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EFFECT OF MAXIMUM CRUISE-POWER OPERATION AT ULTRA-LEAN MIXTURE AND INCREASED SPARK ADVANCE ON THE MECHNICAL CONDITION OF CYLINDER COMPONENTS

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NACA

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MEMORANDUM REPORT

for the

Air Technical Service Command, Army Air Forces

EFFECT OF MAXIMUM CRUISE-POWER OPERATION AT ULTRA-LEAN MIXTURE AND INCREASED SPARK ADVANCE ON THE MECHANICAL CONDITION OF CYLINDER COMPONENTS

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SUMMARY

A continuous 50-hour test was conducted to determine the effect of maximum cruise-power operation at ultra-lean fuel-air mixture and increased spark advance on the mechanical conditions of cylinder components. The test was conducted on a nine-cylinder air-cooled radial engine at the following conditions: brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 pounds per square inch; fuel-air ratio, 0.052; spark advance, 30° B.T.C.; and maximum rear-spark-plug-bushing temperature, 400° F. In addition to the data on corrosion and wear, data are presented and briefly discussed on the effect of engine operation at the conditions of this test on economy, knock, preignition, and mixture distribution.

Cylinder, piston, and piston-ring wear was small and all cylinder components were in good condition at the conclusion of the 50-hour test except that all exhaust-valve guides were bellmouthed beyond the Army's specified limit and one exhaust-valve face was lightly burned. It is improbable that the light burning in one spot of the valve face would have progressed further because the burn was filled with a hard deposit so that the valve face formed an unbroken seal and the mating seat showed no evidence of burning. The bellmouthing of the exhaust-valve guides is believed to have been a result of the heavy carbon and lead-oxide deposits, which were present on the head end of the guided length of the exhaust-valve stem.

Engine operation at the conditions of this test was shown to result in a fuel saving of 16.8 percent on a cooled-power basis as compared with operation at the conditions recommended for this engine by the Army Air Forces for the same power.

INTRODUCTION

The trend in aircraft-engine operation has been toward progressively lower fuel-air ratios for increased fuel economy at cruise-power conditions. Operating instructions for the nine-cylinder air-cooled radial engine used (reference 1) specify cruise-power fuel-air ratios as low as 0.062 for minimum specific fuel flow (minimum brake specific fuel consumption). Reference 2 shows that considerable additional fuel savings may be effected by cruise-power operation at a fuel-air ratio lower than 0.062 and at an increased spark advance. Reference 2 also indicates that, on a cooled-power basis (values corrected for difference in cooling-air drag horsepower), the brake specific fuel consumption is decreased as the fuel-air ratio is lowered at increased spark advance, up to the lean limit for stable engine operation. Thus, for maximum fuel economy it is desirable to operate at the leanest practical fuel-air ratio with increased spark advance. Engine operation at very lean fuel-air ratios (much less than 0.067) introduces two main problems: engine operating instability principally as a result of poor mixture distribution, and possible deterioration of cylinder parts due to the excess oxygen in the charge mixture.

Engine operating stability, neglecting the effect of lean-mixture operation at increased spark advance on mechanical condition and on the knock-limited power, will establish the lowest mixture ratio at which it is advisable to operate aircraft engines in flight. When the engine is operated at very lean fuel-air ratios, unstable engine operation will result when the mixture distribution of the engine causes one or more of the cylinders to have a fuel-air ratio too lean to support combustion; as a result misfiring occurs.

Although fuel economy may be improved by engine operation at very lean mixtures and increased spark advance, such operation has been considered detrimental to cylinder components for two reasons: (1) possible corrosion of cylinder components resulting from engine operation with an oxidizing fuel-air mixture (fuel-air mixture leaner than the stoichiometric mixture, approximately 0.067, reference 3); and (2) resulting high temperatures of internal cylinder components that reach a maximum at very nearly the stoichiometric mixture and then decrease rapidly as the mixture is made still leaner. Also, at increased spark advance, internal cylinder parts operate at a higher temperature than the external cylinder-head temperature indicates (reference 4). No attempt is made herein to separate the effects of these variables on corrosion and wear.

As part of the general investigation of reduction of wear on cylinders, pistons, rings, and valves, requested by the Air Technical Service Command, Army Air Forces, a continuous 50-hour test was conducted at the NACA Cleveland laboratory during April 1945 at steady conditions to determine the effect on cylinder components of engine operation at high cruise power with ultra-lean fuel-air mixtures and advanced spark timing. In addition to the data on corrosion and wear, data are presented and briefly discussed on the effect of engine operation at the conditions of this test on economy, knock, preignition, and mixture distribution. The knock data were obtained from a test conducted during July 1945.

APPARATUS

A nine-cylinder air-cooled radial engine of 1823-cubic-inch displacement was used in this investigation. This engine has a bore and stroke of $6\frac{1}{8}$ and $6\frac{7}{8}$ inches, respectively, a normal rating of 1000 brake horsepower, and the compression ratio is 6.70. The following cylinder components were used on the engine:

Part	Description
Cylinder	Nitrided steel; 7 new, 2 reconditioned[a]
Exhaust valve	Nichrome coated; new[b]
Intake valve	6 new, 3 reconditioned[c]
Piston	New
Piston rings	New

[a]Cylinders 2 and 9 reconditioned.
[b]Described in reference 5.
[c]Reconditioned intake valves used in cylinders 6, 7, and 8.

The engine was mounted on a multicylinder-engine test stand as shown in figure 1. The power was absorbed by a three-blade flight propeller and engine speed was controlled by a hydromatic constant-speed governor. Brake mean effective pressure was indicated by a hydraulic torquemeter, which was integral with the propeller reduction gearing. Combustion air was supplied by an external blower with an aircraft filter element on its intake. The combustion-air flow was measured by the method described in reference 6 (uncompensated metering-suction differential). The carburetor with the inlet elbow was calibrated in a standard carburetor air box to determine the relation between pressure differential and combustion-air flow. The fuel flow was measured with a calibrated rotameter.

Magnetostriction knock pickups were installed on all cylinders of the engine. A flight-type cowling was mounted on the engine and additional cooling was provided by an auxiliary fan that drew air across the engine. Because the temperature of the cooling air varied, the quantity of cooling air was regulated by shutters on the fan discharge to maintain desired cylinder-head temperature. The baffle pressure drop was measured by a total-head tube on each cylinder head and a static-pressure tube on the rear of each intercylinder baffle. The tubes were installed according to the engine manufacturer's recommendations and cooling-air flow was determined from the manufacturer's calibration of the variation of baffle pressure drop with cooling-air flow. The standard exhaust-gas collector ring used had nine stainless-steel exhaust-gas sampling tubes of 5/16-inch outside diameter so welded in that the open end of each tube was flush with the cylinder exhaust-port flange and centrally located.

The oil was supplied to the engine through a full-flow filter with a cotton-waste element. The oil consumption was measured by observing the decrease in the weight of the oil in a weighing tank. The oil-flow rate was measured by diverting the returning oil into a flow tank instead of the weighing tank and observing the rate at which the oil was pumped to the engine from the weighing tank. The use of special oil-scavenge tubes made it possible to measure separately the main-case oil flow. Blow-by past the piston rings was measured by a positive-displacement gas meter.

PROCEDURE

All cylinder components were weighed and measured; the engine was then assembled and given a 4-hour run-in as described in reference 7. The cylinders were slushed with Navy 1120 lubricating oil when the engine was shut down for a week end. The engine was started again and a mixture-control curve was run to determine the fuel-air ratio for minimum specific fuel consumption for 750 brake horsepower at an engine speed of 1900 rpm and a spark advance of 30° B.T.C. The 50-hour test was then started at this fuel-air ratio and concluded without a shutdown during the test. The test was run under the following conditions:

Brake horsepower	750
Engine speed, rpm	1900
Brake mean effective pressure, pounds per square inch	172
Fuel-air ratio	0.052 ±0.002

Spark advance (both plugs), deg B.T.C. 30
Maximum rear-spark-plug-bushing temperature, °F 400
Carburetor-air temperature, °F 100
Oil-in temperature, °F 165
Engine oil pressure, pounds per square inch 80
Main section oil-flow rate, pounds per minute 30
Lubricating oil . . . . Navy 1120 (AN-VV-O-446A)
Fuel (See Fuel and oil analysis.) AN-F-28, Amendment-2

At the completion of the 50-hour test, the engine was shut down and the cylinders were slushed with Navy 1120 lubricating oil. The engine was then removed from the test stand and disassembled.

RESULTS AND DISCUSSION

Test Conditions

Choice of test conditions. - The test conditions were chosen to approximate probable operating conditions for maximum practical economy obtainable at maximum cruise power (75 percent) with ultra-lean fuel-air mixtures and increased spark advance. In order to select definitely the optimum values for the operating variables, a complete investigation of the effect of all operating variables on economy, knock, and the other factors involved would be required. The data of reference 2 and unpublished data obtained at the Cleveland laboratory were used to select the spark advance of 30° B.T.C. and the brake mean effective pressure of 172 pounds per square inch, which were believed to be very near the optimum practical values for 750 brake horsepower. Although fuel economy should have been further improved by increasing the spark advance to more than 30° B.T.C. and raising the brake mean effective pressure to more than 172 pounds per square inch, the increased severity of operation and decrease in the knock limit might have made it impractical. A complete discussion of the effect of the operating variables on economy, severity of operation, and knock is beyond the scope of this report but they will be compared with the results obtained with operation as recommended by the Army Air Forces (reference 1).

Mixture-control curve. - The optimum fuel-air ratio for the power, the speed, and the spark advance chosen was determined by the constant-power mixture-control curve (fig. 2), which was run as the first part of this test. This curve shows decreasing brake specific fuel consumption up to the lean limit for stable engine operation, fuel-air ratio of 0.052, for these conditions. The brake specific fuel consumption for this engine operating at 750 brake horsepower at the conditions recommended in reference 1 was determined and is plotted on figure 2 for comparison. The difference between the specific fuel consumption (at the conditions of reference 1) and that for the conditions of this test indicates a fuel saving of 14.6 percent for the same power output neglecting the difference in cooling-air drag horsepower between the two conditions. The saving taking into account the difference in cooling-air drag horsepower (cooled-power basis) was calculated according to the method of reference 2 and found to be 16.8 percent.

The external supercharger power required by the test-stand blower to furnish ram air to the carburetor was not accounted for in the calculation of the brake specific fuel consumption at the conditions of this test. The blower horsepower required, however, was calculated and found to be very small. When it is assumed that the external supercharging is supplied by a turbosupercharger, the effect of the required increase of exhaust back pressure (less than 2 in. Hg) on the engine will be negligible. Knock was not encountered at any time during the running of the mixture-control curve.

Mixture distribution. - The mixture distribution is an important factor in determining the lean limit for stable operation of the engine. When the fuel-air ratio of the cylinder having the leanest mixture is so low that the charge will not ignite, this cylinder will misfire and engine operation becomes unstable. The mixture distribution in the engine operating at the conditions of this test is shown in figure 3. The maximum variation of fuel-air ratio from the average was 8.8 percent. Figure 3 also shows the close agreement between the average fuel-air ratio as determined by Orsat analysis of the oxidized exhaust gas and by fuel-air intake measurements. Because diluted exhaust-gas samples from cylinder 1 existed during the entire test as the result of a leaky flange on the exhaust-gas collector ring, the values of fuel-air ratio for cylinder 1 were corrected using unpublished data from a test run under similar conditions on the same engine.

Test Results

Graphic log of test. - A graphic log of the test, which was run continuously to avoid the corrosion caused by shutdown and the excessive wear of starting, is shown in figure 4. During the entire test, the fuel-air ratio as determined by measured intake was closely checked by Orsat analysis of the oxidized exhaust gas. Because of a defective manometer line, the values of combustion-air flow and consequently fuel-air ratio by measured intake were faulty for the period of 4 to 20 hours of the test. Orsat analysis, however, showed that the maximum variation in fuel-air ratio for this period was within the limits of variation for the entire test. Therefore this portion of the fuel-air-ratio curve is indicated as a straight dashed line on the graphic log. Specific oil consumption showed no tendency to rise during the test and was well below the manufacturer's maximum allowable specific oil consumption of 0.020 pound per brake horsepower hour for 1900 rpm cruise operation (reference 8). Blow-by also showed no tendency to rise during the test. No indication of knock was ever present.

