PISTON TEMPERATURE MEASUREMENT AND PISTON DESIGN INVESTIGATION ON A C. F. R. ENGINE

BY

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AND

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ON A C.F.R. ENGINE

By

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Submitted in Partial Fulfillment of the
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from the

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June 1, 1946

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

Dear Professor Swett:

We submit herewith, a thesis entitled "Piston Temperature Measurement and Piston Design Investigation on a C.F.R. Engine".

This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Science in Aeronautical Engineering.

Respectfully submitted,

ACKNOWLEDGMENT

The investigation reported in this thesis was conducted in the Sloan Automotive Laboratory, Massachusetts Institute of Technology, over the period March 1, 1946 to June 1, 1946.

Acknowledgment of, and appreciation for, assistance in this thesis is given to the following sources:

Professor W. A. Leary (M.I.T. Staff)
Pratt and Whitney Aircraft, East Hartford, Conn.
Mr. J. C. Livengood (M.I.T. Staff)
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The mechanics and assistants of the Sloan Laboratory.

Any opinons or statements contained herein represent the private views of the authors, and are not to be construed as official or in any sense reflecting those of the Navy and the naval service.

PREFACE

The purposes of this investigation were twofold:

1. To construct a satisfactory arrangement for the measurement of piston crown temperature in a C. F. R. Engine.
2. To determine the effect of piston crown design on piston temperature, with and without a forced system of cooling on the inside of the piston.

The subject was chosen for its particular interest to the authors in view of the considerable amount of piston "scouring" in present day engines of high speed and power. So much time has been spent on cylinder head design and so relatively little on interior piston design that it was thought advisable to attempt to find some of the trends occurring with changes in the design of the piston crown interior, and to note the effect of changes in some engine operating variables on piston crown temperatures.

T. Yamamoto and H. Nakamura ("Effect of Changes in Design and Operating Conditions on Cooling" M.I.T., 1935) attempted to measure piston temperatures on a C.F.R. engine and note the change of piston temperature with changes in crown thickness but were not highly successful due to

mechanical difficulties. They made no attempt to investigate the effect on piston temperature of changes in interior piston crown design.

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PISTON TEMPERATURE MEASUREMENT
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SUMMARY

A method of measuring piston temperature on a C.F.R. engine under operating conditions was carried through with the following results noted:

1. The method of piston temperature measurements proved very satisfactory.
2. Finning on the inside of the piston crown causes the piston to run hotter than with no finning.
3. A stream of oil under pressure applied to the under side of the piston crown lowers the piston temperature considerably, and is much more effective on a piston with deep fins on the inside of the crown than on one with no fins.
4. Piston temperatures tend to increase with an increase of engine speed.
5. Piston temperatures tend to increase with an increase of water jacket temperature.
6. Piston temperatures are highest as the fuel air ratio approaches that of best power, and drop off rapidly as the mixture is made leaner or richer than this value.
7. Inlet temperature has little effect on piston temperature.
8. Indications on one run tended to show that "blow by", caused by damaged piston rings, caused piston temperatures to be higher until rings were "worn in", indicating that a portion of the heat transfer from the piston goes to the cylinder walls via the rings.

There is a considerable amount of investigation to be done in this field and it provides an excellent opportunity for future students to study other phases of this subject. The working system has already been constructed, they need only investigate.

All tests were made in the Sloan Automotive Laboratory of the Massachusetts Institute of Technology by Lt. Com. N. O. Wittmann, USN, and Lt. Com. J. H. Smith, Jr., USN, under the direction of Prof. W. A. Leary of the school staff.

PISTON TEMPERATURE MEASUREMENT AND PISTON DESIGN INVESTIGATION ON A C.F.R. ENGINE.

INTRODUCTION

Although there have been investigations made on piston temperatures, there has been little successful work along these lines attempted in this laboratory. This project has been a necessarily hastened attempt to get some satisfactory results from the measurement of piston temperature in a standard C.F.R. engine under operating conditions.

Briefly, the objects of this project were:

1. To set up a satisfactory system of measuring piston temperatures in a C.F.R. engine under operating conditions.
2. To measure the piston head temperature of three different types of pistons and note how their designs affected cooling.
3. To determine the cooling effect of a stream of oil on the lower side of the crown of each piston.
4. To determine the effect on piston temperature of changes in some of the engine operating variables.

All tests were made in the Sloan Automotive Laboratory of the Massachusetts Institute of Technology by Lt. Com. N. O. Wittmann, USN, and Lt. Com. J. H. Smith, Jr., USN, under the direction of Prof. W. A. Leary of the school staff.

EQUIPMENT

A standard C.F.R. single cylinder, water cooled, variable compression ratio engine of 3.25 inch bore and 4.5 inch stroke was used. (Figures 1 and 2.)

The fuel air inlet system consisted of a puff tank and a vaporizing tank, the temperature of which was controlled by any desired combination of steam or cold water. The air supply came directly from the atmosphere through a measuring orifice. The pressure differential across the orifice was measured with a standard manometer, enabling the air flow to be computed exactly at all engine speeds and conditions. The fuel was metered through a calibrated rotometer which allowed any desired fuel air ratio to be set and held constant.

The exhaust system led through a puff tank around which cold water circulated. The exhaust pressure remained essentially constant at atmospheric pressure.

The spark was controlled by a breaker mechanism coupled directly to the crankshaft in order to hold a constant spark advance.

The cylinder jacket was water cooled and the temperature of the jacket could be maintained as desired by proper admittance of cold water or steam.

The power generated by the engine was absorbed by a dynamometer of the conventional cradle type. The speed could be accurately controlled by means of a variable field coil, tachometer, and strobotac operating on a 60 cycle frequency.

The engine oil temperature could be varied by the proper regulation of steam and cold water to the oil heat exchanger.

The three pistons used were essentially standard C.F.R. pistons with variations in design of the inside of the crown. All the pistons had the

same crown thickness and the same ring arrangement.

The first piston (termed the "plain piston") was a standard cast C.F.R. piston with no machining on the inside (Figures 3 and 4).

The second piston (termed the "ribbed piston") was a special casting with a grilled ribbing on the inside of the crown (Figure 5).

The third piston (termed the "finned piston") was another special casting with the deepest possible fins cast on the inside of the crown (Figures 6 and 7).

The iron constantan thermocouples were installed at a distance of 1/32 inch from the top of the piston and in the same relative position from the center of the piston, 3/8 inch from the center, laterally. The iron and constantan leads were brought down inside the piston to iron and constantan buttons on the lower edge of the piston skirt. These leads were held in place by small wire loops through drilled "V" holes in the piston wall. The thermocouples were installed in drilled holes approximately 1/32 inch in diameter, and were held in place with dental cement. The iron and constantan buttons in the edge of the piston skirt were installed in micarta blocks which were shrunk fit into drilled holes in the piston skirt. The entire system, except the actual faces of the contact points, was given several coatings of glyptol (Figures 3, 5 and 6).

The take off switch was mounted on a bracket and plate which was attached to the side of the crankcase after removal of one of the crankcase side plates. Elongated holes in the plate allowed for up and down adjustment to get proper contact of switch points with the contact points on the piston skirt.

The switches were constructed from magneto breaker points that were modified to give desired results. One switch required the addition of a

constantan button to which a constantan lead wire was directly soldered. The other switch had an iron button attached to the spring, from which an iron wire was led. Both switches were insulated from each other and the bracket by bakelite. The whole assembly was covered with several coatings of glyptol (Figure 8). The switches could be adjusted laterally and vertically by set screws to match the piston skirt contacts and to contact simultaneously.

The iron and constantan leads were covered with plastic tubing and glyptol, to prevent entrance of moisture. They were led out through the switch plate to a direct reading Leeds and Northrup type potentiometer. The potentiometer was equipped with a special sensitive type of galvanometer with the following characteristics:

Resistance	17 ohms
Period	5 seconds
Sensitivity	0.66 A/MM

The potentiometer was located far enough from the engine to be free of all vibrations.

The oil stream for use on the under side of the piston was taken directly from the electrically driven engine oil pump, through the contact bracket plate, and into a nozzle formed from a piece of copper tubing. The oil was supplied at a rate of 17 lbs. per minute.

PROCEDURE

All runs were made by setting the engine up at the desired running condition, loosening the take off switch bracket cap screws, raising the contact points until contact was evidenced on the potentiometer and then setting the contacts up approximately .02 inches further. It was found that this setting gave the most consistent results.

For each of the three pistons, the following runs were made:

1. Variation of water jacket temperature (90°F, 150°F, 210°F) for each of three different engine speeds (800, 1000 and 1200 rpms).

2. Same runs as above, but with a continuous stream of oil on the under side of the piston crown.

3. For the grilled piston, the following additional runs were made:

   (a) Variation of fuel air ratio.

   (b) Variation of fuel air inlet temperature.

