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NITRIDED-STEEL PISTON RINGS FOR ENGINES OF HIGH SPECIFIC POWER

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NITRIDED-STEEL PISTON RINGS FOR ENGINES OF HIGH SPECIFIC POWER

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SUMMARY

Several designs of nitrided-steel piston rings were performance-tested under variable conditions of output. The necessity of good surface finish and conformity of the ring to the bore was indicated in the first tests. Nitrided-steel rings of the same dimensions as cast-iron rings operating on the original piston were not satisfactory. The final design was a lighter, rectangular, thin face-width ring used on a piston having a maximum cross-head area and the proper skirt shape. Results were obtained from tests of single-cylinder and multicylinder engines.

The thin, nitrided-steel rings were performance-tested in both nitrided and porous chromium-plated cylinder barrels with good results. The nitrided-steel cylinders were stock production items and the porous chromium-plated cylinders were worn cylinders that had been reclaimed by plating back to size. The use of nitrided-steel rings in chromium-plated cylinders offers attractive possibilities that require further investigation.

Good performance characteristics of ring and cylinder barrel were obtained. Tests under dust conditions indicated that the nitrided-steel rings maintained acceptable oil control from three to four times longer than the stock cast-iron rings. Lubricating-oil consumption was somewhat higher with nitrided-steel rings than that usually encountered with the original cast-iron ring assembly when the cast-iron rings are in the best condition of run-in. The lubricating-oil consumption with nitrided-steel rings tended to improve with operating time, whereas the opposite trend was exhibited by cast-iron rings.

Dust tests, in particular, should be made on the combination of thin nitrided-steel rings and chromium-plated cylinders. Extensive flight tests of the rectangular nitrided-steel piston rings are recommended.

INTRODUCTION

For many years the NACA has been conducting tests of aircraft-engine cylinders at specific power outputs in excess of their maximum ratings. The first engine parts to fail as the specific power is increased are the piston rings; the failure manifests itself by general increases in specific oil consumption, in rapid ring wear, in blow-by, and in subsequent loss in power.

Variables that considerably affect piston-ring and cylinder-barrel wear are: dust; lubrication, both quantity and quality; brake mean effective pressure; engine speed; and operating temperatures. Both bench tests and engine tests were made on a variety of piston-ring materials and ring designs. Some of the materials and ring designs were eliminated by the bench tests. The others were tested in single-cylinder engines. The choice of the procedure for the engine-ring test covered by this report was chosen with a view to picking test conditions that would give the required results in the minimum time. The final combination of nitrided-steel rings in both nitrided-steel and chromium-plated cylinder barrels was performance-tested under a wide variety of operating conditions in both single-cylinder and multicylinder engines.

The thin, nitrided-steel rings used in these tests were manufactured by and tested in cooperation with the Borg-Warner Corporation, Spring Division, Bellwood, Ill.

The nitrided-steel piston rings were performance-tested in single-cylinder engines at Langley Memorial Aeronautical Laboratory from 1939 through 1942. At the recommendation of the National Advisory Committee for Aeronautics, multicylinder and single-cylinder engines were tested by the Bureau of Aeronautics, Navy Department, at the Aeronautical Engine Laboratory of the Naval Aircraft Factory in Philadelphia and by the Army Air Forces, Materiel Command, at Wright Field.

DEFINITIONS

Piston-ring terms to be used in this report are defined as follows:

face - The part of the piston ring that is adjacent to, or in direct contact with, the cylinder wall.

face width - The width of the ring face.

side - The part of the ring that contacts the piston grooves.

ring assembly - The entire group of rings used on any individual piston, regardless of ring type, material, or position with respect to the piston pin.

radial depth - The radial dimension from the center of the face to the center of the back of the ring.

diametral tension - The force in pounds, which is applied along a radius 90° from the gap, required to close the ring to its nominal diameter. Ring tension as used and measured in this investigation is purely an arbitrary measurement of the characteristics of a piston ring.

unit wall pressure - The force exerted by the piston-ring face against the cylinder wall, pounds per square inch. This unit pressure is obtained by use of the following equation[1] from reference 1:

$$p = \frac{0.76T}{DW}$$

where

p	unit pressure, pounds per square inch
T	diametral tension, pounds
D	ring diameter, inches
W	face width, inches

The unit wall pressure as defined in this report is only an approximate average value inasmuch as true unit pressures can be determined only by such an instrument as a radial-pressure gage.

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[1] An analysis made subsequent to the original publication of this paper indicates that the constant 0.76 applies to measurements made with the ring compressed to the correct gap. The analysis showed that a value of 0.88 should be used if measurements are made with the ring compressed to the proper diameter, as was done in the tests reported. Correction of the data reported is felt to be unwarranted, however, since the values obtained were used only for qualitative comparison.

APPARATUS AND TEST PROCEDURE

Temperature Tests

The heater shown in figure 1 was designed and built to check the effect of temperature on stress relief. Stress relief may be defined as the loss in tension of a ring at elevated temperatures. Two piston rings with two thermocouples leading from each ring can be simultaneously tested in this heater. Rings were placed in the heater, which compressed them to their nominal diameter. They were heated to the predetermined temperature and held at this temperature for 10 minutes, after which they were removed from the heater and cooled in still air. The diametral tension of the rings was determined before and after each heat period. The tension of the rings was determined by applying a force at 90° to the gap until the ring was compressed to its nominal diameter. This application of force was accomplished by placing a balance under a press, the spindle of which was accurately set, in order that it could be moved only the proper distance. Practically all of the commercially available ring materials, such as alloy cast iron, high-speed steel, and several kinds of nitrided steel, were included in these temperature tests.

The object of these short tests was to eliminate quickly the materials that had the least chance of proving satisfactory for rings intended to operate at high power outputs. In the determination of the effect of prolonged heating at elevated temperatures, rings were compressed to their nominal diameter by installing them in a section of a cylinder of the proper size. This assembly was then placed in a heat-treating oven that had been heated to the predetermined temperature. An unconfined ring was also placed in the furnace. At the expiration of the heating period (1 hr in one test, 6 to 8 hr in another test), the cylinder was removed from the oven and the rings still confined in the cylinder were allowed to cool. The unconfined ring was removed at the same time and allowed to cool in the unconfined condition. Diametral tension was determined before and after each heating period. In these tests the same rings were tested over a range from room temperature to 1100° F or until the ring collapsed.

Single-Cylinder-Engine Tests

The following single-cylinder test-engine setups were used in the NACA tests:

Cylinder	Crankcase	Bore and stroke (in.)	Compression ratio	Valve timing	Engine speed (rpm)	imep (lb/sq in.)	Fuel system
NACA compression ignition; displacer piston design	NACA universal test engine	5 by 6	12.0	-----	2000	150 to 240	Fuel injection
Wright C9GC	NACA universal test engine	$6\frac{1}{8}$ by 7	6.7	Standard	2200	225	Carburetor
Wright C9GC	[1]Wright R-1820-73	$6\frac{1}{8}$ by $6\frac{7}{8}$	6.7	Standard	1160 to 2500	125 to 288	Carburetor
Wright C9GC	[1]Wright R-1820-45	$6\frac{1}{8}$ by $6\frac{7}{8}$	6.7	Standard	2200	236	Carburetor

[1] Rebalanced for single-cylinder operation. (See fig. 2 for a typical setup.)

Combustion-air flow to the engines was measured by a sharp-edge, thin-plate orifice assembled according to A.S.M.E. standards. Power was absorbed and measured by a cradle-type electric dynamometer in all single-cylinder-engine tests.

All cylinders except that of the compression-ignition engine were air-cooled. The compression-ignition-engine cylinder was cooled with water at atmospheric pressure. Cooling air was supplied by separately driven blowers and flow was varied to produce the desired cylinder-head and cylinder-barrel temperatures. These temperatures were measured by 13 iron-constantan thermocouples distributed over head and barrel.

High-power endurance tests were run under speed, lubrication, and temperature conditions conducive to ring failure through scuffing, scoring, and feathering.

Blow-by was measured by a positive-displacement gas meter connected to the crankcase-breather system (fig. 3). As indicated in the diagrammatic sketch, blow-by is piped through a large surge tank with a flexible head, which is installed to damp out pressure fluctuations. By use of this surge tank, the effect of variable speed on the meter calibration becomes negligible. As is the case in all oil-system installations utilizing a dry sump and a large-capacity oil-scavenge pump, some of the blow-by gases are pumped into the oil-storage tank. This condition is taken care of by using a sealed storage tank and by returning this blow-by to the crankcase; thereby all blow-by will eventually pass through the meter.

The crankcase pressure was arbitrarily set at 1/2 inch of water below atmospheric pressure (to permit leakage corrections to be made) and was maintained at this value throughout a complete run by means of the throttle valve K in figure 3. A leakage-calibration curve was taken at variable speeds for the crankcase pressure set at 1/2 inch of water below atmospheric pressure. In this calibration, the engine was motored without compression in order that no gas would leak by the rings. Leakage losses in all tests were found to be negligible. Calibration of the leakage was repeated from time to time as a check on the efficiency of the sealing of crankcase and blow-by system.

Ring wear was measured by cleaning and weighing the rings before and after each test. Specific oil consumption was measured in the single-cylinder-engine tests by the volume method corrected for temperature. The installation of special fittings and a separate scavenging pump permitted the measurement of the power-section oil flow for the single-cylinder test engine using the Wright R-1820-73 crankcase.

Measurement of surface quality was made by measuring surface roughness of the nitrided surfaces of cylinder and rings. Surface roughness was measured with a Brush surface analyzer and a Profilometer; porosity of the chromium-plated surfaces was measured by a replica method developed by the NACA. In this method, a replica of the surface is taken with a plastic such as stripping lacquer or celluloid and this replica is photographed at a magnification of 100. It has been found by experiment that a good correlation is obtained between the porosity as measured by the replica method and the porosity obtained by the method of photomicrography of the sample itself. Percentage porosity is defined as the percentage of pits per unit area in a photomicrograph of the surface. The pitted area on the photomicrographs was determined by the method of counting squares and the percentage porosity, based on the nominal surface area, was thus obtained.

The single-cylinder-engine tests performed by the Bureau of Aeronautics at the Naval Aircraft Factory were conducted on a Wright C9GC cylinder to determine the effect of dust on ring wear and on oil control. These dust tests were performed at an engine speed of 2000 rpm, a brake mean effective pressure of 160 pounds per square inch, a carburetor-air temperature of 100° F, an oil-in temperature of 185° F, and a specific fuel consumption of 0.70 pound per brake horsepower-hour. At these test conditions, a dust cycle was run consisting in the injection of 2 grams of dust into the combustion air over a 10-minute period every half hour for 3 hours; an oil-consumption check run was also made without dust for 4 hours.

The dust used in these tests was made from a natural Arizona dust, the analysis of which is given in the following table:

ANALYSIS OF TEST DUST

[a]Particles in sample		Chemical composition	Compounds in sample (percent)
Size (microns)	Percentage		
0-5	39 ±2	Ignition loss	2.68
5-10	18 ±3	Fe_2O_3	4.58
10-20	16 ±3	Al_2O_3	15.98
20-40	18 ±3	CaO	2.91
Over 40	9 ±3	MgO	.77
		Na_2O	4.61
		SiO_2	68.47

[a]100 percent of test dust passes through a 200-mesh screen.

Multicylinder-Engine Tests

The multicylinder-engine tests performed by the Bureau of Aeronautics at the Naval Aircraft Factory were on a Wright R-1820-40 engine with C9GC cylinders mounted on a test stand and loaded with a propeller. Cooling-air flow was varied to obtain the desired cylinder temperatures. Specific oil consumption was measured by the weight method using a balanced weighing tank.

The following tests were performed:

1. Continuous operation at take-off power, 1200 brake horsepower, at an engine speed of 2500 rpm

2. A type test made according to Army-Navy Specification AN-9502b

3. Dust tests at an engine speed of 2000 rpm, a brake mean effective pressure of 160 pounds per square inch, a brake horsepower of 740, and an oil-in temperature of 180° F

In the dust tests, the piston rings were run in after which a 1-hour endurance run without dust was made as an oil-consumption check under test conditions of item 3. Dust was injected at the rate of 18 grams over a 10-minute period every 1/2 hour for $1\frac{1}{2}$ hours. This injection was followed by $4\frac{1}{2}$ hours of endurance without dust injection. Oil-weight readings were obtained every 15 minutes. Figure 4 shows the dust-injection equipment. The dust used was identical with that used in the single-cylinder-engine dust tests.

Multicylinder-engine tests made by the Army Air Forces at Wright Field were in the form of service tests on engines installed on an airplane operating from dusty air fields. These tests were accelerated by operation of the engines at take-off power for longer periods of time than usual. Total operating time at completion of the tests was 143 hours including 197 take-offs.

RESULTS AND DISCUSSION

Temperature Tests

The analysis made of ring materials indicated that cast-iron rings did not have the desired physical characteristics under conditions of high operating temperatures. This indication is best shown by the results of the temperature tests.

Results of these tests on a variety of piston-ring materials are shown in figures 5, 6, and 7. A study of the curves shows that the nitrided-steel rings are more satisfactory on the basis of resistance to stress relief than the rings of other materials tested at elevated temperatures. Loss of strength was particularly noticeable in the high-speed steel rings and resulted in near or complete collapse at the elevated temperatures.

The cast-iron rings showed a sharp break in the tension curve above 700° F (fig. 5) for the 10-minute heating period. The 6- to 8-hour and the 1-hour heating-period tests (figs. 6 and 7) showed that the loss in tension, expressed as a percentage of the original tension, was appreciably less with nitrided steel than with cast iron. This difference in tension loss would indicate that prolonged high-temperature operation would have a greater adverse effect on the cast iron than on the nitrided steel.

Single-Cylinder-Engine Tests

Compression-ignition-engine tests. - Because the nitrided-steel rings showed greatest resistance to high temperatures, it was considered that these rings would give the best service in an engine of high output. The rings as obtained from the manufacturer were installed in a used, nitrided-steel cylinder liner that was in good condition and, without an attempt to run the rings in, the load on the engine was slowly increased. Excessive breather smoke immediately developed and the rings and the liner were inspected. It was found that the edges of the rings had chipped and the small particles had scratched the nitrided-steel cylinder liner, the rings, and the piston; the small particles could be seen imbedded in the aluminum piston at the end of the scratches. The sharp edges of a set of rings were removed by grinding with a small, high-speed emery wheel and the engine was set up again after the liner was refinished. A slightly greater load was obtained before failure, and the parts were again inspected. The scratches resulting from the chipping of the rings were much less, but a microscopic examination of the ring faces indicated numerous points where "spot welding" between the ring face and the cylinder wall had taken place during the test.

New rings were obtained with a nitrided-steel case of only 0.015-inch depth instead of the original case of 0.030-inch depth. The sharp edges were removed from a set of the new rings and the rings were placed on a lapping jig that was made with ring grooves of the same dimensions as the piston-ring grooves. A strip of steel 0.015 inch thick was imbedded in the groove and perpendicular to it to make the ends of the rings butt against the steel and to prevent the rings from turning in the groove. The rings had previously been fitted to the bore for the correct end gap. With the use of a 320-grit, silicon-carbide valve-grinding compound, the rings were lapped in a dummy cylinder by hand with a spiral motion until they showed good contact over the entire face of the ring. The grinding compound used was changed to a 400-grit, silicon-carbide valve-grinding compound, and the lapping was continued. They were finish-lapped with 500-grit aluminum oxide in the bore in which they were to be used. After the lapping operation, the rings were measured and set up in the engine for testing. Again the engine was slowly brought up to operating conditions and run at an indicated mean effective pressure of 150 pounds per square inch for 20 hours without a trace of breather smoke. At the end of this test the rings were inspected and measured; no chipping and very little wear were evident.

A new liner was then obtained with a surface finish of less than 3 microinches, rms, and a second set of rings of 0.015-inch nitrided-steel case was prepared by grinding off all sharp corners. The surface finish on the rings was poor, and they were therefore lapped with 500-grit aluminum oxide in the cylinder that was to be used. When the grinding marks had been removed, levigated alumina was substituted for aluminum oxide and the rings and the liner were lapped to a mirror finish. During the process there was no dimensional change in either the rings or the liner.

The engine was assembled, warmed up under power, and gradually brought up to an output of 240-pounds-per-square-inch indicated mean effective pressure at an engine speed of 2000 rpm and a maximum cylinder pressure of 1250 pounds per square inch. The warm-up and the gradual application of the load required approximately 30 minutes. After 25 hours at this output, the rings were inspected and measured with a micrometer, and only a trace of wear was discernible.

The compression-ignition-engine tests indicated the necessity for smooth surface finishes on both cylinder barrel and rings for the combination of nitrided-steel rings and nitrided-steel cylinder. Under high-output conditions, the assembly of cylinder and rings that had smooth initial surface finishes proved to be the most successful with respect to wear and blow-by. The attainment of smooth finishes permitted the use of a short run-in time without adversely affecting engine performance and wear.

Preliminary spark-ignition-engine tests. - Nitrided-steel rings (made to the same dimensions as the stock wedge-shaped compression rings used in the Wright C9GC cylinder) and a nitrided-steel barrel were obtained for the test. These rings had a considerably better surface finish than the original rings. The cylinder barrel was a stock production item with a bore finish of 3 to 5 microinches, rms. The rings were installed in the engine cylinder as received from the manufacturer. The engine was run in for 1 hour and then operated 1 hour at a brake mean effective pressure of 200 pounds per square inch and an engine speed of 2200 rpm. In spite of the improved surface finish of the cylinder, severe scuffing was experienced. Scuffing may be defined as an area rupture of metal surfaces. The preparation of the surfaces and the fitting of new rings to the bore were repeated as previously described for the last test of the compression-ignition-engine series and, after a run-in period of 1 hour, a test run of 25 hours at a brake mean effective pressure of 200 pounds per square inch and an engine speed of 2200 rpm was completed. The surfaces were in good condition although there was excessive wear of the rings. Temperature tests on similar rings were made with the results shown in figure 7 under Nitralloy G.

A second type of nitrided-steel ring made of Nitralloy N and shown in figure 8 was obtained for testing. This type will be referred to as the "thin" ring. Most of the early tests using thin rings were conducted to determine the necessary piston design for use with thin rings. The progressive steps in this part of the research are shown in table I. Most test runs were of 1-hour duration at a brake mean effective pressure of 204 pounds per square inch because this period was considered sufficiently long to get an idea as to the functioning of the rings and the piston. It will be noted that the run-in period consists of 1 hour rather than the usual 5 to 10 hours required for cast-iron rings.

After some of the initial problems of piston design and ring assembly were solved, test runs for periods of 25 hours and longer were made to check further performance. These runs are listed as tests 9, 10, and 11 of table I. Figures 9 and 10 are photographs of the piston and ring assembly after test 10 and are representative of the appearance of piston and rings after all three tests.

The final piston design was made from the results of the preliminary tests. Figure 11 shows a photograph of the piston and ring equipmement used in the piston investigation. Before acceptance and incorporation in the final piston design, the following features, based on the tests just discussed, were considered:

1. Maximum length of cross head as limited by allowable dimensions. This feature is one of extreme importance inasmuch as length of cross head influences ring performance by effect on piston rocking.

2. Location of rings. The ring belt was located as far from the piston crown as practicable to protect the top ring from the high-temperature combustion gases.

3. Shape of piston. Piston shape was carefully chosen, from the results of the preliminary runs, to conform as nearly as possible to the cylinder bore at operating temperatures. This shape will insure against possibility of piston seizure because of thermal distortion.

4. Location of oil-drain holes. For maximum effect of oil control, unrestricted passages must be provided and advantage taken of the inertia effect of the oil in the matter of scavenging the grooves.

5. Simplicity of ring assembly. The choice of the number of rings was made to obtain the least number of rings that would result in efficient operation. Two compression and two oil rings, all located above the piston pin, were the final result. The rings were of rectangular cross section because this simple shape was easily machined.

The final piston design is shown in figure 12 and a new, complete piston assembly is shown in figure 13.

In order to check the final piston and ring design, a 150-hour type test in accordance with Army-Navy Specification AN-9502a was performed. This test was a check on both piston and ring performance under the wide range of test conditions specified by the type test. General engine performance with respect to ring and cylinder wear, blow-by, and power was excellent. Lubricating-oil control (that is, specific oil consumption) was poor. Results are shown in table II and in figure 14. Figures 15 and 16 show the piston and ring assembly after the type test.