Cylinders. - Inspection of the cylinder components after engine disassembly indicated that they were in good condition. The cylinder barrels were in good condition. All the barrels were lightly lacquered and had a few light scuff marks on the major-thrust wall. The major-thrust wall of a typical cylinder barrel is shown in figure 5. The cylinder-bore wear in both the thrust and nonthrust directions resulting from the test is shown in table I. Cylinder wear, which was heaviest in the choke, was very light on the thrust and nonthrust diameters. The valve seats were in good condition. The cylinder domes had a light carbon coating with a few localized heavy-lead deposits (fig. 6). In the cylinder photographed, the localized-lead deposits were near the junction of the head and barrel between the front spark-plug bushing and the intake-valve seat insert. The localized-lead deposits in the rest of the cylinders were heavier and occurred near the junction of the head and barrel but in different places around the cylinder.

Pistons and piston rings. - The pistons were in very good condition at the end of the test. The piston crowns were covered with a light carbon deposit and small localized-lead deposits similar to those on the dome of the cylinders. The major-thrust and minor-thrust faces of a typical piston with rings after cleaning at the end of the test are shown in figure 7. These photographs show the light face contact at the top and bottom of the thrust faces and the light scuff marks on the piston thrust face. Piston wear resulting from the test was too small to measure. No pounding out of the ring lands existed as shown by the values of piston-ring side clearance in table II.

The condition of the piston rings after the test was very good. No ring scuffing, scoring, or sticking was evident. The piston-ring wear data are presented in table II. The ring wear as indicated by weight loss was small and nonuniform in the different cylinders.

Valves. - All the valve heads were covered with a heavy deposit when they were removed from the engine. The typical heavy deposits on the heads of both the intake and exhaust valves are shown in figure 8. The deposits on the intake valves were greenish-yellow with a glazed surface and completely covered the concave portion of the valve head. The coating on the exhaust valves varied from the smooth greenish-yellow deposits shown on the valve in figure 8 to the dark red globular deposits shown on the valve head in figure 9. The weight of the deposits on the valves is given in table III. The average weight of deposit was 4.15 and 7.26 grams for the exhaust and intake valves, respectively.

A spectrographic analysis made of the deposits on the intake and exhaust valves indicated that lead was the chief constituent. (See table IV.) A chemical analysis was then made according to the method of reference 9 to determine in what compounds the lead appeared. The composition of the lead deposit on the valves is shown in the following table:

	Percentage composition of deposit on	
	Exhaust valve	Intake valve
$PbBr_2$	1.2	1.4
Lead oxides calculated as Pb_2O_3	28.7	20.2
Pb (metal)	59.3	58.5
Carbonaceous matter	10.8	19.9

The under side of the exhaust-valve heads had a light even coating of yellow lead oxide. A factor contributing in part to the heavy lead deposits may have been the small excess of tetraethyl lead indicated by the fuel analysis, which is discussed in a later section.

The stems and seating faces of a typical intake and exhaust valve after removal from the engine are shown in figure 10. An examination of the valves after cleaning showed that all of the exhaust-valve faces were in good condition with the exception of the valve from cylinder 9, which was lightly burned in one spot. The burn was very shallow and before cleaning was filled with a hard deposit so that the valve face formed an unbroken seal and the mating seat showed no evidence of burning. It is therefore improbable that the light valve-face burning would progress further. The lightly burned portion of the exhaust-valve face of cylinder 9 after the deposits had been removed is shown in figure 11.

Heavy carbon and lead-oxide deposits and light bronze pickup from the exhaust-valve guide were present for one-half inch at the head end of the exhaust-valve stem guided length. All the exhaust-valve guides were worn to a bellmouth beyond the Army limits stated in reference 10. Three of the valve guides were worn beyond the manufacturer's bellmouth limit (reference 11), which is less severe than the Army's limit. The bellmouthing of the exhaust-valve guides is believed to have been a result of heavy carbon and lead-oxide deposits on the head end of the valve stem. All the intake-valve faces were in excellent condition. Light soft carbon deposits were present on the under side of the intake-valve heads (fig. 10). The intake-valve stems were in excellent condition and the intake-valve guides were not excessively worn. No indication of valve sticking as a result of the heavy stem deposits was evident at any time during the test.

All of the valves, except two sets, were cleaned by the electrolytic method of reference 12. The deposits were not removed from these two sets of valves pending further investigation of the deposits. Of the valves cleaned, the crowns of two were in excellent condition, four had numerous "pin point" pit marks, and one was severely pitted as shown in figure 12. Some of the intake valves had a few very small scattered pin-point pits. (See table III.)

Spark plugs. - In this investigation the spark plugs, which incorporate an integral resistor to help retard the rate of electrode wear, are recommended by the Army for use in the test engine (reference 13). As shown in table V, the average increase in spark-plug gap resulting from this test was 0.002 inch. The values of the integral resistor before and after the test are also shown in table V.

Fuel and oil analysis. - As mentioned in the valve discussion, the lead deposits on the valves were unusually heavy. For this reason an analysis was made of a fuel sample taken from the test-stand fuel system to determine if it met the AN-F-28, Amendment-2, specifications. Analysis of this sample showed the tetraethyl-lead and ethylene-dibromide (lead-scavenging agent) content to be 4.95 milliliters per gallon and 3.89 grams per gallon, respectively. The fuel specification AN-F-28, Amendment-2, limits the maximum tetraethyl-lead content to 4.6 milliliters per gallon and the ethylene-dibromide content should be the theoretical amount to combine chemically with all the lead present (4.03 grams/gal). The tetraethyl-lead content was therefore 0.35 milliliter per gallon (7.6 percent) too high and the ethylene-dibromide content was 0.14 gram per gallon (3.6 percent) too low.

Analysis of a sample taken from the oil system after the test was completed gave the following results:

Viscosity, centistoke		Conradson carbon (percent)	Naptha insoluble (percent)	Neutralization number
100° F	210° F			
328.6	24.30	1.11	0.39	0.07

Makeup oil was added after $10\frac{1}{2}$ hours.

Knock. - Engine operation at knocking conditions is harmful because knock can either cause engine failure itself or can lead to preignition, which might result in engine failure. The engine must therefore be operated under conditions at which there is no probability of encountering knock. As part of a knock test on the same engine used in this test, data were obtained for the two knock curves of figure 13. Curve A was run with the engine operating at the speed and spark-advance conditions recommended by the Army (reference 1) for 750 brake horsepower; curve B was run at the speed and spark-advance conditions of this test for the same power. Because the combustion-air flow that would have been required was more than the test-stand system could supply, incipient knock could not be obtained for both sets of conditions at fuel-air ratios either lower or higher than those plotted. The limiting maximum rear-spark-plug-bushing temperature for both curves had to be raised from 400° to 500° F during the running of these curves because of insufficient capacity of the test-stand cooling fan.

For this engine, the maximum brake mean effective pressure as limited by incipient knock was approximately 15 percent lower for the conditions of this test (fuel-air ratio, 0.052; spark advance, 30° B.T.C.; and engine speed, 1900 rpm) than for those recommended by the Army (fuel-air ratio, 0.076; spark advance, 20° B.T.C.; and engine speed, 2000 rpm). (See fig. 13.)

As shown in figure 13, the knock-limited brake mean effective pressure at a fuel-air ratio of 0.052, spark advance of 30° B.T.C., and engine speed of 1900 rpm, and at a maximum rear-spark-plug-bushing temperature of 500° F was 192 pounds per square inch. Therefore, operation of this engine at 750 brake horsepower at the conditions of this test should allow a margin of safety on the brake mean effective pressure for incipient knock of approximately 12 percent if the higher cylinder temperature allowed during the running of the knock curves were neglected. Although no attempt will be made to correct the margin of safety for the 100° F difference in maximum cylinder-head temperature, it should be pointed out that an increase in cylinder-head temperature will decrease the knock-limited brake mean effective pressure a considerable amount at low fuel-air ratios (reference 14). Therefore, the actual margin of safety for incipient knock for a maximum rear-spark-plug-bushing temperature of 400° F should be considerably higher than the 12 percent indicated on figure 13.

Preignition. - Although preignition may be the result of engine knock, it may lead to engine failure without any indication of knock (reference 15). Figure 14 has been included to indicate the effect on the preignition-limited power output of engine operation at the conditions of this test as compared with operation at the conditions recommended by the Army for the same power. The data for this preignition-limit curve were obtained from a single-cylinder CFR test engine at an engine speed of 1800 rpm, at a spark advance of 20° B.T.C., and at a compression ratio of 7.0 (reference 15). Because the engine and operating conditions for this curve are different from those of the test reported herein, a comparison of absolute values is not possible. The relative values, however, should be indicative of the effort of fuel-air ratio on the preignition limit of the engine used in this test.

The preignition-limited power for a fuel-air ratio of 0.052 is 21 percent higher than that for a fuel-air ratio of 0.076 for the same spark advance and engine speed (fig. 14). A correction of the preignition-limited power at a fuel-air ratio of 0.052 for the increase in spark advance from 20° to 30° B.T.C. made according to the data of reference 16 showed that it should be decreased approximately 20 percent. The effect of the 100 rpm difference in speed between the two conditions should be of comparatively small magnitude as indicated by the data of this reference. The net effect on the preignition-limited power output of engine operation at the conditions of this test as compared with operation at the conditions recommended by the Army for the same power should therefore be negligible.

The test reported herein is not conclusive in itself but it is a part of the evidence being accumulated to determine the feasibility of ultra-lean-mixture operation.

SUMMARY OF RESULTS

The continuous 50-hour test conducted on a nine-cylinder air-cooled radial engine with a normal rating of 1000 brake horsepower at 750 brake horsepower, an engine speed of 1900 rpm, a brake mean effective pressure of 172 pounds per square inch, a fuel-air ratio of 0.052, a spark advance of 30° B.T.C., and a maximum rear-spark-plug-bushing temperature of 400° F to determine the effect on cylinder components of maximum cruise-power engine operation at ultra-lean mixture and increased spark advance gave the following results:

1. Cylinder, piston, and piston-ring wear was small and all cylinder components were in good condition at the conclusion of the 50-hour test except that all exhaust-valve guides were bellmouthed beyond the Army's specified limit and one exhaust-valve face was lightly burned. It is improbable that the light burning in one spot at the valve face would have progressed further because the burn was filled with a hard deposit so that the valve face formed an unbroken seal and the mating seat showed no evidence of burning. The bell-mouthing of the exhaust-valve guides is believed to have been a result of the heavy carbon and lead-oxide deposits, which were present on the head end of the exhaust-valve stem guided length.

2. Engine operation at the conditions of this test was shown to result in a fuel saving of 16.8 percent on a cooled-power basis as compared with operation at the same power and at the conditions recommended for the engine by the Army.

3. Although engine operation at the conditions of this test was found to reduce the knock-limited brake mean effective pressure approximately 15 percent compared with operation at the Army's recommended conditions, the margin of safety on the brake mean effective pressure for incipient knock was found to be considerably more than 12 percent.

4. The preignition-limited power should be the same for engine operation at the conditions of this test as for operation for the same power at the conditions recommended by the Army.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, September 27, 1945.

REFERENCES

1. Anon.: Handbook of Operating Instructions R-1820-40, -60, -65, -71, -73, -87, -97 Aircraft Engines. T.O. No. 02-35GC-1, Air Service Command, Army Air Forces, May 15, 1943.

2. Farmer, J. Elmo, and Munger, Maurice: Fuel Consumption Corrected for Cooling Drag of an Air-Cooled Radial Aircraft Engine at Low Fuel-Air Ratios and with Variable Spark Advance. NACA ARR No. E5B01b, 1945.

3. Williams, C. G.: Factors Influencing Wear of Valve Seats in Internal-Combustion Engines. Engineering, vol. CXLII, no. 3715, March 26, 1937, pp. 357-358; vol. CXLIII, no. 3719, April 23, 1937, pp. 475-476.

4. Manganiello, Eugene J.: Piston Temperatures in an Air-Cooled Engine for Various Operating Conditions. NACA Rep. No. 698, 1940.

5. Anon.: Wright-----Inspection, Reconditioning, and Grinding Limits for Exhaust Valves and Identification and Proper Matching of Valve Upper Washers, Locks, and Springs---R-1820, R-2600, and R-3350 Series. T.O. No. 02-35-65, Headquarters, Army Air Forces (Washington, D.C.), May 1, 1944.

6. Voglewede, T. J.: A Proposed Method of Measuring Engine Charge Air Flow in Flight. NACA CB No. L4E25, 1944.

7. Anon.: Handbook of Specific Installation and Test Instructions with Run-In Schedules for Aircraft Engines. T.O. No. 02-1-4A, Air Service Command, Army Air Forces, Jan. 10, 1944.

