pound of air, the resulting efficiency is multiplied by the ratio of chemically correct to actual fuel-air ratio and we get a result which more nearly approximates the actual

$$(.541)\left\{\frac{.0665}{.0782}\right\} = .460$$

<u>Computation of Keenan and Kaye Air Cycle for Run #1</u>

State	^oR	u	v_r	v	P
1	<u>580</u>	3.46	3946	21.5	10
2	1231	119.4	<u>563.7</u>	<u>3.07</u>	149
3	6500	<u>1316</u>	2.997	3.07	784
4	3599	626.4	20.979	21.5	62

The mixture of air and octane is assumed to be equivalent to air as regards the relationship between its properties. State 1 is determined by the manifold temperature and pressure, the values of u and v_r being read from the tables. Since internal energy enthalpy, and specific heats depend upon the temperature only, the manifold temperature of 580°R. determines these properties. The specific volume is determined however, from the perfect gas law, the manifold pressure being used.

$$v = \frac{RT}{P} = \frac{53.34 \times 580}{144 \times 10} = 21.5$$

The compression ratio being 7, the relative volume which determines state 2 must be 1/7 of state 1, the entropy being constant.

$$3946/7 = 563.7$$

The internal energy at point 3 equals the energy of the products base at 2 plus the energy of combustion. The energy of combustion being computed by

$$(19{,}240 \times F) \times 1/2 + F \quad \times \frac{r-1}{r} =$$

$$19{,}240 \times \frac{.0782}{1 + .0782} \times \frac{(7-1)}{7} = 1197$$

19,240 = Btu/ lb. fuel

F = fuel-air ratio

$\frac{r-1}{r}$ = factor based on assumption that fresh charge fills the piston displacement only. (19,240 x F) Btu/lb. air never is greater than 1280, the equivalent heat of chemically correct combustion, and the factor $\frac{1}{1 + F}$ lbs. air/lb. mixture, determines the basis of combustion as Btu/lb. mixture.

$$u_3 = u_2 = 119.7 + 1197 = 1316$$

From this value and Keenan and Kaye table, T_3, v_3 are determined. Since 2-3 is a constant volume process:

$$P_3 = \frac{RT_3}{v_2} = \frac{53.34 \times 650}{144 \times 3.07}$$

The relative volume at state 4 is 7 times that at state 3 and the remaining properties correspond to this value.

Computation of Equivalent Standard Air and Equivalent Keenan and Kaye Air Cycles for Run 1

The pressure and volume of point 1 are taken from the Equivalent Fuel-Air Cycle and the temperature calculated.

$$V_1 = 25.83 \text{ cu. ft.}$$

$$P_1 = 10 \text{ psi}$$

$$T_1 = \frac{P_1V_1}{R} = \frac{(25.83)(10)(144)}{53.35} = 695°R$$

Each cycle is then calculated by the methods shown above except that the heat added in both is (1-f) times the chemical energy of a chemically correct mixture where f is also obtained from the Equivalent Fuel-Air Cycle.

$$f = .065$$

$$Q = (1-f)(F)(19,240) = (.925)(.0665)(19,240)$$

$$= 1196 \text{ Btu}$$

EXTENSION OF KEENAN AND KAY AIR TABLE

T°R	u	vr
5400	1051.51	5.197
5420	1056.32	5.130
5440	1061.13	5.064
5460	1065.94	4.999
5480	1070.75	4.935
5500	1075.56	4.872
5520	1080.37	4.810
5540	1085.18	4.749
5560	1089.99	4.689
5580	1094.80	4.630
5600	1099.61	4.572
5620	1104.42	4.515
5640	1109.23	4.459
5660	1114.04	4.404
5680	1118.85	4.350
5700	1123.66	4.297
5720	1128.47	4.245
5740	1133.28	4.194
5760	1138.09	4.144
5780	1142.90	4.095
5800	1147.71	4.047
5820	1152.52	4.000
5840	1157.33	3.954
5860	1162.14	3.909
5880	1166.95	3.865
5900	1171.76	3.822
5920	1176.57	3.780
5940	1181.38	3.739
5960	1186.19	3.699
5980	1191.00	3.660
6000	1195.81	3.622
6020	1200.62	3.585
6040	1205.43	3.549
6060	1210.24	3.514
6080	1215.05	3.480
6100	1219.86	3.447
6120	1224.67	3.415
6140	1229.48	3.384
6160	1234.29	3.354
6180	1239.10	3.325
6200	1243.91	3.297
6220	1248.72	3.270
6240	1253.53	3.244
6260	1258.34	3.219
6280	1263.15	3.195

