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Compatibility of Military Standard Engines with Unleaded and Low-Lead Gasolines

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FINAL REPORT
AFLRL NO.19

by

J. V. Moffitt

prepared by

U.S. Army Fuels and Lubricants Research Laboratory
Southwest Research Institute
San Antonio, Texas

under contract to

U.S. Army Mobility Equipment Research and Development Center
Fort Belvoir, Virginia

Contract No. DAAK02-72-C-0254

November 1972

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13. ABSTRACT

The proposed military changeover within CONUS from normally leaded to lead-free fuels by 1975 is of immediate concern to the Army. This concern stems from commercial evidence, to date, that these newer, more highly aromatic fuels deleteriously affect engine performance and cause abnormal, often catastrophic, wear. Thus, the Army needs to know if these lead-free fuels will have a similar impact on its gasoline-powered equipment. This report covers an initial, short-term evaluation of this impact on three different MIL STD generator set models. Comparative results with normally leaded MIL-G-46015, low-lead VV-G-001690, and unleaded VV-G-001690 fuels indicated that these generator sets were as compatible with the low-lead and unleaded fuels as with the current MIL-G-46015 fuel.

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I. INTRODUCTION

Current Federal statutes relating to the reduction and control of vehicle emissions may require the complete elimination of lead from all military and commercial gasolines within CONUS by 1975. There are two major reasons for this lead deletion. First, the free lead and lead compounds resulting from combustion are very toxic, and, when exhausted into the atmosphere, constitute a potential health hazard, particularly in areas of high vehicle density. Second, the 1975 allowable limits on CO, HC, and NO_x emissions will be considerably lower than at present, and, therefore, they will necessitate further purification of the engine exhaust. Present technology indicates that an add-on device, called an exhaust catalytic converter, may best meet this requirement. The platinum catalyst in present converters is incompatible with lead, so that the effectiveness of the unit rapidly diminishes even when trace lead is present.

Unleaded and/or low-lead (about 0.5 g/gallon) fuels are already available in several areas of the United States. The hydrocarbon composition of these fuels differs from that of normally leaded (2.0 to 3.0 g/gallon) gasolines in that they contain larger percentages of aromatics and lower percentages of saturates. The additional aromatics restore the octane quality lost through deleting the lead.

To date, commercial use of these newer fuels has revealed several serious engine/fuel incompatibility problems. These include abnormal exhaust valve recession, burned pistons, carbon-fouling of spark plugs, and generally poorer vehicle driveability.

Since, by Presidential directive, the Department of Defense (DoD) is required to comply with Federal emissions standards within CONUS, it is obvious that unleaded fuels are a near-future possibility for the Army. In view of the aforementioned incompatibility problems and the high reliability requirements of military engines, the impact of such fuels on all types of gasoline-powered equipment currently in the military supply system is of immediate concern to the Army.

Thus, in order to obtain an answer to the fuel impact question, specifically as it relates to portable military generator sets, the U.S. Army Fuels and Lubricants Research Laboratory (USAFLRL), located at Southwest Research Institute, San Antonio, Texas, conducted an investigation under cognizance of the U.S. Army Mobility Equipment Research and Development Center (MERDC), Fort Belvoir, Virginia to determine the comparative short-term effects of normally leaded, low-lead, and unleaded fuel on the performance, wear, and emissions characteristics of 1.5-, 3.0-, and 10-kW MIL STD generator sets. This report covers the details and results of that fuel/engine compatibility study.

II. SUMMARY OF RESULTS

The results obtained from this investigation indicated that, with respect to performance, the 1.5-, 3.0-, and 10-kW generator sets were as compatible with the low-lead and unleaded VV-G-001690 fuels as with the normally leaded MIL-G-46015 referee fuel. None of the generator sets displayed any tendency to knock or run-on with any of the three test fuels. Also, there were no fuel-related mechanical failures in any of the tests; however, the ignition breaker assembly in one each of the 1.5- and 10-kW sets required replacement due to spring malfunction during the 125-hour endurance tests. In all, there were seven incidents of spark plug fouling, five of which occurred in one 3.0-kW set during the endurance run with MIL-G-46015 and were definitely attributable to lead deposits. One of the two remaining plugs carbon-fouled in the 3.0-kW generator set using unleaded VV-G-001690 test fuel. The other plug carbon-fouled in the 1.5-kW generator set on normally leaded MIL-G-46015 fuel.

With respect to wear, these generator sets were essentially compatible with both the low-lead and unleaded VV-G-001690 test fuels. Valve recession was observed in all sets, but the magnitude was significantly less with the low-lead and unleaded fuels than with MIL-G-46015, particularly in the 3.0- and 10-kW sets. Piston ring wear, as determined by end-gap increase, was minor, and the wear trends were generally more dependent upon engine model than test fuel.

It was found that high oil consumption characterized all of the 3.0-kW generator set tests and resulted in the formation of copious coke deposits in all combustion chambers. Both oil consumption and deposit levels for the 1.5- and 10-kW sets were proportionally much less.

Valid determinations of fuel lead content effects on exhaust emissions from any given generator set model at the beginning and end of the 125-hour endurance tests were obviated by engine-to-engine differences in optimum initial carburetor setting and by the subsequent permissible readjustments of the carburetors during test.

During the initial emissions tests with unleaded fuel, concurrent evaluations of Engelhard PTX Purifiers®, installed on one each of the three generator set models, indicated that these exhaust catalytic converters effected relatively large reductions in NO, NO_x, CO, CO_2, and HC (unburned hydrocarbons). However, when these converters were close-coupled to the tailpipe, they tended to overheat, in all cases, at less than 100 percent of rated generator load. Detailed interface design and test efforts will be required to attain operational compatibility.

A brief evaluation of the Fairbanks-Morse capacitor discharge ignition system, when installed on a 1.5- and a 3.0-kW generator set, showed that the CD system performed satisfactorily over the generator load range at 3600 rpm. However, it had no effect on the corresponding emissions levels obtained over the same load range with the conventional ignition system.

III. DESCRIPTION OF MATERIEL

A. MIL STD Generator Sets

In order to enable the conduct of this engine/fuel compatibility investigation, which involved three different test fuels, MERDC loaned three each new 1.5-, 3.0-, and 10-kW MIL STD generator sets, respectively equipped with MIL STD engine Models 2A016 III, 4A032 II, and 4A084 III, to the USAFLRL. General specifications of these engines are listed in Table I. It will be noted that, due to excessive oil consumption during break-in, one of the 4A032 II engines was exchanged for another of the same model but from a different manufacturer. Figure 1 shows the cylinder numbering sequence for each engine model.

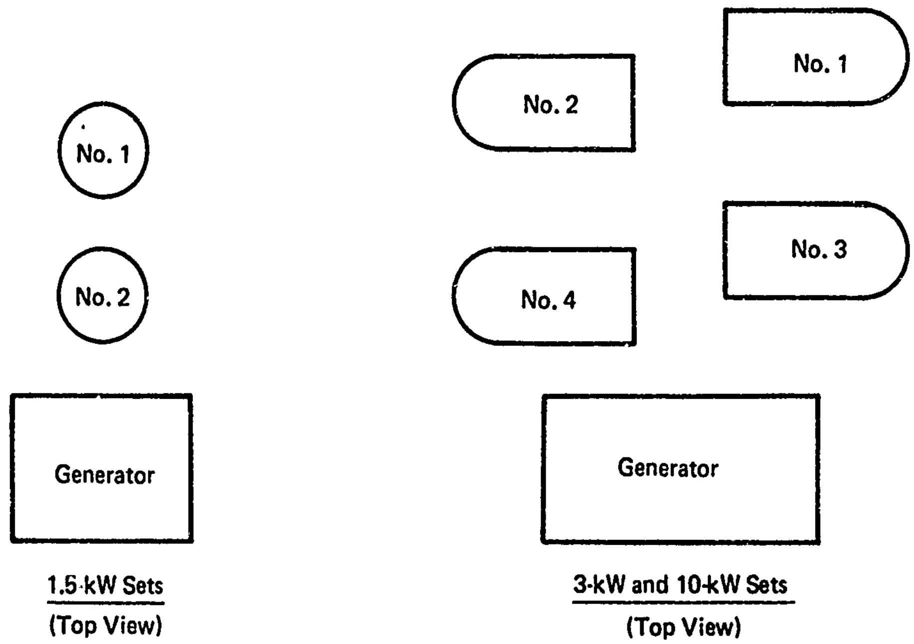

FIGURE 1. ENGINE CYLINDER NUMBERS–MIL STD GENERATOR SETS

B. Fuels

Four different fuels, one unleaded commercial fuel and three test fuels, were required for this study. The unleaded commercial fuel, Indolene clear, was obtained from the American Oil Company and was used as the break-in and emissions reference fuel in all engines. The three test fuels, MIL-G-46015 (MR) Referee Combat Grade I (normally leaded), VV-G-001690 (low-lead), and VV-G-001690 (unleaded) were manufactured by the Howell Refining Company, San Antonio, Texas. The properties of these four fuels, as determined by USAFLRL inspections, are presented in Table II. The test fuel inspection data indicate compliance with government specifications.

C. Lubricant

A MIL-L-2104C lubricant, Mobil Delvac, grade 30, was selected by the USAFLRL as the only oil to be used in these generator set engines. The properties of this lubricant, again as determined by USAFLRL analyses, are listed in Table III.

TABLE I. DESCRIPTION OF MIL STD GENERATOR ENGINES

	Generator Size		
	1.5 kW	3.0 kW	10 kW
Generator output	28 VDC	28 VDC	120/240 VAC, 30, 60 cps
Engine model	2A016-III	4A032-II	4A084-III
Engine type	4-cycle, gasoline, OHV, air-cooled	4-cycle, gasoline, OHV, air-cooled	4-cycle, gasoline, OHV, air-cooled
Number of cylinders/configuration	2 in-line	4 opposed	4 opposed
Bore, in.	2.25	2.25	3.0
Stroke, in.	2.0	2.0	3.0
Displacement, cu. in.	16	32	84
Horsepower at 3600 rpm	3	6	20
Crankcase oil capacity, qt.	5/8	1-5/8	4
Type of lubrication	Splash	Pressure	Pressure
Valve lifter type	Mechanical	Mechanical	Hydraulic
Exhaust valves	Stellite	Stellite	Stellite
Engine manufacturer	Wisconsin	Wisconsin*	Hercules

*Due to abnormally high oil consumption during break-in of one Wisconsin-built engine, MERDC substituted a Chrysler-built engine of the same model.

TABLE II. USAFLRL INSPECTIONS OF REFERENCE AND TEST FUELS

	Indolene Clear Reference	MIL-G-46015 Combat Grade I Referee	VV-G-001690 Low-Lead	VV-G-001690 Unleaded
Fuel Manufacturer	Amoco	Howell	Howell	Howell
Property				
Gravity, °API	58.0	57.6	57.3	56.8
Reid vapor pressure	9.2	8.7	8.9	8.4
Distillation, °F				
IBP	86	93	93	99
10% evap.	128	129	133	135
20% evap.	159	149	162	161
50% evap.	220	221	232	228
90% evap.	315	333	328	328
EP	409	392	378	373
Recovered, %	98.0	98.0	98.0	98.0
Residue, %	1.0	1.0	1.0	1.0
Loss, %	1.0	1.0	1.0	1.0
Gum, mg/100 ml				
Unwashed	3.3	2.5	0.4	6.7
Washed	0.3	0.8	0.0	0.3
Sulfur, wt %	0.010	0.157	0.003	0.006
Lead, g/gal	0.012	2.12	0.44	0.03
Aromatics, % (FIA)	30	27	26	30
Olefins, % (FIA)	3	7	2	3
Research octane no.		93.5	91.0*	93.0
Motor octane no.		82.7	84.9	83.7

*Howell data.

D. Instrumentation

During all generator set operations, speed, load, and (in the 3.0-kW and 10-kW sets) oil pressure were monitored by means of instruments included with the sets. Since, however, the 1.5-kW sets were not equipped with tachometers, a calibrated stroboscope aimed toward the starting pulley was used in determining the speeds of the 2A016 III engines. In addition, calibrated thermocouples were installed in each spark plug gasket, oil pan, and exhaust tailpipe. The spark plug gasket and oil pan thermocouples were connected through a selector switch to a cold junction temperature-compensated potentiometer, while the exhaust thermocouple was connected to an indicating pyrometer.

TABLE III. USAFLRL INSPECTION OF MOBIL DELVAC, GRADE 30 MIL-L-2104C LUBRICANT

Property	Value
Kinematic viscosity, centistokes at 100°F	95.84
Kinematic viscosity, centistokes at 210°F	10.36
Total acid no.	2.49
Total base no.	7.29
Viscosity index	98
Flash point, COC, °F	445
Sulfated ash, wt %	1.45
Barium, wt %	0.06
Calcium, wt %	0.35
Zinc, wt %	0.09
Phosphorus, wt %	0.074

The emissions instrumentation, fully calibrated by the USAFLRL, was of the conventional, EPA-approved analytical type. A stainless steel impact sampling tube was installed in the exhaust tailpipe just upstream from the thermocouple, and the gas sample was passed through an ice-cooled condenser en route to the analytical equipment.

E. Special Tools

In order to permit measurements of valve recession, it was necessary to fabricate a special sleeve-type depth micrometer, which, with the rocker arm assembly removed, could be slipped over the valve spring assembly to rest on the valve deck. With the sleeve held firmly on the deck, the spindle of the micrometer, which was affixed to the opposite end of the sleeve, could be distended by turning the thimble until the spindle contacted the valve tip, at which point the micrometer reading was recorded. Successive, periodic measurements with this tool enabled the monitoring of valve recession by comparison of micrometer readings.

In this investigation, piston ring wear was evaluated solely on the basis of end-gap increase, with no consideration being given to reductions in ring width, thickness, or weight. Usually, ring end-gap is measured with the ring compressed in the cylinder bore. This procedure is satisfactory for assembly purposes; however, after the engine has been run and the cylinder has worn, ring wear measurement based on end-gap increase becomes meaningless. Therefore, in order to obtain a true assessment of ring gap increase, it was necessary to fabricate a ring wear reference gauge block that could accommodate the rings from the 2A016 III and 4A032 II engines and those from the larger bore, 4A084 III engines. The gauge diameters were identical to the standard cylinder bore diameters.

IV. METHOD OF TEST

Before describing the procedures and test plan of this investigation, it should be emphasized that these generator sets were operated under simulated field conditions in that any onsite maintenance, if and when required, was permissible in order to keep the sets operable. This allowable servicing included carburetor adjustments, replacement of fouled spark plugs, and any other external repairs not requiring partial, or complete, engine disassembly. Only in the event of catastrophic failure would a test be terminated.

A. Test Preparations

A uniform procedure was followed in preparing each of the generator sets for test. First, the engine was disassembled and inspected for possible defects. The components were then permanently marked as to their original locations to assure and facilitate proper reassembly. Next, all visible deposits from the factory green run were then removed from the pistons, rings, combustion chambers, valves, and cylinder bores by solvent cleaning. The valves were than reseated.

At this point, since the corresponding components of all three engines of a given model were virtually indentical in appearance, photographs were taken of a representative combustion chamber (including valve seats), cylinder, piston, valve (intake and exhaust), and spark plug tip from one engine of each model. Originally, these pre-test photographs were to be used for comparison with post-test photographs of the same parts. With approval of MERDC, however, these pre-test pictures are not included in this report since they do not contribute significant information.

Next, in order to provide the basis for wear evaluations, measurements were made of (a) all intake and exhaust valve seat widths, (b) all piston ring end-gaps, (c) all intake and exhaust valve total lengths, and (d) the longitudinal and transverse bore diameters of each cylinder at each of three selected horizontal planes. Upon completing the measurements, the rubbing components were pre-oiled with test lubricant, and the engine was reassembled to the technical manual specifications, using new gaskets and seals, then reinstalled in its generator set. The generator set was then removed to the test cell and made ready for break-in.

B. Break-In

Upon completing the make-ready, the crankcase was charged to the "full" mark on the dipstick with new test lubricant. The break-in fuel, Indolene clear, was then introduced to the carburetor from a 55-gallon drum, and the engine given a 16-hour break-in according to the following schedule:

Time, hours	Speed, rpm	Load, % rated
1	3600	0
4	3600	25
5	3600	75
6	3600	100

Just prior to the break-in, the initial, optimum carburetor setting was established by operating the engine briefly at 3600 rpm and 100 percent rated load. During this time, the fuel needle valve, first, was closed until operation became unstable, then the valve was slowly opened until the engine again became unstable. Having noted the valve setting at the lean and rich stability extremes, the valve was finally positioned midway between the two settings. This final setting was considered to be optimum.

Upon completing the first hour of break-in, the 1.5- and 3.0-kW sets were stopped to permit checking the intake and exhaust valve clearances and also the crankcase oil level. Since the 10-kW generator sets were equipped with hydraulic valve lifters, this clearance check was not performed on those sets. Following the valve clearance and oil checks, the break-in was resumed and completed, with hourly readings of engine data being recorded.

At the end of the break-in, the compression pressure of each cylinder was checked and recorded. Shortly after the compression check, measurements were made and recorded of the intake and exhaust valve stem heights above the valve decks. The used oil was then drained from the engine, and the sump was fully recharged with new test oil.

C. Initial Emissions Tests

Next, while operating the generator set at rated speed (3600 rpm) with Indolene clear fuel, exhaust gas samples were obtained at no-load, 25, 50, 75, 100, and 125 percent of rated load (or at maximum overload, if less than 125 percent). Each sample was passed through an ice-cooled condenser, then analyzed for dry NO, NO_x, CO, CO_2, and HC before proceeding to the next higher load condition.

Upon completing the reference emissions test with Indolene clear fuel, the test was repeated with either MIL-G-46015, low-lead VV-G-001690, or unleaded VV-G-001690, whichever test fuel was designated for that particular generator set. The oil level was then restored to full, and the weight of the makeup oil was recorded.

D. Performance and Wear Test

The engine was then restarted and run for 125 hours at 3600 rpm and 100 percent rated load using the same test fuel as in the initial emissions test. Engine conditions were recorded hourly, and close attention was paid to the occurrence of any knock or dieseling. Neither condition was noted. Mandatory shutdowns were made at 25-hour intervals to enable the measurement of valve stem heights for the purpose of monitoring valve recession. The shutdown schedule for oil level adjustments was flexible and depended upon the oil consumption rate of the engine.

At the conclusion of the 125-hour endurance test, the engine was stopped for restoration of the oil level as well as to perform the final cylinder compression pressure check. Again, measurements were made and recorded of the intake and exhaust valve stem heights.

E. Final Emissions Tests

Final emissions tests were then conducted, first, with the same fuel as that used in the 125-hour endurance run, and second, with Indolene clear reference fuel. The operating schedule sampling procedure for these final runs was the same as in the initial emissions tests.

F. Post-Test Procedures

Upon completing the final emissions tests, the engine was stopped and the oil was drained into a clean, sealable container. Final measurements of valve stem heights were then made and recorded.

The engine exhaust system, chassis ground strap, and all wiring were disconnected and the generator set was removed to the shop teardown area.

The engine was then carefully disassembled so as not to disturb any deposits that may have formed on the various components. Photographs were then taken of all combustion chambers, valve seats, valves, pistons, cylinder bores, and spark plug tips.

After the photographs were taken, the same engine components that were measured before assembly were cleaned and remeasured for comparison with the initial dimensions.

The engine was then loosely reassembled, reinstalled in its generator set, and prepared for return to MERDC.

V. DISCUSSION

In discussing these fuel compatibility tests, reference will be made to the resultant data which are contained in four appendices to this report. These appendices and their respective contents are as follows:

Appendix A – Operating data summary tables for the 125-hour performance and wear tests

Appendix B – Tabulated wear data

Appendix C – Post-test photographs of engine components

Appendix D – Emissions data

It will be observed that, in general, these data are arranged in a manner that facilitates direct comparisons of the effects of the three test fuels on a given generator set model.

A. Performance

Spark Plug Fouling. As stated in the Summary of Results, none of the nine generator sets exhibited any tendency to knock or run-on whether operating on normally leaded, low-lead, or unleaded fuels. However, in the 3.0-kW sets, five spark plugs lead-fouled and one plug carbon-fouled. Also, one plug carbon-fouled in one of the 1.5-kW sets. Referring to Table A-I, it will be observed that the single carbon-fouling incident with the 1.5-kW generator set occurred at 60 test hours while operating with normally leaded MIL-G-46015 fuel. Unfortunately, that spark plug was cleaned and reinstalled without documenting its appearance. The same plug (No. 2) as it appeared at the end of the test is shown in the upper photograph of Figure C-19; however, here the dominant deposit is lead, not carbon.

The Model 4A032 II MIL STD engine (3.0-kW generator set) appeared to be particularly susceptible to spark plug lead-fouling since all five of the lead-fouling incidents in these tests occurred in this engine model. As noted in Tables A-IV and A-VI, five plugs lead-fouled with normally leaded MIL-G-46015 fuel and one plug carbon-fouled with unleaded VV-G-001690 fuel. The upper photograph in Figure C-39 shows the condition of the plugs that were replaced at 121 hours of the MIL-G-46015 endurance test. At that replacement, only the No. 2 plug was actually fouled; however, all four plugs were changed, since lead-fouling of the other three appeared to be imminent. Figure C-40 shows the set of plugs as removed after the 125-hour test with unleaded VV-G-001690. The relative cleanliness of the No. 2 plug (second from left) is due to the fact that the plug was newly installed at 108 test hours.

Statistically, the spark plug fouling experience with the nine MIL STD generator sets was good. Since carbon fouling is one of the major field problems associated with the use of unleaded fuel, it is especially significant that, in these generator set tests, only one such failure was encountered with unleaded VV-G-001690. This record is particularly impressive in view of the inherent, rich-mixture operating characteristics of these generator sets as opposed to the much leaner mixtures in automobile engines.

Oil Economy. Although not a fuel-related performance problem, high oil consumption characterized the operations of all the 3.0-kW generator sets. This characteristic was first observed during the 16-hour break-in of one of the 3.0-kW sets, which consumed 5.34 lb as opposed to 2.80 and

3.35 lb, respectively, for the other two 3.0-kW sets under the same conditions. As a result, the engine having the highest oil consumption was removed from its generator and subsequently returned to MERDC in exchange for another new engine of the same model but from a different manufacturer. The replacement engine (S/N J-069253) consumed 2.23 lb of oil during its 16-hour break-in, and, later, in the 125-hour endurance run, also had the lowest average consumption (0.093 lb/hr) of the three 3.0-kW generator sets.

A record of the time and weight of each oil addition during each of the 125-hour tests is included in the engine operating summary tables in Appendix A. Since each test was started on a full crankcase charge and since the same oil level was restored at the end of test, the sum of the oil add weights represents the total weight of oil consumed within the 125-hour run. Thus, the average oil consumption rate, expressed in pounds per hour, is equal to the total weight of oil additions divided by 125. These average consumption rates are also shown in the same tables. From these data, it is clear that the oil economy of the 3.0-kW generator sets was disproportionally poorer than that of either the 1.5- or 10-kW sets, when differences in engine size and output are considered.

The effects of the exceptionally poor oil economy exhibited by the 3.0-kW generator sets were clearly evident in the form of heavy coke deposits in all combustion chambers. In addition to these carbonaceous deposits, there were also lead deposits, which varied in severity from "heavy" with the normally leaded MIL-G-46015 to "light" with unleaded VV-G-001690 test fuel. These deposition trends are illustrated in Figures C-21, C-22, and C-23, which respectively show typical combustion chambers from the 3.0-kW sets that were operated with normally leaded, low-lead, and unleaded test fuels. Although the abnormally severe carbonaceous deposits had no noticeable effect on the performance of these generator sets, it is reasonable to presume that if the endurance tests had been longer than 125 hours, some form of malcombustion eventually would have ensued.

Fatigue Problems. Throughout this investigation, the operation of the generator sets was essentially trouble-free. However, a few isolated incidents of component failure which, although not fuel-oriented, should be mentioned, since they relate directly to reliability. Two of these incidents involved ignition breaker malfunctions and required replacement of the breaker assemblies. In the first case, the breaker spring in one of the 1.5-kW generator sets softened during either the break-in or the initial emissions tests and prevented restart at the beginning of the 125-hour endurance run. In the second case, the breaker pivot pin in one of the 10-kW generator sets worked loose, thereby causing speed and load surging at 21 hours of the 125-hour test. These incidents are documented in Tables A-II and A-IX, respectively. In another failure, which could have had disastrous results, the oil dipstick in one of the 3.0-kW generator sets broke off, apparently due to vibration, about four inches from the tip. This failure occurred some time during the break-in, but it was not discovered until the next oil level check. Fortunately, the broken segment dropped harmlessly into the oil pan without contacting any moving parts and was later retrieved and repaired.

B. Wear

The wear data shown in Appendix B represent only the resultant changes or differences between the initial and final measurements (in inches) of each of the various engine components.

Valve Recession. Contrary to expectations, the average valve recession in these MIL STD generator sets was *significantly less* with *low-lead* and *unleaded fuels* than with *normal leaded* fuel. This was true for both the intake and *stellite* exhaust valves, as shown in Table B-1. It will be noted that these data were corrected for permanent changes in valve overall length due to stem stretching or tip wear during test. These deformations were not accounted for in the interim measurements of valve stem height which involved only that portion of the stem protruding above the valve deck when the valve was fully closed. Table B-II shows how much each valve changed in overall length. It will be observed that, in most instances, these changes were less than 0.001 inch.

Typical valve sets (intake and exhaust) from the three each 1.5-, 3.0-, and 10-kW generator sets are depicted in Figures C-4 through C-6, C-24 through C-26, and C-44 through C-46, respectively. These photographs show the tulip end of the valve, including the valve face. In each valve set, the larger diameter valve is the intake valve. It will be observed that, in each generator set model, lead deposits on the exhaust valve faces decreased from moderately heavy with the normally leaded fuel to practically zero with the unleaded fuel. However, it will also be noted that, as the lead deposits diminished, the exhaust valve faces exhibited signs of wear. The most severe valve face wear occurred on the No. 2 exhaust valve from the 10-kW generator set that used the unleaded test fuel. This valve is illustrated in the lower photograph of Figure C-46. The picture clearly shows that the central area of the valve face was concave, but that the outer surfaces had not worn. The latter observation probably explains why, as indicated in Table B-I, no measurable recession of that valve occurred.

Valve Seat Wear. Table B-III presents the resultant intake and exhaust valve seat wear data, expressed in terms of seat width increase, for each MIL STD generator set involved in this study. Since, with a given fuel, valve recession severity largely depends upon the magnitude of valve seat wear, it seemed logical to expect a reasonable degree of correlation between the two. However, data comparisons between Tables B-I and B-III show that, with the exception of the intake valves and seats in the 1.5-kW generator sets, no such relationship existed. Plausible explanations for the lack of correlation are that (a) the interim and final recession measurements were made *before* the valves were cleaned, whereas the final seat width measurements were made *after* the seats were cleaned, and (b) the optical method of measuring valve seat width was, as previously explained, less precise than the micrometric measurement of valve recession.

Despite relatively coarse measurements of valve seat width, certain wear trends are evident in Table B-III. In the 1.5-kW generator sets, intake seat wear decreased with low-lead and unleaded fuel, but exhaust seat wear increased. In the 3.0-kW and 10-kW generator sets, both intake and exhaust seat wear were least with low-lead fuel, but were approximately the same with normally leaded and unleaded fuels.

Because of the small size of the combustion chambers and the focal limitations of the camera, it was impossible to obtain closeup photographs of the valve seats. However, some indication of their condition may be gained by again referring to Figures C-1, C-2, C-3; C-21, C-22, C-23; and C-41, C-42, and C-43.

Ring Wear. Piston ring wear data, expressed in terms of end-gap increase, are summarized in Table B-IV for each compression and oil control ring of each generator set. Included in this presentation are the average gap increases of the compression and oil rings for each generator set. These data show that, regardless of test fuel or generator set model, ring wear was quite low. Overall, compression ring gap increases ranged from zero to 0.005 inch, while those of the oil rings ranged from 0.001 to 0.006 inch. Even within these narrow ranges, however, certain wear trends were detectable. For instance, it will be observed that, in each generator set, the average oil ring wear was greater than that of the compression rings. With respect to the effects of test fuel on ring wear of each generator set model, the averaged data in Table B-IV indicate that, in the 1.5-kW generator set model, both compression ring and oil ring wear were slightly less with low-lead and unleaded fuel than with the normally leaded fuel, whereas in the 10-kW sets, the reduction of fuel lead content resulted in increased wear of both types of piston rings. These averaged data further show that ring wear in the 3.0-kW generator set model was not affected by either low-lead or unleaded test fuel.

In connection with ring wear, it should be mentioned that the post-test inspections revealed no evidence of ring sticking or clogging of oil ring slots. Moreover, all compression ring grooves were essentially deposit-free.

Cylinder Wear. The use of low-lead and unleaded test fuel resulted in very slight increases in cylinder wear in all three generator set models over the wear obtained with the normally leaded fuel. However, this fuel effect diminished with increased engine displacement. These observations are based on cylinder wear data for the 1.5-, 3.0-, and 10-kW generator sets as presented in Tables B-V, B-VI, and B-VII, respectively. Post-test photographs of the thrust and anti-thrust sides of a typical cylinder (No. 1) from each generator set are presented in Appendix C. Thus, Figures C-16, C-17, and C-18 are representative of the cylinders from the 1.5-kW sets that were run on normally leaded, low-lead, and unleaded test fuels, respectively; Figures C-36, C-37, and C-38 similarly represent cylinders from the 3.0-kW sets; and Figures C-56, C-57, and C-58 represent cylinders from the 10-kW sets. It will be observed that the factory honing patterns are still clearly visible in each cylinder.

Piston Burning. Although piston burning is not a wear factor, it is a form of distress that is of major concern when using unleaded fuel. Thus, it is significant to note that, upon removing crown and ring belt deposits, no evidence of burning was found on any piston of the nine generator sets.

C. Emissions

Fuel Effects. Evaluations of the comparative effects of normally leaded, low-lead, and unleaded test fuels on the initial and final exhaust emissions from each of the three generator set models were inconclusive. The test fuel effects, if any, were overshadowed by engine-to-engine nonrepeatability as clearly shown in Tables D-I, D-II, and D-III. This nonrepeatability problem was largely attributable to the fact that each carburetor was initially adjusted, as in the field, to provide smooth engine operation rather than to a common emissions baseline for each engine model. Thus, these optimum performance carburetor settings resulted in significantly different reference fuel emissions levels for the three engines of each model, and these engine-to-engine differences were also reflected in the initial emissions data with the test fuels.

In the final emissions tests, repeatability with the reference fuel was still poor in each engine model, so that emissions degradation (or improvement) with any of the three test fuels could not be assessed. Figures D-1 through D-9 compare the initial and final NO_x, CO, and HC emissions patterns obtained with each generator set model when operating with Indolene clear reference fuel and with each of the three test fuels. These graphical data are offered in support of the preceding comments.

Catalytic Converters. As originally defined, the scope of this fuel compatibility study did not include evaluations of exhaust pollution abatement devices. However, it was soon realized that the test schedule provided an excellent opportunity to determine, at no additional cost, the applicability, effectiveness, and durability of one of the better known exhaust catalytic converter designs, the Engelhard PTX Purifier, with respect to the three MIL STD generator set models. Consequently, by mutual consent of the USAFLRL and MERDC, arrangements were made with Engelhard Industries Division to supply two Model PTX-3 Purifiers and one Model PTX-4 Purifier to the USAFLRL for evaluation within this program. The two models differ only in size; the PTX-3 being suitable for engines of up to 75 CID, which includes those of the 1.5- and 3.0-kW generator sets, and the PTX-4 for engines of from 75 to 150 CID, which includes the engine in the 10-kW generator set.

At present, catalytic converters are the most promising means for minimizing exhaust emissions; however, the platinum catalyst in these add-on devices is susceptible to lead poisoning which, therefore, precludes their use with normally leaded and even low-lead fuels. Thus, the Engelhard units were evaluated only on the MIL STD generator sets that were used in the tests involving unleaded VV-G-001690 and Indolene clear fuels.

Following the 16-hour break-in of each generator set, the appropriate PTX Purifier was inserted between the exhaust manifold and tailpipe with special adaptor sections which included taps for obtaining upstream and downstream gas samples. It had been intended that the catalytic converters would remain *in situ* throughout both the initial and final emissions tests and also the 125-hour endurance tests, thereby enabling evaluations of their effectiveness and durability in these applications. However, for reasons that will be discussed, the converters were removed after limited initial emissions data had been obtained, and their further evaluation was discontinued.

Emissions data, presented in Table D-IV, show the effectiveness of the PTX-3 Purifier in reducing the NO, NO_x, CO, and HC components from the 1.5-kW generator set exhaust at each of five load levels when operating on Indolene clear and on the unleaded test fuel. While, at all load levels, the emission reductions were substantial, the converter's reaction temperature increased with generator load, so that, at 75 and 100 percent of rated load, it was necessary to fan-cool the converter to avoid overheating.

