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EFFECT OF PROGRESSIVE RING FAILURE ON PISTON DESTRUCTION

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SUMMARY

Object. - To determine the effect of progressive ring failure on piston life.

Scope. - Two endurance runs were conducted on an Allison single-cylinder engine at high power output until destruction of the pistons occurred at 33.1 and at 84.25 hours. Periodic inspections of the piston and ring assemblies were made during the tests.

Conclusions. - From the tests reported herein, the following conclusions can be drawn:

1. Complete failure of the compression rings may require a relatively long period of operation after initial failure of the top ring by sticking or breaking.

2. Complete failure of the compression rings does not necessarily bring about destruction of the piston unless operation of the engine is continued for a considerable length of time.

3. The power loss accompanying high blow-by rates cannot be entirely accounted for on the basis of gas leakage.

INTRODUCTION

During a general program relative to increasing the power of aircraft engines, several piston failures occurred in which complete destruction of the piston took place. At that time these failures were attributed to various causes, such as preignition, inadequate piston cooling, lack of sufficient piston clearance, and compression-ring failure. Subsequent work indicated that preignition and lack of sufficient piston clearance accounted for practically all of the failures. The possibility that compression-ring failure could cause piston destruction, however, was still present. The tests reported herein were conducted during October and December 1943 by the NACA at Cleveland, Ohio, in order to determine the effect of progressive ring failure on the life of the piston.

APPARATUS

The tests were carried out on an Allison single cylinder mounted on a CUE crankcase. The apparatus was conventional in most respects. Standard Allison pistons were used, equipped with standard rectangular-cross-section compression rings. The top ring was straight-faced, with a bevel along its upper edge, and the second and third rings were taper-faced.

The piston used in the first test had previously been used to obtain preignition data in connection with another project. These tests comprised about 15 hours running time. The severe operating conditions encountered in the preignition tests resulted in breaking of the top ring and sticking of the second ring. Figure 1 shows the piston prior to installation in the cylinder at the beginning of the endurance test. A clean used piston equipped with new piston rings was used for the second test.

An oil spray from a calibrated jet, installed in the crankcase and directed upward against the bottom of the piston, cooled and lubricated the piston during both tests. The flow through this jet was controlled by throttling the oil-supply line. A baffle installed between the crank chamber and the cylinder barrel prevented the throw-off oil of the crankpin bearing from reaching the piston.

Crankcase pressures were measured with a mercury manometer and rate of blow-by was indicated by a displacement-type gas meter.

TESTS AND RESULTS

First Endurance Test

Endurance test. - The inlet-air pressure at the beginning of the first endurance test was 30 inches of mercury absolute. This pressure was increased in increments of 5 inches every 15 minutes over a period of 1.5 hours until a value of 60 inches was reached. It was held constant at this value until about 2 minutes before the end of the test. After the first 1.5 hours, readings of the blow-by rate and the crankcase pressure were taken at 1-minute intervals.

The following operating conditions were held constant throughout the test:

Engine speed, rpm	2600
Inlet-air temperature, °F	100
Fuel-air ratio	0.095
Compression ratio	6.65
Fuel	AN-F-28, Amendment-2, + 3 ml TEL per gallon
Oil-in temperature, °F	185
Outlet-coolant temperature, °F	250
Spark advance, degrees B.T.C.:	
Inlet	28
Exhaust	34
Oil flow to piston, pounds per minute (approximate)	2.0
Oil	Navy 1120

At the end of 7.5 hours the piston was removed for inspection. By this time complete failure of the compression rings had taken place but the oil rings were still in reasonably good condition (fig. 2). The piston and ring assembly was reinstalled and the test continued. After an additional 10.6 hours, the inlet-air pressure was increased to determine the power level at which immediate and complete piston failure would take place. This failure occurred at an inlet-air pressure of 68 inches of mercury absolute with the results shown in figure 3. The total test time was 33.1 hours including the preignition tests conducted previous to the endurance run.

Blow-by and crankcase pressure. - The curves of the rate of blow-by and the crankcase pressure are shown in figures 4 and 5. Because the crankcase pressure is directly related to the blow-by rate, these curves are similar. It must be borne in mind, in the interpretation of the results of the crankcase-pressure curve, that the magnitudes of the crankcase-pressure values are entirely dependent upon the system used for the removal of the blow-by gases from the crankcase; a system having many restrictions, such as small piping, a flowmeter, and numerous valves, will result in high pressures, whereas a system having fewer obstructions to the gas flow will result in low pressures. The actual pressure in the crankcase was somewhat higher than the values measured because the manometer was connected to the blow-by line some distance from the crankcase.

Figures 4 and 5 indicate that, after failure of the top and second rings had taken place (beginning of endurance test), an increasing degree of failure of the compression rings did not affect the sealing qualities of the piston and ring assembly to any marked extent. The rate of blow-by and the crankcase pressure at the beginning of the test were approximately the same as those values at the time of the inspection when all the compression rings had failed (fig. 2), which suggests that the oil-control rings had a considerable effect in sealing the combustion chamber.

A marked rise in the rate of blow-by is evident after 11.5 hours of operation. Immediately after these values reached a maximum, the engine was shut down. When the test was continued on the next day, the blow-by rate was found to have dropped to a relatively low value. Upon examination of the piston at the end of the test, small particles of aluminum alloy were found lodged in the oil-ring groove. These aluminum-alloy particles suggested that the marked rise in the rate of blow-by may have been caused by similar particles which served to partly stick the oil-control rings and which were later displaced upon idling the engine to a stop or during the subsequent starting and warming-up operations on the following day. The fact that these deposits were found in the oil-ring groove and displaced as much as 90° from the point of final failure indicates that considerable time was required for their formation and that they were not a result of melted aluminum alloy finding its way into the groove at the time of final failure. The irregularities in the rate of blow-by throughout the rest of the test further substantiate the occasional partial sticking of the oil-control rings.

Instrumentation used with the test engine showed that preignition occurred at 16.7 hours on the endurance test and that it may have occurred again a few seconds before the final piston failure. The preignition at the 16.7-hour point of the endurance run coincides with a large and sudden increase in rate of blow-by. The most pronounced effect of preignition is to increase greatly the maximum combustion-chamber pressures and temperatures, which would considerably increase the rate of blow-by. A smaller effect is the more rapid deterioration of the piston rings caused by these high pressures and temperatures.

The sudden rise in rate of blow-by at 15.5 hours may also have been caused by preignition although none was detected by the time-pressure diagram on the oscilloscope. The loss in power output recorded at this point is somewhat higher than would be expected from blow-by alone (fig. 6), suggesting that preignition may have advanced only a few degrees, become stable, and shortly afterward disappeared. This type of preignition has been known to occur many times in other tests and would probably be unnoticed on the time-pressure diagram.

During the last 1.5 hours of the test the blow-by curve shows an irregular gradual rise until the final failure took place.

Analysis of failed piston. - Figure 3 shows the piston and ring assembly after the final failure of the first test. A wide deep channel has been burned down the entire length of the piston and a hole has been made through the piston skirt above the oil rings. This damage was confined to the minor thrust face of the piston; the major thrust face remained comparatively unharmed.

The ultimate failure was most likely caused by the action of high-temperature gases against the side of the piston, probably taking place over a relatively long period of time. Figure 7 shows the ring belt of a piston that had been operated under severe conditions in another test program. The large flow of high-temperature gases resulting from compression-ring failure has begun an erosion of one of the ring lands, which probably would have resulted in a large channel similar to figure 3 if operation had been continued long enough. These high-temperature gases are not necessarily all blow-by gases. A portion of these gases leaks by all the rings as blow-by gases, whereas part of them travel down and back up past the ineffective rings as the pressure in the combustion chamber is alternately increased and decreased. The net result is a scouring action, which in all probability causes the erosion shown in figures 3 and 7.

Further evidence that this channeling took place over a prolonged period of time is found in the fact that the entire top ring and parts of the second ring are missing from the piston in figure 3. The channel in the face of the piston provides the only escape path for these ring pieces. Because the broken rings were partly stuck in the grooves, the time required for them to work their way along the grooves to the channel would probably be quite appreciable. The pieces of rings imbedded in the top of the piston at the end of the test (shown by arrows in fig. 3) were covered with a coating of carbon, indicating their presence on the top of the piston for a considerable length of time. The preignition in the engine previously mentioned may have been caused by these ring pieces in the combustion chamber or by the ends of the compression rings left exposed by the formation of the channel down the side of the piston. The fact that particles of aluminum alloy were found lodged in the oil-ring groove, displaced as much as 90° from the channel in the face of the piston, lends further support to the supposition that the channeling of the piston took place over an extended period of time.

The final destruction of the piston occurred without any forewarning other than the high blow-by rates and did not extend beyond a few engine cycles. The piston skirt had been weakened by the channeling and by the increased temperature and the full pressure of the combustion chamber was acting on the sides of the channel.

The stresses in the aluminum became so great and the temperature so high that the skirt collapsed and permitted the free flow of burning gases into the crankcase.