Unless otherwise noted, the engine operating variables were kept at the following values:

Inlet temperature	T_i	150°F
Water jacket temperature	T_w	150°F
Crankcase oil temperature	T_o	90°F
Engine oil pressure	P_o	50 $\#/in.^2$
Engine fuel pressure	P_f	10.7 $\#/in.^2$
Fuel air ratio	F	.08

RESULTS AND DISCUSSION

A tabulation of the results obtained for this project is given in Tables I, II and III.

This arrangement for the measurement of piston temperatures seemed to be entirely satisfactory. No part of the system gave mechanical trouble and once the arrangement was set up, no particular difficulty in measuring the temperature was encountered. All runs were checked as many times as possible and in all cases the results were in excellent agreement.

Contrary to what had been anticipated, the plain piston ran cooler than the ribbed piston, and the latter cooler than the finned piston. In Fig. 9 the effect of changes in engine speed on piston temperature can be seen. There is a general rise in piston temperature when engine speed is increased, with all other engine operating conditions held constant. It can be seen that the finned piston ran the hottest. Just why this is so is not definitely known, although it is suspected that the deep fins retard air circulation and oil splashing on the under side of the piston crown and thus more heat is retained by the crown, causing higher temperatures. Some of the difference in temperature may be due to the additional amount of piston material above the piston pin bosses in the plain piston, causing more heat to be carried away through this path, and consequently giving better cooling of the piston. However, the fact that the finned piston runs hotter than the ribbed piston of similar design and weight tends to discount this theory.

The forced system of carrying heat away proves very effective in all cases, and particularly so in the case of the finned piston. The final

result is not as encouraging as was to be expected since the finned piston ran much hotter before the oil stream was applied. However, there are indications that some combination of deep finning plus forced heat removal may have possibilities in lowering the piston crown temperature and preventing scouring of pistons at present day high engine speeds and power.

Fig. 10 and Fig. 11 are repetitions of Fig. 9 at higher water jacket temperature and show the same trends.

Figs. 12, 13 and 14 show the variation of piston temperature with change in water jacket temperature at 800, 1000 and 1200 rpms respectively. Again, the finned piston runs hot and the plain piston cooler, until a forced oil stream is added and then the temperature trends are reversed. In general, the piston temperatures increase with increase in water jacket temperature, but the rate of increase is lowered as piston temperature is lowered.

Fig. 15 shows the effect of changes in fuel air ratio and inlet temperature on piston temperature. At very lean fuel air ratios, piston temperatures are low, but build up rapidly with an increase in fuel air ratio until approximately best power fuel air ratio is reached, at which point the temperatures reach their maximum, then drop off rapidly with further enrichening of fuel air ratio.

Changes of inlet temperature within the range of this setup gave little change in piston temperature.

Fig. 16 was an accidental occurrence that might well be investigated by future students. When the engine was started with new rings on the piston, "blow by" was indicated by a considerable amount of smoke coming

through the crankcase breather pipe. Also, piston temperatures were considerably higher than on all previous runs starting under the same conditions but with no apparent "blow by". As the time after starting increased, the smoke gradually decreased and piston temperatures lowered, until after about six hours of running, the temperatures were constant and agreed with previous runs; and the smoke from the breather ceased. It is thought that these new rings may have been scratched or were in some other way irregular, allowing "blow by" until they were properly "worn in". The "blow by" prevented the usual amount of heat transfer between the piston, piston ring, and cylinder walls, and caused higher piston temperatures until the point was reached where the rings were "worn in", no "blow by" occurred, and normal heat transfer to the cylinder walls took place.

It is suggested that further investigation along these lines could profitably be made by future students. The actual set-up is now completed and another group would not have to spend a considerable portion of their limited time in repeating what has already been accomplished, and could devote all of their time to more thorough and complete investigation of actual piston designs. It is further suggested that the plain piston should be machined on the under side of the crown to the same dimensions as the other two pistons and that perhaps another piston with slightly shorter fins could be investigated. Other subjects for investigation would be the use of a stream of compressed air on the under side of the piston crown, and a check on the effects of "blow by" on piston temperatures.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were arrived at as the result of this investigation:

1. The method of piston temperature measurement used proved very satisfactory.
2. Finning on the inside of the piston crown causes the piston to run hotter than with no finning.
3. A stream of oil under pressure applied to the under side of the piston crown lowers the piston temperature considerably, and is much more effective on a piston with deep fins on the inside of the crown than on one with no fins.
4. Piston temperatures tend to increase with an increase of engine speed.
5. Piston temperatures tend to increase with an increase of water jacket temperature.
6. Piston temperatures are highest as the fuel air ratio approaches that of best power, and drop off rapidly as the mixture is made leaner or richer than this value.
7. Inlet temperature has little effect on piston temperature.

8. Indications on one run tended to show that "blow by", caused by damaged piston rings caused piston temperatures to be higher until rings were "worn in", indicating that a portion of the heat transfer from the piston goes to the cylinder walls via the rings.

The following recommendations are made as suggestions for future study:

1. More intensive investigation of the three piston designs used for this project, with the "plain piston" machined under the crown to the wall dimensions of the other pistons.
2. Investigation of pistons of other designs, particularly with fin length between that of the "ribbed piston" and that of the finned piston.
3. Investigation of the use of compressed air on the under side of the piston crown to produce forced cooling.
4. Investigation of the effects of "blow by" on piston temperature.
5. Investigation of the heat flow through the piston crown by putting a number of thermocouples in the crown and upper ring "lands".