At the outset of the emissions test of the PTX-3 Purifier on the 3.0-kW generator set, it was found that the reaction temperature was excessive even under no-load conditions. It was then decided to move the PTX unit further downstream from the exhaust manifold in order to reduce not only the temperature of the exhaust entering the converter, but also that of the converter itself. A distance of eight feet was arbitrarily selected as being appropriate.

After relocating the converter, a second emissions evaluation was attempted. It was found that no converter overheating occurred at any generator load up to, and including, 120 percent of rated output. The emissions data obtained from the relocated PTX-3 Purifier with Indolene clear and with the unleaded test fuel are presented in Table D-V. It is evident that, at all load levels, the reductions in all measured exhaust components were significant but were not as impressive as the reductions shown by the same converter model on the 1.5-kW generator set.

Excessive reaction temperature was also encountered at no-load with the PTX-4 Purifier installed near the exhaust manifold of the 10-kW generator set. Therefore, the converter was moved eight feet downstream as in the 3.0-kW generator set emissions tests. However, in its new location, the PTX-4 Purifier overheated at 50 percent of rated generator load, although emissions data were obtained at no-load and at 25 percent of rated load. Finally, the PTX-4 Purifier was moved 15 feet downstream from its initial location and the emissions test was repeated. The additional distance permitted operation up to, and including, 75 percent of rated generator load without overheating the PTX-4 Purifier. Consequently, emissions data were obtained at no-load, 25, 50, and 75 percent of rated load, all with the converter in this more remote location.

The results of the emissions experiments with the PTX-4 Purifier are presented in Table D-VI. These data show that, within its overheat limits, the PTX-4 Purifier effected reductions in NO, NO_x, CO, and HC at both remote locations, although its effectiveness diminished as the distance from the generator set increased.

These cursory evaluations of the Engelhard PTX Purifiers clearly indicate that extensive modifications to the present exhaust systems of these MIL STD generator sets would be necessary in order to accommodate these catalytic converters, but, in view of their demonstrated effectiveness in controlling emissions, such adaptation efforts would seem worthwhile.

CD Ignition Systems. At the conclusion of the scheduled final emissions tests with the 1.5- and 3.0-kW generator sets, which had operated on unleaded VV-G-001690 fuel, a technician from MERDC installed a Fairbanks-Morse capacitor discharge ignition system on each of the two engines. Following these installations, the generator sets were operated on the unleaded test fuel and on the reference fuel, each at 3600 rpm and at no-load, 50, and 100 percent of rated load. Emissions samples were taken at each load level and with each fuel, and the resultant analyses were compared with emissions data obtained when operating with the standard ignition system at the same generator loads. These comparative data, which are presented in Table D-VII, indicate that the CD system had no appreciable effects on the emissions from either the 1.5- or 3.0-kW generator sets with either fuel. It was noted that, when operating the 3.0-kW generator set at rated load on unleaded VV-G-001690, the emissions with the CD ignition system varied considerably. However, this instability was attributed to spark plug deposits (Figure C-40) rather than malfunctioning of the CD system.

VI. CONCLUSIONS

The results from this investigation of the compatibility of three different MIL STD generator set models with low-lead and unleaded fuels led to the following conclusions:

- All of the 1.5-, 3.0-, and 10-kW generator set models performed satisfactorily on the normally leaded, low-lead, and unleaded test fuels without exhibiting any tendency to knock or run-on.

- Valve recession in all generator set models was virtually nil with the unleaded VV-G-001690 test fuel; whereas, with normally leaded MIL-G-46015 valve recession ranged from 0.001 inch to as high as 0.017 inch, which is quite severe for 125 hours of test.

- Wear in other areas was minor, and, with the exception of the exhaust valve seats and cylinder bores in the 1.5-kW sets and the piston rings in the 10-kW sets, no wear increases that could be attributed to the use of either low-lead or unleaded fuel were evident.

- Abnormally high oil consumption rates characterized the operations of all 3.0-kW generator sets and resulted in the formation of copious coke deposits in all combustion chambers.

- Under the simulated field operation of these generator sets, the engine-to-engine emissions repeatability with Indolene clear reference fuel was too poor to enable a valid determination of the effects of fuel lead content, either at a given point in time or over a period of time, on the emissions characteristics of any of the three generator set models involved in this study.

- The Engelhard PTX Purifiers effected relatively substantial reductions in NO, NO_x, CO, CO_2, and HC exhaust emissions from each of the three generator set models; however, these catalytic converter units, when close-coupled to the tailpipe, tended to overheat at less than 100 percent rated generator load.

- The Fairbanks-Morse capacitor discharge ignition systems functioned satisfactorily on both a 1.5- and 3.0-kW generator set, when operating with unleaded fuel at 0, 50, and 100 percent rated load, all at 3600 rpm, but the CD systems had no effect on emission levels previously obtained with the conventional ignition system.

APPENDIX A

OPERATING DATA—125-HOUR ENDURANCE TESTS

TABLE A-1. 125-HOUR PERFORMANCE AND WEAR TEST

Normally Leaded MIL-G-46015

MIL STD Engine Model: 2A016 III (Wisconsin)
Engine/Gen. Rating: 3 Bhp/1.5 kW at 3600 rpm
Engine Serial No.: N-054142
Fuel: Normally Leaded MIL-G-46015
Lube: Mobil Delvac 0E30

Operating Conditions

	Min	Max	Avg
Speed, rpm	3600	3600	3600
Load, % rated	100	100	100
Generator output, VDC	28	28	28
Temperature, °F			
No. 1 cylinder head	303	377	347
No. 2 cylinder head	311	391	356
Sump oil	200	243	218
Exhaust	781	972	855
Ambient	74	100	87
Barometer, in. Hg	28.97	29.13	29.05

Makeup Oil Required

Test Hour	New Oil Added, lb
50	0.20
125	0.38
Total:	0.58

Avg consumption 0.005 lb/hr

Maintenance Log

Test Hour	Problem	Solution
1	No. 2 spark plug not firing	Increased fuel flow slightly
60	No. 1 spark plug misfiring due to carbon deposits	Machine-cleaned and reinstalled plug.

Cylinder Compression (psig at 480 rpm)

Cylinder No.	After Break-In	After 125-Hour Test
1	95	90
2	106	93

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TABLE A-II. 125-HOUR PERFORMANCE AND WEAR TEST

Low-Lead VV-G-001690

MIL STD Engine Model: 2A016 III (Wisconsin)
Engine/Gen. Rating: 3 Bhp/1.5 kW at 3600 rpm
Engine Serial No.: N-051180
Fuel: Low-Lead VV-G-001690
Lube: Mobil Delvac 0E30

Operating Conditions

	Min	Max	Avg
Speed, rpm	3600	3600	3600
Load, % rated	100	100	100
Generator output, VDC	28	28	28
Temperatures, °F			
No. 1 cylinder head	346	434	376
No. 2 cylinder head	324	406	356
Sump oil	198	247	217
Exhaust	805	887	841
Ambient	79	104	91
Barometer, in. Hg	28.60	29.05	28.97

Makeup Oil Required

Test Hour	New Oil Added, lb
16	0.64
40	0.37
71	0.20
88	0.50
125	0.23
Total:	1.94

Avg consumption = 0.016 lb/hr

Maintenance Log

Test Hour	Problem	Solution
0	Breaker points would not close due to soft spring	Replaced breaker point assembly

Cylinder Compression (psig at 480 rpm)

Cylinder No.	After Break-In	After 125-Hour Test
1	92	89
2	82	86

TABLE A-III. 125-HOUR PERFORMANCE AND WEAR TEST

Unleaded VV-G-001690

MIL STD Engine Model: 2A016 III (Wisconsin)
Engine/Gen. Rating: 3 Bhp/1.5 kW at 3600 rpm
Engine Serial No.: N-054137
Fuel: Unleaded VV-G-001690
Lube: Mobil Delvac 0E30

Operating Conditions

	Min	Max	Avg
Speed, rpm	3600	3600	3600
Load, % rated	100	100	100
Generator output, VDC	28	28	28
Temperatures, °F			
No. 1 cylinder head	420	448	436
No. 2 cylinder head	413	436	426
Sump oil	226	255	242
Exhaust	818	917	866
Ambient	71	99	87
Barometer, in. Hg	28.93	29.06	28.99

Makeup Oil Required

Test Hour	New Oil Added, lb
32	0.86
80	0.60
125	0.26
Total:	1.72

Avg consumption = 0.014 lb/hr

Maintenance Log

Test Hour	Problem	Solution
-	No problems	-

Cylinder Compression (psig at 480 rpm)

Cylinder No.	After Break-In	After 125-Hour Test
1	75	103
2	73	84

TABLE A-IV. 125-HOUR PERFORMANCE AND WEAR TEST

Normally Leaded MIL-G-46015

MIL STD Engine Model: 4A032 II (Wisconsin)
Engine/Gen. Rating: 6 Bhp/3.0 kW at 3600 rpm
Engine Serial No.: J-036889
Fuel: Normally Leaded MIL-G-46015
Lube: Mobil Delvac 0E30

Operating Conditions

	Min	Max	Avg
Speed, rpm	3600	3609	3600
Load, % rated	100	100	100
Generator output, VDC	28	28	28
Temperatures, °F			
No. 1 cylinder head	307	465	388
No. 2 cylinder head	286	390	326
No. 3 cylinder head	336	420	378
No. 4 cylinder head	323	407	373
Sump oil	209	281	247
Exhaust	881	1196	1069
Ambient	74	100	87
Barometer, in. Hg	28.97	29.13	29.05

Makeup Oil Required

Test Hour	New Oil Added, lb	Test Hour	New Oil Added, lb
4	0.71	72	0.76
12	1.22	75	0.99
20	1.04	80	0.85
25	0.82	84	1.16
28	0.52	88	0.65
32	0.99	92	0.90
36	0.79	96	0.88
40	0.94	100	0.98
44	0.75	104	1.03
48	0.43	108	1.07
50	0.52	112	0.73
55	0.93	116	1.29
60	1.20	120	1.00
64	0.85	125	0
68	0.90	Total:	24.90

Avg consumption = 0.199 lb/hr

Maintenance Log

Test Hour	Problem	Solution
50	Nos. 1, 2 and 3 spark plugs Pb-fouled	Replaced all plugs
104	No. 1 spark plug Pb-fouled	Replaced spark plug
121	No. 2 spark plug Pb-fouled.	Replaced all plugs

Cylinder Compression (psig at 480 rpm)

Cylinder No.	After Break-In	After 125-Hour Test
1	92	70
2	102	100
3	104	122
4	102	105

TABLE A-V. 125-HOUR PERFORMANCE AND WEAR TEST

Low-Lead VV-G-001690

MIL STD Engine Model: 4A032 II (Chrysler)
Engine/Gen. Rating: 6 Bhp/3.0 kW at 3600 rpm
Engine Serial No.: J-069253
Fuel: Low-Lead VV-G-001690
Lube: Mobil Delvac 0E30

Operating Conditions

	Min	Max	Avg
Speed, rpm	3580	3610	3600
Load, % rated	95	100	100
Generator output, VDC	28	28	28
Temperatures, °F			
No. 1 cylinder head	412	478	445
No. 2 cylinder head	394	466	430
No. 3 cylinder head	428	474	449
No. 4 cylinder head	432	490	458
Sump oil	268	302	284
Exhaust	820	1000	905
Ambient	76	102	88
Barometer, in. Hg	28.89	29.18	29.03

Makeup Oil Required

Test Hour	New Oil Added, lb	Test Hour	New Oil Added, lb
4	1.00	66	0.94
8	0.74	73	0.78
12	0.74	81	0.50
16	0.34	88	0.48
25	0.98	96	0.20
33	0.80	104	0.79
41	0.90	112	0.59
49	0.40	125	0.46
57	0.96	Total:	11.60

Avg consumption = 0.093 lb/hr

Maintenance Log

Test Hour	Problem	Solution
–	No problems	–

Cylinder Compression (psig at 480 rpm)

Cylinder No.	After Break-In	After 125-Hour Test
1	100	95
2	105	113
3	106	114
4	107	112

TABLE A-VI. 125-HOUR PERFORMANCE AND WEAR TEST

Unleaded VV-G-001690

MIL STD Engine Model: 4A032 II (Wisconsin)
Engine/Gen. Rating: 6 Bhp/3.0 kW at 3600 rpm
Engine Serial No.: J-038279
Fuel: Unleaded VV-G-001690
Lube: Mobil Delvac 0E30

Operating Conditions

	Min	Max	Avg
Speed, rpm	3600	3600	3600
Load, % rated	100	100	100
Generator output, VDC	28	28	28
Temperatures, °F			
No. 1 cylinder head	366	459	415
No. 2 cylinder head	302	415	354
No. 3 cylinder head	368	445	397
No. 4 cylinder head	368	446	392
Sump oil	240	324	270
Exhaust	695	1133	1032
Ambient	71	99	87
Barometer, in. Hg	28.93	29.06	28.99

Makeup Oil Required

Test Hour	New Oil Added, lb	Test Hour	New Oil Added, lb
4	0.75	68	0.70
8	0.89	72	0.95
12	0.98	80	0.80
16	1.09	84	0.61
20	0.92	88	0.81
25	0.78	92	0.81
32	1.33	96	0.86
36	0.97	104	1.05
40	0.92	108	0.57
44	0.75	112	0.67
48	0.60	115	0.59
56	1.49	120	1.39
60	0.80	125	0.59
64	1.00	Total:	23.67

Avg consumption = 0.189 lb/hr

Maintenance Log

Test Hour	Problem	Solution
75	No. 1 cylinder head gasket leak. Oil temperature rose 57°F from 228°F.	Replaced gasket
108	No. 2 spark plug carbon fouled.	Replaced plug

Cylinder Compression (psig at 480 rpm)

Cylinder No.	After Break-In	After 125-Hour Test
1	100	114
2	110	104
3	105	106
4	112	120

TABLE A-VII. 125-HOUR PEFFORMANCE AND WEAR TEST

Normally Leaded MIL-G-46015

MIL STD Engine Model: 4A084 III (Hercules)
Engine/Gen. Rating: 20 Bhp/10.0 kW at 3600 rpm
Engine Serial No.: U-011658
Fuel: Normally Leaded MIL-G-46015
Lube: Mobil Delvac 0E30

Operating Conditions

	Min	Max	Avg
Speed, cycles/sec	60	60	60
Load, % rated	100	100	100
Generator output, VAC	240	240	240
Temperatures, °F			
No. 1 cylinder head	431	494	466
No. 2 cylinder head	311	410	384
No. 3 cylinder head	404	499	464
No. 4 cylinder head	325	407	354
Sump oil	215	247	231
Exhaust	1101	1215	1197
Ambient	74	100	87
Pressures			
Oil, psig	40	49	45
Barometer, in. Hg	28.97	29.13	29.05

Makeup Oil Required

Test Hour	New Oil Added, lb	Test Hour	New Oil Added, lb
4	1.15	72	1.54
12	1.01	80	0.59
20	1.20	88	1.40
25	0.67	96	1.68
32	1.40	104	1.21
40	1.77	112	1.52
50	1.93	120	0.96
58	0.29	125	0
64	0.85	Total:	19.17

Avg consumption = 0.153 lb/hr

Maintenance Log

Test Hour	Problem	Solution
59	No. 4 spark plug gasket thermocouple malfunction	Replaced thermocouple at 75-hour shutdown
106	Oil pressure gauge malfunction—not indicating	Substituted temporary gauge and resumed test

Cylinder Compression (psig at 320 rpm)

Cylinder No.	After Break-In	After 125-Hour Test
1	165	158
2	150	147
3	140	94
4	165	150

TABLE A-VIII. 125-HOUR PERFORMANCE AND WEAR TEST

Low Lead VV-G-001690

MIL STD Engine Model: 4A084 III (Hercules)
Engine/Gen. Rating: 20 Bhp/10.0 kW at 3600 rpm
Engine Serial No.: U-013814
Fuel: Low-Lead VV-G-001690
Lube: Mobil Delvac 0E30

Operating Conditions

	Min	Max	Avg
Speed, cycles/sec	60	60	60
Load, % rated	100	100	100
Gen. output, VAC	240	240	240
Temperatures, °F			
No. 1 cylinder head	473	544	516
No. 2 cylinder head	329	390	345
No. 3 cylinder head	453	551	527
No. 4 cylinder head	368	435	396
Sump Oil	231	264	247
Exhaust	1160	1228	1202
Ambient	79	104	91
Pressures			
Oil, psig	29	45	37
Barometer, in. Hg	28.60	29.05	28.97

Makeup Oil Required

Test Hour	New Oil Added, lb	Test Hour	New Oil Added, lb
4	1.00	80	1.60
16	1.48	88	0.98
25	1.20	100	0.60
32	0.71	104	0.58
40	1.07	112	1.13
50	1.02	120	0.48
56	0.65	125	0.65
64	1.45	Total:	14.60

Avg consumption = 0.117 lb/hr

Maintenance Log

Test Hour	Problem	Solution
–	No problems	–

Cylinder Compression (psig at 320 rpm)

Cylinder No.	After Break-In	After 125-Hour Test
1	160	140
2	168	140
3	160	130
4	170	150

TABLE A-IX. 125-HOUR PERFORMANCE AND WEAR TEST

Unleaded VV-G-001690

MIL STD Engine Model: 4A084 III (Hercules)
Engine/Gen. Rating: 20 Bhp/10 kW at 3600 rpm
Engine Serial No.: U-008113
Fuel: Unleaded VV-G-001690
Lube: Mobil Delvac 0E30

Operating Conditions

	Min	Max	Avg
Speed, cycles/sec	60	60	60
Load, % rated	100	100	100
Generator output, VAC	240	240	240
Temperatures, °F			
No. 1 cylinder head	429	509	479
No. 2 cylinder head	327	376	351
No. 3 cylinder head	350	496	451
No. 4 cylinder head	372	473	449
Sump oil	219	256	238
Exhaust	1055	1183	1134
Ambient	77	99	88
Pressures			
Oil, psig	29	45	36
Barometer, in. Hg	28.89	29.06	28.98

Makeup Oil Required

Test Hour	New Oil Added, lb	Test Hour	New Oil Added, lb
8	1.10	75	0.53
12	0.61	80	0.46
16	0.81	88	0.49
32	1.25	96	0.93
40	1.01	112	0.70
56	1.15	120	0.86
64	1.20	125	0
		Total:	11.10

Avg consumption = 0.089 lb/hr

Maintenance Log

Test Hour	Problem	Solution
15	Generator set hour meter failed	None
21	Engine breaker point pivot pin loose, causing rpm and load surge	Replace breaker point set
22	No. 1 spark plug gasket thermocouple failed	Replaced thermocouple at 25 hours
49	Ball end on governor control rod "froze" in socket	Lubricated ball and socket

Cylinder Compression (psig at 320 rpm)

Cylinder No.	After Break-In	After 125-Hour Test
1	157	139
2	165	149
3	158	139
4	155	145

APPENDIX B
WEAR DATA

TABLE B-I. SUMMARY OF INTAKE AND EXHAUST VALVE RECESSION DATA

(All data corrected for valve stretch and tip wear)

Test Fuel	Intake Valves, inches					Exhaust Valves,* inches				
	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Avg	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Avg
1.5-kW Generator Sets										
Normally Leaded	0.0156	0.0137	–	–	<0.0147	0.0012	0.0008	–	–	0.0010
Low-Lead	0.0014	0.0010	–	–	0.0012	0.0016	0.0000	–	–	0.0008
Unleaded	0.0005	0.0000	–	–	<0.0003	0.0000	0.0004	–	–	0.0002
3.0-kW Generator Sets										
Normally Leaded	0.0023	0.0042	0.0000	0.0000	<0.0017	0.0014	0.0127	0.0012	0.0000	<0.0039
Low-Lead	0.0000	0.0007	0.0000	0.0000	<0.0002	0.0000	0.0000	0.0010	0.0000	<0.0003
Unleaded	0.0000	0.0000	0.0000	0.0026	<0.0007	0.0000	0.0000	0.0005	0.0000	<0.0002
10-kW Generator Sets										
Normally Leaded	0.0000	0.0024	0.0304	0.0000	0.0082	0.0155	0.0000	0.0226	0.0307	0.0172
Low-Lead	0.0000	0.0025	0.0013	0.0000	<0.0010	0.0000	0.0020	0.0000	0.0211	<0.0058
Unleaded	0.0001	0.0001	0.0009	0.0011	<0.0006	0.0000	0.0000†	0.0000	0.0004	0.0001

*Valve face concave at teardown (see Figure C-46).

TABLE B-II. SUMMARY OF VALVE STEM STRETCH (+) OR VALVE TIP WEAR (–) DATA

Test Fuel	Intake Valves, inches				Exhaust Valves,* inches			
	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Cyl 1	Cyl 2	Cyl 3	Cyl 4
1.5-kW Generator Sets								
Normally Leaded	0.0000	0.0001	–	–	0.0001	0.0000	–	–
Low-Lead	-0.0001	0.0003	–	–	0.0003	0.0010	–	–
Unleaded	0.0000	0.0008	–	–	-0.0005	-0.0005	–	–
3.0-kW Generator Sets								
Normally Leaded	-0.0026	0.0019	-0.0010	0.0000	0.0002	0.0006	0.0002	0.0000
Low-Lead	0.0000	-0.0005	0.0000	-0.0002	-0.0004	-0.0005	-0.0014	-0.0002
Unleaded	0.0006	-0.0001	-0.0006	-0.0011	-0.0005	-0.0001	0.0000	-0.0008
10-kW Generator Sets								
Normally Leaded	0.0001	-0.0004	-0.0011	-0.0003	-0.0004	0.0002	0.0002	-0.0008
Low-Lead	0.0002	-0.0004	-0.0002	-0.0004	-0.0001	-0.0005	0.0007	-0.0002
Unleaded	-0.0003	-0.0002	-0.0003	-0.0007	0.0000	-0.0001	-0.0008	-0.0006

*Stellite Exhaust Valves.
†Valve face concave at teardown (see Figure C-46).

TABLE B-III. SUMMARY OF VALVE SEAT WIDTH INCREASE DATA

Test Fuel	Intake Seats, inches					Exhaust Seats, inches				
	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Avg	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Avg
1.5-kW Generator Sets										
Normally Leaded	0.004	0.000	–	–	0.002	0.000	0.000	–	–	0.000
Low-Lead	0.000	0.002	–	–	0.001	0.000	0.006	–	–	0.003
Unleaded	0.000	0.000	–	–	0.000	0.012	0.000	–	–	0.006
3.0-kW Generator Sets										
Normally Leaded	0.000	0.005	0.006	0.000	<0.003	0.005	0.003	0.003	0.000	<0.00[illegible]
Low-Lead	0.000	0.000	0.002	0.000	<0.001	0.000	0.000	0.000	0.000	0.000
Unleaded	0.008	0.000	0.000	0.004	0.003	0.011	0.010	0.013	0.000	<0.009
10-kW Generator Sets										
Normally Leaded	0.018	0.010	0.017	0.018	<0.014	0.015	0.013	0.007	0.021	0.014
Low-Lead	0.004	0.001	0.000	0.003	0.002	0.004	0.001	0.000	0.003	0.002
Unleaded	0.020	0.014	0.015	0.010	<0.015	0.020	0.014	0.015	0.010	0.015

TABLE B-IV. SUMMARY OF RING WEAR DATA (END-GAP INCREASE)

Test Fuel	Ring	Cyl 1, in.	Cyl 2, in.	Cyl 3, in.	Cyl 4, in.	Avg, in.
1.5-kW Generator Sets						
Normally Leaded	Top	0.001	0.002	–	–	–
	2nd	0.002	0.003	–	–	0.002 (top and 2nd)
	Oil	0.004	0.004	–	–	0.004
Low Lead	Top	0.002	0.002	–	–	–
	2nd	0.001	0.002	–	–	<0.002 (top and 2nd)
	Oil	0.003	0.003	–	–	0.003
Unleaded	Top	0.000	0.000	–	–	–
	2nd	0.001	0.001	–	–	<0.001 (top and 2nd)
	Oil	0.002	0.003	–	–	0.002+
3.0-kW Generator Sets						
Normally Leaded	Top	0.000	0.001	0.000	0.000	–
	2nd	0.000	0.000	0.001	0.001	<0.001 (top and 2nd)
	Oil	0.004	0.004	0.005	0.002	0.003+
Low-Lead	Top	0.000	0.003	0.000	0.001	–
	2nd	0.000	0.005	0.003	0.000	0.001+ (top and 2nd)
	Oil	0.003	0.006	0.003	0.002	0.003+
Unleaded	Top	0.001	0.001	0.000	0.001	–
	2nd	0.001	0.000	0.002	0.001	<0.001 (top and 2nd)
	Oil	0.003	0.004	0.005	0.004	0.004
10-kW Generator Sets						
Normally Leaded	Top	0.000	0.000	0.001	0.000	–
	2nd	0.001	0.001	0.001	0.001	<0.001 (top and 2nd)
	Oil	0.001	0.002	0.001	0.002	0.001+
Low-Lead	Top	0.000	0.002	0.001	0.002	–
	2nd	0.002	0.002	0.002	0.004	0.001+ (top and 2nd)
	Oil	0.004	0.003	0.005	0.003	0.003+
Unleaded	Top	0.001	0.001	0.001	0.002	–
	2nd	0.003	0.003	0.003	0.003	0.002+ (top and 2nd)
	Oil	0.005	0.005	0.005	0.006	0.005+

TABLE B-III. SUMMARY OF VALVE SEAT WIDTH INCREASE DATA

Test Fuel	Intake Seats, inches					Exhaust Seats, inches				
	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Avg	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Avg
1.5-kW Generator Sets										
Normally Leaded	0.004	0.000	–	–	0.002	0.000	0.000	–	–	0.000
Low-Lead	0.000	0.002	–	–	0.001	0.000	0.006	–	–	0.003
Unleaded	0.000	0.000	–	–	0.000	0.012	0.000	–	–	0.006
3.0-kW Generator Sets										
Normally Leaded	0.000	0.005	0.006	0.000	<0.003	0.005	0.003	0.003	0.000	<0.003
Low-Lead	0.000	0.000	0.002	0.000	<0.001	0.000	0.000	0.000	0.000	0.000
Unleaded	0.008	0.000	0.000	0.004	0.003	0.011	0.010	0.013	0.000	<0.009
10-kW Generator Sets										
Normally Leaded	0.018	0.010	0.017	0.018	<0.014	0.015	0.013	0.007	0.021	0.014
Low-Lead	0.004	0.001	0.000	0.003	0.002	0.004	0.001	0.000	0.003	0.002
Unleaded	0.020	0.014	0.015	0.010	<0.015	0.020	0.014	0.015	0.010	0.015

TABLE B-IV. SUMMARY OF RING WEAR DATA (END-GAP INCREASE)

Test Fuel	Ring	Cyl 1, in.	Cyl 2, in.	Cyl 3, in.	Cyl 4, in.	Avg, in.
1.5-kW Generator Sets						
Normally Leaded	Top	0.001	0.002	–	–	–
	2nd	0.002	0.003	–	–	0.002 (top and 2nd)
	Oil	0.004	0.004	–	–	0.004
Low Lead	Top	0.002	0.002	–	–	–
	2nd	0.001	0.002	–	–	<0.002 (top and 2nd)
	Oil	0.003	0.003	–	–	0.003
Unleaded	Top	0.000	0.000	–	–	–
	2nd	0.001	0.001	–	–	<0.001 (top and 2nd)
	Oil	0.002	0.003	–	–	0.002+
3.0-kW Generator Sets						
Normally Leaded	Top	0.000	0.001	0.000	0.000	–
	2nd	0.000	0.000	0.001	0.001	<0.001 (top and 2nd)
	Oil	0.004	0.004	0.005	0.002	0.003+
Low-Lead	Top	0.000	0.003	0.000	0.001	–
	2nd	0.000	0.005	0.003	0.000	0.001+ (top and 2nd)
	Oil	0.003	0.006	0.003	0.002	0.003+
Unleaded	Top	0.001	0.001	0.000	0.001	–
	2nd	0.001	0.000	0.002	0.001	<0.001 (top and 2nd)
	Oil	0.003	0.004	0.005	0.004	0.004
10-kW Generator Sets						
Normally Leaded	Top	0.000	0.000	0.001	0.000	–
	2nd	0.001	0.001	0.001	0.001	<0.001 (top and 2nd)
	Oil	0.001	0.002	0.001	0.002	0.001+
Low-Lead	Top	0.000	0.002	0.001	0.002	–
	2nd	0.002	0.002	0.002	0.004	0.001+ (top and 2nd)
	Oil	0.004	0.003	0.005	0.003	0.003+
Unleaded	Top	0.001	0.001	0.001	0.002	–
	2nd	0.003	0.003	0.003	0.003	0.002+ (top and 2nd)
	Oil	0.005	0.005	0.005	0.006	0.005+

TABLE B-V. SUMMARY OF CYLINDER WEAR DATA–1.5-kW GENERATOR SETS–(BORE DIAMETER INCREASE)

Test Fuel	Plane*	Cyl 1, in.		Cyl 2, in.		Avg (2 cycles), in.	
		L†	T	L	T	L	T
Normally Leaded	A	0.0004	0.0008	0.0010	0.0010	0.0007	0.0009
	B	0.0003	0.0006	0.0005	0.0007	0.0004	0.0006+
	C	0.0002	0.0005	0.0005	0.0005	0.0003+	0.0005
Low-Lead	A	0.0007	0.0010	0.0011	0.0012	0.0009	0.0011
	B	0.0006	0.0007	0.0007	0.0005	0.0006+	0.0006
	C	0.0003	0.0006	0.0006	0.0006	0.0004+	0.0006
Unleaded	A	0.0013	0.0016	0.0016	0.0016	0.0014+	0.0016
	B	0.0010	0.0011	0.0012	0.0012	0.0011	0.0011+
	C	0.0009	0.0010	0.0010	0.0011	0.0009+	0.0010+

*Vertical distance from top of cylinder. A = 0.50 in.; B = 1.00 in.; C = 1.50 in.
†Diameter–L = longitudinal; T = transverse.

TABLE B-VI. SUMMARY OF CYLINDER WEAR DATA–3.0-kW GENERATOR SETS (BORE DIAMETER INCREASE)

Test Fuel	Plane*	Cyl 1, in.		Cyl 2, in.		Cyl 3, in.		Cyl 4, in.		Avg (4 cycles), in.	
		L†	T	L	T	L	T	L	T	L	T
Normally Leaded	A	-0.0015	-0.0010	-0.0004	-0.0001	0.0002	-0.0009	-0.0008	-0.0004	-0.0006	-0.0006
	B	-0.0008	-0.0005	-0.0002	-0.0002	0.0006	0.0003	-0.0004	-0.0003	-0.0002	-0.0002
	C	-0.0002	0.0000	-0.0001	0.0000	0.0006	0.0008	0.0000	0.0007	0.0001	0.0003+
Low-Lead	A	0.0001	0.0001	0.0002	0.0001	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001
	B	0.0002	0.0001	0.0002	0.0005	0.0000	0.0002	-0.0004	0.0001	0.0001	0.0002+
	C	0.0001	0.0002	0.0002	0.0001	0.0002	0.0001	0.0001	0.0001	0.0001+	0.0001+
Unleaded	A	-0.0011	0.0002	0.0002	0.0000	0.0002	-0.0012	-0.0002	-0.0001	-0.0002	-0.0003
	B	-0.0002	-0.0006	0.0010	0.0009	0.0011	0.0004	0.0001	0.0009	0.0005	0.0004
	C	0.0005	0.0004	0.0009	0.0011	0.0010	0.0012	0.0007	0.0012	0.0007+	0.0009+

*Vertical distance from top of cylinder. A = 0.50 in.; B = 1.00 in.; C = 1.50 in.
†Diameter–L = longitudinal; T = transverse.

TABLE B-VII. SUMMARY OF CYLINDER WEAR DATA—10-kW GENERATOR SETS (BORE DIAMETER INCREASE)

Test Fuel	Plane*	Cyl 1, in.		Cyl 2, in.		Cyl 3, in.		Cyl 4, in.		Avg (4 cycles), in.	
		L†	T	L	T	L	T	L	T	L	T
Normally Leaded	A	0.0006	0.0018	0.0013	0.0022	0.0008	0.0015	0.0008	0.0012	0.0008+	0.0016+
	B	0.0014	0.0014	0.0023	0.0019	0.0015	0.0014	0.0011	0.0012	0.0015+	0.0014+
	C	0.0014	0.0014	0.0018	0.0017	0.0015	0.0012	0.0009	0.0011	0.0014	0.0013+
Low-Lead	A	0.0009	0.0019	-0.0003	0.0022	0.0008	0.0014	0.0016	0.0012	0.0007+	0.0016+
	B	0.0024	0.0020	0.0017	0.0020	0.0027	0.0017	0.0011	0.0011	0.0019+	0.0017
	C	0.0022	0.0018	0.0012	0.0016	0.0023	0.0014	0.0008	0.0009	0.0016+	0.0014+
Unleaded	A	0.0000	0.0021	0.0009	0.0024	0.0008	0.0012	0.0010	0.0014	0.0006+	0.0017+
	B	0.0008	0.0016	0.0019	0.0020	0.0020	0.0016	0.0012	0.0010	0.0014+	0.0015+
	C	0.0006	0.0013	0.0017	0.0014	0.0016	0.0015	0.0008	0.0008	0.0011+	0.0012+

*Vertical distance from top of cylinder. A = 0.50 in.; B = 1.00 in.; C = 1.50 in.
†Diameter of cylinder—L = longitudinal; T = transverse.