T°R	u	vr
6300	1267.96	3.172
6320	1272.77	3.150
6340	1277.58	3.129
6360	1282.39	3.109
6380	1287.20	3.090
6400	1292.01	3.072
6420	1296.82	3.055
6440	1301.63	3.039
6460	1306.44	3.024
6480	1311.25	3.010
6500	1316.06	2.997
6520	1320.87	2.985
6540	1325.68	2.974
6560	1330.49	2.964
6580	1335.30	2.955
7000	1340.11	2.947
7020	1344.92	2.940
7040	1349.73	2.934
7060	1354.54	2.929
7080	1359.35	2.925
7100	1364.16	2.922

Sloan Automotive Laboratory, M.I.T. C.F.R. Engine #1

Fuel 100 Octane S.G. 0.695

Bore 3-1/4 ins. Stroke 4-1/2 ins. Compression Ratio Variable

	Time	Run	MAP ins Hg	P_E ins Hg	MAT °R	Air Cons. #/sec.	Fuel Cons. #/sec.	F	S.A.	r
Nov.16,1943	1:30 PM	1	25	31	580	.00915	.000716	.0782	18	7
Bar.29.85" Hg	2:00 PM	2	25	31	580	.00915	.000608	.0665	19.5	7
	2:50 PM	3	25	31	580	.00915	.000554	.0605	25	7
	3:30 PM	4	25	31	580	.00915	.000869	.095	24	7
	4:20 PM	5	19.65	31	580	.00697	.000545	.0782	23	7
Nov.17,1943	10:55 AM	6	14.6	31	580	.00485	.000380	.0782	32	7
Bar. 30.01"	11:30 AM	7	12.0	31	580	.00371	.000290	.0782	36	7
Hg	12:20 AM	8	29.1	31	580	.0111	.000870	.0782	16	7
	2:30 PM	9	25	31	580	.00904	.000708	.0782	16	8
	2:55 PM	10	25	31	580	.00929	.000727	.0782	20	6
	3:20 PM	11	25	31	580	.00907	.000709	.0782	23	5
	3:50 PM	12	25	31	580	.00877	.000685	.0782	30	4

Run #1 F = .0782 r = 7 MAP = 12.3 psi

MAT = 580°R. Pc = 15.3 psi

Equivalent Fuel-Air Cycle

State	T	P	V	E	f
1	670	10	25.83	30 s	.0645
2	1265	130	3.69	165 s	
3	5000	560	3.69	1594	
4	3230	53	25.83	990	

Work = 469 Btu MEP = 114 psi Eff = .333

Standard Air Cycle

State	T	P	V
1	580	12.3	17.46
2	1260	187	2.49
3	7760	1152	2.49
4	3570	75.9	17.46

Work = 594 Btu MEP = 214 psi Eff = .460

Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	580	12.3	17.45	3946	3.46
2	1231	183	2.49	563.7	119.46
3	5760	865	2.49	4.144	1138
4	3279	69.5	17.45	29.008	550.3

Work = 472 Btu MEP = 169 psi Eff = .394

Actual Cycle

Work = 442 Btu 1 MEP = 101 psi Eff = .293

P_{max} = 414 psi

Run #1

Equivalent Standard Air Cycle

State	T	P	r
1	695	10	25.83
2	1515	152	3.69
3	8595	860	3.69
4	3960	56.6	3.69

Work = 645 Btu MEP = 157 psi Eff = .460

Equivalent Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	700	10	25.83	2458	24.16
2	1458.7	146	3.69	351.1	163.01
3	7070	710	3.69	2.927	1357
4	3632.1	52	25.83	20.489	632.17