8. Anon.: Instructions for the Installation, Operation and Maintenance of the Wright Cyclone Aviation Engine Model GR-1820-G200. Wright Aero. Corp., July 1940.

9. Griffin, A. R., and Hambling, S. K.: Factors Affecting Spark Plug Fouling. Appendix II, "The Quantitative Analysis of Spark Plug and Piston Crown Deposits," by G. H. N. Chamberlin. Rep. No. 121, Thornton Aero Eng. Res. Lab., Thornton-Le-Moors (Cheshire, England), May 29, 1944, pp. 29-31.

10. Anon.: Overhaul Instruction for Aircraft Engines. Models R-1820-40, -40B, -54, -60, -65, -71, -73, -87, -97. T.O. No. AN 02-35GC-3, Army Air Forces, Bur. Aero., Air Council (British), Nov. 25, 1943

11. Anon.: Valve Guide Bell Mouthing Limits. Service Bull. No. C9-72, Wright Aero. Corp., Jan. 6, 1945.

12. Heron, S. D., Calingaert, George, and Dykstra, F. J.: The Electrolytic Cleaning of Exhaust Valves. SAE Jour., vol. 37, no. 6, Dec. 1935, pp. 19-21.

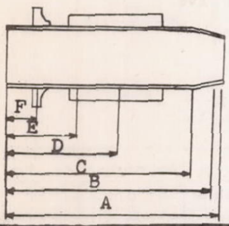
13. Anon.: Electrical Equipment---Spark Plugs---Approved Types for AAF Engines. T.O. No. 03-5E-3, Headquarters, Army Air Forces, (Washington, D. C.), May 18, 1945.

14. Droegemueller, E. A., Hersey, D. S., and Kuhrt, W. A.: The Relation of Intake-Charge Cooling to Engine Performance. SAE Jour. (Trans.), vol. 52, no. 12, Dec. 1944, pp. 614-620.

15. Male, Donald W., and Evvard, John C.: Preignition-Limited Performance of Several Fuels. NACA ARR No. E5A11, 1945.

16. Male, Donald W.: The Effect of Engine Variables on the Preignition-Limited Performance of Three Fuels. NACA MR No. E5B05, Bur. Aero. Feb. 5, 1945. (Available as NACA TN No. 1131, 1946.)

TABLE I



CYLINDER-BORE WEAR RESULTING FROM 50-HOUR TEST OF NINE-CYLINDER AIR-COOLED RADIAL ENGINE

[Brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 lb/sq in.; fuel-air ratio, 0.052; spark advance, 30° B.T.C.]

Position[a]	Length (in.)[b]	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4	Cylinder 5	Cylinder 6	Cylinder 7	Cylinder 8	Cylinder 9
Thrust-diameter wear (in.)										
a	$11\frac{1}{8}$	0.0003	0.0004	0.0004	0.0007	0.0000	0.0000	0.0000	-0.0014	0.0006
b	$10\frac{7}{8}$	.0007	.0002	.0005	.0008	.0000	-.0006	.0005	-.0013	.0022
c	$9\frac{1}{4}$	.0001	.0004	.0010	.0005	.0001	.0004	.0001	..0001	.0004
d	$7\frac{3}{8}$	.0001	.0000	.0007	.0002	.0002	-.0002	.0002	.0003	.0002
e	4	.0001	.0001	.0009	.0005	.0006	.0007	.0004	.0002	.0004
f	$2\frac{3}{8}$	.0007	.0004	.0011	.0009	.0009	.0007	.0010	.0000	.0009
Average---		0.0003	.0003	.0008	.0006	.0003	.0008	.0004	-.0004	.0008
Nonthrust-diameter wear (in.)										
a	$11\frac{1}{2}$	0.0007	0.0006	0.0016	0.0005	0.0005	0.0007	0.0005	0.0000	0.0001
b	$10\frac{7}{8}$	.0008	-.0001	.0017	.0009	.0005	.0002	.0010	.0001	.0011
c	$9\frac{1}{4}$	.0006	.0000	.0002	.0001	.0000	.0008	.0005	.0003	.0002
d	$7\frac{3}{8}$	.0003	.0001	.0002	.0004	.0000	-.0015	.0002	.0002	.0004
e	4	-.0001	-.0001	.0001	-.0006	-.0003	-.0001	-.0002	.0002	.0000
f	$2\frac{3}{8}$	-.0002	-.0001	.0000	-.0009	-.0005	-.0004	-.0003	.0006	-.0001
Average---		0.0004	0.0001	0.0006	0.0006	0.0000	-0.0001	0.0003	0.0002	0.0003

[a]Description of ring positions: a, top of barrel; b, top of ring travel; c, start of choke; d, middle of barrel; e, bottom of top ring travel; f, flange.
[b]Distance from open end of barrel.

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

E-268

TABLE II

PISTON-RING WEAR DATA FOR 50-HOUR TEST OF NINE-CYLINDER AIR-COOLED RADIAL ENGINE

[Brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 lb/sq in.; fuel-air ratio, 0.052; spark advance, 30° B.T.C.; maximum rear-spark-plug-bushing temperature, 400° F; main-case air-flow pressure, 30 lb/min; oil inlet temperature, 165° F; oil, Navy 1120]

Cylinder	Ring	Ring weight, gram		Face width, in.		Diametral tension, lb		Free gap, in.		Side clearance, in.	
		Before	Loss	Before	Increase	Before	Decrease	Before	Decrease	Before	After
1	1	42.6505	0.0486	0.023	0.012	8.49	0.35	0.83	0.04	0.005	0.004
	2	43.8498	.0071	.008	.010	8.04	.27	.96	.09	.005	.005
	3	42.1841	.0053	.024	.000	8.62	.13	1.06	.08	.006	.005
	4	41.4397	.0042	.024	-.008	7.67	.23	1.17	.14	.011	.011
	5	41.5790	.0029	.015	-.004	7.89	-.08	0.97	.06	.011	.011
	6	41.7019	.0027	.011	.004	7.89	.10	1.01	.08	.006	.006
2	1	43.0998	0.0240	0.029	0.007	7.97	0.20	0.80	0.05	0.005	0.005
	2	43.0695	.0096	.006	.008	7.74	.20	1.01	.11	.005	.006
	3	42.1914	.0056	.002	.016	8.07	.10	1.08	.10	.006	.006
	4	40.8954	.0034	.013	.004	7.57	.08	1.08	.11	.011	.011
	5	40.9275	.0053	.013	.002	9.17	1.08	1.10	.07	.011	.011
	6	40.6795	.0038	.020	-.003	7.32	.00	1.06	.05	.006	.006
3	1	43.0319	0.0314	0.026	0.011	8.54	0.25	0.83	0.04	0.005	0.006
	2	43.6837	.0092	.009	.009	7.47	-.25	1.01	.11	.005	.004
	3	43.7407	.0047	.009	.005	7.74	-.10	1.03	.10	.005	.004
	4	41.3102	.0045	.008	.001	7.77	.08	0.96	.09	.010	.011
	5	41.4861	.0023	.009	-.001	7.34	-.33	1.03	.06	.010	.011
	6	41.4368	.0043	.006	.002	7.89	.15	1.03	.06	.006	.006
4	1	43.0771	0.0373	0.026	0.018	8.59	0.37	0.83	0.05	0.005	0.005
	2	43.4896	.0162	.007	.015	7.47	.33	1.11	.17	.005	.004
	3	43.5532	.0111	.009	.013	7.84	.10	1.04	.11	.004	.004
	4	40.4184	.0085	.015	.006	6.87	-.92	1.10	.10	.011	.011
	5	41.8619	.0060	.011	.004	7.79	-.13	.98	.08	.011	.011
	6	41.6948	.0072	.014	.007	6.99	.15	1.00	.08	.006	.006
5	1	43.0253	0.0144	0.019	0.007	8.12	0.05	0.83	0.05	0.005	0.005
	2	43.2129	.0039	.022	-.011	7.44	.15	1.10	.12	.005	.004
	3	43.5653	.0033	.009	.001	7.89	.05	1.05	.09	.005	.005
	4	41.0455	.0025	.001	.009	6.59	-.03	1.00	.12	.011	.011
	5	41.5528	.0012	.031	-.019	6.34	-.20	1.06	.15	.011	.011
	6	41.9775	.0023	.016	-.004	9.19	-.07	1.03	.06	.006	.006
6	1	42.6568	0.0828	0.021	0.016	7.92	0.28	0.82	0.05	0.004	0.004
	2	43.5043	.0089	.011	.007	7.27	.23	1.03	.12	.004	.003
	3	42.3505	.0097	.011	.004	7.19	.00	1.05	.13	.006	.005
	4	41.9613	.0053	.022	-.009	7.89	.15	1.07	.13	.011	.011
	5	41.4106	.0024	.010	.003	7.22	-.20	.95	.08	.011	.011
	6	41.6560	.0030	.009	.005	7.62	-.30	1.10	.16	.006	.006
7	1	43.0727	0.0751	0.016	0.010	8.99	0.10	0.82	0.04	0.004	0.006
	2	43.4664	.0113	.005	.013	7.97	.13	1.01	.10	.004	.004
	3	43.8296	.0099	.007	.010	8.12	.03	1.03	.11	.004	.004
	4	41.9472	.0043	.008	.003	8.64	.02	1.06	.12	.011	.011
	5	41.7265	.0048	.009	.001	6.82	-.07	1.01	.12	.011	.011
	6	40.9435	.0054	.016	-.002	8.54	.10	1.07	.05	.006	.006
8	1	42.5870	0.0370	0.014	0.015	8.04	0.20	0.82	0.06	0.006	0.006
	2	43.3412	.0090	.011	.009	7.24	.35	1.08	.16	.005	.004
	3	43.5087	.0076	.007	.009	7.04	.02	1.08	.16	.005	.004
	4	40.3767	.0098	.014	.000	7.94	.02	1.10	.10	.011	.011
	5	40.8680	.0047	.020	-.002	8.37	.03	1.09	.08	.011	.011
	6	40.8127	.0027	.014	.002	8.69	.05	1.07	.04	.006	.006
9	1	42.6241	0.0252	0.024	0.001	7.52	0.08	0.81	0.06	0.005	0.004
	2	43.4803	.0083	.010	.005	7.29	.02	1.03	.13	.005	.004
	3	43.4954	.0053	.009	.008	7.14	-.13	1.01	.10	.005	.004
	4	41.7854	.0056	.009	.000	7.79	.22	1.12	.15	.011	.011
	5	42.1212	.0030	.022	-.006	7.82	.08	1.01	.08	.011	.011
	6	41.6680	.0045	.006	.001	7.87	.13	1.00	.06	.006	.006

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

E-268

TABLE III

VALVE-WEIGHT LOSS AND VALVE-DEPOSIT WEIGHT FOR 50-HOUR TEST OF NINE-CYLINDER AIR-COOLED RADIAL ENGINE

[Brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 lb/sq in.; fuel-air ratio, 0.052; spark advance, 30° B.T.C.; maximum rear-spark-plug-bushing temperature, 400° F]

Cylinder	Description (Nichrome coated)	Valve weight, (grams)		Deposit, (grams)	Condition after test
		Before	Loss		
EXHAUST VALVES					
1	New	522.95	0.23	(a)	Light pin-point corrosion on center of crown
2	New	517.98	.23	4.19	Excellent
3	New	518.70	(a)	4.02	Valve not cleaned, pending further investigation of deposits
4	New	532.87	(a)	4.59	Valve not cleaned, pending further investigation of deposits
5	New	513.43	.09	4.71	Small shallow pits on center of crown
6	New	539.77	.09	5.23	Two or three pin-point pits on crown
7	New	535.64	.10	5.03	Excellent
8	New	540.35	.19	2.94	Pin-point corrosion covering entire crown
9	New	534.75	.29	2.51	Big shallow marks covering entire crown (fig. 10)
INTAKE VALVES					
1	New	486.83	(a)	6.15	Valve not cleaned, pending further investigation of deposits
2	New	484.68	0.05	4.91	Excellent
3	New	481.47	.07	(a)	Scattered shallow corrosion covering approximately one-third of hollow in valve crown
4	New	474.61	(a)	10.31	Valve not cleaned, pending further investigation of deposits
5	New	482.21	.02	7.31	Light corrosion on approximately one-fourth of rim of valve crown
6	Reconditioned	473.61	.07	7.94	Pin-point corrosion over entire top and bottom of valve head
7	Reconditioned	478.05	.13	7.86	Pin-point corrosion over entire top and bottom of valve head
8	Reconditioned	471.38	.05	5.85	Pin-point corrosion over entire top and bottom of valve head
9	New	479.08	.06	7.74	Scattered very small pin-point corrosion on valve head