APPENDIX C

POST-TEST PHOTOGRAPHS OF ENGINE COMPONENTS

NOTE

The figure captions and subcaptions are positioned to correspond with the photographs on the facing page.

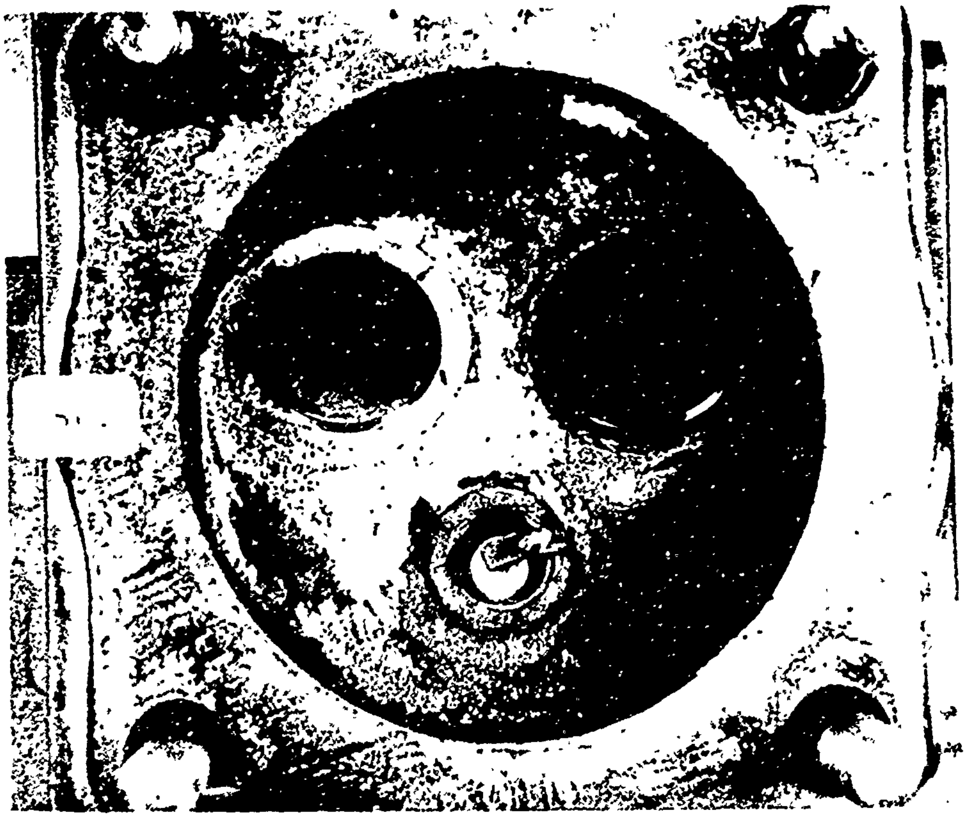
PHOTOGRAPH INDEX

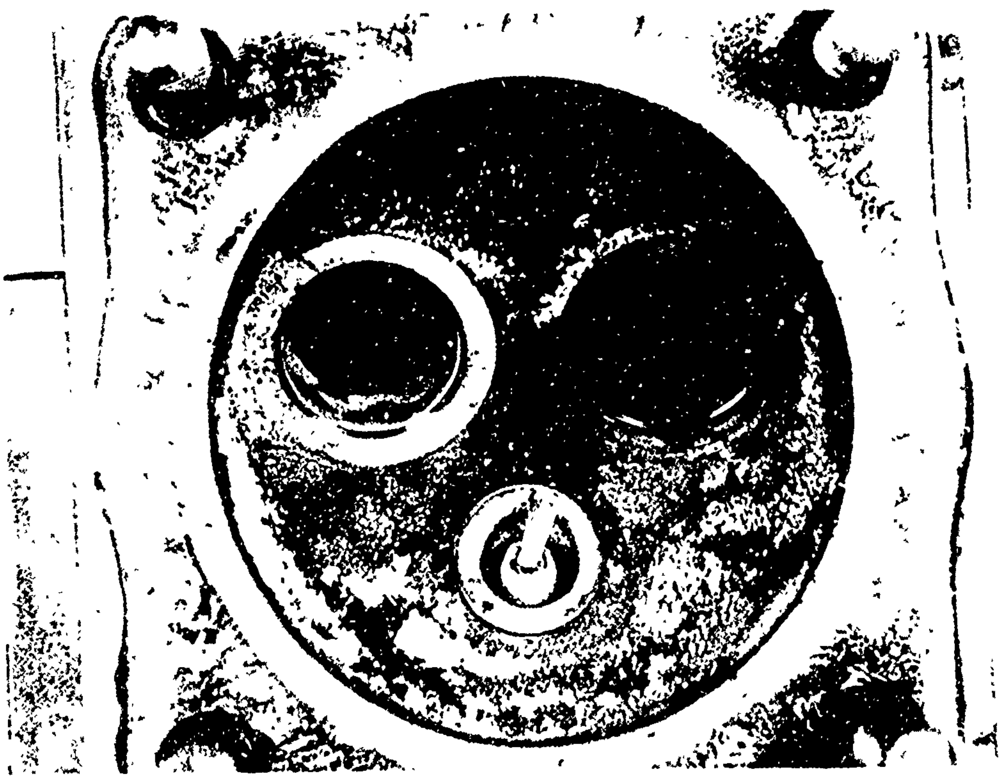
1.5-kW MIL STD GENERATOR SETS

No. 1 Chamber

No. 2 Chamber

FIGURE C-1. COMBUSTION CHAMBERS–NORMALLY LEADED FUEL

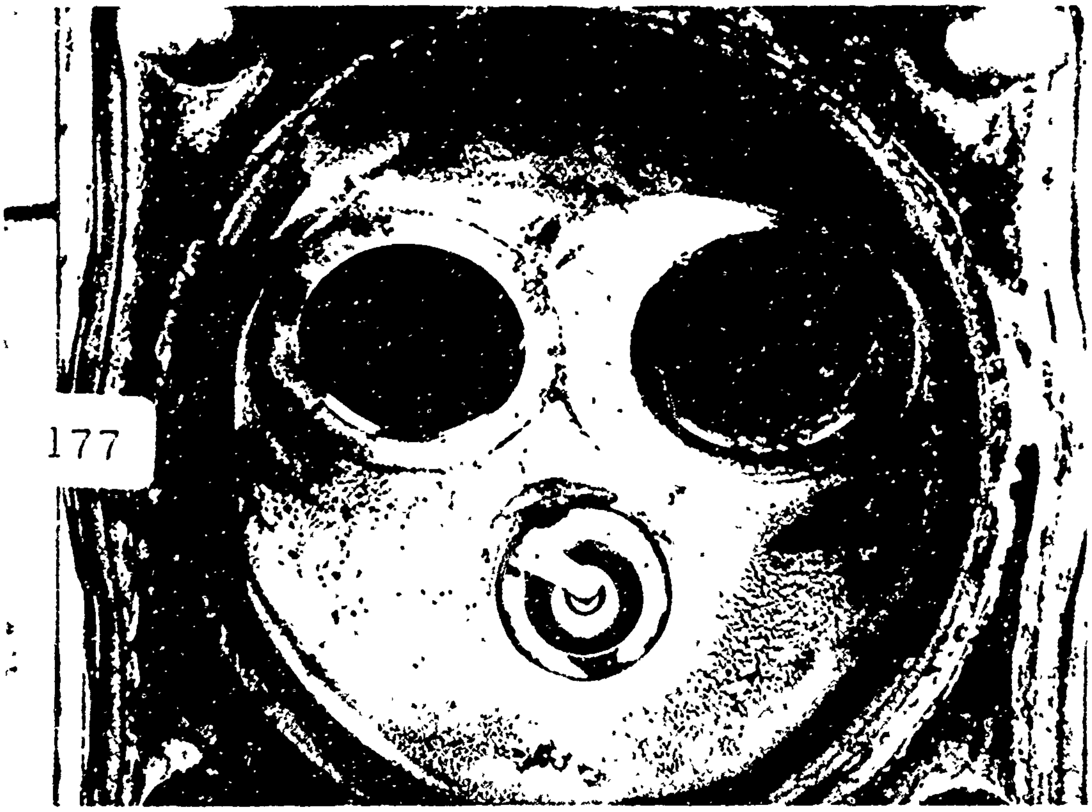




No. 1 Chamber

No. 2 Chamber

FIGURE C-2. COMBUSTION CHAMBERS--LOW LEAD FUEL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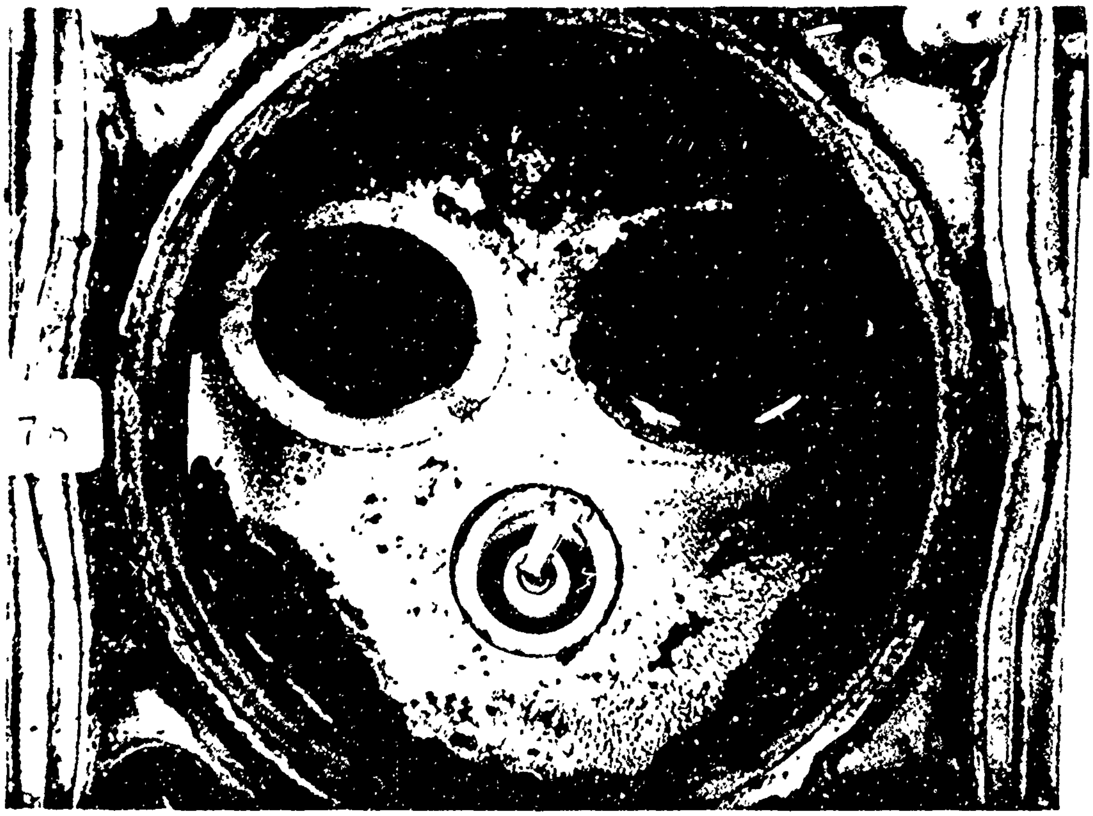
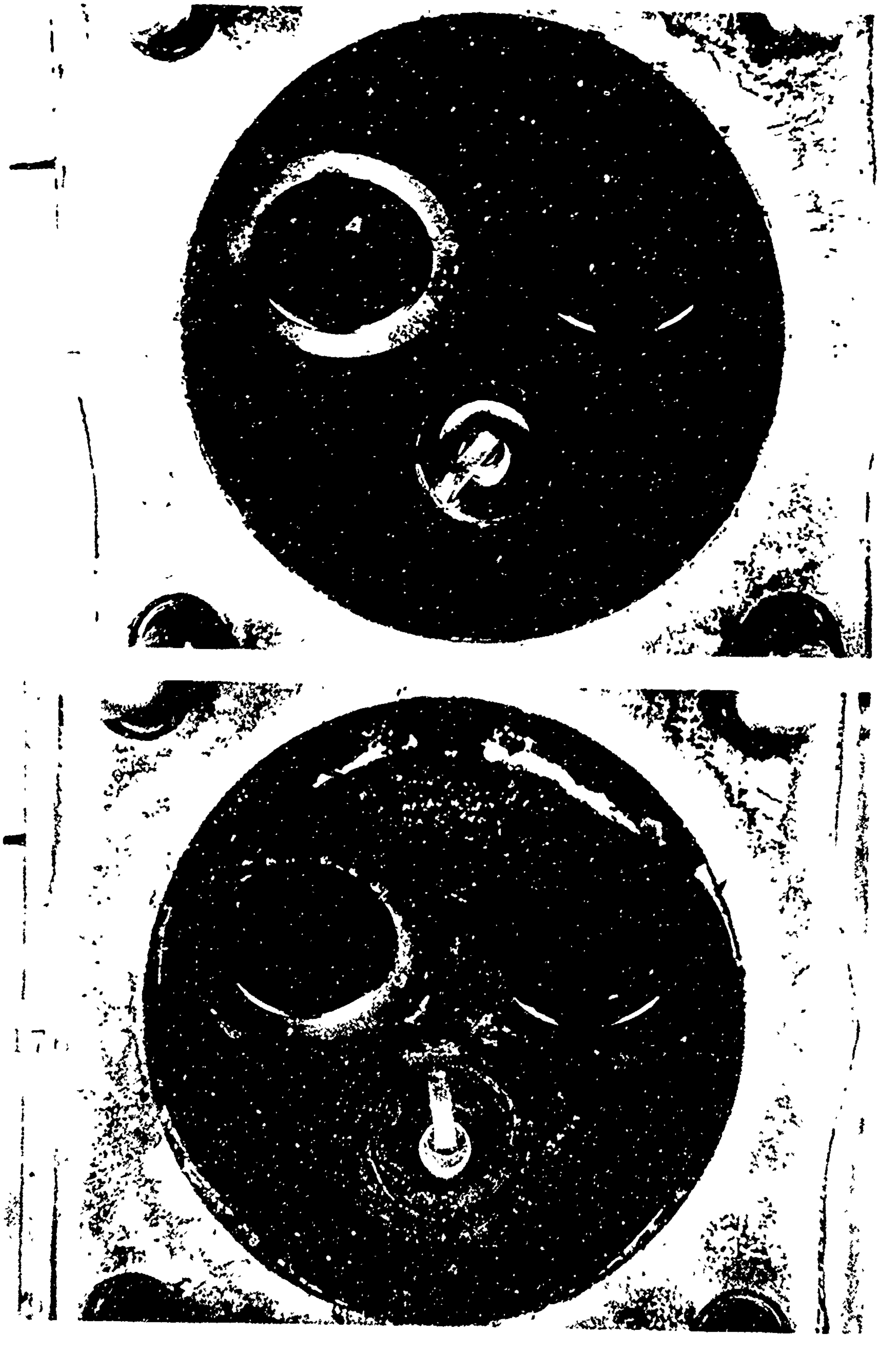


No. 1 Chamber

No. 2 Chamber

FIGURE C-3. COMBUSTION CHAMBERS–UNLEADED FUEL



No. 1 Valve Set

No. 2 Valve Set

FIGURE C-4. INTAKE AND EXHAUST VALVES–NORMALLY LEADED FUEL

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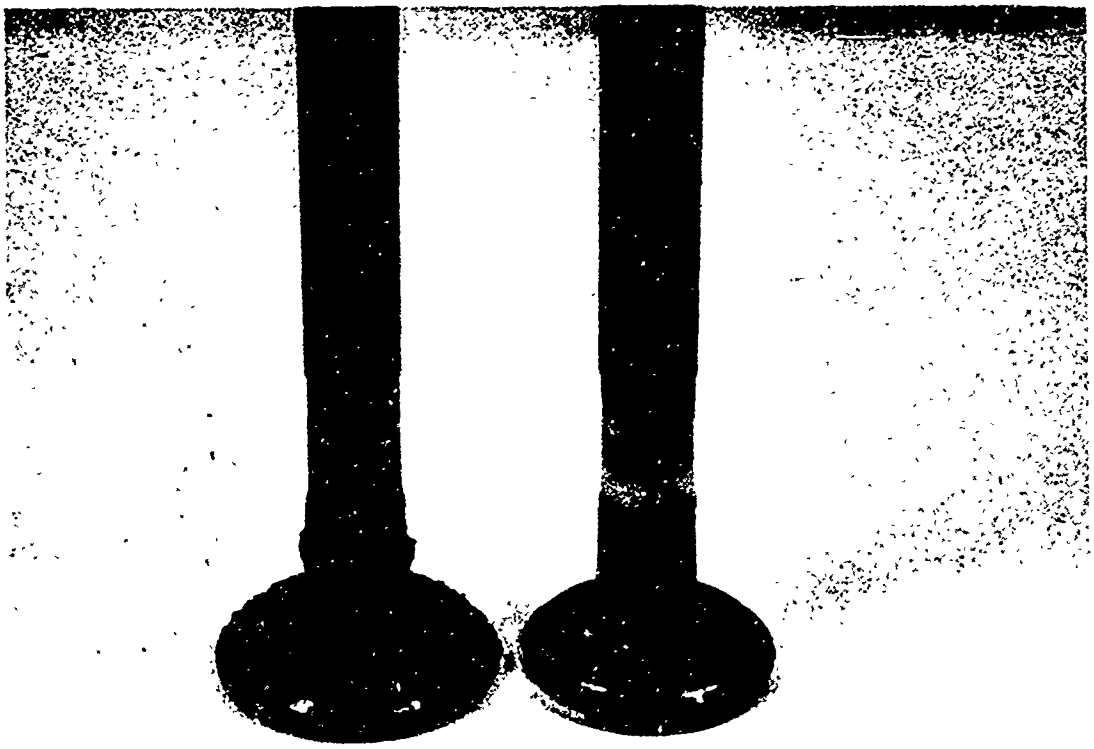
No. 1 Valve Set

No. 2 Valve Set

FIGURE C-5. INTAKE AND EXHAUST VALVES--LOW LEAD FUEL



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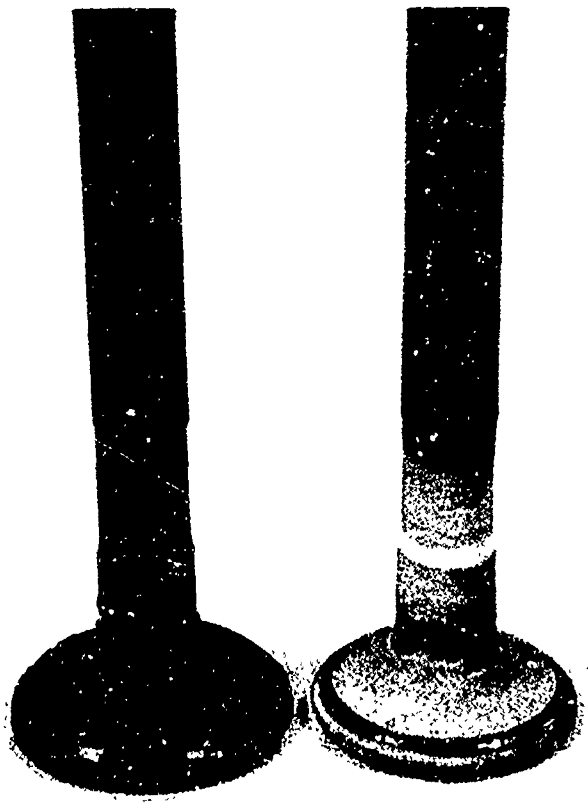
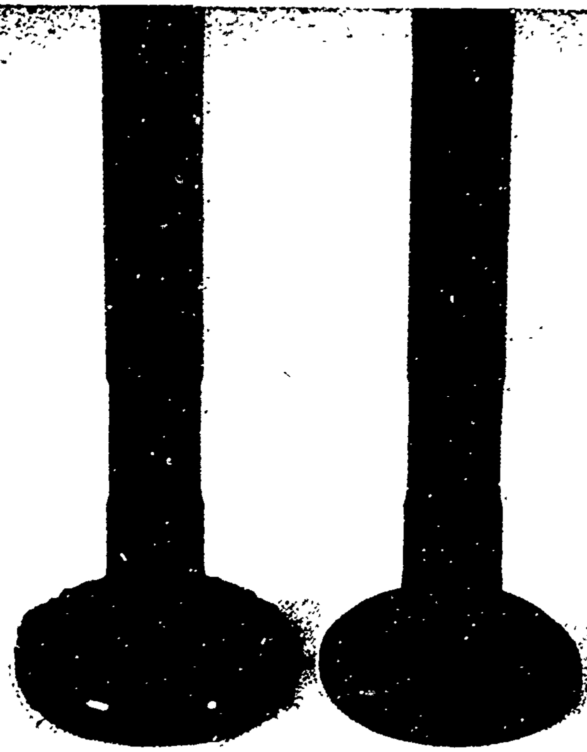


No. 1 Valve Set

No. 2 Valve Set

FIGURE C-6. INTAKE AND EXHAUST VALVES–UNLEADED FUEL



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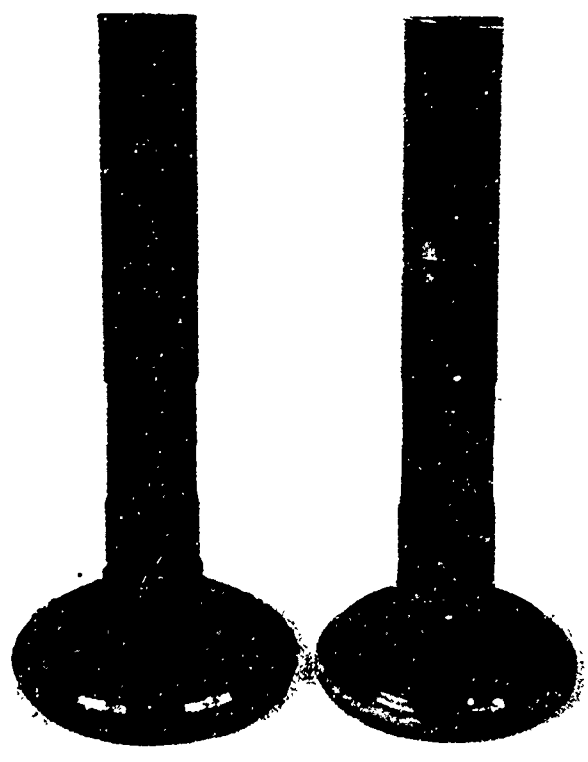

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No. 1 Piston (Front Right)

No. 2 Piston (Front Right)

FIGURE C-7. PISTON CROWN--NORMALLY LEADED FUEL


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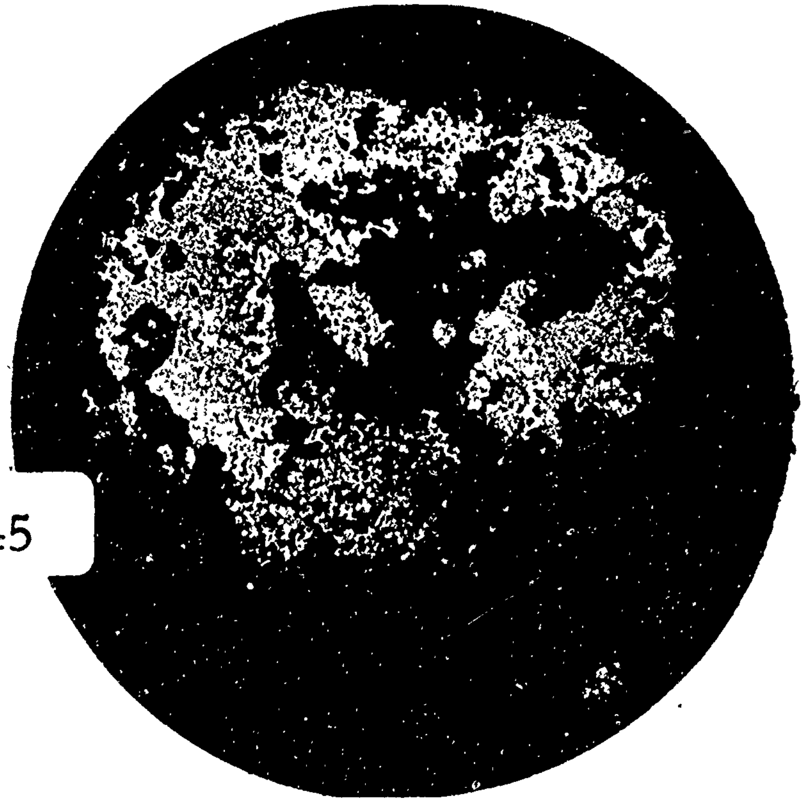
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No. 1 Piston (Front Right)

No. 2 Piston (Front Right)

FIGURE C-8. PISTON CROWNS–LOW LEAD FUEL


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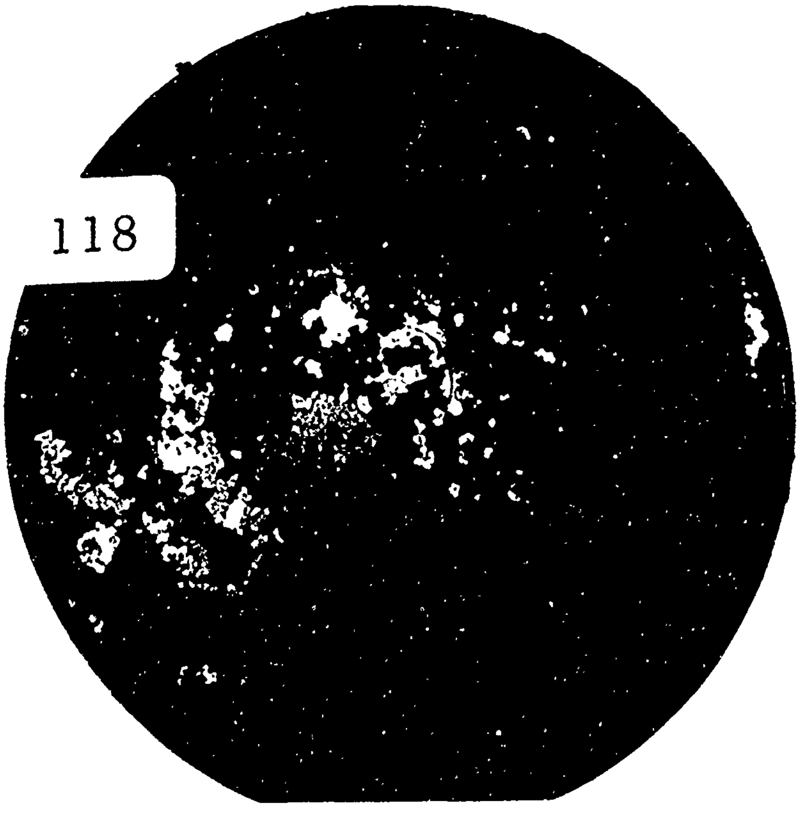
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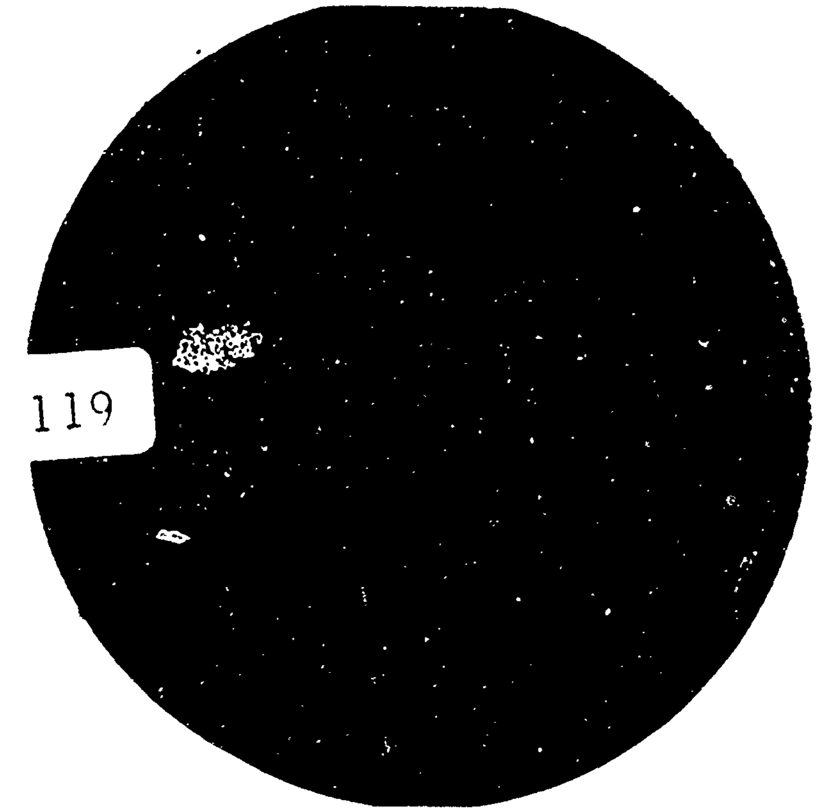
No. 1 Piston (Front Right)

No. 2 Piston (Front Right)

FIGURE C-9. PISTON CROWNS--UNLEADED FUEL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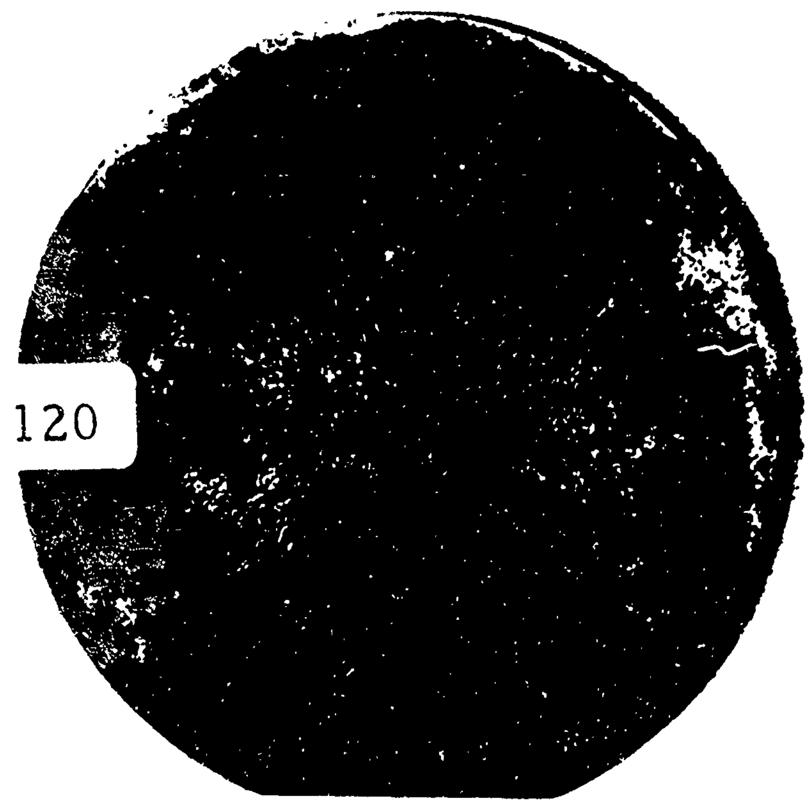
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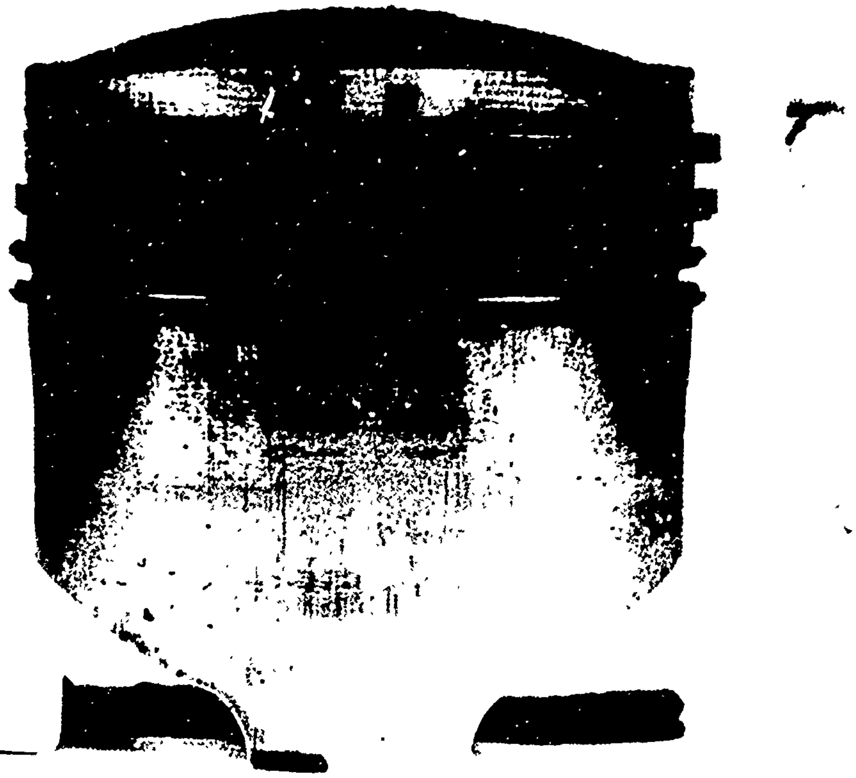
No. 1 Piston