The excellent condition of ring and cylinder rubbing surfaces indicated that these surfaces were compatible with each other. The extremely low wear of rings as indicated from the low weight loss was also an indication that very successful operation with this ring assembly is possible. As can be noted in table II, a maximum ring-weight loss of approximately 0.6 percent was recorded in this 150-hour type test.

Results of test on the stock cast-iron-ring assembly in a stock nitrided-steel cylinder at a brake mean effective pressure of 250 pounds per square inch are shown in table III, test 1, and in figure 17. Test conditions with respect to speed, output, oil temperature, and cylinder temperatures were made extremely severe. It will be noted that oil control was poor from the start of the test, possibly indicating that the rings had scuffed and feathered during run-in. Wear of the rings was also very high. The photographs of the ring assembly after testing show that the rings were scuffed, scored, and feathered. Figure 17, concluded, also shows that the top rings had lost appreciable tension; this loss was manifested by a loss in free gap of the rings.

Tests 2, 3, and 4 of table III show results of tests of the piston and ring assembly used in table II under the test conditions of test 1 in table III as a comparative check, at these conditions, of nitrided-steel and cast-iron rings. The run-in period of 1 hour was still maintained at this high output. It will be noted that weight losses are low, considering the extreme severity of test conditions. Figures 18 and 19 are included to show the excellent condition of the piston and rings after these tests even though two of the tests resulted in exhaust-valve failures and much of the loose valve-steel particles passed by the faces of the rings and imbedded themselves in the piston skirt.

The last test listed on table III was successful with respect to wear and general engine-performance characteristics. Oil control, however, was still relatively poor although the oil consumption was constant, a condition that is rather unusual in high-output tests of this duration. The large increase in oil consumption for stock rings is best shown in test 1 of table III.

Because the previously described tests of the nitrided-steel rings indicated that the oil rings (fig. 8, low-unit-wall-pressure oil rings, 39 lb/sq in.) were unsatisfactory on the basis of oil control, tests were made with rings of lesser face width, 0.010 inch, and of diametral tension that was identical with the original rings. This decrease in face width with the same diametral tension resulted in an approximate initial unit wall pressure of 78 pounds per square inch. The tests indicated that these rings decreased oil consumption at least 50 percent. Rings were accordingly procured that obtained a high unit wall pressure by an increase of diametral tension and a decrease in face width. It was preferred to obtain the high unit wall pressure in this manner rather than by a large decrease in face width alone, because a ring of large face width will have a lower percentage change of face width for an equal amount of wear than a ring of small face width.

<u>Final spark-ignition-engine tests</u>. - The final design of nitrided-steel oil rings was one that had a free gap of approximately $1\frac{5}{8}$ inches rather than the free gap of approximately $1\frac{1}{16}$ inches in the original rings. A decrease in face width from 0.020 to 0.014 inch was also made at this time. The increase in free-joint opening resulted in a change of diametral tension from 6.3 to 9.4 pounds. Corresponding values of initial unit wall pressure are 39 and 84 pounds per square inch. Oil rings with both low and high initial unit wall pressure are shown in figure 8.

Table IV shows the results of two tests with these oil rings. Test 31 from table IV can be directly compared with test 19 of table III. These two tests furnish a direct comparison of performance with oil rings of high and low initial unit wall pressure. The oil consumption decreased from 0.022 pound per brake horsepower-hour in test 19 to 0.013 pound per brake horsepower-hour in test 31. In both tests the wear of the compression rings and the cylinder barrels was considered small. Oil-ring wear was relatively high until the rings had seated themselves and apparently reached a stable condition of rate of wear and oil control. In test 30, oil consumption decreased from 0.020 to 0.008 pound per brake horsepower-hour. This decrease would apparently correspond to the seating period of the rings inasmuch as test 31 showed a constant oil consumption of 0.013 pound per brake horsepower-hour during the entire test. Figure 20 shows the photograph of the piston and ring assembly after test 31. It will be noted that the top oil ring was cold-stuck and the second compression ring was tight at the gap. No ring sticking was apparent in any of the previous high-output tests.

In all tests using oil rings of the high unit wall pressure, the initial wear was high, which resulted in a fairly large increase in face width.

After satisfactory operation with respect to wear and lubricating-oil consumption had been achieved in nitrided-steel cylinders, single-cylinder-engine tests of the nitrided-steel rings in a porous chromium-plated, straight-bore cylinder were conducted. The rings from test 31 (table IV) were installed directly in a porous chromium-plated, straight-bore cylinder barrel and were operated for three tests according to the operating conditions indicated in tests 1, 2, and 3 of table V.

Results were good with respect to wear and oil control in each of these three tests. Figures 21 and 22 show the piston and ring assembly after tests in the chromium-plated barrel.

In order to investigate the reason for successful performance of the chromium-plated cylinder, porosity was measured after test 3 (table V) in two locations. Some replicas were taken in ring travel and others were taken in the section of cylinder above ring travel. Measurements in the section of cylinder above ring travel are considered representative of the porosity before the tests. Porosity range above ring travel was 50 to 65 percent and in ring travel was 30 to 40 percent. Figures 23 and 24 show typical plan-view photomicrographs at 100 magnification of the chromium-plated surface above and in ring travel after the test. Surface roughness of the cylinder before the test was approximately 40 to 60 microinches, rms. After the test, surface roughness measured 25 to 35 microinches, rms. These measurements of surface roughness of porous chromium-plated cylinders do not represent actual surface finish on the chromium plateaus because the tracer point traveled through the pores or pits as well as over the plateaus. More significance should therefore be attached to the percentage porosity than to the surface roughness.

The set of rings used in the tests reported in table V had completed 155 hours of test operation after test 3. Figure 25 shows the effect of running time on this particular set of nitrided-steel rings. The curves of figure 25 indicate that the rings had apparently reached a constant rate of wear. This constant rate of wear is low, as can be computed from the weight loss during the last three tests. Weight loss in test 3 was less than one quarter of 1 percent of the initial weight of the ring.

It would appear from the results of these tests that the most satisfactory combination of rings and cylinders might be that of the nitrided-steel rings in the porous chromium-plated cylinder barrels. This assembly should result, after seating and complete compatibility of the rubbing surfaces has been attained, in a very stable assembly with respect to both rate of wear and oil control. Dust tests of this assembly should be run, however, before a final recommendation can be made.

Results of the single-cylinder-engine dust tests showed that the nitrided-steel ring assembly in nitrided-steel cylinders resulted in acceptable oil control through the fourth dust cycle (fig. 26). The oil consumption after the fifth dust cycle was approximately that obtained by the stock cast-iron rings after the first dust cycle. The test of the cast-iron-ring assembly was discontinued after the first dust cycle because the slope of the oil-consumption curve indicated that the assembly was wearing out rather than seating in, and consequently no better oil control than that after the first dust cycle (which was unacceptable at the conditions of this test) could be expected. The wear curves in figure 26 show that oil control was satisfactory as long as the rate of wear of the rings was constant.

Some results of other tests of single-cylinder engines under dust injection have been reported by the W ight Aeronautical Corporation. These tests showed that the nitrided-steel rings are much better on the basis of oil control than the conventional cast-iron, taper-faced ring assembly. Wear of the nitrided-steel rings in these tests, however, was reported to be not much less than wear of cast-iron rings, but wear of the cylinder barrels tested with nitrided-steel rings was very slight.

Surface finishes. - Surface finishes of 2 to 8 microinches, rms, on the face of the nitrided-steel rings were investigated in preliminary tests and the final result was a ring finished by honing on the face or outside diameter to 5 to 8 microinches, rms.

It was found that for nitrided-steel cylinders a cross-hatch-honed finish of 4 to 6 microinches, rms, was suitable for use with the nitrided-steel ring assembly after a number of tests covering a range of surface finishes in the cylinder barrel of 1 to 6 microinches, rms.

Surface finish on the sides of the rings and on the piston-ring lands was set at 5 microinches, rms, in the belief that this finish (5 microin., rms) would be adequately smooth to prevent ring sticking. No tests were made with this finish as a variable, however, because very few of the tests on the nitrided-steel ring assembly showed any signs of ring sticking.

Multicylinder-Engine Tests

The multicylinder-engine test performed by the Bureau of Aeronautics on a Wright R-1820-40 engine at take-off power and speed of the original, thin, nitrided-steel ring assembly with oil rings of low unit wall pressure was terminated because of failure of the master-rod bearing after approximately 30 hours at take-off power. Results of this test were good with respect to wear in spite of a complete bearing failure that covered all rubbing surfaces with bearing material and contaminated the lubricating oil. The oil control in this test, however, was relatively poor (specific oil consumption, 0.030 lb per bhp-hr). The trend of oil consumption decreased throughout the test.

Additional multicylinder-engine tests were made by the Navy Department on the nitrided-steel ring assembly with the oil ring of high unit wall pressure after the NACA single-cylinder-engine tests had shown this assembly to be acceptable with respect to oil control. These single-cylinder-engine tests have been previously described and discussed.

A 150-hour type test according to specification AN-9502b was performed by the Navy Department and resulted in good performance with regard to wear and oil control. Specific oil consumption at normal rated power and speed (1000 hp at 2300 rpm) decreased from approximately 0.013 to 0.010 pound per brake horsepower-hour after approximately 40 hours of the endurance run had been completed (fig. 27). Average specific oil consumption at normal rated power and speed during the rest of the endurance test averaged 0.010 pound per brake horsepower-hour. The rings showed no tendency toward sticking. No ring breakage was encountered even though overspeed dive tests were run at 3100 rpm. The general operating characteristics were normal. Specific oil consumption at normal rated power and speed after the overspeed dives was 0.007 pound per brake horsepower-hour. The specific-oil-consumption check completed the type test. The value of 0.007 pound per brake horsepower-hour is considered satisfactory even though it is higher than is usually obtained with the standard cast-iron ring assembly under these conditions.

The oil flow (total and power section) was accidentally more than 45 percent above the prescribed maximum for most of the test, and tests on this engine showed that decreasing the total oil flow (at normal rated power and speed) 22 percent decreased the specific oil consumption 13 percent. The 22-percent decrease in rate of oil flow resulted in a rate of flow 18 percent higher than the recommended maximum. It is possible that normal oil flow would have resulted in still lower specific oil consumption.

Multicylinder-engine flight tests of nitrided-steel rings assembled in both nitrided-steel and chromium-plated cylinders as performed by the Army Air Forces, Materiel Command, resulted in good performance of the rings in both types of cylinder with respect to wear and oil control. All rings were free after these tests. Wear was low, considering severity of test conditions and amount of operation in dusty atmospheres. The total operating time of 143 hours resulted in more severe operation than this amount of time normally represents because a large number of take-offs (197) were included. Condition of the rubbing surfaces was considered excellent in all three engines tested. The condition of the pistons, especially the skirts, was very good and the acceptable oil control proved that no bottom ring is necessary in this piston design.

Results of the multicylinder-engine dust tests conducted by the Bureau of Aeronautics indicated that the nitrided-steel ring assemblies were very successful with respect to oil control (fig. 28). Wear and specific oil consumption started to become excessive only after an appreciable number of dust cycles. The top compression ring in most of the cylinders was excessively worn before any great effect on oil consumption was evident. The slope of the oil-consumption curve was not very great even at the end of the seventh dust cycle.

Figures 29 and 30 show the trend of oil consumption for standard piston assemblies of cast-iron rings. Both curves show that oil consumption increased very rapidly during the first two dust cycles and became excessive after the first cycle. It can be seen that this rapid increase is true in both porous chromium-plated cylinders and in nitrided-steel cylinders.

When figure 28 is compared with figures 29 and 30, it is apparent that the nitrided-steel rings should provide acceptable oil control for much longer periods of time than the cast-iron rings, inasmuch as the oil-consumption curve for nitrided-steel rings shows a much more gradual increase than the curve of the cast-iron rings. Although it is true that no quantitative comparisons should be made of figures 28, 29, and 30 because the dust cycles are somewhat different, it is believed that the indicated trends in the three tests can be used on a comparative basis.

CONCLUDING REMARKS

The nitrided-steel ring assembly under dust conditions is more successful on the basis of oil control than the cast-iron, taper-faced ring assembly because a large part of the oil-control function is performed by the oil rings and little oil control is required from the compression rings. Wear on the compression rings, consequently, has little effect on oil control.

From the results of the tests reported, further investigation of the combination of nitrided-steel rings in porous chromium-plated cylinders should be made because this combination offers attractive possibilities for use. The use of worn cylinders that have been reclaimed by porous chromium plating is attractive from the salvage viewpoint, and any ring assembly that can be successfully operated in these cylinders should be completely engine-tested. These engine tests should include dust tests to check abrasion resistance.

SUMMARY OF RESULTS

Based on the test data of the single-cylinder and multicylinder engines, the following results were obtained:

1. Performance characteristics of the nitrided-steel ring assembly of final design were excellent with respect to wear and abrasion resistance.

2. The condition of the rubbing surfaces of nitrided-steel rings and chromium-plated cylinders indicated that these surfaces were compatible with each other.

3. The nitrided-steel ring assembly of final design resulted in average specific oil consumptions of 0.013 and 0.011 pound per brake horsepower-hour at a brake mean effective pressure of 250 pounds per square inch and an engine speed of 2500 rpm in the

single-cylinder engine. The average specific oil consumption in the Wright R-1820-40 engine was 0.010 pound per brake horsepower-hour at normal rated power and speed (1000 hp at 2300 rpm). In all cases, the trend of oil consumption was constant or decreasing.

4. Under dust-test conditions, acceptable oil control can be obtained three to four times longer with the nitrided-steel ring assembly than with the stock cast-iron rings.

5. Resultant wear of the cylinder barrels was exceptionally low.

6. Excellent resistance to ring breakage, at the severe overspeed-dive condition of 3100 rpm, on a Wright R-1820-40 engine, was exhibited by the nitrided-steel ring assembly.

7. The use of a shorter run-in time (1 hr) was found to be possible with the nitrided-steel ring assembly.

CONCLUSION

Based on the test data of the single-cylinder and multicylinder engines, the following conclusion may be drawn:

The nitrided-steel ring assembly in either nitrided-steel or porous chromium-plated cylinders should be very desirable for use in high-output aircraft engines.

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REFERENCE

1. Englisch, C.: Messgerat zur Bestimmung des radialen Anpressdruckes von Kolbenringen. Auto. tech. Zeitschr., Jahrg. 43, Nr. 2, Jan. 25, 1940, pp. 42-44. (Tech. Trans. No. 129, R. A. Castleman.)

TABLE I

SUMMARY OF DEVELOPMENT TESTS FOR NITRIDED RINGS WITH NITRIDED BARREL

[Oil, Navy symbol No. 1120; spark timing, 20° B.T.C.; limiting temperatures: rear spark-plug bushing, 450°F; rear center of barrel, 350° F; power-section oil flow, 19.5 pounds per minute at 2200 rpm]

Test	Description	Test conditions						Results					Remarks
		Run-in (hr)	Endurance (hr)	Speed (rpm)	bmep (lb/sq in.)	imep (lb/sq in.)	Oil-in temperature (°F)	Ring weight			Blow-by (cu ft/min) (a)	Specific oil consumption (lb/bhp-hr)	
								Weight loss (gram)	Percentage of original ring weight	Percentage of total loss			
1	Piston, stock. Rings, stock cast-iron; 3 compression, 3 oil. Cylinder, stock, honed finish.	6	1	2200	204	240	167	-----	--------	-------	0.36	---------	Oil control good; incipient scuffing of top ring.
2	Piston, stock except compression ring belt. Rings, 2 nitrided compression, 3 stock cast-iron oil. Cylinder, stock, polished with abrasive paper.	1	1	2200	204	240	167	0.032 .128	0.13 .52	------- -------	-------	---------	Oil control poor; more crosshead required on piston; second-ring wear high.
3	Same type assembly as test 2 except bottom ring inverted to scrape down. Cylinder, same as test 2, repolished.	1	1	2200	204	240	166	0.090 .048	0.36 .20	------- -------	0.42	---------	Oil control slightly improved; scuffing still present, believed due to iron carbide from cast-iron rings.
4	Piston, new design. Rings 4 same type, nitrided; 2 as compression, 2 as oil. Cylinder, same as test 3, repolished.	1	1	2200	204	240	177	-----	--------	-------	0.33	---------	Rings too high; bearing area on piston insufficient; redesign of piston required; oil control fair.
5	Piston, stock. Rings, stock cast-iron; 3 compression, 3 oil. Cylinder, stock, polished with abrasive paper.	6	1	2200	204	240	181	0.246 .018 .015 .010 .013 -	0.56 .04 .03 .02 .03 -	61.6 4.5 3.8 2.5 3.3 -	0.89	---------	Oil control good; incipient scuffing of top ring.
6	Piston, new design. Rings, nitrided; 2 compression, 2 oil (low pressure)[b]. Cylinder, same as test 4, without repolishing.	1	1	2200	204	239	175	0.011 .026	0.04 .11	------- -------	0.32	---------	Oil control improved but still insufficient; condition of piston, rings, and cylinder good.
7	Piston, from test 6 with high spots on skirt removed. Rings, nitrided; 2 compression, 2 oil (high pressure)[c]. Cylinder, from test 6 without repolishing.	1	1	2200	204	238	172	0.012 .004	0.05 .02	------- -------	0.32	---------	Oil control fair; rings too high; skirt now satisfactory.

[a] Average Value.

[b] Low-pressure oil rings: radial depth, 0.150 in.; free gap, approx. $1\frac{1}{16}$ in.; initial unit wall pressure, approx. 28 lb/sq in.

[c] High-pressure oil rings: radial depth, 0.170 in.; free gap, approx. $1\frac{1}{16}$ in.; initial unit wall pressure, approx. 37 lb/sq in.

TABLE I - Concluded

SUMMARY OF DEVELOPMENT TESTS FOR NITRIDED RINGS WITH NITRIDED BARREL - Concluded

Test	Description	Test conditions						Results					Remarks
								Ring wear					
		Run-in (hr)	Endurance (hr)	Speed (rpm)	bmep (lb/sq in.)	imep (lb/sq in.)	Oil-in temperature (°F)	Weight loss (gram)	Percentage of original ring weight	Percentage of total loss	Blow-by (cu ft/min) (a)	Specific oil consumption (lb/bhp-hr)	
8	Piston, new design, ring grooves lowered. Rings, nitrided; 2 compression, 2 oil (low pressure)[b]. Cylinder, honed (co-axial).	1	1	2200	204	238	172	0.017 .006	0.07 .02	------ ------	0.38	--------	Oil control poor; top of piston skirt breaking oil film in choke.
9	Piston, from test 8, hand honed to fit choke. Rings, nitrided; 2 compression, 2 oil (high pressure)[c]. Cylinder from test 8, repolished.	1	25	2200	204	235	177	0.043 .024 .051 .062	0.17 .10 .19 .23	23.9 13.5 28.1 34.5	0.33	0.026 to .020 a.023	Oil control fair; general conditions good.
10	Piston, machined to shape of one in test 9. Rings, 2 compression, 2 oil (high pressure)[c]. Cylinder, stock, honed finish.	1	25	2200	204	235	176	0.046 .009 .005 .008	0.19 .04 .02 .03	67.6 13.0 7.8 11.7	0.33	0.048 to .028 a.034	Oil control poor; condition of piston, rings, and cylinder satisfactory.
11	Continuation of test 10.	$\frac{1}{2}$	27	2200	204	237	179	0.059 .019 .013 .012	0.24 .07 .05 .05	57.1 18.6 12.2 12.1	0.34	0.046 to .091 a.070	Oil control poor; general conditions very good.
12	Piston stock. Rings, stock cast-iron; 3 compression, 3 oil. Cylinder, same as in test 5, repolished.	6	2	2200	204	239	178	0.041 ----- ----- ----- .001 .003	0.10 ------- ------- ------- .02 .06	------ ------ ------ ------ ------ ------	0.95	--------	Oil control good, general conditions good.
13	Piston, more skirt taper to increase clearance in choke, less and larger drain holes. Rings, nitrided; 2 compression, 2 oil (high pressure)[c]. Cylinder, stock honed, finish.	1	1	2500	206	244	197	0.089 .033 .031 .027	0.36 .13 .12 .10	49.6 18.1 17.4 14.9	0.50	--------	Oil control fair; original barrel condition found bad was concealed by honed finish.

