AN INVESTIGATION OF THE EFFECTS OF SUPERCHARGING A LIQUEFIED PETROLEUM GAS ENGINE

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PREFACE

Although the applications of the uses of liquefied petroleum gas and the supercharging of internal combustion engines have individually been subjected to considerable investigative effort, prior to this time no examination of the effects of supercharging an engine using liquefied petroleum gas has been made.

The purpose of this investigation was to determine the desirability of supercharging such an engine. A one-cylinder Cooperative Fuel Research engine was used in this investigation. The procedures followed closely approximated those recommended in the power test codes of the American Society of Mechanical Engineers and the Society of Automotive Engineers.

I wish to express my sincere appreciation to Professors W. H. Easton and Bert S. Davenport of the School of Mechanical Engineering, Oklahoma Institute of Technology, for their guidance and assistance in the preparation of my project equipment and in the preparation of this thesis. I wish to also acknowledge the extensive assistance I have received from the other members of the Mechanical Engineering Faculty; Mr. Archie P. Barnard who assisted in the collection of data during this experiment; and my wife, Jewel Karen, who typed and proofread the manuscript, assisted in the running of the experiment and acted as a wonderful inspiration in the completion of this project.

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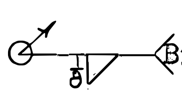
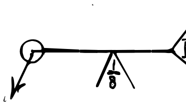
LIST OF ABBREVIATIONS AND SYMBOLS

AFR	Air-Fuel ratio
bhp	brake horsepower
bhp_c	brake horsepower corrected for temperature
$bmep_c$	corrected brake mean effective pressure
BSFC	brake specific fuel consumption, $\frac{lb}{bhp\ hr}$
cu ft	cubic feet
D	total engine piston displacement, cubic inches
dc	direct current
e	efficiency
°F	degrees Fahrenheit
G	weight rate of flow, lb/min
h_1	initial enthalpy
h_2	final enthalpy
Hg	mercury
hp_{comp}	horsepower required for air compression
hp_r	resultant horsepower
hr	hour
in.	inches
lb	pounds
LH	left hand
LPG	liquefied petroleum gas
m	meters
min	minutes

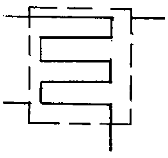
N	revolutions per minute
p	pressure
P	dynamometer scale load
p_{r_1}	initial pressure ratio
p_{r_2}	final pressure ratio
psf	pounds per square foot
psi	pounds per square inch
psia	pounds per square inch absolute
psig	pounds per square inch gauge
R	gas constant
R	length of dynamometer lever arm, ft
°R	degrees Rankine
RH	right hand
rpm	revolutions per minute
SFC	specific fuel consumption, lb fuel/bhp hr
T	torque, corrected
T	temperature, °R
T_m	manifold temperature, °R
T_s	standard temperature, °R
v	volume, cubic feet
 Brazed	Brazing - 1/8 in. fillet joint, all around
 Brazed	Brazing - 1/8 in. "V" joint, all around
	Check Valve
— A —	Compressed air line

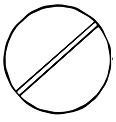

Flexible line

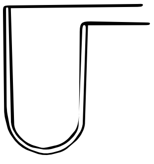
Gas line

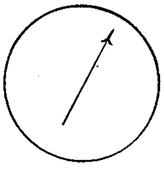

Gate valve

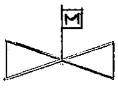

Globe valve


Heat exchanger


Liquefied petroleum gas converter

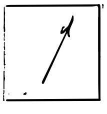

Manometer

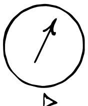

Meter

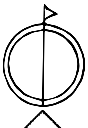


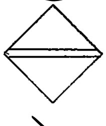
Motor operated valve

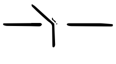
Pipe cross-over

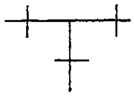

Potentiometer


Pressure gauge

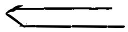

Pressure reducing valve


Pressure regulator


Switch, single pole double throw

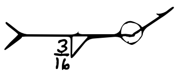


"T" connection



Thermocouple

Venturi



Welding - 3/16 in fillet joint, all around

CHAPTER I

INTRODUCTION

A. LIQUEFIED PETROLEUM GAS

The increasing cost of gasoline has stimulated a vigorous search for other less costly substitutes that would furnish equal or greater power with greater economy combined with convenience of handling. Liquefied petroleum gas currently sells on the market at a much lower price than does gasoline with a considerable saving in operating costs. In addition, many other advantages are to be realized by the application of liquefied petroleum gas. This fuel burns "clean" and leaves little or no deposit in the combustion chamber. The gaseous "blow-by" products are readily and speedily evacuated from the engine crankcase resulting in a considerable decrease in the sludge formation in the crankcase oil as compared with the situation that prevails in the gasoline and diesel engines. Liquefied petroleum gas has an inherent anti-knock rating that corresponds to an octane number of approximately 100 and can be used in high compression engines thus permitting more efficient operation.

Although prior to World War II, liquefied petroleum gas was principally used for heating and as a fuel for cooking purposes in the home, it was also used to a limited extent as an engine fuel. During this period, the principal component of commercial liquefied petroleum gas was butane but since that time, the composition of this fuel has been changed so that propane is generally the main constituent of the gas with varying amounts of butane, propolene, and other gases. This change in composition was brought about by the increased use of butane in the manufacture of gasoline.

Of late, many devices have been placed on the market embodying significant advances in the metering and carburetion of this fuel for use with internal combustion engines. Some engines have been designed to use this fuel and conversion kits are available to change-over gasoline and diesel engines to the use of liquefied petroleum gas. The scope of applications for this fuel has increased radically during recent years.

B. SUPERCHARGING

"The power of an engine is directly limited by the amount of air that can be inducted. The air consumption can be increased by increasing the number and size of the cylinders or, to save weight, by using a compressor to supercharge the cylinder with air or mixture."[1]

Supercharging has been practiced as far back as 1901 to 1902 by Sir Dugald Clerk, the inventor of the two-stroke cycle engine. Clerk's idea was to use supercharging principally to control the maximum cycle temperature because considerable difficulty resulting from excessively high temperatures was encountered in the use of the internal combustion engine at that time. However, he did improve both power output and efficiency by some 6%.[2]

By World War I, extensive experimentation was going forward in the realm of supercharging. The problems of powered flight greatly emphasized the need for a lightweight engine and supercharging was instituted to cope with this need. Between the two World Wars, the

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[1]E. F. Obert, <u>Internal Combustion Engines</u> (Scranton, 1952), p. 567.

[2]E. T. Vincent, <u>Supercharging the Internal Combustion Engine</u> (New York, 1948), p. 1.

aircraft industries further investigated supercharging applications and extensive use of superchargers was made for powered flight installations during World War II. The benefits derived from the experiences of the aircraft industries have been applied to land and sea power units, both compression-ignition and spark-ignition internal combustion engines.

C. SUPERCHARGING A LIQUEFIED PETROLEUM GAS ENGINE

Although the use of liquefied petroleum gas as an engine fuel and the practice of supercharging have each individually been investigated, prior to this time, no research into the combination of both of these practices has been made. The author undertook, in February, 1954, to ascertain the advisability of supercharging an engine using commercial liquefied petroleum gas. Tentatively, it was decided to check on the variations of the following while maintaining the engine at some convenient speed and varying the manifold pressure:

Power output

Least spark advance for maximum power output

Exhaust temperature

Specific fuel consumption

Air-fuel ratio.

It was also decided to obtain these data at different compression ratios. At that time, it was anticipated that the results would very closely approximate those obtained from supercharging an engine using gasoline as a fuel.

CHAPTER II

EQUIPMENT AND MATERIAL

A. EQUIPMENT AND MATERIAL USED

The fuel used in this investigation was liquefied petroleum gas purchased on the commerical market and having the following analysis:

96.5 - 97% Propane

2.5 - 3% Propolene

The fuel mentioned above was used in the Cooperative Fuel Research engine and the power output was measured by means of a dynamometer and scale combination. The weight of the fuel was determined through the use of a scale and the volume of air consumed by the engine was obtained by passing the air through a large commercial type displacement gas meter. A conventional shop compressor was used to furnish the large volume of air required at the desired pressure.

The equipment and instruments were physically arranged so that control could be exercised by one person operating the engine. However, it was found that assistance was required in order to read the many instruments during the course of a test run.

A complete listing of the equipment used in this project may be found in Appendix A.

B. SELECTION OF EQUIPMENT AND INSTRUMENTATION

The choice of equipment for this project was dictated and limited by considerations of the availability and suitability of apparatus.

It was decided to use the Cooperative Fuel Research engine for the running of the tests because of its sturdy construction and also because the compression ratio could be readily altered by simply turning a crank. Although it was anticipated that the results of supercharging an engine using liquefied petroleum gas as a fuel would closely conform to those resulting from supercharging a gasoline engine, the element of uncertainty required that the precaution of using a sturdily built engine be taken. The possibility of the need for a control of the manifold temperature was also considered and this feature is incorporated in this unit. The carburetor, which was fabricated by the Mechanical Engineering Department, Oklahoma Institute of Technology, was constructed of standard size pipe with a venturi section press-fitted into the proper position. The method of construction is indicated in Figure 4.

The large Kron Company scale equipped with the General Electric photoelectric cell was used to weigh the amount of fuel consumed during the course of a test run. The photoelectric cell was connected to the Interval Timer and Revolutions Counter which were located in the instrument panel. A schematic arrangement of the components in this circuit is indicated in Figure 5. The relay was adjusted so that the Timer and the Revolutions Counter started to operate at the beginning of a run and stopped when a predetermined amount of fuel had been consumed by the engine.

The thermo-electric circuits were arranged as indicated in Figure 6. Iron-constantan thermocouples were used throughout. As it was expected that the exhaust temperatures would be in the 1000° to 1600°F range, the Brown potentiometer was used to measure exhaust gases. A protective shield was fabricated according to the specifications of Figure 7 which permitted the location of the hot junction of the exhaust gas thermocouple in close proximity to the exhaust port of the engine.

Note that the protective shield tip protrudes $\frac{1}{4}$ inch into the head of the engine. The other five thermo-electric circuits were connected to a common switchboard with a common "jumper" to the Celectray potentiometer so that by operating the throw switches on the panel with one hand and balancing the potentiometer with the other hand, temperatures for five separate hot junctions could be measured readily with the same potentiometer.

Preliminary calculations revealed the advisability of using a large volume air compressor or blower to provide the air for supercharging the engine. Investigation demonstrated that the Gardner-Denver two-stage compressor could furnish the volume required but that it would be necessary to regulate the pressures to the desired levels. This was effected by a two-stage regulation system as pictured in Figure 8. The large size gas meter shown in the same figure was choosen as being superior in accuracy of flow measurement to those metering systems commonly encountered in the laboratory.[1]

The selection of the dynamometer shown in Figure 9 was largely dictated by the consideration of availability. Unfortunately, this choice was a poor one for the time lag between opening and closing of the load water valves and the resultant effect on the dynamometer's actions made for extreme difficulty in the stabilization of the engine's speed. The load on the engine was also subject to every minor variation in the flow of the load water into the dynamometer. Moreover, the lack of sensitivity of this instrument made for great difficulty

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[1]Displacement Gas Meters, Handbook E-4, American Meter Company (Erie, 1952), p. 115.

in selecting the least spark advance and the air-fuel ratio for maximum power output. Schematic diagrams of the water supply and the fuel-compressed air systems are shown in Figures 10 and 11.

