THE EFFECT OF INTAKE AIR TEMPERATURES ON SUPERCHARGE METHOD FUEL RATINGS

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

Bernard Arthur Johnson

1952

This is to certify that the

thesis entitled

THE EFFECT OF INTAKE AIR TEMPERATURES

ON SUPERCHARGE METHOD FUEL RATINGS

presented by

BERNARD ARTHUR JOHNSON

has been accepted towards fulfillment
of the requirements for

MASTER OF SCIENCE degree in MECHANICAL ENGINEERING

Louis L. O[illegible]
[illegible] G. W. Hobbs
Major professor

Date March 13, 1952

O-169

THE EFFECT OF INTAKE AIR TEMPERATURES ON SUPERCHARGE METHOD FUEL RATINGS

By

BERNARD ARTHUR JOHNSON

A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Mechanical Engineering

THESIS

4/11/52
(9)

ACKNOWLEDGMENT

The author wishes to take this opportunity to express his sincere thanks to Dr. L. L. Otto, under whose kind guidance and unfailing interest this investigation was undertaken. The author also wishes to thank Mr. R. V. Kerley of Ethyl Corporation, Mr. Mr. R. M. Gooding of the Bureau of Mines, and Mr. J. M. Snell of Standard Oil Company for furnishing valuable information in connection with this investigation.

TABLE OF CONTENTS

INTRODUCTION

An important requisite of an aircraft engine operating at high altitudes is that it use a minimum amount of air for each unit of energy it produces. This is necessary since the density of air decreases as the altitude increases, and the difference between the available air and the necessary air at that altitude must be made up by the supercharger. Consequently, a greater amount of engine output must be diverted to the supercharger for operation at higher altitudes. The smaller the engine's appetite for air for a given output, the less energy will be lost to the supercharger.

Some of the factors which have an influence on the energy-air relationship of an engine are engine speed, manifold pressure, grade of fuel, intake air temperature, spark advance, cylinder compression ratio and cylinder temperature. Nearly all of these are inter-related.

It is the purpose of this paper to investigate the effect of intake air temperatures on the fuel properties which influence the energy-air characteristics of the engine. The fuel properties that will be considered are octane rating and sensitivity. Sensitivity indicates the tendency of a fuel to lose octane number as the engine conditions get more severe.

A considerable amount of work is now being carried on by the American Society of Testing Materials and the National Advisory Committee on Aeronautics on the "effect of intake air temperatures on the octane rating of aviation fuels," which is a closely related subject, but very little of this information has been published. It was the intention of the investigation described in this thesis to assist the efforts of these agencies by determining the effects of intake air temperature variations upon the knock rating produced by a supercharge fuel testing engine.

APPARATUS

All tests were conducted with the aid of a modified F-4 CFR "Supercharge Method" testing unit. This unit consists of a standard CFR engine with an air induction system which permits operation over a wide range of inlet pressures.

The engine is operated at a constant compression ratio of seven to one, and at a constant speed of 1800 RPM. Spark advance is set at 45 degrees before top dead center.

An evaporative cooling system closely controls engine jacket temperature. The boiling point of the coolant, a mixture of ethylene glycol and water, is fixed by varying the concentration of the solution. The coolant is maintained at the boiling temperature. The vapors given off are passed into a water-cooled reflux condenser, and, having been condensed, drop back into the system.

The induction system consists of a series of surge tanks and pressure regulators. Air, under pressure, enters the induction system through a filter which eliminates entrained solids, and then passes through an automatic pressure-regulating valve before entering the air flowmeter. The flowmeter consists of a sharp-edged orifice in a flange mounting between two surge tanks with a water manometer indicating the pressure differential. The manometer is calibrated in minutes per 1/4 pound of air, which makes the calculation of fuel-air ratio a very simple matter. Air leaving the flowmeter passes through another pressure-regulating valve before it enters the engine. The two surge tanks, one on each side of the flowmeter, are used to reduce pulsations to a minimum. A third surge tank is used between the air inlet to the engine and the pressure-regulating valve which controls the manifold pressures under which the engine operates. To this surge tank is connected a 100-inch mercury manometer which measures the manifold or boost pressure. Two thermostatically controlled heaters preheat the air to the correct temperature before it enters the engine.

The power absorption system used with this engine has been changed from that used by the regulation F-4 testing unit. The regulation F-4 CFR testing unit employs a twenty-five horsepower alternating current synchronous induction generator for motoring and loading. In place of this, a fifteen horsepower direct current dynamometer (Fig. 1) was employed. A slide wire rheostat, mounted on the control panel (Fig. 3), was connected in series with the field circuit so that the load could be varied smoothly as the fuel and the manifold pressure were varied.

The exhaust system employed by the regulation F-4 CFR testing unit consists of a flexible water-cooled hose leading