[a] Average value.

[b] Low-pressure oil rings: radial depth, 0.150 in.; free gap, approx. $1\frac{1}{16}$ in.; initial unit wall pressure, approx. 28 lb/sq in.

[c] High-pressure oil rings: radial depth, 0.170 in.; free gap, approx. $1\frac{1}{16}$ in.; initial unit wall pressure, approx. 37 lb/sq in.

TABLE II

RESULTS OF 150-HOUR TYPE TEST WITH NITRIDED RINGS AND NITRIDED BARREL

[Oil, Navy symbol No. 1120; spark timing, 20° B.T.C.; limiting temperatures; rear spark-plug bushing, 450° F; rear center of barrel, 350° F; power-section oil flow, 19.0 pounds per minute at 2500 rpm and 185° F oil-in temperature]

Test	NACA reference test	Description	Test conditions						Ring unit wall pressure (lb/sq in.)	Results					Remarks
			Run-in (hr)	Endurance (hr)	Speed (rpm)	bmep (lb/sq in.)	imep (lb/sq in.)	Oil-in temperature (°F)		Ring wear			Blow-by (cu ft/min) (a)	Specific oil consumption (lb/bhp-hr)	
										Weight loss (gram)	Percentage of original ring weight	Percentage of total loss			
1	14	Piston, from test 13, cleaned. Rings, nitrided; 2 new compression, 2 oil, from test 13. Cylinder, stock, honed finish.	1	150	1165 to 2520	75 to 206	125 to 234	205	--- --- --- ---	0.147 .062 .042 .069	0.60 .25 .16 .26	46.0 19.4 13.0 21.6	0.35 to .65	0.018 to .061 [a].042	General conditions of piston, rings, and barrel very good; oil control poor.

[a] Average value.

TABLE III

RESULTS OF HIGH-OUTPUT TESTS FOR NITRIDED RINGS WITH NITRIDED BARREL

[Oil, Navy symbol No. 1120; spark timing, 20° B.T.C.; limiting temperature, rear spark-plug bushing, 450° F; rear center of barrel, 350° F; power-section oil flow, 19.0 pounds per minute at 2500 rpm and 185° F oil-in temperature]

Test	NACA reference test	Description	Test conditions						Ring unit wall pressure (lb/sq in.) (c)	Results							Remarks
			Run-in (hr)	Endurance (hr)	Speed (rpm)	bmep (lb/sq in.)	imep (lb/sq in.)	Oil-in temperature (°F)		Ring wear			Free gaps		Blow-by (cu ft min) (a)	Specific oil consumption (lb/bhp-hr)	
										Weight loss (gram)	Percentage of original ring weight	Percentage of total loss	Before test (in.)	After test (in.)			
1	16	Piston, stock. Rings, stock cast-iron, 3 compression, 3 oil. Cylinder from test 15, repolished.	6	$9\frac{1}{2}$	2500	250	288	210	6 6 10 21 26 37	2.721 2.452 .873 .788 .787 .753	6.28 5.67 2.02 1.87 1.87 1.79	32.5 29.3 10.4 9.4 9.4 9.0	0.98 1.00 1.00 .91 .91 .84	0.79 .81 .88 .82 .82 .80	0.90	0.022 to .112 [a].071	Oil control poor; rings worn, scuffed and feathered slightly; cylinder exhaust valve guide boss broken, barrel condition good.
2	17	Piston, from test 14 with only the ring grooves cleaned. Rings, from test 14. Cylinder, from test 14 without repolishing	1	8	2500	250	286	210	----- ----- ----- -----	0.099 .026 .026 .017	0.41 .11 .10 .06	58.9 15.6 15.6 9.9	----- ----- ----- -----	1.03 1.03 1.00 1.00	0.36	0.045 to .024 [a].030	Complete exhaust-valve failure; particles found in ring grooves and piston skirt.
3	18	Piston, from test 17; cleaned completely, stoned lightly on thrust faces. Rings from test 17. Cylinder from test 17, without repolishing	1	$15\frac{1}{2}$	2500	250	286	210	----- ----- ----- -----	0.191 .051 .045 .044	0.79 .21 .17 .17	57.6 15.5 13.5 13.4	1.03 1.03 1.00 1.00	1.03 1.00 .98 .98	1.07	0.040 to .022 [a].028	Exhaust-valve failure; cylinder discarded because of broken valve guide and boss; second ring, partly cold stuck.
4	19	Piston, from test 18, cleaned. Rings from test 18 Cylinder, stock, honed finish.	1	50	2500	250	285	210	8 9 25 24	0.103 .014 .015 .010	0.43 .06 .06 .04	72.7 9.7 10.5 7.1	1.03 1.00 .98 .98	1.03 1.02 .98 .98	0.6 to 1.3	[b]0.022	Rings, piston, and barrel in very good condition; piston boss cracked; incipient exhaust-valve failure.

[a] Average value.
[b] Constant value.
[c] After test.

TABLE IV

RESULTS OF HIGH-OUTPUT TESTS WITH HIGH-PRESSURE NITRIDED OIL RINGS WITH NITRIDED BARREL

[Oil, Navy symbol No. 1120; spark timing, 20° B.T.C.; limiting temperature, rear spark-plug bushing, 450° F; rear center of barrel, 350° F; power-section oil flow: test 30, 17 pounds per minute; test 31, 19 pounds per minute at 185° F oil-in temperature]

Test	NACA reference test	Description	Test conditions						Ring unit wall pressure (lb/sq in.) (b)	Results							Remarks
										Ring wear			Free gaps				
			Run-in (hr)	Endurance (hr)	Speed (rpm)	bmep (lb/sq in.)	imep (lb/sq in.)	Oil-in temperature (°F)		Weight loss (gram)	Percentage of original ring weight	Percentage of total loss	Before test (in.)	After test (in.)	Blow-by (cu ft/min) (a)	Specific oil consumption (lb/bhp-hr)	
1	30	Piston, new. Rings, nitrided; 2 compression, 2 oil, high tension, 1.5 in. free-joint opening. Cylinder, stock, standard honed finish.	1	25	2500	210	242	185	---- ---- 57 62	0.151 .059 .194 .177	0.62 .22 .73 .67	26.0 10.2 33.4 30.4	1.10 1.08 1.62 1.62	1.07 1.06 1.61 1.61	1.25 to .75	0.020 to .008 [a].014	Incipient compression-ring scuffing; steel particles from overhaul in piston skirt.
2	31	Piston, from test 30, cleaned. Rings, from test 30. Cylinder, from test 30, without repolishing.	1	$49\frac{1}{2}$	2500	250	278	210	---- ---- ---- ----	0.137 .041 .026 .020	0.56 .17 .10 .08	61.2 18.3 11.6 8.9	1.07 1.06 1.61 1.61	1.07 1.06 1.61 1.61	1.22 to .75	[c]0.013	General condition good; incipient compression-ring scuffing; 2nd ring partly cold stuck; 3rd ring completely cold stuck; broken valve spring.

[a] Average value.

[b] Diametral tension measured by closing ring to gap as measured in cylinder before test.

[c] Constant value.

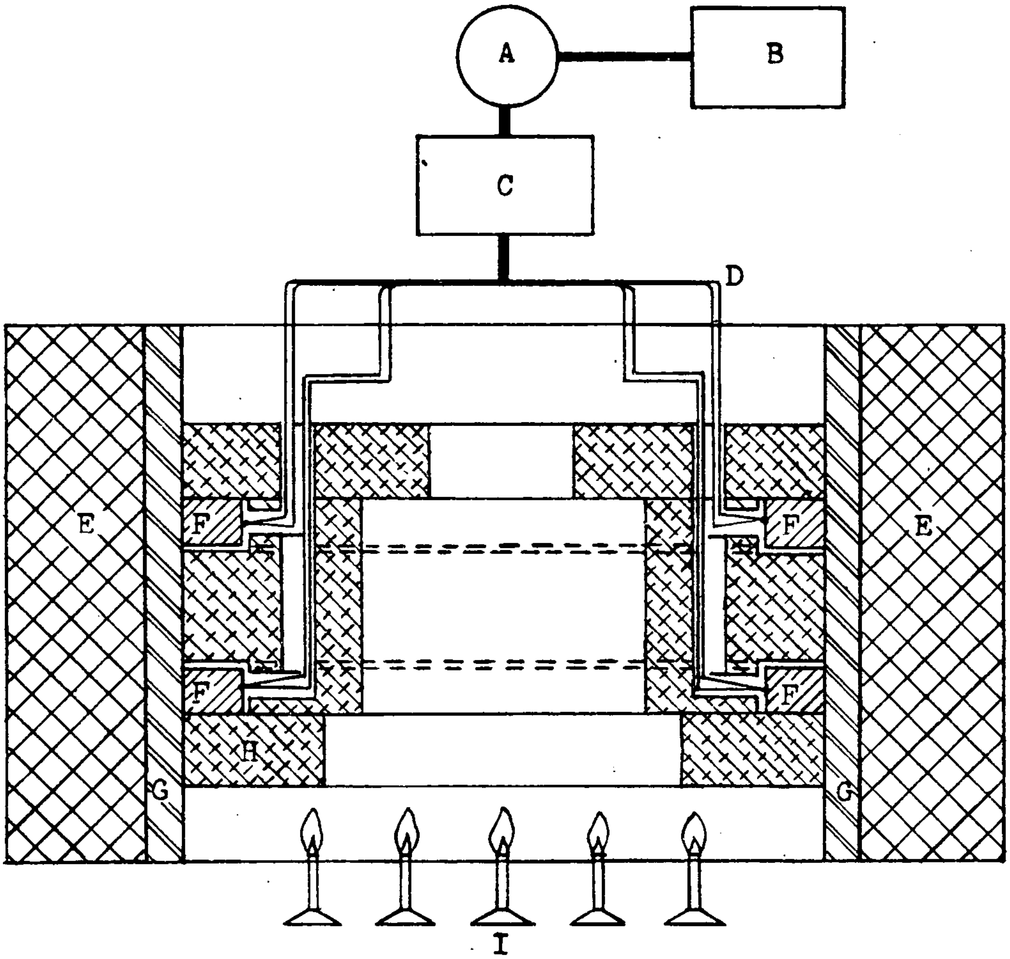
TABLE V

SUMMARY OF TESTS FOR CHROMIUM-PLATED BARREL WITH NITRIDED RINGS

[Oil, Navy symbol No. 1120; spark timing, 20° B.T.C.; limiting temperatures; rear spark-plug bushing, 450° F; rear center of muff, 350° F; power - section oil flow, 34 pounds per minute (maximum) at 2500 rpm and 185° F oil-in temperature]

Test	Description	Test conditions						Ring unit wall pressure (lb/sq in.) (c)	Results							Remarks
									Ring wear			Free gaps		Blow-by (cu ft/min) (a)	Specific oil consumption (lb/bhp-hr)	
		Run-in (hr)	Endurance (hr)	Speed (rpm)	bmep (lb/sq in.)	imep (lb/sq in.)	Oil-in temperature (°F)		Weight loss (gram)	Percentage of original ring weight	Percentage of total loss	Before test (in.)	After test (in.)			
1	Piston, from test 31. Rings nitrided, from test 31. Cylinder, straight bore, chromium-plated.	6	25	2300	190	226	185	------- ------- ------- -------	0.055 .019 .024 .025	0.24 .08 .09 .10	44.7 15.4 19.5 20.4	1.08 1.06 1.61 1.31	1.09 1.08 1.63 1.63	0.65	0.012 to .007 [a].008	Cylinder, piston, and rings in excellent condition.
2	Continuation of above test; piston and cylinder untouched.	1	25	2500	210	250	185	------- ------- ------- -------	0.042 .007 .005 .007	0.17 .03 .02 .03	68.8 11.5 8.2 11.5	1.09 1.08 1.63 1.63	1.09 1.06 1.94 1.94	0.80	0.010 to .007 [a].008	Cylinder, piston, and rings in excellent condition; porosity on barrel evident; piston cracked through pin boss; top ring has convex surface.
3	Continuation of above test. Piston from test 2 replaced with used, cleaned piston.	1	20½	2500	250	283	210	10 10 45 42	0.045 .009 .015 .014	0.19 .04 .06 .05	54.2 10.8 18.1 16.9	1.09 1.06 1.94 1.94	1.09 1.06 1.59 1.63	0.95	[b]0.011	Cylinder, piston, and rings in excellent condition; porosity evident on entire barrel; compression rings have convex surface; head cracked between fifth and sixth fin, exhaust side, causing oil leak from rocker box and termination of test.

[a] Average value.
[b] Constant value.
[c] After test.



A	Selector switch
B	Potentiometer
C	Cold-junction box
D	Thermocouple leads, constantan and iron
E	Insulation
F	Piston rings
G	Section of 5-inch cylinder
H	Aluminum
I	Gas burner

Figure 1. - Piston-ring heater.

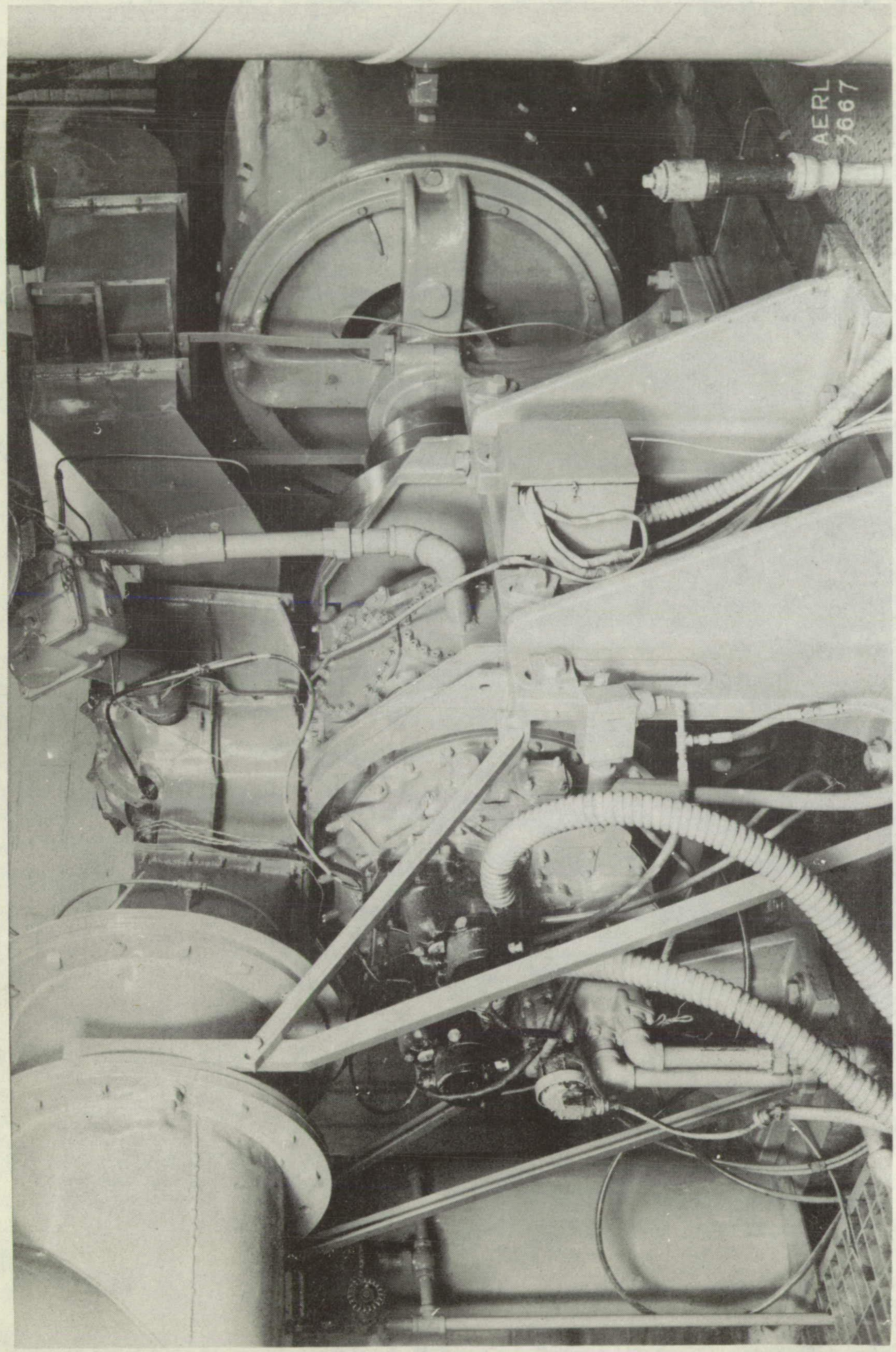
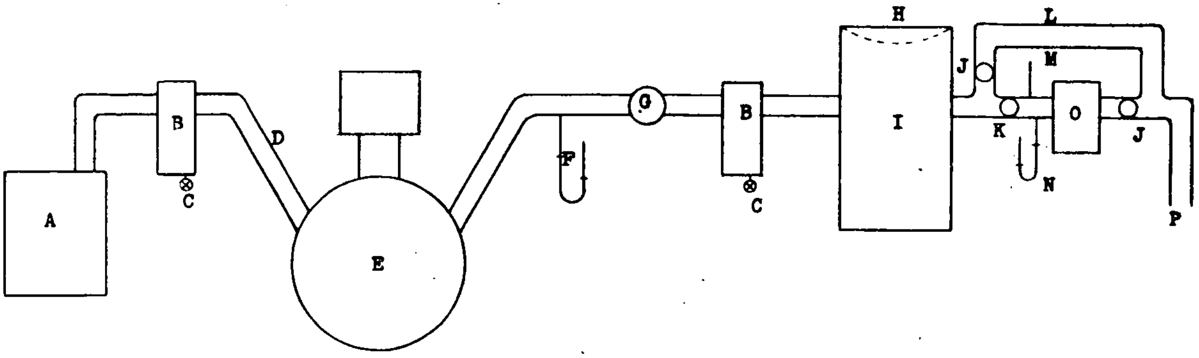
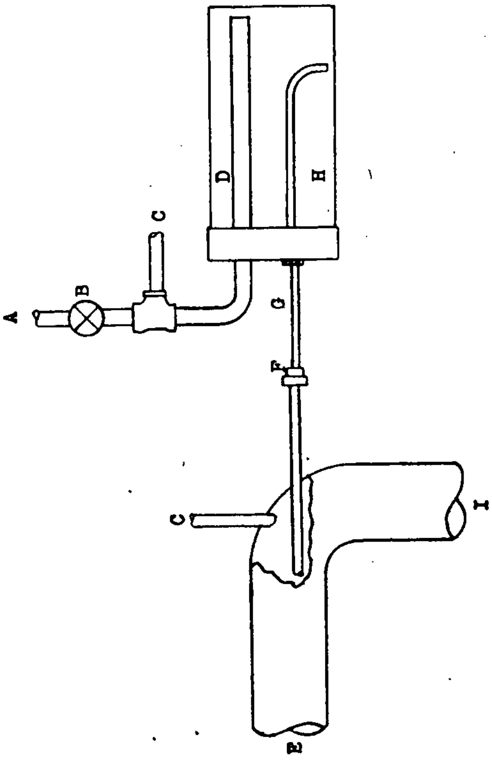


Figure 2.- Single-cylinder-engine assembly.



A	Oil-storage tank
B	Surge tank and oil separator
C	Drain
D	Line for returning to crankcase the blow-by handled by oil-scavenging pump in maintaining dry sump crankcase
E	Crankcase
F	Crankcase-pressure manometer
G	Sight glass
H	Flexible head
I	Surge tank
J	Shut-off valves
K	Throttle valve
L	Bypass
M	Meter inlet thermometer
N	Meter inlet-pressure manometer
O	Gas meter
P	Pipe leading to exhaust trench (approximately 7 in. water vacuum)

Figure 3. - Schematic diagram of blow-by system.