Figure 1. Right Half of Instrument Panel

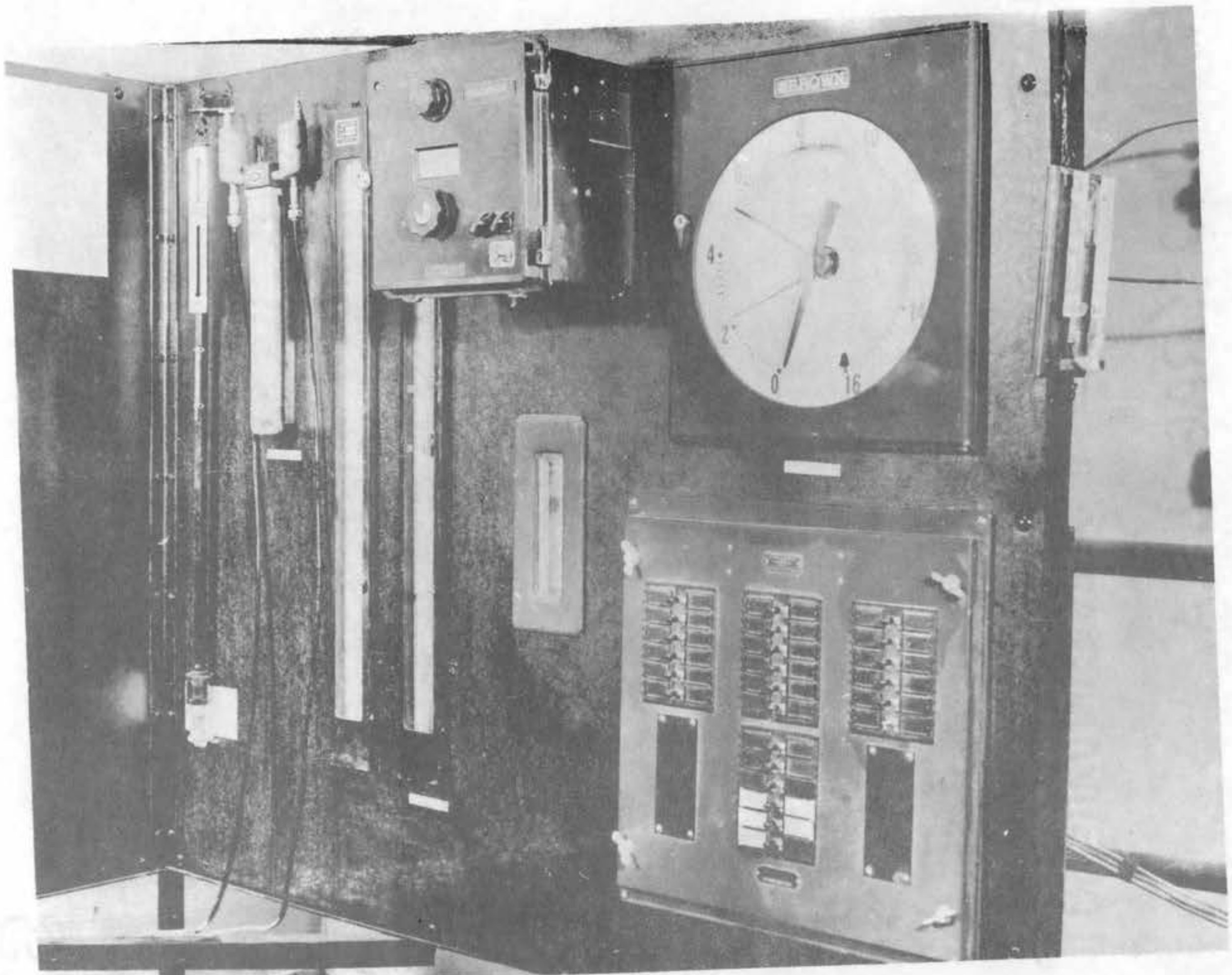


Figure 2. Left Half of Instrument Panel

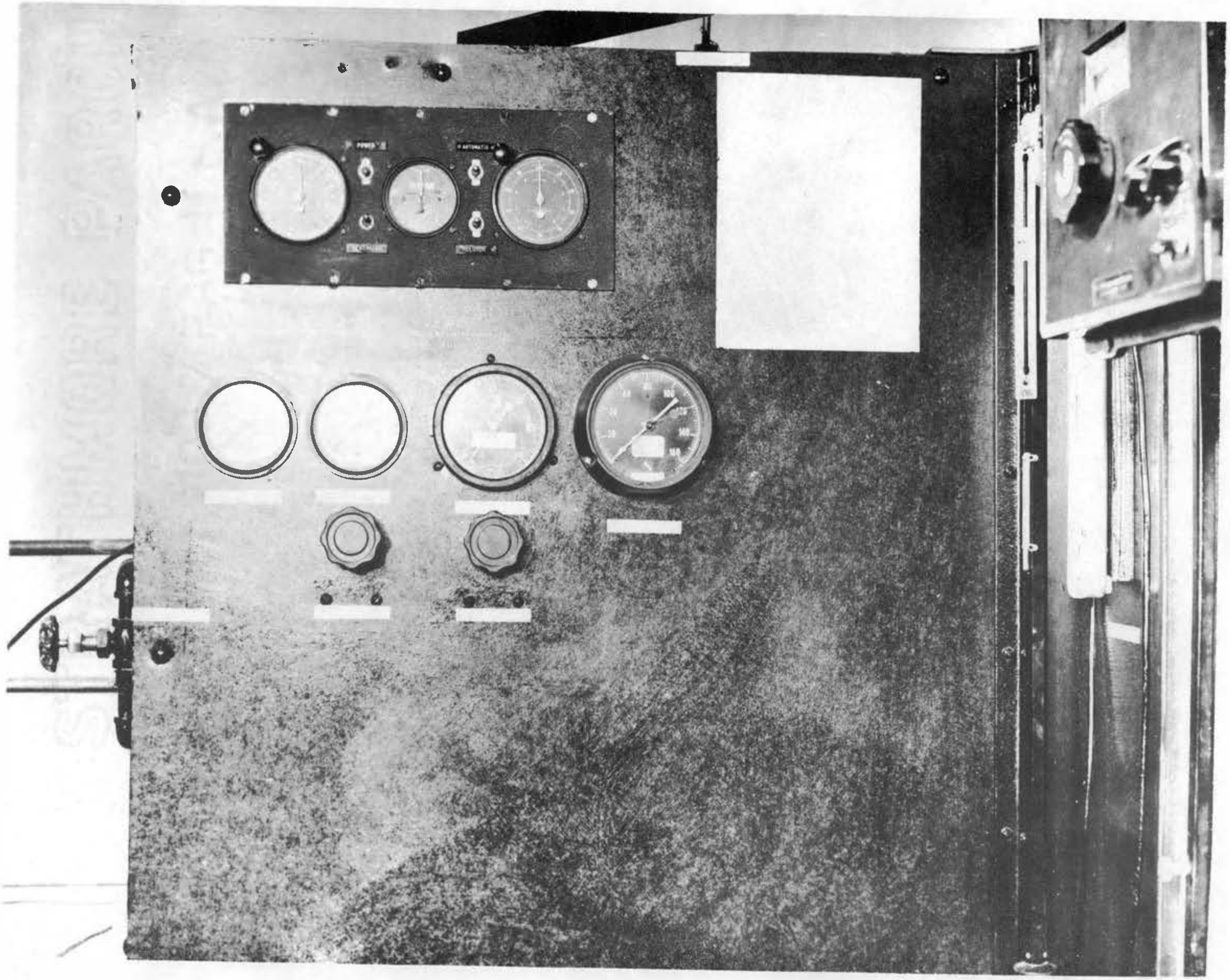
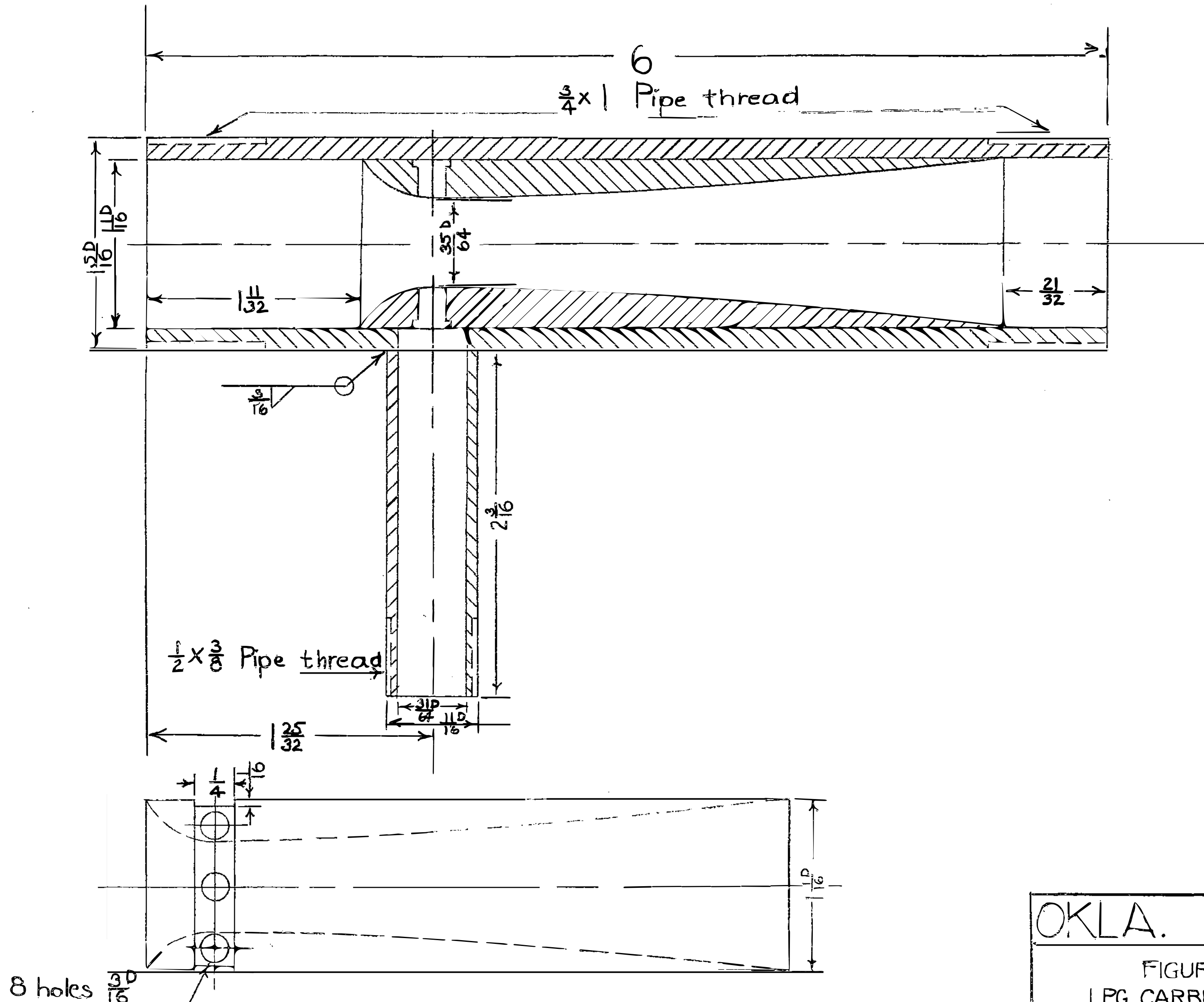