Work = 586 Btu MEP = 220 psi Eff = .389

Run #2 F = .0665 r = 7 MAP = 12.3 psi

MAT = 580°R Pc = 15.3 psi

Equivalent Fuel-Air Cycle

State	T	P	V	E	f
1	665	10	25.83	30 s	.065
2	1260	130	3.69	160 s	
3	4970	550	3.69	1360	
4	3400	56	25.83	750	

Work = 480 BTU MEP = 117 psi Eff. = .401

Standard Air Cycle

State	T	P	V
1	580	12.3	17.46
2	1260	187	2.49
3	7760	1152	2.49
4	3570	75.9	2.49

Work = 594 Btu MEP = 214 psi Eff. = .541

Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	580	12.3	17.45	3946	3.46
2	1231	183	2.49	563.7	119.46
3	5813	863	2.49	4.031	1149.46
4	3294	69.9	17.45	28.217	556.37

Work = 477 btu MEP = 172 psi Eff. = .463

Actual Cycle

Work = 447 Btu MEP = 102 psi Eff. = .349

P_{max} = 401 psi

Run #3 F = .0605 r = 7 MAP = 12.3 psi

MAT = 580°R. Pc = 15.3 psi

Equivalent Fuel-Air Cycle

State	T	P	V	E	f
1	650	10	25.62	27 s	.07
2	1260	128	3.66	150 s	
3	4825	530	3.66	1230	
4	3200	50	25.62	660	

Work = 447 Btu MEP = 110 psi Eff. = .413

Standard Air Cycle

State	T	P	V
1	580	12.3	17.46
2	1260	187	2.49
3	7160	1060	2.49
4	3300	70	17.46

Work = 538 Btu MEP = 194 psi Eff. = .541

Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	580	12.3	17.45	3946	3.46
2	1231	183	2.49	563.7	119.46
3	5420	805	2.49	5.13	1056.46
4	3062	65	17.45	35.91	503.9

Work = 436 Btu MEP = 158 psi Eff. = .466

Actual Cycle

Work = 405 Btu MEP = 93 psi Eff. = .347

Pmax = 395 psi

Run #4 F = .095 r = 7 MAP = 12.3 psi
MAT = 580°R. Pc = 15.3 psi

Equivalent Fuel-Air Cycle

State	T	P	V	E	f
1	740	11	25.8	44 s	.095
2	1340	135	3.7	.183 s	
3	4790	580	3.7	1933	
4	2960	52	25.8	1348	

Work = 446 Btu MEP = 109 psi Eff. = .262

Standard Air Cycle

State	T	P	V
1	580	12.3	17.46
2	1260	187	2.49
3	7760	1152	2.49
4	3570	75.9	17.46

Work = 594 Btu MEP = 214 psi Eff. = .378

Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	580	12.3	17.45	3946	3.46
2	1231	183	2.49	563.7	119.46
3	5680	843	2.49	4.35	1119.46
4	3219	68.3	17.45	30.45	539.4

Work = 464 Btu MEP = 167 psi Eff. = .320

Actual Cycle

Work = 409 Btu MEP = 96 psi Eff. = .223

Pmax. = 476 psi

Ruh #5 F = .0782 R = 7 MAP = 9.65 psi
MAT = 580°R. Pc = 15.3 psi

Equivalent Fuel-Air Cycle

State	T	P	V	E	f
1	720	8	33.32	40 s	.08
2	1305	105	4.67	185 s	
3	5000	450	4.67	1595	
4	3200	40	33.32	985	

Work = 465 Btu MEP = 88 psi Eff. = .335

Standard Air Cycle

State	T	P	V
1	580	9.7	22.26
2	1260	147	3.18
3	7760	904	3.18
4	3570	59	22.26

Work = 594 Btu MEP = 168 psi Eff. = .460

Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	580	9.65	22.2	3946	3.46
2	1231	144	3.17	563.7	119.46
3	5760	674	3.17	4.144	1138.
4	3279	54.8	22.2	29.008	550.3