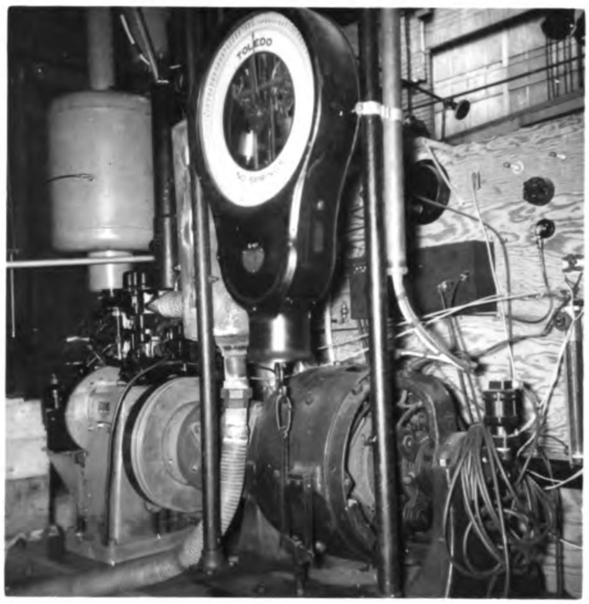


Figure 1
F-4 unit showing D. C. Dynamometer

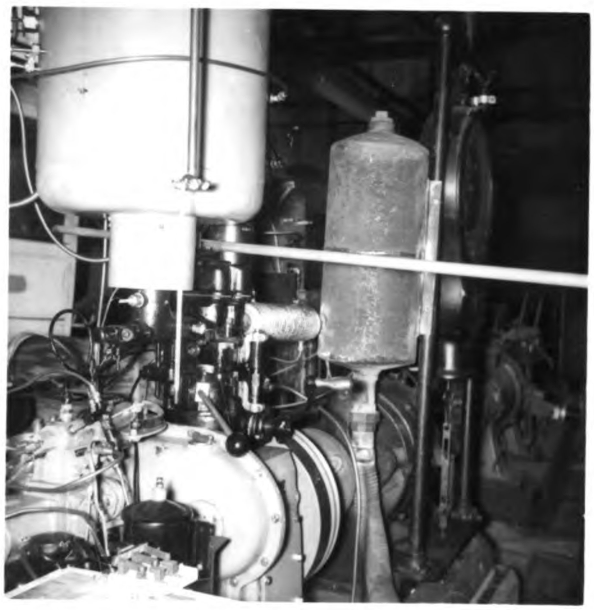


Figure 2
F-4 unit showing the exhaust surge tank

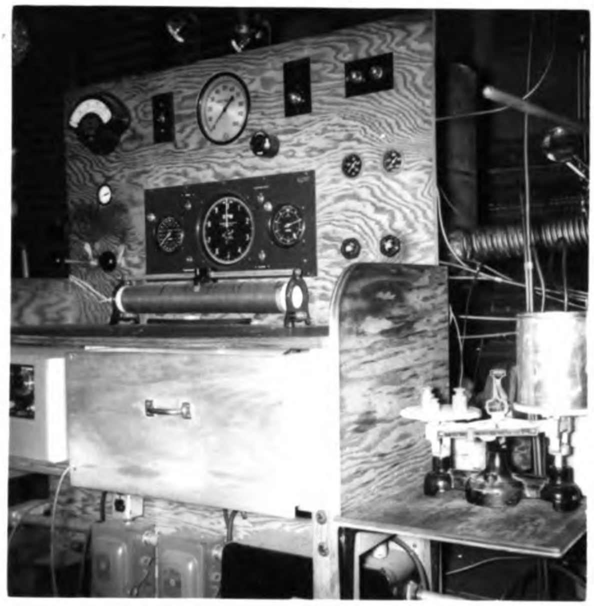


Figure 3
Control panel and fuel weighing apparatus

from the engine exhaust ports to a double-wall surge tank. Water jets are placed in the entrance to the surge tank and water is removed from the bottom of the tank. In this experiment, a single-wall surge tank (Fig. 2) meeting the dimensional requirements of the regulation tank were employed and no water injection was used. Exhaust back pressure was held to one-half inch of mercury.

The fuel weighing apparatus consisted of a balance and weights, a fuel container and stop watch. No allowance was made for the bouyancy of the inlet and outlet tubes in the fuel container.

Complete details as to the description, operation and maintenance of a regulation F-4 CFR testing unit are given in the "ASTM Manual of Engine Test Methods for Rating Fuels", 1948.

PROCEDURE

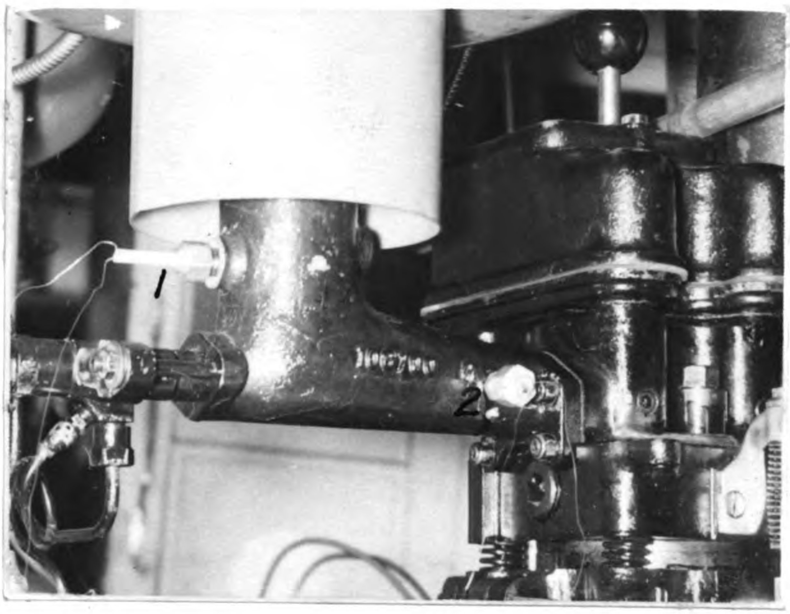
The F-4 "Supercharge Method" testing unit was designed primarily to simulate engine conditions at take off or at other situations requiring rich fuel-air ratios. Since the energy-air relationship is not very important at these conditions, the F-4 unit is not the ideal apparatus for these tests. The American Society for Testing Materials employs a F-3 unit for lean fuel-air ratio tests. However, the lean end of the fuel-air ratio range of the F-4 should at least show the trend of the energy-air relationship with changing intake air temperatures.

The following four objectives were sought in this experiment: first, to determine the percent of energy loss due to increasing air temperatures; second, to determine the relationship between intake temperature and fuel sensitivity; third, to investigate the effect of intake air temperatures and fuel sensitivity on the energy-air relationship of the engine in respect to fuel it consumes; and, fourth, to investigate the accuracy of the test by determining the relationship between the recorded intake temperatures and the actual intake temperatures.

The first three objectives were investigated experimentally by running five knock-limited mean effective pressure versus fuel-air ratio curves over a temperature range extending from 130 degrees to 300 degrees Fahrenheit. Indicated mean effective pressure, weight of fuel and air consumed, and fuel-air ratio were recorded. The exact procedure used to run these curves is given in the Appendix.

To determine the effect of fuel sensitivity, the preceding curves were run for, both, an insensitive fuel and a sensitive fuel. A reference fuel made up of 95 percent iso-octane and 5 percent normal-heptane was used for the insensitive fuel and a commercial aviation gas with a 91/96 octane rating was used as the sensitive fuel. The fact that the latter fuel is sensitive is indicated by its double rating. 91 indicates its lean mixture rating as made by the F-3, while 96 indicates its rich mixture rating as made by the F-4 used in this experiment. The reference fuel actually has a 95/95 rating.

To determine the drop in temperature in the inlet passage between the surge tank and the engine, two thermocouples were placed in the inlet elbow as shown in Figure 4. The temperatures at these points were determined for two reasons: first, to see how the temperature drop varied with air flow rate, and, second, to determine the effect, if any, which



Inlet elbow showing positions of thermocouples

Figure 4

vaporization of the fuel has on cooling the charge. The temperatures were recorded, both, with the engine running, and with the engine being motored.

DISCUSSION

One of the early obstacles in fuel testing was the inconsistency of ratings made by different testing machines. To correct this situation, testing units like the F-4 were developed and standardized so that different operators in different parts of the country could all give the same rating for the same fuel. Along with the standardization of testing equipment, certain fuels possessing desirable characteristics were also standardized and called reference fuels. For the F-4 testing unit, a series of reference curves of knock limited indicated mean effective pressure versus fuel-air ratio were run using these reference fuels and standardized into a reference chart. Thus, by running a certain reference fuel in the testing unit and comparing the resultant curve with those in the reference chart, it can be seen whether that particular testing unit is rating fuels properly. If not, the unit must be checked and the difficulty remedied.

It was never possible to duplicate these reference fuel curves with the F-4 unit used in this investigation. A considerable amount of time was spent investigating the possible reasons for this discrepancy. People with a great deal of experience in this field were contacted and their suggestions followed, but an answer to the difficulty was not found. However, it appeared that the results were always in error in the same direction and, therefore, this should not limit the ability of the engine to make comparison of different fuels with sufficient accuracy for this investigation.

The series of curves in Figures 5, 6, and 7 illustrate how the engine knock-limited power drops off as the inlet temperatures are increased. The knock-limited power at the rich end of the mixture range drops off nearly inversely to the absolute temperature rise, while on the lean end the power drops off almost inversely to the square of the temperature rise. Another important characteristic of these series is that the maximum points all shift toward the right or toward richer fuel-air ratios as the intake temperature is increased.

Figures 5 and 7 show a comparison between sensitive and insensitive fuel characteristics. The slopes of the mean effective pressure curves for the sensitive fuel become steeper at higher inlet temperatures, while the slopes for the insensitive fuel remain relatively constant. Thus, the sensitive fuel has lost a much more power on the lean side than has the insensitive or reference fuel. On the other hand, close scrutiny of the curves shows that the sensitive fuel has not lost as much of its power on the rich side of the mixture range. Two conclusions can be drawn from these curves. First, intake temperature has a profound effect on fuel sensitivity, and, second, fuel sensitivity is only a factor at lean fuel-air ratios.