[a]Valve not available for weighing.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TABLE IV. - SPECTROGRAPHIC ANALYSIS OF VALVE-HEAD DEPOSITS RESULTING FROM 50-HOUR TEST OF NINE-CYLINDER AIR-COOLED RADIAL ENGINE

[Brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 lb/sq in.; fuel-air ratio, 0.052; spark advance, 30° B.T.C.; maximum rear-spark-plug-bushing temperature, 400° F]

Chief constituent	Strong indication	Medium indication	Weak indication
Exhaust-Valve Deposit			
Lead	Chromium Aluminum Nickel Iron Manganese Magnesium	Copper Silicon	Tin
Intake-Valve Deposit			
Lead	Chromium Iron	Tin Aluminum Nickel Manganese Copper	Manganese

National Advisory Committee
for Aeronautics

TABLE V. - SPARK-PLUG-GAP WEAR RESULTING FROM 50-HOUR TEST IN NINE-CYLINDER AIR-COOLED RADIAL ENGINE

[Brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 lb/sq in.; fuel-air ratio, 0.052; spark advance, 30° B.T.C.; maximum rear-spark-plug-bushing temperature, 400° F]

Cylinder	Spark plug	Average gap, in.			Spark-plug resistance, ohms	
		Before	After	Increase	Before	After
1	1	0.012-	0.014+	0.002+	1060	750
	2	.012-	.014-	.002	710	650
2	3	.012	.014-	.002-	1130	830
	4	.012	.013+	.001+	1060	700
3	5	.012	.014-	.002-	1120	810
	6	.012	.014	.002	1080	770
4	7	.012	.014-	.002-	1070	740
	8	.012	.014	.002	1110	790
5	9	.012	.014	.002	1030	940
	10	.012	.014	.002	1130	1010
6	11	.012	.014	.002	990	600
	12	.012	.014-	.002-	930	700
7	13	.012	.014+	.002+	1090	740
	14	.012	.013-	.001-	1070	670
8	15	.012+	.014-	.001+	1150	940
	16	.012	.014+	.002+	1080	810
9	17	.012	.014-	.002-	1040	580
	18	.012	.014-	.002-	1040	750

National Advisory Committee for Aeronautics

E-268

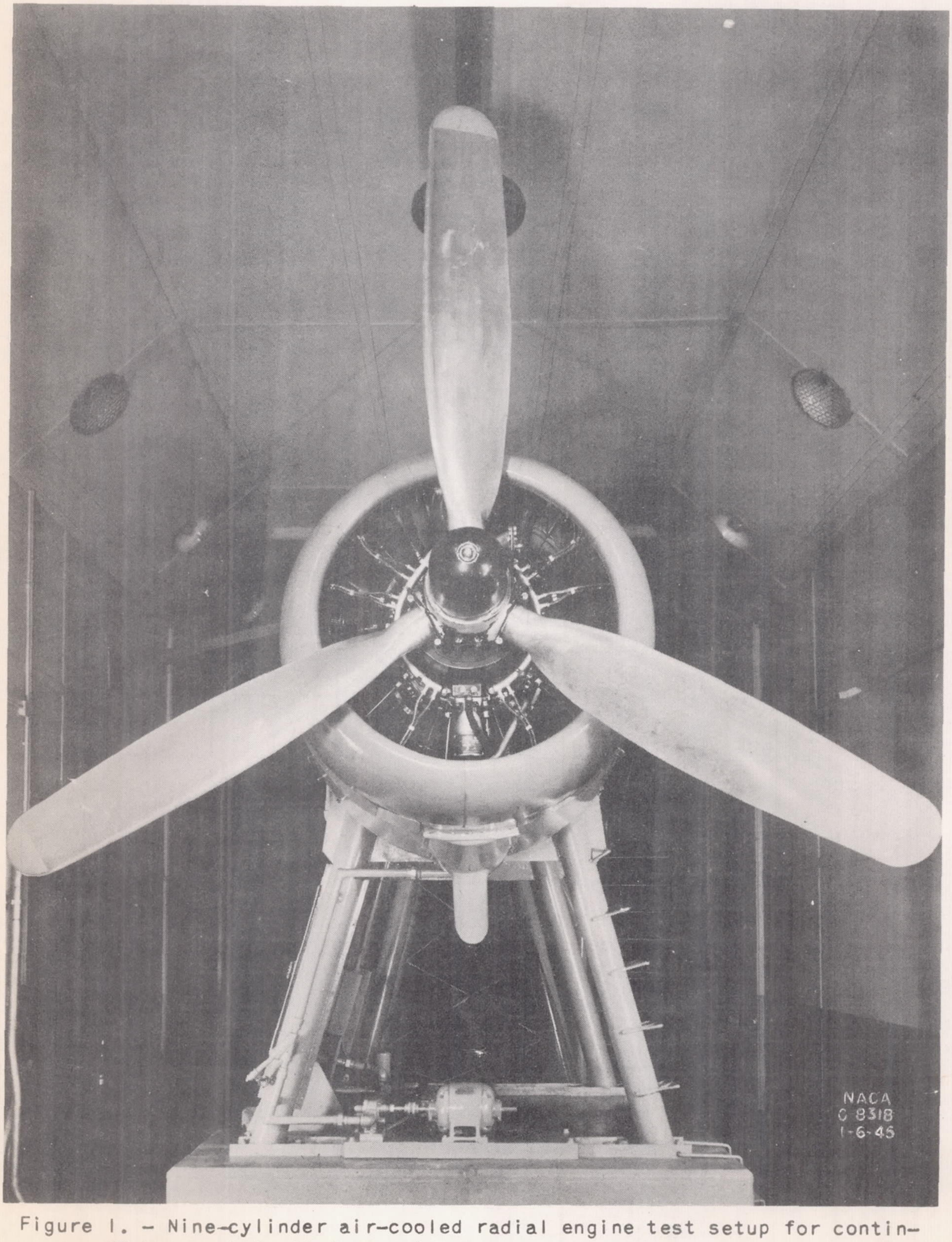


Figure I. - Nine-cylinder air-cooled radial engine test setup for continuous 50-hour multicylinder-engine test.

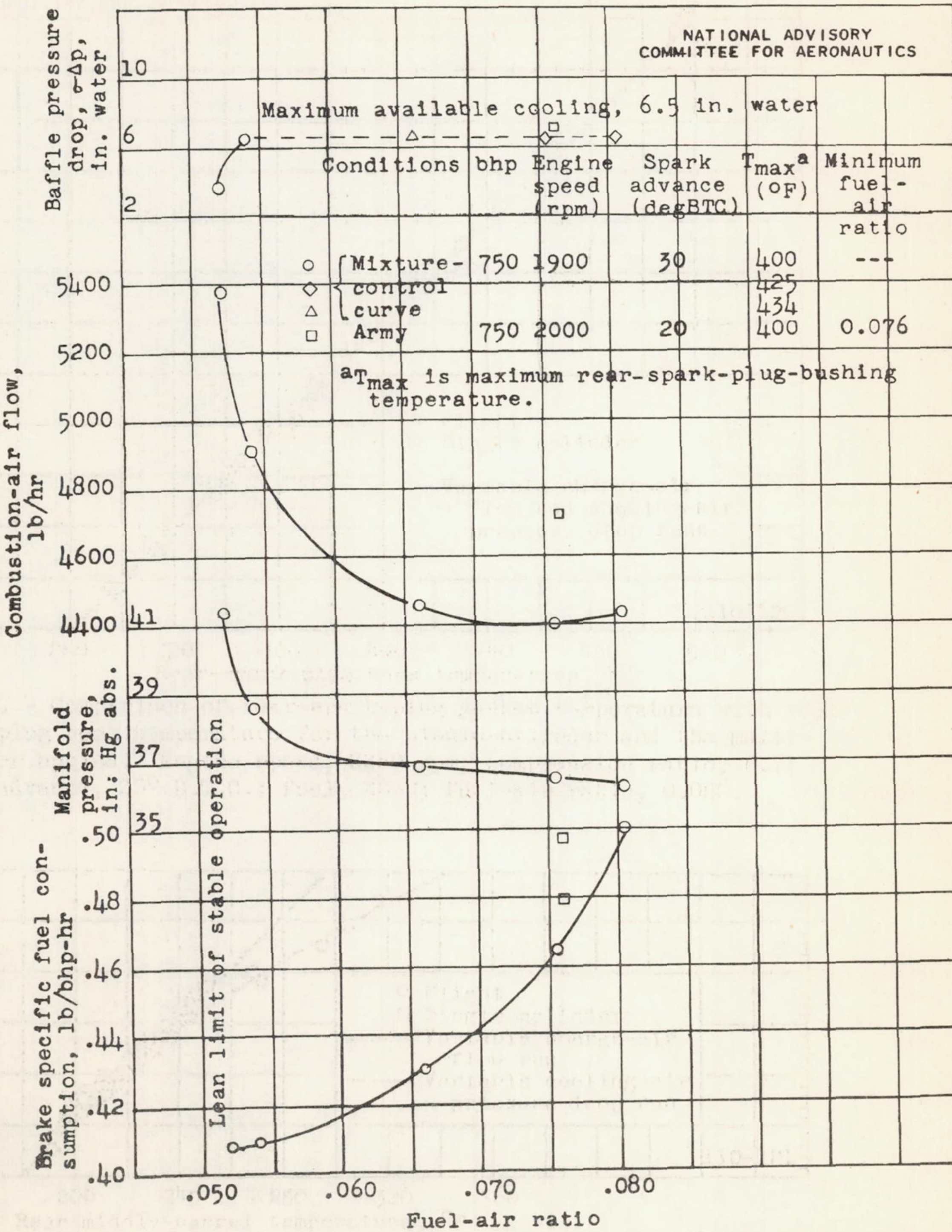


Figure 2. - Mixture-control curve for nine-cylinder air-cooled radial engine tested. Values added for the same engine operating at the conditions recommended in reference 1.

E-268

E-268

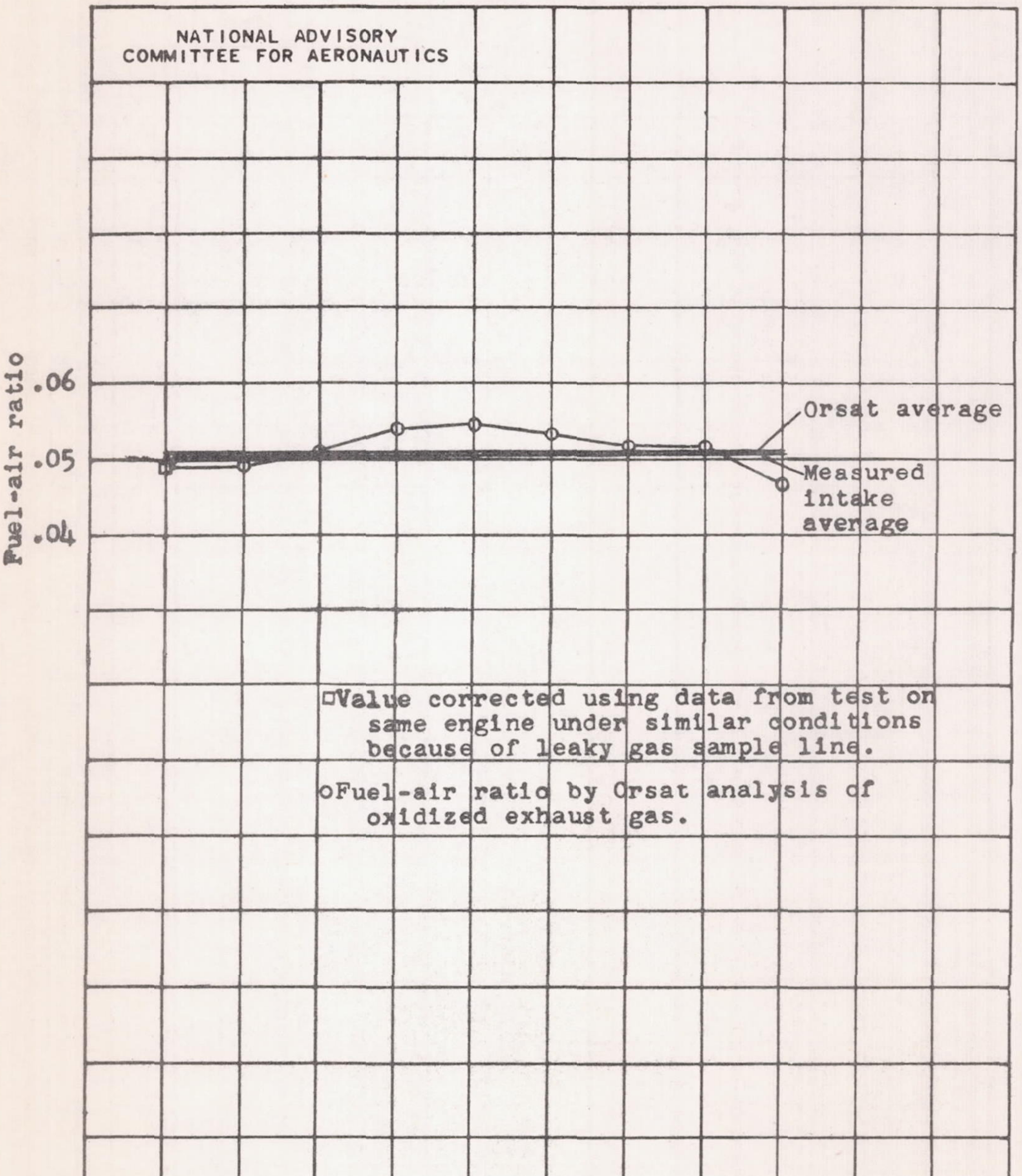


Figure 3. - Mixture distribution in nine-cylinder aid-cooled radial engine tested. Brake horsepower, 750; engine speed, 1900 rpm; fuel-air ratio, 0.052; spark advance, 30° B.T.C.