A	Compressed-air supply
B	Globe valve
C	Pipe leading to 20-inch mercury manometer
D	3/8-inch diameter tube, end plugged, with 5 equally spaced 1/8-inch-diameter holes
E	Pipe leading to carburetor-air scoop
F	Knurled knob clamped to tube
G	1/8-inch inside diameter stainless-steel tube, slip-type fitting on bottle
H	Extra heavy bottle for dust
I	Pipe leading from combustion-air source

Figure 4. - Dust-injection equipment used by Bureau of Aeronautics. Pressure differential of 2 pounds per square inch maintained between bottle and manifold. Bottle moved on tube to pick up dust. Hood and slide provided for bottle to aid in operation and to prevent injury in case of excess air pressure.

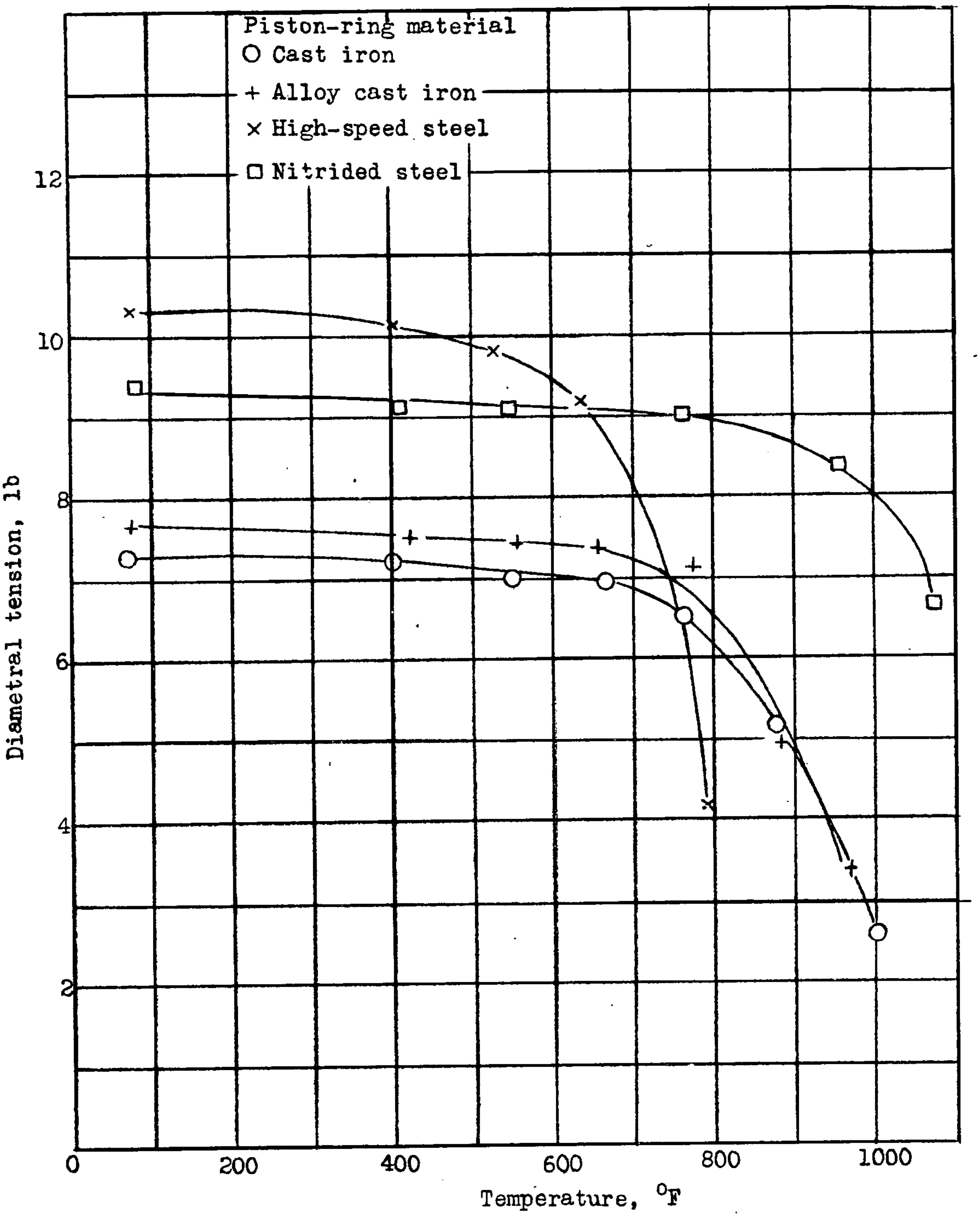


Figure 5.- Effect of piston-ring temperature on diametral tension. (Rings held 10 min at each temperature.)

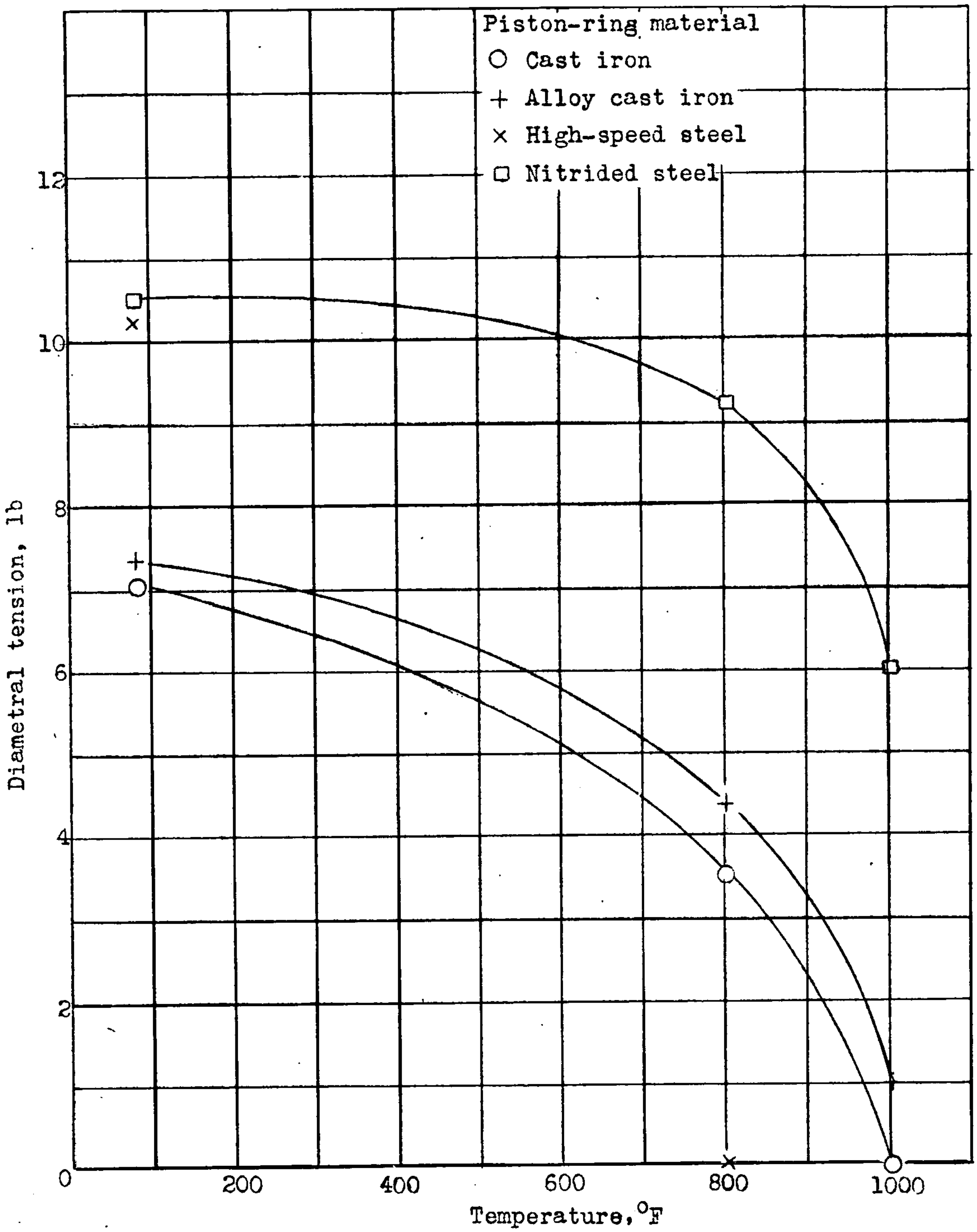


Figure 6.- Effect of piston-ring temperature on diametral tension. (Rings held 6 to 8 hr at each temperature.)

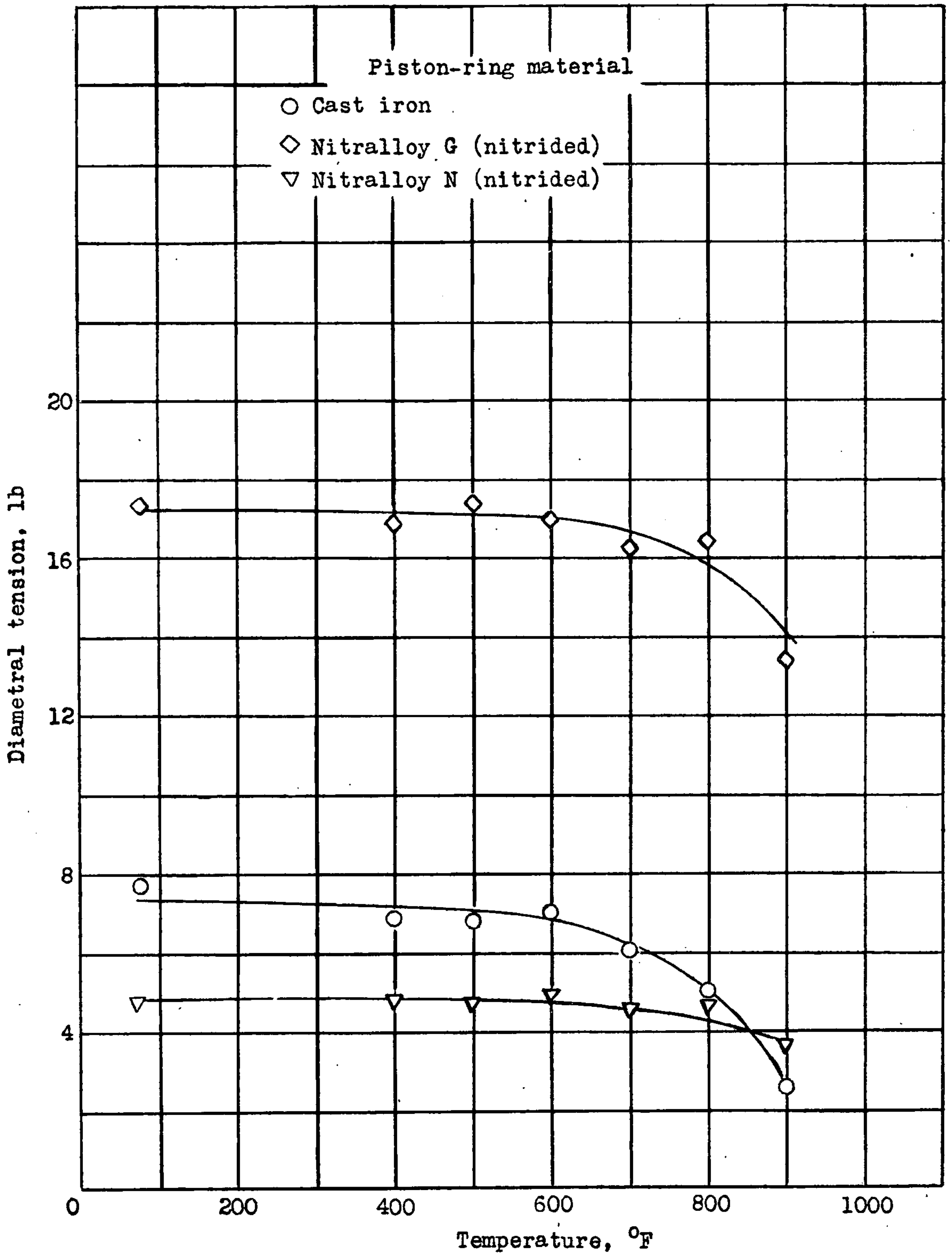


Figure 7.- Effect of piston-ring temperature on diametral tension. (Rings held 1 hr at each temperature.)

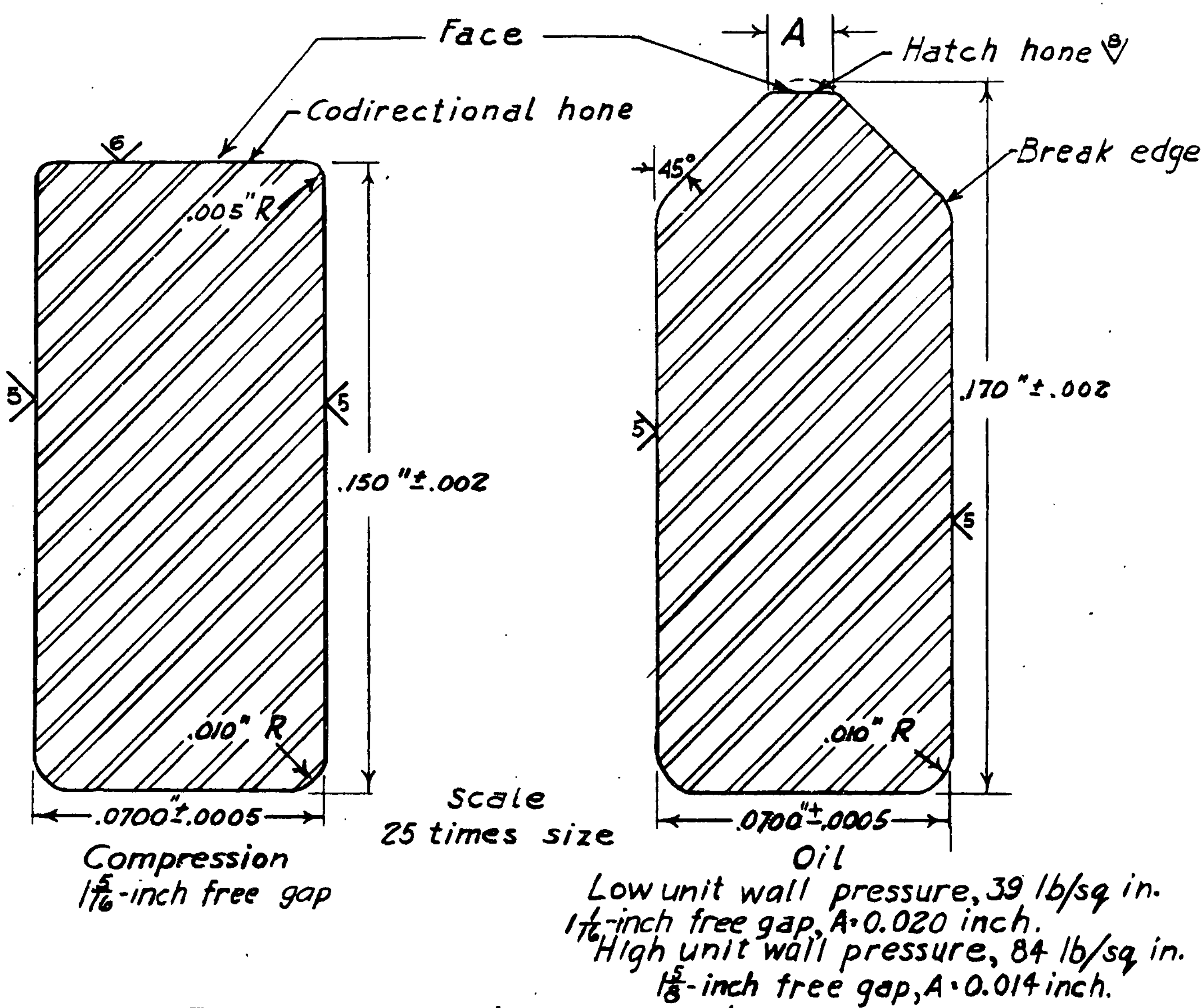


Figure 8. - Nitrided rings for $6\frac{1}{8}$-inch bore.

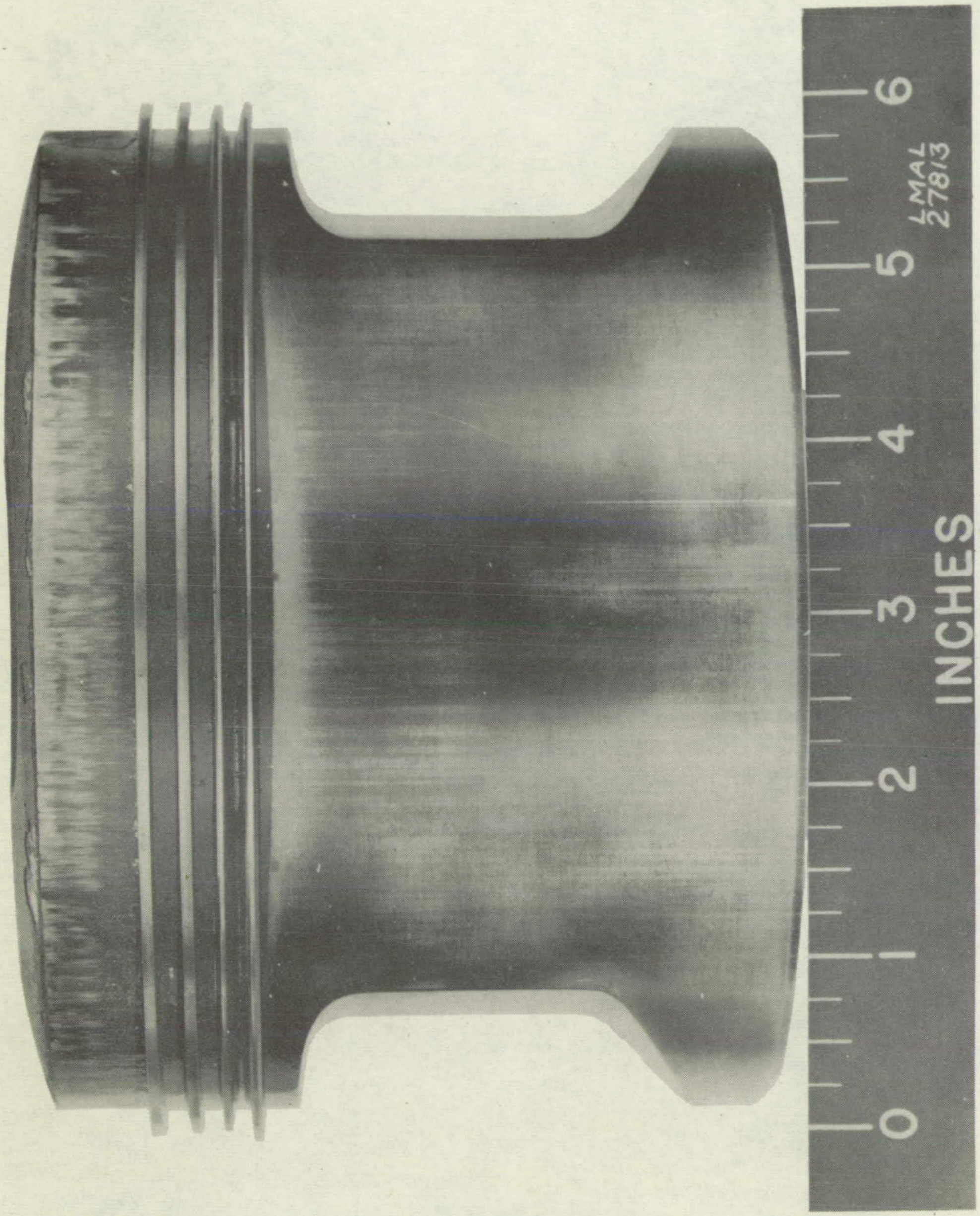


Figure 9.- Piston assembly after 25 hours at 2200 rpm and 204 pounds per square inch brake mean effective pressure.