Figures 10 and 11 show the effect of intake temperatures on the energy-air characteristics of the engine when operating with the two different fuels. In Figure 10 the energy per weight of air decreases as the inlet temperatures increase, and at rich fuel-air ratios the energy per unit weight of air increases as the intake temperatures increase. For the 91/96 octane sensitive fuel in Figure 11, the opposite is true. Here the energy per weight of air increases at lean fuel-air ratios and decreases at rich fuel-air ratios as the intake temperature is increased. For both fuels at the fuel-air ratio of .100, the amount of energy per weight of air remains nearly constant.

Obviously, from the preceding curves, the energy-air characteristics are very dependent on the sensitivity of the fuel in a severe engine or an engine that heats excessively during operation.

The tendency of the sensitive fuel to make better use of its air at rich fuel-air ratios is probably due to the fact that the sensitive fuel actually loses less power at rich mixtures than at lean mixtures.

In connection with fuel sensitivity, it might be presumed by some people that since there is not much difference between the octane ratings at rich and lean mixtures (91 and 96), this fuel is not very sensitive. This is not true, however, as the octane rating is not an indication of knock-limited power. If it is desired to compare the ratings from a standpoint of power, which is the only logical way to do it, the performance number must be used. The actual performance numbers of this fuel would be 75/90.

Table VI indicates the amount of temperature drop in the passage between the surge tank and the engine at different air flow rates. At 300 degrees there is a sizeable drop of 20 degrees. However, on an absolute temperature basis, this drop only amounts to two percent. At 180 degrees, the temperature drop is negligible.

Figure 12 shows the amount of temperature drop, when the engine is running, for five temperature ranges from 130 degrees to 300 degrees. Once again the drops only amounts to a few degrees. Figure 12 does show, however, that the heat of the engine eliminates any cooling effects that were present when the engine was being motored. From these curves it is logical to assume that the temperatures recorded at the final surge tanks are sufficiently accurate for the temperatures up to 300 degrees Fahrenheit.

SUMMARY

The following conclusions were obtained from this investigation:

1. Knock limited power varies nearly inversely to the absolute temperature rise at rich fuel-air ratios, and inversely to the square of the temperature rise at lean fuel-air ratios.

2. The maximum peaks of the indicated mean effective pressure curves move toward richer fuel-air ratios at higher intake air temperatures.

3. Fuel sensitivity is only a serious factor at lean fuel-air ratios.

4. The energy-air relationship of an engine is greatly effected by the sensitivity of the fuel.

5. The recorded intake air temperatures for the F-4 unit are accurate to within two percent for intake temperatures up to 300 degrees Fahrenheit.

REFERENCE FUEL FRAMEWORK FOR ASTM SUPERCHARGE METHOD (D 909)

SAMPLE NO.	SAMPLE	SYM-BOL	RICH MIXTURE RATING	IMEP. RATING	FUEL-AIR RATIO	
2	Iso-octane, heptane		95			

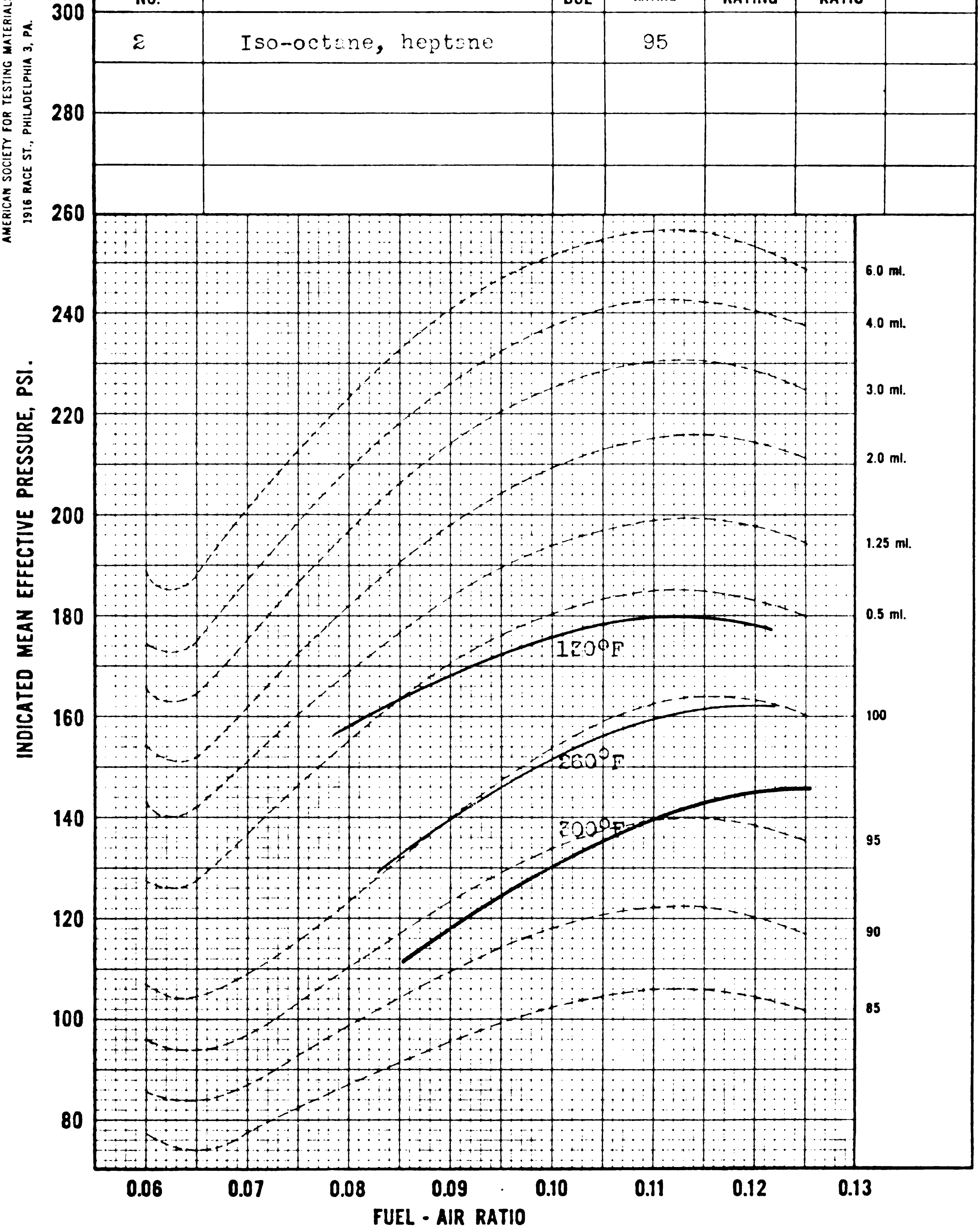


Figure 5

ENGINE NO. ________________ OPERATOR Johnson ________

DATA SHEET NO. 7 ____________ DATE ____________ FRAMEWORK NO. ____________

REFERENCE FUEL FRAMEWORK FOR ASTM SUPERCHARGE METHOD (D909)

AMERICAN SOCIETY FOR TESTING MATERIALS
1916 RACE ST., PHILADELPHIA 3, PA.