APPENDIX A

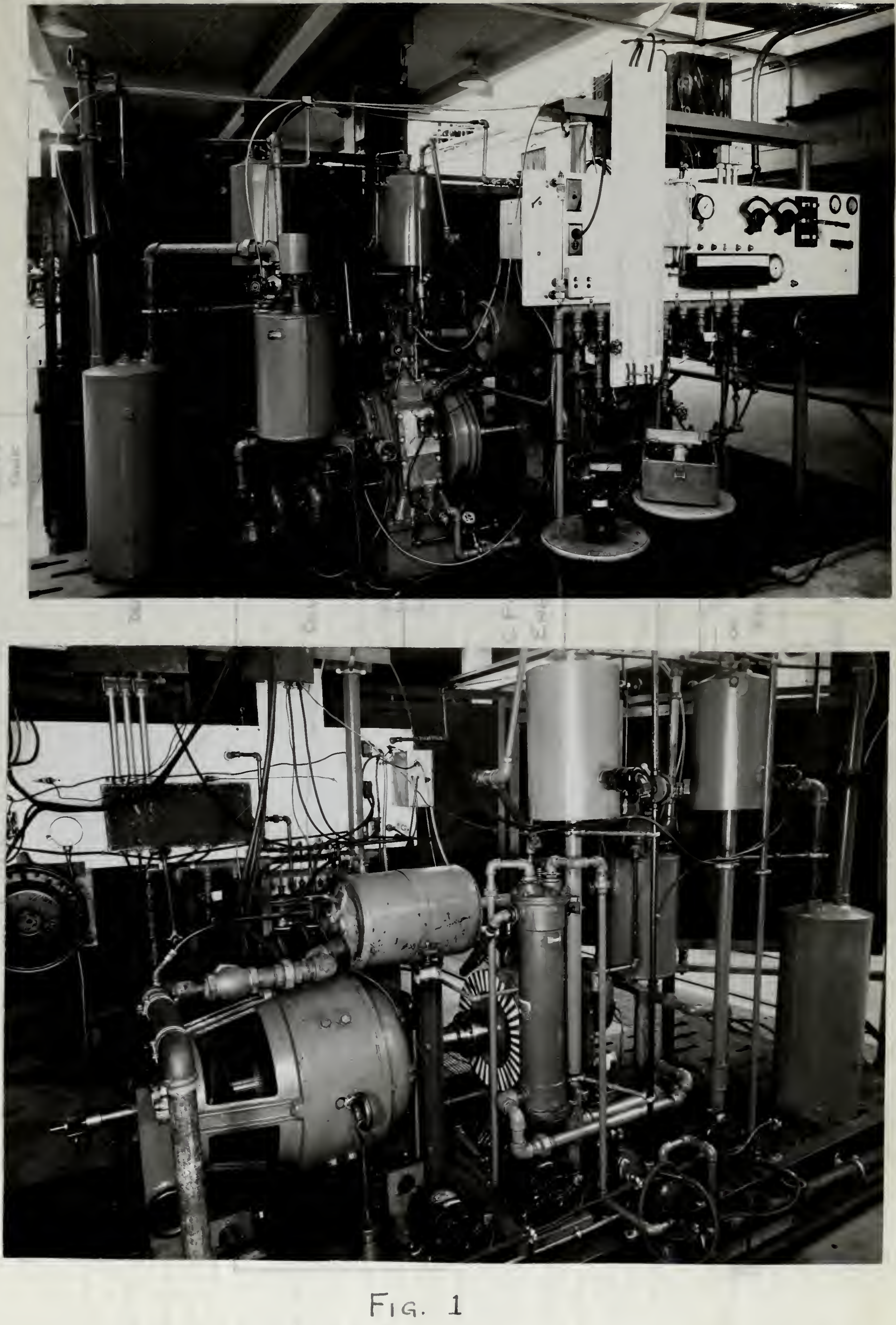

FIG. 1
ENGINE LAYOUT

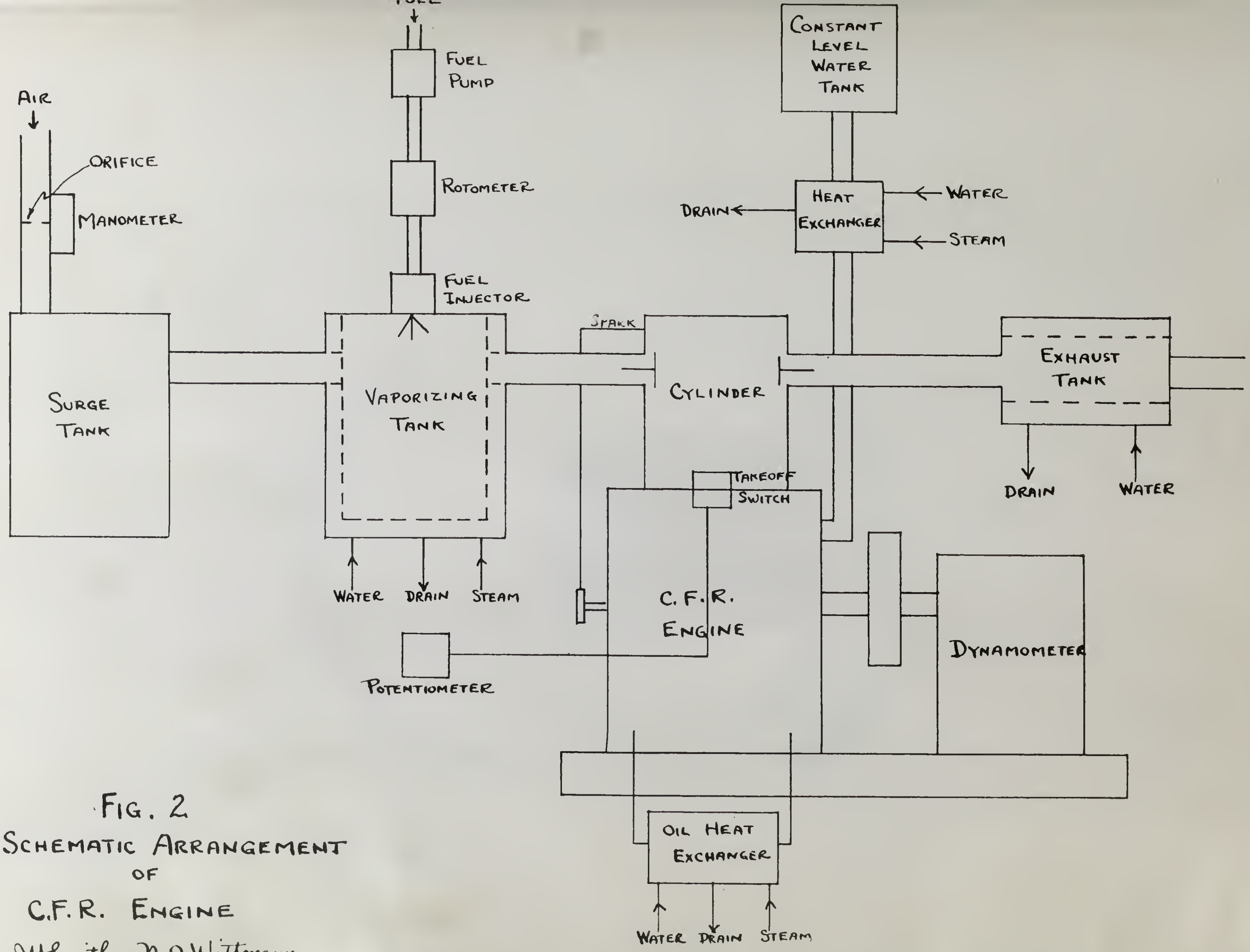

Fig. 2
Schematic Arrangement
of
C.F.R. Engine

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Fig. 3
Plain Piston

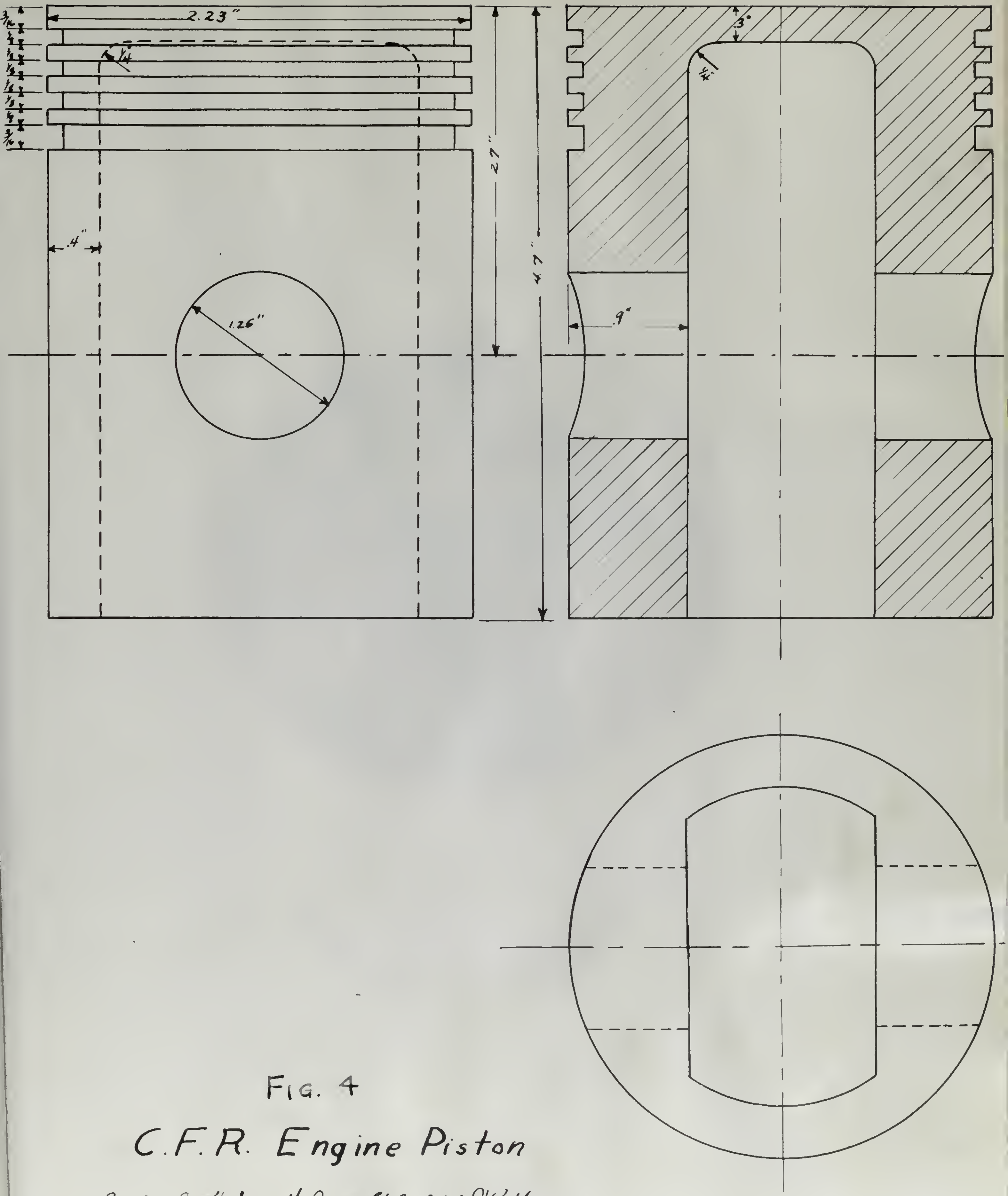


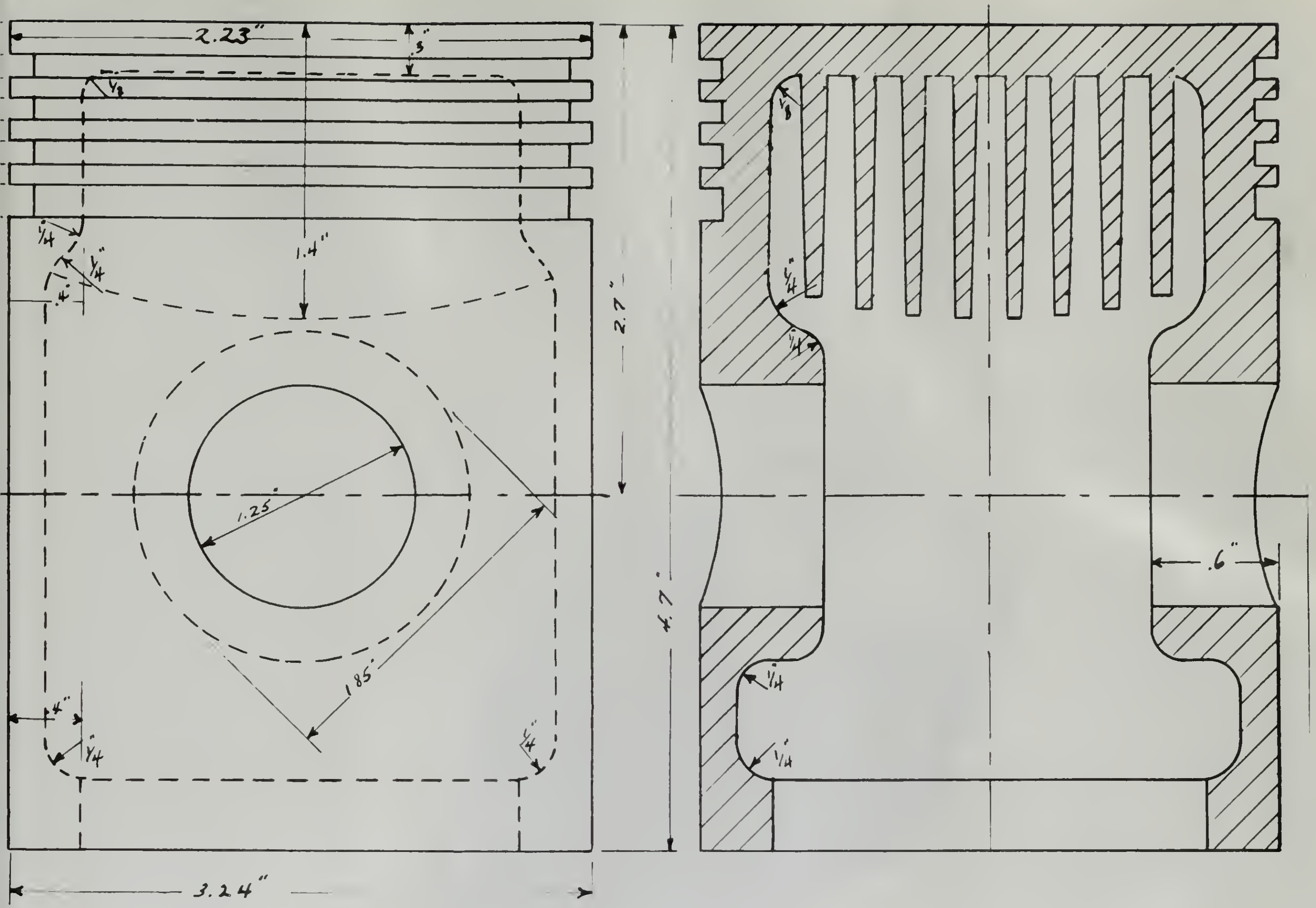
Fig. 4

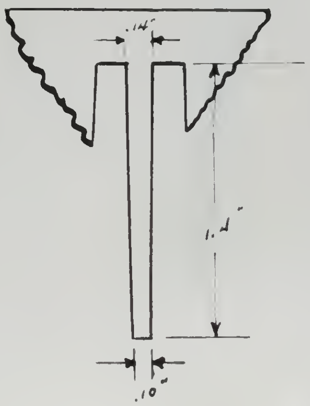
C.F.R. Engine Piston

Lt. Com. J. H. Smith, Jr + Lt. Com. N. O. Hittmann

FIG. 5
RIBBED PISTON

Fig. 6
Finned Piston





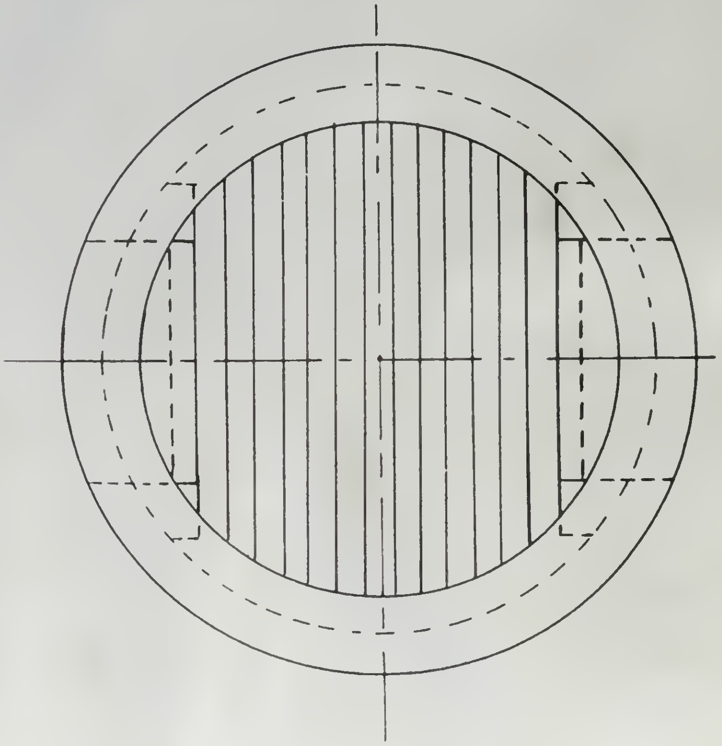
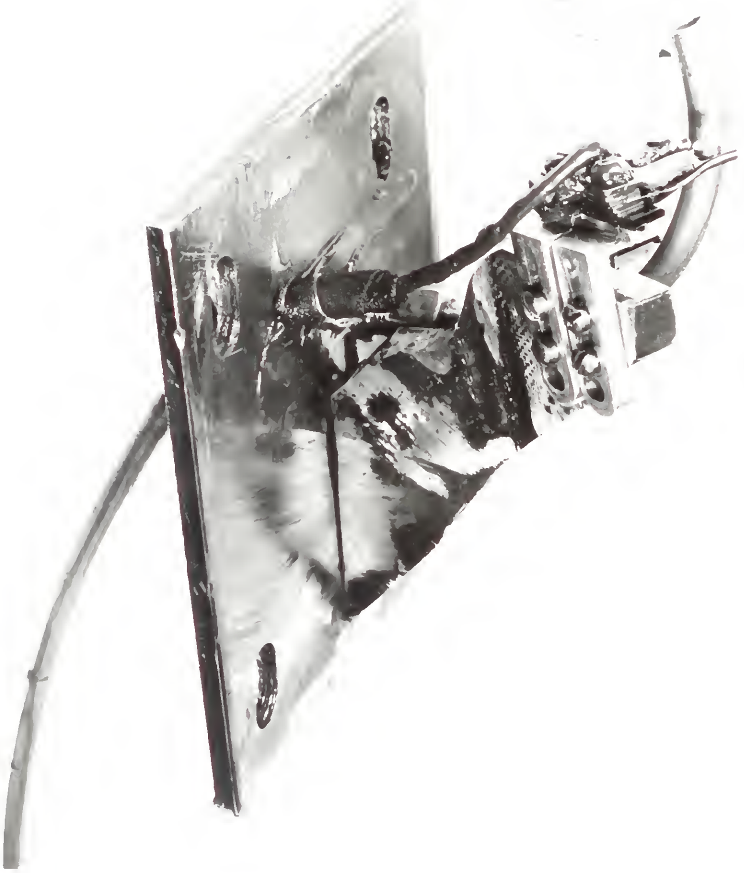


Fig. 7

C.F.R. Engine Piston

With Deep Fins

Lt. Com. J. H. Smith, Jr. + Lt. Comdr. N. O. Wittmann



[illegible]

APPENDIX B

PLAIN PISTON

REV. PER MINUTE	T_w (°F)	RUN #1 PISTON TEMP (°F)	RUN #2 PISTON TEMP. (°F)	RUN #3 PISTON TEMP (°F)	RUN #4 PISTON TEMP (°F)	PISTON TEMP (WITH OIL) (°F)	PISTON TEMP (WITH OIL) (°F)
800	90	248	255	258	246	203	202
"	150	282	291	298	283	222	232
"	210	323	325	328	326	245	260
1000	90	267	265	275	255	218	220
"	150	298	302	295	297	236	242
"	210	333	347	351	346	261	270
1200	90	275	282	285	272	244	225
"	150	310	312	321	318	250	257
"	210	340	348	342	351	261	270
			RIBBED PISTON				
800	90	275	257	256		198	
"	150	312	303	297		215	
"	210	352	347	343		234	
1000	90	286	265	267		187	
"	150	320	287	287		215	
"	210	358	345	342		226	
1200	90	299	277	282		207	
"	150	329	312	315		207	
"	210	370	347	351		235	
			FINNED PISTON				
800	90	308	288	270		175	
"	150	340	330	312		175	
"	210	372	352	349		175	
1000	90	318	312	310		185	
"	150	344	341	342		198	
"	210	382	370	365		202	
1200	90	328	330	318		200	
"	150	358	365	345		202	
"	210	380	370	365		195	