Second Endurance Test

Endurance test. - The second endurance test was begun, after a normal run-in of the rings, at an inlet-air pressure of 50 inches of mercury absolute with the oil flow to the cylinder reduced, below that for the first test, to 0.5 pound per minute. Operating conditions held constant during the test were as follows:

Engine speed, rpm	2600
Inlet-air temperature, °F	200
Fuel-air ratio	0.085
Compression ratio	6.65
Fuel	AN-F-28, Amendment-2
Oil-in temperature, °F	185
Outlet-coolant temperature, °F	250
Spark advance, degrees B.T.C.:	
Inlet	28
Exhaust	34
Oil flow to piston, pound per minute	0.5
Oil	Navy 1120

Complete data were taken at 1/2-hour intervals throughout the test.

After 12.5 hours of operation the rings were examined. (See fig. 8.) The top ring was stuck and broken a short distance from the gap; the second ring was stuck for a part of its length. All the rings were considerably worn and had an etched appearance. After 42.0 additional hours of running the cylinder was again removed and a visual inspection showed all the compression rings to be broken. Upon reassembly the inlet-air pressure was raised to 56 inches of mercury absolute and the test was continued until complete piston failure occurred at a total running time of 84.25 hours (fig. 9).

Blow-by and crankcase pressure. - The curves of rate of blow-by and crankcase pressure for the second test are shown in figures 10 and 11. These curves show a marked increase in the blow-by rate and the crankcase pressure after the first 4.5 hours of running, which indicates the beginning of compression-ring failure probably by sticking of the top ring. Unpublished data taken on this engine have shown that 0.5 cubic foot per minute is an average value for the rate of blow-by with a new piston and ring assembly when operating under conditions similar to normal rated power. An increase to about 1.0 cubic foot per minute usually indicates sticking of the top ring.

From the time the top ring became stuck until the first inspection, the rate of blow-by showed a gradual upward trend, probably indicating the rapid rate of deterioration to the condition shown in figure 8. Between the first and the second inspections the rate of blow-by was quite irregular but, after the second inspection, began an upward climb continuing almost to the end of the test. A similar upward climb, which may be associated with the gradual channeling of the piston, occurred during the last 1.5 hours of the first test. Such channeling would provide a more unrestricted path for the blow-by gases past the broken compression rings.

Analysis of failed piston. - Figure 9 shows the piston at the end of the second test. The failure was quite similar to that of the first test. In this case, however, much of the top two compression rings was still in the ring grooves, probably caused by the rings' being more severely stuck than in the first test and therefore not so free to rotate in the grooves.

Particles of aluminum alloy were found in the oil-ring groove displaced a considerable distance from the point of failure. Here again is evidence that the channeling of the piston took place over an appreciable period of time. It appears unlikely that these aluminum particles could have moved so far along the groove at the instant of final failure.

Effect of Blow-By on Power Output

The values of brake mean effective pressure at various times during the two tests (figs. 4 and 12, respectively) are plotted against rate of blow-by in figure 6. The data for the lower curve were taken from the last part of the second test (inlet-air pressure of 56 in. Hg absolute) because the rate of blow-by during the first part of the test was so low that a reasonably accurate curve could not be obtained.

The two curves of figure 6 are straight lines and are roughly parallel. Calculations based on the slopes of these curves indicate that the power loss for a given rate of blow-by is about three times what would be expected if the weight of blow-by gases were considered as an equivalent weight loss of fresh charge. An Orsat analysis of the blow-by gases showed an oxygen content of about 15 percent, and unpublished data taken at this laboratory confirm this value for the blow-by gases of another engine. The blow-by gases therefore probably consisted of about two-thirds unburned charge and one-third burned charge and the rates of blow-by shown in figure 6 should account for somewhat less than one-third of the power loss on the basis of gas leakage alone. The rest of the power loss can be accounted for only by possible increases in piston and ring friction and by pumping losses caused by the high crankcase pressure.

CONCLUSIONS

From endurance tests to determine the effect of progressive ring failure on piston life in an Allison single-cylinder engine, the following conclusions can be drawn:

1. Complete failure of the compression rings may require a relatively long period of operation after initial failure of the top ring by sticking or breaking.

2. Complete failure of the compression rings does not necessarily bring about destruction of the piston unless operation of the engine is continued for a considerable length of time.

3. The power loss accompanying high blow-by rates cannot be entirely accounted for on the basis of gas leakage.

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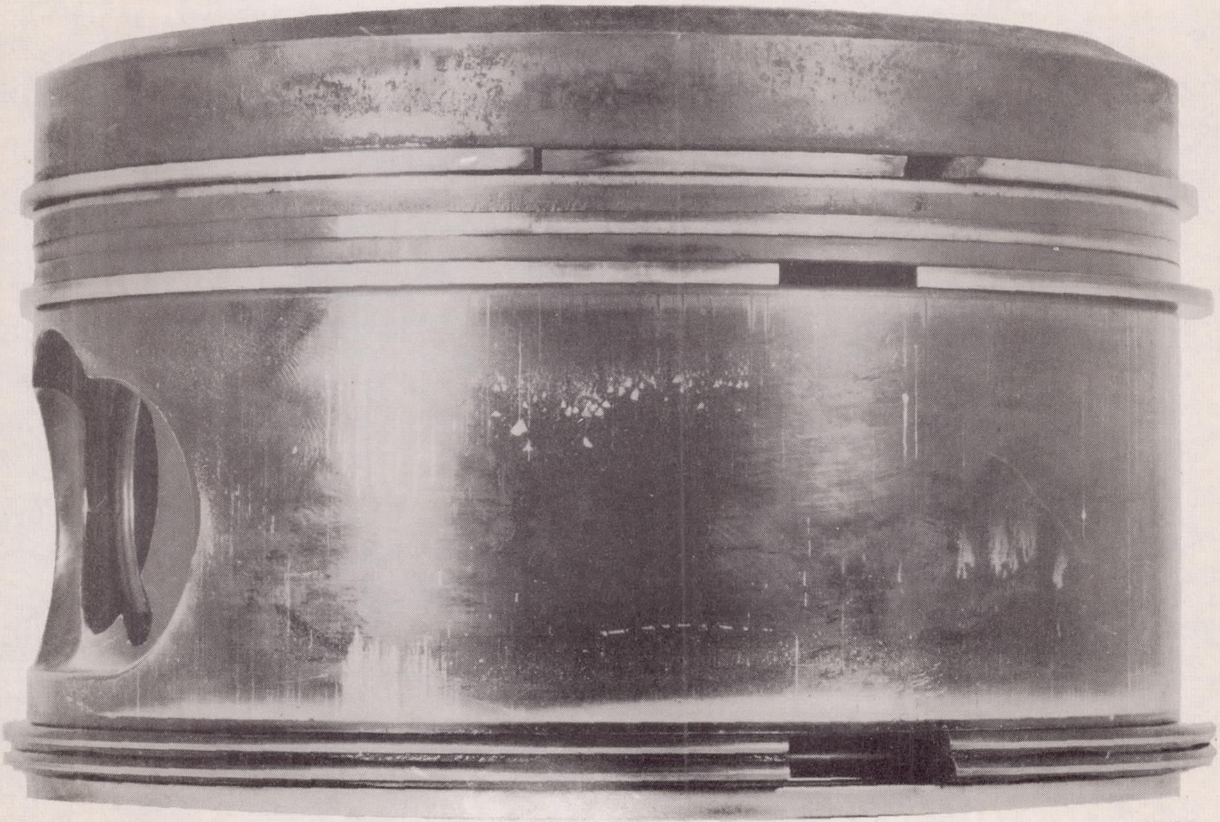