Work = 469 Btu MEP = 133 psi Eff. = .394

Actual Cycle

Work = 437 Btu MEP = 76 psi Eff. = .290

Pmax. = 343 psi

Run #6 F = .0782 r = 7 MAP = 7.18 psi

MAT = 580°R. Pc = 15.3 psi

Equivalent Fuel Air Cycle

State	T	P	V	E	f
1	800	7	46.9	57 s	.10
2	1420	80	6.7	205 s	
3	4950	320	6.7	1590	
4	3250	29	46.9	992	

Work = 450 Btu MEP = 60.5 psi Eff. = .332

Standard Air Cycle

State	T	P	V
1	580	7.2	29.9
2	1260	109	4.3
3	7760	673	4.3
4	3570	44	29.9

Work = 594 Btu MEP = 125 psi Eff. = .460

Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	580	7.18	29.9	3946	3.46
2	1231	106	4.3	563.7	119.46
3	5760	496	4.3	4.144	1138
4	3279	40.6	29.9	29.008	550.3

Work = 469 Btu MEP = 99 psi Eff. = .394

Actual Cycle

Work = 424 Btu MEP = 51 psi Eff. = .282

Pmax = 255 psi

Run #7 F = .0782 r = 7 MAP = 5.9 psi

MAT = 580°R. Pc = 15.3 psi

Equivalent Fuel-Air Cycle

State	T	P	V	E	f
1	745	5	59.4	45 s	.127
2	1340	60	8.5	185 s	
3	4820	242	8.5	1536	
4	3120	22	59.4	958	

Work = 438 Btu MEP = 46.5 psi Eff. = .333

Standard Air Cycle

State	T	P	V
1	580	5.9	36.4
2	1260	89.6	5.2
3	7760	553	5.2
4	3570	36.4	36.4

Work = 594 Btu MEP = 106 psi Eff. = .460

Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	580	5.9	36.4	3946	3.46
2	1231	87.7	5.2	563.7	119.46
3	5760	411	5.2	4.144	1138
4	3279	33.4	36.4	29.008	550.3

Work = 469 Btu MEP = 81.2 psi Eff. = .394

Actual Cycle

Work = 403 Btu MEP = 37 psi Eff. = 268

Pmax = 191 psi

Run #7

Equivalent Standard Air Cycle

State	T	P	V
1	720	5	59.4
2	1560	76	8.49
3	8179	355	8.49
4	3760	23.4	59.4

Work = 604 Btu MEP = 64 psi Eff = .460

Equivalent Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	800	5	59.4	1751.4	41.57
2	1642	71.6	8.5	250.2	199
3	6492	283	8.5	3.002	1314
4	3598.7	22.1	59.4	21.014	626

Work = 531 Btu MEP = 56 psi Eff = .353

Run #8 F = .0782 r = 7 MAP = 14.3 psi

MAT = 580°R. Pc = 15.3 psi

Equivalent Fuel-Air Cycle

State	T	P	V	E	f
1	670	12	22	30 s	.056
2	1220	152	3.14	156 s	
3	5000	680	3.14	1593	
4	3200	61	22	980	

Work = 487 Btu MEP = 139 psi Eff. = .342

Standard Air Cycle

State	T	P	V
1	580	14.3	15.0
2	1260	217	2.14
3	7760	1340	2.14
4	3570	88	15.0

Work = 594 Btu MEP = 249 psi Eff. = .460

Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	580	14.3	15	3946	3.46
2	1231	217.	2.1	563.7	119.46
3	5760	1010.	2.1	4.144	1138.
4	3279	81.1	15.	29.008	550.3

Work = 469 Btu MEP = 196 psi Eff. = .414

Actual Cycle

Work = 418 Btu 1 MEP = 116 psi Eff. = .278

Pmax ≐ 497 psi

Run #9 F = .0782 r = 8 MAP = 12.3 psi

MAT = 580°R. Pc = 15.3 psi

Equivalent Fuel-Air Cycle

State	T	P	V	E	f
1	640	8	26.5	23 s	.056
2	1220	145	3.3	155 s	
3	5000	640	3.3	1592	
4	3100	49	26.5	950	