Figure 3. Instrument Panel of Cooperative Fuel
Research Unit



VENTURI SECTION

OKLA. A & M

FIGURE 4
LPG CARBURETOR

DRAWN BY: Ken
CHECKED BY: WHE
SCALE: Full 6/5/54

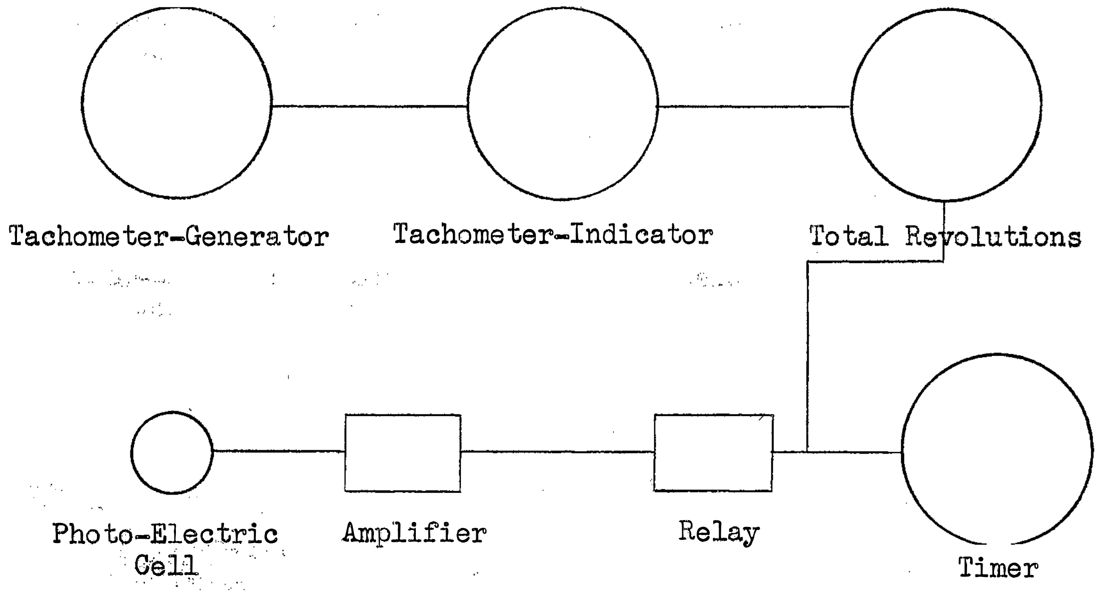


Fig. 5. Schematic Diagram of Timer-Tachometer Circuit

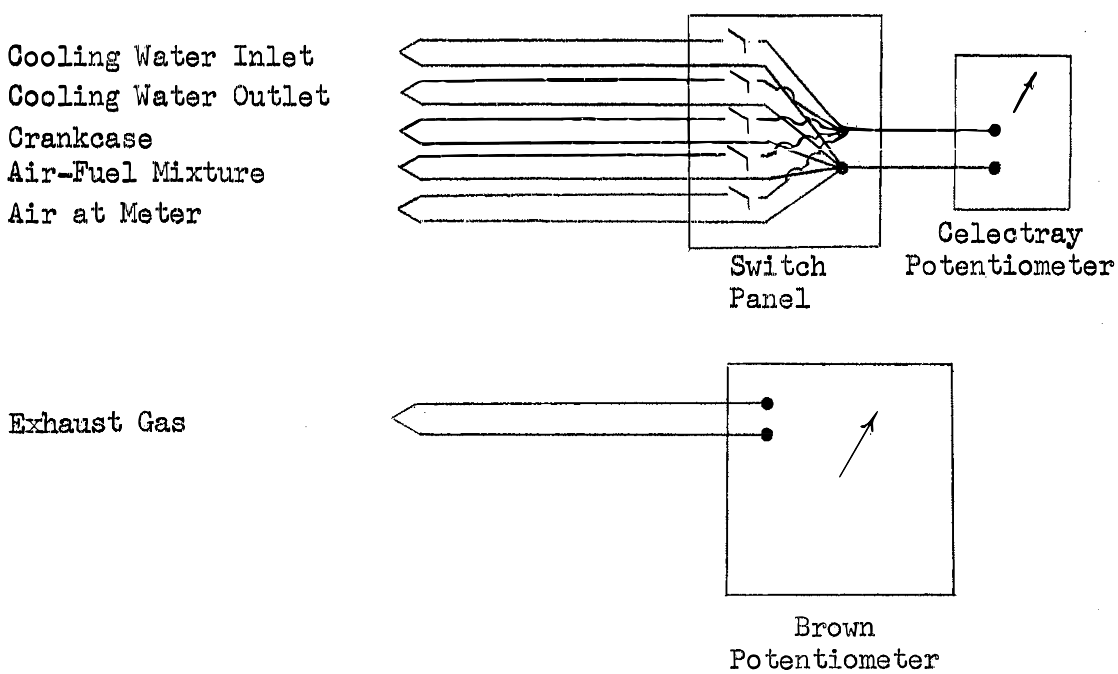
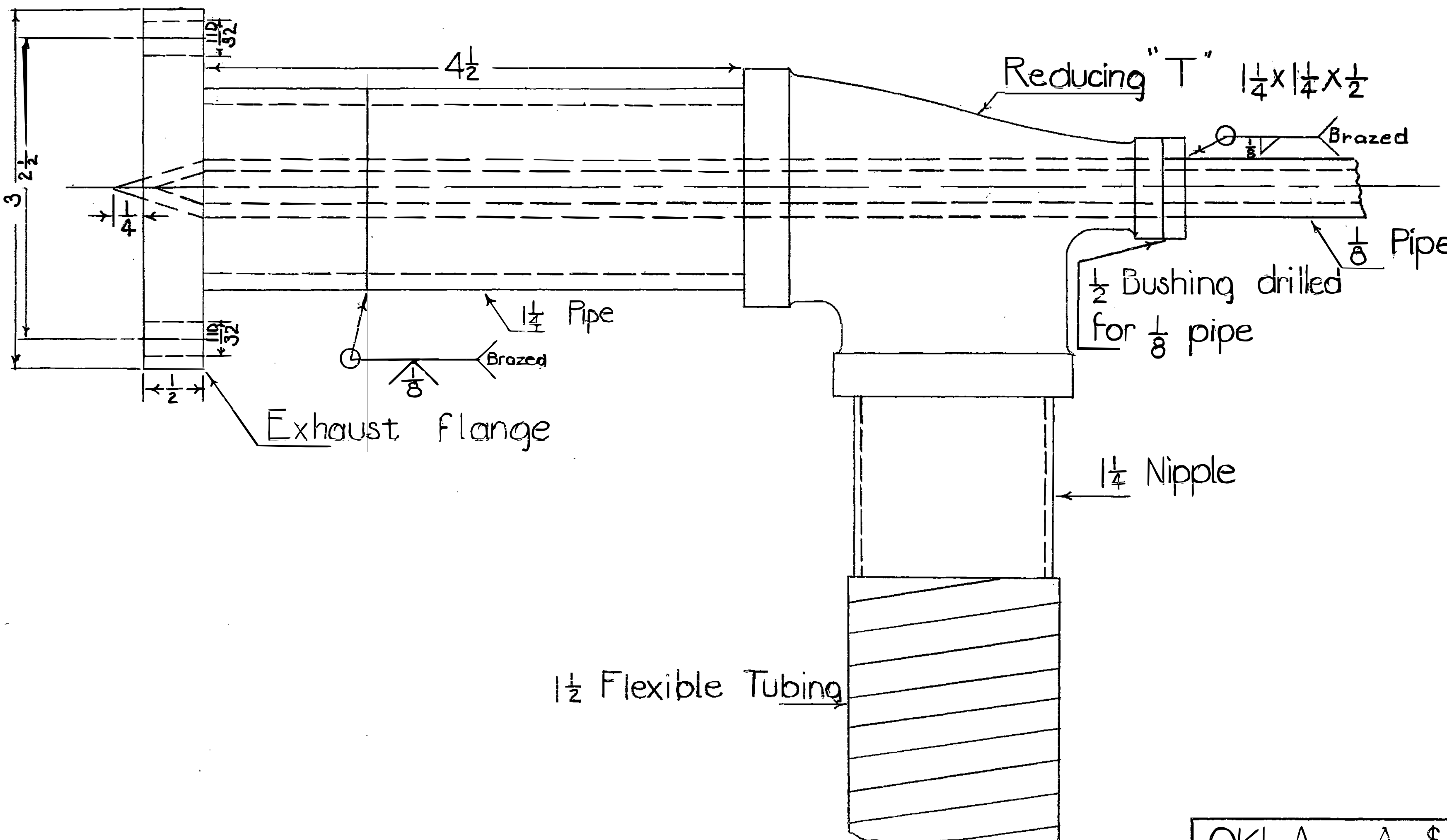