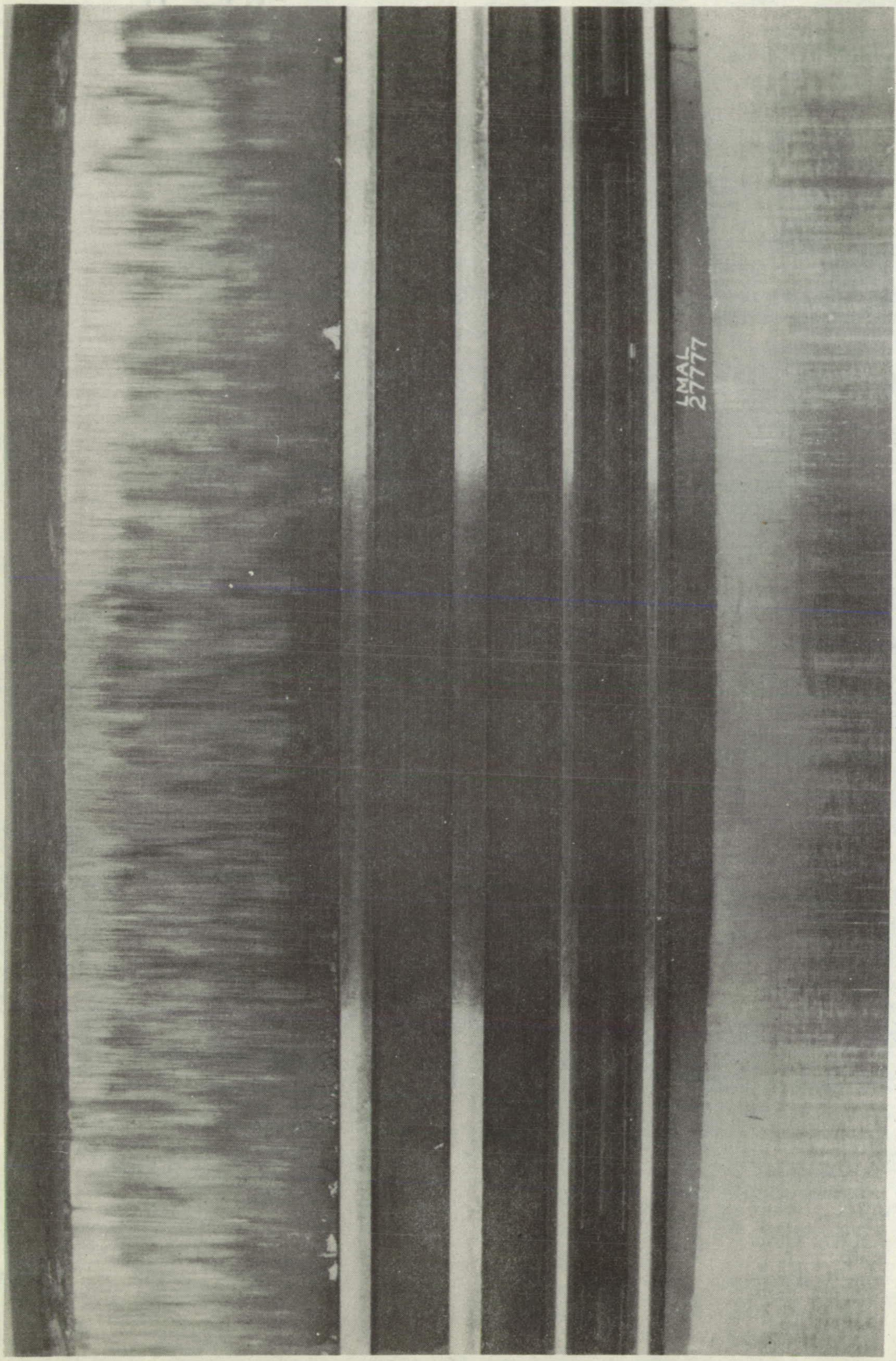


Figure 10.- Nitrided-steel rings after 25 hours at 2200 rpm and 204 pounds per square inch brake mean effective pressure. X3.

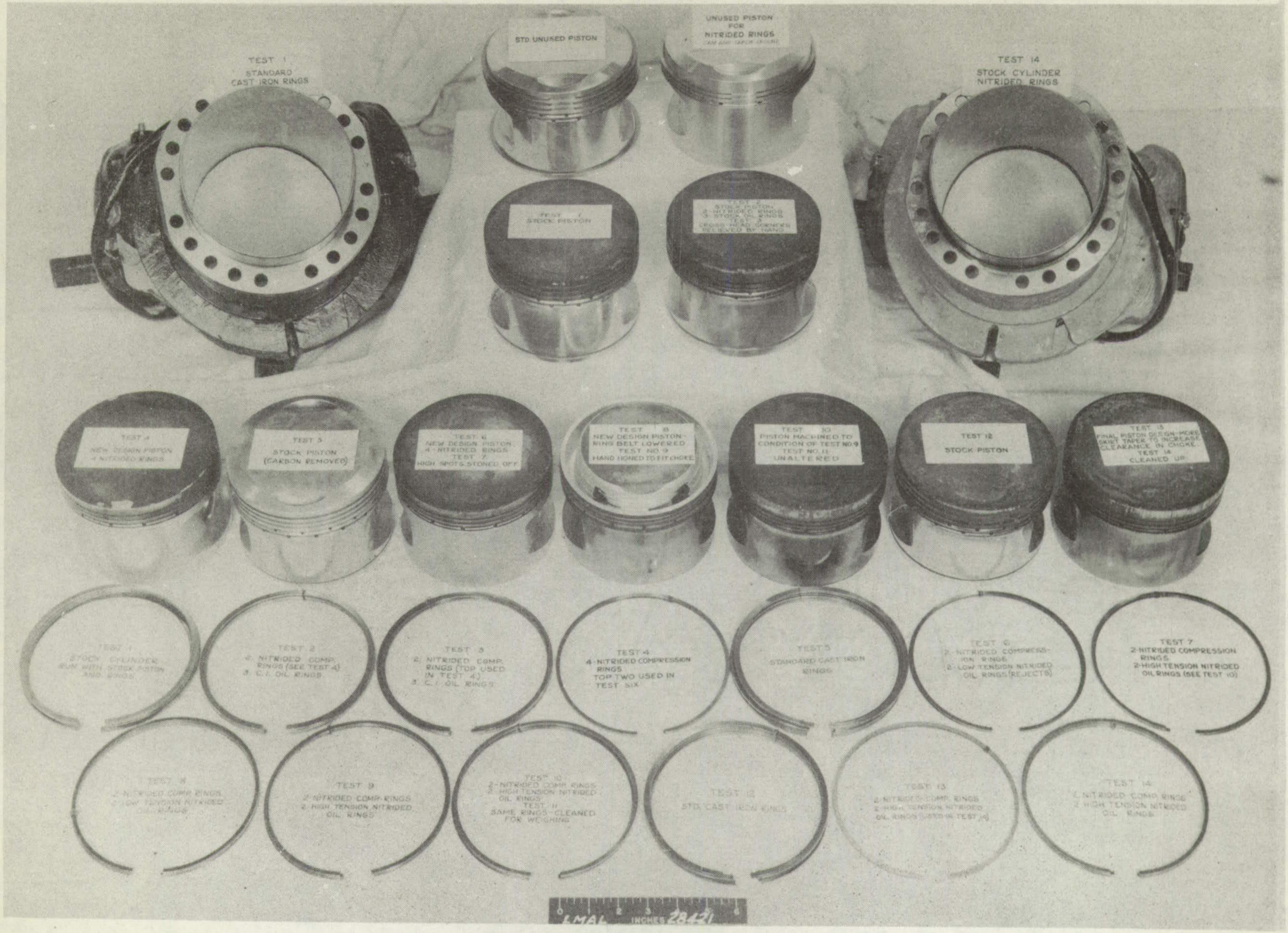
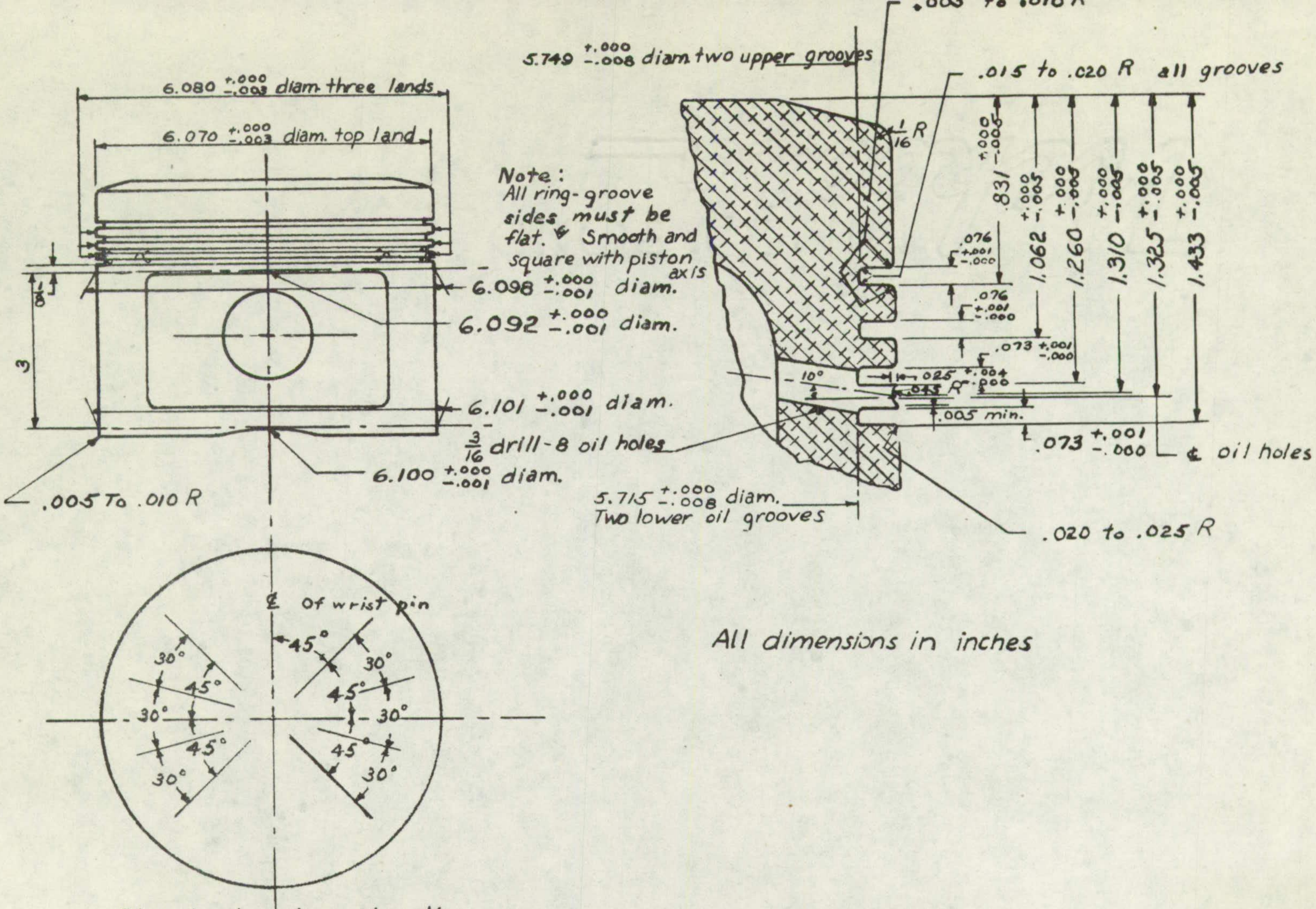


Figure 11.- Piston and nitrided-steel-ring development display.



All dimensions in inches

Chart showing location of oil-drain holes

Figure 12. - Piston for nitrided rings. Bore $6\frac{1}{8}$ inches.

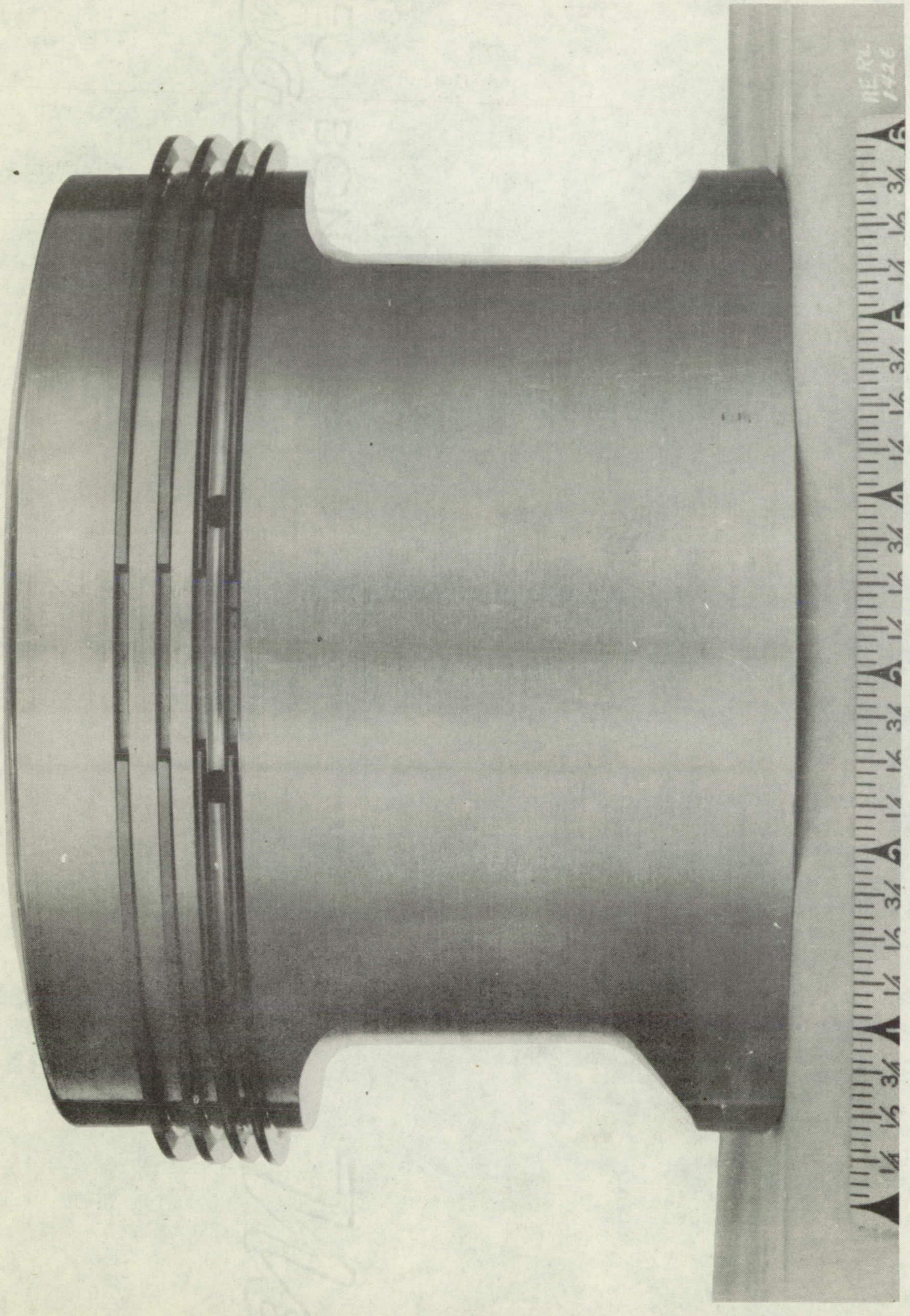


Figure 13.- New piston assembly.

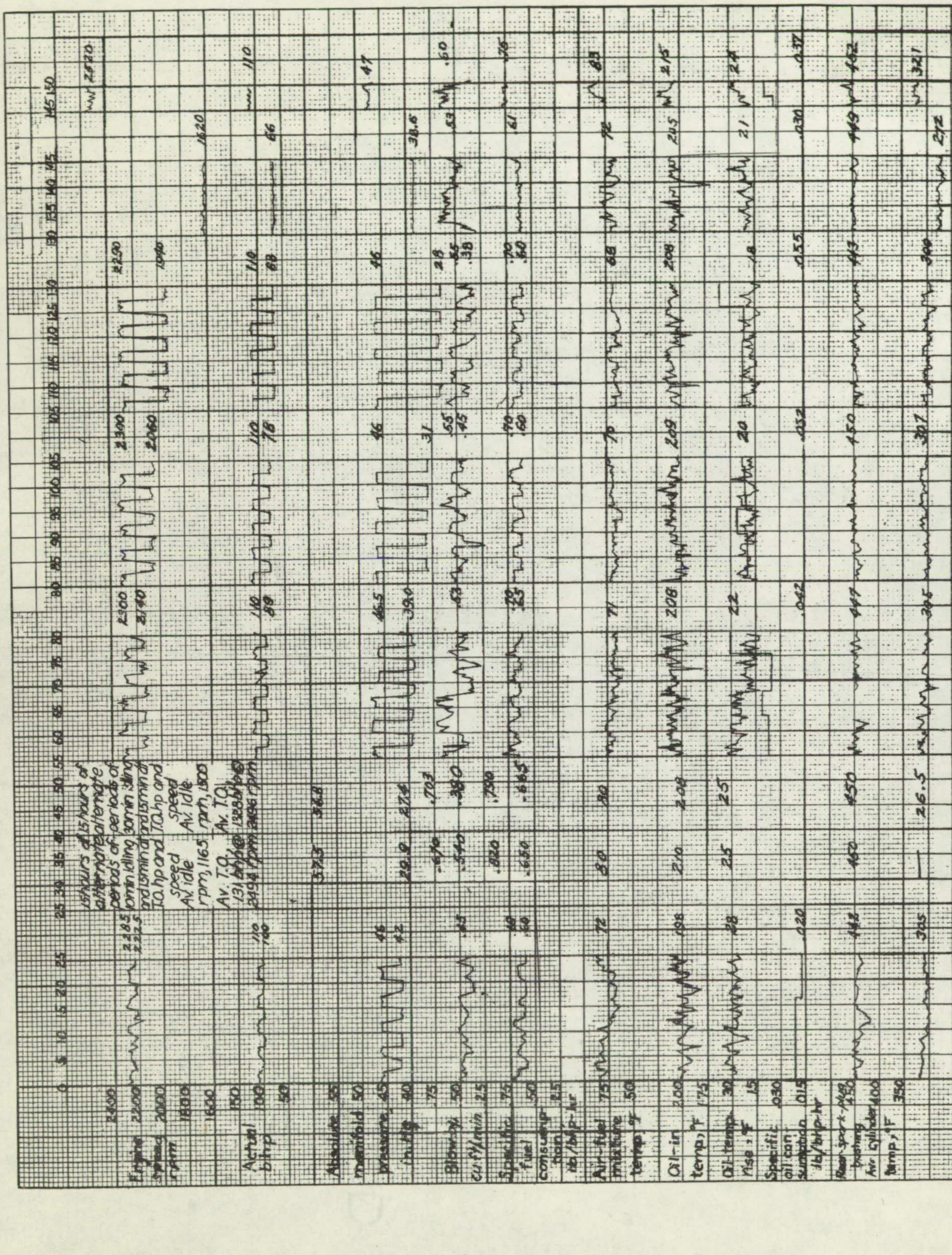


Figure 14.- A 150-hour type test of nitrided piston rings. Crankcase, multicylinder converted to single-cylinder; fuel, Army 100 octane; oil, Navy symbol No. 120; average barometer, 30.07 in. Hg; T.O.) take-off.