$F/A = .08$ $T_x = 150°F$ $T_o = 90°F$ $p_o = 49 \text{ lb/in}^2$

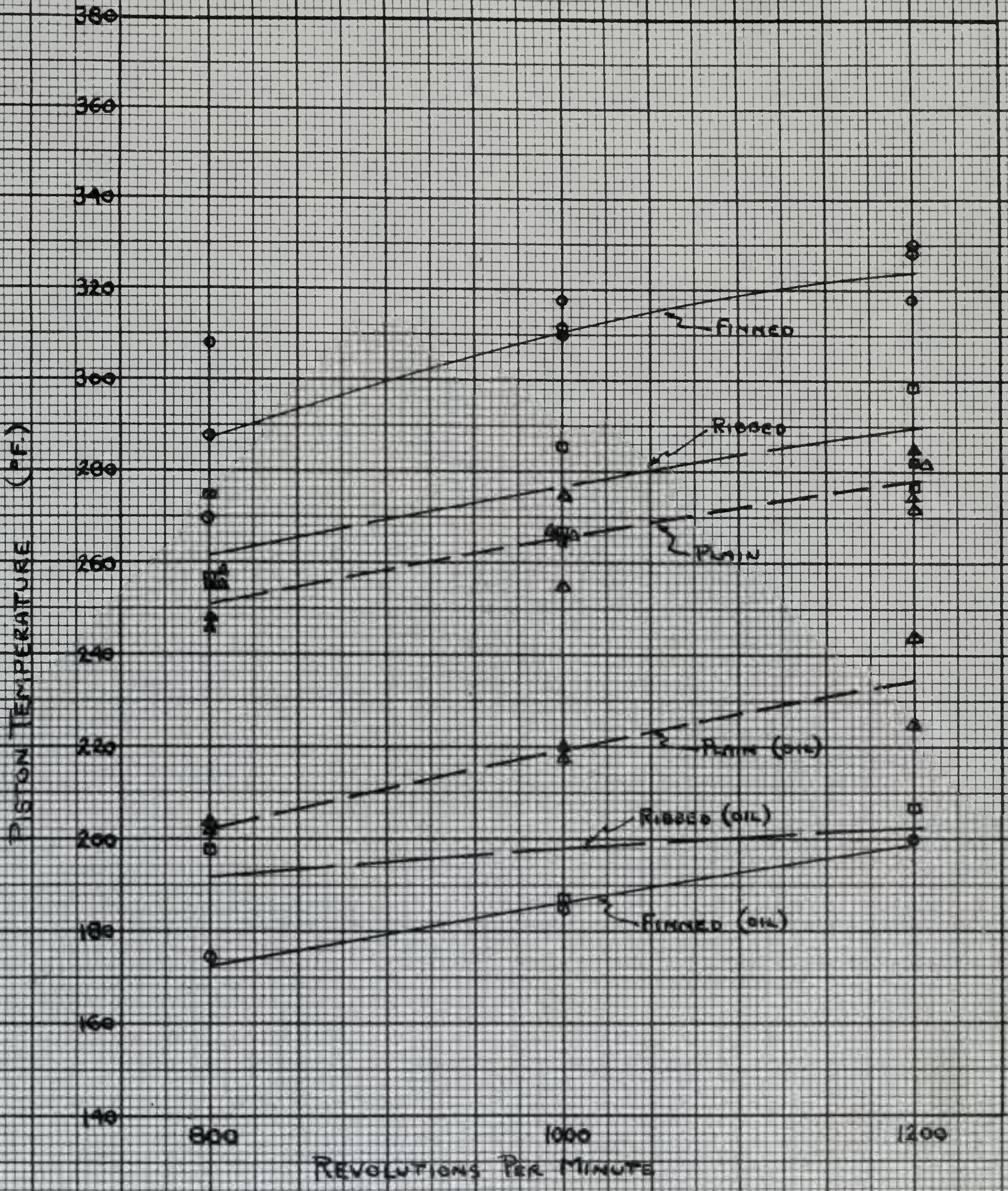
TABLE I
VARIATION OF PISTON TEMPERATURE
WITH RPM AND WATER JACKET TEMPERATURE

FUEL AIR RATIO	PISTON TEMP.	FUEL AIR RATIO	PISTON TEMP.
.055	255	.10	312
.06	278	.11	298
.07	306	.12	285
.08	325	.13	275
.09	320	.14	271