Fig. 6. Thermo-electric Circuits



OKLA. A & M

FIGURE 7
THERMOCOUPLE SHIELD

DRAWN BY: Kuen
CHECKED BY: WHE
SCALE: 3/4" = 1" 6/22/54

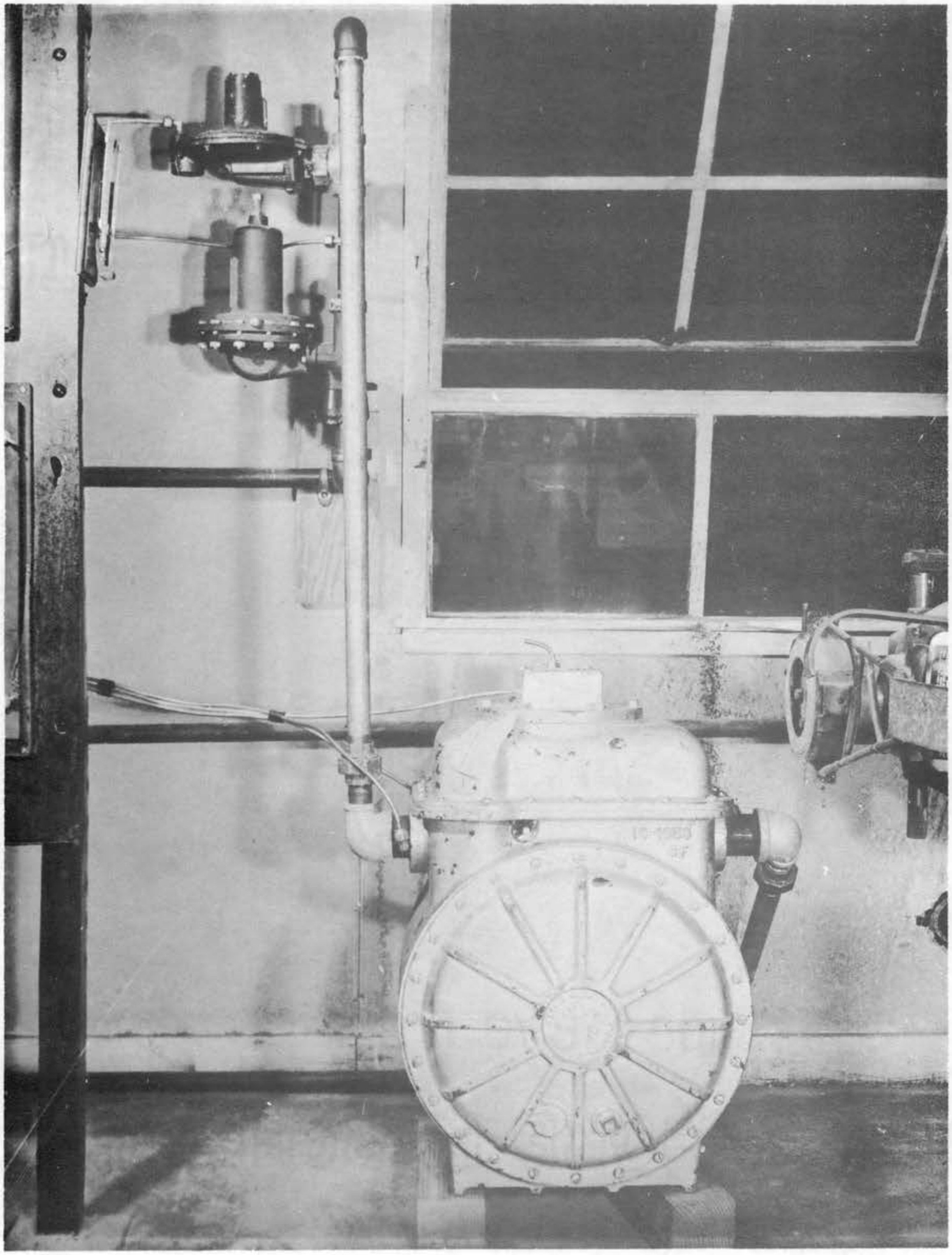


Figure 8. Two Stage Regulation System and Air Meter

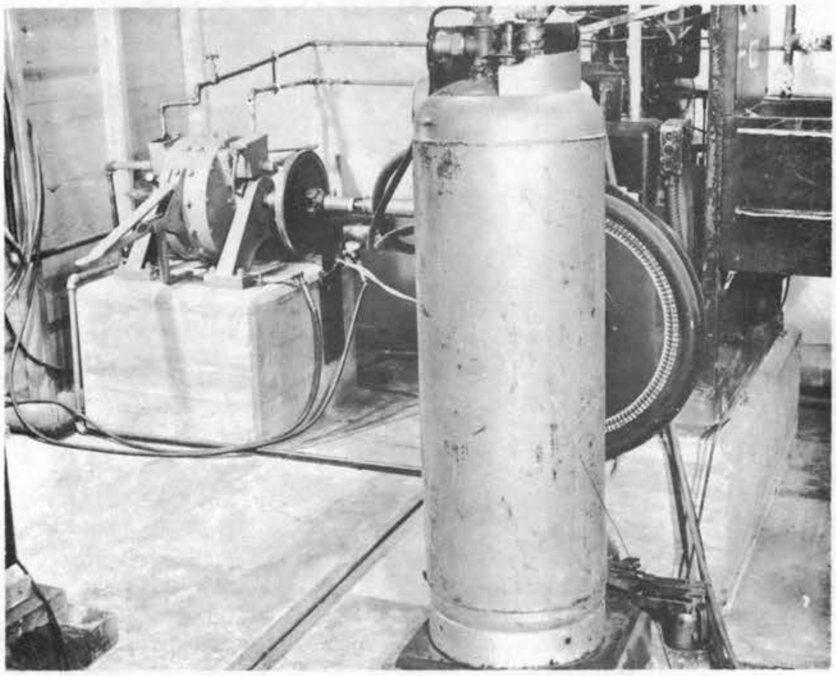


Figure 9. Water Dynamometer with Fuel Tank on Scale in Foreground

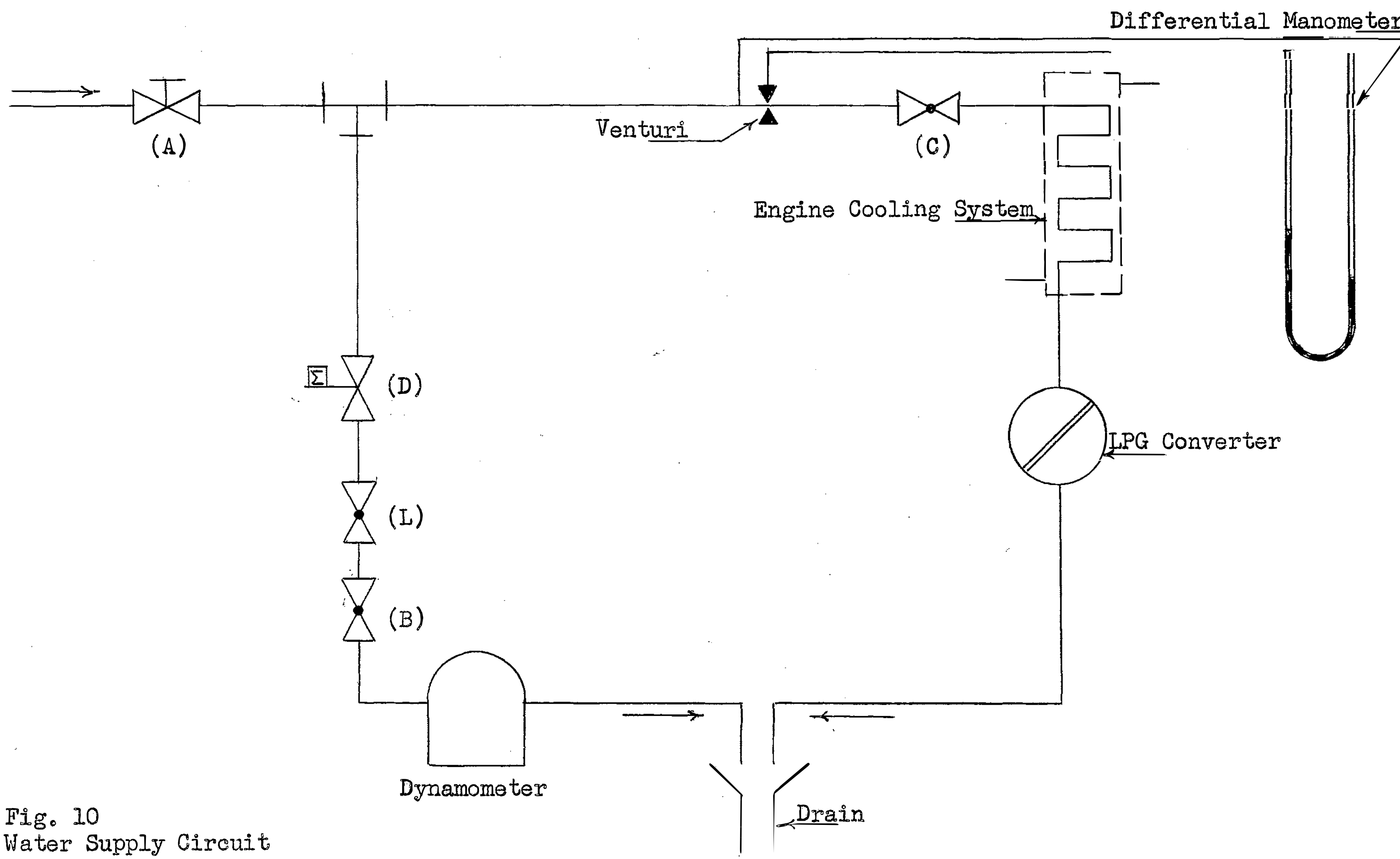


Fig. 10
Water Supply Circuit

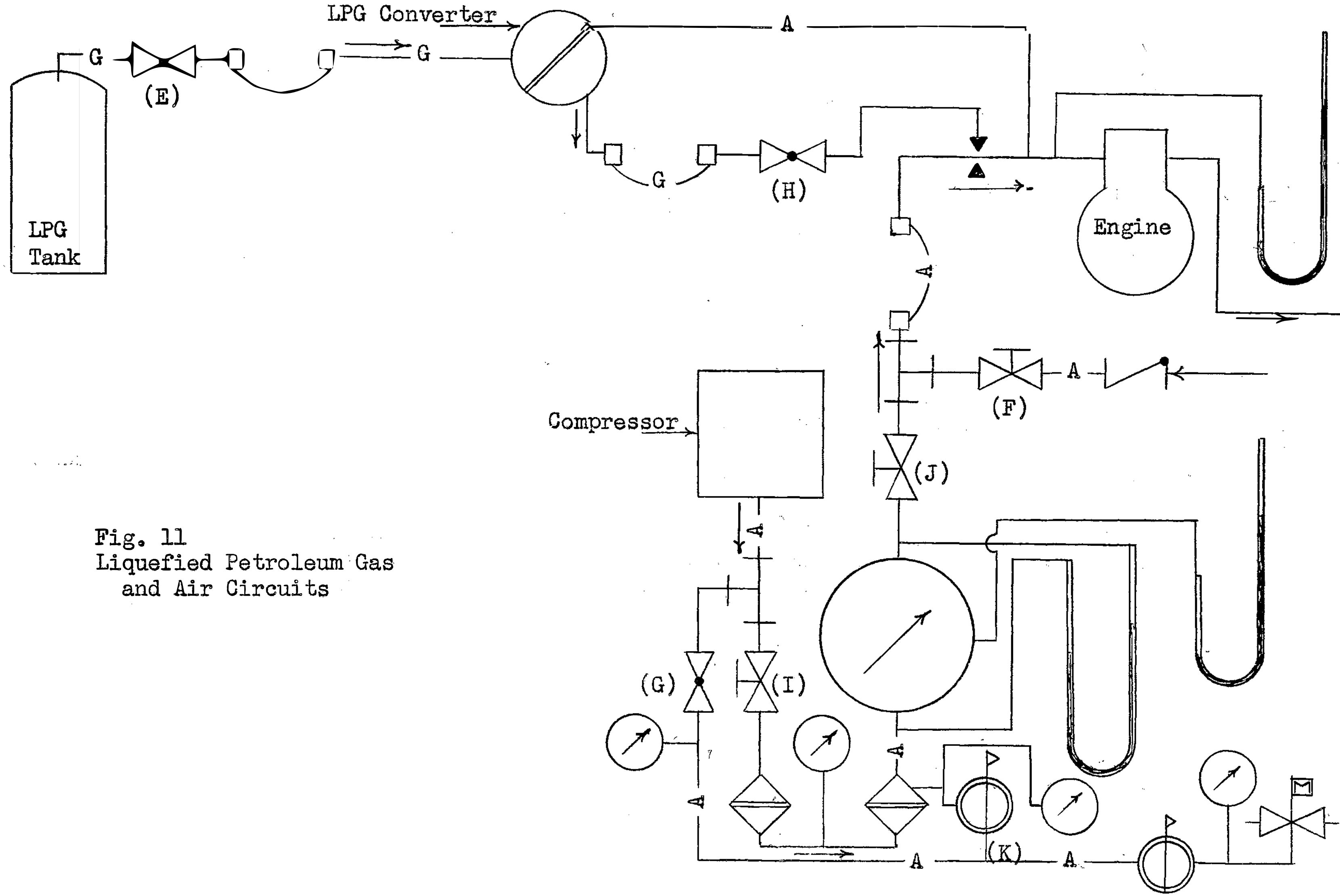


Fig. 11
Liquefied Petroleum Gas
and Air Circuits

CHAPTER III

PROCEDURE

The procedures indicated in the power test codes of the Society of Automotive Engineers and the American Society of Mechanical Engineers were adhered to wherever feasible in the running of the tests. The reader is referred to Appendix B for a step-by-step outline of the procedures entailed in starting, operating, and stopping this test assembly.

After the engine was started with air supplied to it directly from the atmosphere, the valves on the compressed air lines were opened and the engine, from then on, was operated on a supercharged basis. The compression ratio of the engine was adjusted to the desired level by means of the crank located on the engine which raised or lowered the head. The pressure in the manifold was controlled by adjusting the pressure regulating valve located on the panel which controlled the pilot pressure on the diaphragm of the secondary air regulator. The air-fuel ratio of the mixture admitted to the engine was adjusted by means of the small globe valve located near the carburetor on the fuel line. The air-fuel ratio was adjusted so as to yield a maximum power output. The spark setting of the ignition system was adjusted to obtain the least spark advance for maximum power output. The engine speed was maintained at 1250 rpm by regulating a load water valve controlling the flow of water to the dynamometer. This load water valve was placed in a convenient position near the engine.

The engine was operated at a speed of 1250 rpm during the time required for it to reach a stablized condition and also during the course of the test runs. Usually this condition was reached in about fifteen to twenty minutes after the manifold pressure had been changed to a new value. It was not necessary to stop the engine to change to a new set of conditions. The instability of the water dynamometer made it necessary to make frequent adjustments in the volume of water delivered to the dynamometer in order to maintain the engine speed at a constant or nearly constant value of 1250 rpm.

At the beginning of a test run, the electronic timing device was adjusted to start and to stop after a predetermined amount of fuel had been delivered to the engine. Immediately after the run had started, the collection of observed data commenced. The number of sets of observations was determined by the duration of the run. Air meter readings were taken exactly at the beginning and at the end of each test run.

CHAPTER IV

DATA

A. OBSERVED DATA

The data observed in this investigation are presented in Tables I to III.

In the presentation of data, the spaces with dashed lines indicate that the particular test runs in which they appear were made with atmospheric air conducted to the manifold. It should be noted that the manifold pressure is not atmospheric pressure but has some value below that of atmospheric pressure. No provision was made in the instrumentation of the project to determine the manifold pressure when the runs were made with air conducted directly to the engine from the atmosphere. In addition, the volume of air consumed in "atmospheric air" runs was not passed through the air meter and no data were taken on the volume of air used.

In the cases where more than one "set" of data was observed and recorded during the course of a test run, the several observations were averaged and the average observation is presented in the tables of observed data.