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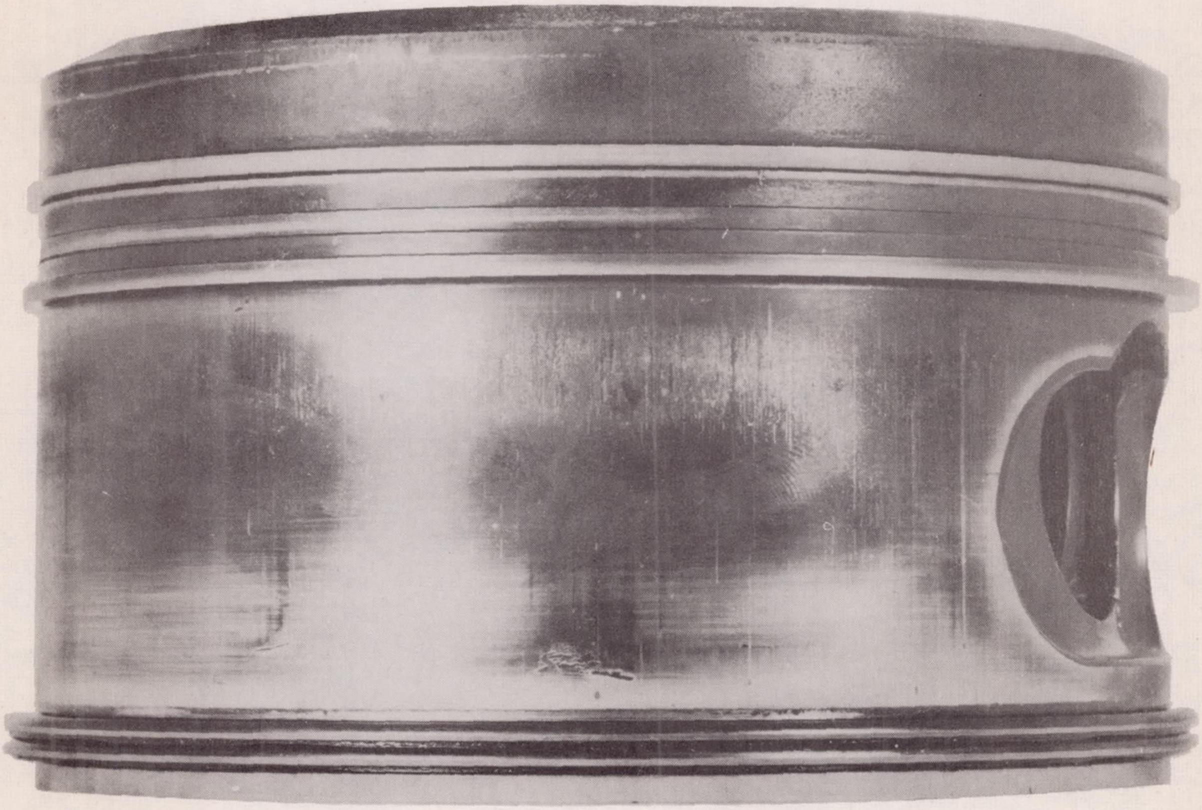
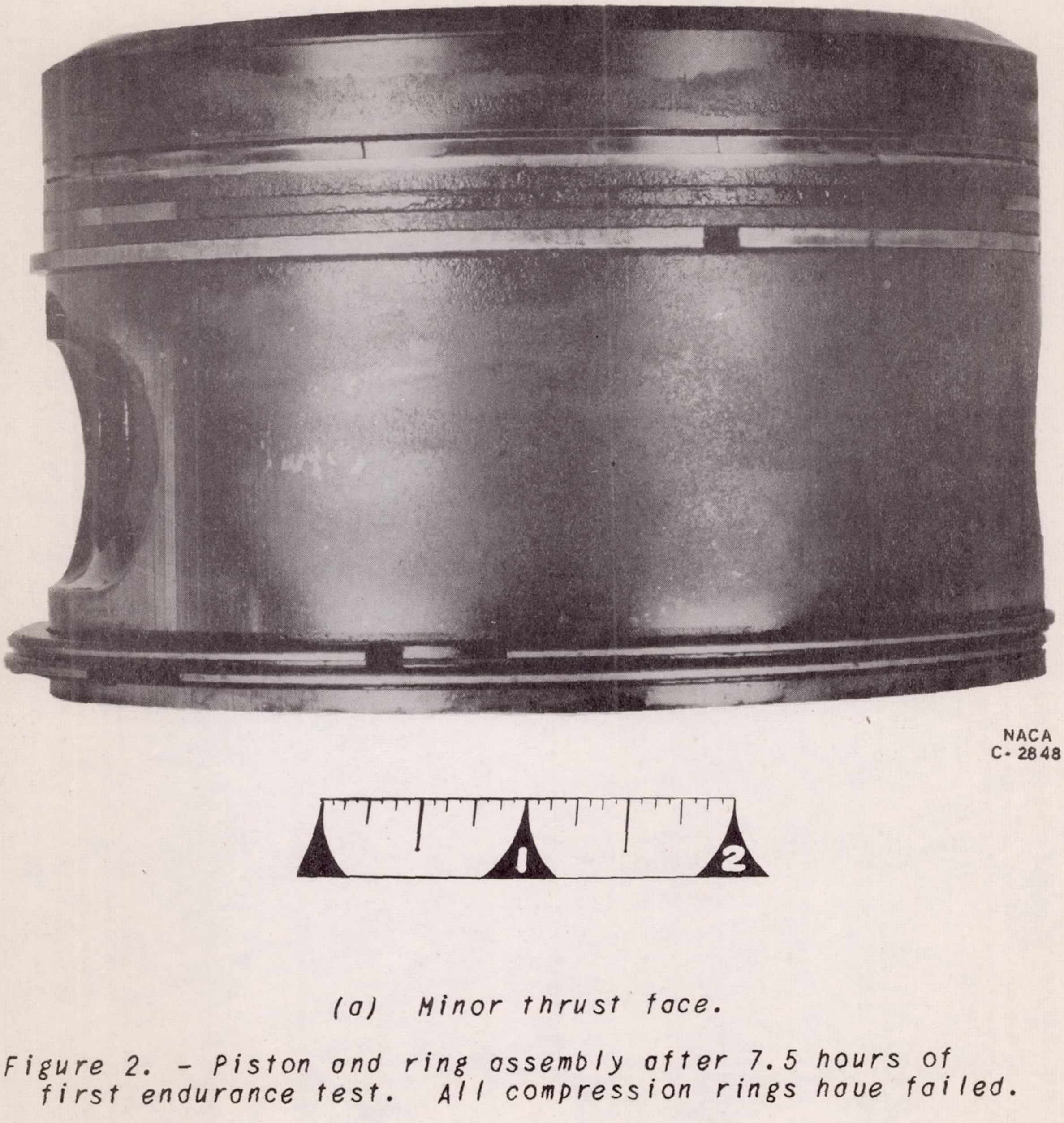
(a) Minor thrust face.

Figure 1. - Piston and ring assembly just before the first endurance test. Failure of top and second rings has taken place.



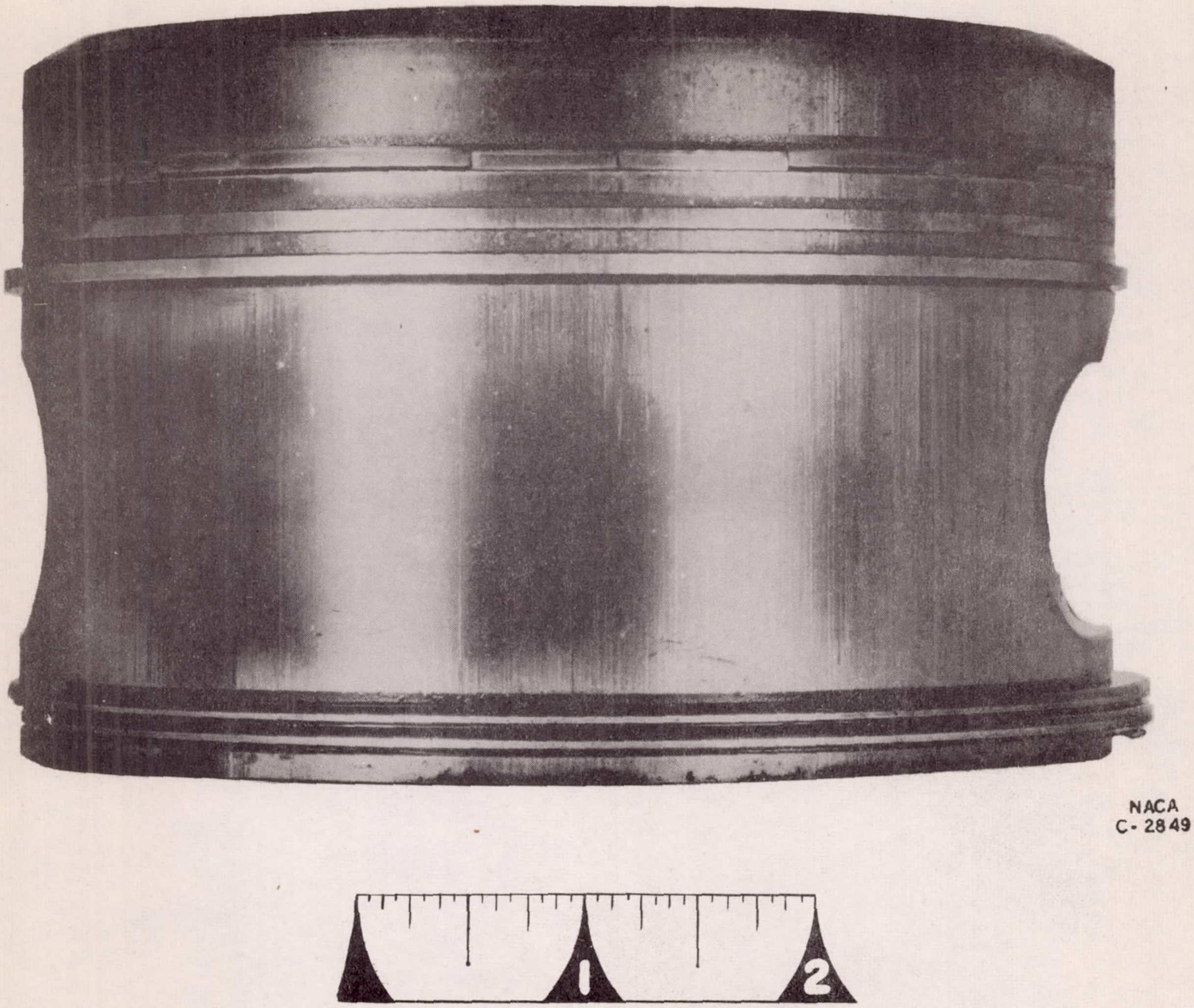
(b) *Major thrust face.*

Figure 1. - Concluded.