TABLE II
VARIATION OF PISTON TEMPERATURE
WITH FUEL AIR RATIO

INLET TEMP	PISTON TEMP
105	328
120	328
140	331
160	332
170	332
174	331

TABLE III
VARIATION OF PISTON TEMPERATURE
WITH INLET TEMPERATURE



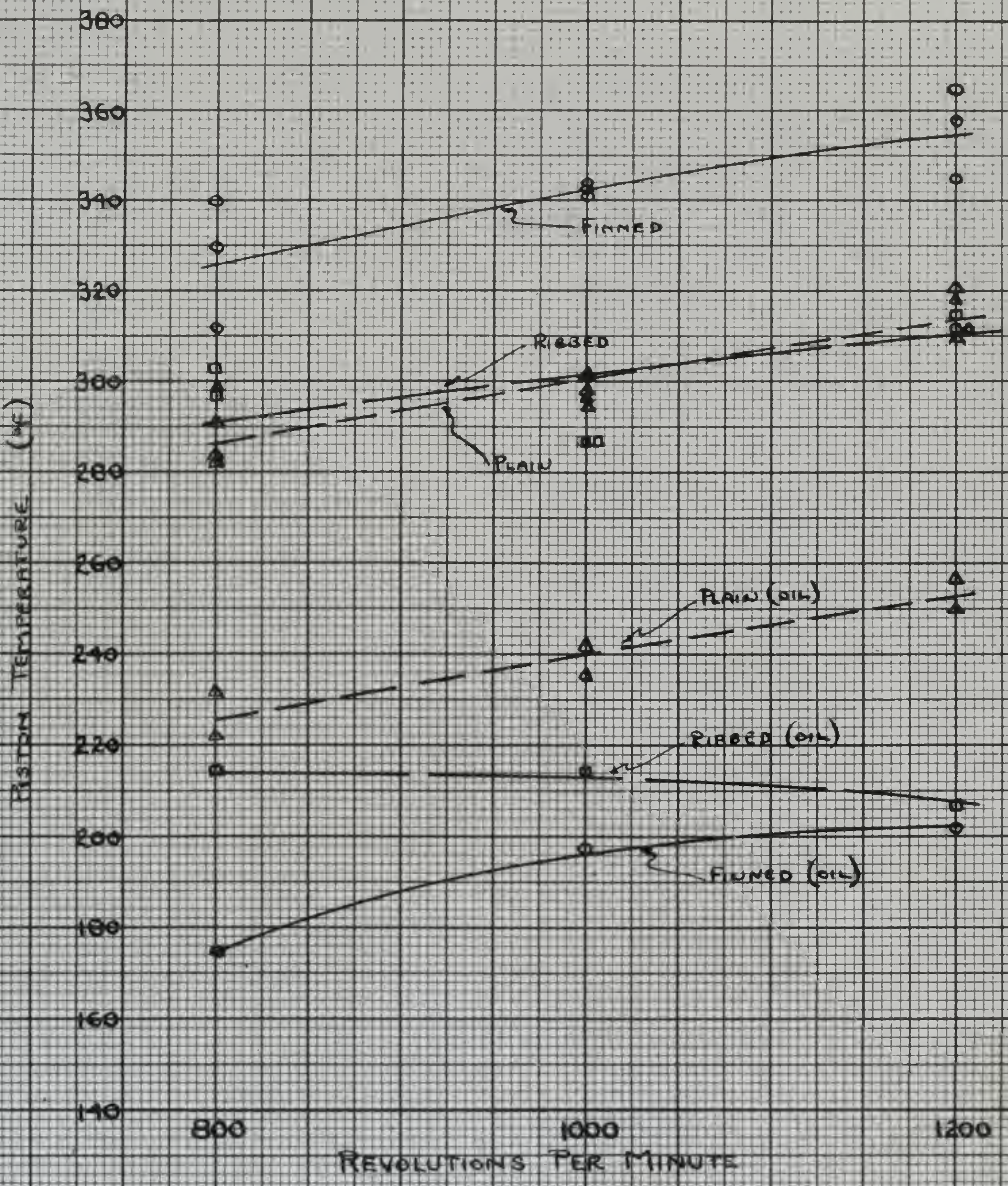
T_W = 90°F

F/A = .08 T_W = 90°F T_L = 150°F T_a = 90°F p_a = 50 lb/in² p_e = 10.7 lb/in²

FIG. 9

VARIATION OF PISTON TEMPERATURE WITH RPM FOR THREE TYPES OF PISTONS – SHOWING EFFECT OF OIL STREAM

JAS N.O.W. 4-27-40



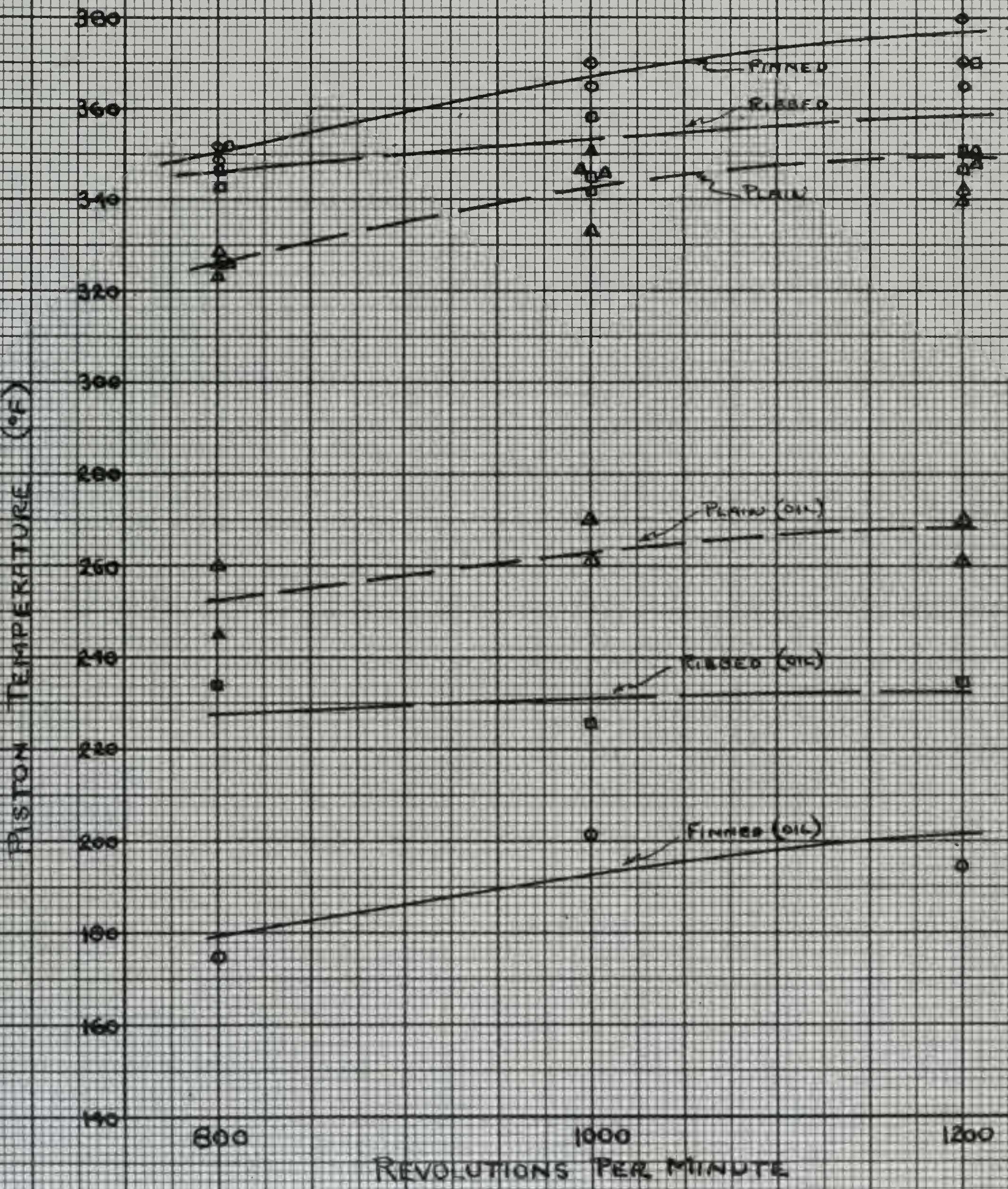
$T_W = 150°F$

$F/A = .08$ $T_i = 150°F$ $T_a = 90°F$ $p_a = 50$ lb/in² $p_c = 10.7$ lb/in²

FIG. 10

VARIATION OF PISTON TEMPERATURE WITH R.P.M. FOR THREE TYPES OF PISTONS - SHOWING EFFECT OF OIL STREAM

R.O.W. 4-27-46



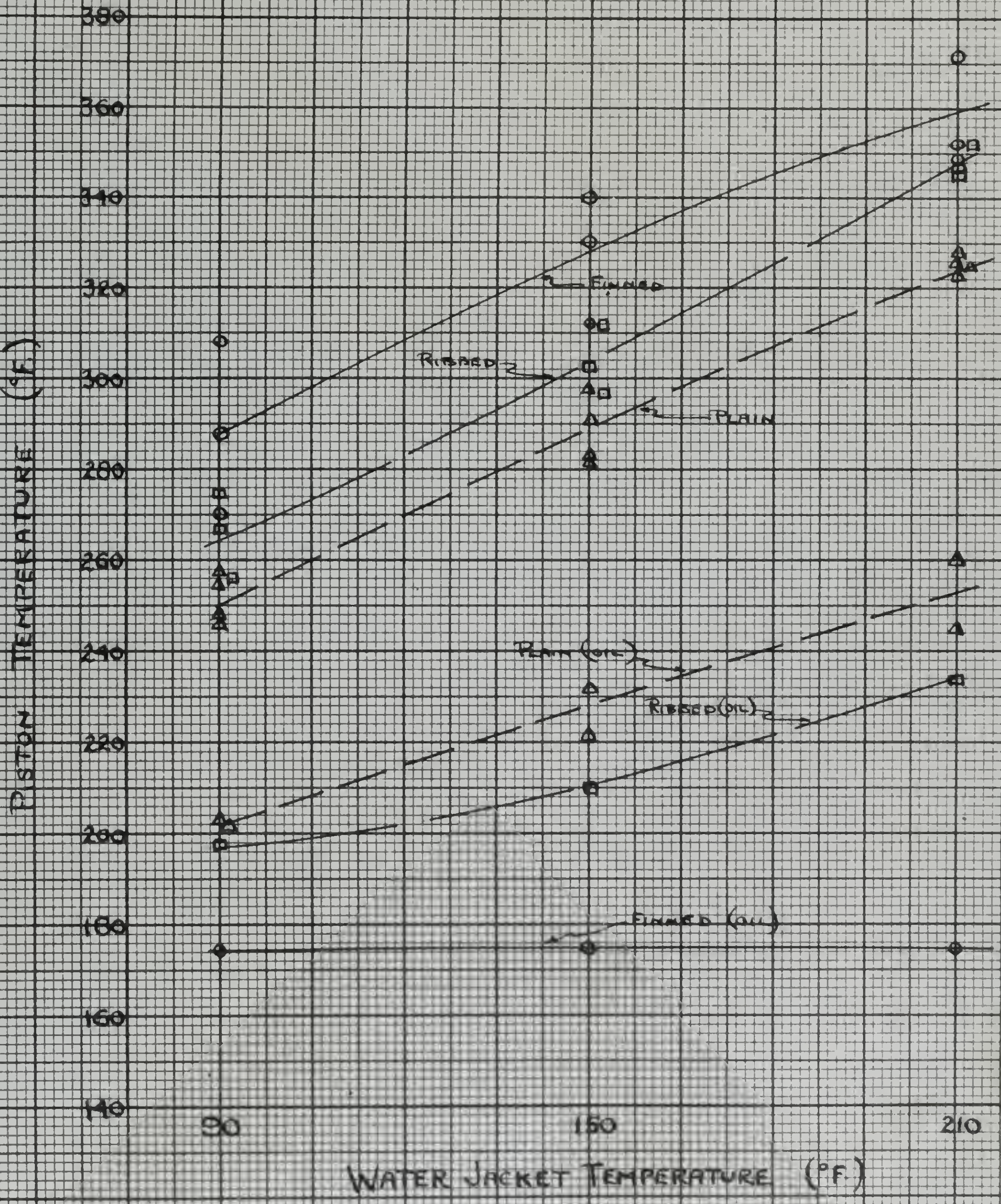
$T_w = 210°F$

$F/A = .08$ $T_o = 150°F$ $T_a = 80°F$ $p_a = 50\ lb/in^2$ $p_f = 10.7\ lb/in^2$