TABLE I

Observed Data - June, 1954
Compression Ratio 9.0

Run Number		1	2	3	4	5
Cooling Water Manometer	LH - in. Hg	0.50	0.47	0.47	0.45	0.45
	RH + in. Hg	0.50	0.47	0.47	0.45	0.45
Manifold Pressure	in. Hg	6.93	5.19	3.02	0.93	———
Air Meter Pressure	in. Hg	7.46	5.61	3.38	1.24	———
Cooling Water Temp-In	°F	82	81	81	82	80
Cooling Water Temp-Out	°F	100	99	97	97	96
Manifold Temp	°F	138	143	149	158	152
Crankcase Temp	°F	145	153	158	166	162
Air Meter Temp	°F	100	100	100	100	———
Exhaust Gas Temp	°F	965	897	880	825	911
Total Revolutions		8279	8478	9765	12798	22022
Revolutions per minute		1260	1265	1250	1250	1267
Time Interval	Minutes	6.555	6.737	7.839	10.279	17.517
Weight of Fuel	lb	0.4	0.4	0.4	0.6	0.6
Spark Setting	°BTDC	16	16	16	16	16
Dynamometer Scale	lb	11.38	10.42	9.58	8.62	7.80
Air Meter Before	cu ft	25682	25921	26145	26675	———
Air Meter After	cu ft	25747	25994	26222	26790	———
Date and Time		251100			251445	
Barometric Pressure	in. Hg	29.23			29.23	
Dry Bulb Temp	°F	100			102	
Wet Bulb Temp	°F	76.5			78	

TABLE II

Observed Data - June, 1954
Compression Ratio 7.0

Run Number		1	2	3	4	5
Cooling Water Manometer	LH - in. Hg	0.50	0.52	0.50	0.50	0.50
	RH + in. Hg	0.50	0.52	0.50	0.50	0.50
Manifold Pressure	in. Hg	———	19.13	17.20	15.93	14.18
Air Meter Pressure	in. Hg	———	19.79	17.88	16.61	14.88
Cooling Water Temp-In	°F	84	86	83	81	80
Cooling Water Temp-Out	°F	100	108	104	103	104
Manifold Temp	°F	149	130	131	147	146
Crankcase Temp	°F	146	151	154	153	158
Air Meter Temp	°F	—	99	98	98	99
Exhaust Gas Temp	°F	983	1057	1025	1033	996
Total Revolutions		20107	9413	9918	10225	11038
Revolutions per minute		1245	1240	1240	1240	1250
Time Interval	Minutes	16.181	7.648	8.360	8.258	8.753
Weight of Fuel	lb	0.6	0.6	0.6	0.6	0.6
Spark Setting	°BTDC	16	16	16	16	16
Dynamometer Scale	lb	7.88	15.80	13.88	14.02	13.58
Air Meter Before	cu ft	———	26895	27184	27579	27836
Air Meter After	cu ft	———	26972	27267	27659	27922
Date and Time		261000			261400	
Barometric Pressure	in. Hg	29.45			29.41	
Dry Bulb Temp	°F	92			98.5	
Wet Bulb Temp	°F	75			77	

TABLE II

Observed Data - June, 1954
Compression Ratio 7.0
(Continued)

Run Number		6	7	8	9
Cooling Water Manometer	LH - in. Hg	0.51	0.33	0.45	0.45
	RH + in. Hg	0.51	0.33	0.45	0.45
Manifold Pressure	in. Hg	11.79	8.98	6.36	1.43
Air Meter Pressure	in. Hg	12.35	9.44	6.75	1.83
Cooling Water Temp-In	°F	81	82	82	82
Cooling Water Temp-Out	°F	102	104	100	98
Manifold Temp	°F	145	140	145	148
Crankcase Temp	°F	160	152	161	141
Air Meter Temp	°F	99	100	100	92
Exhaust Gas Temp	°F	983	880	895	922
Total Revolutions		10488	8044	9613	17791
Revolutions per minute		1260	1240	1245	1250
Time Interval	Minutes	8.339	5.748	7.747	14.093
Weight of Fuel	lb	0.6	0.4	0.6	0.6
Spark Setting	°BTDC	16	16	16	16
Dynamometer Scale	lb	12.83	11.25	10.25	8.25
Air Meter Before	cu ft	28144	24057	28894	29593
Air Meter After	cu ft	28226	24113	28967	29723
Date and Time			240900		270900
Barometric Pressure	in. Hg		29.33		29.43
Dry Bulb Temp	°F		93		90
Wet Bulb Temp	°F		76		75

TABLE II

Observed Data - June, 1954
Compression Ratio 7.0

Run Number		1	2	3	4	5
Cooling Water Manometer	LH - in. Hg	0.50	0.52	0.50	0.50	0.50
	RH + in. Hg	0.50	0.52	0.50	0.50	0.50
Manifold Pressure	in. Hg	------	19.13	17.20	15.93	14.18
Air Meter Pressure	in. Hg	------	19.79	17.88	16.61	14.88
Cooling Water Temp-In	°F	84	86	83	81	80
Cooling Water Temp-Out	°F	100	108	104	103	104
Manifold Temp	°F	149	130	131	147	146
Crankcase Temp	°F	146	151	154	153	158
Air Meter Temp	°F	--	99	98	98	99
Exhaust Gas Temp	°F	983	1057	1025	1033	996
Total Revolutions		20107	9413	9918	10225	11038
Revolutions per minute		1245	1240	1240	1240	1250
Time Interval	Minutes	16.181	7.648	8.360	8.258	8.753
Weight of Fuel	lb	0.6	0.6	0.6	0.6	0.6
Spark Setting	°BTDC	16	16	16	16	16
Dynamometer Scale	lb	7.88	15.80	13.88	14.02	13.58
Air Meter Before	cu ft	------	26895	27184	27579	27836
Air Meter After	cu ft	------	26972	27267	27659	27922
Date and Time		261000			261400	
Barometric Pressure	in. Hg	29.45			29.41	
Dry Bulb Temp	°F	92			98.5	
Wet Bulb Temp	°F	75			77	

TABLE III

Observed Data - June, 1954
Compression Ratio 5.5
(Continued)

Run Number	6	7	8	9
Cooling Water Manometer LH - in. Hg	0.53	0.52	0.39	0.38
Cooling Water Manometer RH + in. Hg	0.53	0.52	0.39	0.38
Manifold Pressure in. Hg	7.12	4.91	2.96	0.71
Air Meter Pressure in. Hg	7.53	5.29	3.27	1.08
Cooling Water Temp-In °F	80	80	80	80
Cooling Water Temp-Out °F	98	99	101	99
Manifold Temp °F	148	147	149	152
Crankcase Temp °F	165	159	160	162
Air Meter Temp °F	98	99	98	97
Exhaust Gas Temp °F	960	1047	1025	1032
Total Revolutions	10868	16852	17434	17929
Revolutions per minute	1240	1250	1260	1265
Time Interval Minutes	9.154	13.407	13.772	14.192
Weight of Fuel lb	0.6	0.6	0.6	0.6
Spark Setting °BTDC	16	16	16	16
Dynamometer Scale lb	10.00	9.25	8.45	7.56
Air Meter Before cu ft	31400	31612	31854	32078
Air Meter After cu ft	31485	31740	31984	32209
Date and Time				271700
Barometric Pressure in. Hg				29.29
Dry Bulb Temp °F				99
Wet Bulb Temp °F				76.5

B. CALCULATED DATA

The data calculated from the data observed in this investigation are presented in Table IV.

Variations of the following items were plotted against manifold pressure, gauge:

Corrected brake horsepower (Figure 12)

Resultant horsepower (after allowance for air compression power requirement has been made) (Figure 13)

Specific fuel consumption (Figure 14)

Brake mean effective pressure (Figure 15)

Exhaust temperature (Figure 16)

Similar to the situation in part A of this chapter, spaces with dashed lines indicate that the particular test runs in question were made with atmospheric air conducted to the manifold. For such a run, the manifold pressure is not atmospheric pressure but some value below that of atmospheric pressure.

Sample calculations are to be found in Appendix C.

TABLE IV

CALCULATED DATA

Manifold p (gauge) in. Hg	Manifold p (abs.) in. Hg	bhp_c	hp_{comp}	hp_r	BSFC $\frac{\text{lb fuel}}{\text{bhp hr}}$	AFR $\frac{\text{lb air}}{\text{lb fuel}}$	$bmep_c$
			COMPRESSION RATIO 9.0:1				
6.93	35.94	6.39	0.285	6.10	0.570	14.06	107.6
5.19	34.20	5.86	0.225	5.64	0.608	14.98	98.8
3.02	32.03	5.36	0.114	5.25	0.574	14.74	91.3
0.93	29.94	4.86	0.037	4.82	0.729	13.75	82.8
-----	-----	4.41	-----	4.41	0.468	-----	74.4
			COMPRESSION RATIO 7.0:1				
19.13	48.38	8.60	0.942	7.66	0.542	14.92	148.2
17.20	46.45	7.26	0.814	6.45	0.586	15.47	130.3
15.93	45.13	7.79	0.733	7.06	0.561	14.52	133.5
14.18	43.38	7.66	0.647	7.01	0.538	14.99	129.1
11.79	40.99	7.22	0.517	6.70	0.598	13.44	121.9
8.98	38.11	7.03	0.369	6.66	0.593	12.78	106.7
6.36	35.56	5.69	0.243	5.45	0.817	10.36	97.4
1.43	30.67	4.67	0.049	4.62	0.548	16.19	78.7
-----	-----	4.41	-----	4.41	0.507	-----	75.0
			COMPRESSION RATIO 5.5:1				
20.30	49.57	8.63	0.985	7.64	0.633	12.95	146.7
17.57	46.84	7.45	0.839	6.61	0.538	16.77	128.1
15.27	44.44	6.84	0.730	6.11	0.588	16.04	116.2
10.86	40.03	6.08	0.482	5.60	0.541	17.60	102.2
7.12	36.29	5.32	0.276	5.04	0.742	12.36	95.2
4.91	34.08	5.21	0.189	5.02	0.517	17.43	88.0
2.96	32.13	4.81	0.108	4.70	0.547	16.70	80.5
0.71	29.78	4.30	0.023	4.28	0.595	15.68	72.2
-----	-----	4.02	-----	4.02	0.688	-----	69.8

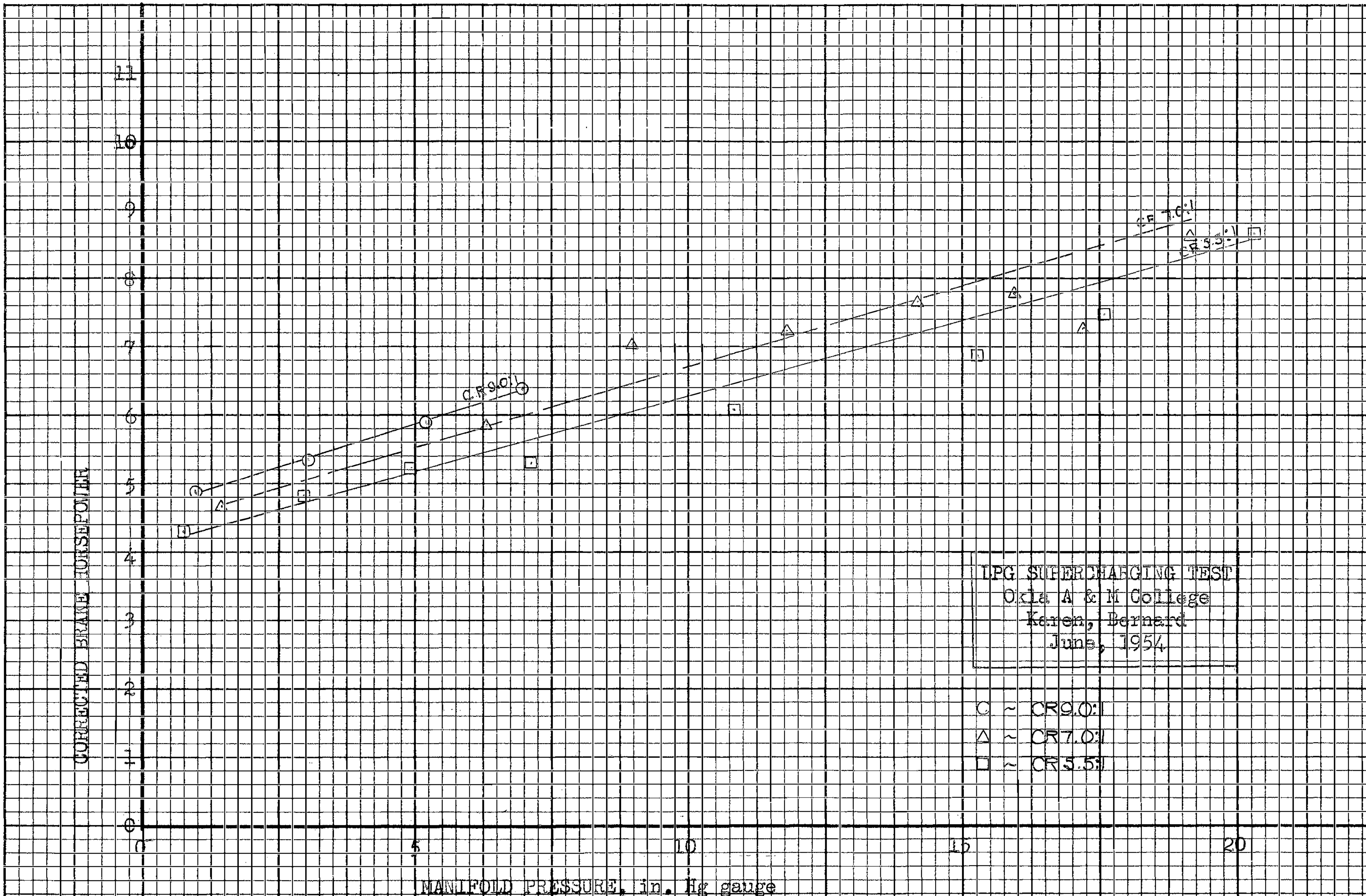

LPG SUPERCHARGING TEST
Okla. A & M College
Karen, Bernard
June, 1954
○ ~ CR 9.0:1
△ ~ CR 7.0:1
□ ~ CR 5.5:1
C.R. 9.0:1
C.R. 7.0:1
C.R. 5.5:1
CORRECTED BRAKE HORSEPOWER
0
1
2
3
4
5
6
7
8
9
10
11
0
5
10
15
20
MANIFOLD PRESSURE, in. Hg gauge