SAMPLE NO.	SAMPLE	SYMBOL	RICH MIXTURE RATING	IMEP. RATING	FUEL-AIR RATIO	
1	Commercial Aviation Fuel		96 octane			

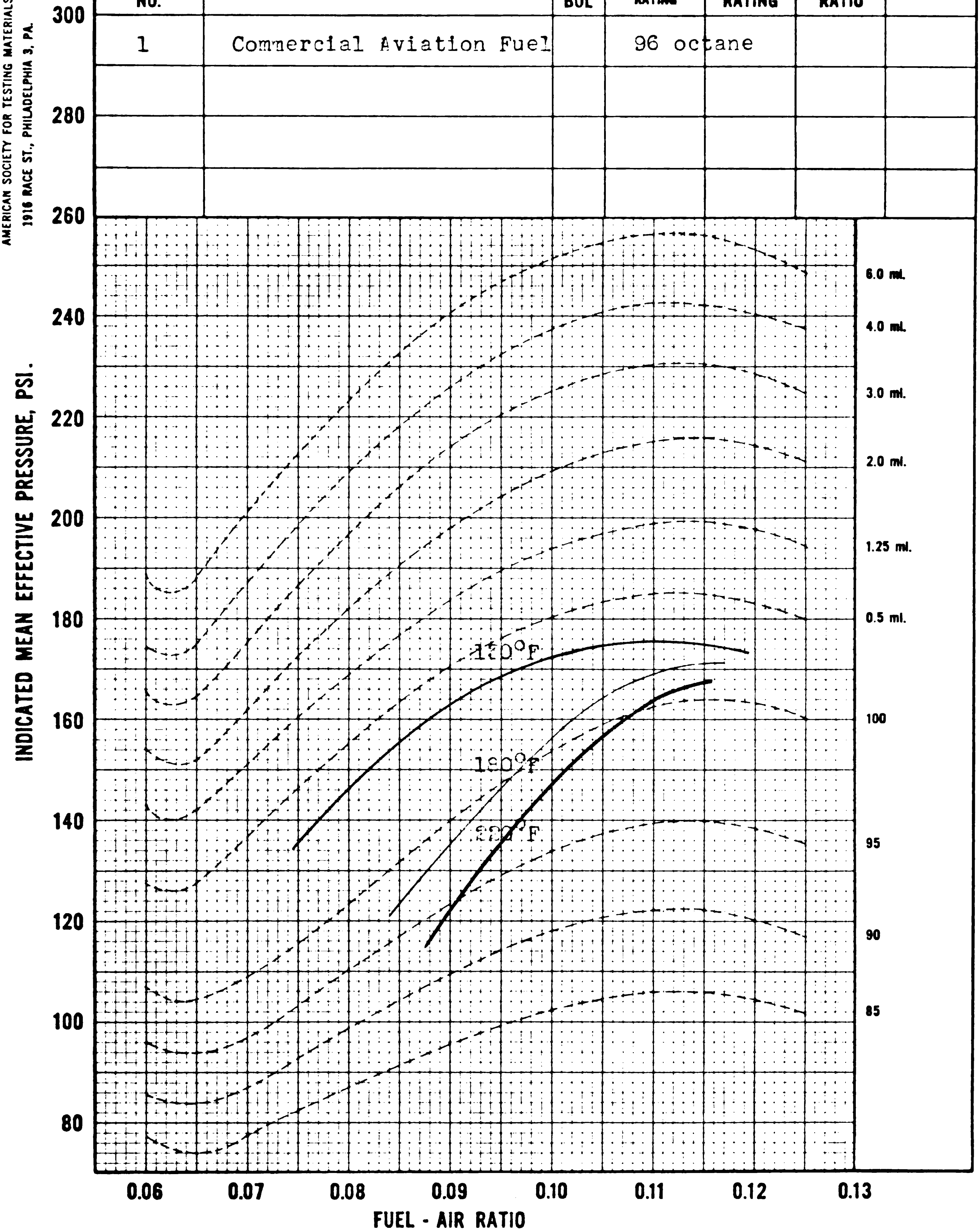


Figure 6

ENGINE NO. ____________ OPERATOR Johnson

DATA SHEET NO. 1 DATE __________ FRAMEWORK NO. __________

REFERENCE FUEL FRAMEWORK FOR ASTM SUPERCHARGE METHOD (D 909)

AMERICAN SOCIETY FOR TESTING MATERIALS
1916 RACE ST., PHILADELPHIA 3, PA.

SAMPLE NO.	SAMPLE	SYMBOL	RICH MIXTURE RATING	IMEP. RATING	FUEL-AIR RATIO	
1	Commercial aviation fuel		96			