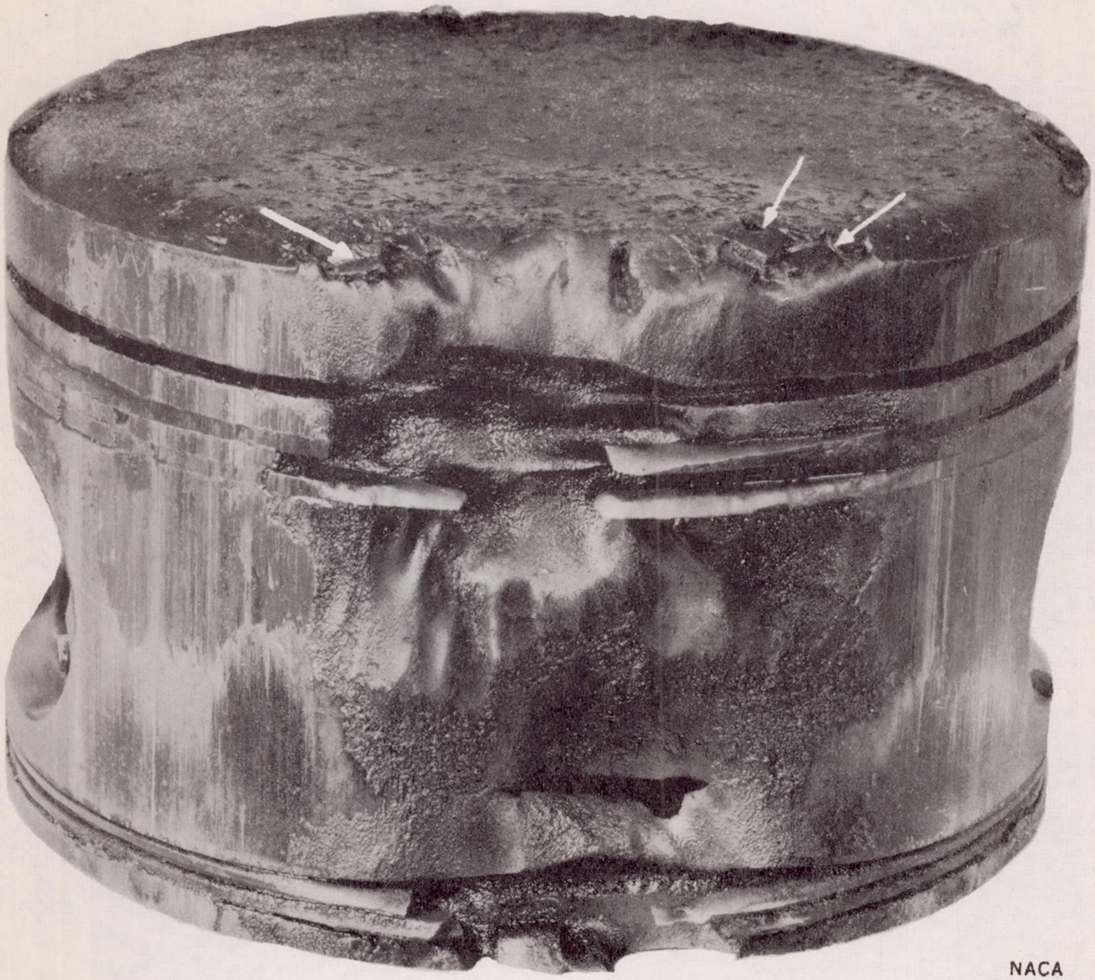
(a) Minor thrust face.

Figure 2. - Piston and ring assembly after 7.5 hours of first endurance test. All compression rings have failed.



(b) Major thrust face.

Figure 2. - Concluded.



(a) Minor thrust face.

Figure 3. - Piston and ring assembly at end of first endurance test. Total test time 33.1 hours. Arrows indicate pieces of piston rings imbedded in piston.

(b) Major thrust face.

Figure 3. - Concluded.

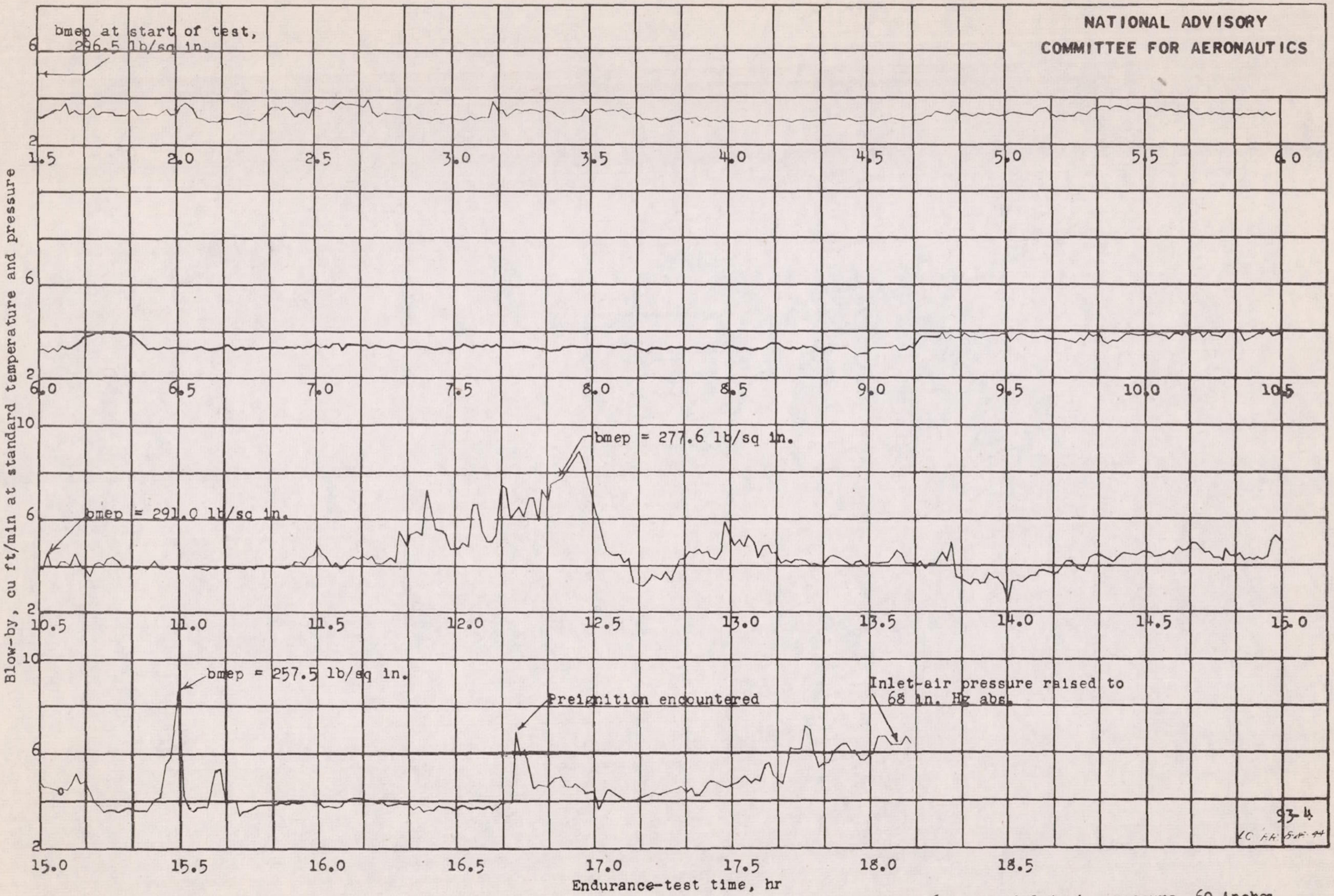


Figure 4. - Effect of running time on rate of blow-by for first endurance test. Engine speed, 2600 rpm; inlet-air pressure, 60 inches of mercury absolute (except as noted); inlet-air temperature, 100° F; fuel-air ratio, 0.095; oil flow to piston, 2.0 pounds per minute.