Fig. 12

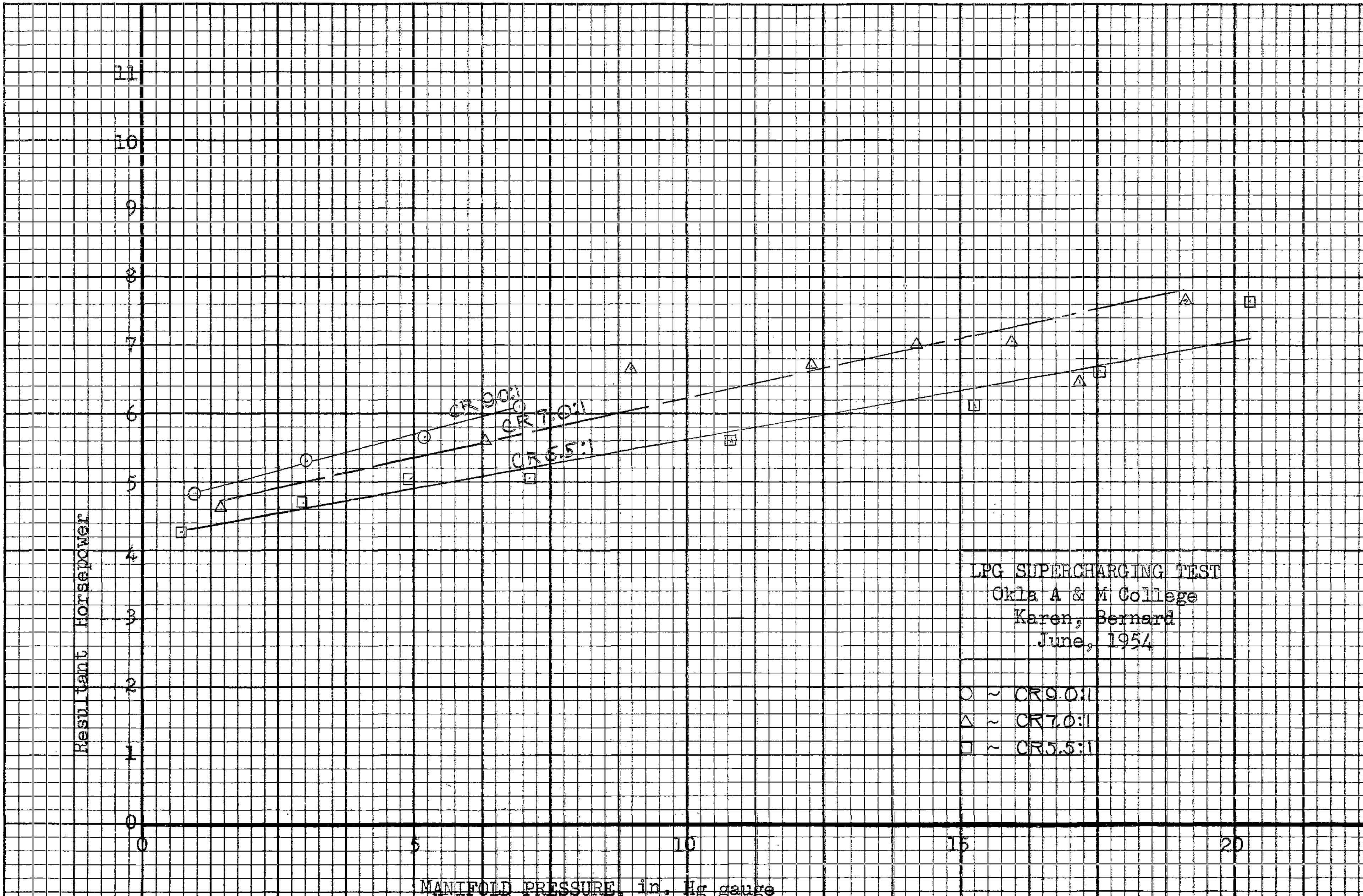

LPG SUPERCHARGING TEST
Okla A & M College
Karen, Bernard
June, 1954
○ ~ CR9.0:1
△ ~ CR7.0:1
□ ~ CR5.5:1
CR 9.0:1
CR 7.0:1
CR 5.5:1
Resultant Horsepower
0
1
2
3
4
5
6
7
8
9
10
11
0
5
10
15
20
MANIFOLD PRESSURE, in. Hg gauge

Fig. 13

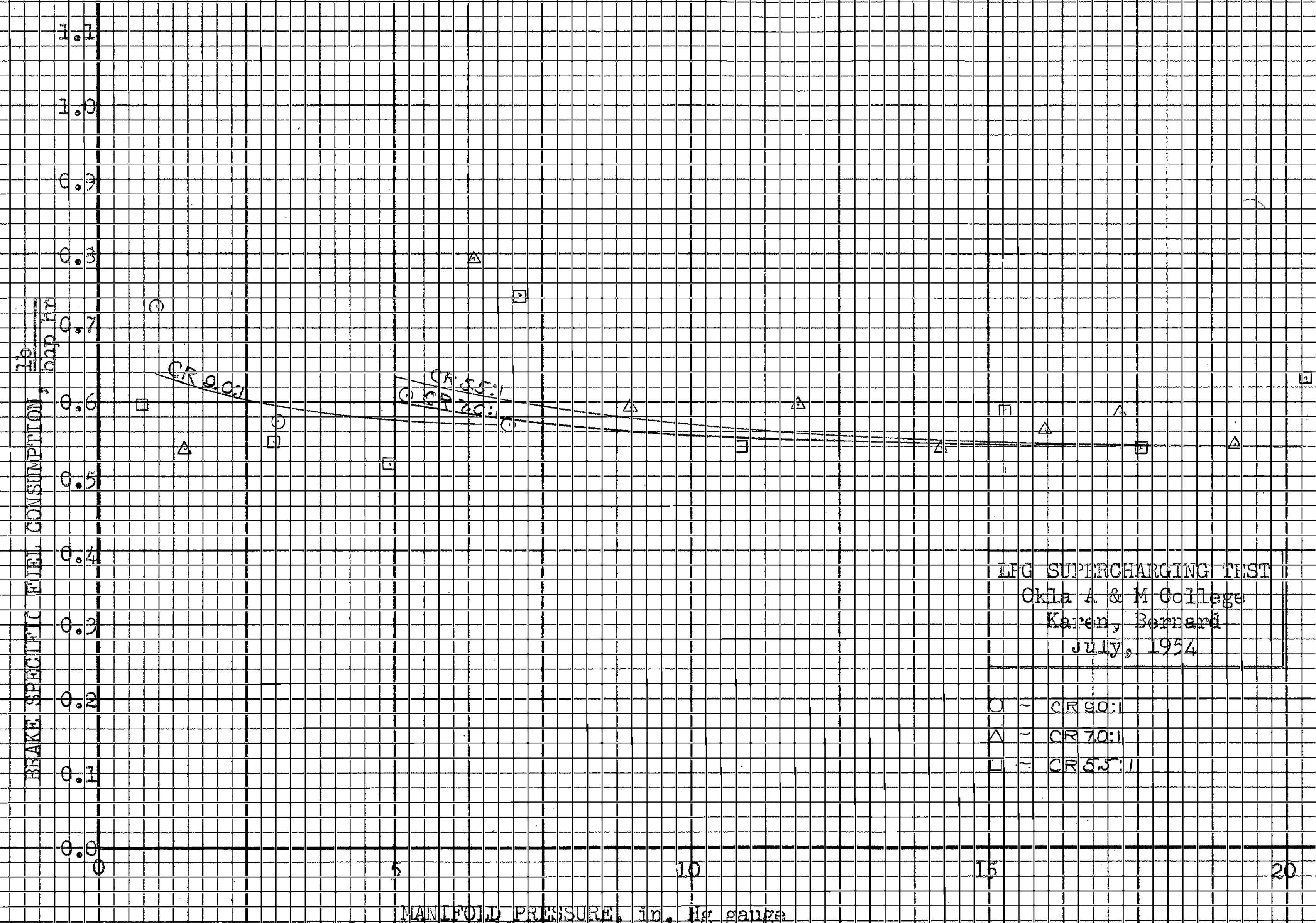

LPG SUPERCHARGING TEST
Okla A & M College
Karen, Bernard
July, 1954
○ ~ CR 9.0:1
△ ~ CR 7.0:1
□ ~ CR 5.5:1
CR 9.0:1
CR 5.5:1
CR 7.0:1
BRAKE SPECIFIC FUEL CONSUMPTION, lb / bhp hr
MANIFOLD PRESSURE, in. Hg gauge
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
0
5
10
15
20