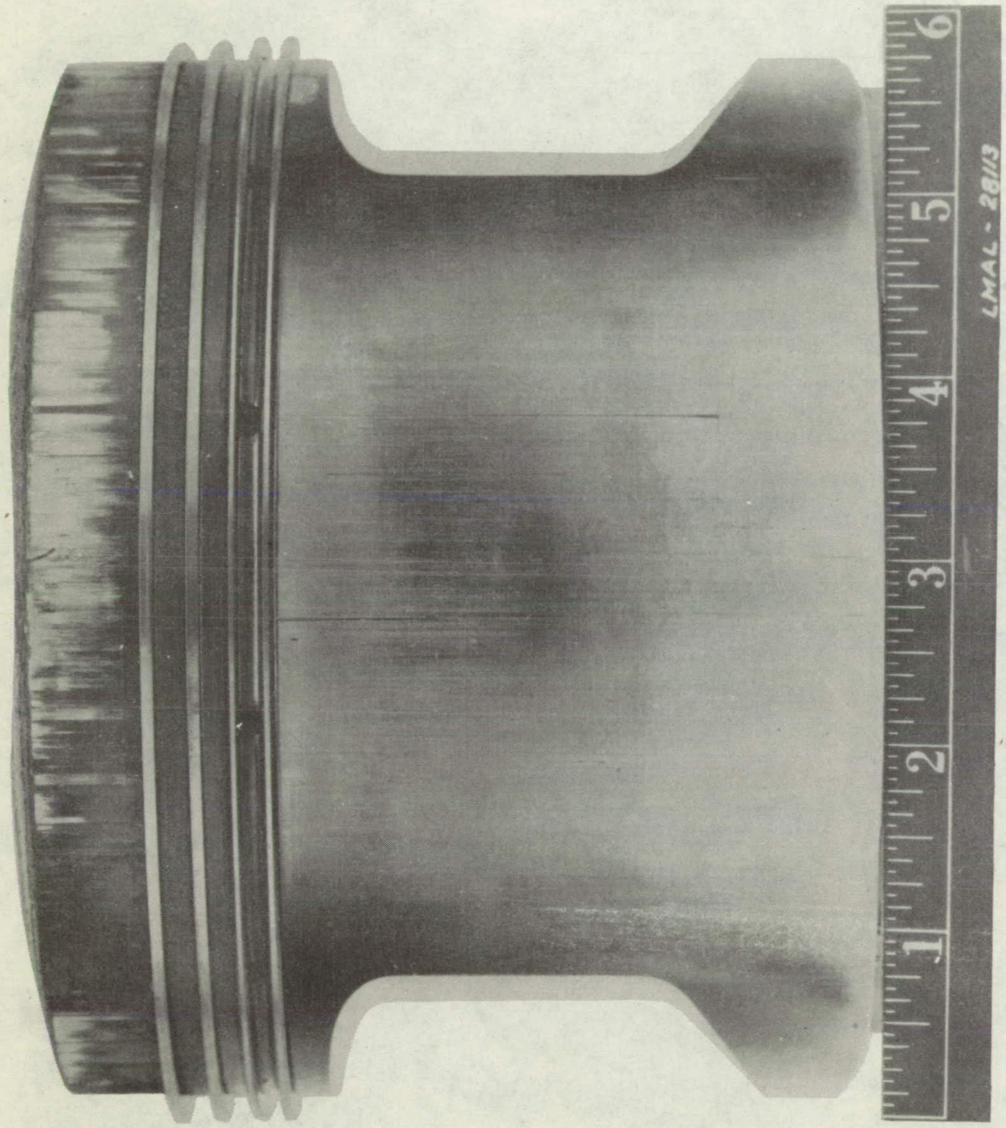


Figure 15.- Piston assembly after 150-hour type test.

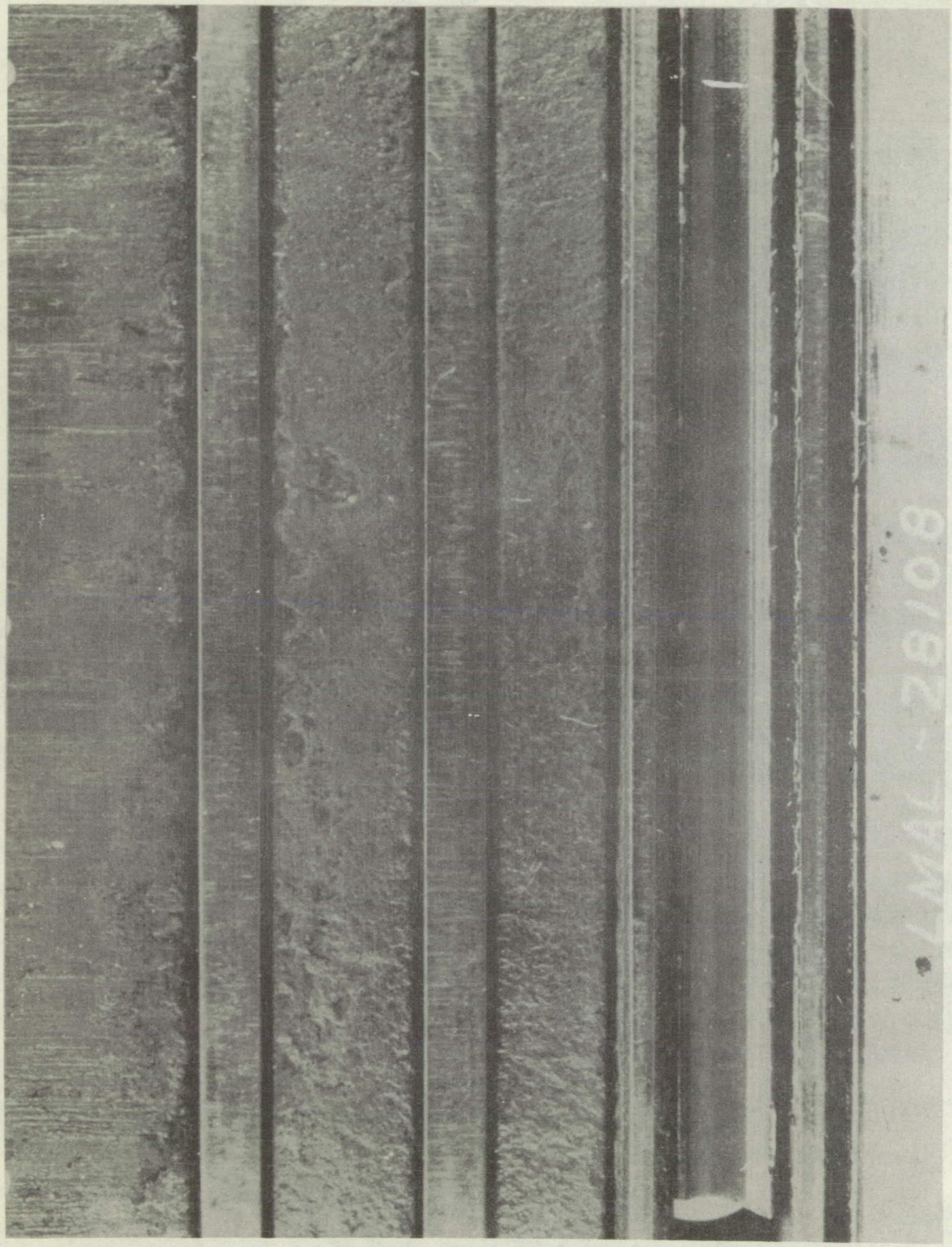


Figure 16.- Nitrided-steel rings after 150-hour type test. X6.

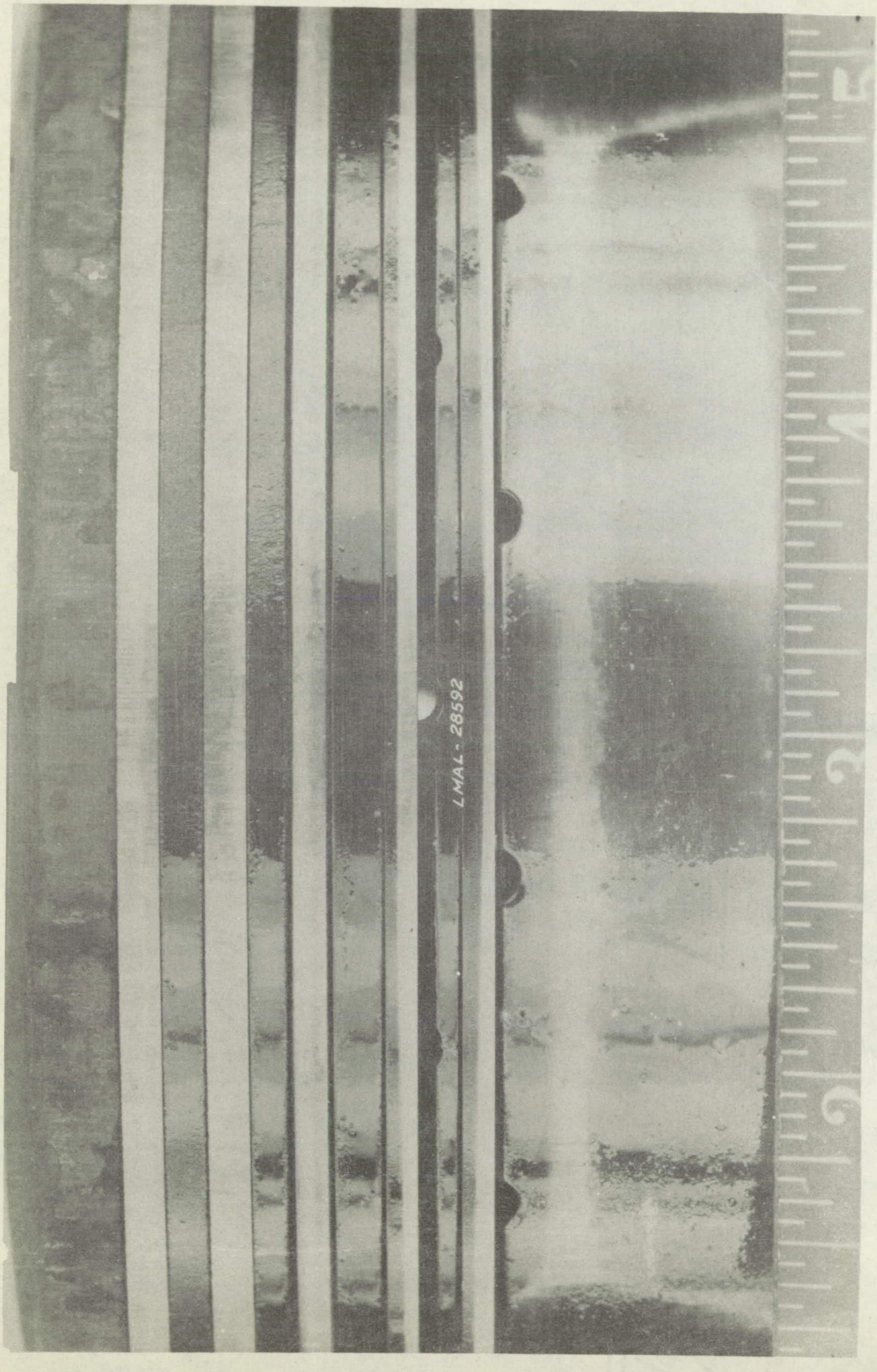


Figure 17.- Stock rings after 9 1/2 hours at 2500 rpm and 250 pounds per square inch brake mean effective pressure. X2.

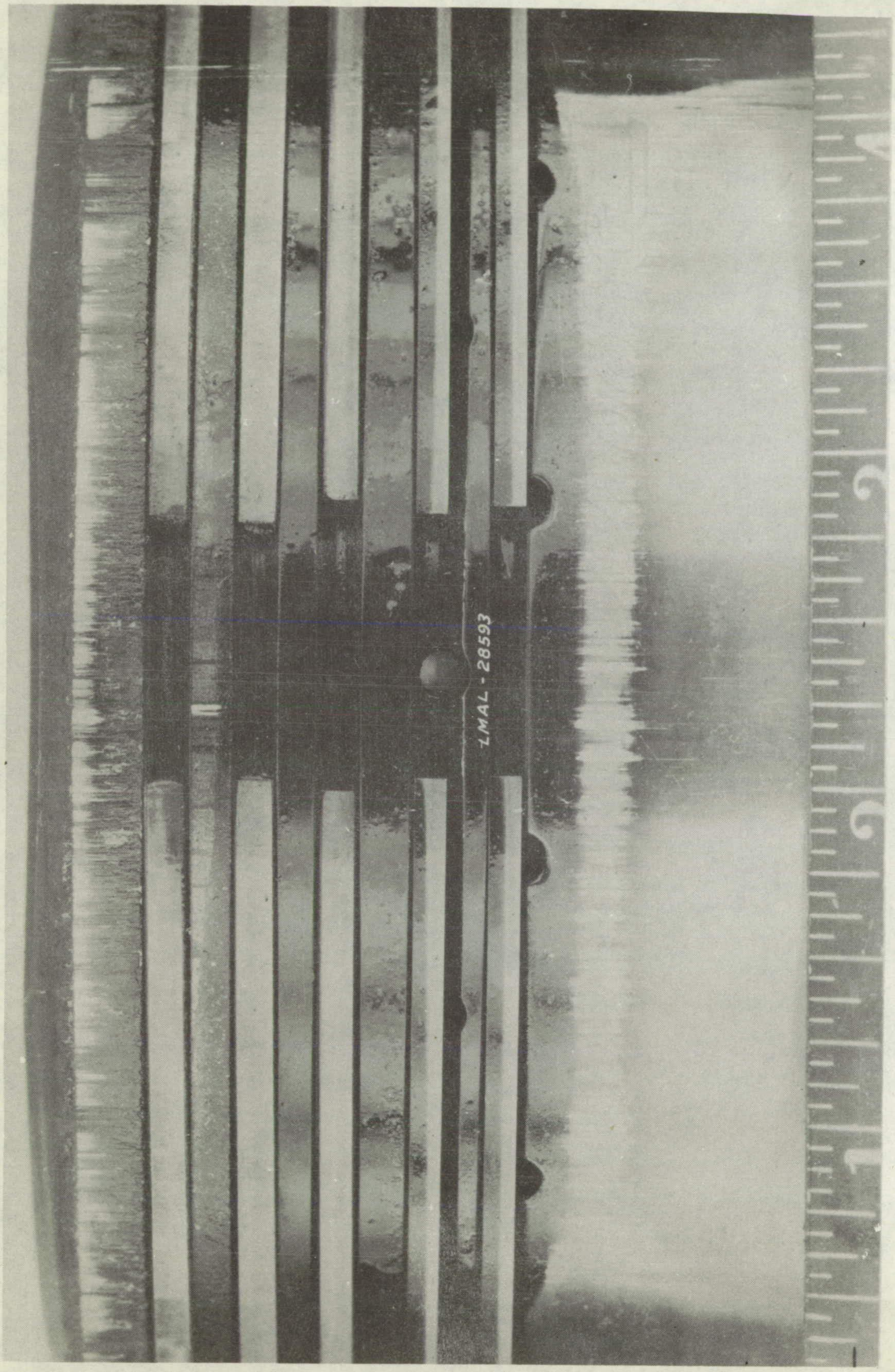


Figure 17.- Concluded.

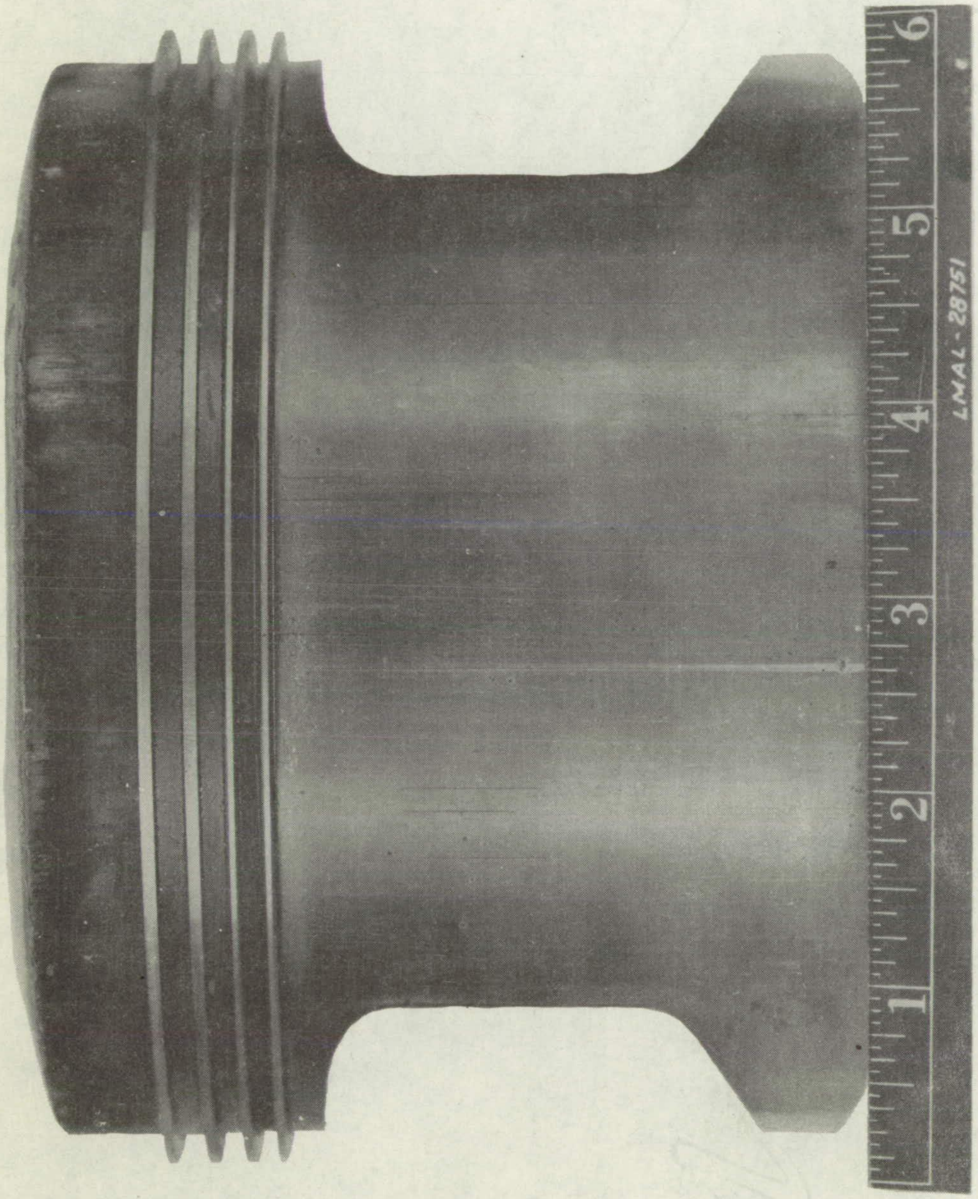


Figure 18.- Piston assembly after high-output tests.

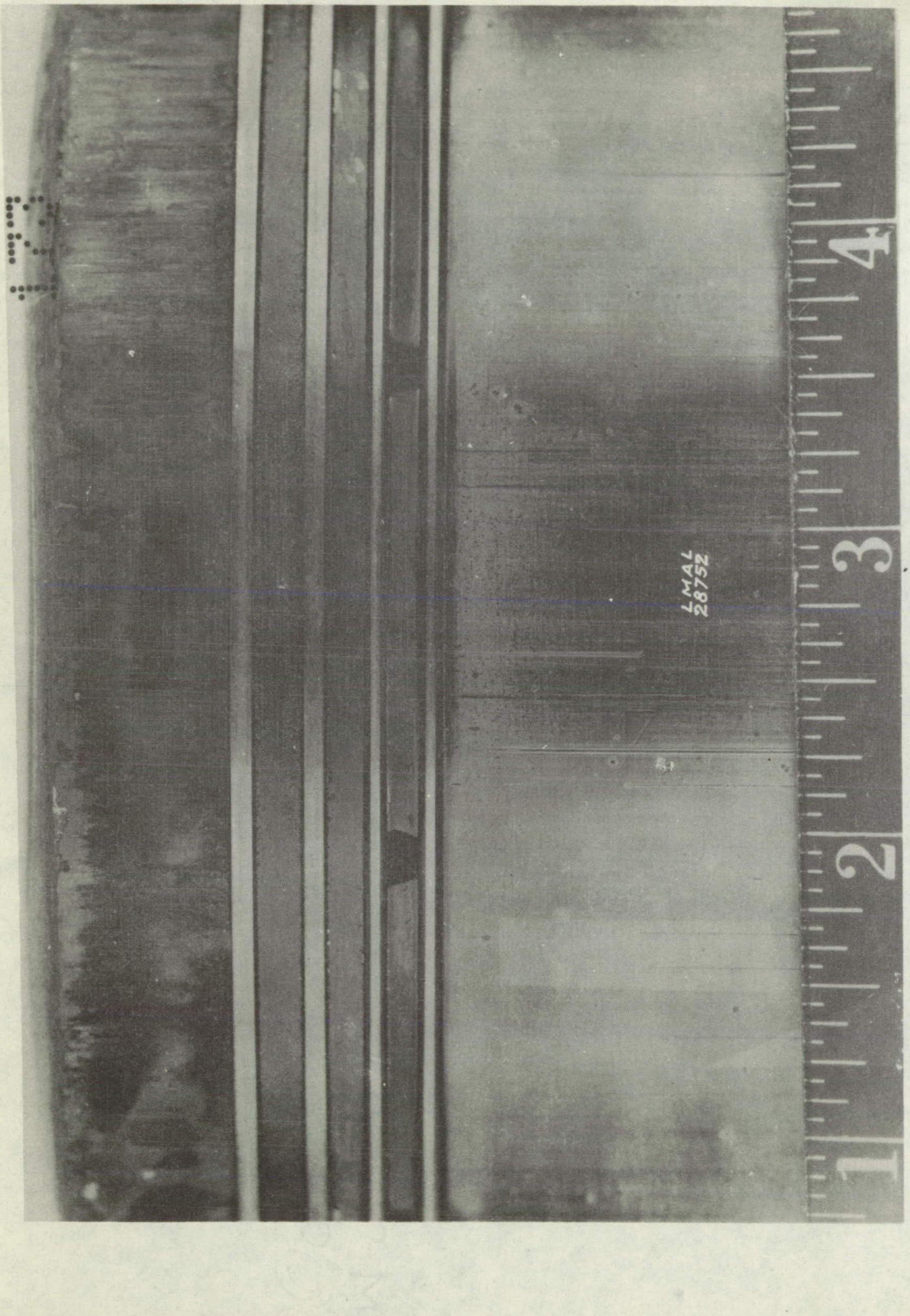


Figure 19.- Nitrided-steel rings after high-output tests. X2.