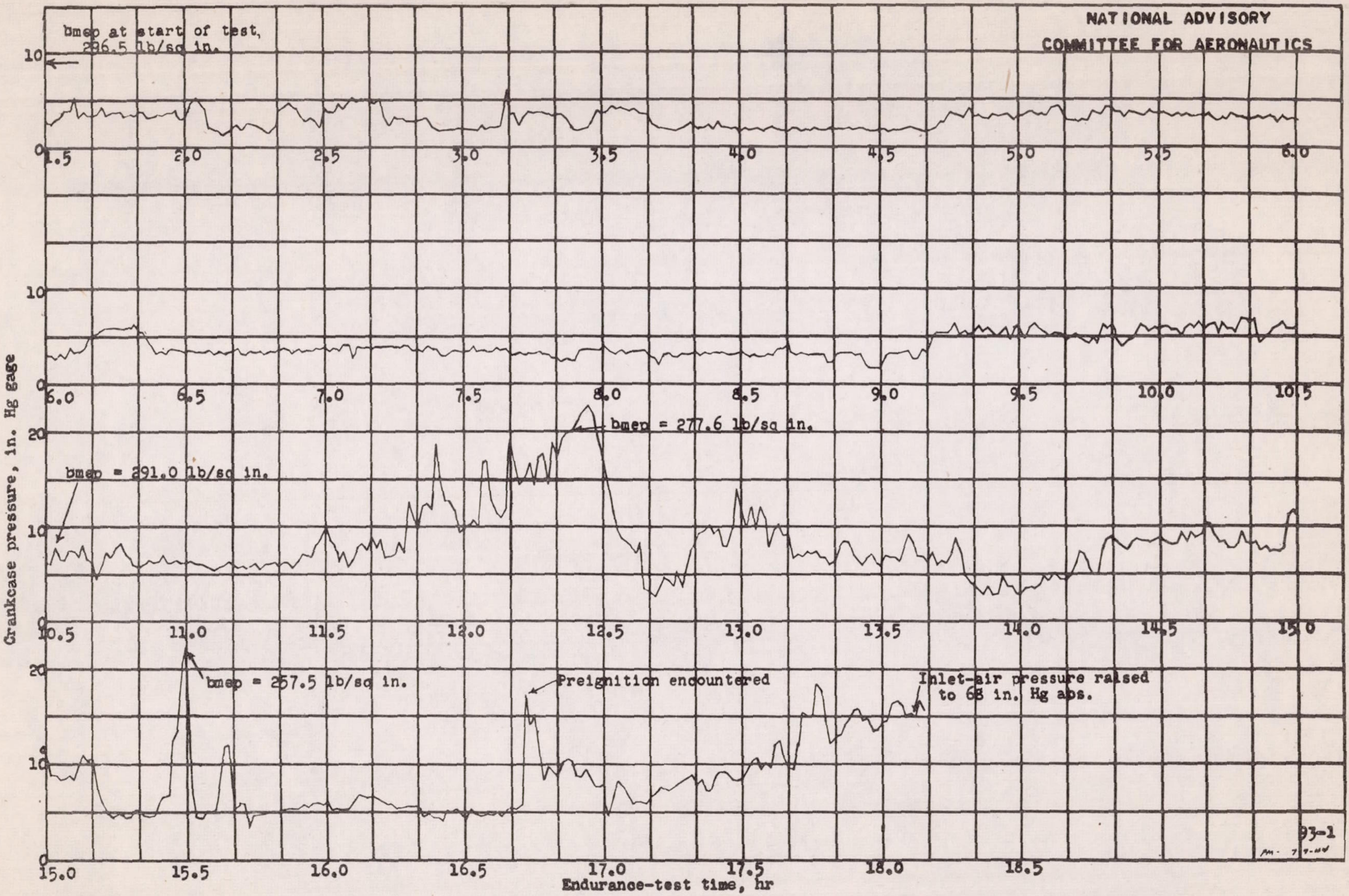


Figure 5. - Effect of running time on crankcase pressure for first endurance test. Engine speed, 2600 rpm; inlet-air pressure, 60 inches of mercury absolute (except as noted); inlet-air temperature, 100° F; fuel-air ratio, 0.095; oil flow to piston, 2.0 pounds per minute.

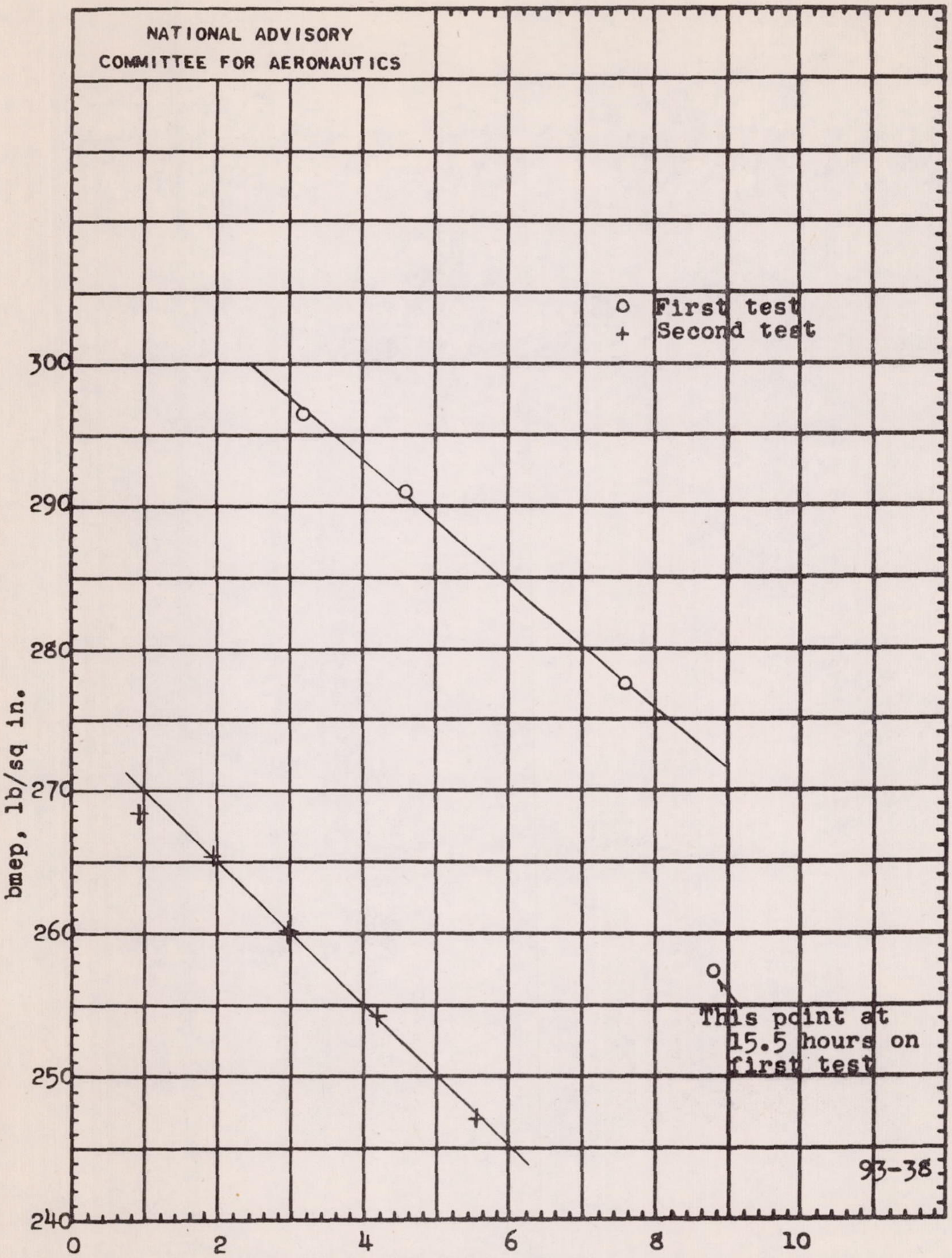


Figure 6. - Effect of rate of blow-by on brake mean effective pressure. Engine speed, 2600 rpm; inlet-air temperature, 100° F for first test, 200° F for second test; fuel-air ratio, 0.095 for first test, 0.085 for second test; oil flow to piston, 2.0 pounds per minute for first test, 0.5 pound per minute for second test.