No. 2 Piston

FIGURE C-10. PISTONS (THRUST SIDE)–NORMALLY LEADED FUEL



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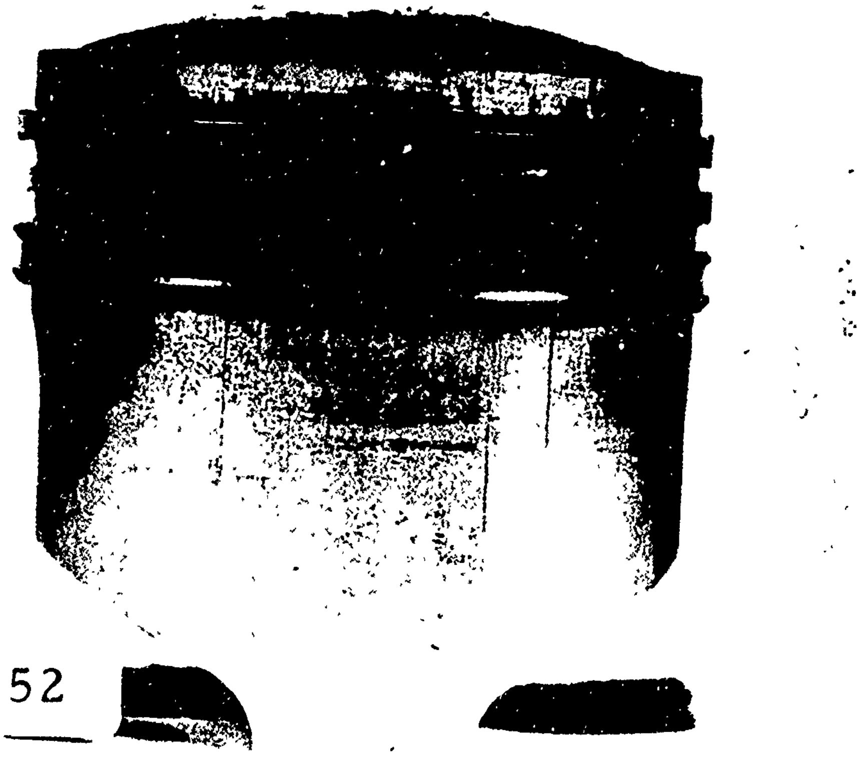

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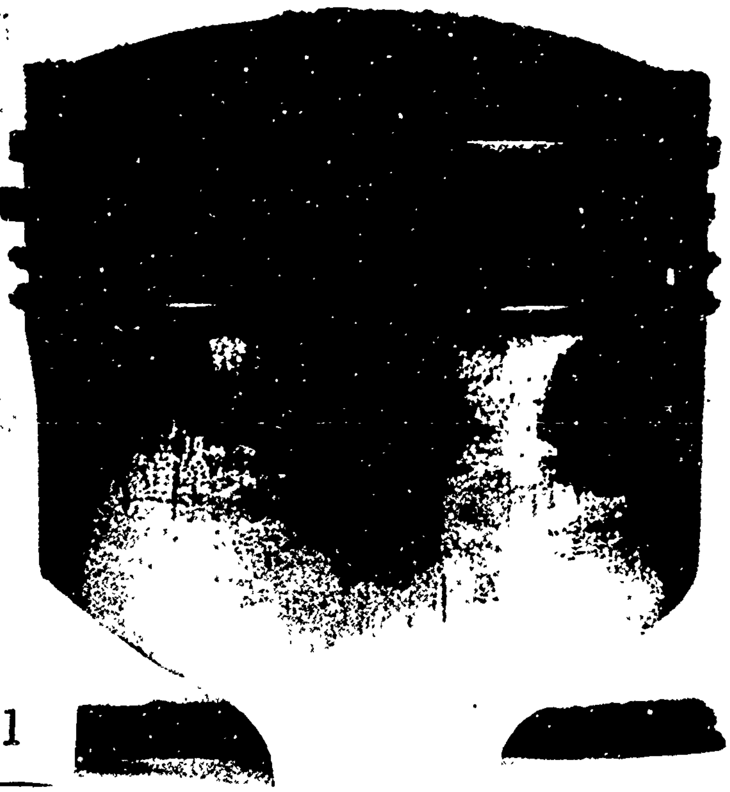
No. 1 Piston

No. 2 Piston

FIGURE C-11. PISTONS (ANTI-THRUST SIDE)–NORMALLY LEADED FUEL



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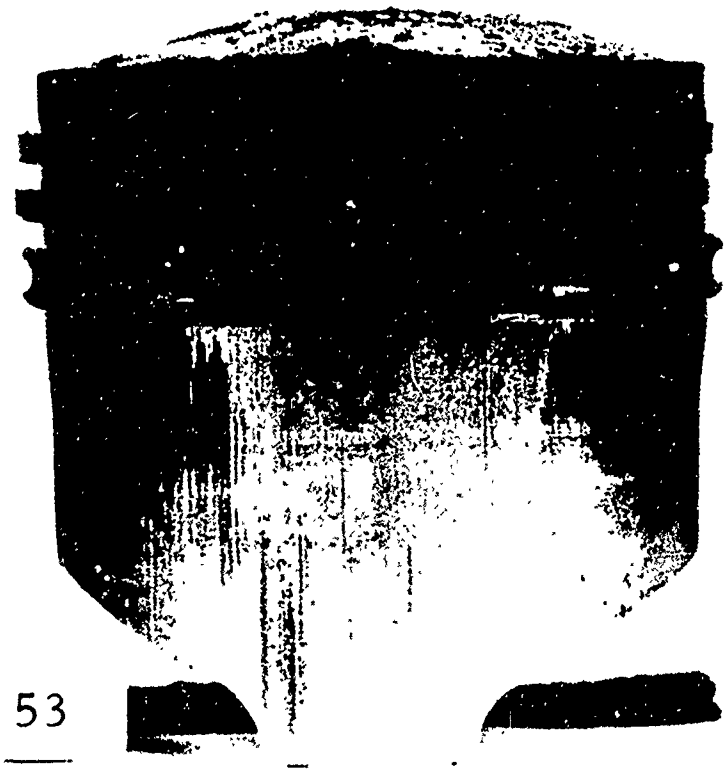

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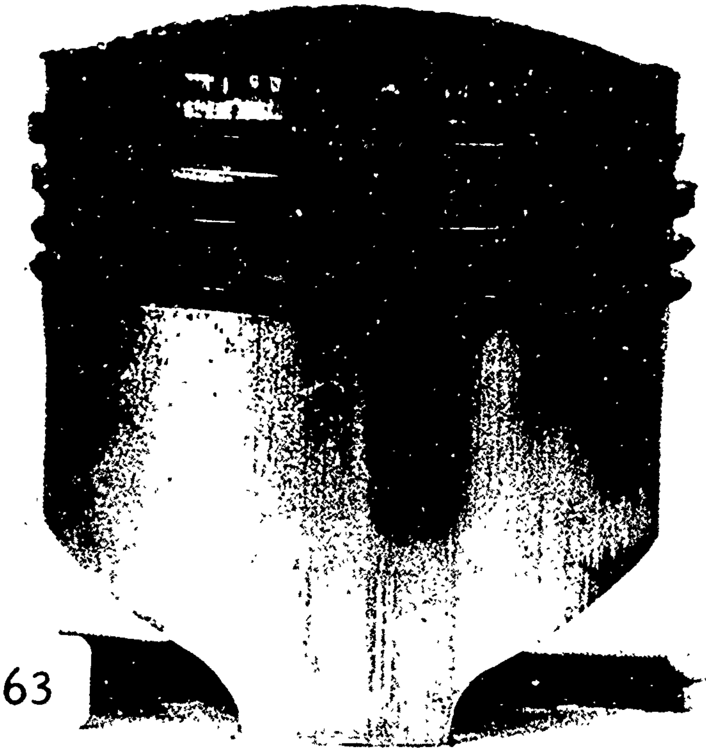
No. 2 Piston

No. 1 Piston

FIGURE C-12. PISTONS (THRUST SIDE)–LOW LEAD FUEL



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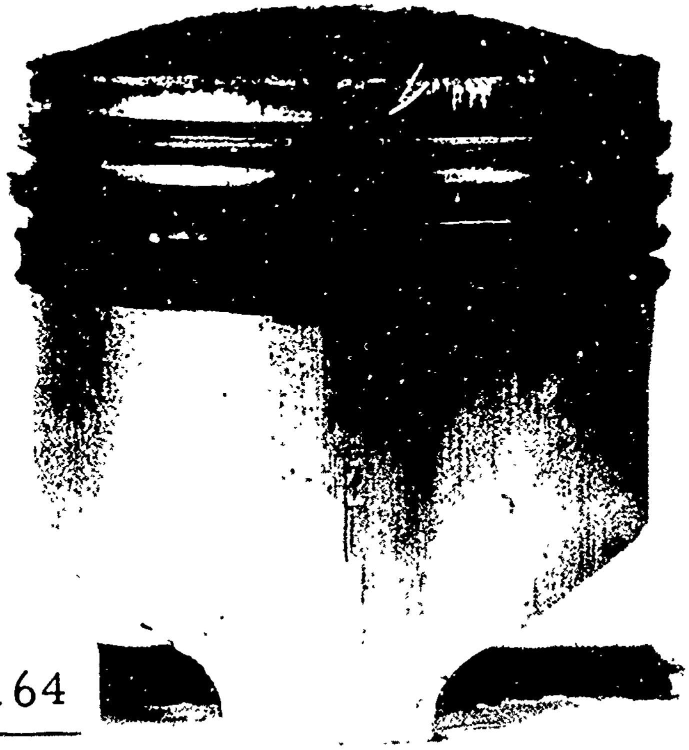
No. 2 Piston

No. 1 Piston

FIGURE C-13. PISTONS (ANTI-THRUST SIDE)–LOW LEAD FUEL



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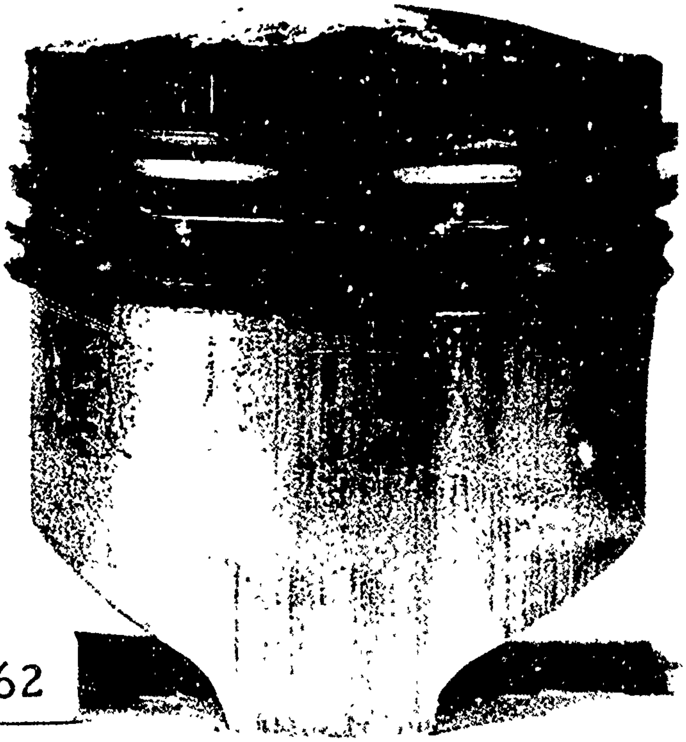

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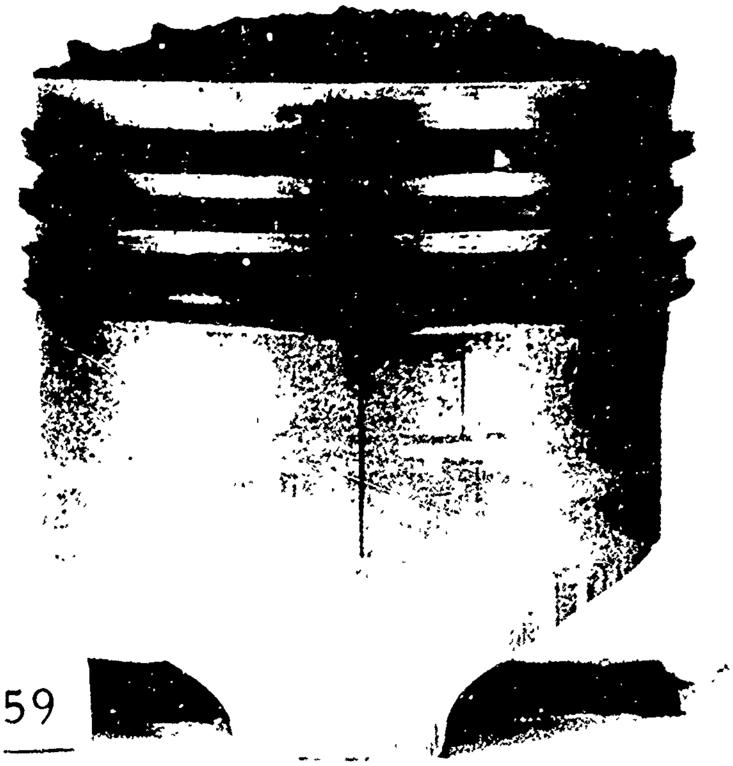
No. 2 Piston

No. 1 Piston

FIGURE C-14. PISTONS (THRUST SIDE)–UNLEADED FUEL



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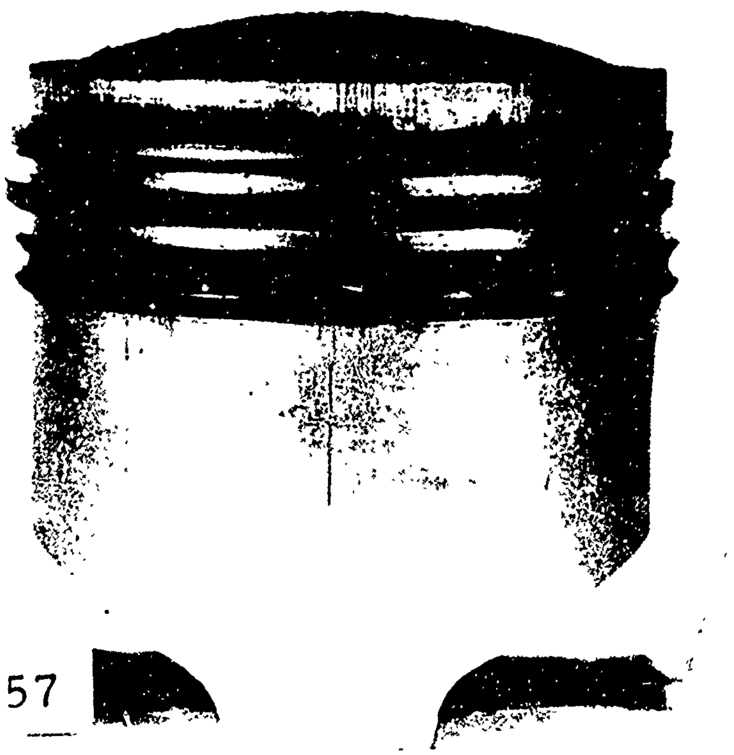

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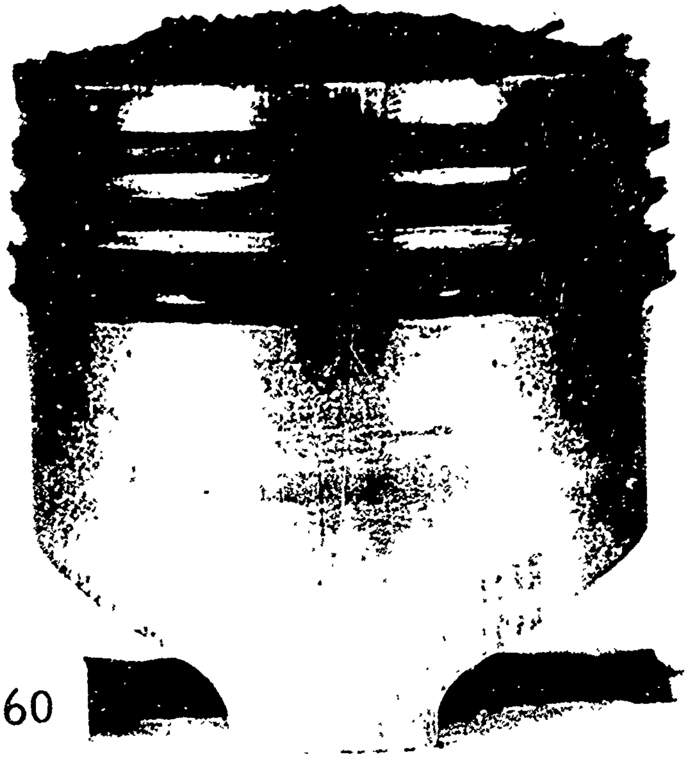
No. 2 Piston

No. 1 Piston

FIGURE C-15: PISTONS (ANTI-THRUST SIDE)--UNLEADED FUEL



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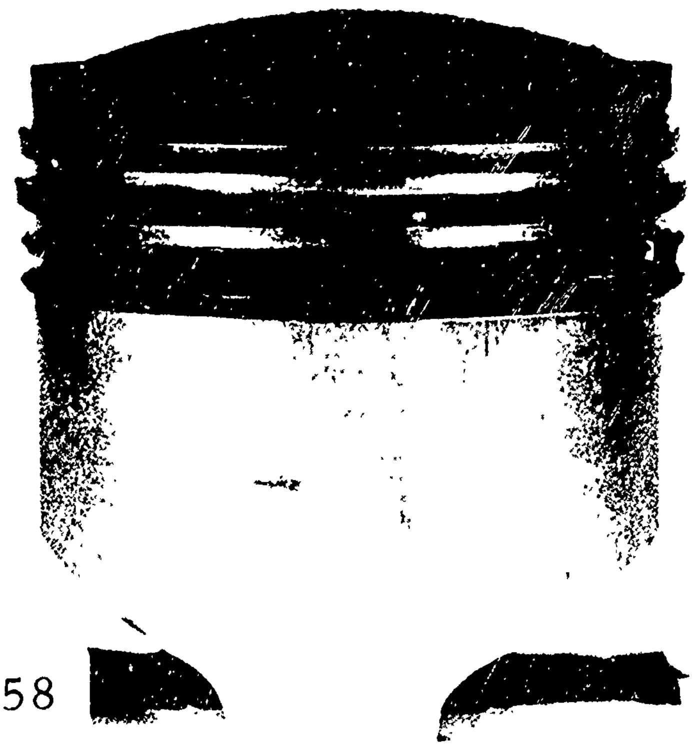

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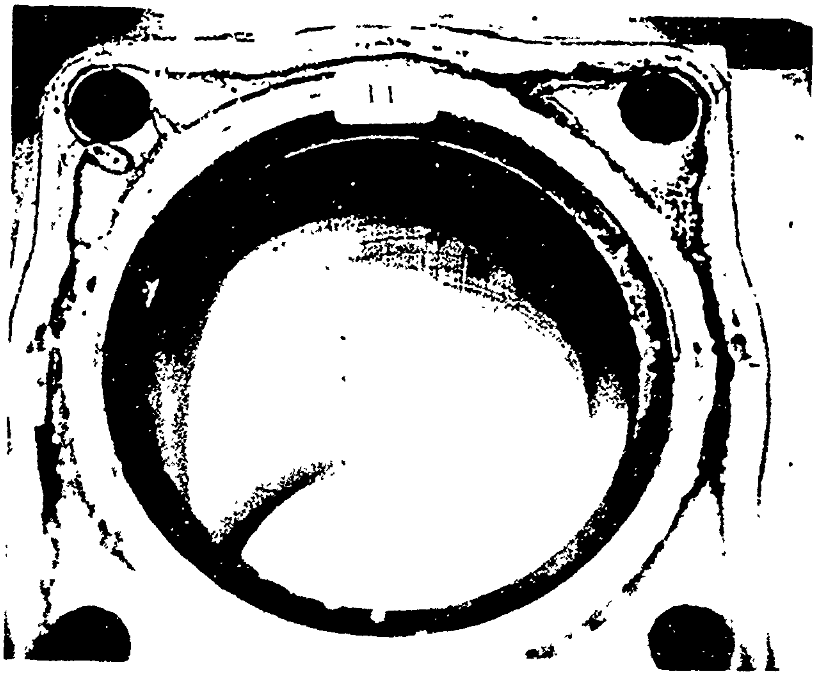
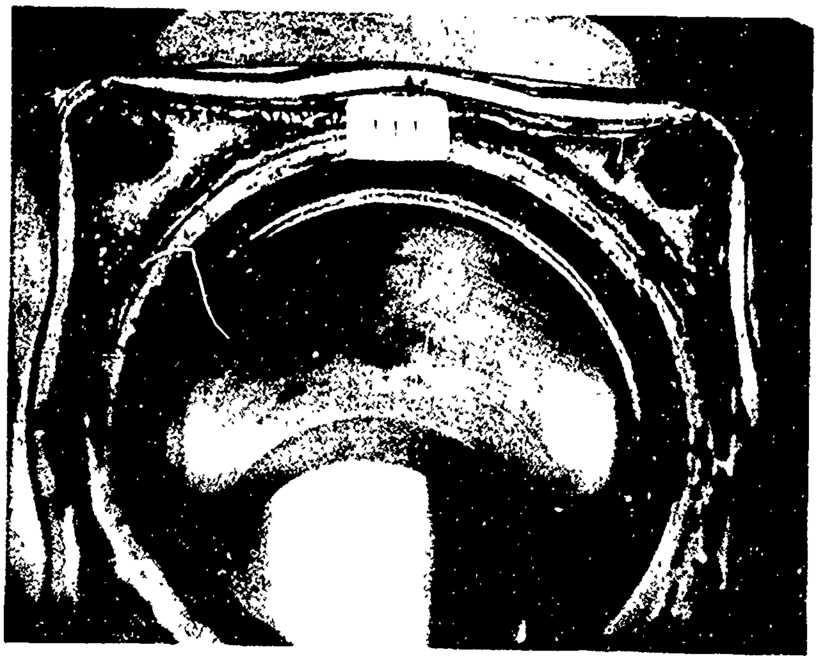
No. 1 Cylinder (Thrust)

No. 1 Cylinder (Anti-Thrust)

FIGURE C-16. TYPICAL CYLINDER BORE–NORMALLY LEADED FUEL

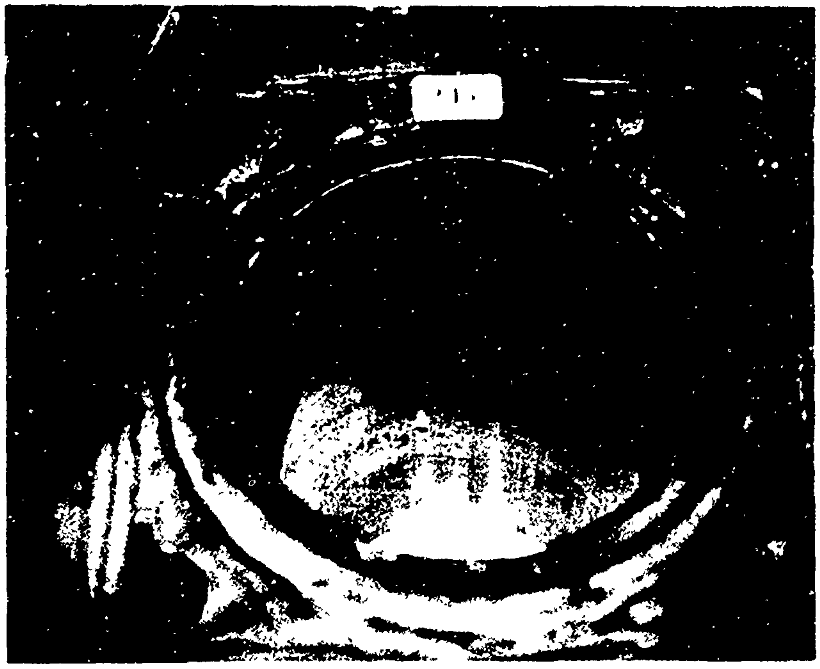


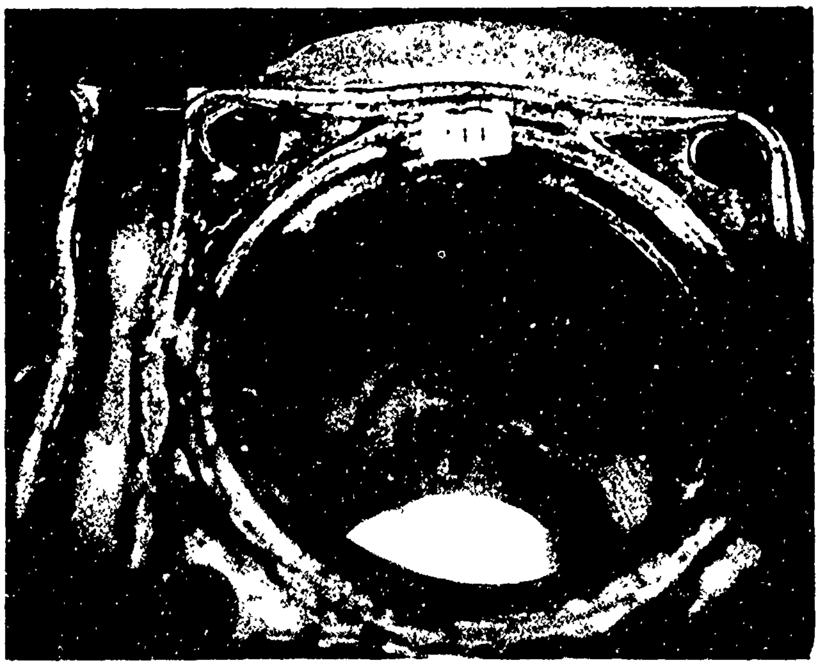


No. 1 Cylinder (Thrust)

No. 1 Cylinder (Anti-Thrust)

FIGURE C-17. TYPICAL CYLINDER BORE–LOW LEAD FUEL

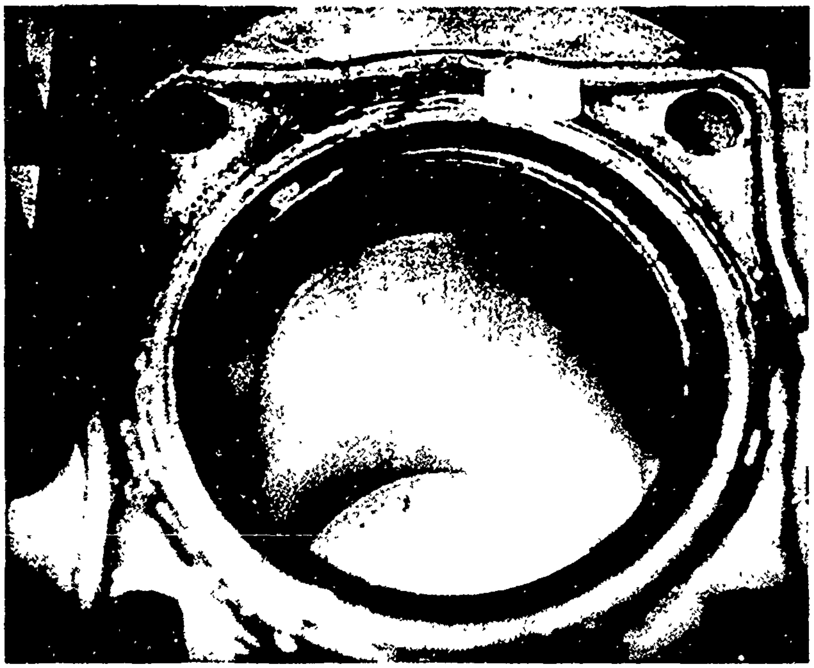


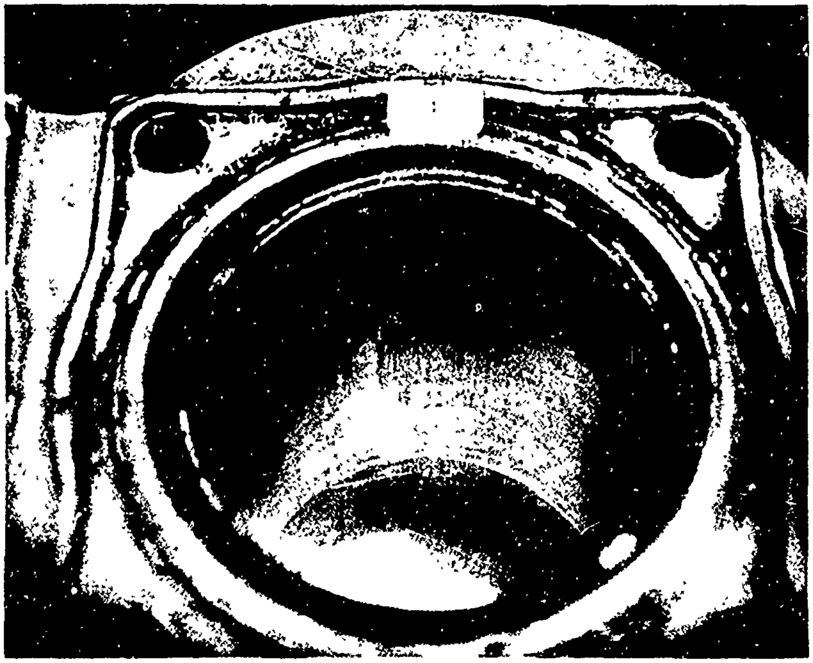


No. 1 Cylinder (Thrust)

No. 1 Cylinder (Anti-Thrust)

FIGURE C-18. TYPICAL CYLINDER BORE–UNLEADED FUEL





(L to R) Nos. 1 and 2 (125 Hours on Normally Leaded Fuel)

(L to R) Nos. 1 and 2 (125 Hours on Low Lead Fuel)

FIGURE C-19. SPARK PLUG TIPS–NORMALLY LEADED AND LOW LEAD FUELS

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(L to R) Nos. 1 and 2 (125 Hours on Unleaded Fuel)