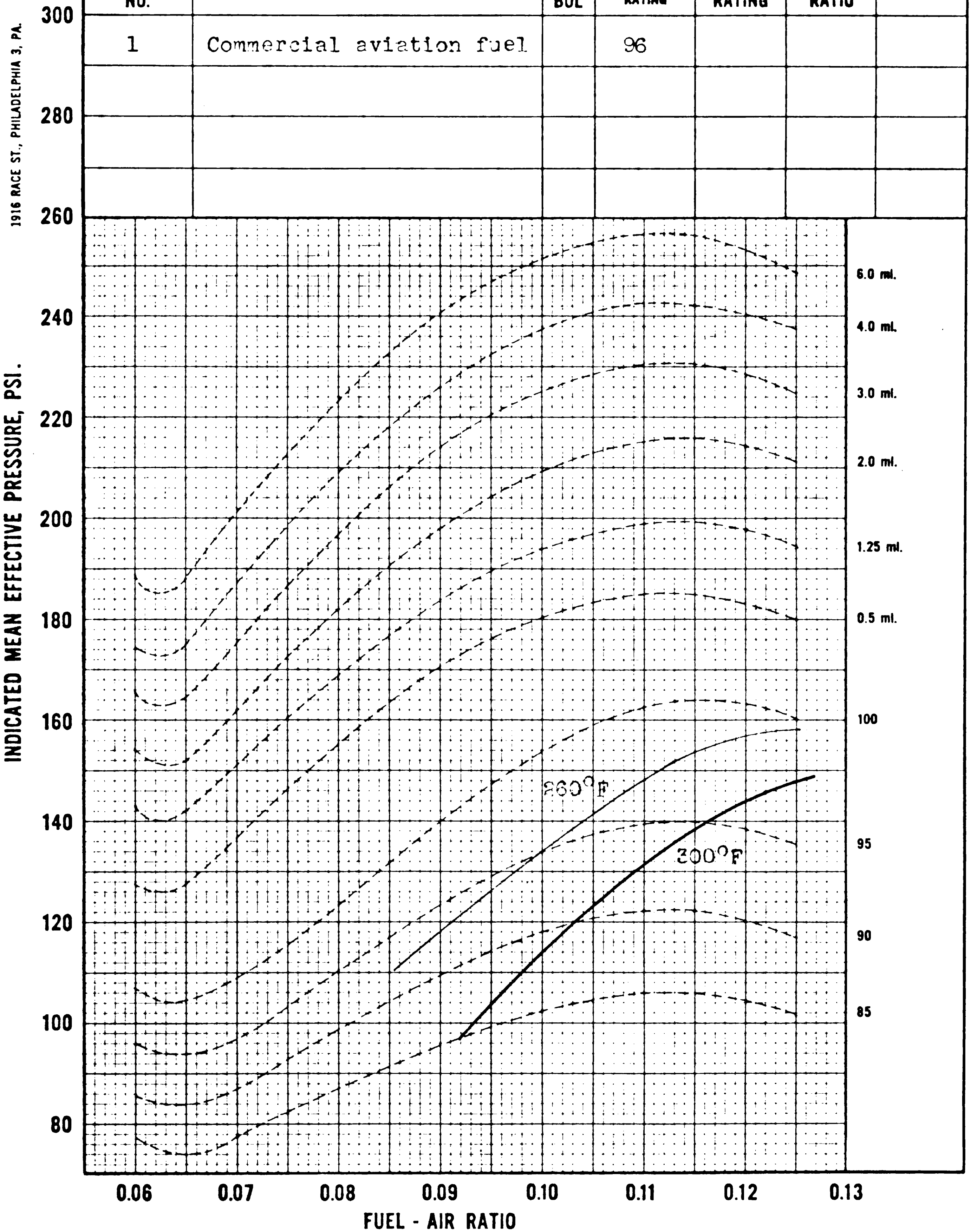


Figure 7

ENGINE NO. ________________ OPERATOR Johnson

DATA SHEET NO. 2 ____________ DATE ____________ FRAMEWORK NO. ____________

Figure 8

WEIGHT OF AIR VERSUS FUEL-AIR RATIO

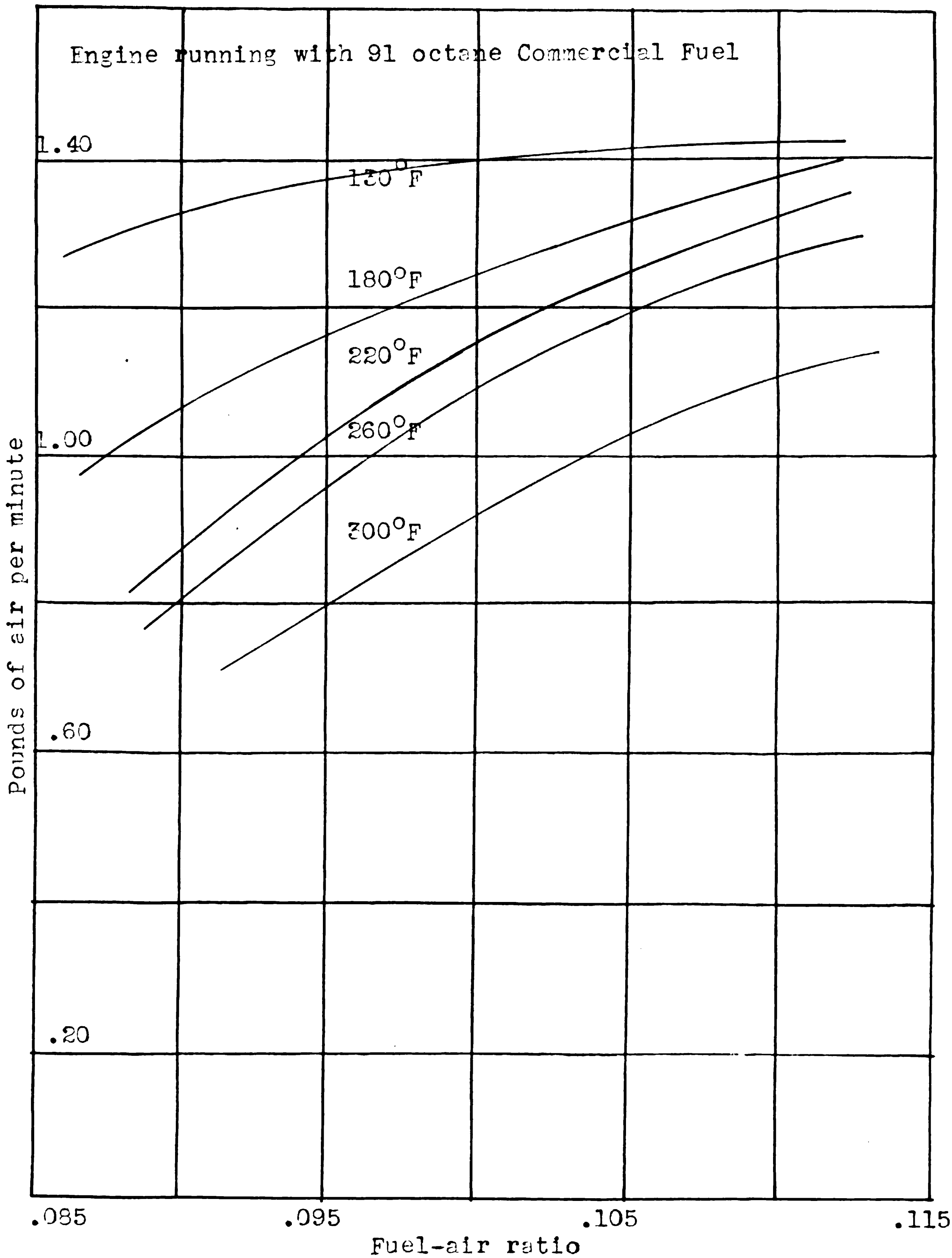


Figure 9

WEIGHT OF AIR VERSUS FUEL AIR RATIO

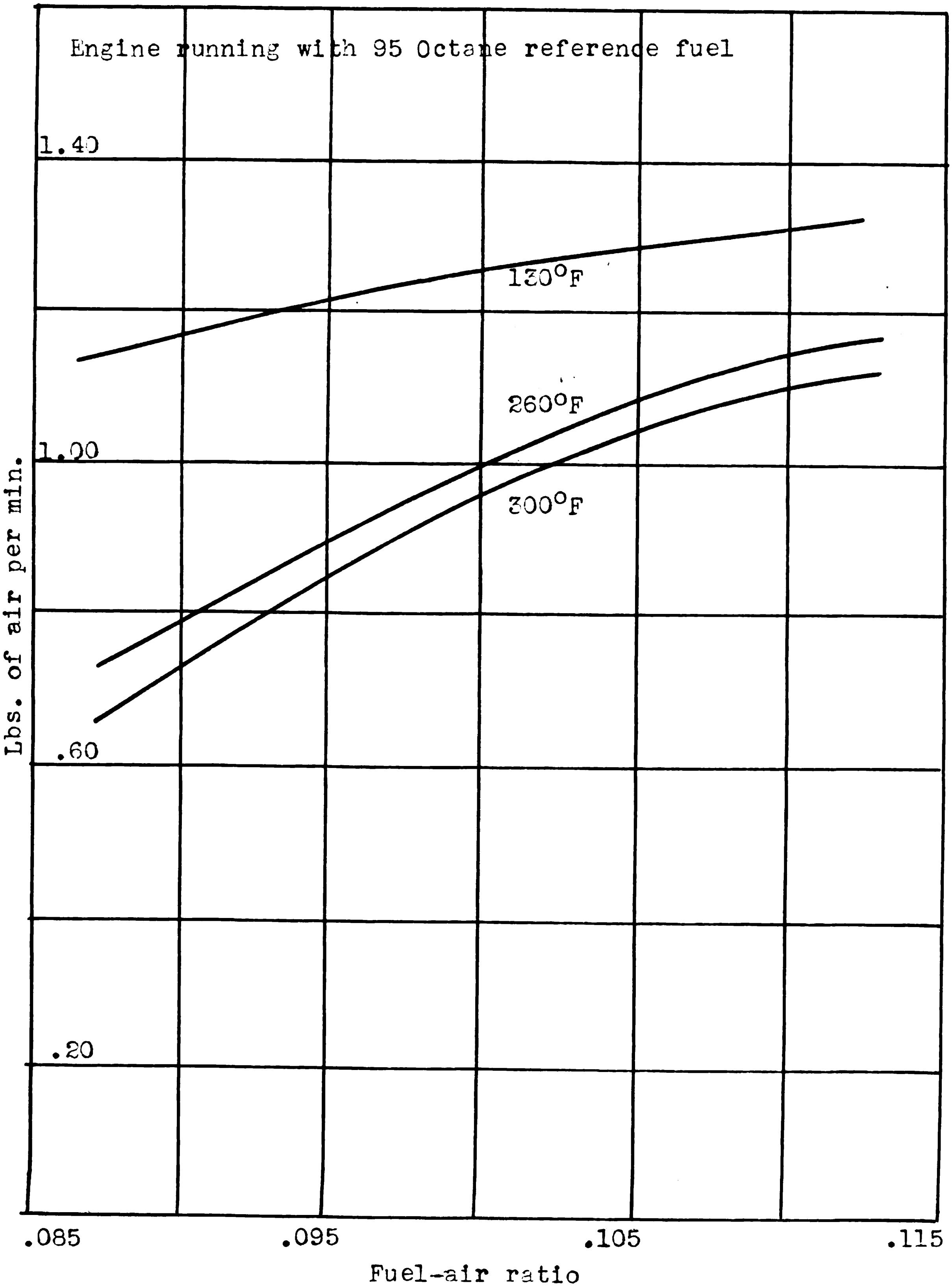


Figure 10

WORK PER WEIGHT OF AIR VERSUS TEMPERTURE

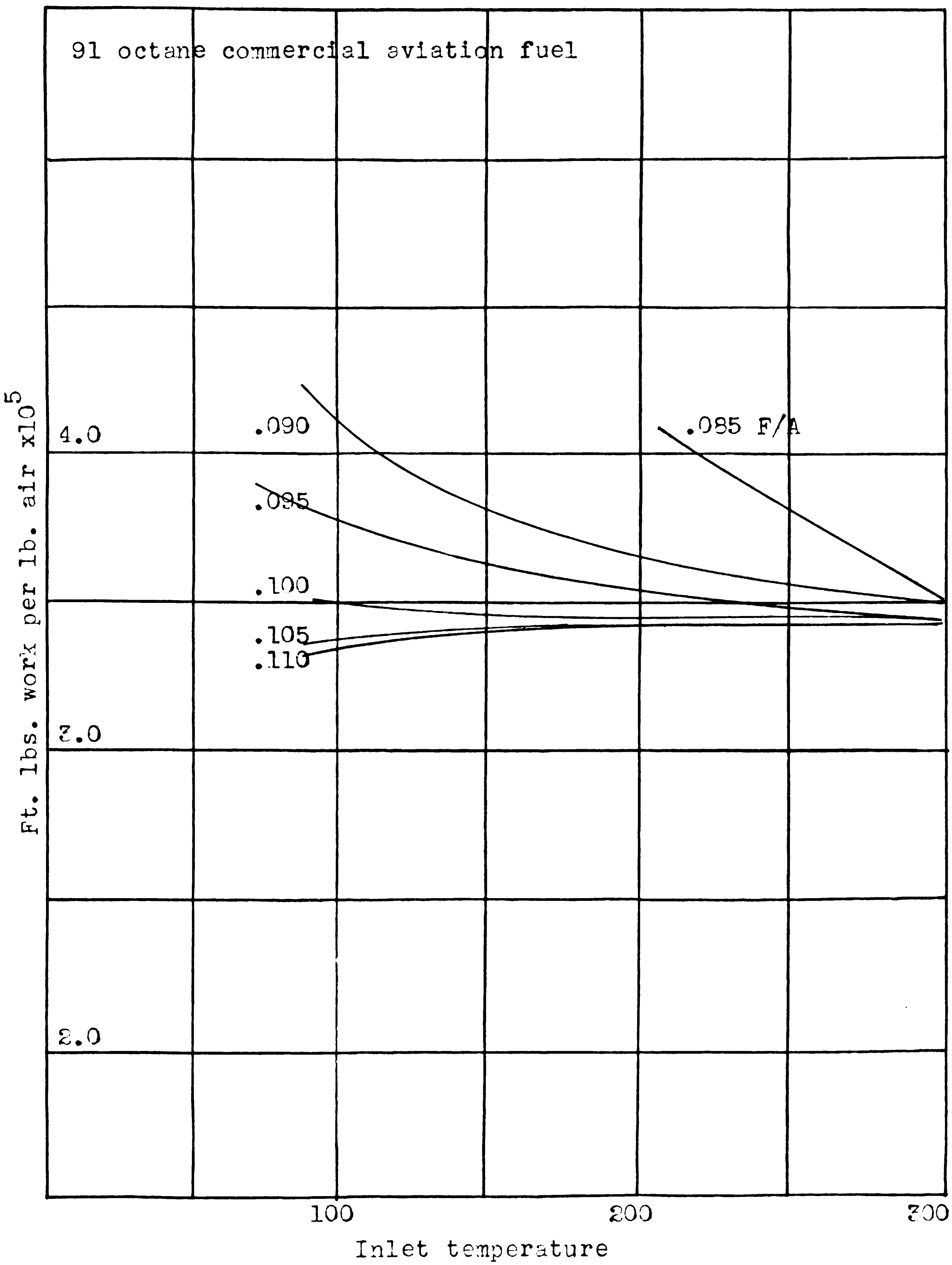


Figure 11

WORK PER WEIGHT OF AIR VERSUS TEMPERATURE

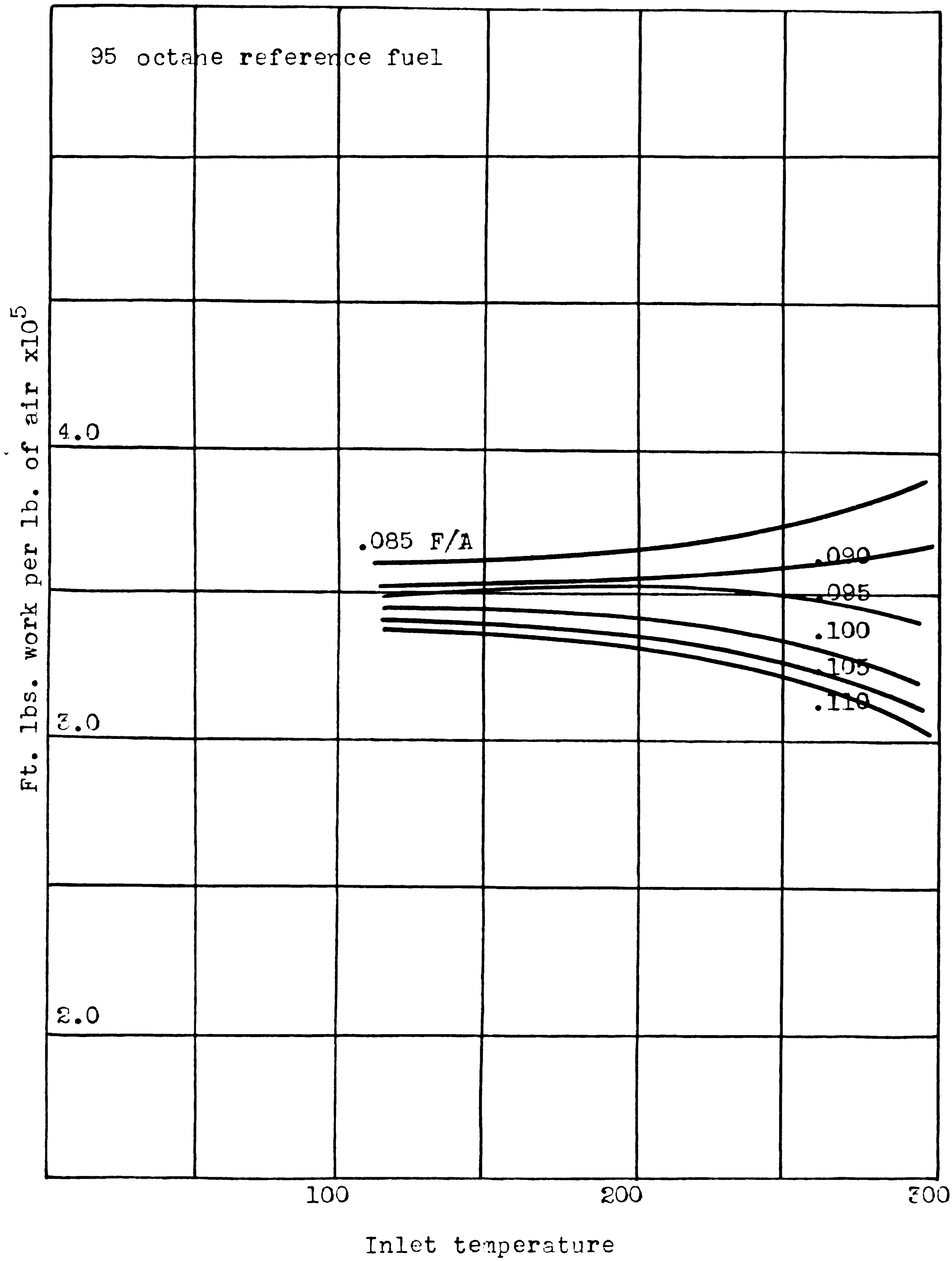
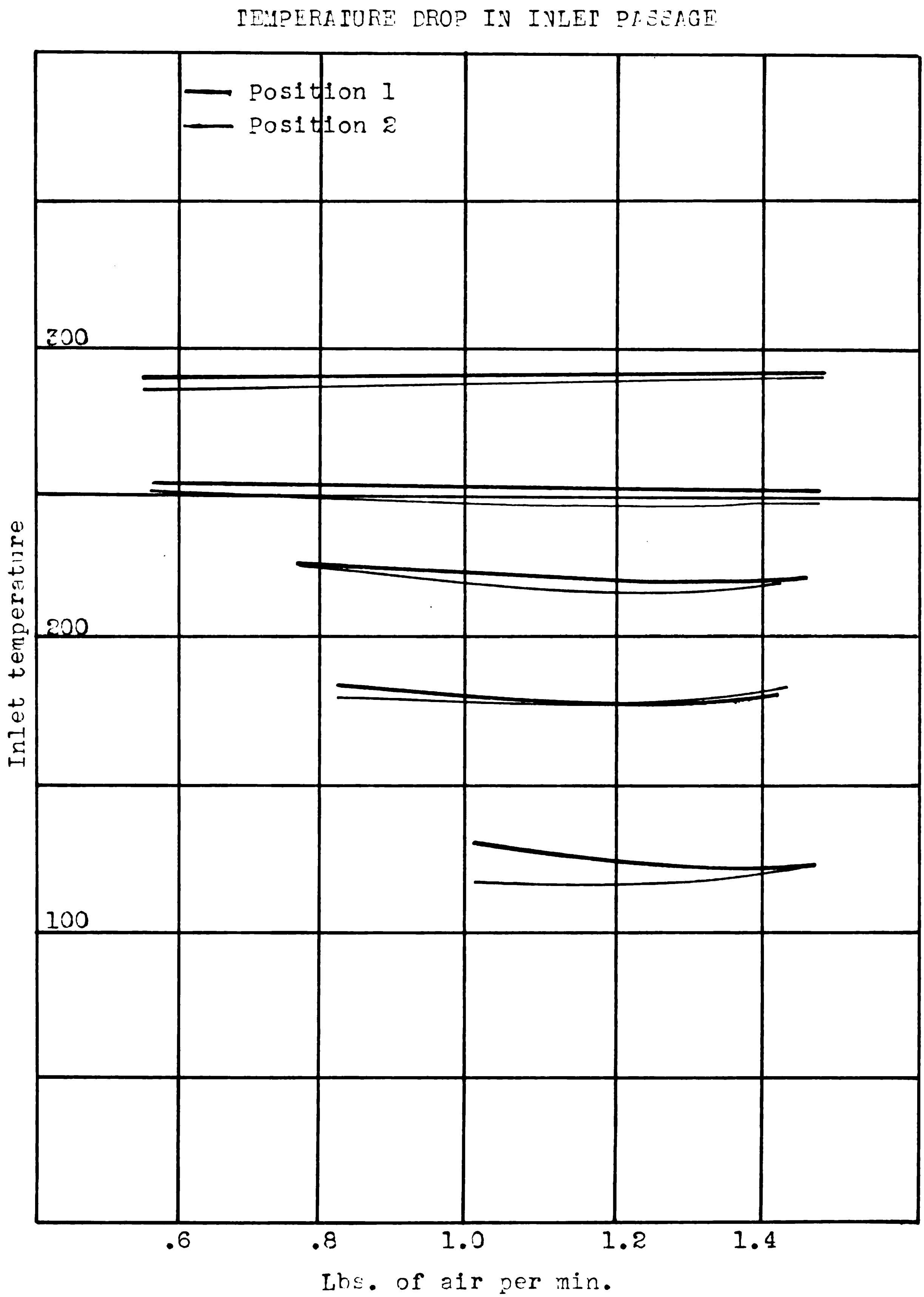


Figure 12


TEMPERATURE DROP IN INLET PASSAGE
Position 1
Position 2
300
200
100
Inlet temperature
.6
.8
1.0
1.2
1.4
Lbs. of air per min.

APPENDIX

PROCEDURE FOR RUNNING KNOCK LIMITED MEAN EFFECTIVE PRESSURE VERSUS FUEL-AIR RATIO CURVES

After the engine has been started and allowed to warm up sufficiently, the following testing conditions must be adhered to:

Oil temperature	165° ± 5° F
Oil pressure	60 ± 5 psi gage
Orifice air pressure	54.4 ± 0.5 psi absolute