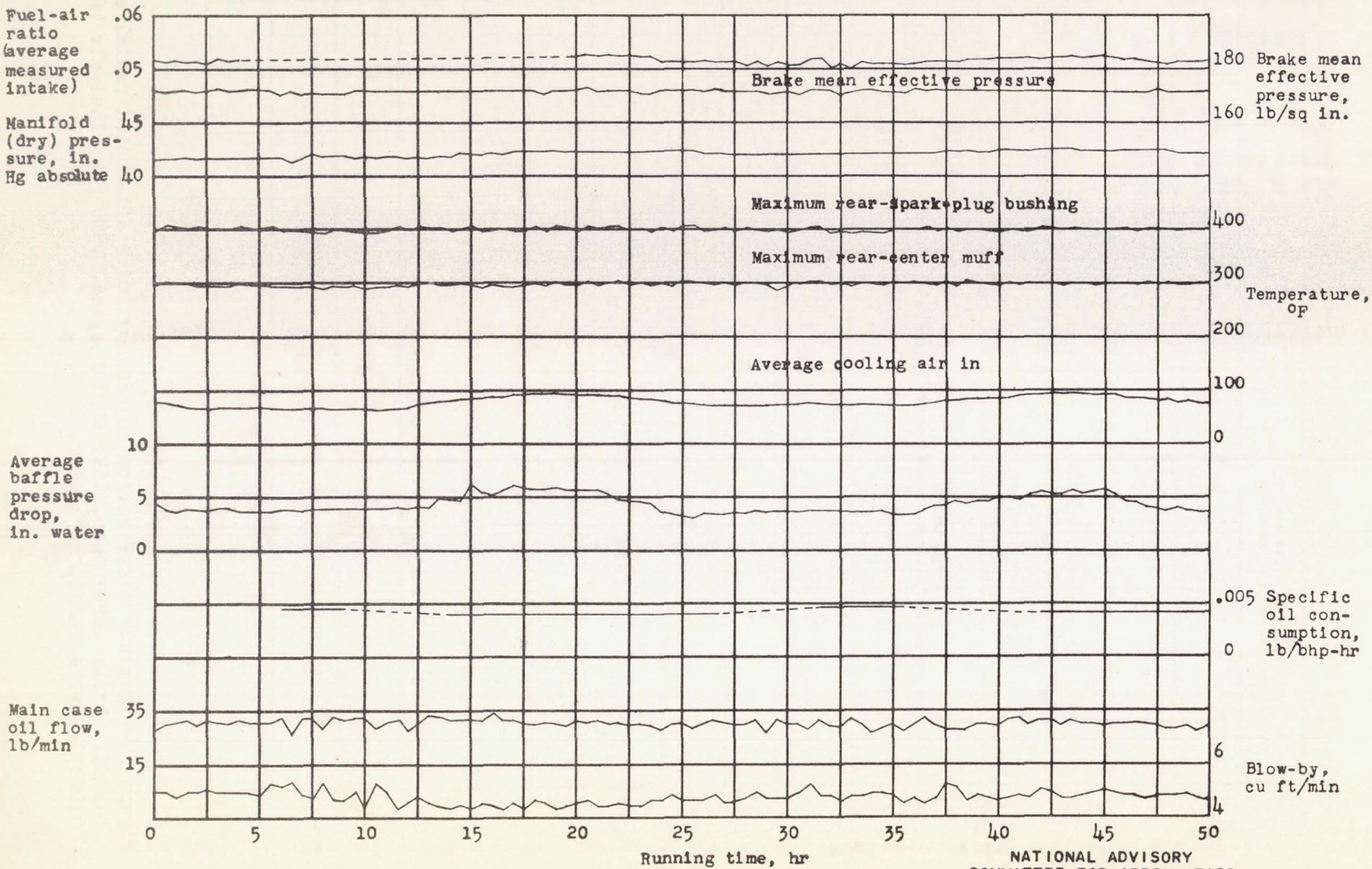


Figure 4. - Graphic log of 50-hour test of nine-cylinder air-cooled radial engine. Brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 pounds per square inch; fuel-air ratio, 0.052; spark advance, 30° B.T.C.

E-268

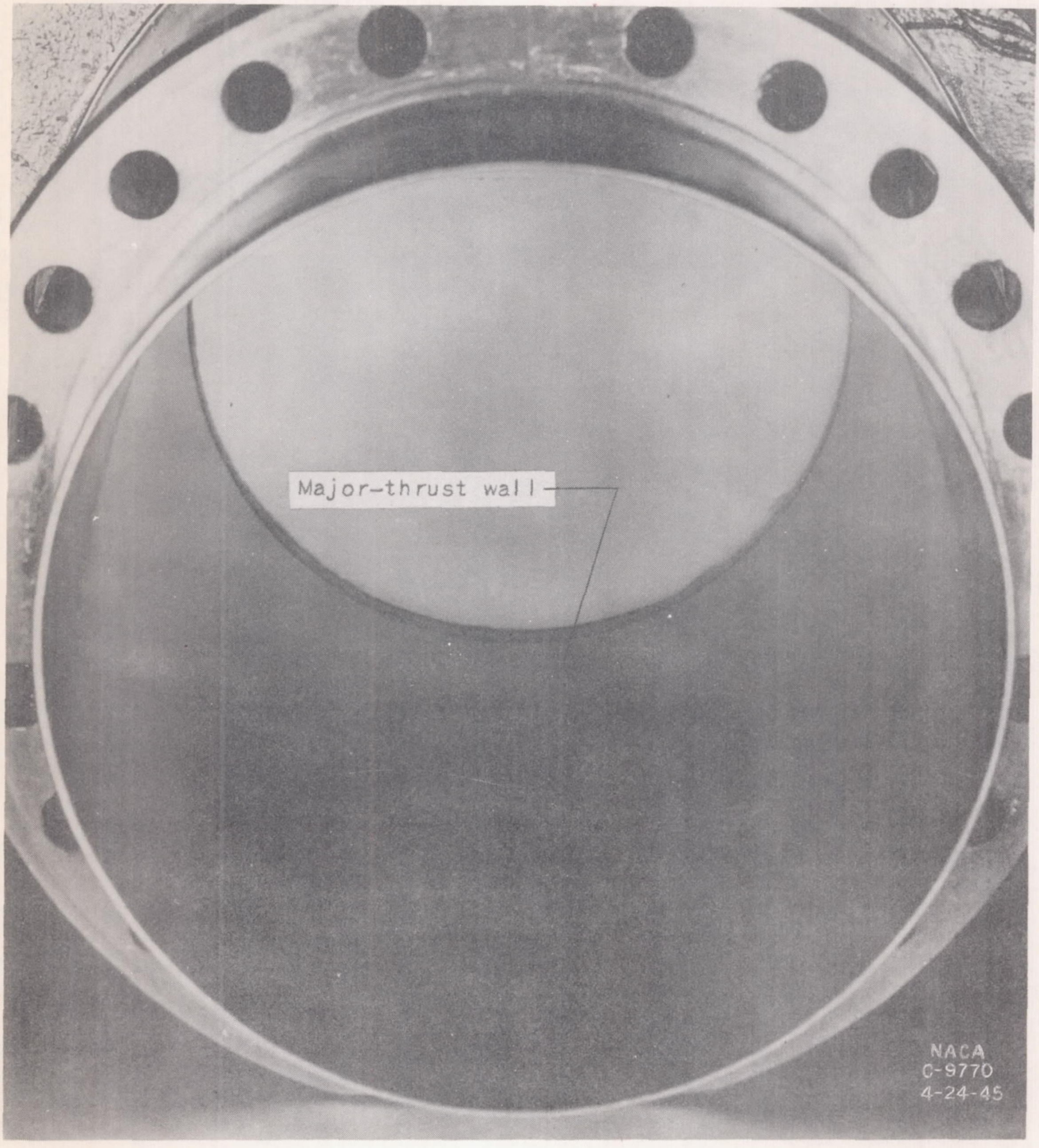


Figure 5. - Condition of bore of typical cylinder after 50-hour test of nine-cylinder air-cooled radial engine. Brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 pounds per square inch; fuel-air ratio, 0.052; spark advance, 30° B.T.C.; maximum rear-spark-plug-bushing temperature, 400° F.