FIGURE C-20. SPARK PLUG TIPS–UNLEADED FUEL

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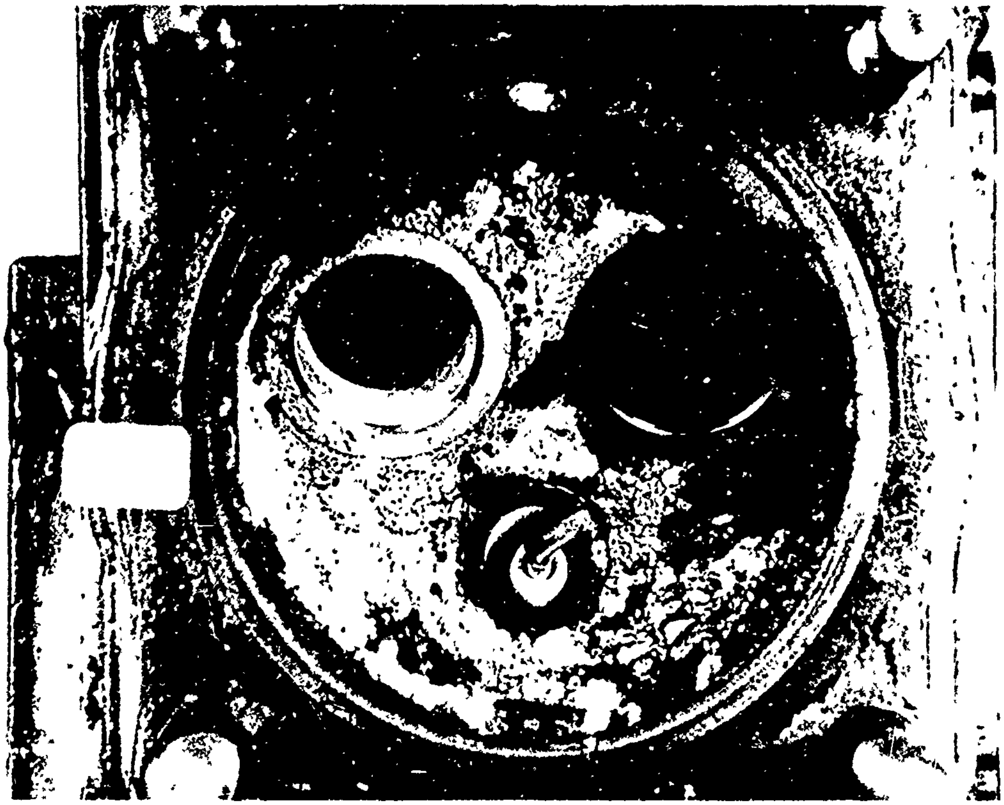
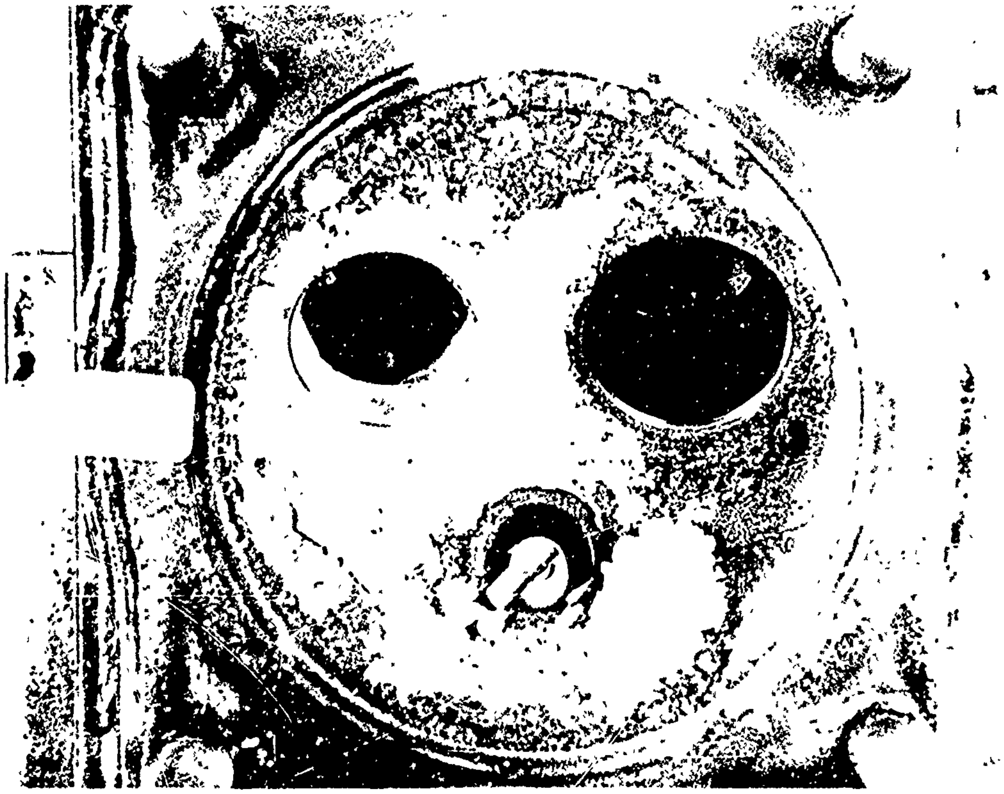
No. 4 Chamber

No. 2 Chamber

FIGURE C-21. COMBUSTION CHAMBERS–NORMALLY LEADED FUEL

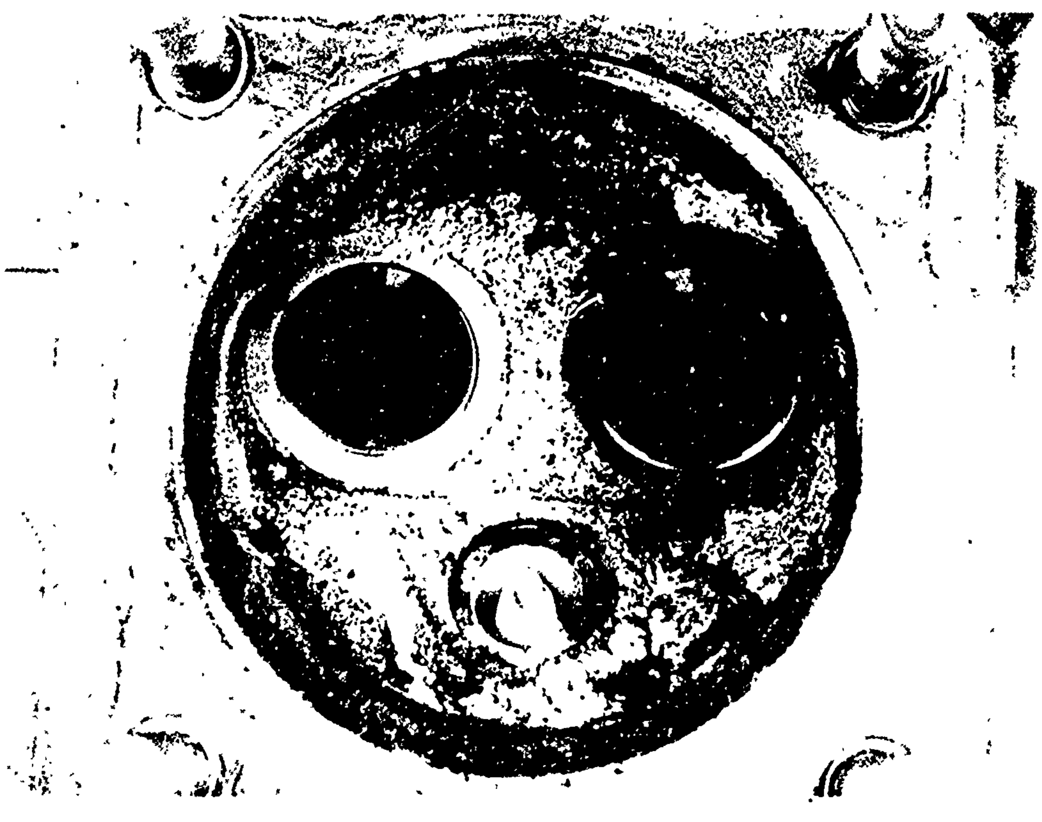




No. 4 Chamber

No. 2 Chamber

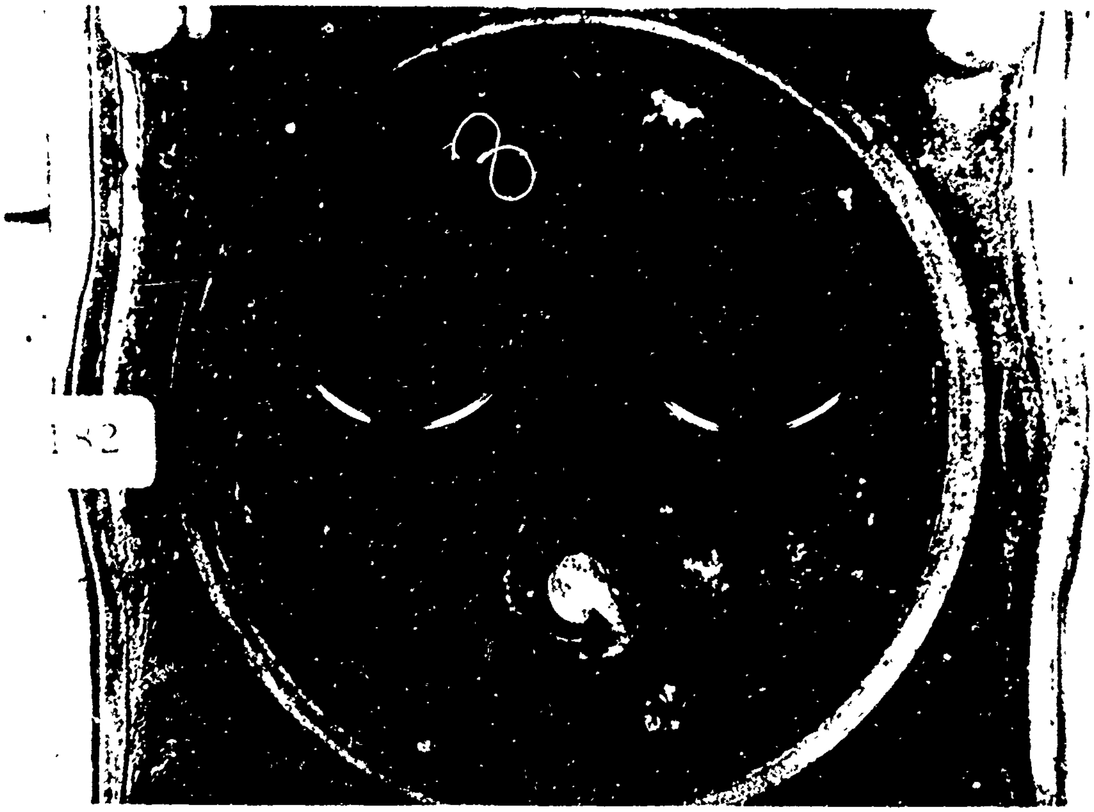
FIGURE C-22. COMBUSTION CHAMBERS–LOW LEAD FUEL



No. 4 Chamber

No. 2 Chamber

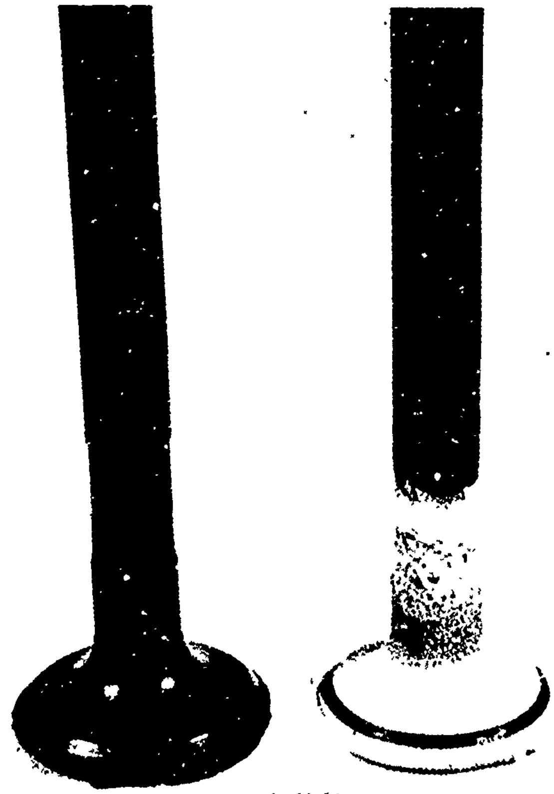
FIGURE 23. COMBUSTION CHAMBERS–UNLEADED FUEL



No. 3 Valve Set

No. 2 Valve Set

FIGURE C-24. INTAKE AND EXHAUST VALVES–NORMALLY LEADED FUEL

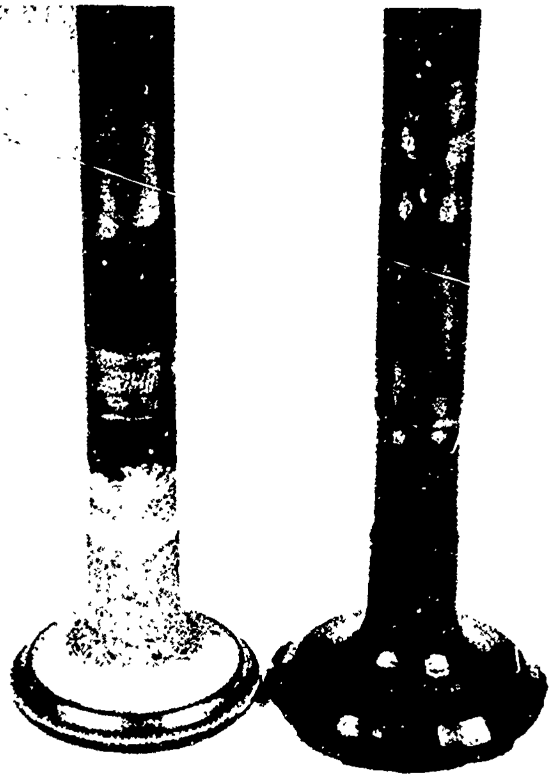


100

No. 3 Valve Set

No. 1 Valve Set

FIGURE C-25. INTAKE AND EXHAUST VALVES–LOW LEAD FUEL



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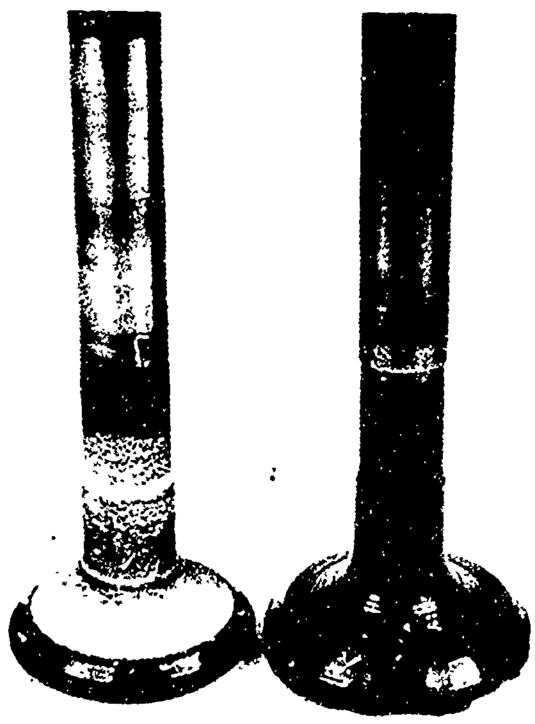

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No. 4 Valve Set

No. 2 Valve Set

FIGURE C-26. INTAKE AND EXHAUST VALVES–UNLEADED FUEL

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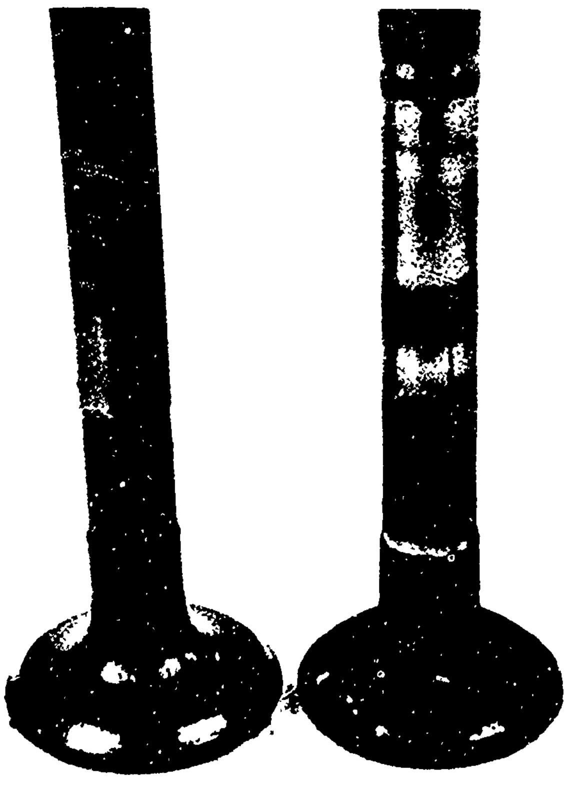
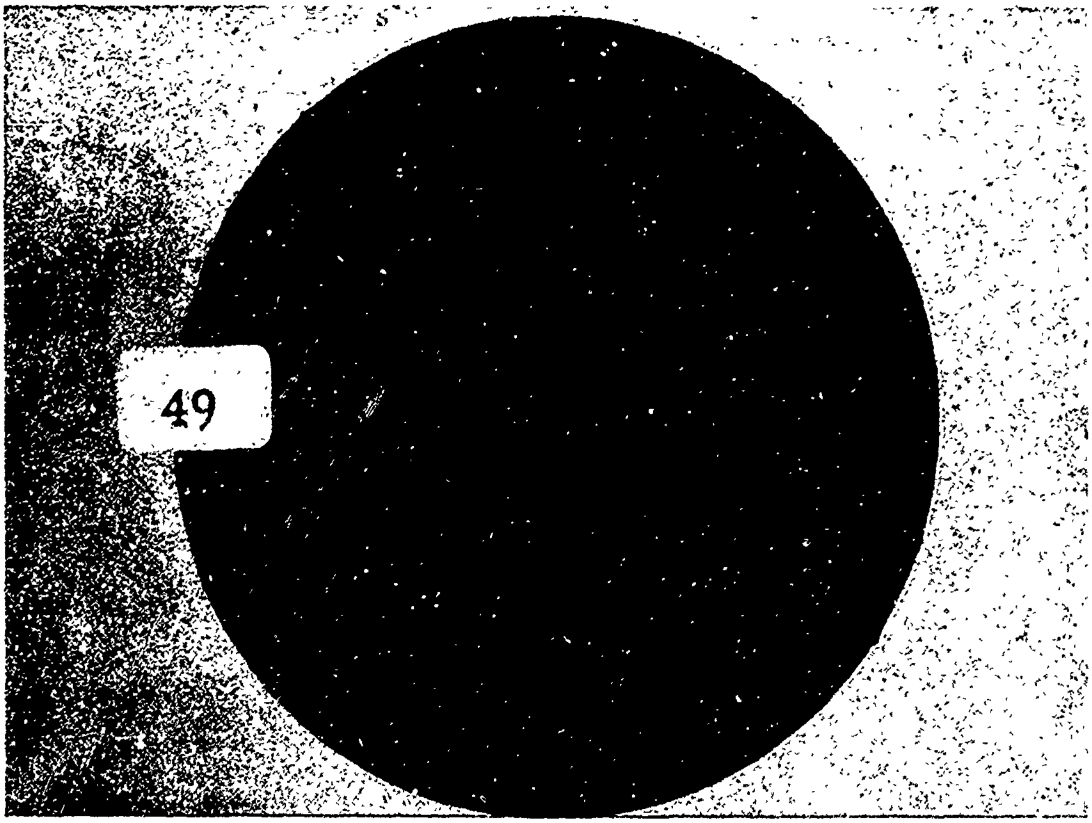


No. 4 Piston (Front Right)

No. 2 Piston (Front Right)

FIGURE C-27. PISTON CROWNS–NORMALLY LEADED FUEL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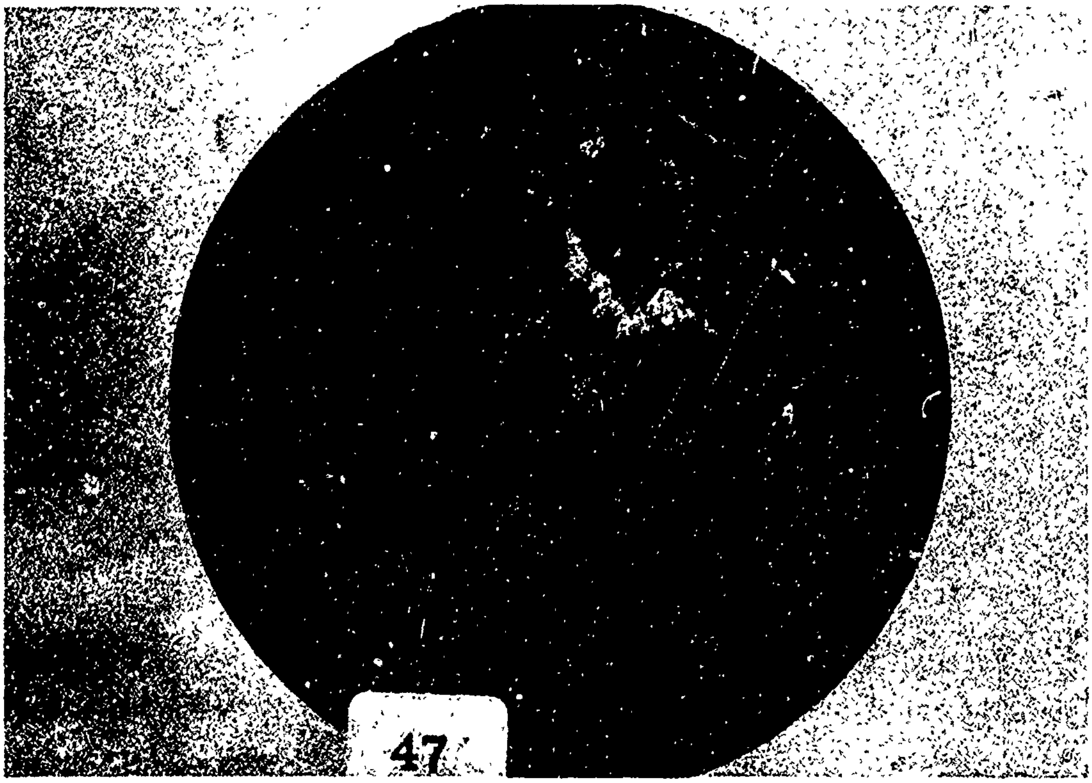
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No. 3 Piston (Front Right)

No. 1 Piston (Front Right)

FIGURE C-28. PISTON CROWNS–LOW LEAD FUEL


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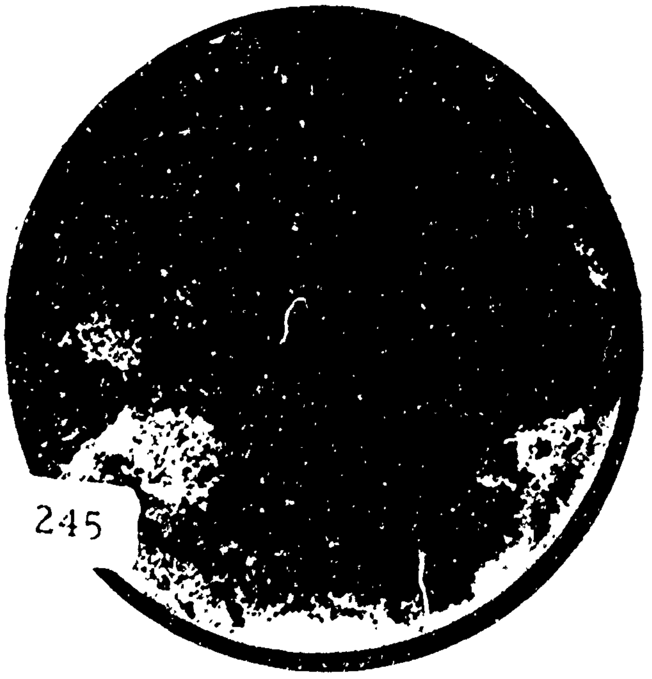
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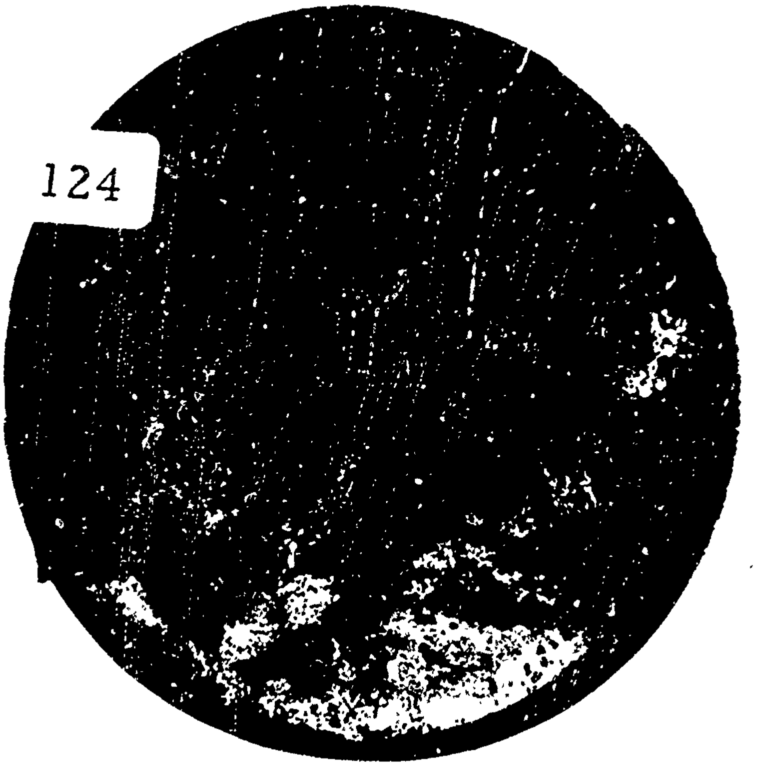
No. 4 Piston (Front Right)

No. 1 Piston (Front Right)

FIGURE C-29. PISTON CROWNS–UNLEADED FUEL



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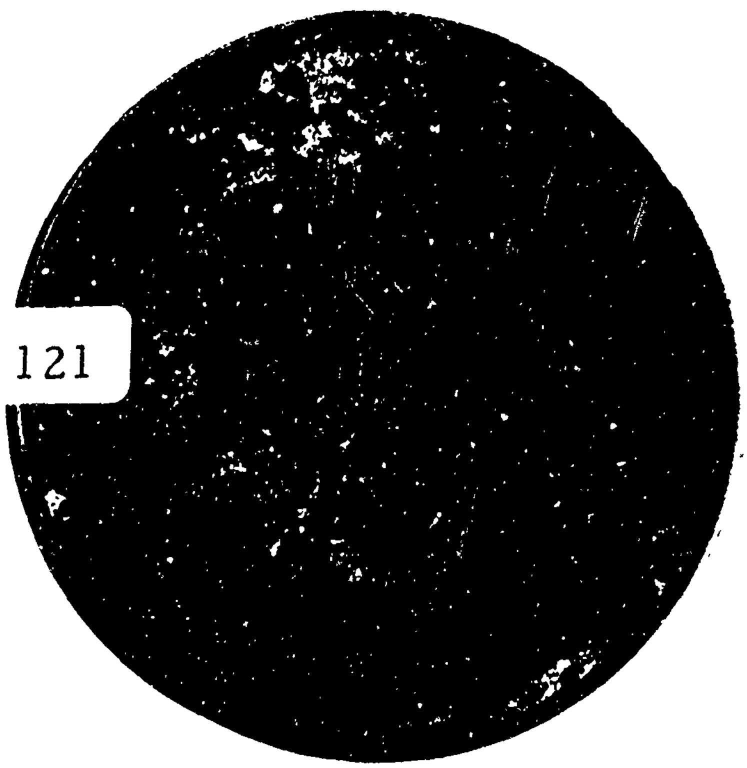

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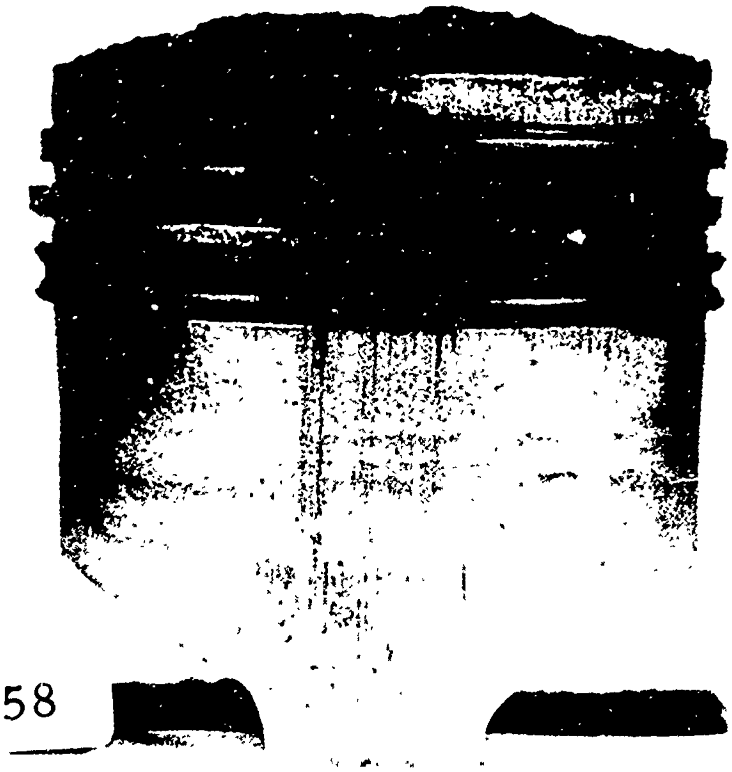
No. 3 Piston

No. 2 Piston

FIGURE C-30. PISTONS (THRUST SIDE)–NORMALLY LEADED FUEL



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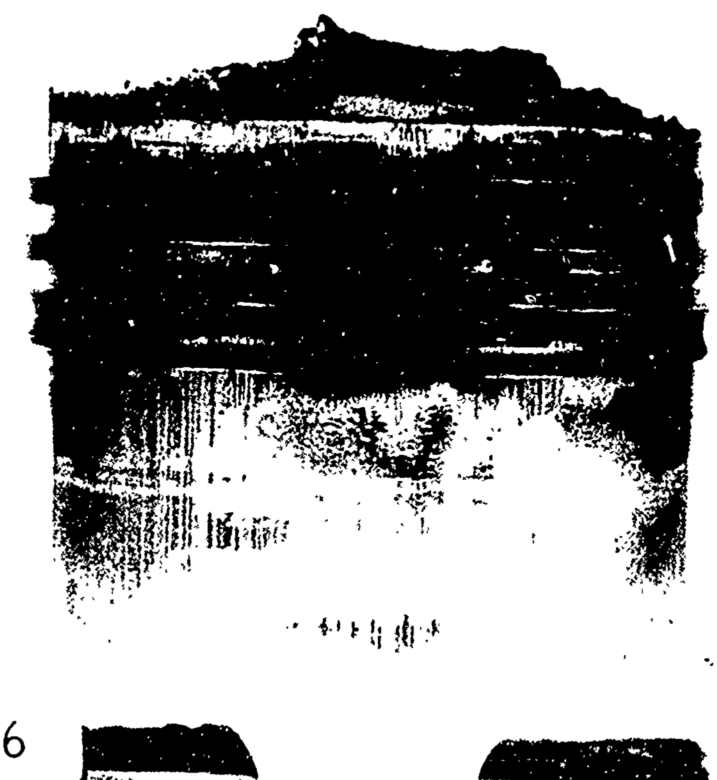

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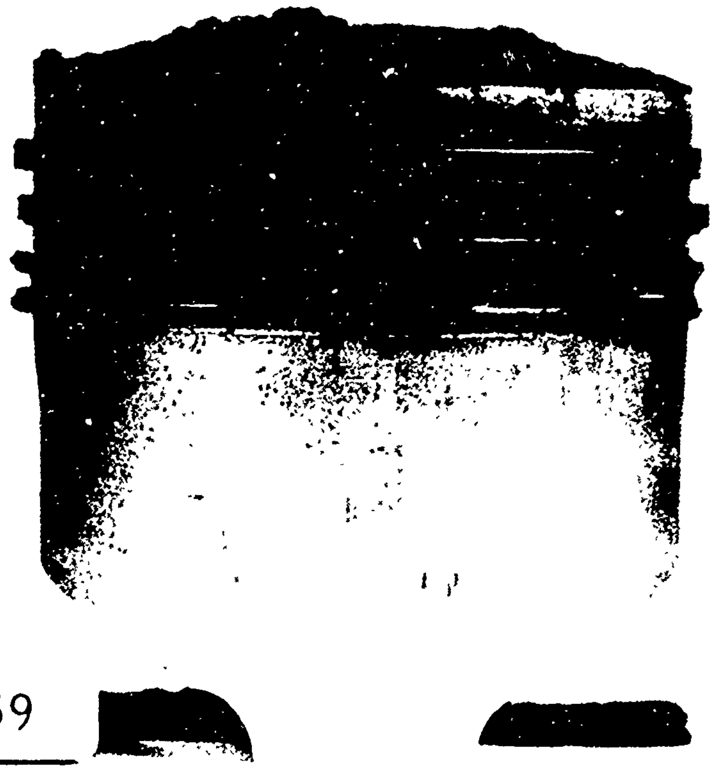
No. 3 Piston