FIG. 11

VARIATION OF PISTON TEMPERATURE
WITH R.P.M. FOR THREE TYPES OF PISTONS
SHOWING EFFECT OF OIL STREAM

4-27-46



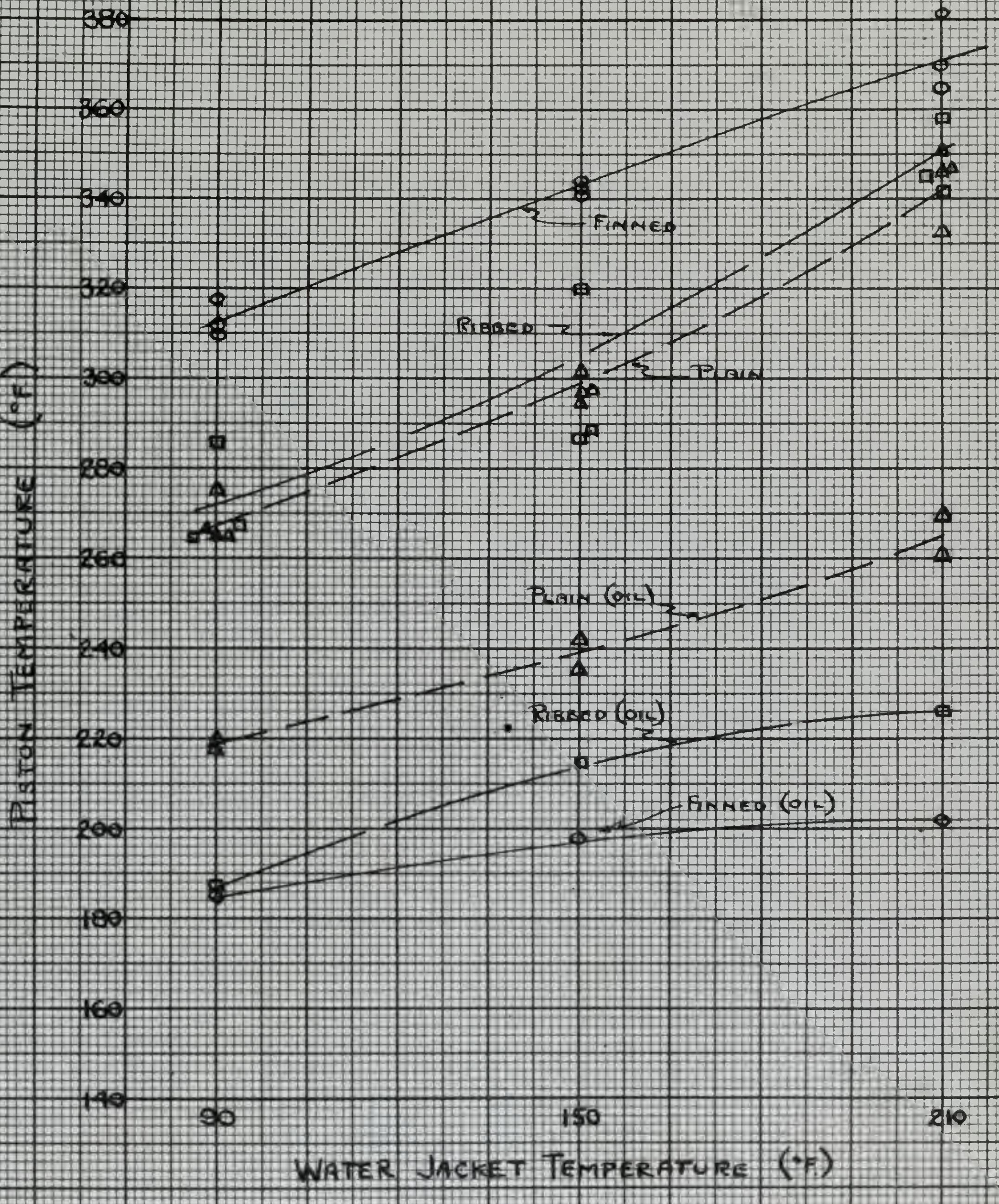
RPM = 800

F/A = .08 T_i = 150°F T_o = 90°F p_i = 50 lb/in² p_e = 10.7 lb/in²

FIG. 12

VARIATION OF PISTON TEMPERATURE
WITH WATER JACKET TEMPERATURE
FOR THREE TYPES OF PISTONS
SHOWING EFFECT OF OIL STREAM

JWS N.O.W. 4-27-46



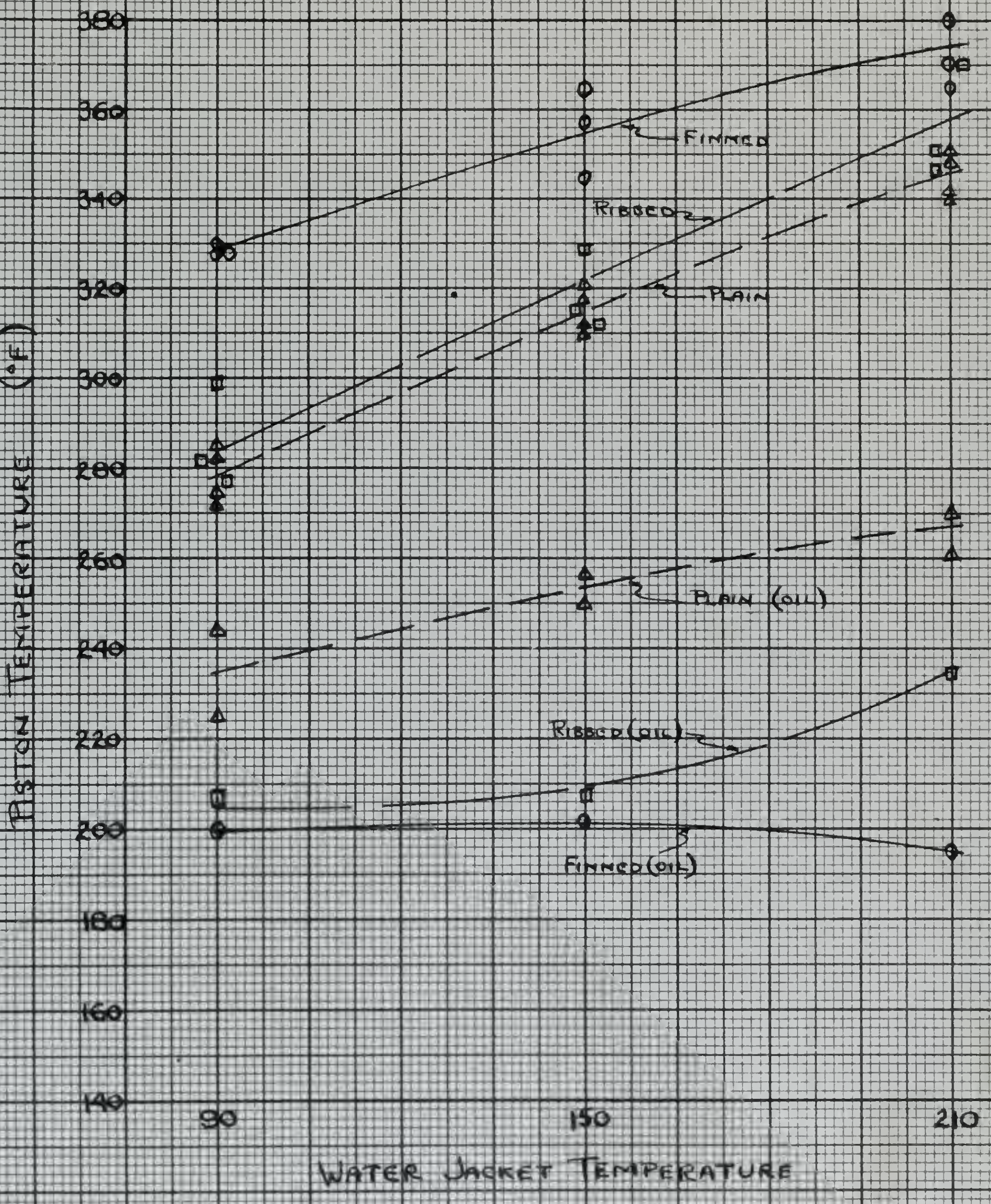
RPM = 1000

F/A = .08 T_i = 150°F T_o = 90°F p_e = 50 lb/in² p_i = 10.7 lb/in²

FIG. 13

VARIATION OF PISTON TEMPERATURE
WITH WATER JACKET TEMPERATURE
FOR THREE TYPES OF PISTONS
SHOWING EFFECT OF OIL STREAM

JAS H.O.W. 4-27-46



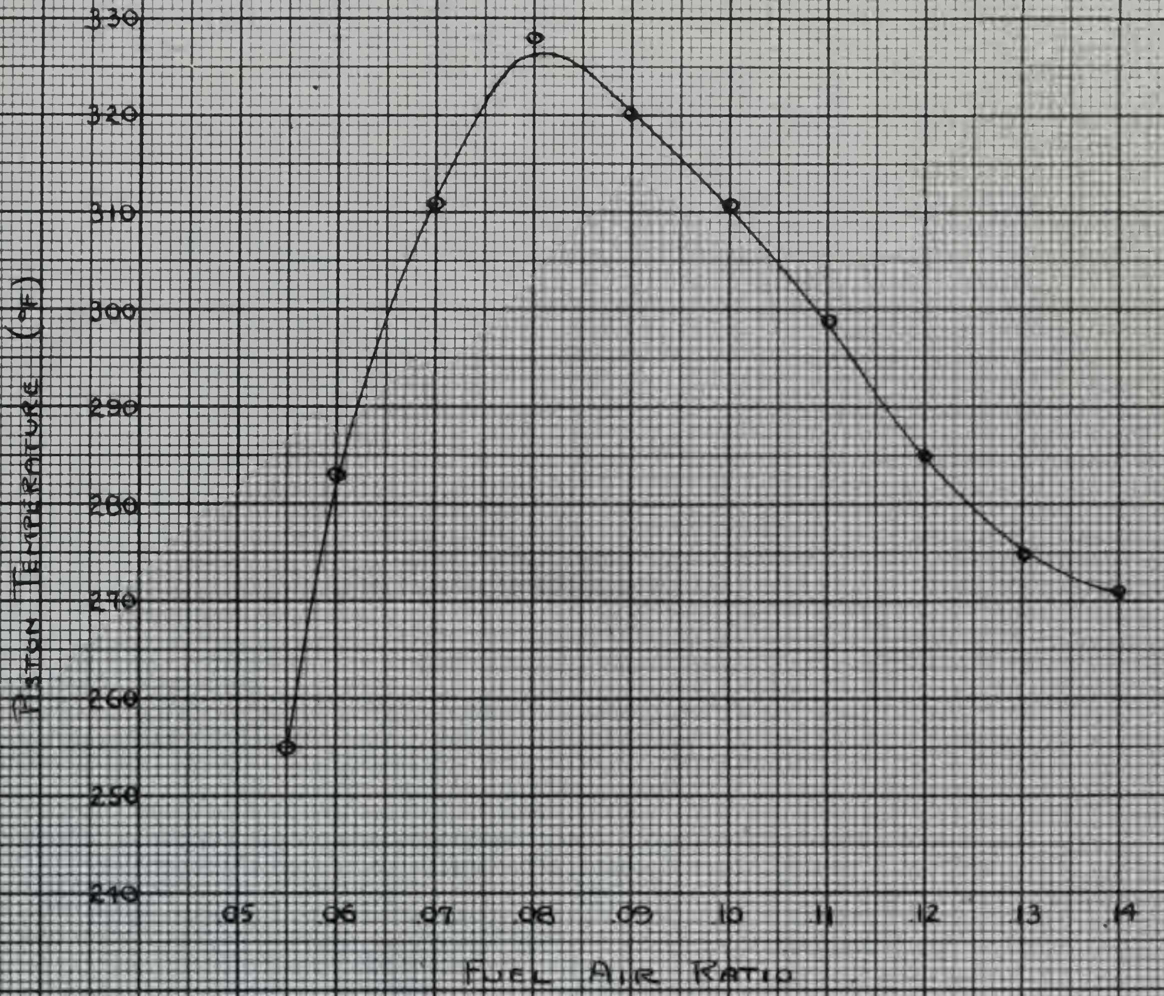
RPM = 1200

F/A = .08 T_i = 150°F T_o = 90°F P_o = 50 lb/in² P_f = 10.7 lb/in²

FIG 14