Orifice air temperature	125° ± 5° F
Surge tank air temperature	225° ± 5° F
Coolant temperature	375° ± 5° F
Spark advance	45 ± 1 deg btdc
Valve clearance	0.008 intake, 0.010 exhaust
Exhaust cooling temperature	200° F

The following procedure, recommended by the American Society for Testing Materials is used in rating fuel samples:

1. The engine is operated at a manifold pressure which does not produce knocking for a period of about 10 minutes so that the previous fuel can be purged from the pumps and lines.

2. The fuel control is adjusted for maximum brake mean effective pressure on the dynamometer scale. If knock is present, the manifold pressure is reduced until the knock disappears, and then the fuel control is readjusted again for maximum brake mean effective pressure.

3. Manifold pressure is gradually increased until standard knock intensity is obtained. Standard knock intensity is the least knock that the operator can definitely and repeatedly recognize by ear. The engine is then allowed to reach equilibrium. Minor adjustments are made at this time to insure that the engine is running under the testing specifications listed previously. After this period, if the knock intensity has changed, the manifold pressure is adjusted until standard knock intensity is regained.

4. The following readings are then recorded: brake mean effective pressure, manifold pressure, oil pressure, air flow, and the temperatures of the inlet air, orifice air, water and oil.

5. Fuel consumption is then measured by recording the time for 1/4 pound of fuel. Since the air flow is calibrated in minutes per 1/4 pound, the fuel-air ratio can be found by merely dividing the recorded value for air flow by the recorded value for fuel consumption.

6. The fuel is then shut off and the engine is motored by the dynamometer at 1800 RPM. The friction mean effective pressure is then recorded from the dynamometer scale. This reading must be taken within a period of 10 seconds after the fuel has been shut off. The fuel and dynamometer controls are then changed back to their previous positions.