Fig. 14

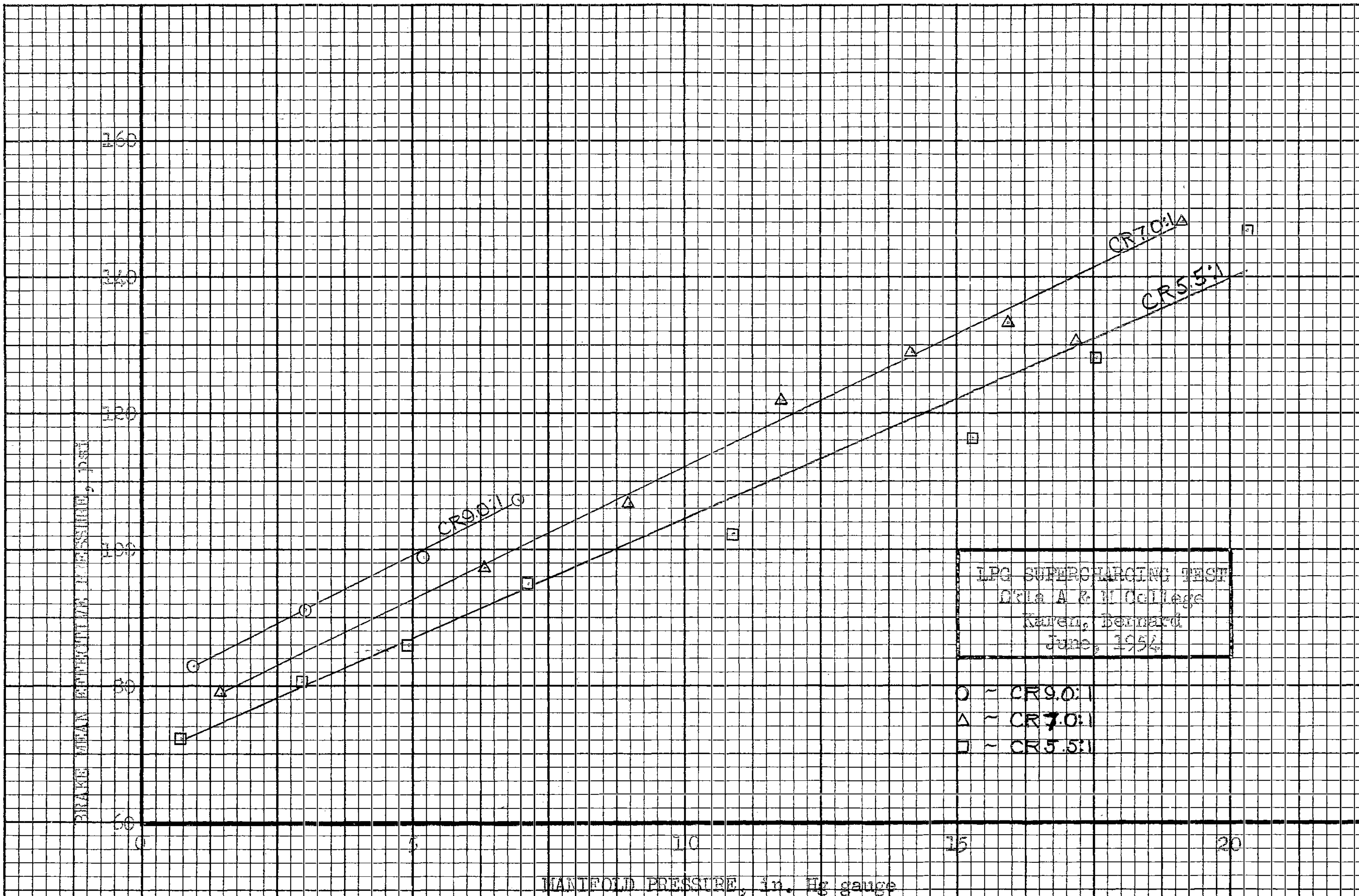
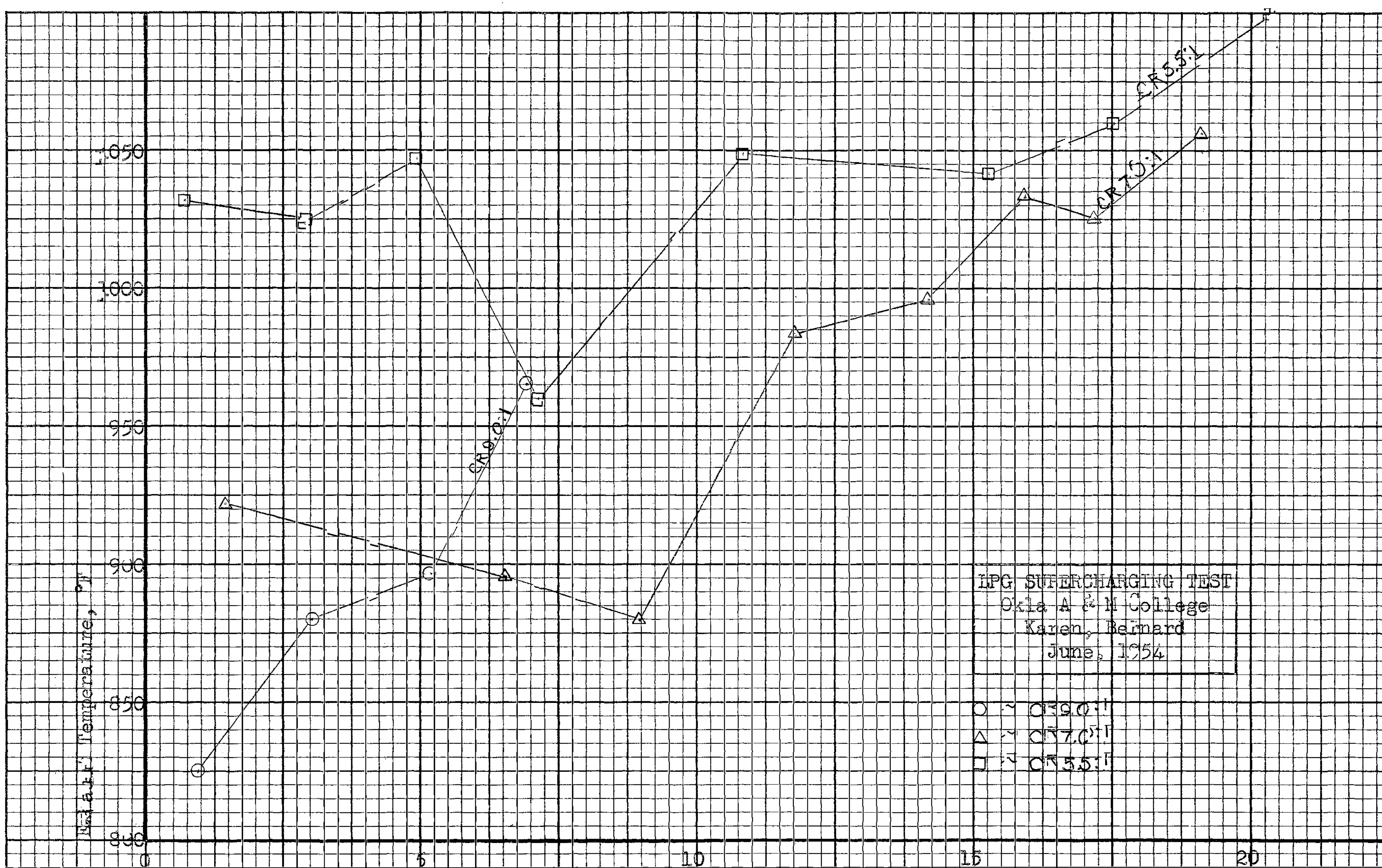

LPG SUPERCHARGING TEST
Okla A & M College
Karen, Bernard
June, 1954
○ ~ CR9.0:1
△ ~ CR7.0:1
□ ~ CR5.5:1
CR9.0:1
CR7.0:1
CR5.5:1
BRAKE MEAN EFFECTIVE PRESSURE, psi
160
140
120
100
80
60
0
5
10
15
20
MANIFOLD PRESSURE, in. Hg gauge

Fig. 15



MANIFOLD PRESSURE, in. Hg gauge

Fig. 16

CHAPTER V

SUMMARY

A. CONCLUSIONS

This investigation was undertaken to ascertain the effects and desirability of supercharging a liquefied petroleum gas engine. It is felt that the object was achieved, however, not as adequately as was originally anticipated.

The curves of the variations of the corrected brake horsepower as plotted against manifold pressure for the different compression ratios shown in Figure 12 clearly indicate that an increase in power output was obtained by increasing manifold pressure. The curves of the resultant brake horsepower (after the horsepower required for the air compression is charged to the engine) plotted against manifold pressure, as shown in Figure 13, also indicated that an increase in power output was realized from an engine-supercharger combination by increasing manifold pressure.

Examination of the tabulation of the different air-fuel ratios for the various test runs made indicated erratic variations in the values which differ radically in many cases from the expected range of values for the fuel for maximum power output.[1] The difficulty in obtaining the proper air-fuel mixture was occasioned by the lack of sensitivity of the water dynamometer used in this project.

[1]Obert, E. F. Internal Combustion Engines (Scranton, 1952), p. 218.

The graph shown in Figure 15 indicates that a straight line relationship exists between brake mean effective pressure and manifold pressure for the three compression ratios for which tests were made. This was the expected result because brake mean effective pressure is proportional to brake horsepower at constant engine speed.

The curves of the values of the specific fuel consumption plotted against manifold pressure shown in Figure 14 closely resemble those obtained in the supercharging of a gasoline engine. Note, however, that several of the values plotted fall well without the region of reasonable values. Examination of the data indicated that these unreasonable values for specific fuel consumption were obtained as a result of being unable to adjust the equipment to the air-fuel mixture for maximum power output. A particularly good example of this is shown in the data for manifold pressure 6.36 inches Hg gauge for compression ratio 7.0:1. The air-fuel ratio was calculated from the observed data as 10.36, a decidedly rich mixture. The specific fuel consumption for this run was calculated as 0.817, a value that is excessively high.

Despite the fact that air-fuel ratios and specific fuel consumption figures were erratic and inconsistent, the horsepower curves and the brake mean effective pressure curves presented approximately smooth straight-line functions. Established data indicates that power output will vary but to a very small degree despite relatively large changes in air-fuel ratios from the air-fuel ratio for maximum power output.[2] These considerations led to the conclusion that the inconsistencies in data resulted from the inherent characteristics of the equipment which would not indicate when the precise adjustment of air-fuel ratio for maximum power output was attained rather than from poor observational techniques.

The lack of sensitivity of the dynamometer also precluded the possibility of obtaining conclusive information regarding the least spark advance for maximum power output.

Examination of Figure 16, showing the variations of exhaust gas temperature plotted against manifold pressure, demonstrates a trend of a slight increase in the exhaust gas temperatures as the manifold pressure was increased. The variations were very erratic and the departures from smooth curves was probably influenced by the fact that many runs were made at other than the desired air-fuel ratio. Variations, either toward lean or rich mixtures, from the air-fuel ratio corresponding to maximum power output will depress combustion temperatures.[3]

During the course of the test runs, the observer noted that excessive knocking and pounding were apparent in the case of compression ratio 9.0:1 for manifold pressures above 7 inch Hg gauge level. Some knocking was evident for the compression ratio 7.0:1 runs for the manifold pressure levels from 17 to 20 inch Hg gauge but this was not regarded as being excessive. No knocking was apparent for the compression ratio 5.5:1 test runs.

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[2]Lichty, L. C. Internal-Combustion Engines (New York, 1951), p. 291.

[3]Ibid., p. 296.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

It is believed that this investigation has but to a slight extent indicated the desirability of the practice of supercharging a liquefied petroleum gas engine. Many of the conclusions indicated in the foregoing should be reinvestigated because of the limitations imposed by the instrumentation. The problem of getting the correct air-fuel ratio for maximum power output could be readily resolved by replacing the water dynamometer with a power measuring instrument of a more sensitive character. A suitable instrument would be an electric dynamometer. A possible solution would be the use of a thermal conductivity type exhaust gas analyzer to indicate the value of the air-fuel ratio during the test. Provision should also be made to obtain the values of manifold pressure for runs made with atmospheric air conducted to the engine and to measure the volume of air consumed for such test runs.

Other avenues of experimentation on the effects of supercharging liquefied petroleum gas engines should include the collection of data for and the preparation of heat balances; the obtaining of the minimum spark advance for maximum power output which could readily be accomplished with a sensitive dynamometer; examining the effects of varying the manifold temperature for it is a well-known phenomenon that liquefied petroleum gases are extremely sensitive to temperature changes; using butane for a complete set of test runs and comparing it with the information obtained from a series of propane test runs; investigating the extent of deterioration induced by supercharging on various engine parts, particularly exhaust valves; and research into the problem of the optimum compression ratio to be used in supercharging a liquefied petroleum gas engine.

BIBLIOGRAPHY

Abell, Carl. Butane-Propane Power Manual. Los Angeles: Jenkins Publications, Inc., 1952.

______. CFR Handbook. Coordinating Fuel Research Committee of the Coordinating Research Council Incorporated. New York: 1944.

______. CFR Knock-Testing Manual. Coordinating Fuel Research Committee of the Coordinating Research Council Incorporated. New York: 1945.

Cornelius, Walter and John D. Caplan. "An Improved System for Control and Measurement of Air Consumption of a Single-Cylinder Engine." Society of Automotive Engineers Quarterly Transactions, Vol. 16 No. 4 (October, 1952) 666-676.

______. Displacement Gas Meters, Handbook E-4. Erie, Pa.: The American Meter Company Incorporated, 1952.

______. Graphical Symbols - ASA A32.2. New York: Standards Association, 1941.

______. Internal-Combustion Engines, PTC 17-1949. New York: American Society of Mechanical Engineers, 1949.

Keenan, Joseph H. and Joseph Kaye. Gas Tables. New York: John Wiley and Sons, Incorporated, 1950.

Lichty, Lester C. Internal-Combustion Engines. New York: McGraw-Hill Book Company, 1951.

Maleev, Vladimir L. Internal-Combustion Engines. New York: McGraw-Hill Book Company, 1945.

Marks, Lionel S. Mechanical Engineers' Handbook. New York: McGraw-Hill Book Company, 1951.

______. New Departure Handbook Vol. II. Bristol, Conn.: New Departure Division General Motors Corporation, 1951.

Obert, E. F. Internal Combustion Engines. Scranton: International Textbook Company, 1952.

Smith, Blanchard. "Fundamental Principals of Regulators." Proceedings of the 1944 Southwestern Gas Measurement Short Course Issue of the University of Oklahoma Bulletin. (December 15, 1944).

Sneed, Richard B. An Investigation of Some of the Fundamentals of Supercharging. Detroit: Ethyl Gasoline Corporation, 1938.

Sneed, Richard B. An Investigation of the Effects of Supercharging on the Performance of a 331 Cubic Inch "L" Head Commercial Vehicle Engine. Detroit: Ethyl Gasoline Corporation, 1941.

Taylor, C. Fayette and Edward S. Taylor. The Internal Combustion Engine. Scranton: International Textbook Company, 1948.

Vincent, E. T. Supercharging the Internal Combustion Engine. New York: McGraw-Hill Book Company, 1948.

Zimmerman, O. T. and Irvine Lavine. Scientific and Technical Abbreviations, Signs and Symbols. Dover, N. H.: Industrial Research Service, 1948.

APPENDIX A

LIST OF EQUIPMENT

1. Cooperative Fuel Research Unit.

   Manufacturer: Waukesha Motor Company.

   Serial Number: 6-37 752.

   Engine Serial Number: 6-37 419946.

   Unit used with electric motor disconnected from engine and with supplementary cooling unit.