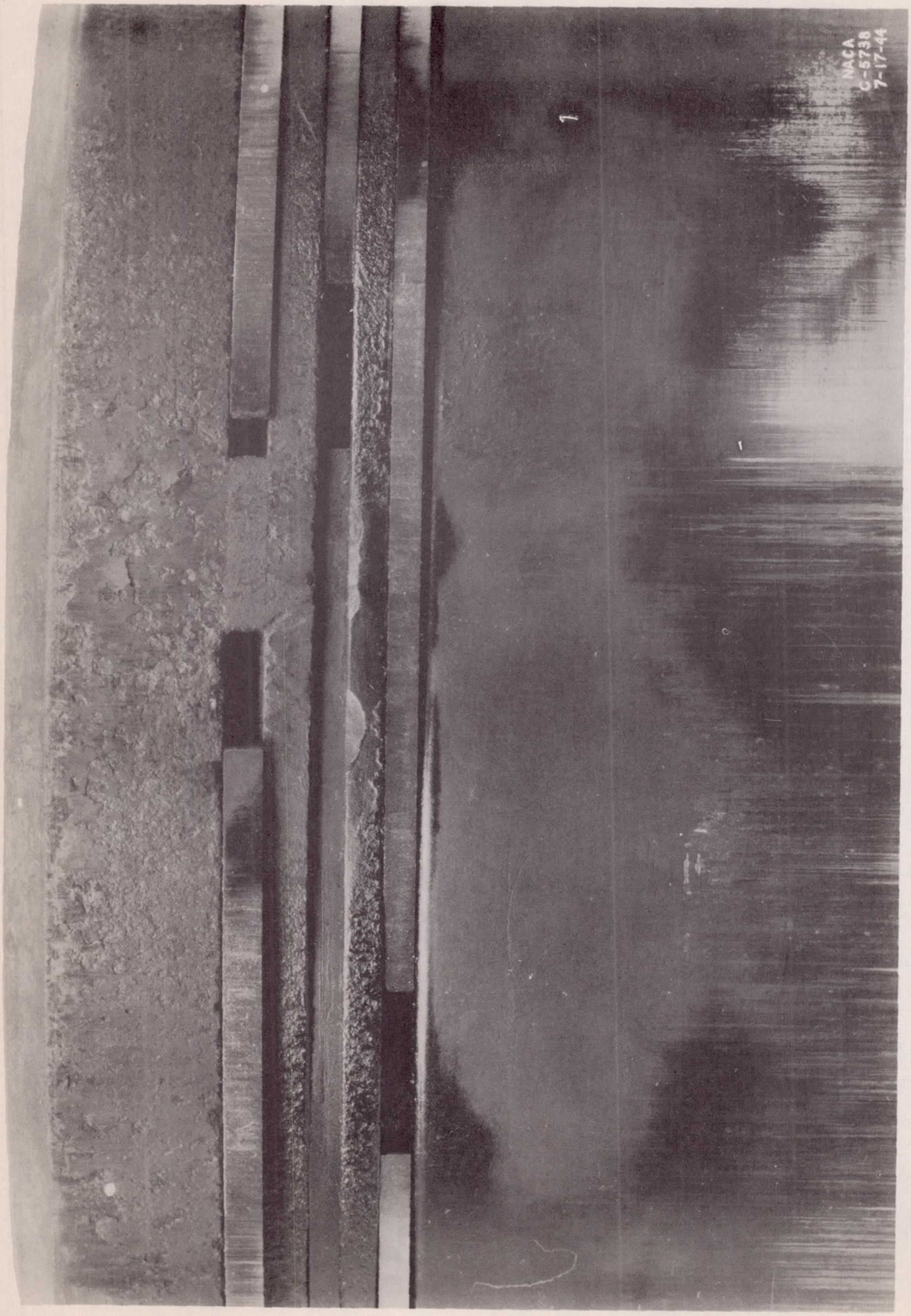
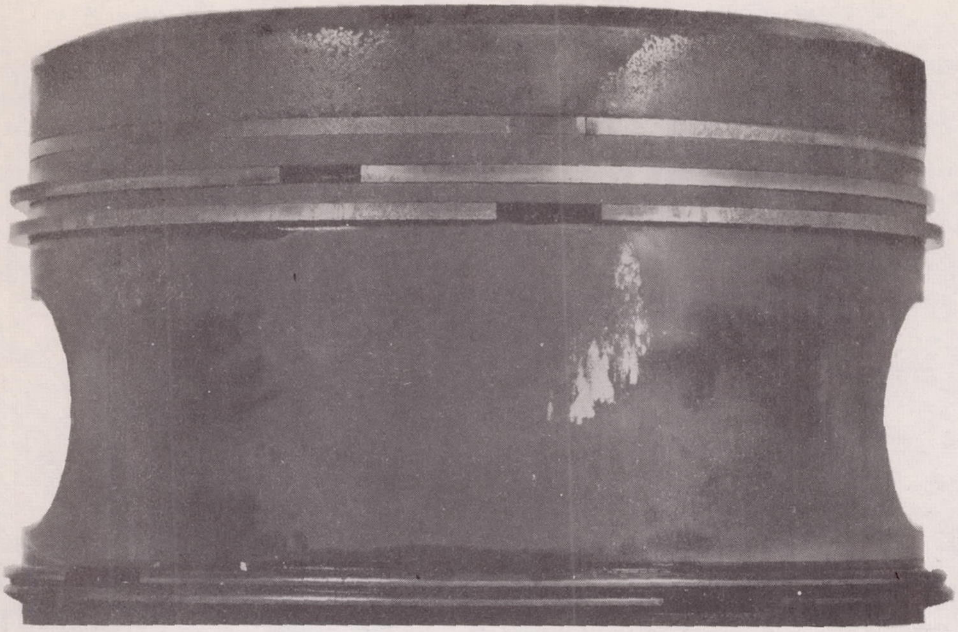
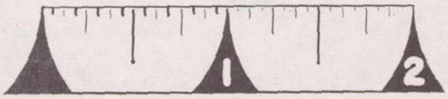


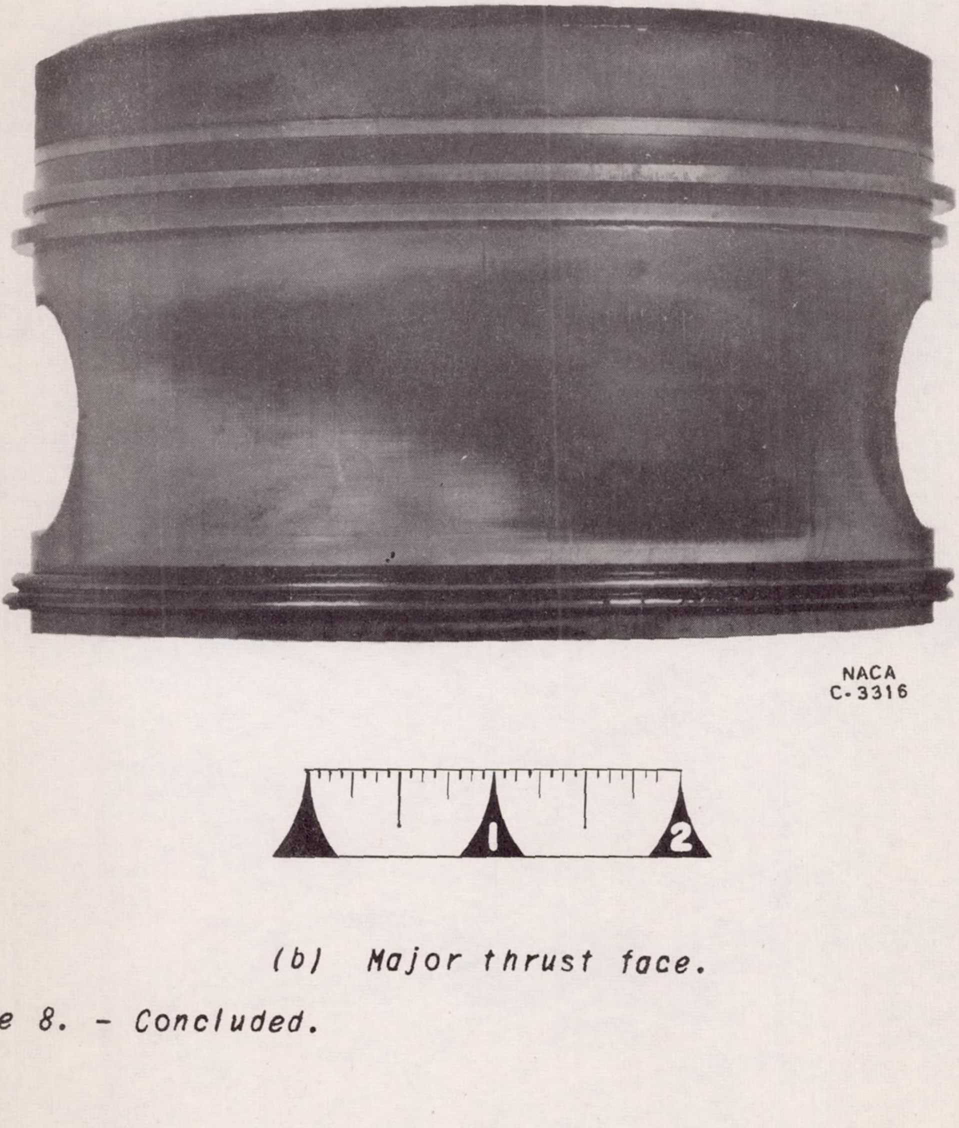
Figure 7. - Beginning of piston erosion as caused by high rate of gas flow past piston rings from another test program.