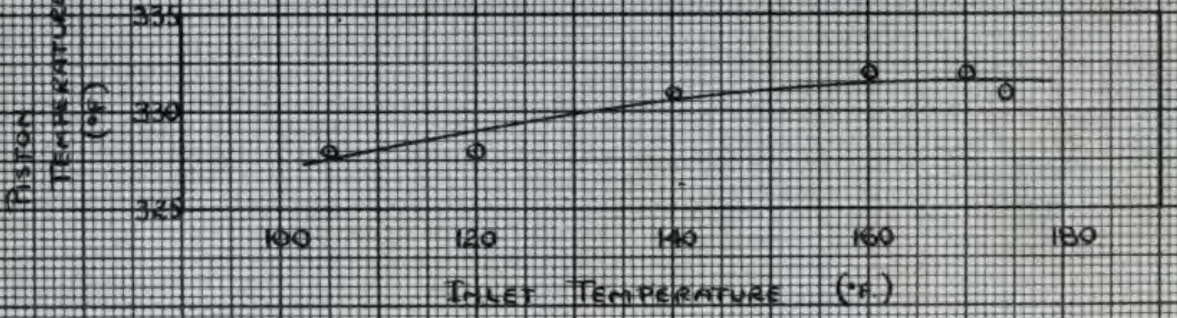
Variation of Piston Temperature
With Water Jacket Temperature
for Three Types of Pistons
Showing Effect of Oil Stream

JAS N.O.W. 4-27-46



T_i = 150°F T_w = 150°F R.P.M. = 1200 T_o = 90°F p_a = 50 lb/in² p_f = 10.7 lb/in²

RIBBED PISTON



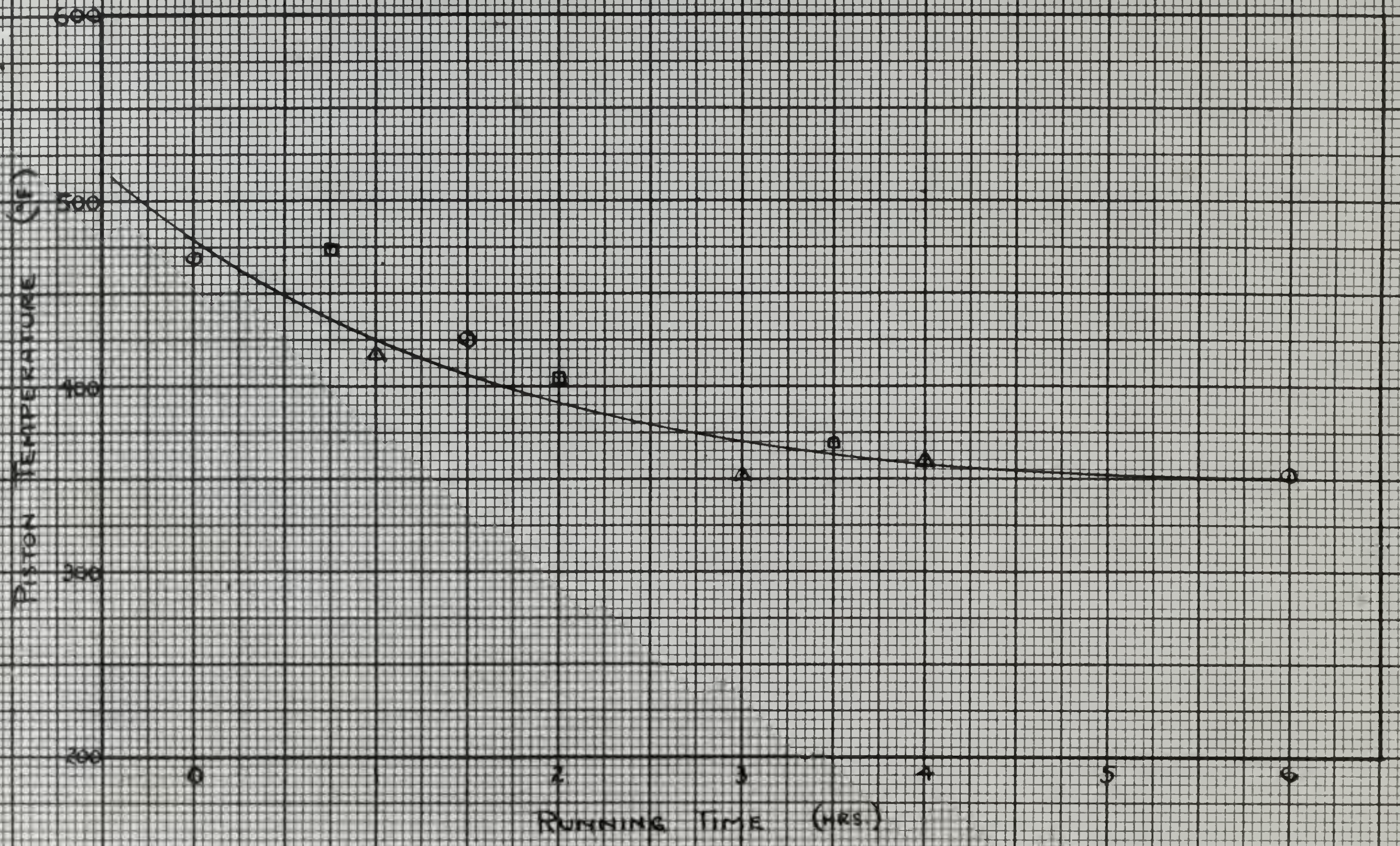
F/A = .08 T_w = 150°F RPM = 1200 T_o = 90°F p_a = 50 lb/in² p_f = 10.7 lb/in²

RIBBED PISTON

FIG 15

VARIATION OF PISTON TEMPERATURE
WITH FUEL AIR RATIO AND INLET TEMPERATURE

JWS N.O.W. 4-26-46



$T_L = 150°F$ F/A = .08 Finned Piston $T_c = 90°F$ $p_o = 50$ lb/in²

$T_W = 150°F$ RPM = 1000 $p_i = 10.7$ lb/in²

FIG 16

Piston Temperature Variation With Ring Wear In When Ring "Blow By" Was in Evidence

JWS RO.W 4-27-46

Wittmann
Piston temperature
measurement and piston
design investigation on
a CFR engine.