2. Scales.

   Manufacturer: Kron Company

   Capacity: 150 pounds.

   Equipped with General Electric photoelectric cell Catalog number 4980621 and General Electric photo-electric relay serial number CR 7505 K2.

   Manufacturer: Hanson Company.

   Capacity: 60 pounds.

   Model: 2060.

3. Tachometer, electric.

   Manufacturer: General Electric Company.

   Type: DJ13.

   Serial Number: 626469.

4. Total Revolutions Counter.

   Manufacturer: Standard Electric Time Company.

5. Interval Timer.

Manufacturer: Standard Electric Time Company.

6. Pressure Gauges.

Manufacturer: U. S. Gauge Company.

Range: 0 - 30 psi.

Quantity: 3.

Manufacturer: Ashcroft Company.

Range: 0 - 160 psi.

7. Pressure Reducing Valves.

Manufacturer: Unknown.

Quantity: 2.

8. Barometer.

Manufacturer: Central Scientific Supply Company.

Type: Mercury.

9. Differential Manometers.

Manufacturer: Meriam Instrument Company.

Type: 10 in. U-tube with mercury.

Type: $6\frac{1}{2}$ in. column with draft gauge oil.

10. Manometers.

Manufacturer: Trimount Instrument Company.

Type: 30 in. column with mercury, cistern type.

Quantity: 2.

11. Potentiometers, Indicating.

Manufacturer: Tagliabue Manufacturing Company.

Model: Celectray.

Serial Number: 81-1986.

Range: 0 - 1000°F

Electricity: 220 volts - 60 cycles.

Used with Iron-constantan thermocouples.

Manufacturer: Brown Instrument Company.

Serial Number: 309954.

Range: 0 - 1600°F

Electricity: 110 volts - 60 cycles.

Used with iron-constantan thermocouple.

12. Switch Panel.

Manufacturer: Brown Instrument Company.

Number of circuits: 48.

13. Storage Tank for Liquefied Petroleum Gas.

Manufacturer: Unknown.

Capacity: 30 gallons.

Equipped with Bastian-Blessing Rotary Gauge.

14. Air Motor Valve.

Manufacturer: Minneapolis-Honeywell Regulator Company.

Size: 1 in.

15. Regulators.

Manufacturer: Fisher Governor Company.

Type: 630.

Orifice: 1.8 in.

Type: 730BU.

Orifice: 3/16 in.

16. Meter, Gas.

Manufacturer: Metric Metal Works of the American Meter Co.

Type: 80B Iron Case.

Serial Number: 05157.

17. Compressor, Air.

Manufacturer: Gardner-Denver Company.

Type: Two-stage "V"

Model: ADS 1002.

Serial Number: 89668.

Bore: Low pressure $5\frac{1}{2}$ in.

High pressure 3 in.

Stroke: 4 in.

Speed: 850 rpm.

Maximum pressure: 200 psi.

18. Converter, Liquefied Petroleum Gas.

Manufacturer: Century Gas Equipment Company.

Model: M.

19. Starting Mechanism.

Manufacturer: Research and Development Laboratory, Oklahoma Institute of Technology.

Motor: 6 volt automotive starting motor of unknown manufacture.

20. Carburetor, Liquefied Petroleum Gas.

Manufacturer: Mechanical Engineering Department, Oklahoma Institute of Technology.

21. Dynamometer.

Manufacturer: German make, manufacturer's name unknown.

Type: Water dynamometer.

Marked as follows:

Type: WP 1.

Unv.-Nr: 301.

Hebellänge: 0.716m (length of lever arm: 0.716m)

Ne = n x G x 0.001 PS.

22. Generator.

Manufacturer: Mallory Company.

Serial Number: 906562-2.

Electricity:

Input: 220 volts - 60 cycles.

Output: 0 - 32 volts dc.

23. Hygrometer, stationary.

Manufacturer: Central Scientific Supply Company.

24. Cooling Water Flow Meter.

Manufacturer: Mechanical Engineering Department, Oklahoma Institute of Technology.

Type: Venturi.

APPENDIX B

OPERATIONAL PROCEDURES

(Letters in parentheses refer to Figures 10 and 11.)

STARTING ENGINE

1. Close air compressor tank water drain valve.
2. Start air compressor motor.
3. Open main water valve.
4. Start direct current generator and adjust output to six to eight volts.
5. Open secondary water valve located near dynamometer base (A).
6. Open load water valve at dynamometer (B).
7. Open cooling water inlet valve (C).
8. Open liquefied petroleum gas tank valve (E).
9. Open atmospheric air valve (F).
10. Open air control line valve (G).
11. Open air motor valve on load water line (D)
12. Switch on electric tachometer.
13. Switch on both pyrometer potentiometers.
14. Throw "start" switch on Cooperative Fuel Research Unit panel.
15. Switch on ignition at Cooperative Fuel Research Unit panel and adjust voltage to 110 volts direct current with variable resistance.
16. Open liquefied petroleum gas valve at carburetor (H).
17. Pull starter rope.

18. After engine starts, adjust liquefied petroleum gas valve at carburetor (H).

RUNNING TESTS

1. Set compression ratio to desired level by use of micrometer setting on engine according to table of values.
2. Admit compressed air to the engine by opening gate valve located near the two regulators (I) and then the valve located near the engine (J).
3. Adjust the manifold pressure to the desired level by controlling the pilot pressure on the diaphragm of the secondary compressed air regulator by turning pressure reducing valve (K).
4. Adjust fuel valve (H) at the carburetor to yield maximum power output.
5. Adjust the load water valve (L) so that the speed of the engine is maintained at 1250 rpm.
6. Refine the adjustments of first part 4 and then part 5.
7. Find the minimum spark advance for maximum power output.
8. Repeat part 6.
9. Allow the engine to reach a "steady state" condition which is determined by checking manifold and crankcase temperatures.
10. Adjust the automatic control located on the scale to start and to finish the run after a specified amount of fuel has been consumed. This quantity of fuel is to be either 0.4 or 0.6 lb.
11. Observe and record barometric pressure, dry bulb temperature and wet bulb temperature.

12. Observe and record the following readings during the course of the run:

Air meter at start of run
Cooling water flow manometer
Manifold pressure
Air meter pressure
Cooling water temperature, both inlet and outlet
Manifold temperature
Crankcase temperature
Air Meter temperature
Exhaust gas temperature
Revolutions per minute
Weight of fuel consumed
Spark setting
Dynamometer scale
Air meter at end of run
Total revolutions
Time interval

The number of sets of observations is determined by the length of the test run. During the course of the run, minor corrections of the load water volume are to be made so as to maintain engine speed at 1250 rpm.

SHUTTING DOWN THE ENGINE AND OTHER EQUIPMENT

1. Shut off liquefied petroleum gas valve at the carburetor (H).
2. Shut off ignition switch on the Cooperative Fuel Research Unit panel.
3. Throw "STOP" toggle switch on the Cooperative Fuel Research Unit panel.
4. Close both compressed air valves (I and J).
5. Close cooling water valve (C).
6. Close load water valves (B and L).
7. Shut off starting generator.
8. Shut off both potentiometer - pyrometers.

9. Pull plug on automatic timer device.

10. Shut off liquefied petroleum gas valve on the tank (E).

11. Close main water valve.

12. Stop air compressor motor.

12. Open air compressor tank water drain valve.

APPENDIX C

SAMPLE CALCULATIONS

All calculations shown are for Run No. 1 of Compression Ratio 9.0 at a manifold pressure of 6.93 psig.

BRAKE HORSEPOWER:

$$bhp = \frac{2\pi RNP}{33000}$$

where bhp = brake horsepower

$$R = \text{length of dynamometer lever arm, ft}$$

$$= \frac{0.716\text{m} \times 39.37 \text{ in./m}}{12 \text{ in./ft}}$$

$$N = \text{revolutions per minute, rpm}$$

$$= \frac{\text{total revolutions}}{\text{time interval, min}}$$

$$P = \text{load on dynamometer scale, lb}$$

$$bhp = \frac{2\pi \times 0.716 \times 39.37}{33000 \times 12} \times NP$$

$$= 0.000447 \times NP$$

$$= 0.000447 \times \frac{8279}{6.555} \times 11.38$$

$$= 6.43$$

BRAKE HORSEPOWER CORRECTED FOR TEMPERATURE TO AN ASSUMED STANDARD MANIFOLD TEMPERATURE OF 145°F (605°R):

$$bhp_c = bhp \times \sqrt{\frac{T_m}{T_s}}$$

where bhp_c = corrected brake horsepower

bhp = brake horsepower

T_m = manifold temperature, °R

$$T_s = \text{standard temperature, } ^\circ R$$

$$= 605^\circ R$$

$$bhp_c = 6.43 \times \sqrt{\frac{598}{605}}$$

$$= 6.39$$

SPECIFIC FUEL CONSUMPTION:

$$\text{fuel/hr} = \frac{(\text{minutes in hour}) \times \begin{pmatrix}\text{weight of fuel consumed}\\ \text{by engine during run, lb}\end{pmatrix}}{(\text{time interval of run, min})}$$

$$= \frac{60 \times 0.4}{6.555}$$

$$= 3.662 \ \frac{\text{lb}}{\text{hr}}$$

$$SFC = \frac{\text{lb fuel/hr}}{\text{bhp}}$$

where SFC = specific fuel consumption

$$= \frac{3.662}{6.43}$$

$$= 0.570 \ \frac{\text{lb fuel}}{\text{bhp hr}}$$

BAROMETRIC PRESSURE CORRECTIONS:

Barometer reading		= 29.23 in. Hg
temperature correction	= -0.19	
gravity correction	= -0.03	
total correction	= -0.22	-0.22
Corrected barometric pressure		= 29.01 in. Hg

WEIGHT OF AIR CONSUMED BY ENGINE DURING TEST RUN:

$$W = \frac{pv}{RT}$$

where W = weight of air delivered to engine, lb

p = absolute pressure at meter, psf

v = volume of air delivered to engine as indicated by difference between "before" and "after" readings of air meter, cu ft

R = gas constant for air

T = meter temperature, °R

$$W = \frac{(29.01 + 7.46) \times 0.491 \times 144 \times 65}{53.35 \times 560}$$

$$= 5.62 \text{ lb}$$

AIR-FUEL RATIO

$$\text{Air-fuel ratio} = \frac{\text{weight of air consumed, lb}}{\text{weight of fuel consumed, lb}}$$

$$= \frac{5.62}{0.4}$$

$$= 14.06$$

HORSEPOWER REQUIRED FOR THEORETICAL AIR COMPRESSION:

Method used for the calculation of h_2 is found in Keenan & Kaye's Gas Tables, 1950, p. 214.

$$hp_{comp} = \frac{G(h_2 - h_1)}{42.42} \times \frac{1}{e}$$

where hp_{comp} = theoretical horsepower required for air compression

G = weight rate of air flow, lb/min

h_1 = enthalpy of ambient air

h_2 = enthalpy of air at manifold pressure

e = compressor efficiency - assumed as 60%[1]

h_1 = 133.86, p_{r_1} = 1.5742 (from Gas Tables)

$$p_{r_2} = p_{r_1} \times \frac{\text{manifold pressure, psia}}{\text{atmospheric pressure, psia}}$$

$$= 1.5742 \times \frac{35.94}{29.01}$$

$$= 1.950$$

h_2 = 142.32 at p_{r_2} = 1.950

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[1]Lichty, L. C. Internal-Combustion Engines, (New York, 1951), p. 472.

$$hp_{comp} = \frac{5.62 \times (142.32 - 133.86)}{6.555 \times 42.42 \times 0.60}$$

$$= 0.285$$

RESULTANT HORSEPOWER:

$$hp_r = bhp_c - hp_{comp}$$

where hp_r = resultant horsepower after horsepower for air compression is charged to engine

$$= 6.39 - 0.285$$

$$= 6.10$$

BRAKE MEAN EFFECTIVE PRESSURE:[2]

$$bmep_c = \frac{150.8}{D} \times T$$

where $bmep_c$ = corrected brake mean effective pressure, psi

T = corrected torque, lb-ft

D = total engine piston displacement, cu in.

$$bmep_c = \frac{150.8}{37.3} \times \frac{0.716 \times 39.37}{12} \times 11.38 \times \sqrt{\frac{598}{605}}$$

$$= 107.6 \text{ psi}$$

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[2]*SAE Gasoline Engine Test Code, Rules and Directions - GA* (New York, 1951), p. 2.

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