7. The indicated mean effective pressure, which is the sum of the brake and friction mean effective pressures, is then plotted on the reference fuel chart at the corresponding fuel-air ratio. This is the first point for the knock limited power curve and should be on the lean side of the fuel-air ratio range.

8. The fuel control is adjusted for more fuel and the manifold pressure is increased until the engine begins to knock. The manifold pressure is then decreased slowly until the knock disappears. The fuel control is then adjusted for maximum brake mean effective pressure on the dynamometer scale. The remaining steps in the procedure are identical with those mentioned above. The value for the indicated mean effective pressure is then plotted on the reference chart for this second fuel-air ratio.

At least five points over the fuel-air ratio range extending from .080 to .120 are obtained and a smooth curve is drawn through these points.

TABLE I

DATA SHEET FOR ASTM SUPERCHARGE METHOD

Fuel: 91 Octane
Commercial Aviation Fuel

Operator: B. Johnson
Date: March 1, 1952

Manifold Pressure In. Hg.	Minutes for 0.25 lb.		BMEP	FMEP	IMEP	Fuel-Air Ratio	Temperatures at Inlet Elbow	
	Air	Fuel					Pos. 1	Pos. 2
Inlet Temperature 130° F								
31.8	.217	2.68	108	39	147	.0810	125	135
34.5	.198	2.33	118	38	156	.0852	122	127
37.5	.180	1.86	133	37	170	.0968	116	122
38.7	.173	1.48	139	36	175	.1170	117	122
38.4	.172	1.57	140	36	176	.1090	119	122
Inlet Temperature 180° F								
29.9	.245	2.80	88	40	128	.0872	179	183
31.9	.235	.257	100	39	139	.0928	177	182
34.5	.212	.217	111	38	149	.0978	176	182
37.1	.195	.189	126	37	163	.1034	176	175
38.4	.184	.173	131	36	166	.1060	176	174
39.7	.175	.151	137	36	172	.1160	175	174

TABLE II

DATA SHEET FOR ASTM SUPERCHARGE METHOD

Fuel: 91 Octane
Commercial Aviation Fuel

Operator: B. Johnson
Date: March 1, 1952

Manifold Pressure In. Hg.	Minutes for 0.25 lb.		BMEP	FMEP	IMEP	Fuel-Air Ratio	Temperatures at Inlet Elbow	
	Air	Fuel					Pos. 1	Pos. 2
Inlet Temperature 220° F								
28.0	.279	3.01	72	40	112	.0870	210	215
30.1	.252	2.11	89	40	129	.0933	212	217
35.8	.211	1.93	112	37	149	.1000	219	215
36.8	.202	1.69	118	37	155	.1045	215	208
38.8	.186	1.53	128	36	164	.1100	216	210
40.1	.179	2.70	129	36	165	.1170	217	214

TABLE III

DATA SHEET FOR ASTM SUPERCHARGE METHOD

Fuel: 91 Octane
Commercial Aviation Fuel

Operator: B. Johnson
Date: March 1, 1952

Manifold Pressure In. Hg.	Minutes for 0.25 lb.		BMEP	FMEP	IMEP	Fuel-Air Ratio	Temperature at Inlet Elbow	
	Air	Fuel					Pos. 1	Pos. 2
				Inlet Temperature 260° F				
27.7	.291	.318	73	40	113	.0855	252	246
29.9	.257	.272	84	40	124	.0944	254	247
33.1	.236	.239	92	38	130	.0976	251	247
35.3	.217	.211	101	38	139	.1030	252	237
37.7	.198	.180	111	37	148	.1100	251	246
39.3	.188	.160	118	36	154	.1180	250	242
42.1	.176	.140	123	36	159	.1290	251	243
				Inlet Temperature 300° F				
26.7	.305	3.27	60	41	101	.0935	288	287
27.0	.298	3.02	70	40	110	.9800	288	283
31.1	.260	2.53	81	39	120	.1030	296	285
33.1	.235	2.16	94	38	132	.1090	286	286
36.1	.217	1.89	101	37	138	.1150	289	286

TABLE IV

DATA SHEET FOR ASTM SUPERCHARGE METHOD

Fuel: 95 Octane
Reference Fuel

Operator: B. Johnson
Date: March 1, 1952

Manifold Pressure In. Hg.	Minutes for 0.25 lb. Air	Minutes for 0.25 lb. Fuel	BMEP	FMEP	IMEP	Fuel-Air Ratio	Temperatures at Inlet Elbow Pos. 1	Temperatures at Inlet Elbow Pos. 2
Inlet Temperature 130° F								
35.5	.196	2.40	129	37	166	.0820	117	125
35.7	.190	2.27	131	37	170	.0838	117	122
37.0	.181	1.98	136	37	173	.0910	117	122
38.6	.173	1.69	142	36	178	.1020	118	125
40.0	.162	1.45	145	36	181	.1120	116	121
Inlet Temperature 260° F								
28.0	.286	3.43	80	40	120	.0830	254	250
33.4	.242	2.57	96	39	135	.0940	256	246
37.3	.208	2.08	110	37	147	.1000	255	242
40.0	.184	1.71	121	37	157	.1070	255	249
41.6	.177	1.54	128	36	164	.1150	254	247

TABLE V

DATA SHEET FOR ASTM SUPERCHARGE METHOD

Fuel: 95 Octane Reference Fuel

Operator: B. Johnson
Date: March 1, 1952

Manifold Pressure In. Hg.	Minutes for 0.25 lb.		BMEP	FMEP	IMEP	Fuel-Air Ratio	Temperatures at Inlet Elbow	
	Air	Fuel					Pos. 1	Pos. 2
			Inlet Temperature 300° F					
26.6	.308	3.94	61	40	101	.0800	---	---
32.2	.242	2.55	89	39	128	.0950	---	---
36.9	.206	2.00	101	37	138	.1030	---	---
38.4	.190	1.62	109	37	146	.1170	---	---

TABLE VI

TEMPERATURE DROP IN INLET PASSAGE

Unit being motored by dynamometer Operator: Johnson

Manifold pressure In. Hg.	Airflow Min. per ¼ lb.	Temperature drop F° Pos. 1	Pos. 2
	Inlet temperature 180°F		
27.2	.252	216	214
34.5	.192	218	214
37.9	.172	218	215
40.9	.156	220	215
43.6	.146	219	215
47.4	.135	220	216
50.5	.127	224	219
54.9	.116	225	220
55.6	.108	224	223
	Inlet temperature 300°F		
27.5	.273	290	279
33.8	.220	295	281
38.0	.192	294	283
42.3	.175	293	286
46.0	.157	296	286
50.0	.148	300	291

TABLE VII

EFFECT OF INLET TEMPERATURE ON IMEP

Temperature	130	180	220	260	300
Fuel-air ratio	Using 96 Octane Commerical fuel				
.085	156	125	108	112	80
.090	164	136	123	116	95
.095	169	147	136	127	105
.100	173	157	147	135	115
.105	175	165	157	142	123
.110	176	170	164	148	131
.115	175	172	166	153	138
	Using Iso-octane, heptane				
.085	160			126	110
.090	168			128	119
.095	175			138	127
.100	178			147	133
.105	180			155	138
.110	181			160	142

LIST OF REFERENCES

1. Dubois and Cronstedt. High Output in Aircraft Engines. SAE Journal. June, 1937.

2. Ethyl Corporation. Aviation Fuels And Their Effect on Engine Performance. 1951

3. Heron, S. D. Fuel Sensivity and Engine Severity in Aircraft Engines. SAE Journal. September, 1946.

4. Wheeler and Lovell. Fuels and Engines. SAE Journal. August, 1947.