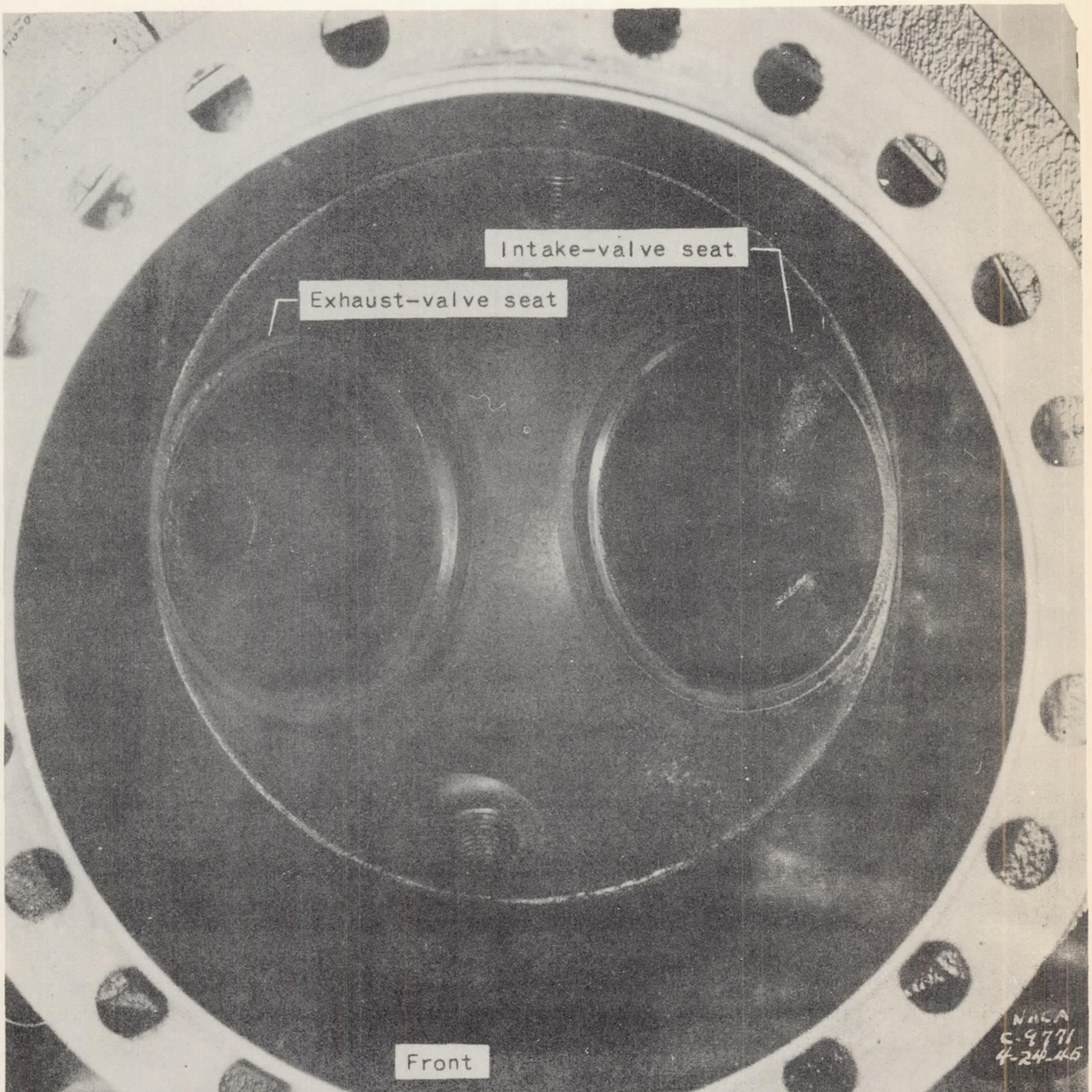
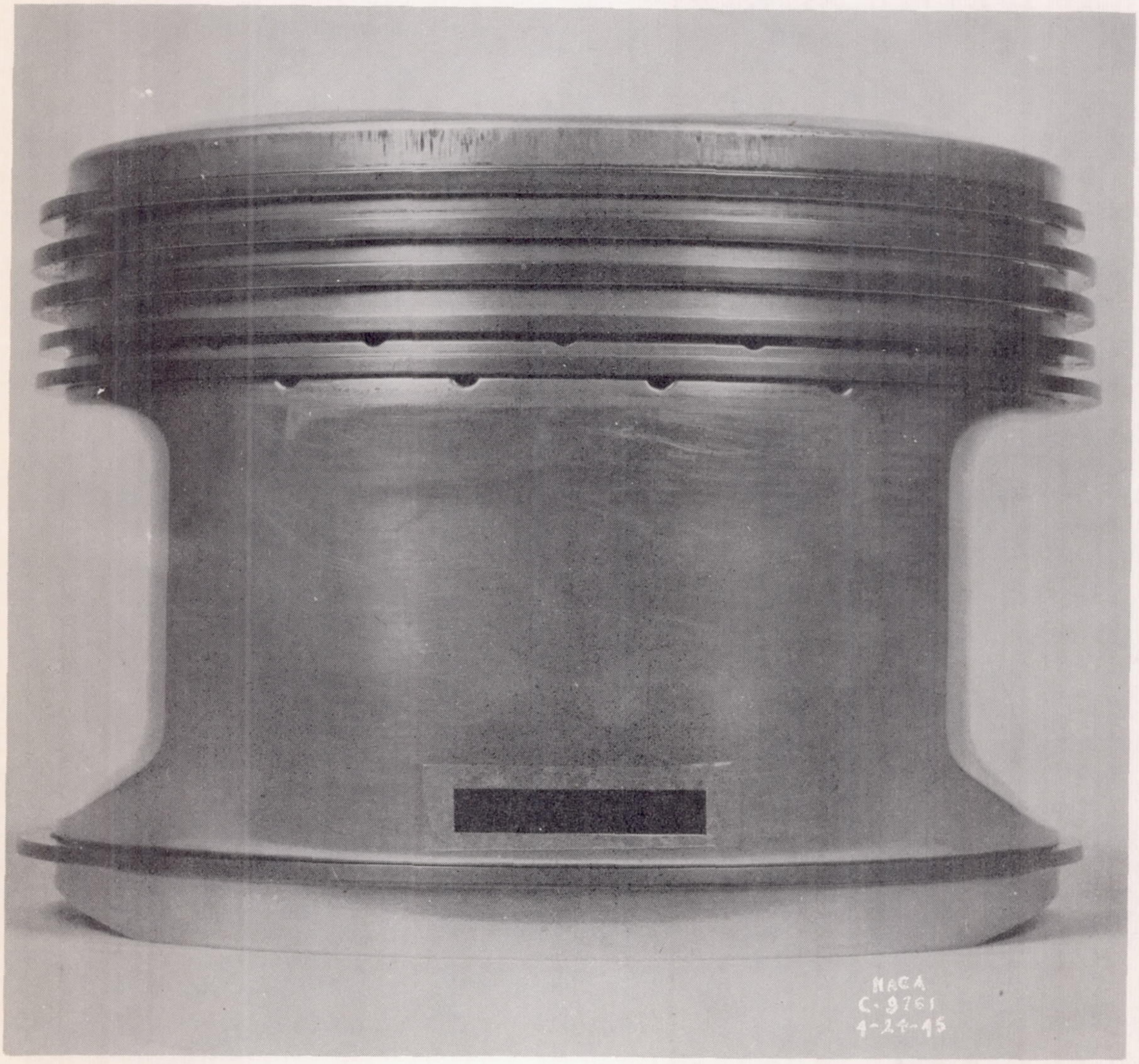


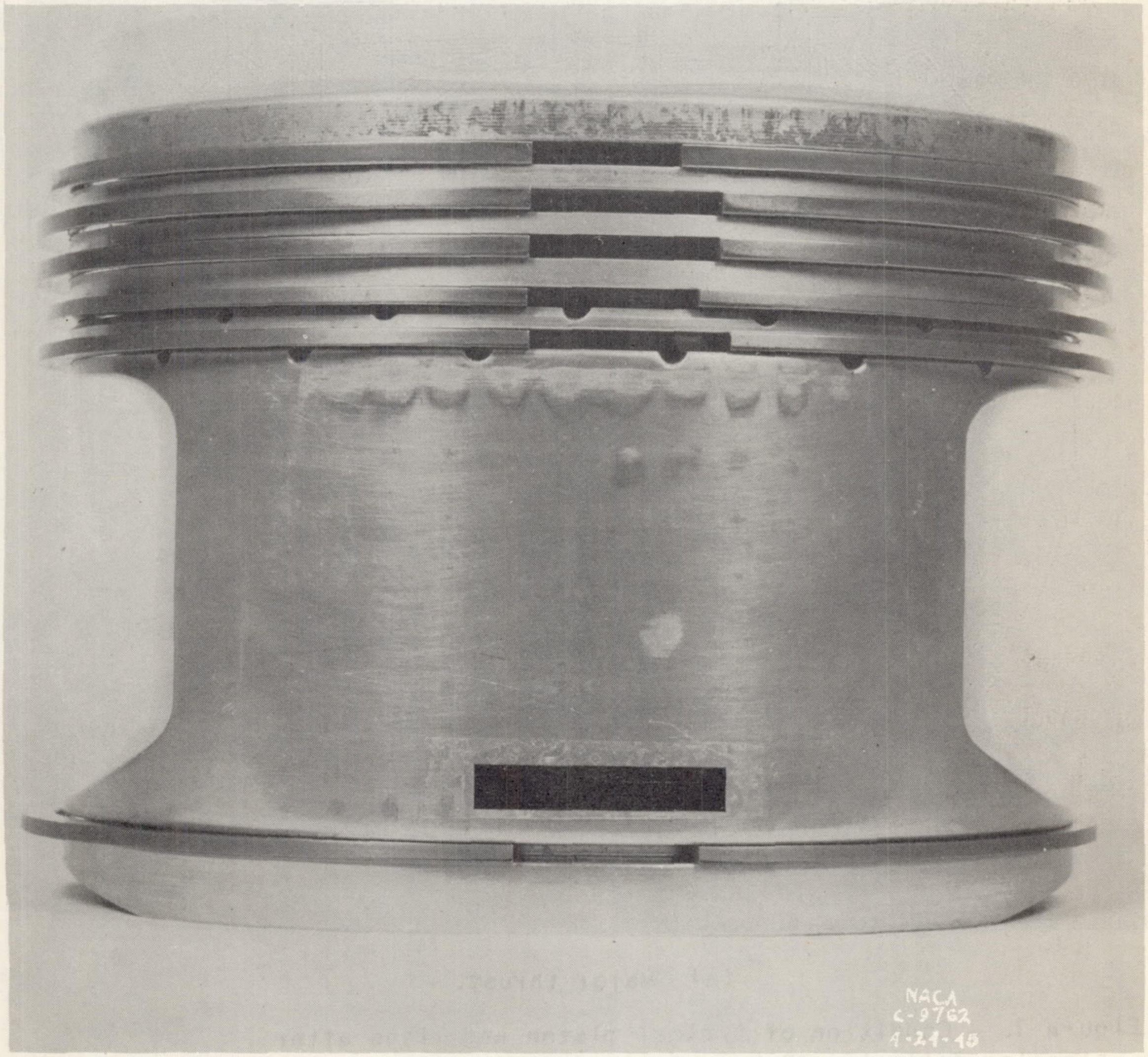
Figure 6. - Condition of combustion chamber of typical cylinder after 50-hour test of nine-cylinder air-cooled radial engine. Brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 pounds per square inch; fuel-air ratio, 0.052; spark advance, 30° B.T.C.; maximum rear-spark-plug-bushing temperature, 400° F.

E-268



(a) Major thrust.

Figure 7. - Condition of typical piston and rings after cleaning following 50-hour test of nine-cylinder air-cooled radial engine. Brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 pounds per square inch; fuel-air ratio, 0.052; spark advance, 30° B.T.C.; maximum rear-spark-plug-bushing temperature, 400° F.



(b) Minor thrust.

Figure 7. - Concluded.

E-268

E-268

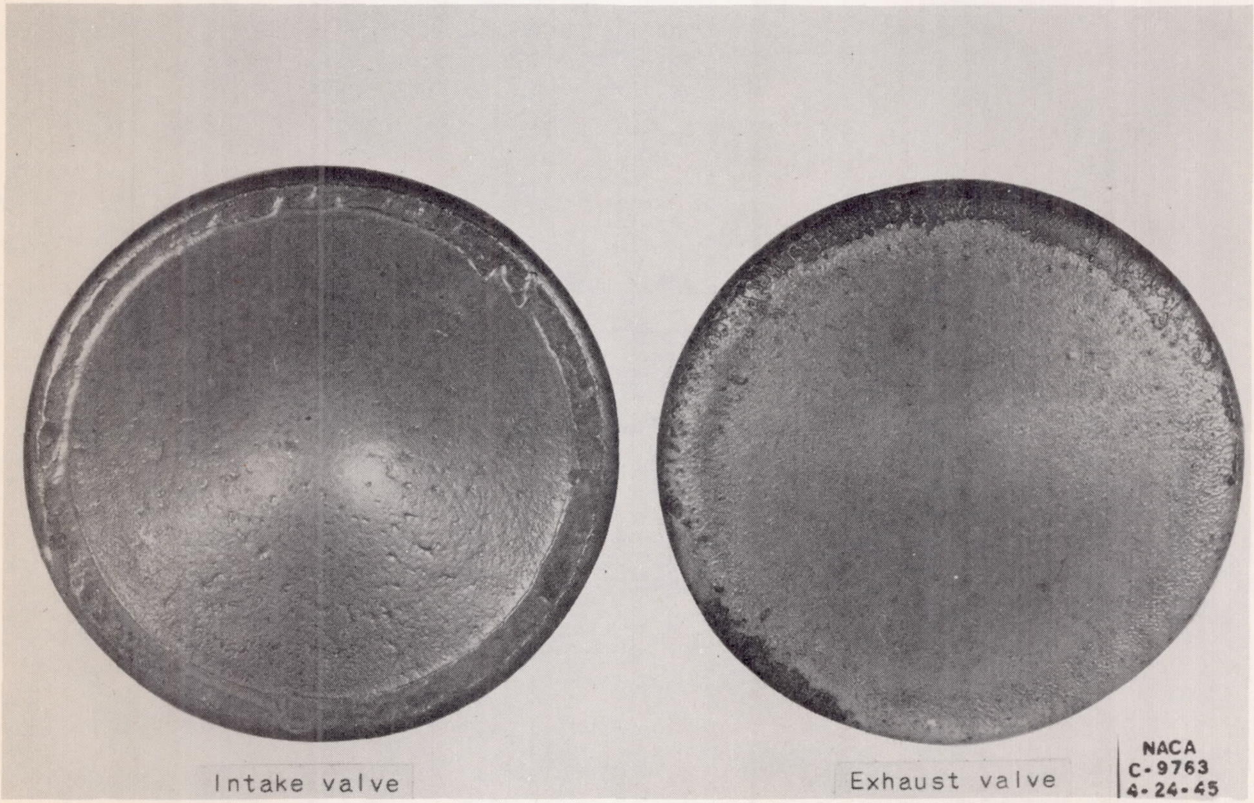


Figure 8. - Valve heads of cylinder 7 typical of intake and exhaust valves after 50-hour test of nine-cylinder air-cooled radial engine. Brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 pounds per square inch; fuel-air ratio, 0.052; spark advance; 30° B.T.C.; maximum rear-spark-plug-bushing temperature, 400° F.