No. 1 Piston

FIGURE C-31. PISTONS (ANTI-THRUST SIDE)--NORMALLY LEADED FUEL



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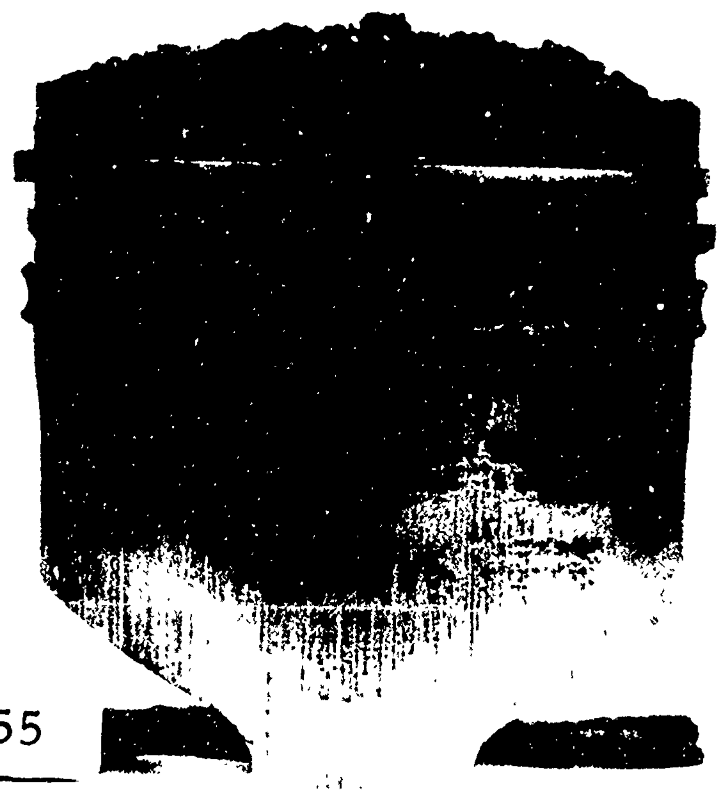
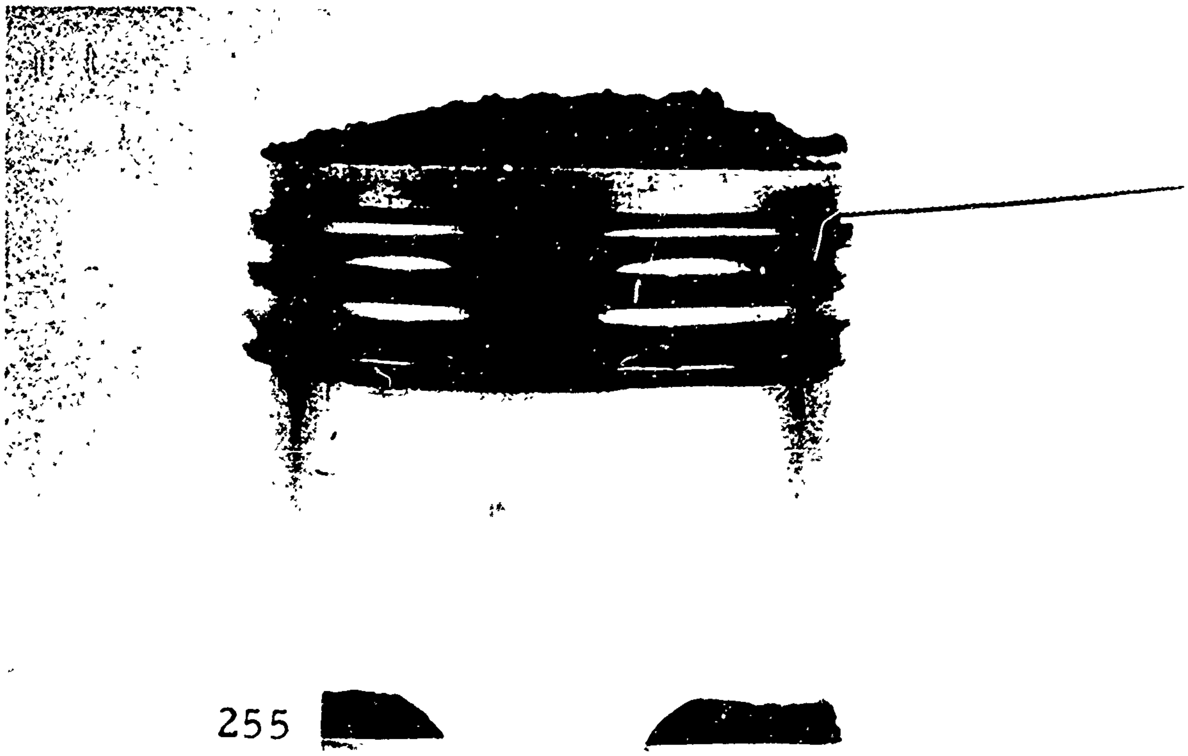


55

No. 1 Piston

No. 4 Piston

FIGURE C-32. PISTONS (THRUST SIDE)–LOW LEAD FUEL



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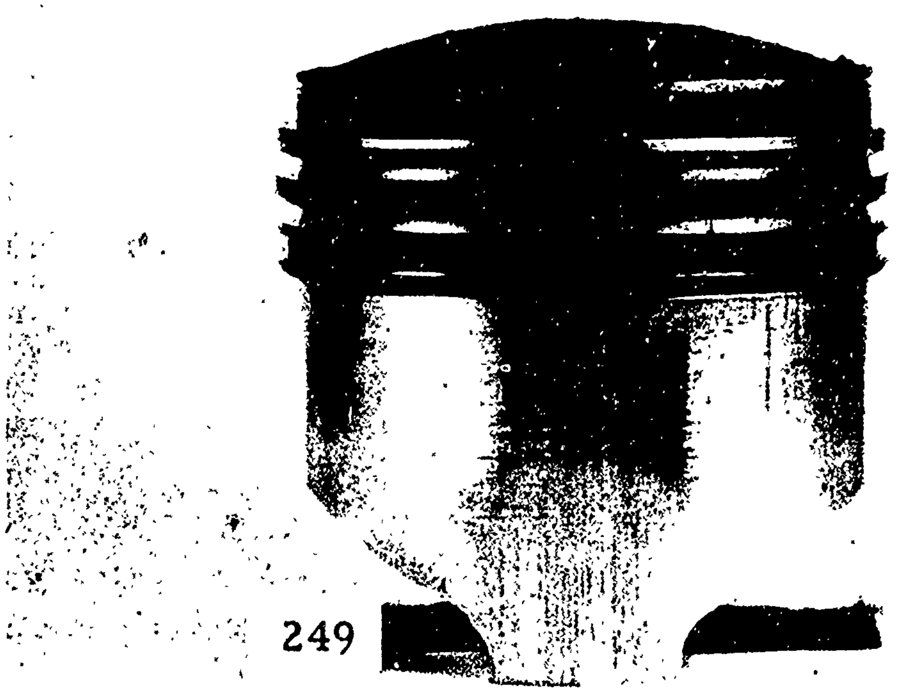
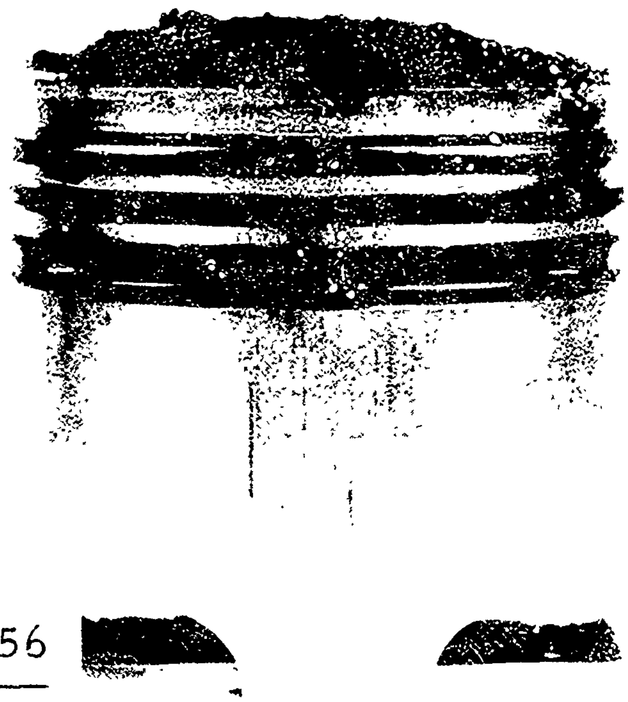


249

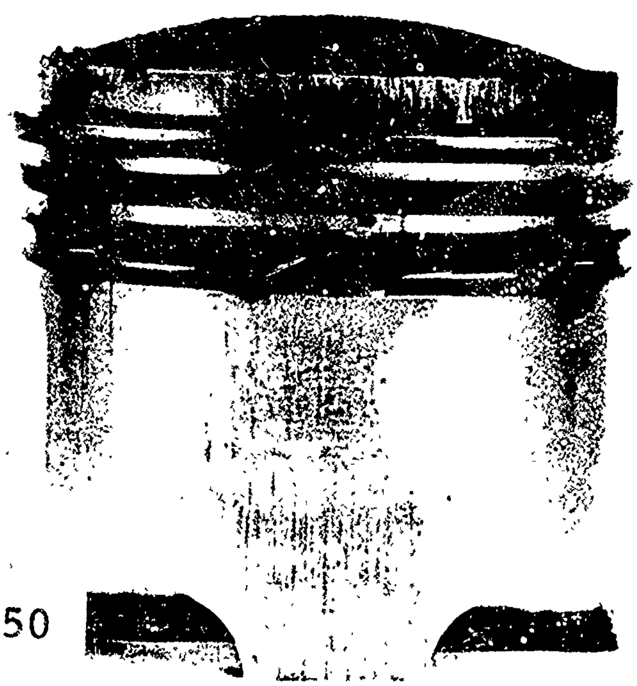
No. 1 Piston

No. 4 Piston

FIGURE C-33. PISTONS (ANTI-THRUST SIDE)--LOW LEAD FUEL



256

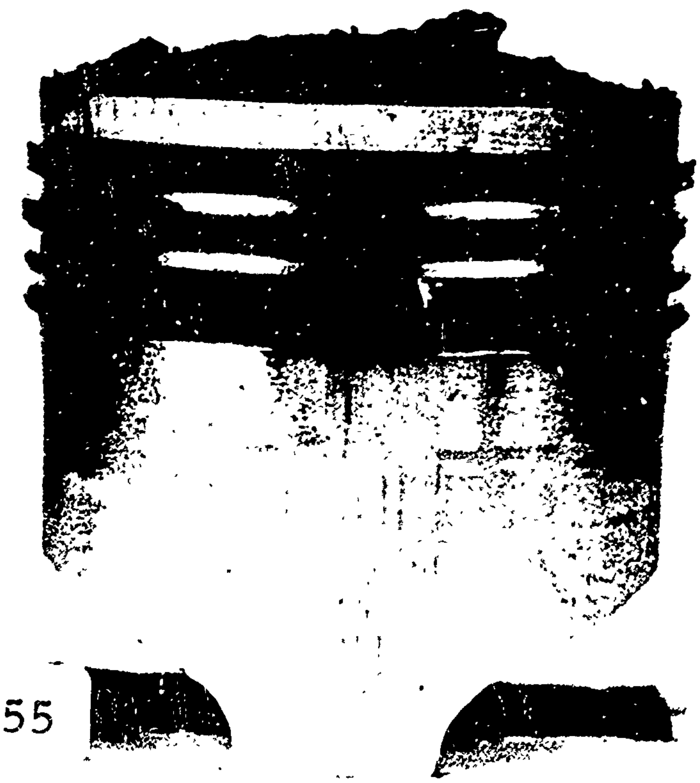


250

No. 4 Piston

No. 1 Piston

FIGURE C-34. PISTONS (THRUST SIDE)--UNLEADED FUEL



155

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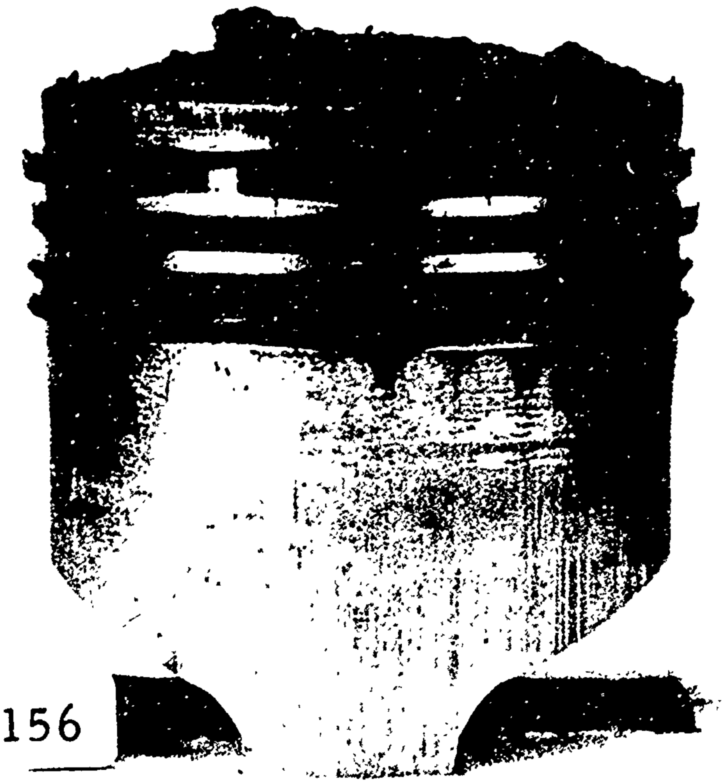
No. 4 Piston

No. 1 Piston

FIGURE C-35. PISTONS (ANTI-THRUST SIDE)–UNLEADED FUEL



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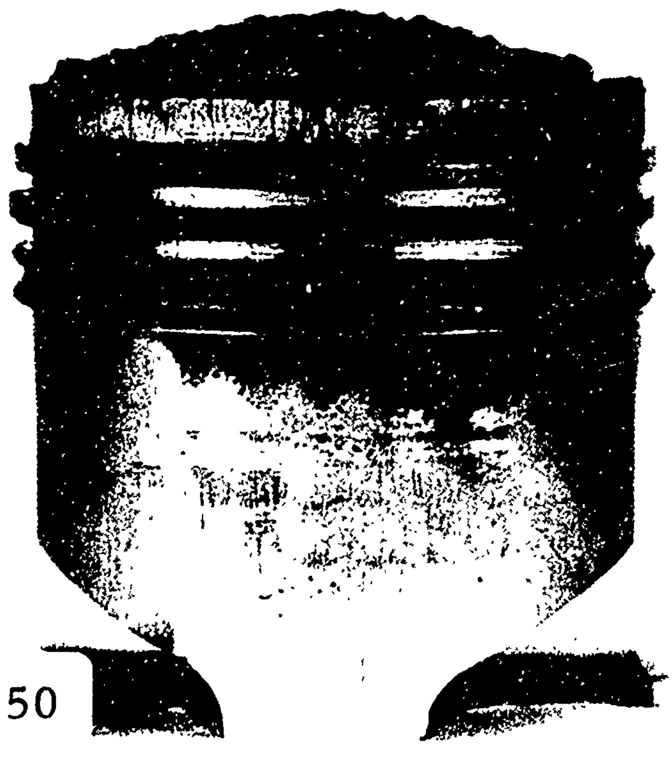
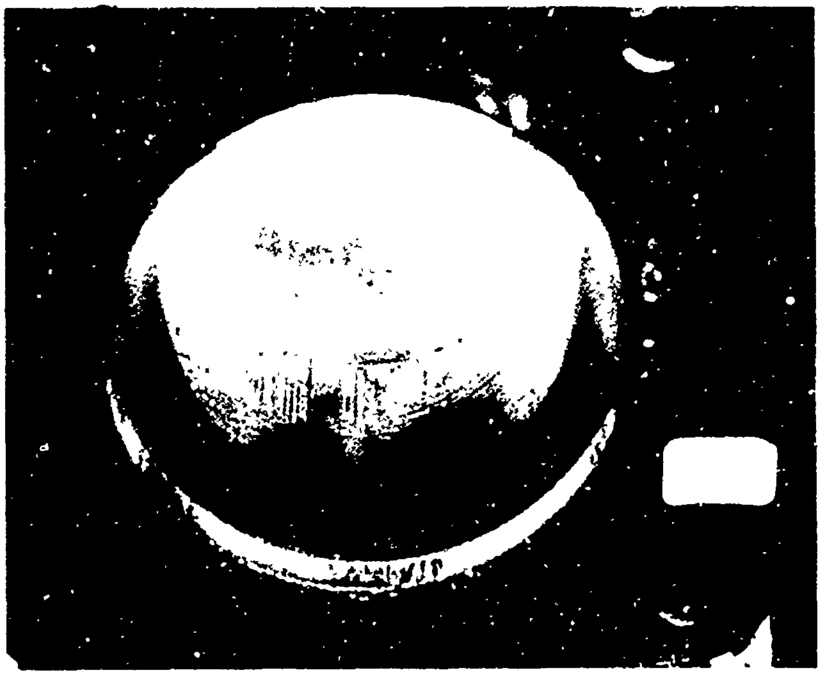


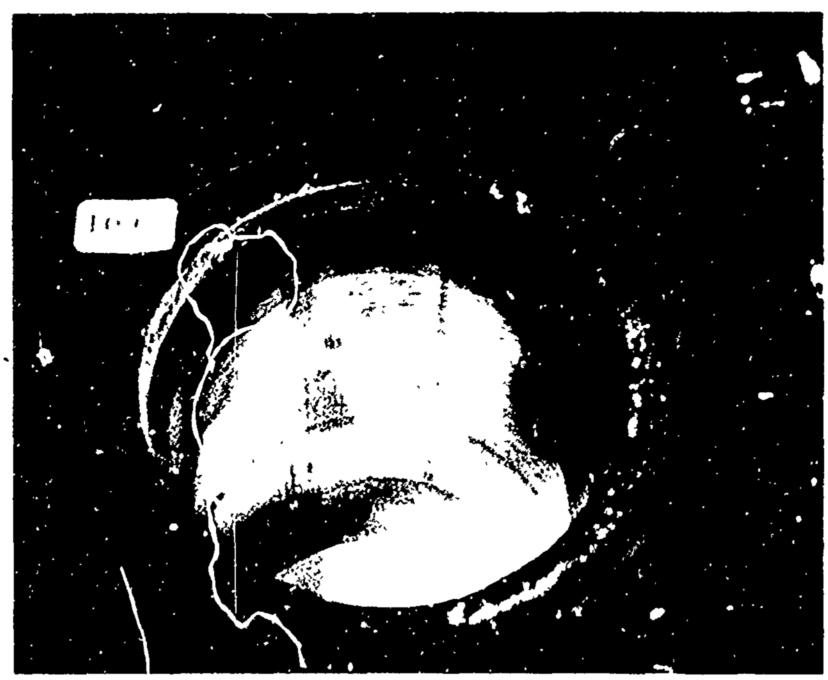
150

No. 1 Cylinder (Thrust)

No. 1 Cylinder (Anti-Thrust)

FIGURE C-36. TYPICAL CYLINDER BORE--NORMALLY LEADED FUEL

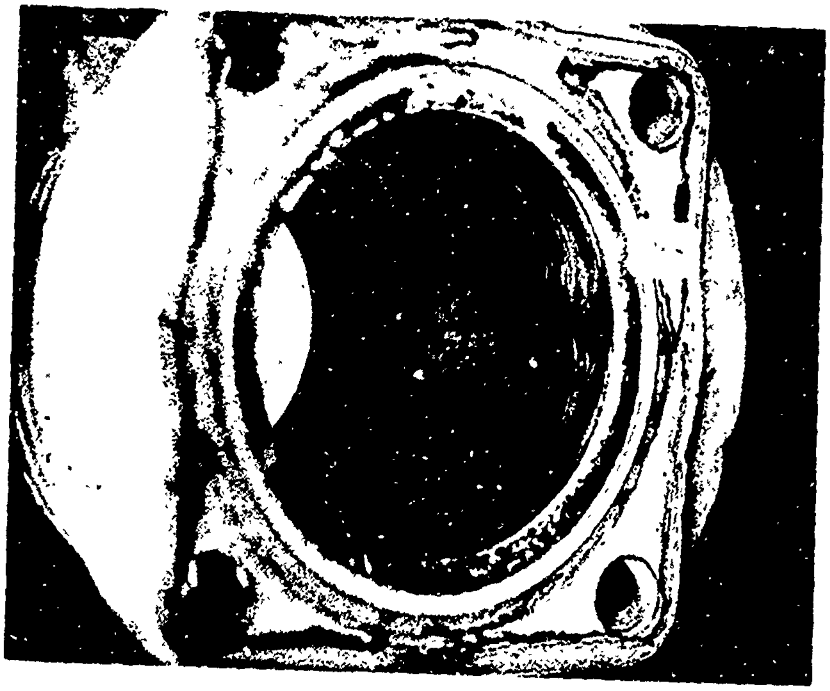


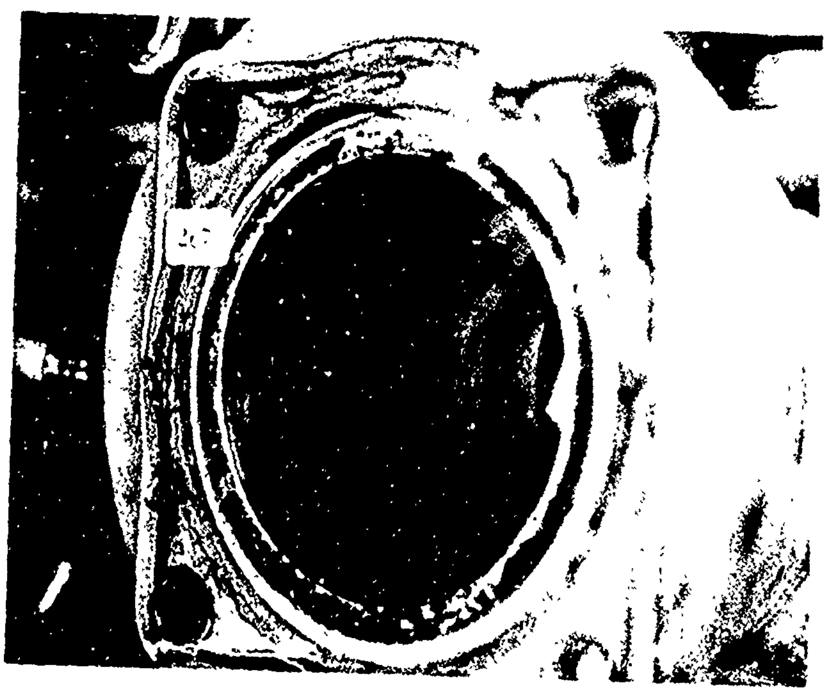


No. 1 Cylinder (Thrust)

No. 1 Cylinder (Anti-Thrust)

FIGURE C-37. TYPICAL CYLINDER BORE–LOW LEAD FUEL

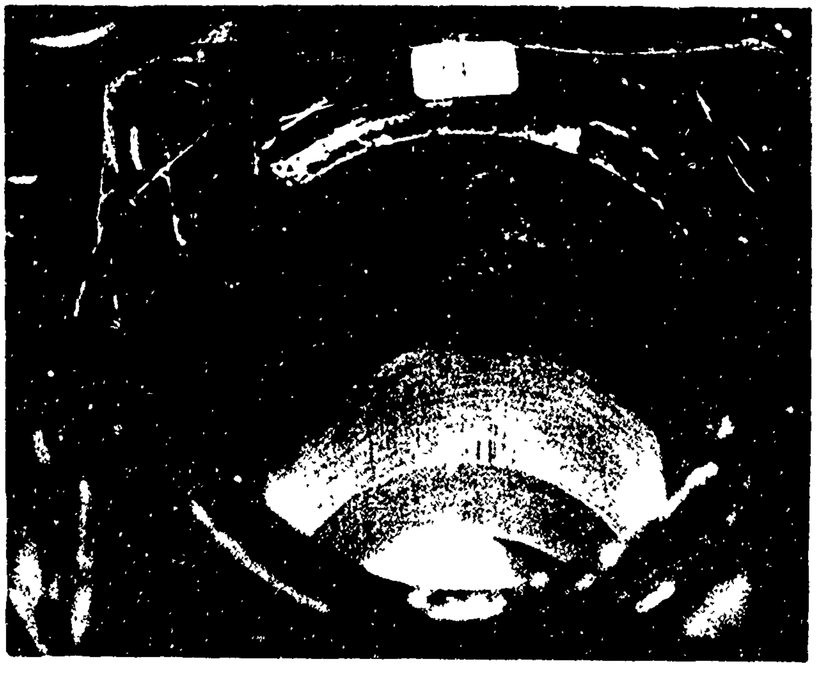




No. 1 Cylinder (Thrust)

No. 1 Cylinder (Anti-Thrust)

FIGURE C-38. TYPICAL CYLINDER BORE–UNLEADED FUEL



(Left to Right) No. 1-17 Hours; Nos. 2, 3, and 4-71 Hours–All on Normally Leaded Fuel

(Left to Right) Nos. 1, 2, 3, and 4 (125 Hours on Low Lead Fuel)

FIGURE C-39. SPARK PLUG TIPS–NORMALLY LEADED AND LOW LEAD FUELS

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(Left to Right) Nos. 1, 2, 3, and 4 (125 Hours on Unleaded Fuel Except 17 Hours for No. 2)

FIGURE C-40. SPARK PLUG TIPS–UNLEADED FUEL

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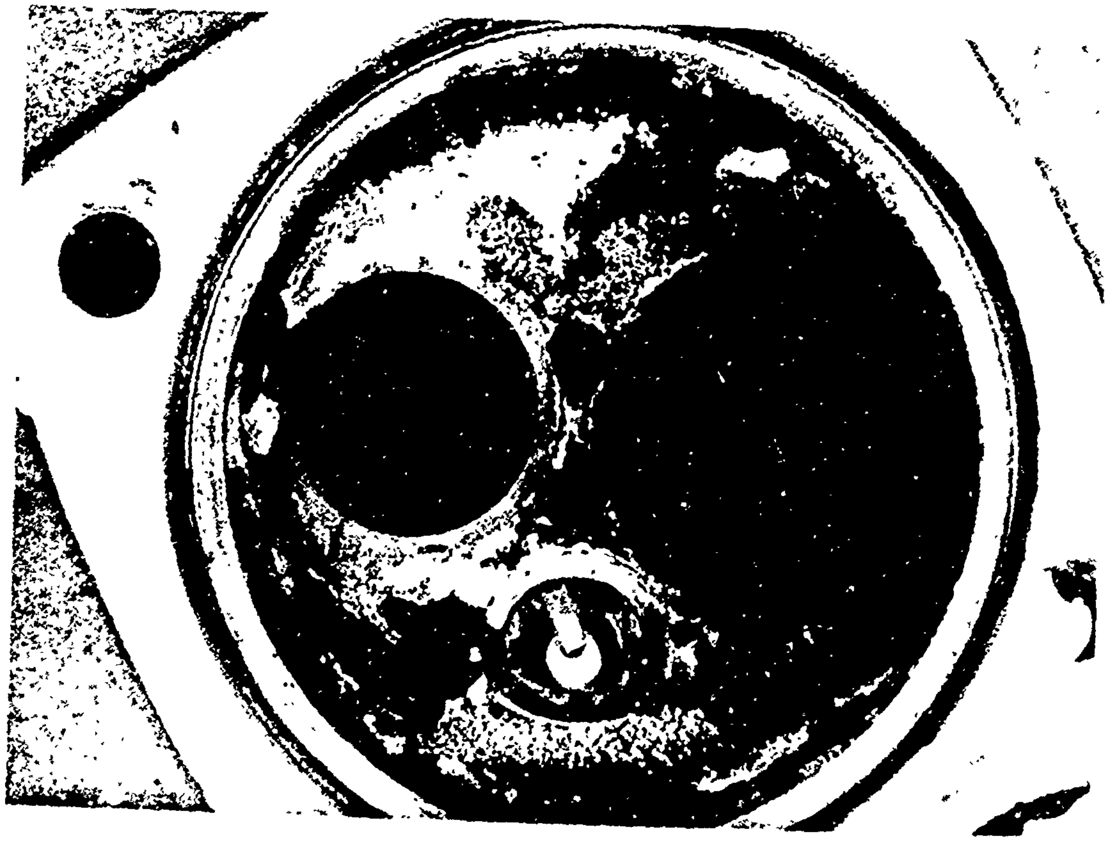
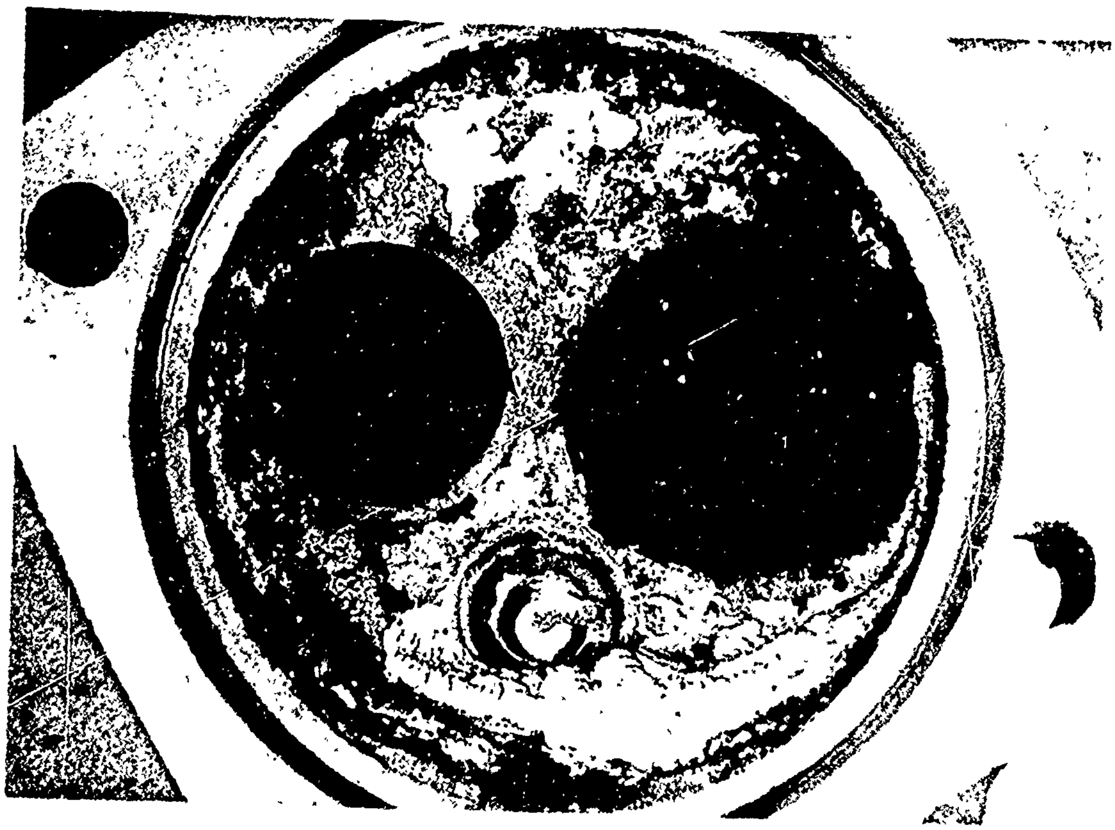
No. 1 Chamber