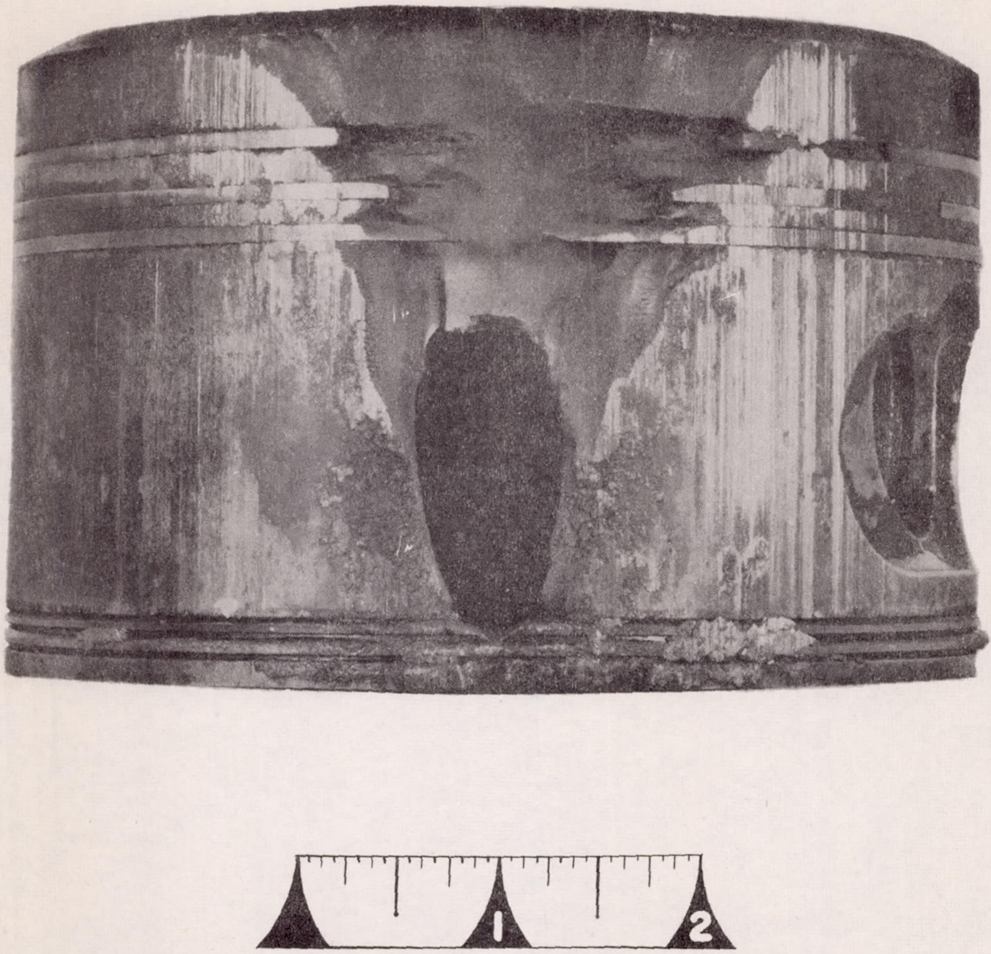
(a) Minor thrust face.

Figure 8. - Piston and ring assembly after 12.5 hours of second endurance test. Top ring broken and stuck; second ring partly stuck.



(b) Major thrust face.

Figure 8. - Concluded.



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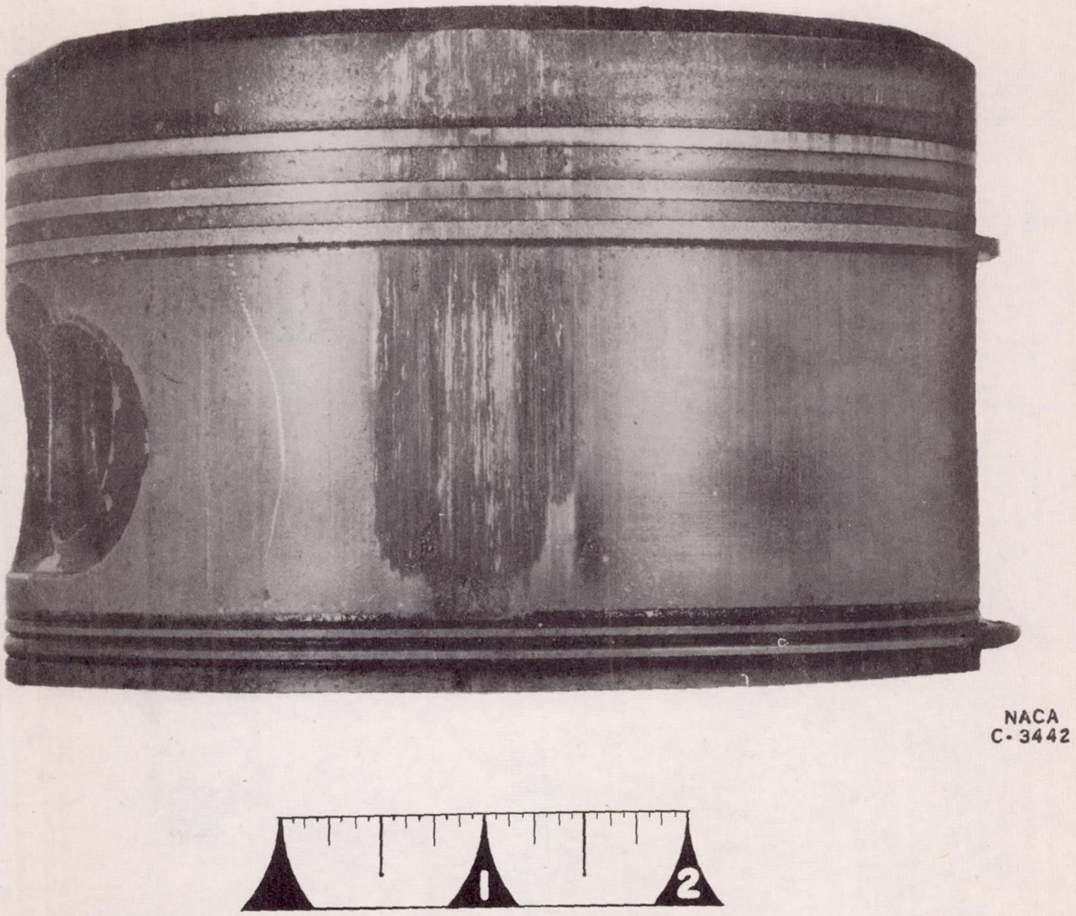
(a) Minor thrust face.

Figure 9. - Piston and ring assembly at end of second endurance test. Total test time, 84.25 hours.



(b) Major thrust face.

Figure 9. - Concluded.

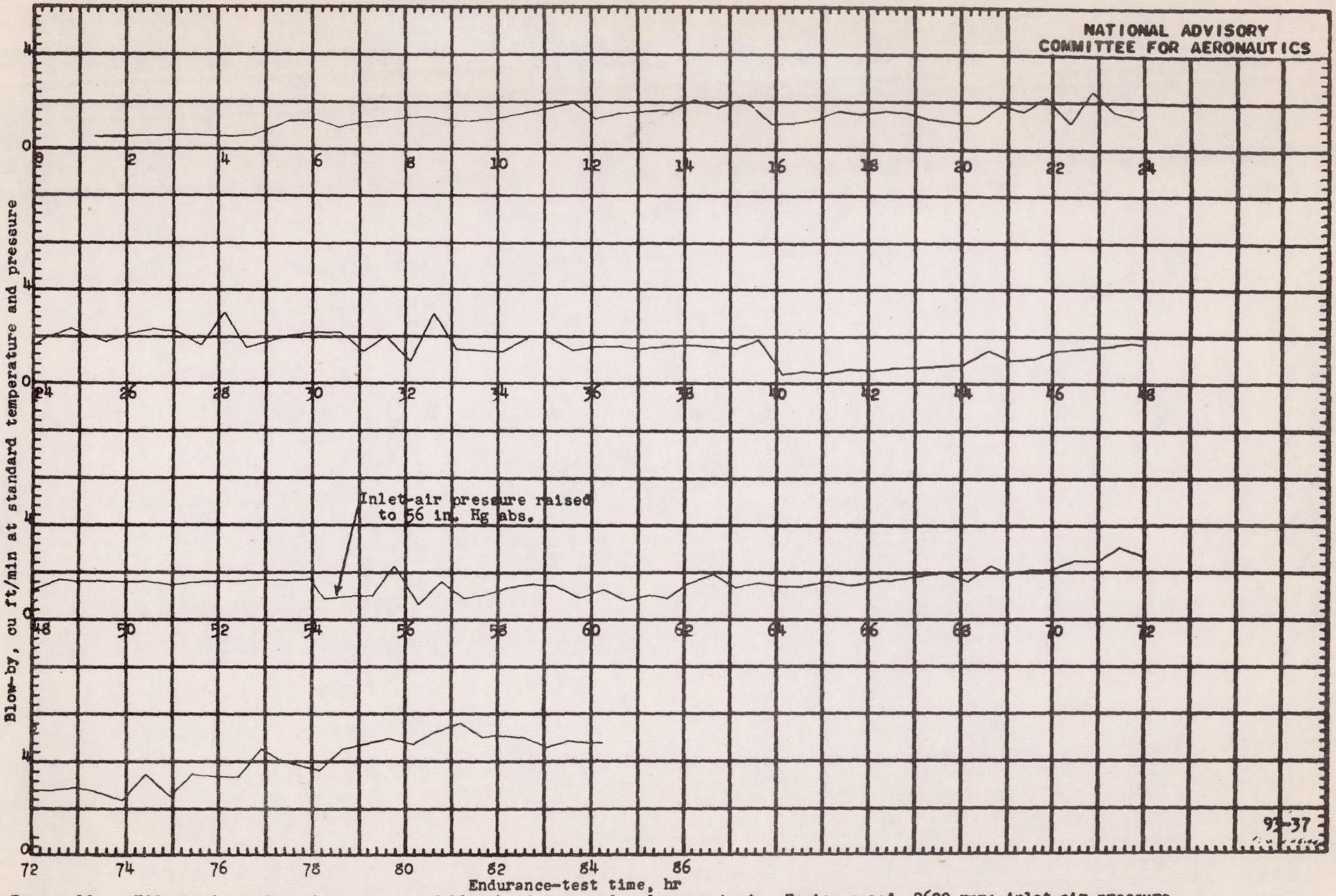


Figure 10. - Effect of running time on rate of blow-by for second endurance test. Engine speed, 2600 rpm; inlet-air pressure, 50 inches of mercury absolute (except as noted); inlet-air temperature, 200° F; fuel-air ratio, 0.085; oil flow to piston, 0.5 pound per minute.