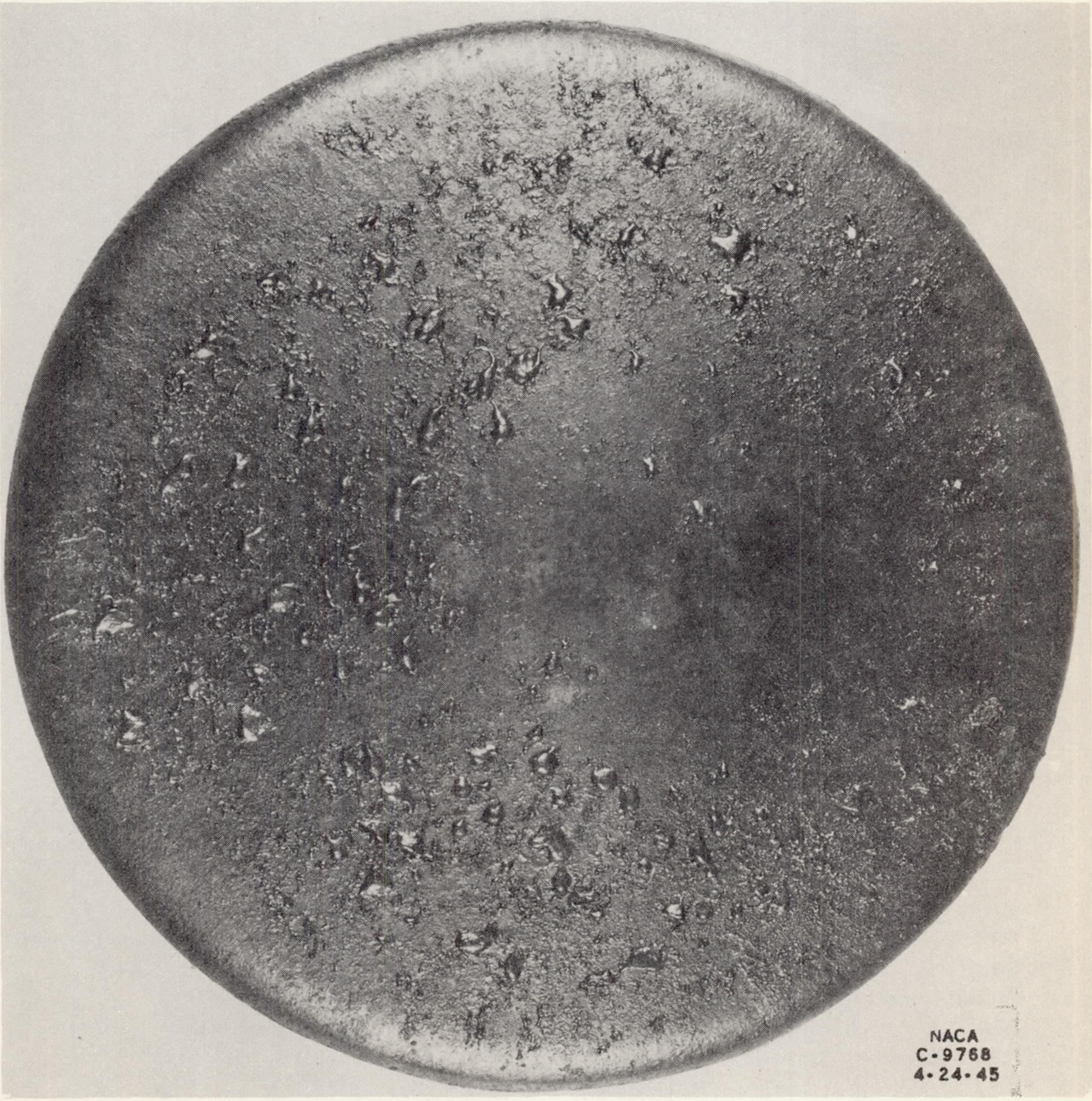


Figure 9. - Condition of exhaust-valve head from cylinder 9 after 50-hour test in nine-cylinder air-cooled radial engine. Brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 pounds per square inch; fuel-air ratio, 0.052; spark advance, 30° B.T.C.; maximum rear-spark-plug-bushing temperature, 400° F.

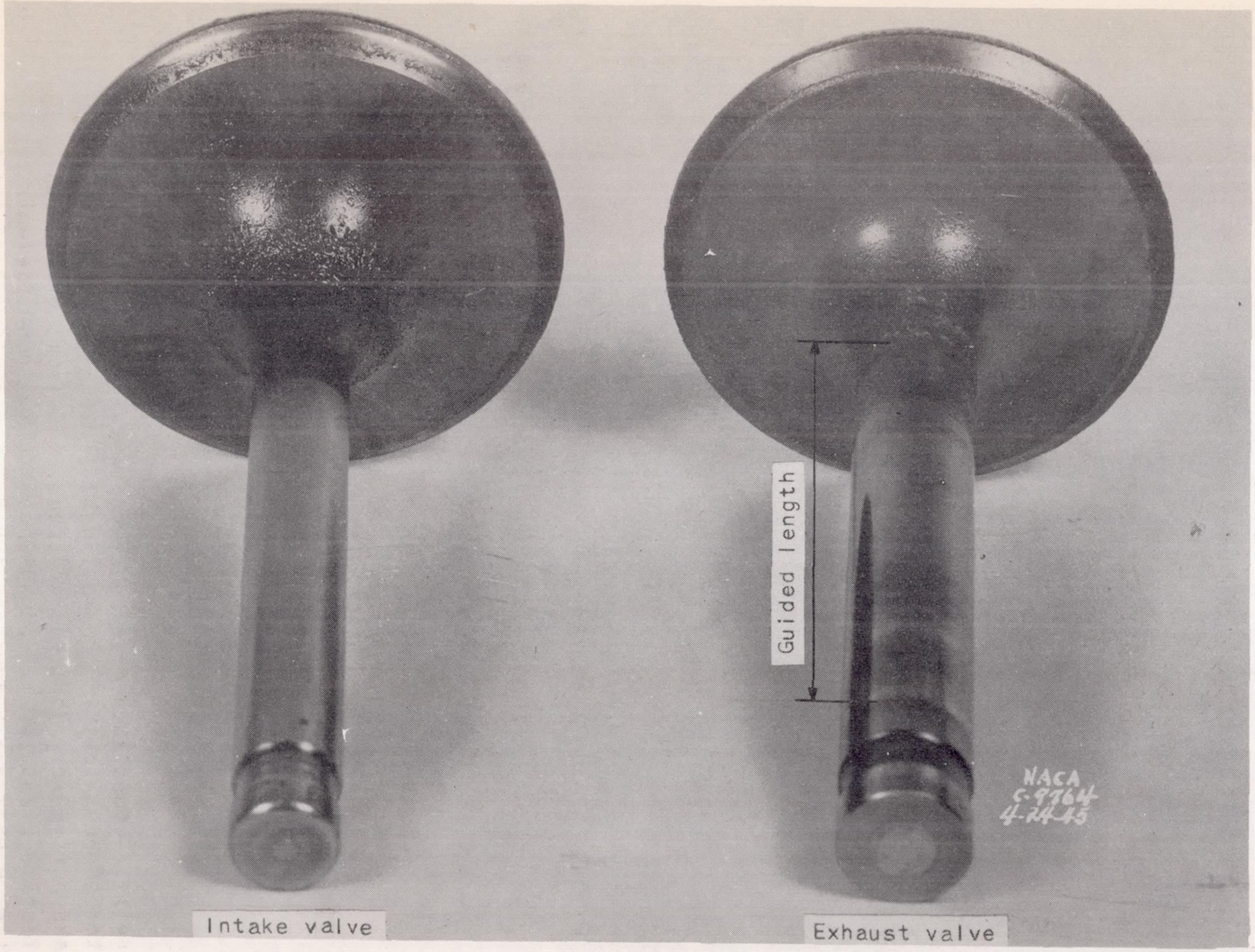


Figure 10. - Condition of valve stems and necks from cylinder 7 typical of intake and exhaust valves after 50-hour test in nine-cylinder air-cooled radial engine. Brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 pounds per square inch; fuel-air ratio, 0.052; spark advance, 30° B.T.C.; maximum rear-spark-plug-bushing temperature, 400° F.

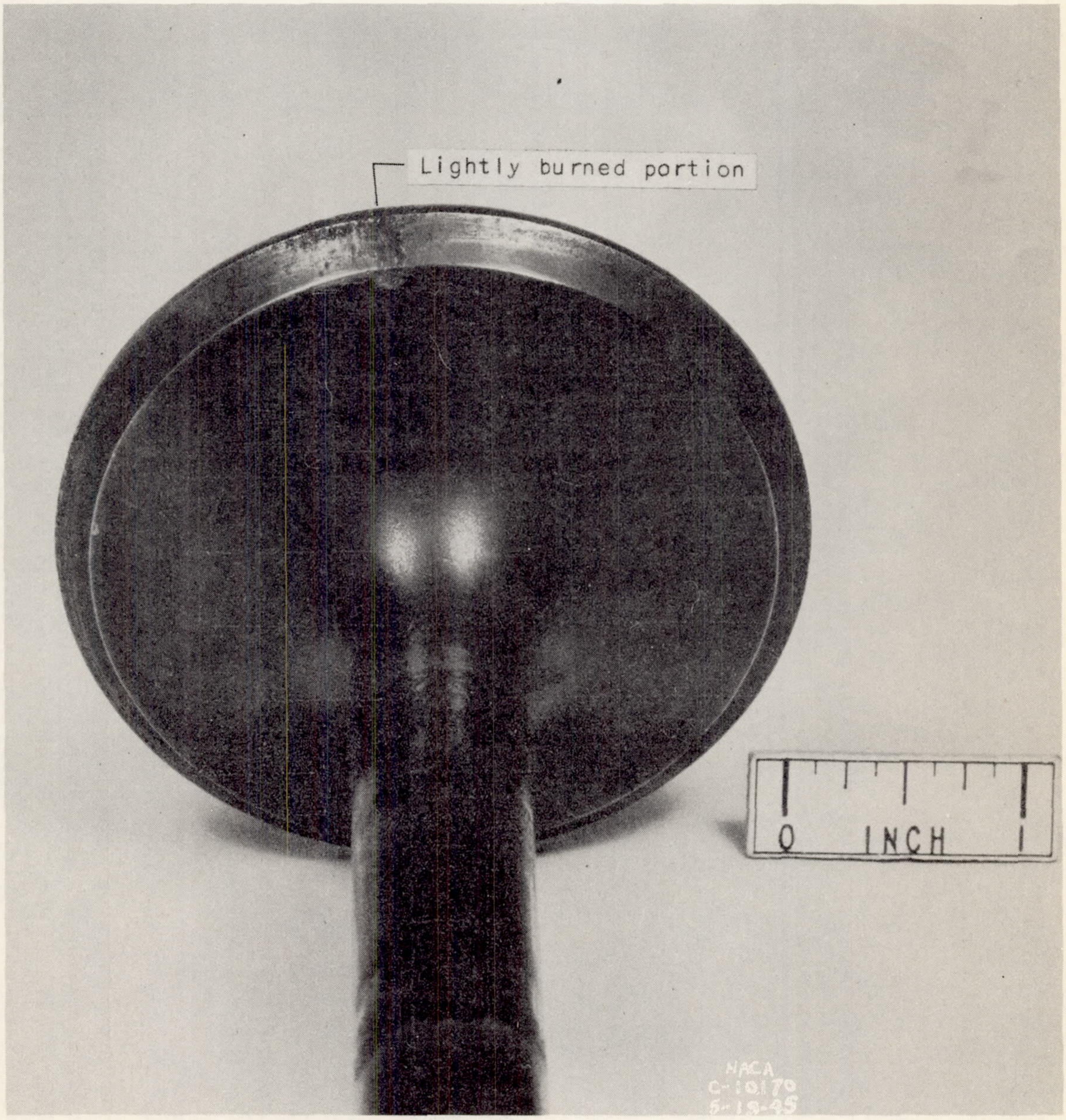


Figure 11. - Condition of exhaust-valve face from cylinder 9 after 50-hour test in nine-cylinder air-cooled radial engine. Brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 pounds per square inch; fuel-air ratio, 0.052; spark advance, 30° B.T.C.; maximum rear-spark-plug-bushing temperature, 400° F.