No. 2 Chamber

FIGURE C-41. COMBUSTION CHAMBERS--NORMALLY LEADED FUEL

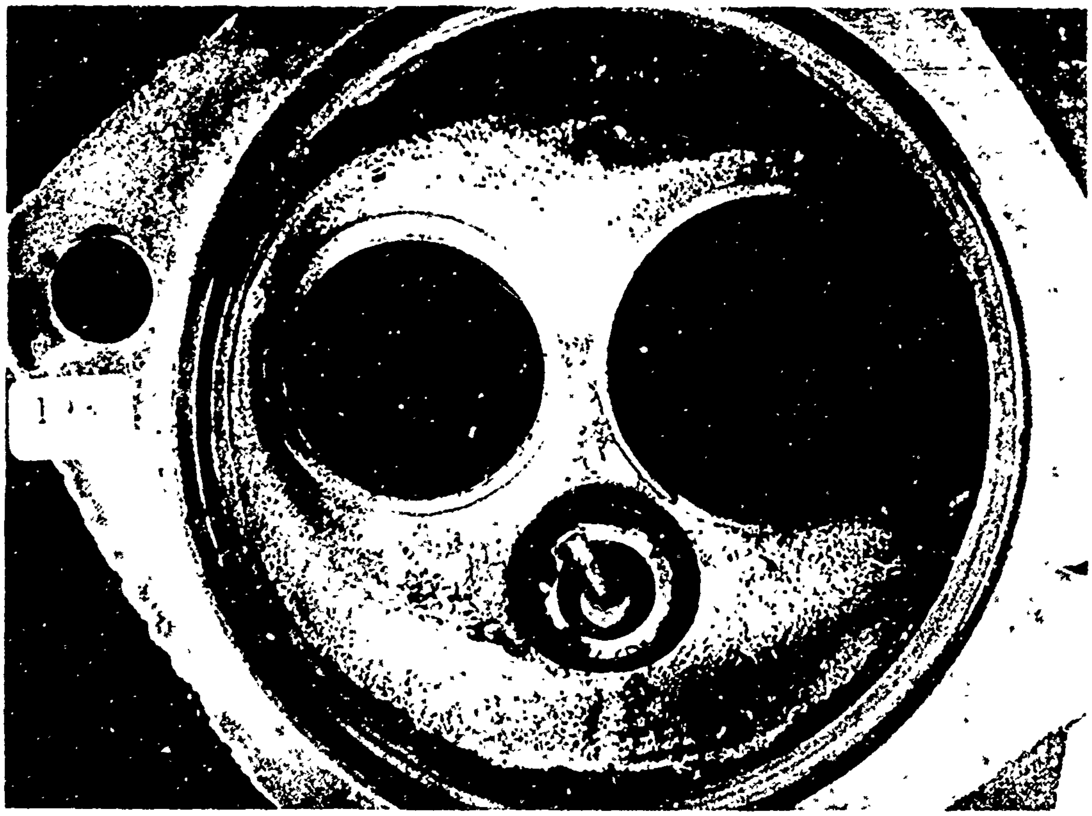


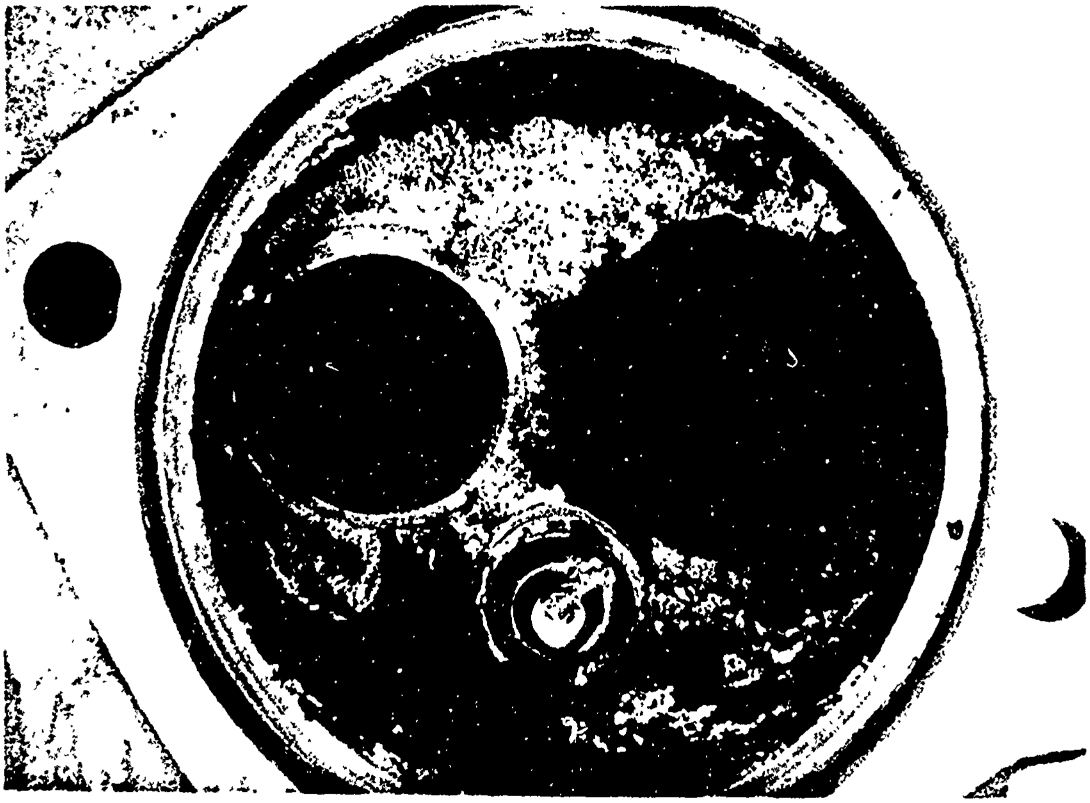


No. 3 Chamber

No. 4 Chamber

FIGURE C-42. COMBUSTION CHAMBERS–LOW LEAD FUEL





No. 2 Chamber

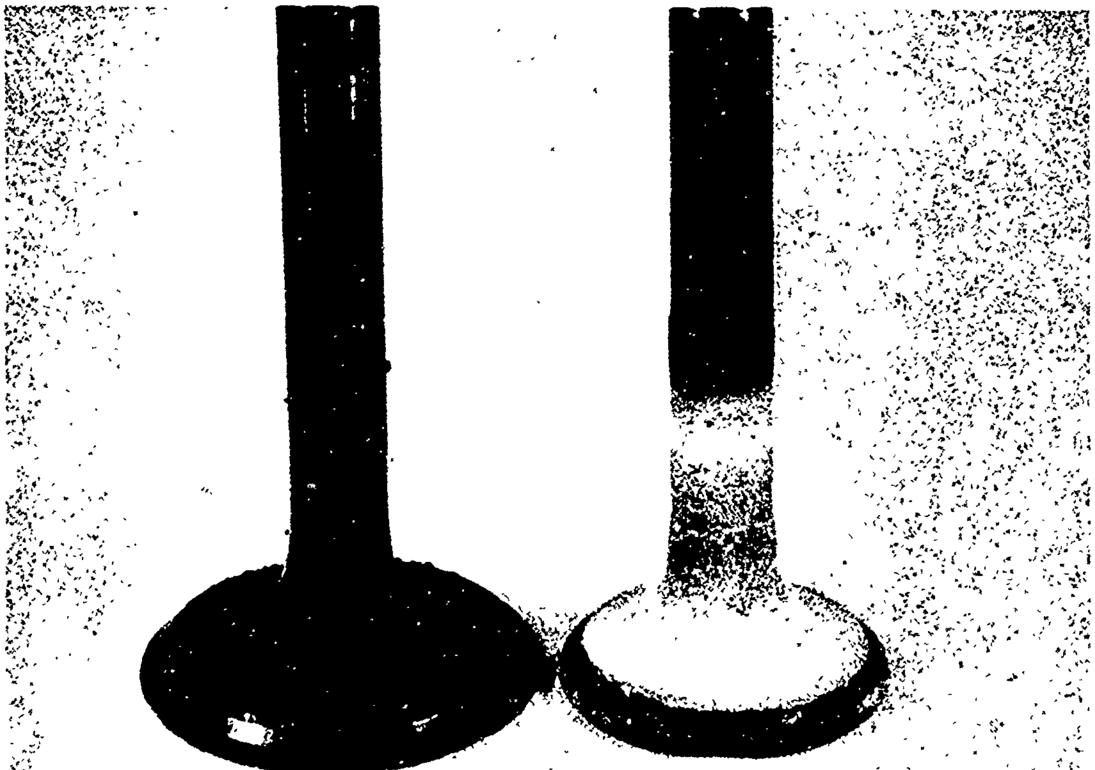
No. 1 Chamber

FIGURE C-43. COMBUSTION CHAMBERS--UNLEADED FUEL

No. 2 Valve Set

No. 4 Valve Set

FIGURE C-44. INTAKE AND EXHAUST VALVES–NORMALLY LEADED FUEL



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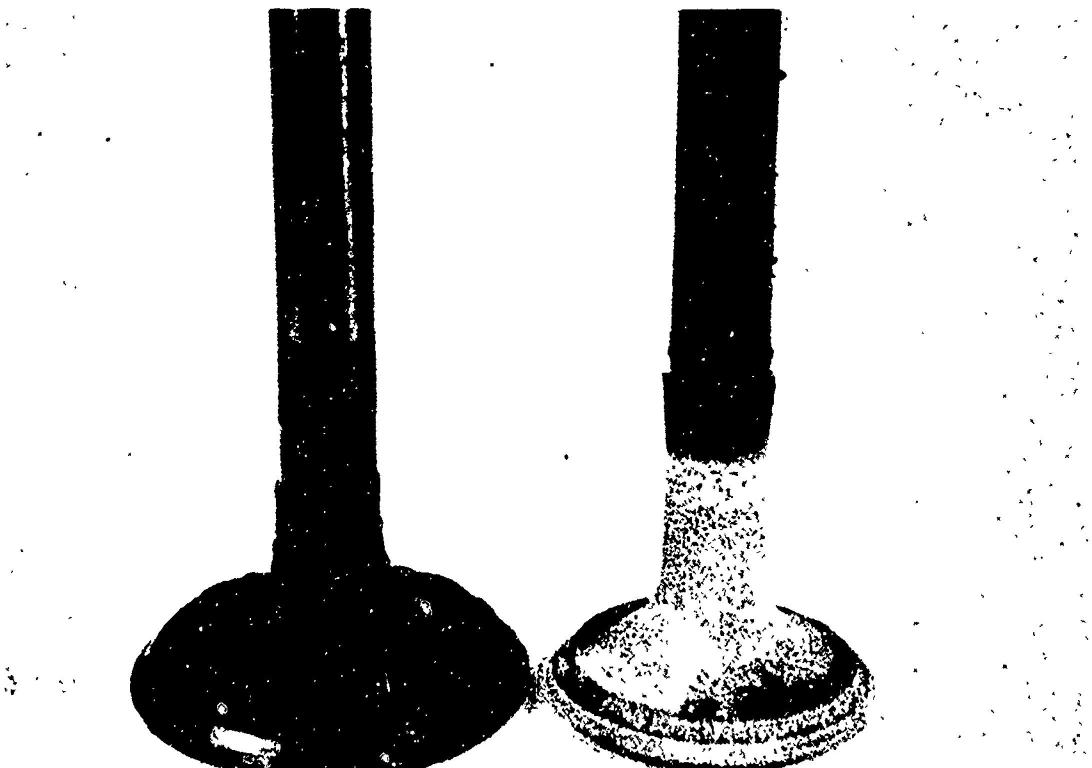

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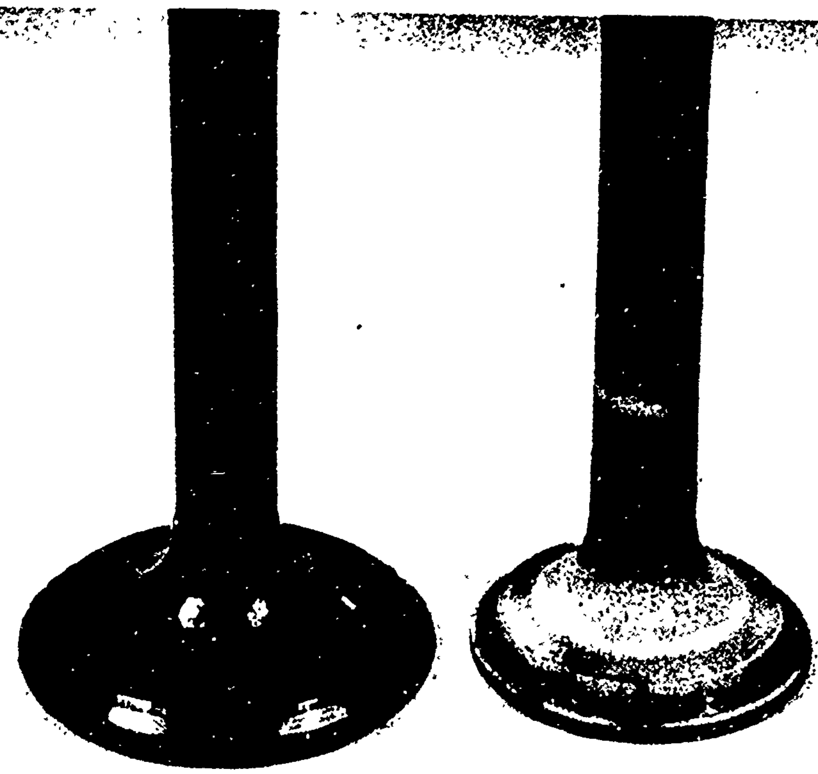
No. 2 Valve Set

No. 3 Valve Set

FIGURE C-45. INTAKE AND EXHAUST VALVES--LOW LEAD FUEL



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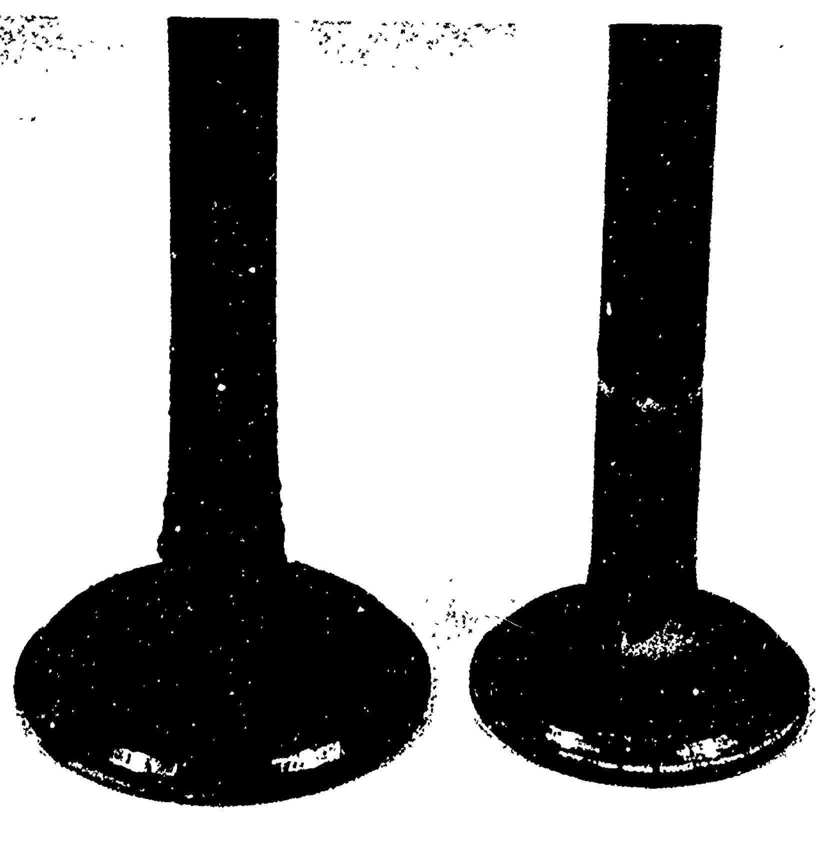
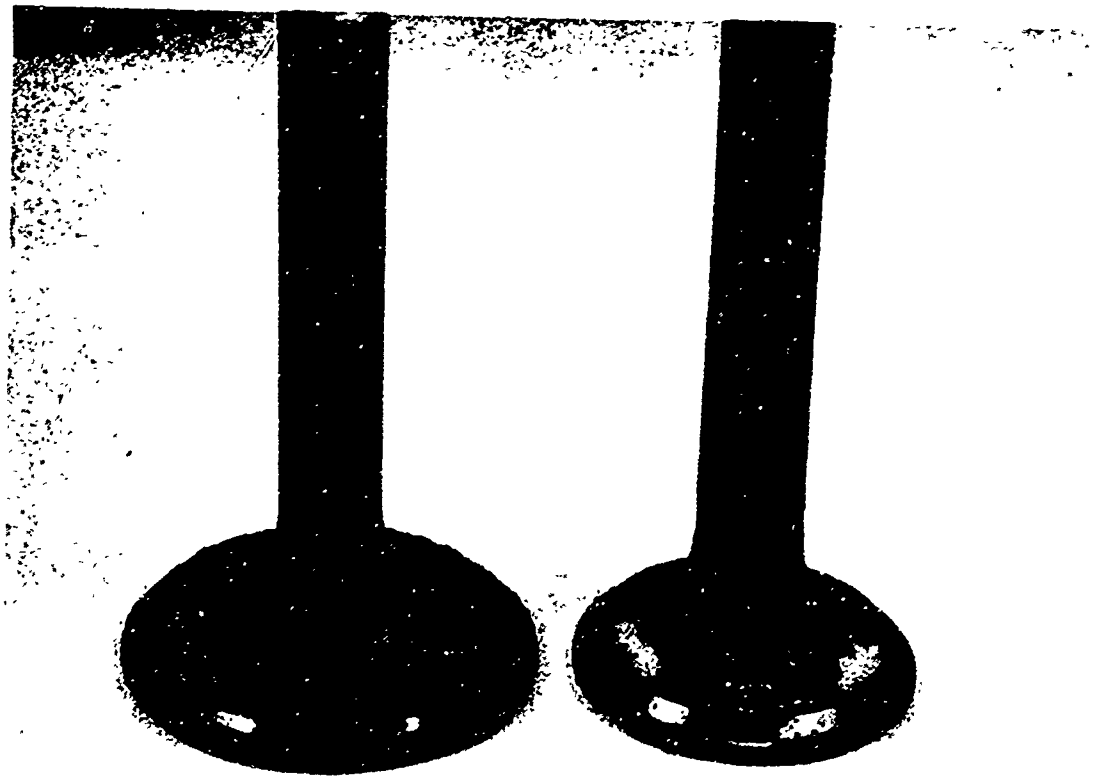


No. 1 Valve Set

No. 2 Valve Set (Internal Face Concave)

FIGURE C-46. INTAKE AND EXHAUST VALVES–UNLEADED FUEL



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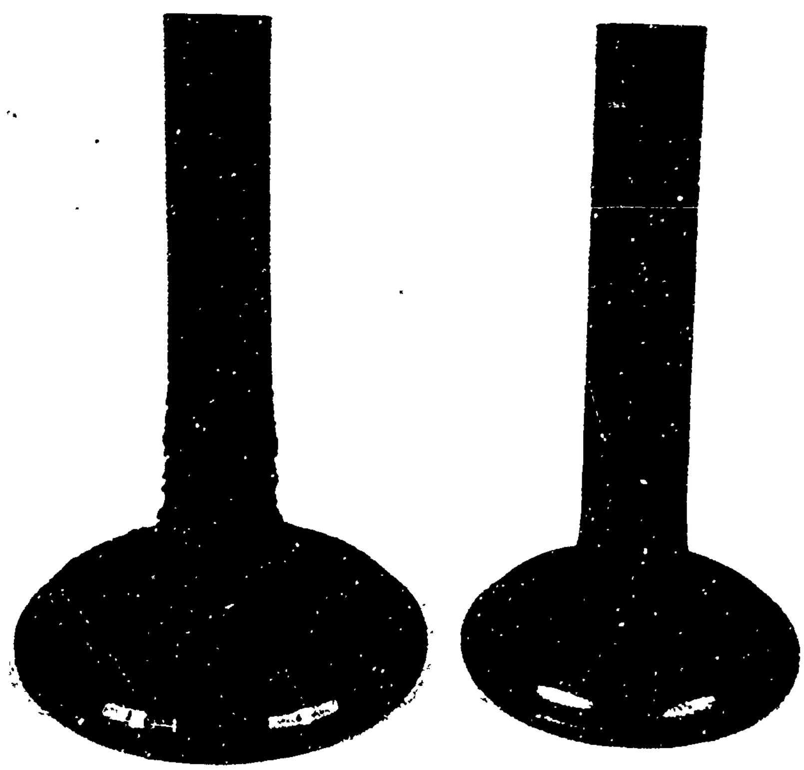

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No. 4 Piston (Front Right)

No. 2 Piston (Front Right)

FIGURE C-47. PISTON CROWNS–NORMALLY LEADED FUEL


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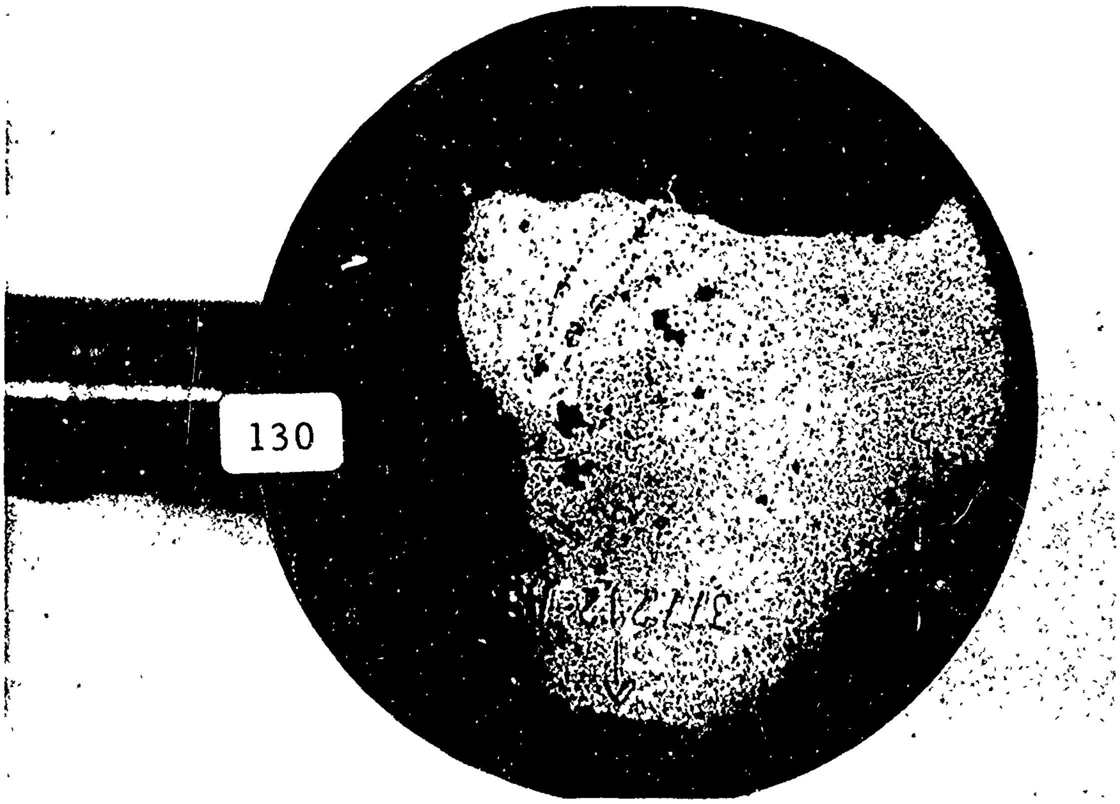
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No. 1 Piston (Front Right)

No. 2 Piston (Front Right)

FIGURE C-48. PISTON CROWNS–LOW LEAD FUEL


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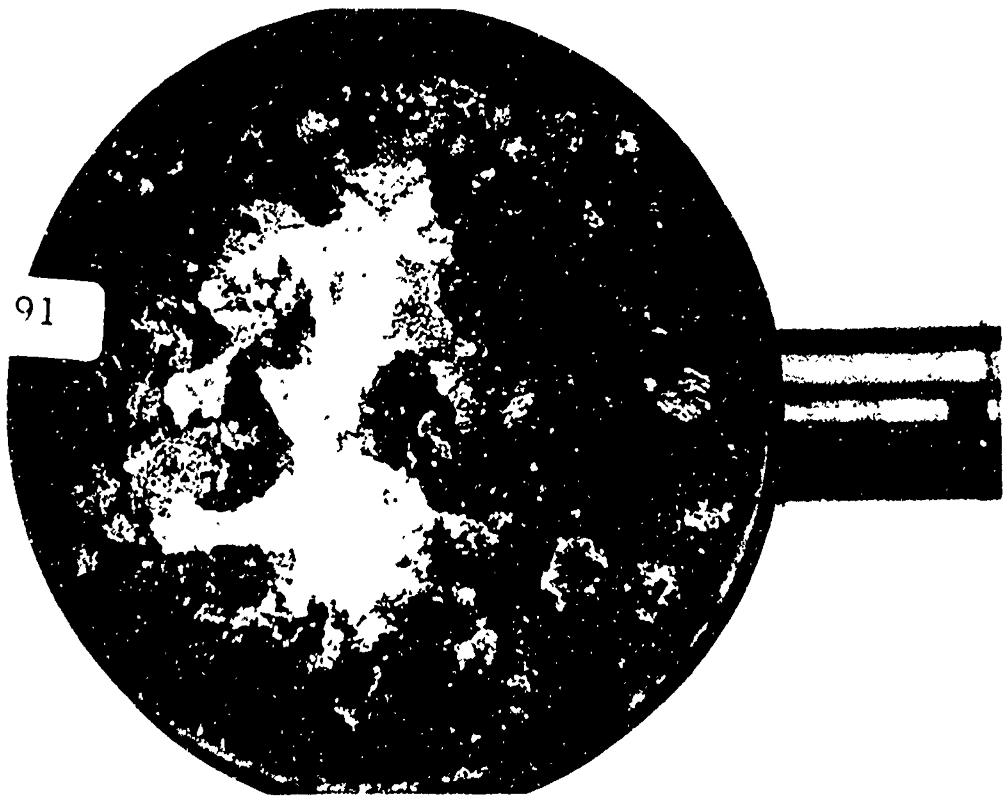
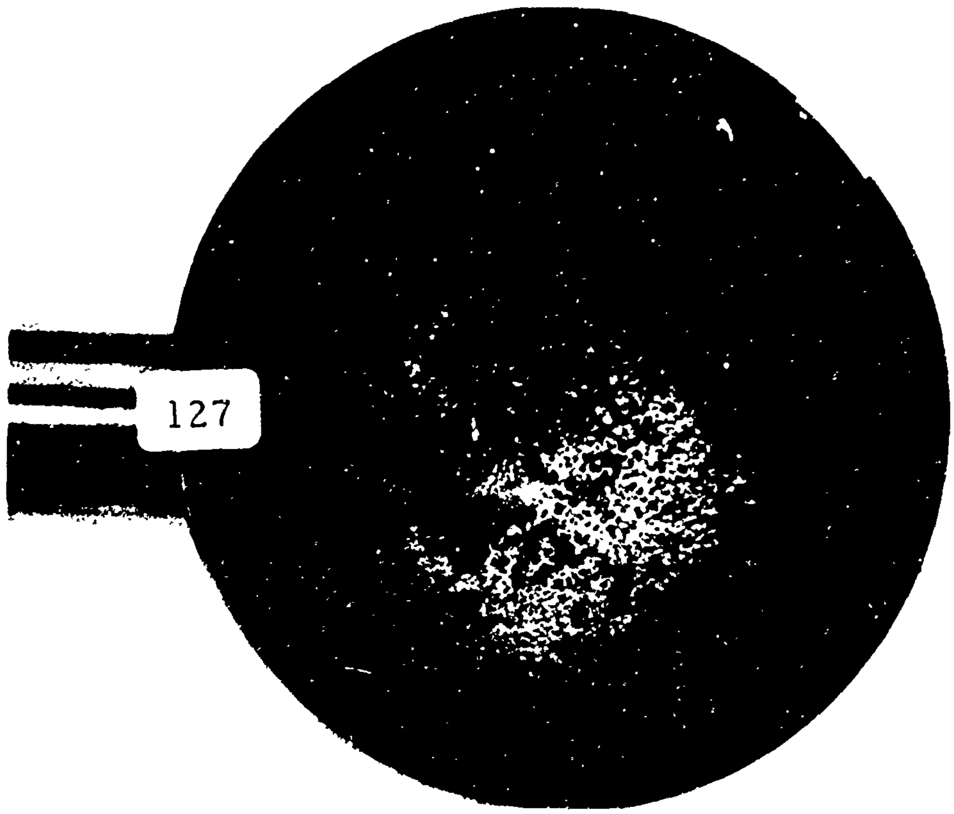

91

No. 3 Piston (Front Right)

No. 1 Piston (Front Right)

FIGURE C-49. PISTON CROWNS–UNLEADED FUEL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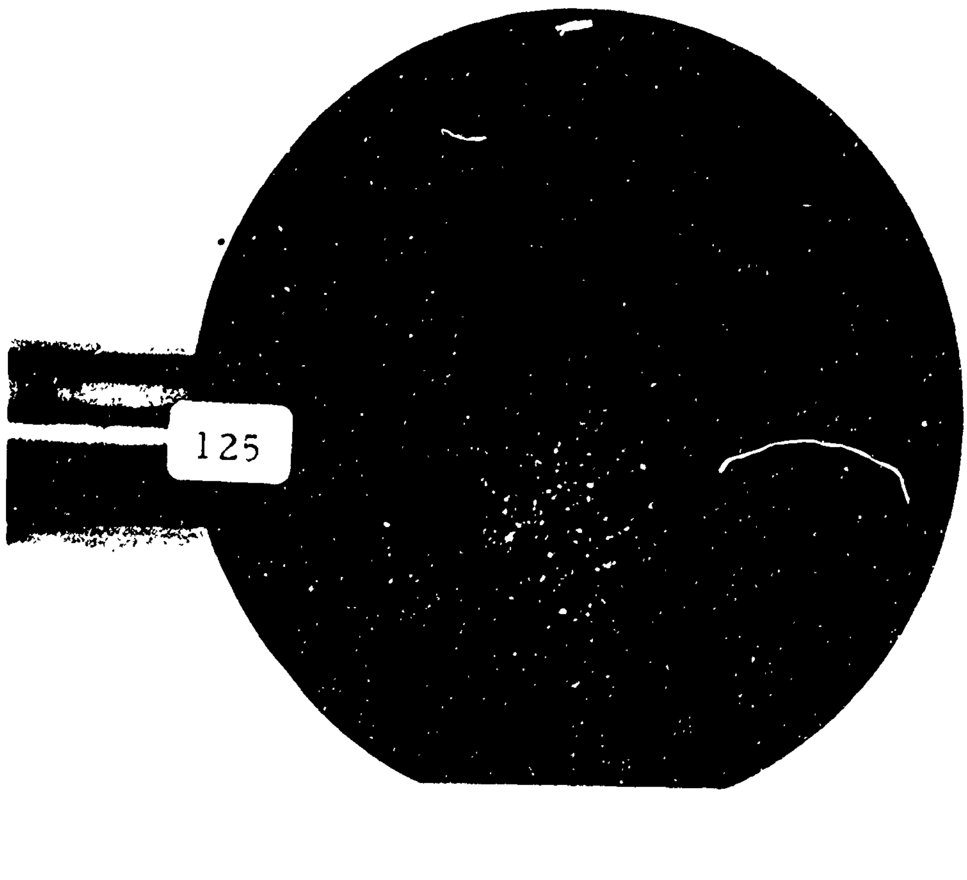
125

No. 4 Piston

No. 2 Piston

FIGURE C-50. PISTONS (THRUST SIDE)–NORMALLY LEADED FUEL

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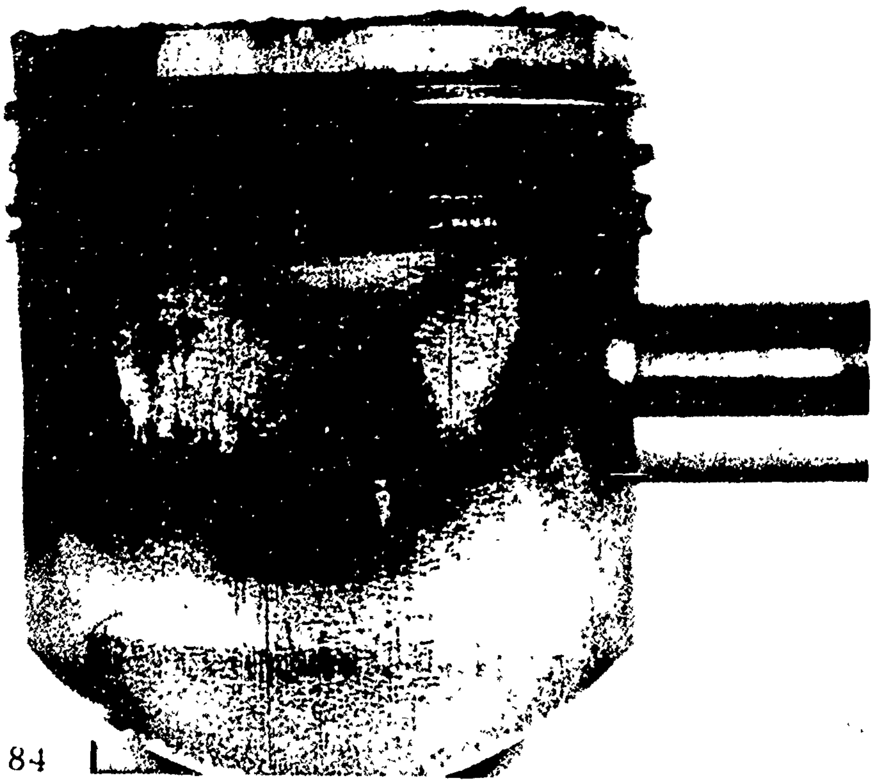

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No. 4 Piston

No. 3 Piston

FIGURE C-51. PISTONS (ANTI-THRUST SIDE)--NORMALLY LEADED FUEL

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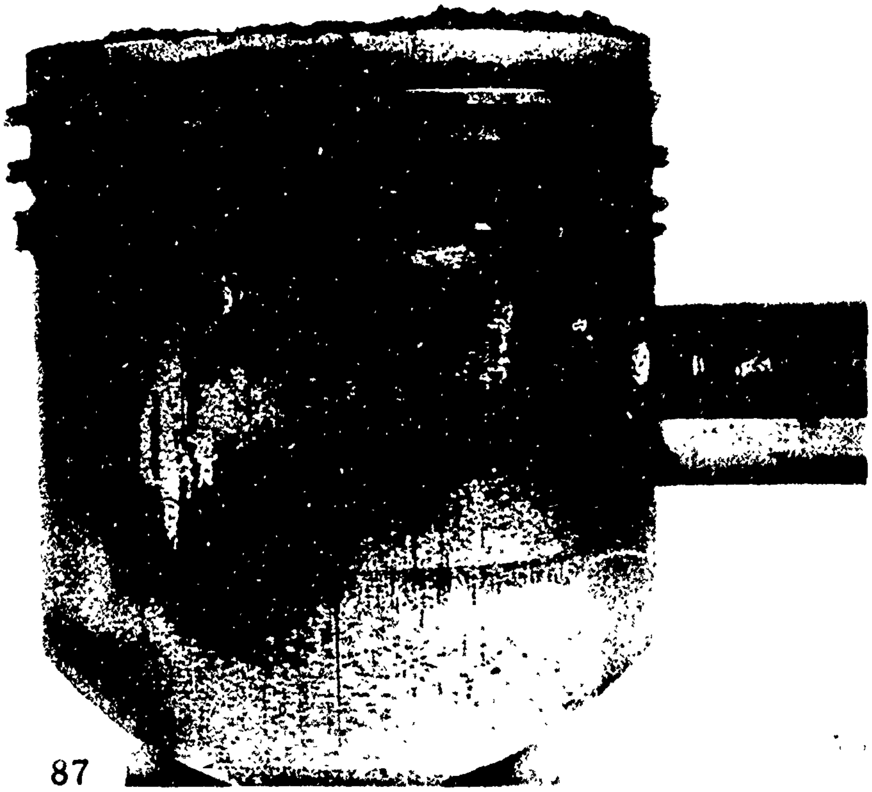