Work = 510 Btu MEP = 119 psi Eff. = .358

Standard Air Cycle

State	T	P	V
1	580	12.3	17.46
2	1328	225	2.18
3	7948	1348	2.18
4	3470	73.6	17.46

Work = 630 Btu MEP = 222 psi Eff. = .480

Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	580	12.3	17.45	3946	3.46
2	1292	219.5	2.18	493.25	131
3	5900	1000	2.18	3.822	1171
4	3215	68.1	17.45	30.576	538.5

Work = 506 Btu MEP = 179 psi Eff. = .394

Actual Cycle

Work = 443 Btu 1 MEP = 103 psi Eff. = .294

Pmax. = 468 psi

Run #10 F = .0782 r = 6 MAP = 12.3 psi

MAT = 580°R. Po = 15.3 psi

Equivalent Fuel-Air Cycle

State	T	P	V	E	f
1	800	12	26	56 s	.07
2	1360	120	4.4	190 s	
3	5020	500	4.4	1611	
4	3400	54	26	1040	

Work = 437 Btu MEP = 109 psi Eff. =.315

Standard Air Cycle

State	T	P	V
1	580	12.3	17.46
2	1186	151	2.91
3	7506	955	2.91
4	3685	77.5	17.46

Work = 546 Btu MEP = 203 psi Eff. = .435

Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	580	12.3	17.45	3946	3.46
2	1163	148	2.91	657.66	106.8
3	5597	710	2.91	4.582	1098.8
4	3320	70.4	17.45	27.492	562.4

Work = 433 Btu MEP = 161 psi Eff. = .372

Actual Cycle

Work = 415 Btu 1 MEP = 96 psi Eff. = .276

Pmax. = 384 psi

Run #11 F = .0782 r= 5 MAP = 12.3 psi

MAT = 580°R. Pc = 15.3 psi

Equivalent Fuel-Air Cycle

State	T	P	V	E	f
1	800	11.5	27.5	58 s	.085
2	1310	90	5.5	176 s	
3	4950	380	5.5	1580	
4	3485	52	27.5	1061	

Work = 401 Btu MEP = 98.5 psi Eff. = .291

Standard Air Cycle

State	T	P	V
1	580	12.3	17.46
2	1102	117	3.49
3	7152	756	3.49
4	3760	80	17.46

Work = 485 Btu MEP = 188 psi Eff. = .404

Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	580	12.3	17.4	3946	3.46
2	1086	115	3.49	789.2	92.76
3	5368	570	3.49	5307	1043.76
4	3355	71	17.4	26.535	570.3

Work = 384 Btu MEP = 148 psi Eff. = .342

Actual Cycle

Work = 388 Btu 1 MEP = 88 psi Eff. = .258

Pmax. = 315 psi

Run #12 F =.0782 r = 4 MAP = 12.3 psi

MAT = 580°R. Pc = 15.3 psi

Equivalent Fuel-Air Cycle

State	T	P	V	E	f
1	720	10	29.4	40 s	.110
2	1120	62	7.3	130 s	
3	4760	280	7.3	1503	
4	3490	49	29.4	1065	

Work = 348 Btu MEP = 85 psi Eff. = .260

Standard Air Cycle

State	T	P	V
1	580	12.3	17.46
2	1010	85.7	4.36
3	5680	565	4.36
4	3830	81.2	17.46

Work = 409 Btu MEP = 169 psi Eff. = .362

Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	580	12.3	17.45	3946	3.46
2	999	84.6	4.36	986.5	76.83
3	5055	429	4.36	6.55	968.8
4	3368	71.5	17.45	26.2	573.3

Work = 322 Btu MEP = 133 psi Eff. = .306

Actual Cycle

Work = 323 Btu 1 MEP = 71 psi Eff. = .214

Pmax. = 216 psi

Run #12

Equivalent Standard Air Cycle

State	T	P	V
1	794	10	29.40
2	1382	69.7	7.35
3	8132	410	7.35
4	4640	58.5	29.40

Work = 490 Btu MEP = 120 psi Eff = .362

Equivalent Keenan and Kaye Air Cycle

State	T	P	V	Vr	u
1	795	10	29.4	1779.6	40.69
2	1341	68	7.3	444.9	140.3
3	6351	320	7.3	3.118	1280.3
4	4195	52.9	29.4	12.472	765

Work = 416 Btu MEP = 103 psi Eff = .276

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