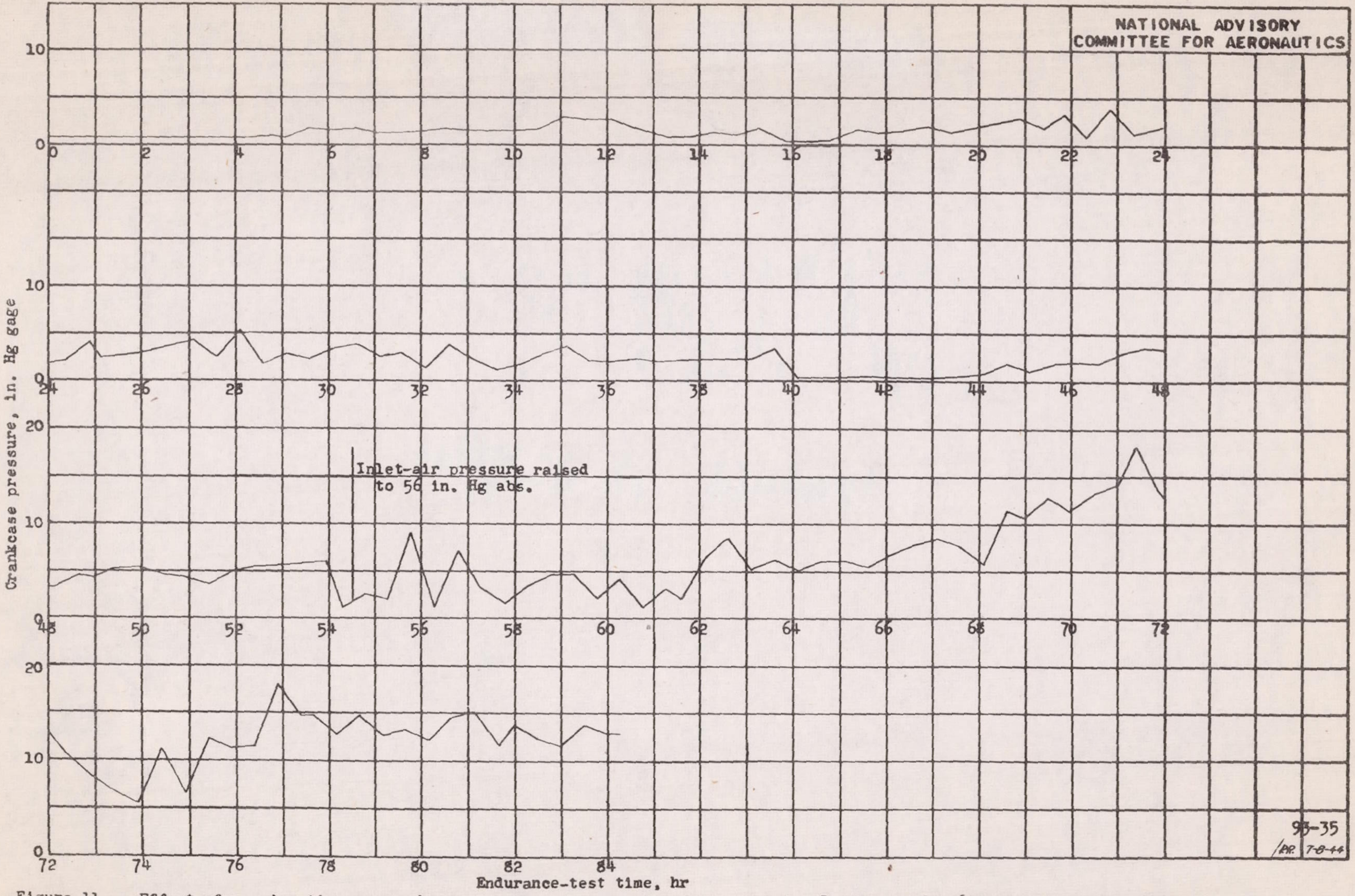


Figure 11. - Effect of running time on crankcase pressure for second endurance test. Engine speed, 2600 rpm; inlet-air pressure, 50 inches of mercury absolute (except as noted); inlet-air temperature, 200° F; fuel-air ratio, 0.085; oil flow to piston, 0.5 pound per minute.

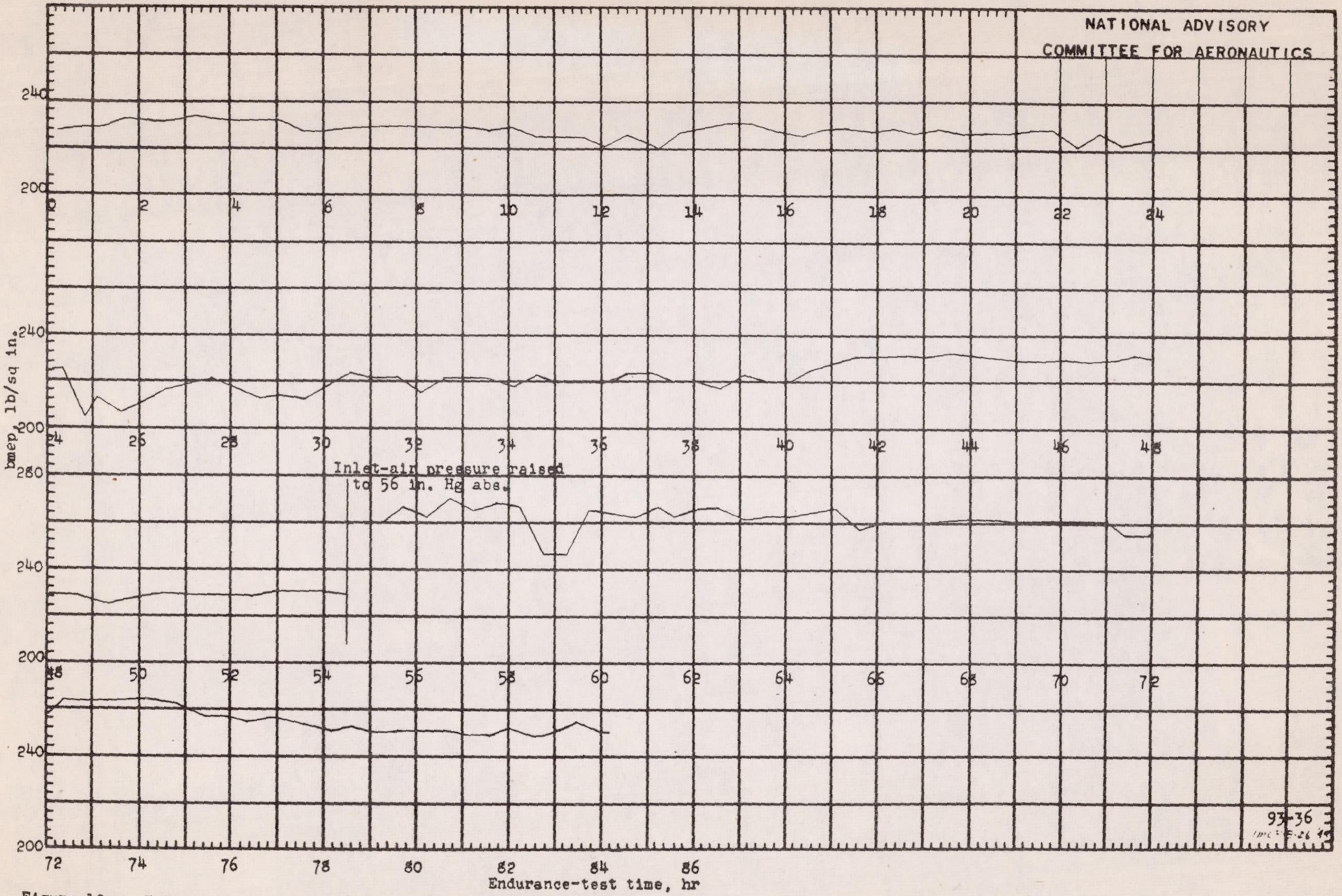


Figure 12. - Effect of running time on brake mean effective pressure for second endurance test. Engine speed, 2600 rpm; inlet-air pressure, 50 inches of mercury absolute (except as noted); inlet-air temperature, 200° F; fuel-air ratio, 0.085; oil flow to piston, 0.5 pound per minute.