E-268

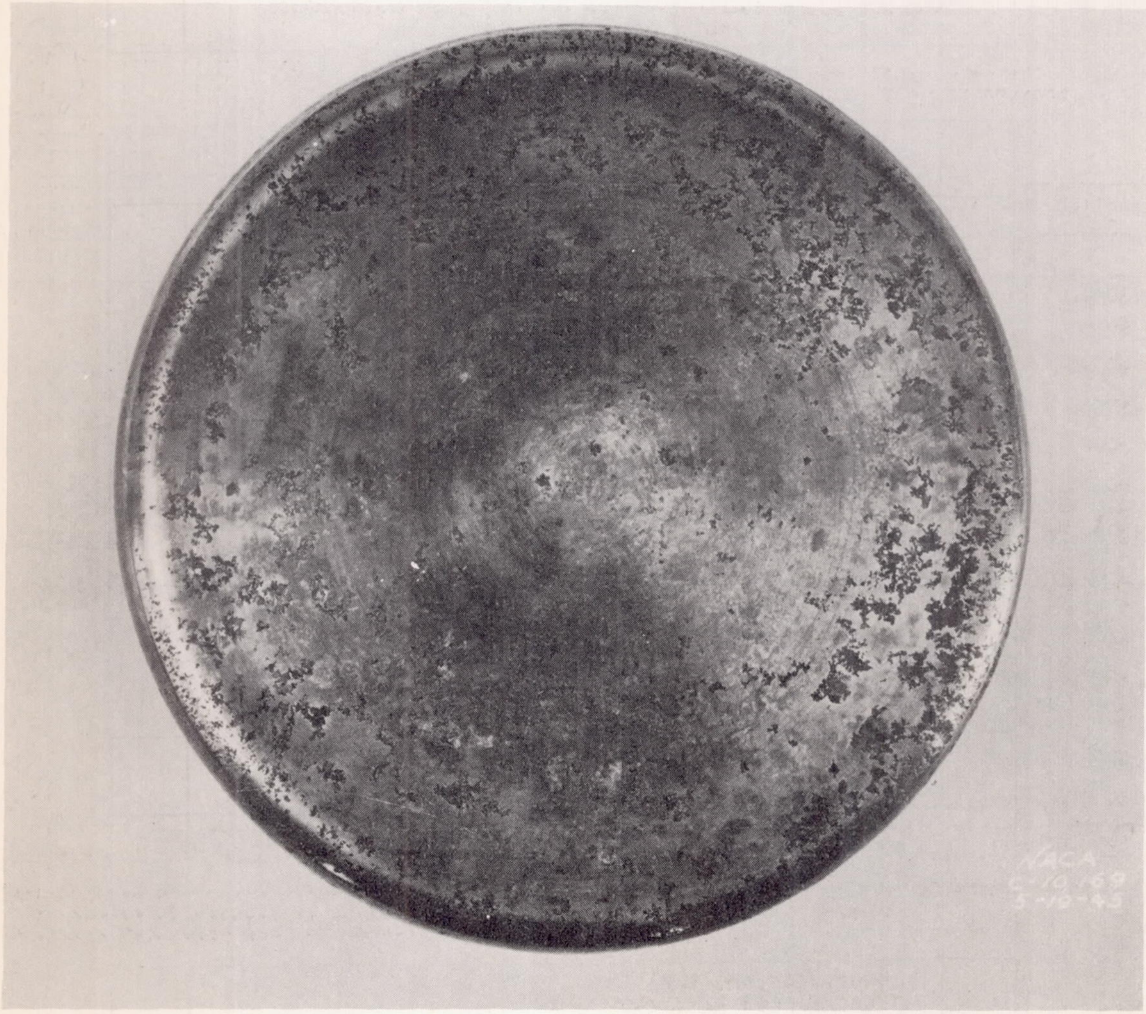


Figure 12. - Condition of exhaust-valve crown from cylinder 9 after cleaning following 50-hour test in nine-cylinder air-cooled radial engine. Brake horsepower, 750; engine speed, 1900 rpm; brake mean effective pressure, 172 pounds per square inch; fuel-air ratio, 0.052; spark advance, 30° B.T.C.; maximum rear-spark-plug-bushing temperature, 400° F.

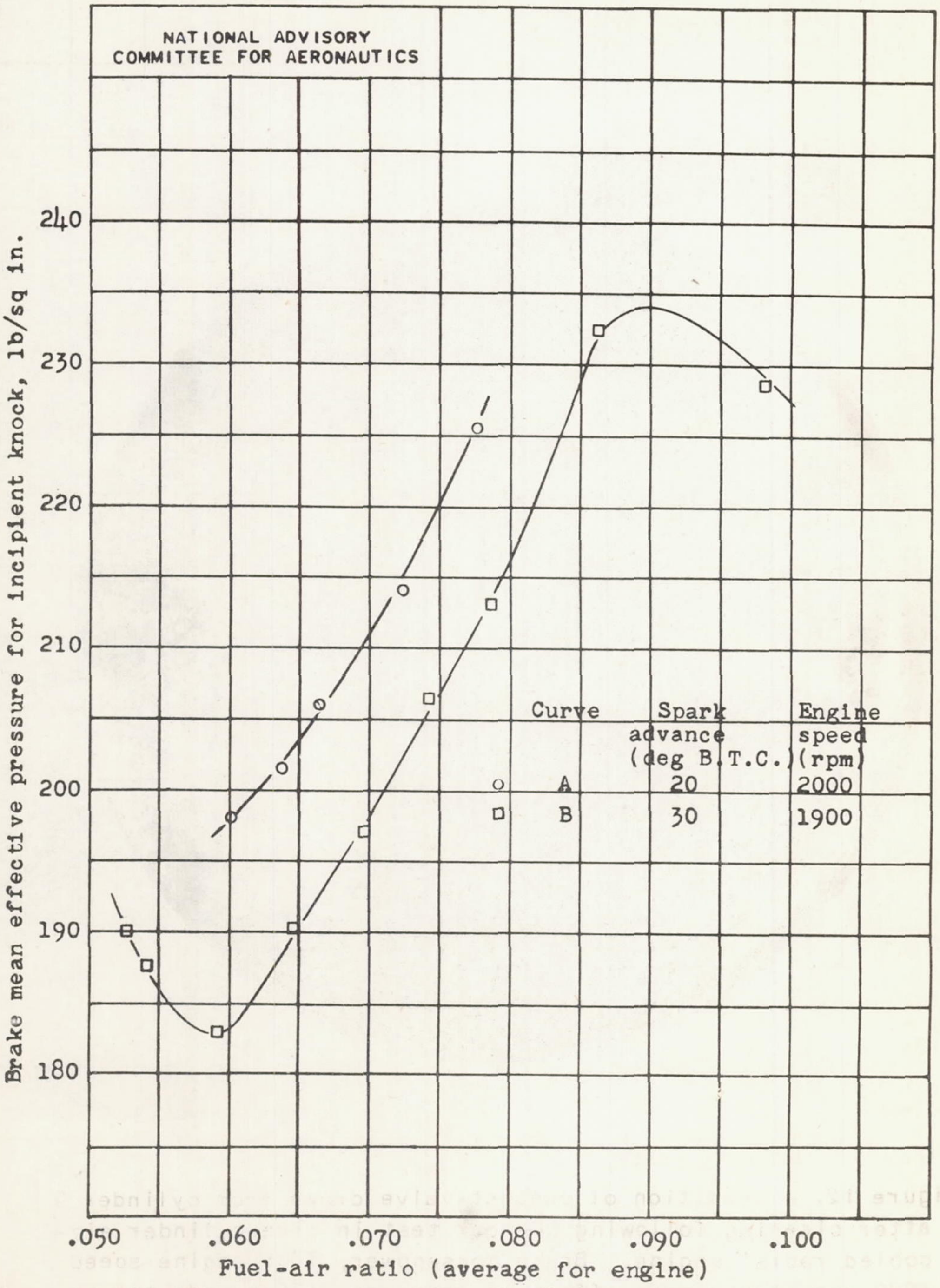


Figure 13. - Maximum brake mean effective pressure as limited by incipient knock, for two conditions of speed and spark advance obtained from tests of nine-cylinder air-cooled radial engine. Carburetor-air temperature, 100° F; maximum rear-spark-plug-bushing temperature, 500° F; fuel, AN-F-28, Amendment-2.

E-268

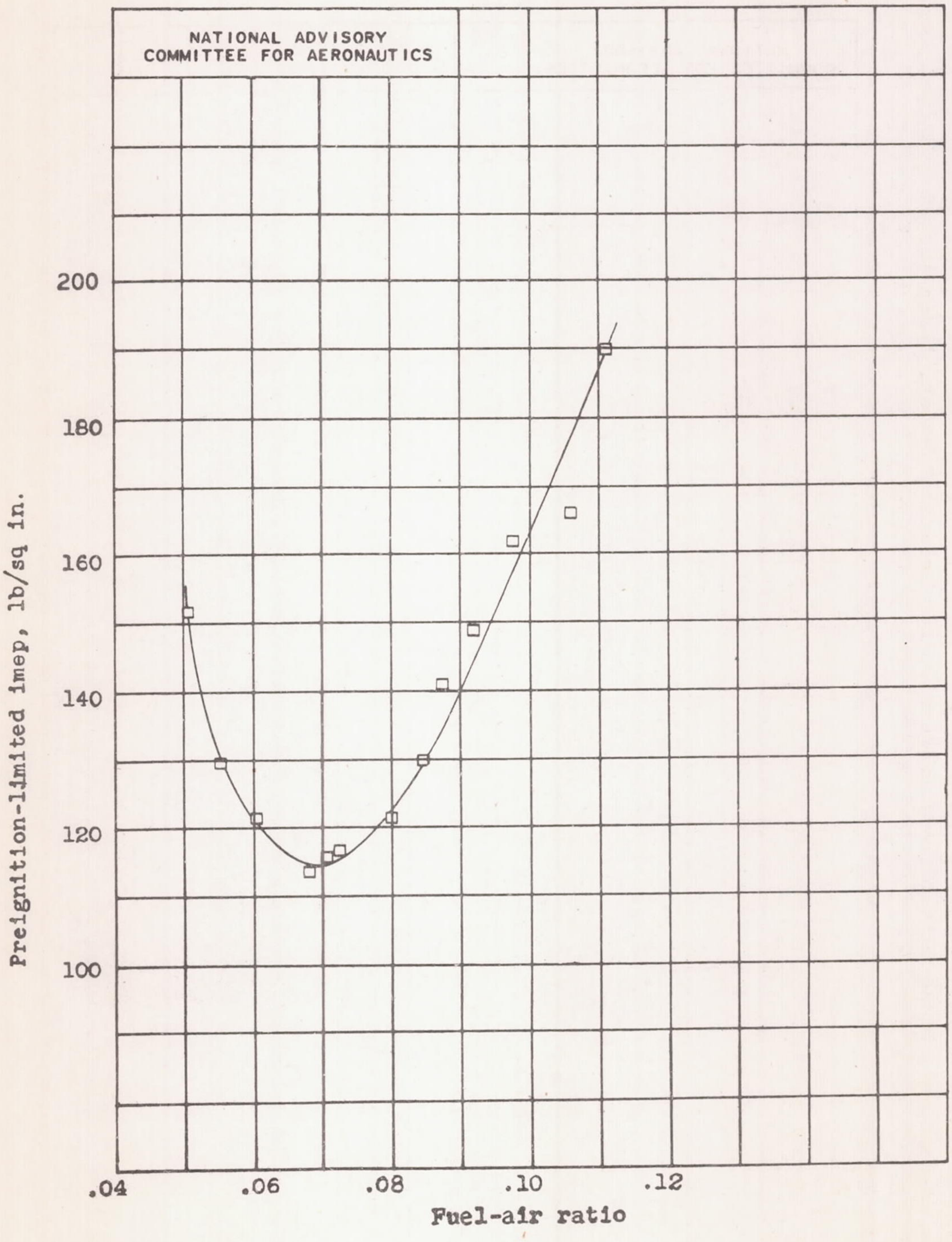


Figure 14. - Preignition-limited performance of 28-R fuel. CFR engine; open tube hot spot; engine speed, 1800 rpm; inlet-air temperature, 225° F; coolant temperature, 250° F; spark advance, 20° B.T.C.; compression ratio, 7.0. (Data from reference 15.)