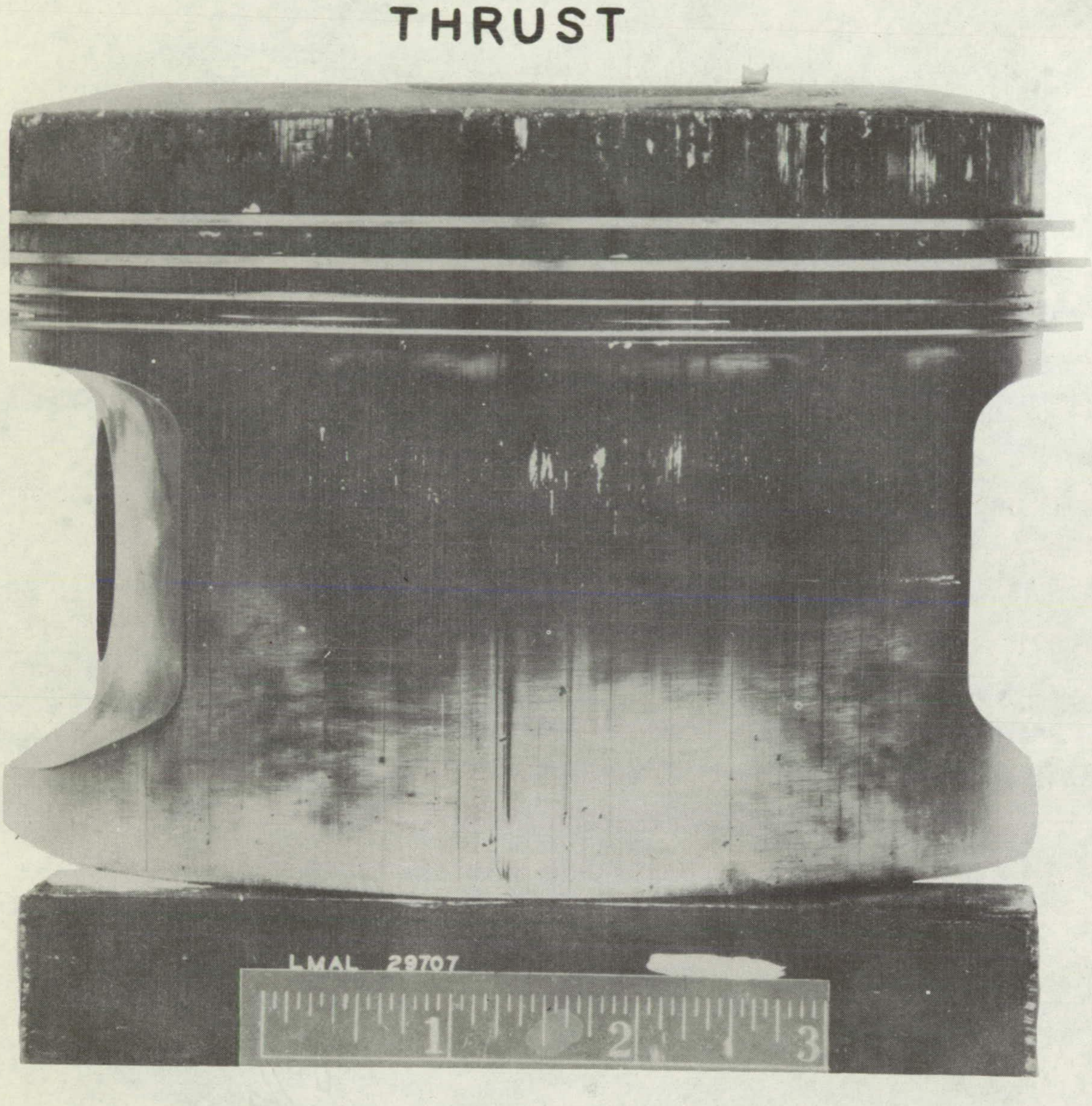


Figure 20.- Piston assembly after high-output tests. High-tension oil rings.

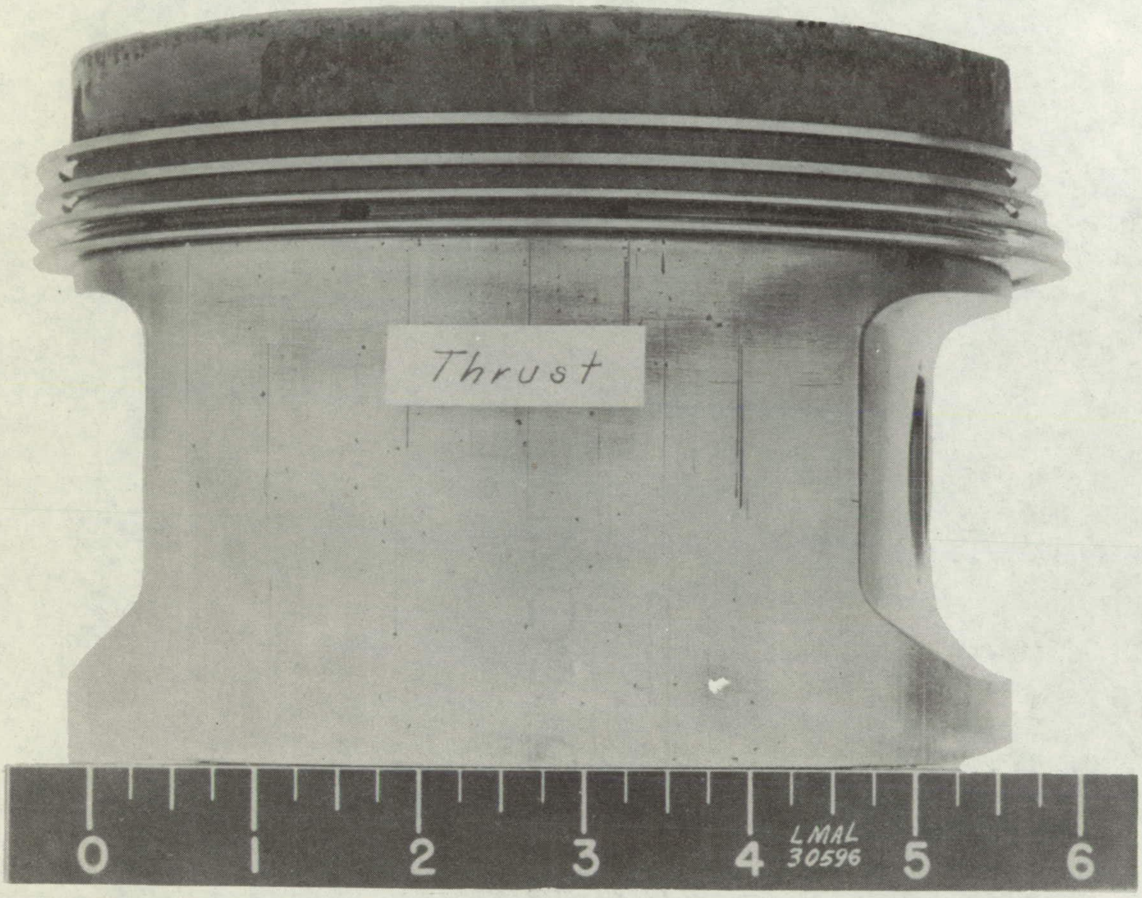


Figure 21.- Piston assembly after tests in porous chromium-plated barrels.

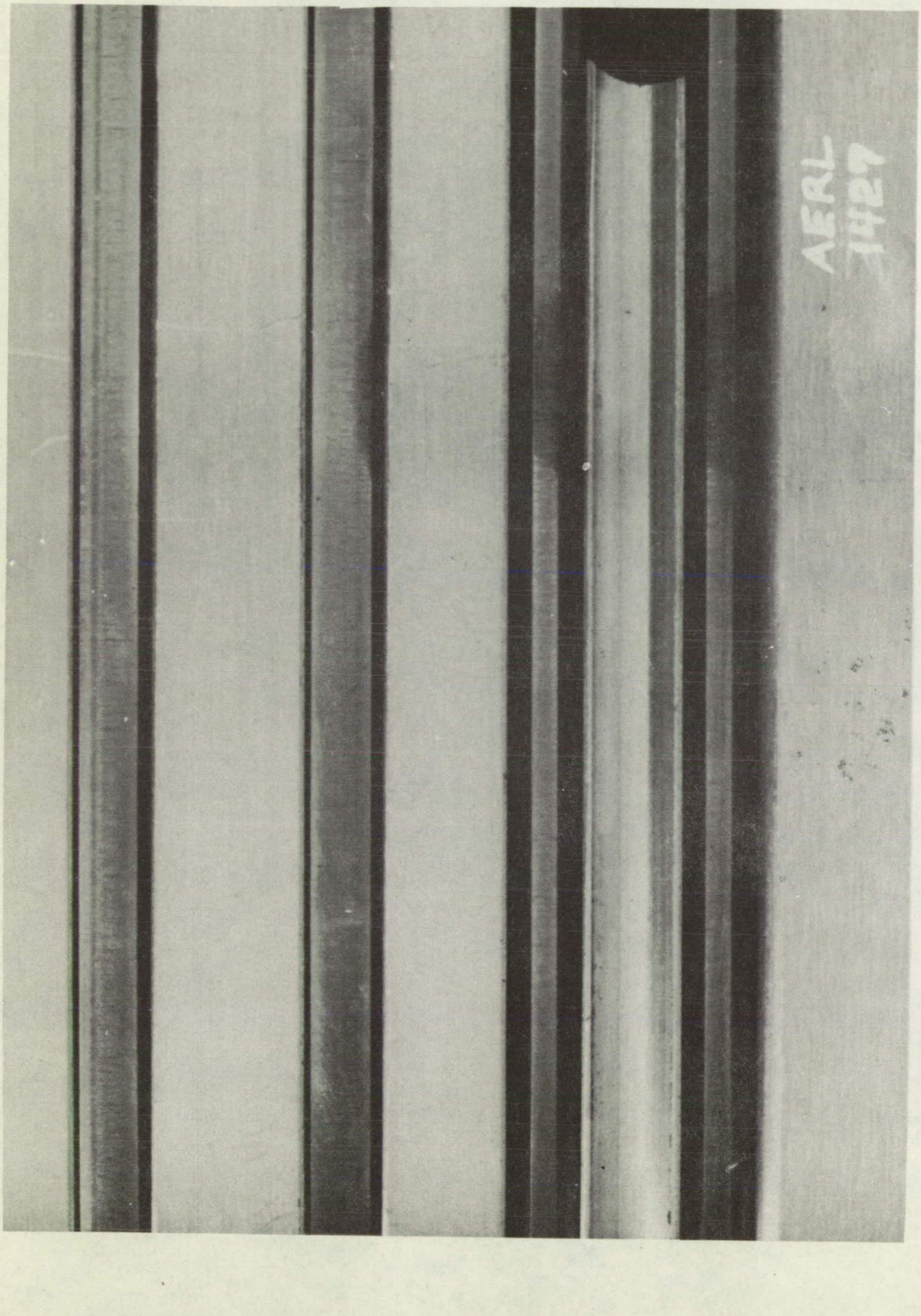


Figure 22.- Nitrided-steel rings after tests in porous chromium-plated barrel. (Rings assembled on new piston for photographing.) X6.

Figure 23.- Plan view of porous chromium-plated cylinder above ring travel; after test. Porosity 52 percent. X100

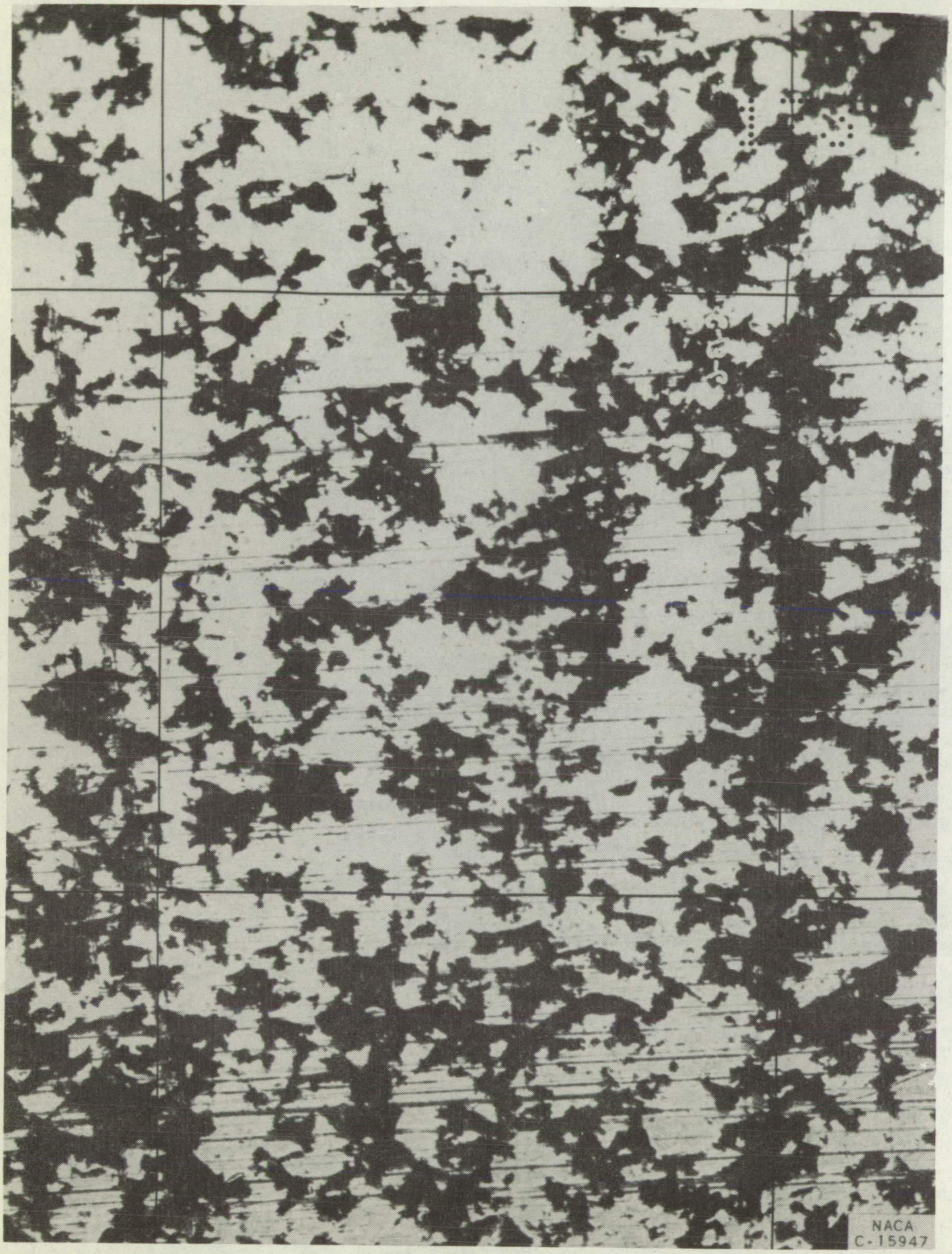
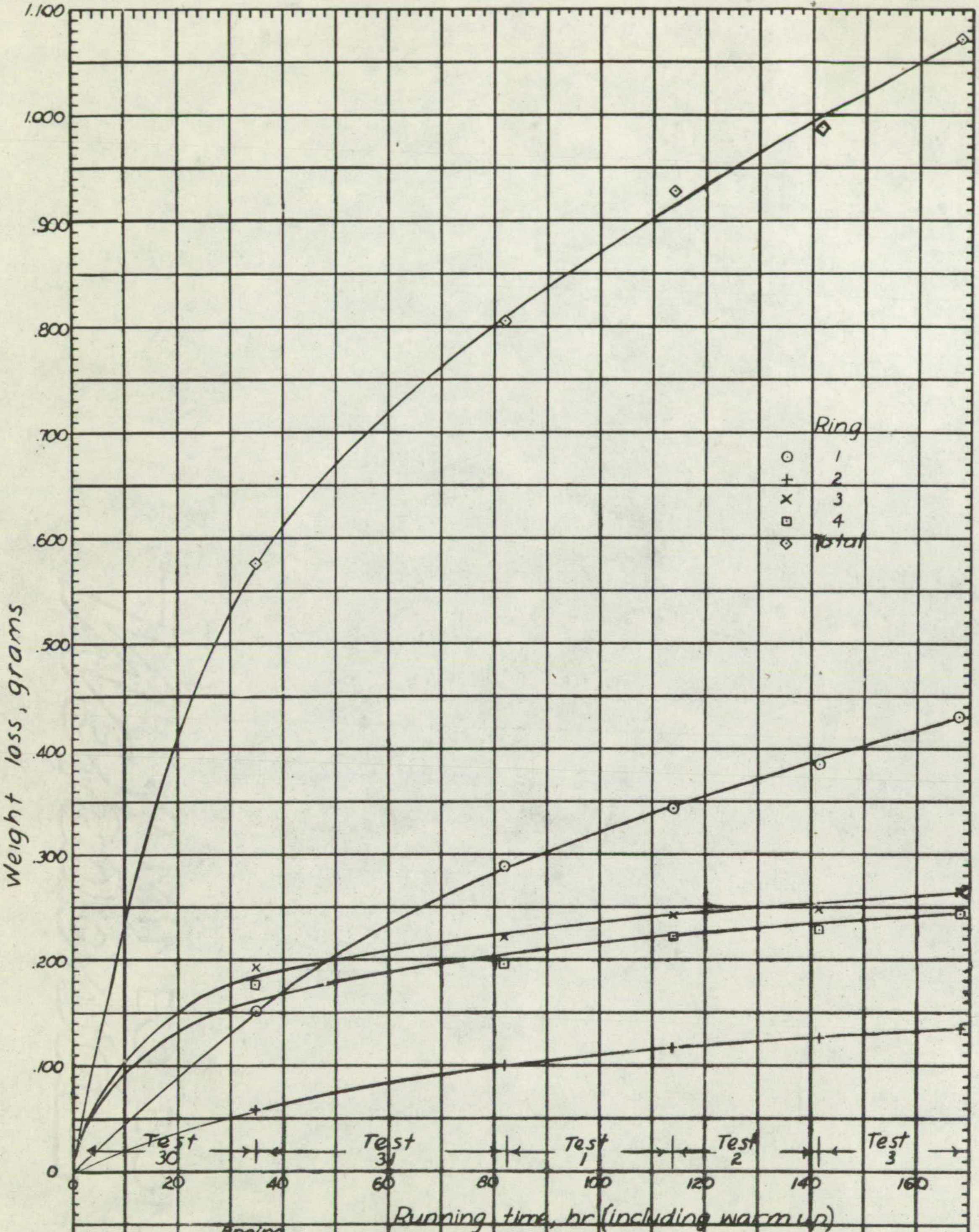


Figure 24.- Plan view of porous chromium-plated cylinder in ring travel, after test. Porosity, 40 percent. X100.



Test	Engine speed (rpm)	bmep (lb/sq in.)	Cylinder
30 (Table IV)	2500	210	Nitrided
31	2500	250	Nitrided
1 (Table V)	2300	190	Porous chromium-plated
2	2300	210	Porous chromium-plated
3	2500	250	Porous chromium-plated

Figure 25.– Ring wear of one nitrided-ring assembly. Rings cleaned and weighed after each test, then reassembled for next test.

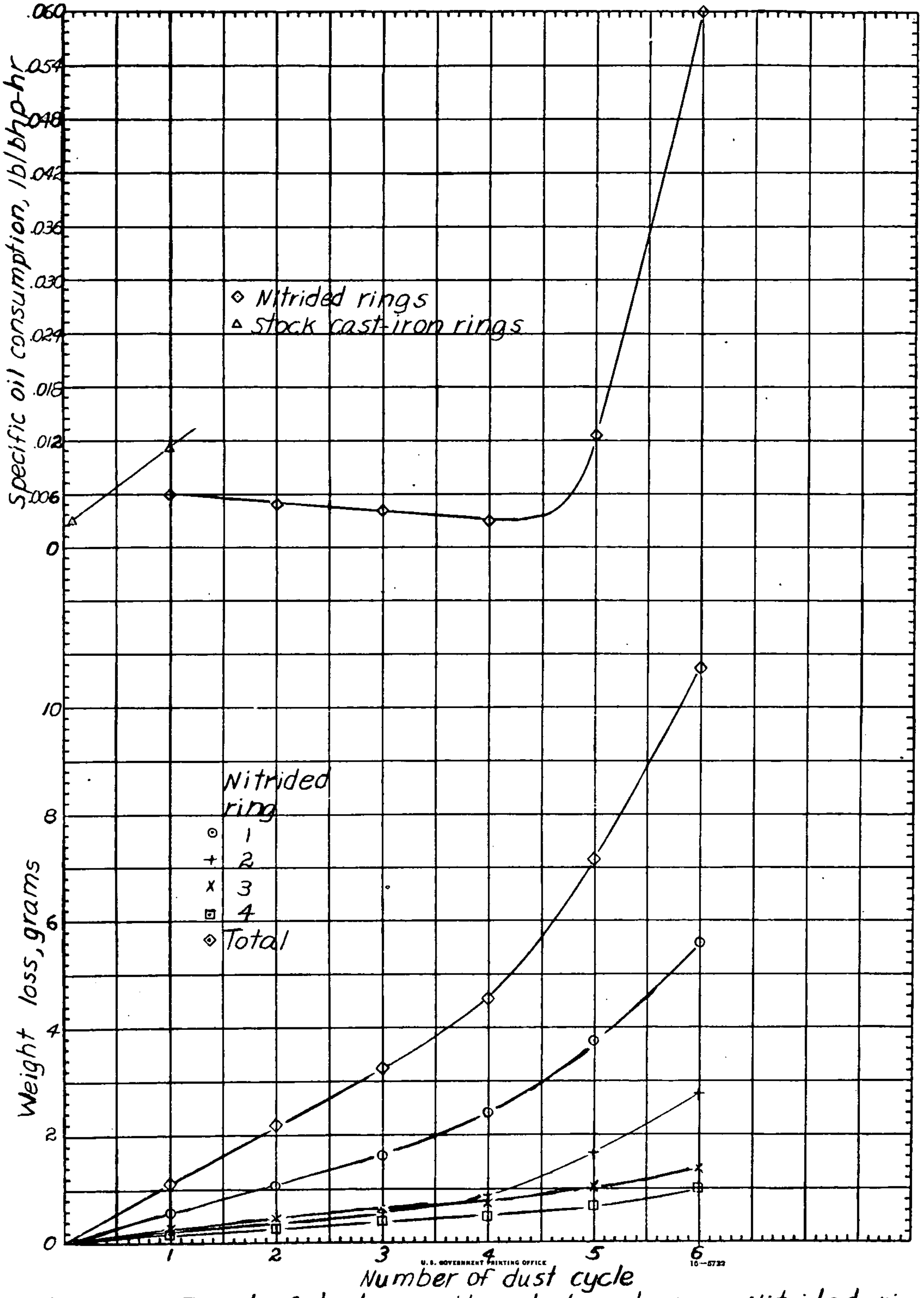


Figure 26 - Effect of dust on oil control and wear. Nitrided-ring assembly; single-cylinder engine. Data from Bureau of Aeronautics, Aircraft Engine Laboratory.

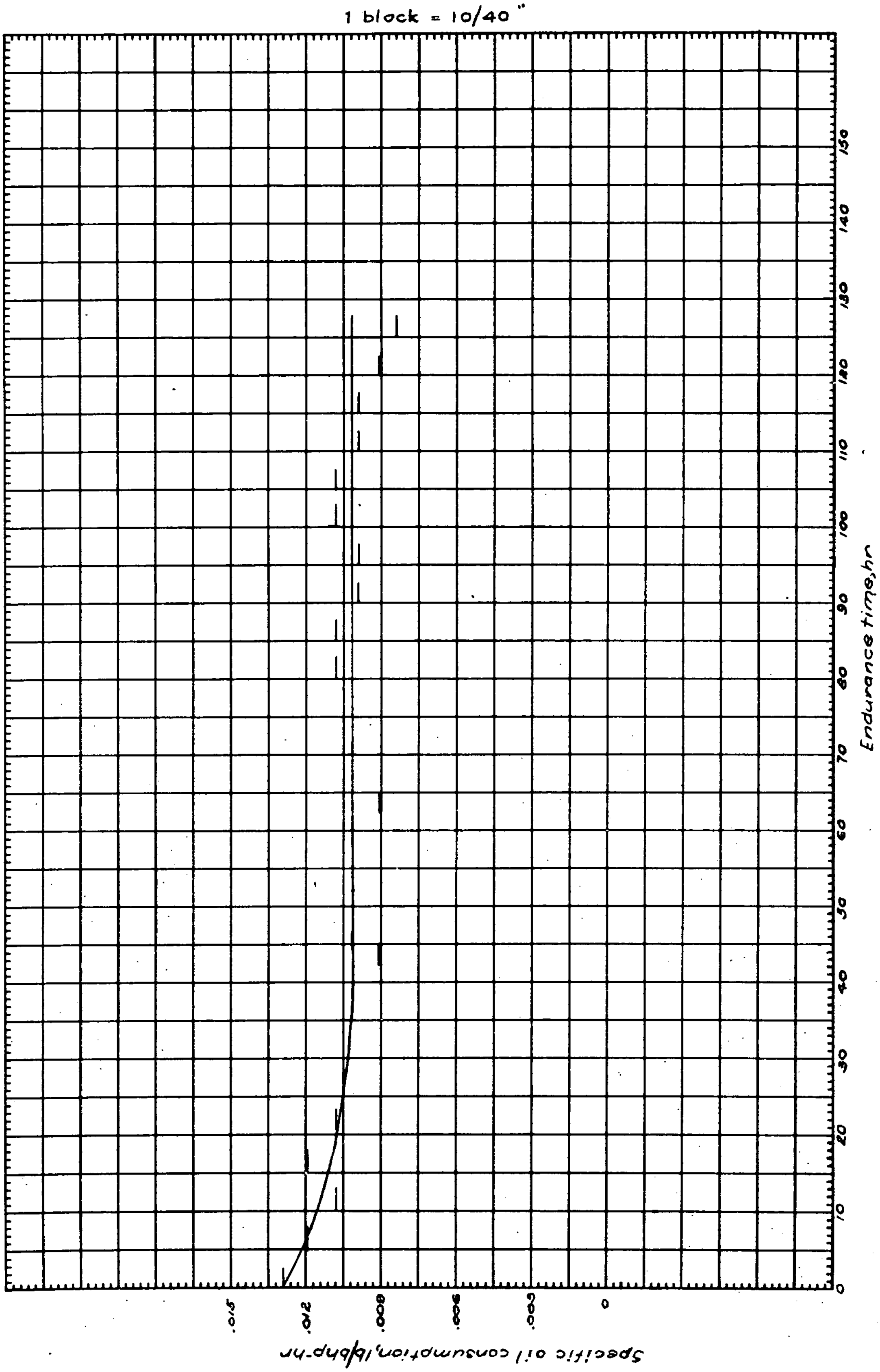


Figure 27. Effect of running time on oil control with nitrided-ring assembly. Type test of Wright R-1820-40 engine. All points at normal rated power and speed (1000 bhp at 2300 rpm). Data from Bureau of Aeronautics. Aircraft Engine Laboratory.

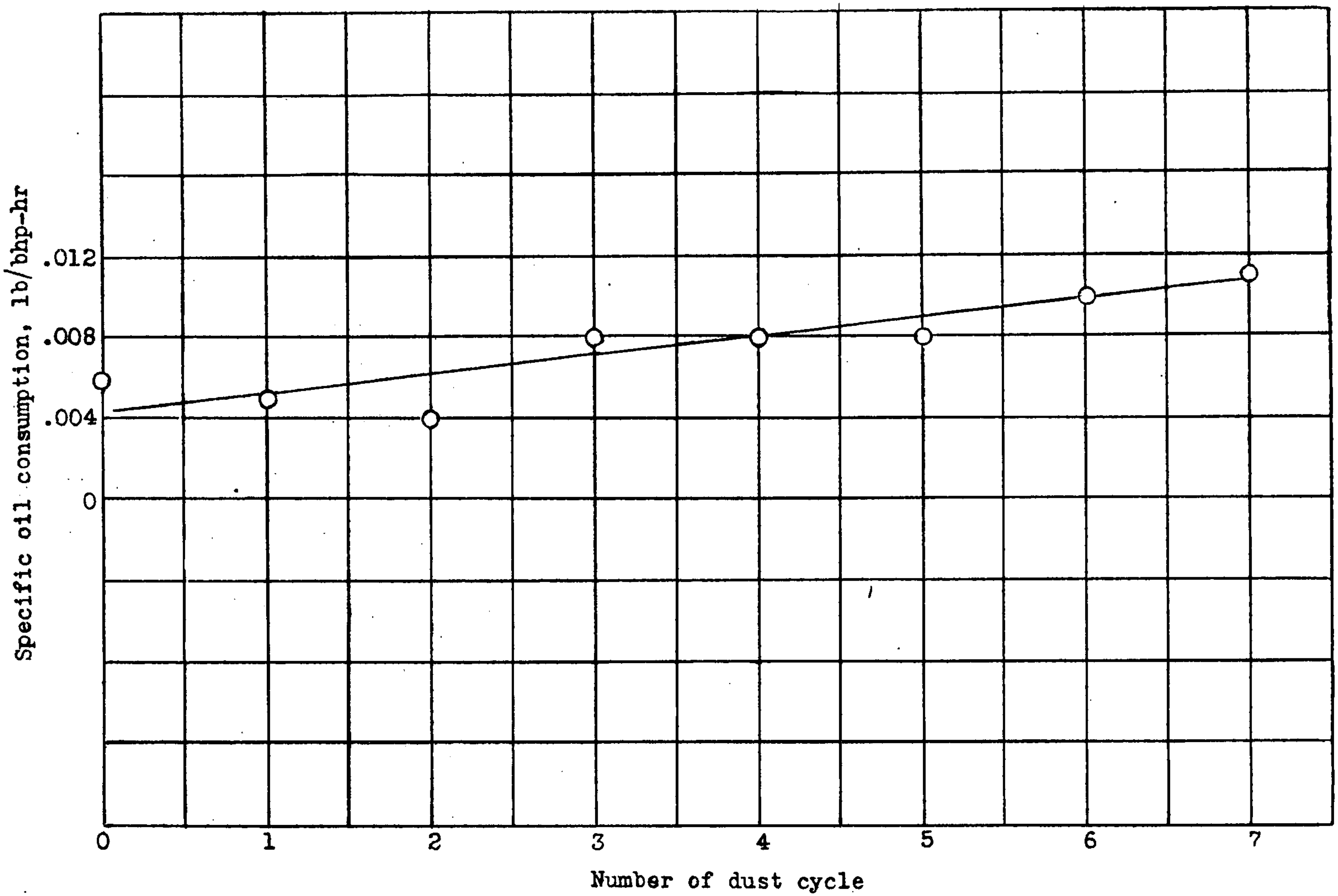


Figure 28.- Effect of dust on oil control, Nitrided rings in stock C9GC, nitrided cylinders in a Wright R-1820-40 engine. Data from Bureau of Aeronautics, Aircraft Engine Laboratory.

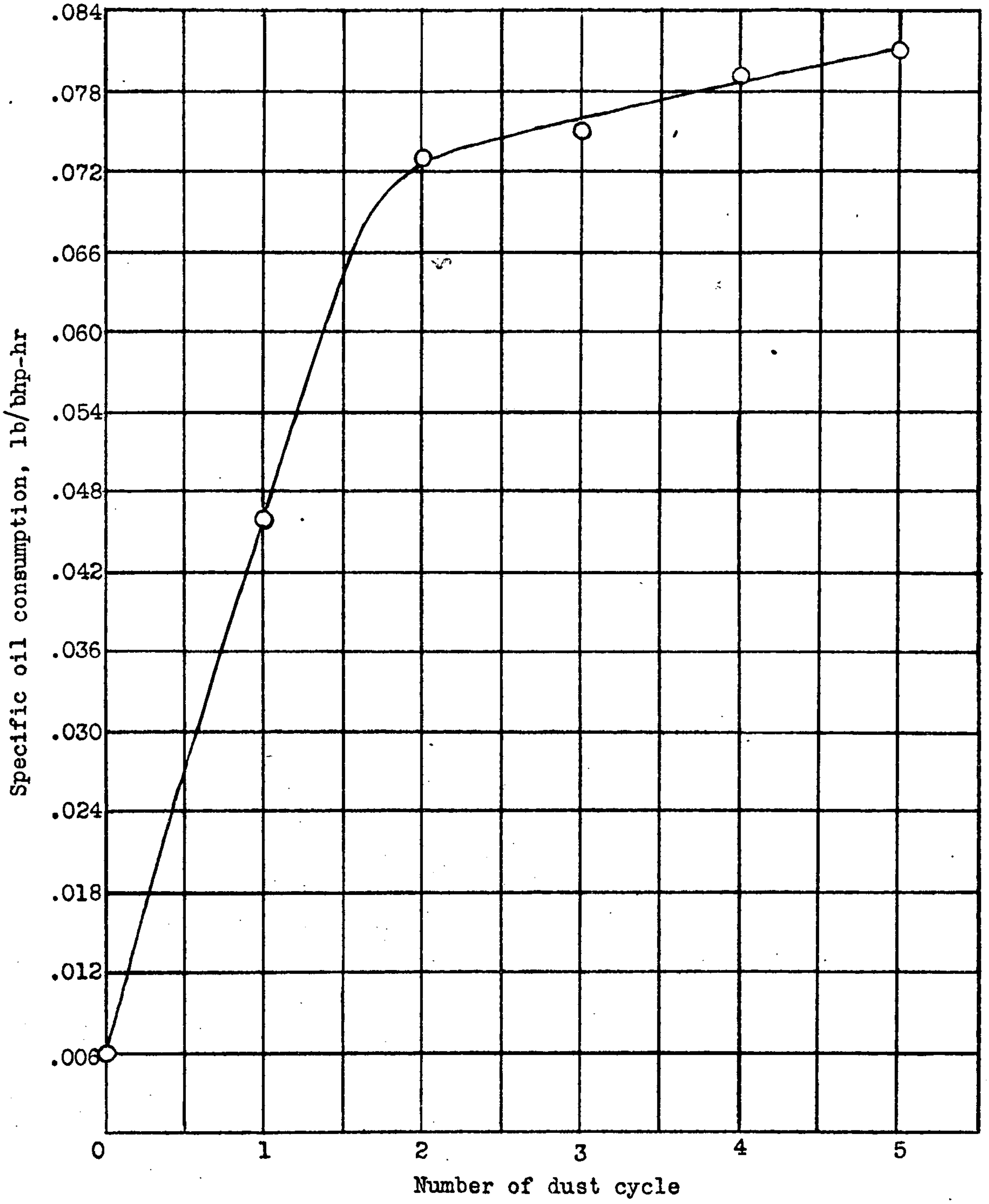


Figure 29.- Effect of dust on oil control. Stock cast-iron rings in porous chromium-plated cylinders. Wright R-1820-22 engine. Data from Bureau of Aeronautics, Aircraft Engine Laboratory.

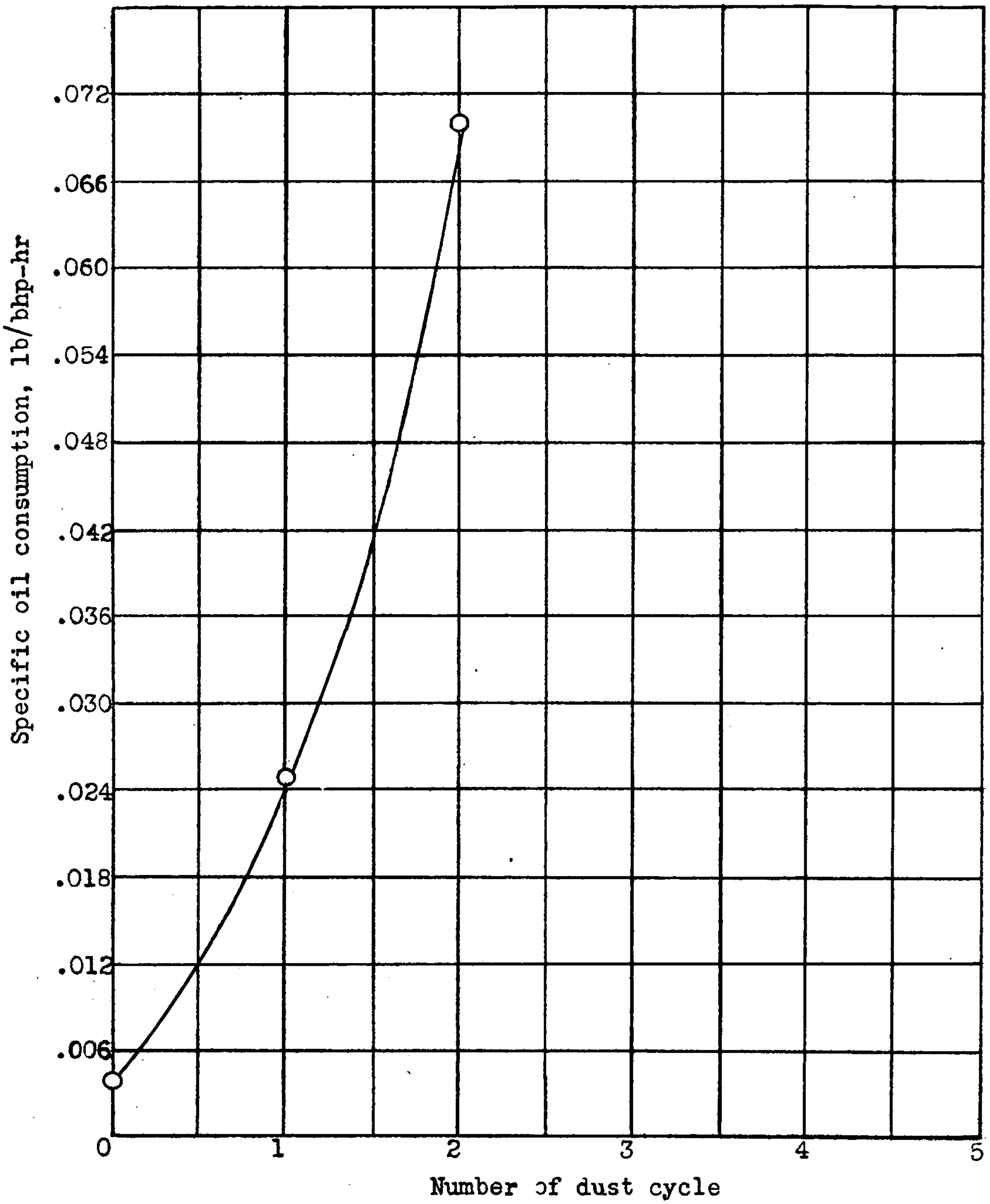


Figure 30.- Effect of dust on oil control. Nitrided cylinder and cast iron piston rings, Wright R-2600-8 engine. Data from Bureau of Aeronautics, Aircraft Engine Laboratory.