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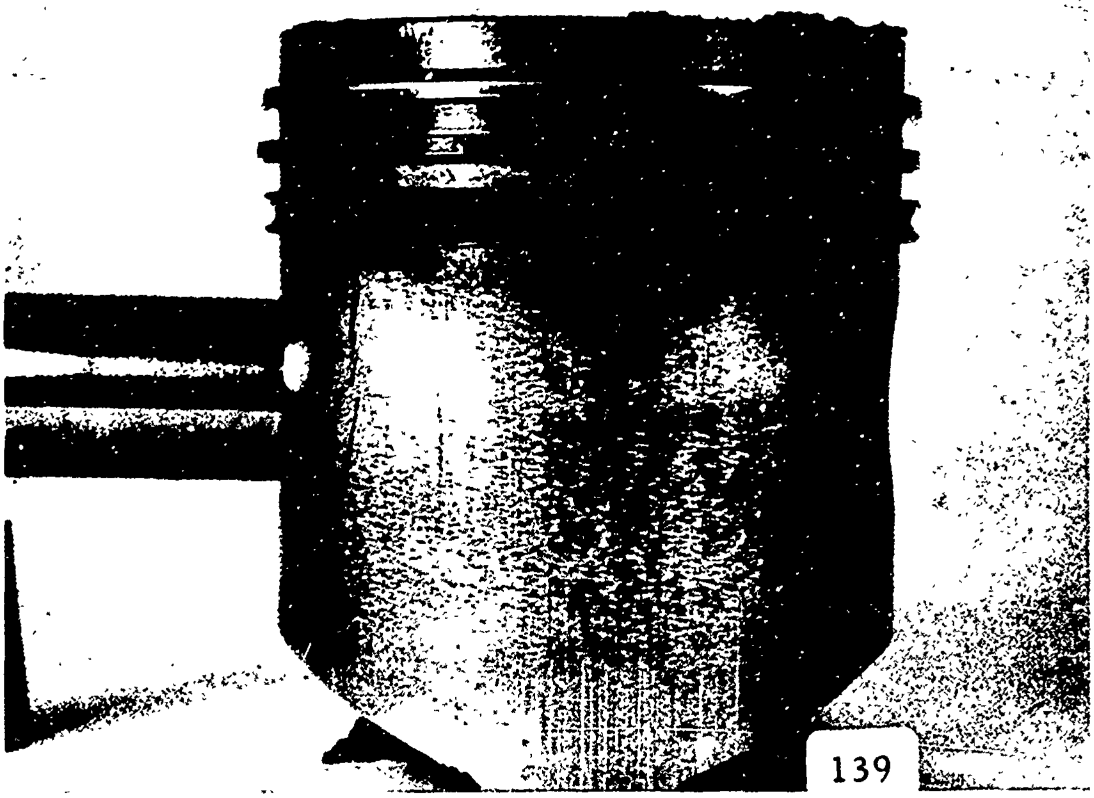
No. 4 Piston

No. 1 Piston

FIGURE C-52. PISTONS (THRUST SIDE)–LOW LEAD FUEL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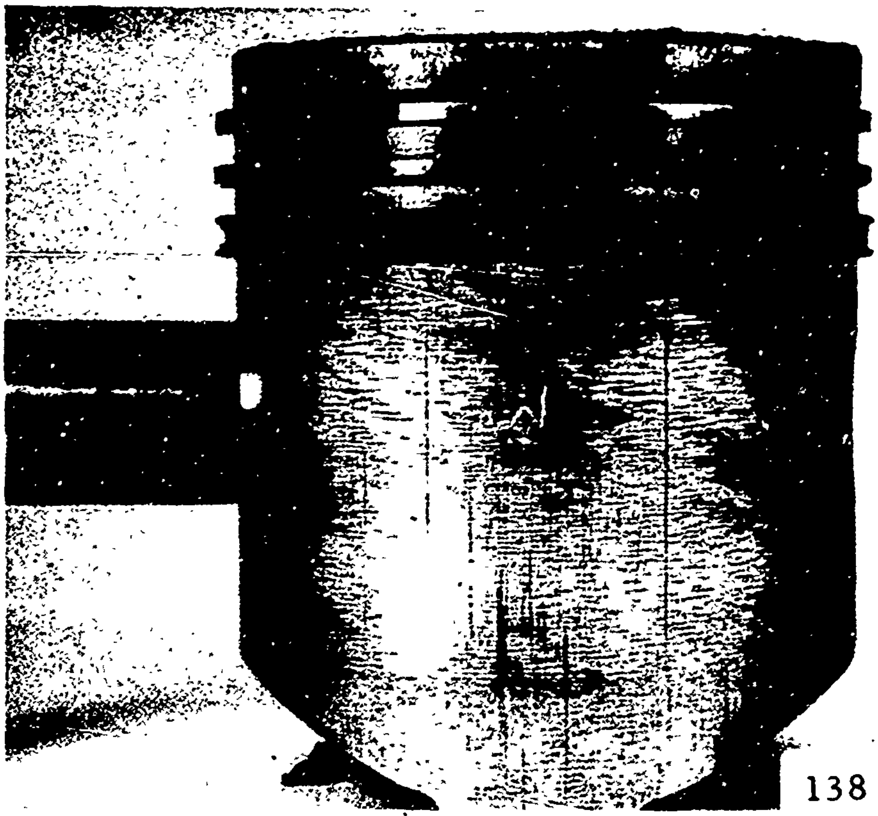
No. 3 Piston

No. 1 Piston

FIGURE C-53. PISTONS (ANTI-THRUST SIDE)–LOW LEAD FUEL



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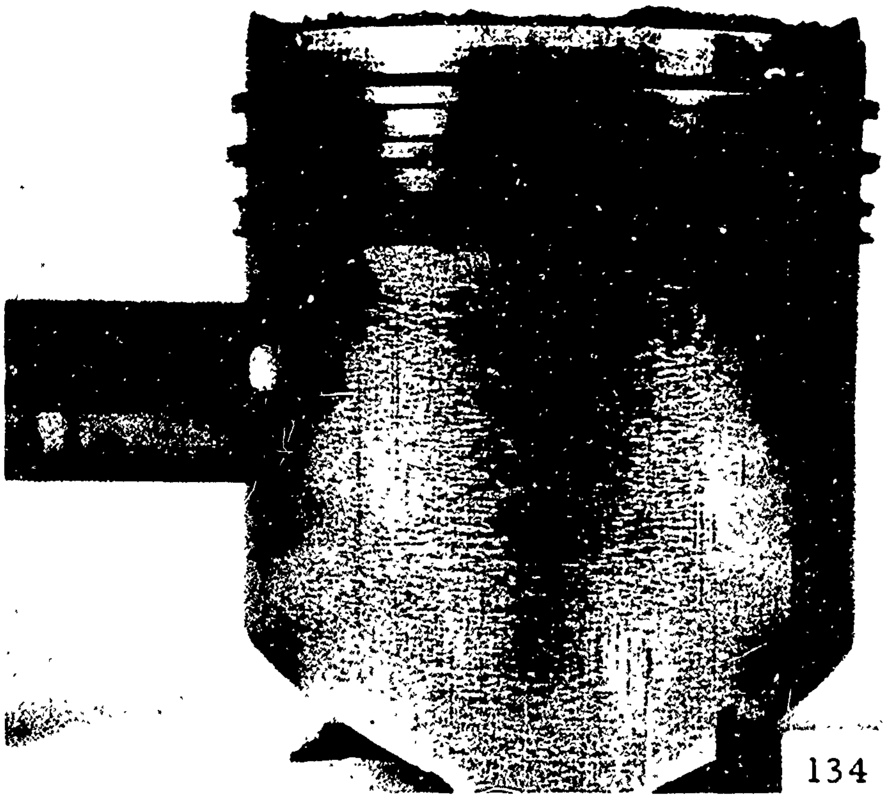

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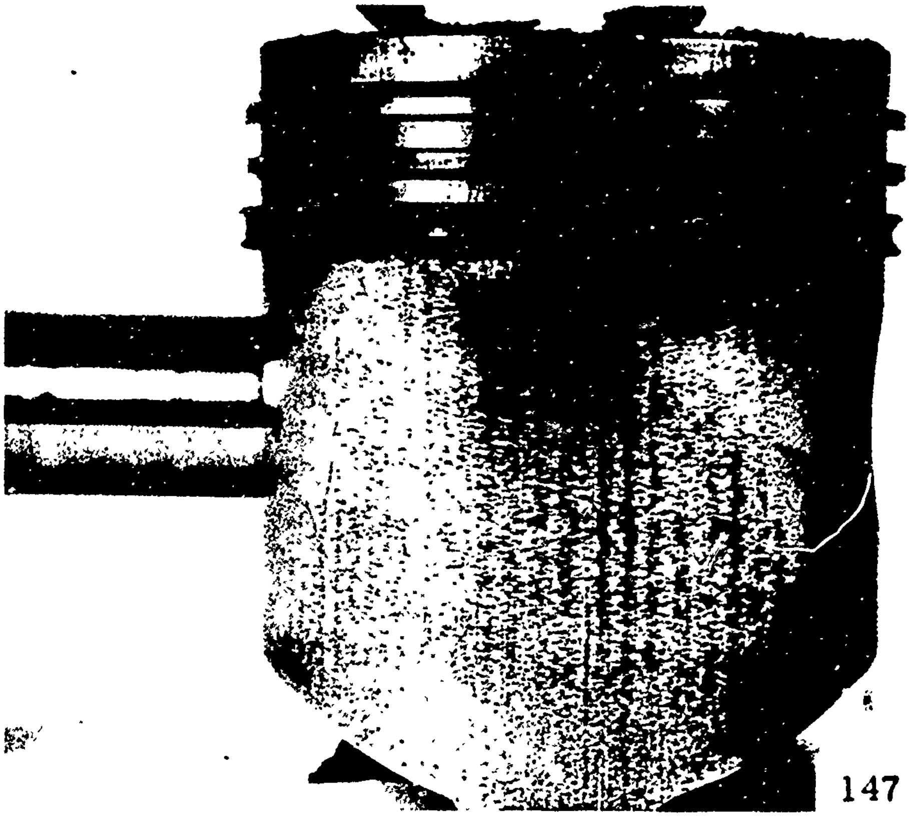
No. 4 Piston

No. 1 Piston

FIGURE C-54. PISTONS (THRUST SIDE)–UNLEADED FUEL



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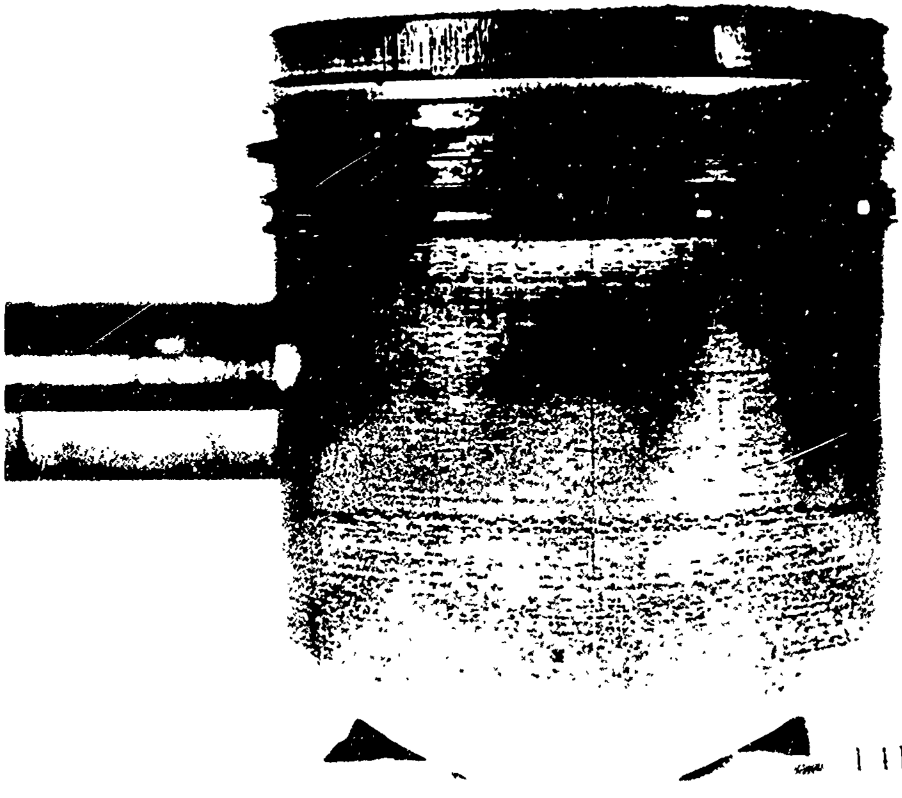

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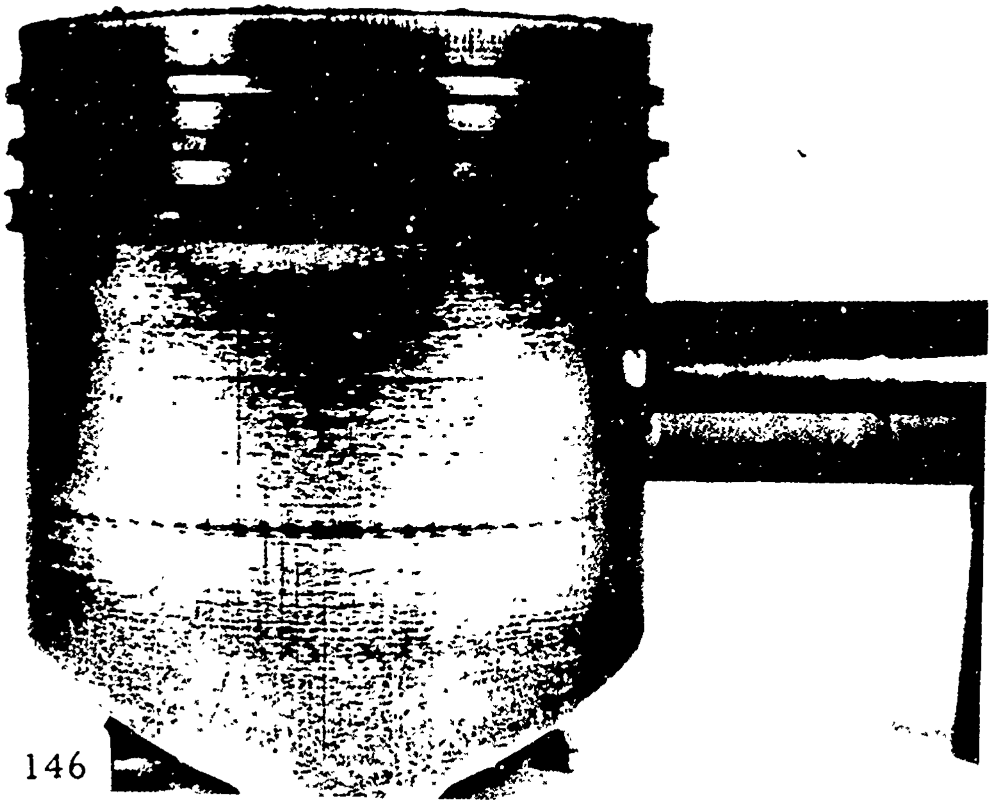
No. 3 Piston

No. 1 Piston

FIGURE C-55. PISTONS (ANTI-THRUST SIDE)–UNLEADED FUEL



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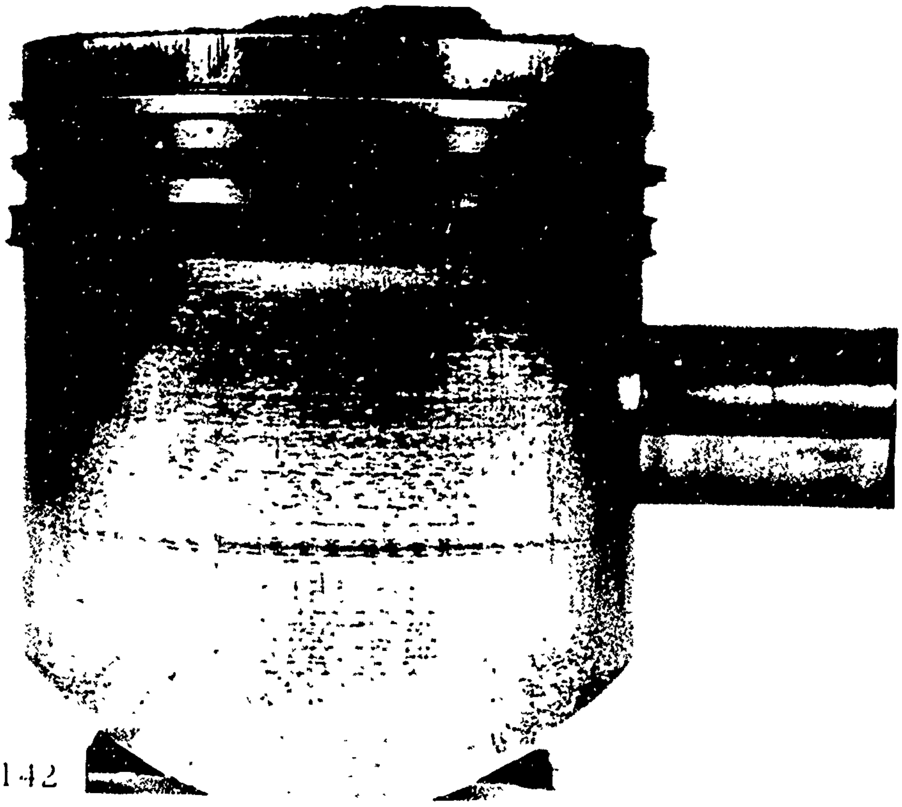

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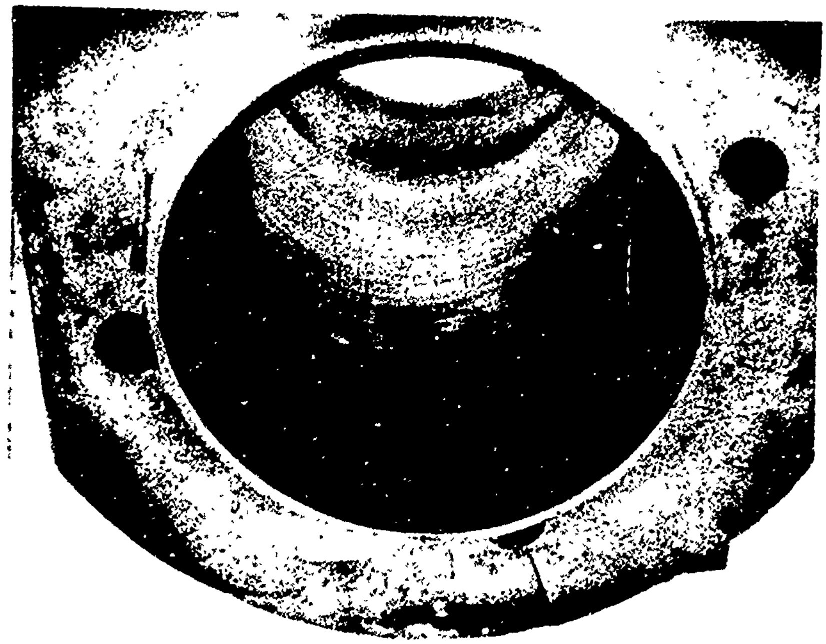
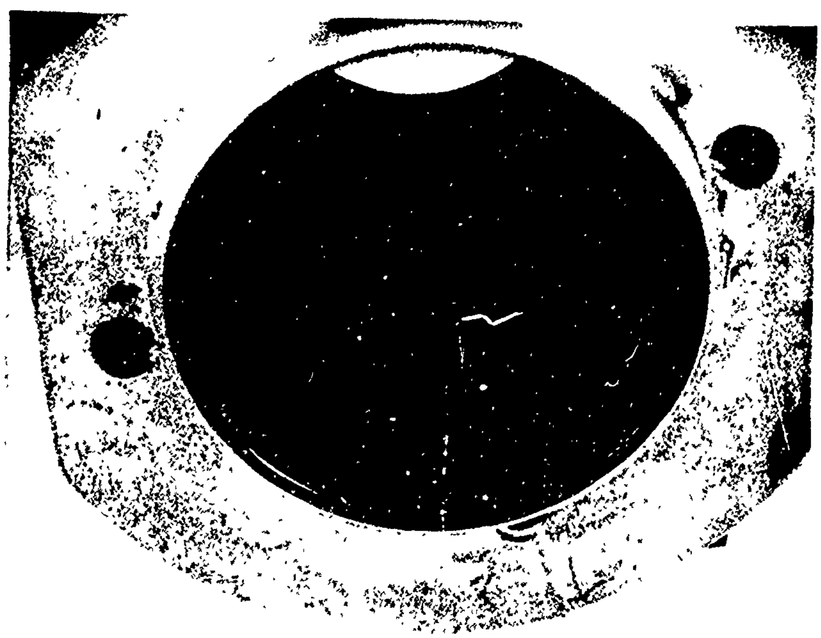
No. 3 Cylinder (Thrust)

No. 3 Cylinder (Anti-Thrust)

FIGURE C-56. TYPICAL CYLINDER BORE–NORMALLY LEADED FUEL

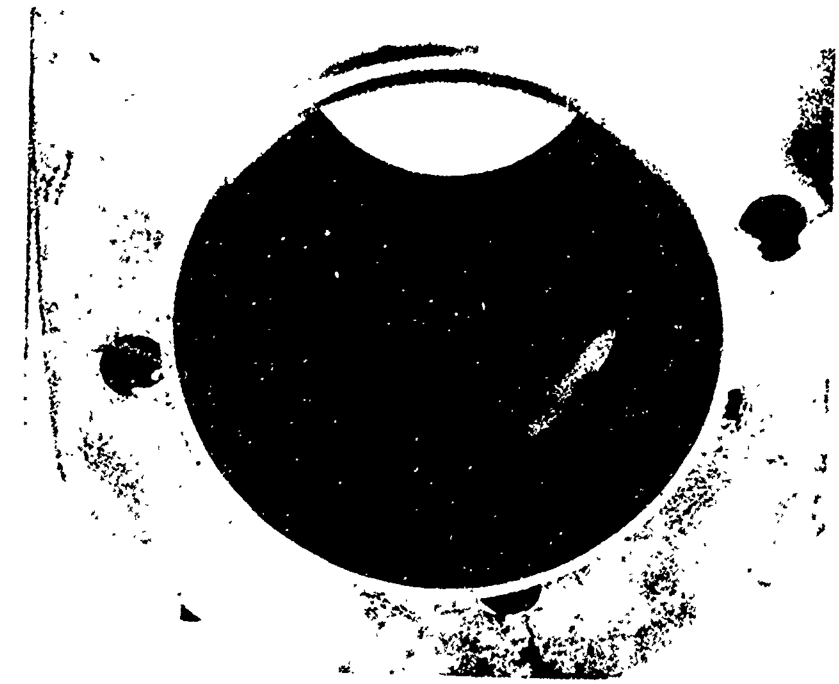


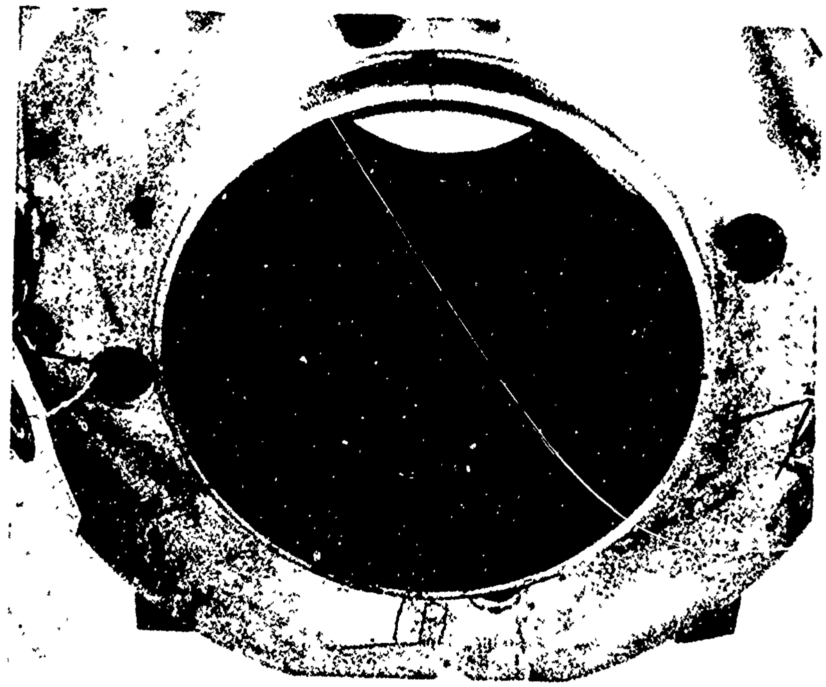


No. 1 Cylinder (Thrust)

No. 1 Cylinder (Anti-Thrust)

FIGURE C-57. TYPICAL CYLINDER BORE–LOW LEAD FUEL

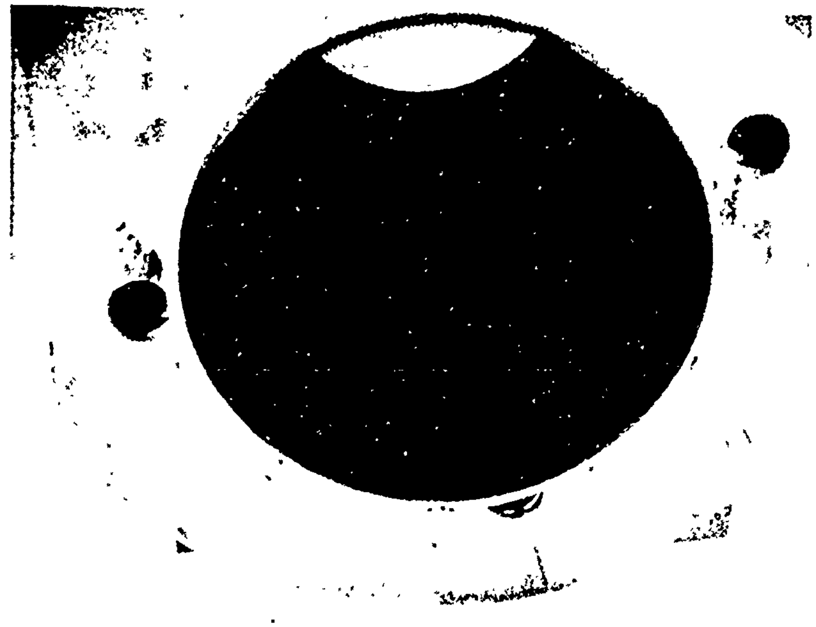


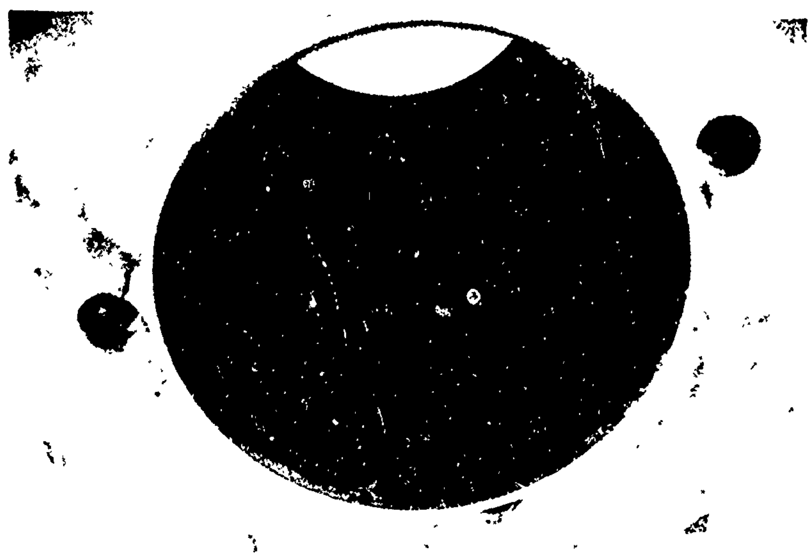


No. 1 Cylinder (Thrust)

No. 1 Cylinder (Anti-Thrust)

FIGURE C-58. TYPICAL CYLINDER BORE–UNLEADED FUEL





(L to R) Nos. 1, 2, 3, and 4 (125 Hours on Normally Leaded Fuel)

(L to R) Nos. 1, 2, 3, and 4 (125 Hours on Low Lead Fuel)

FIGURE C-59. SPARK PLUG TIPS–NORMALLY LEADED AND LOW LEAD FUELS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(L to R) Nos. 1, 2, 3, and 4 (125 Hours on Unleaded Fuel)

FIGURE C-60. SPARK PLUG TIPS–UNLEADED FUEL

APPENDIX D

EMISSIONS DATA

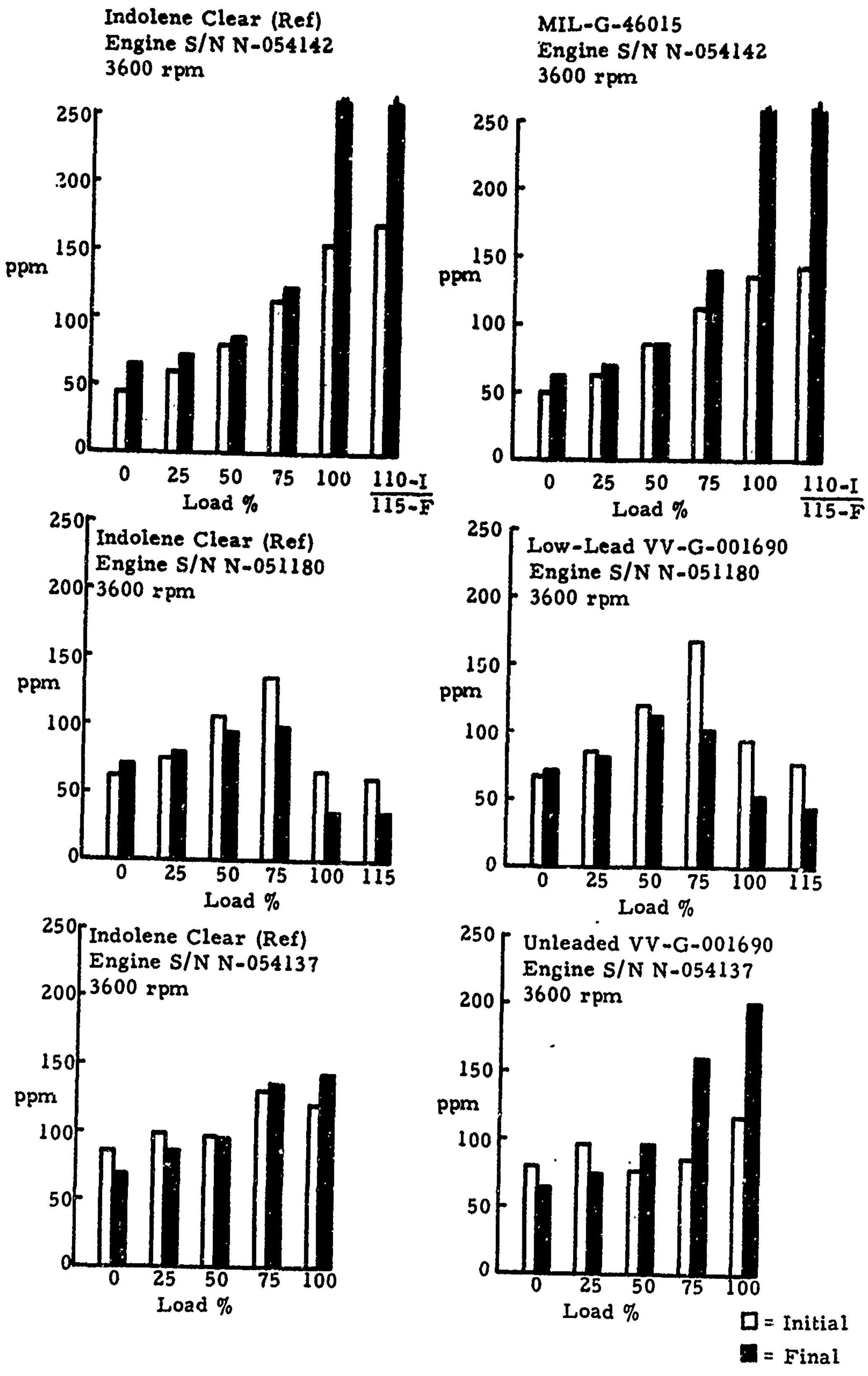

FIGURE D-1. MIL STD 1.5-kW GENERATOR SETS—125-HOUR ENDURANCE TESTS OXIDES OF NITROGEN (NO_X) EMISSIONS PATTERNS

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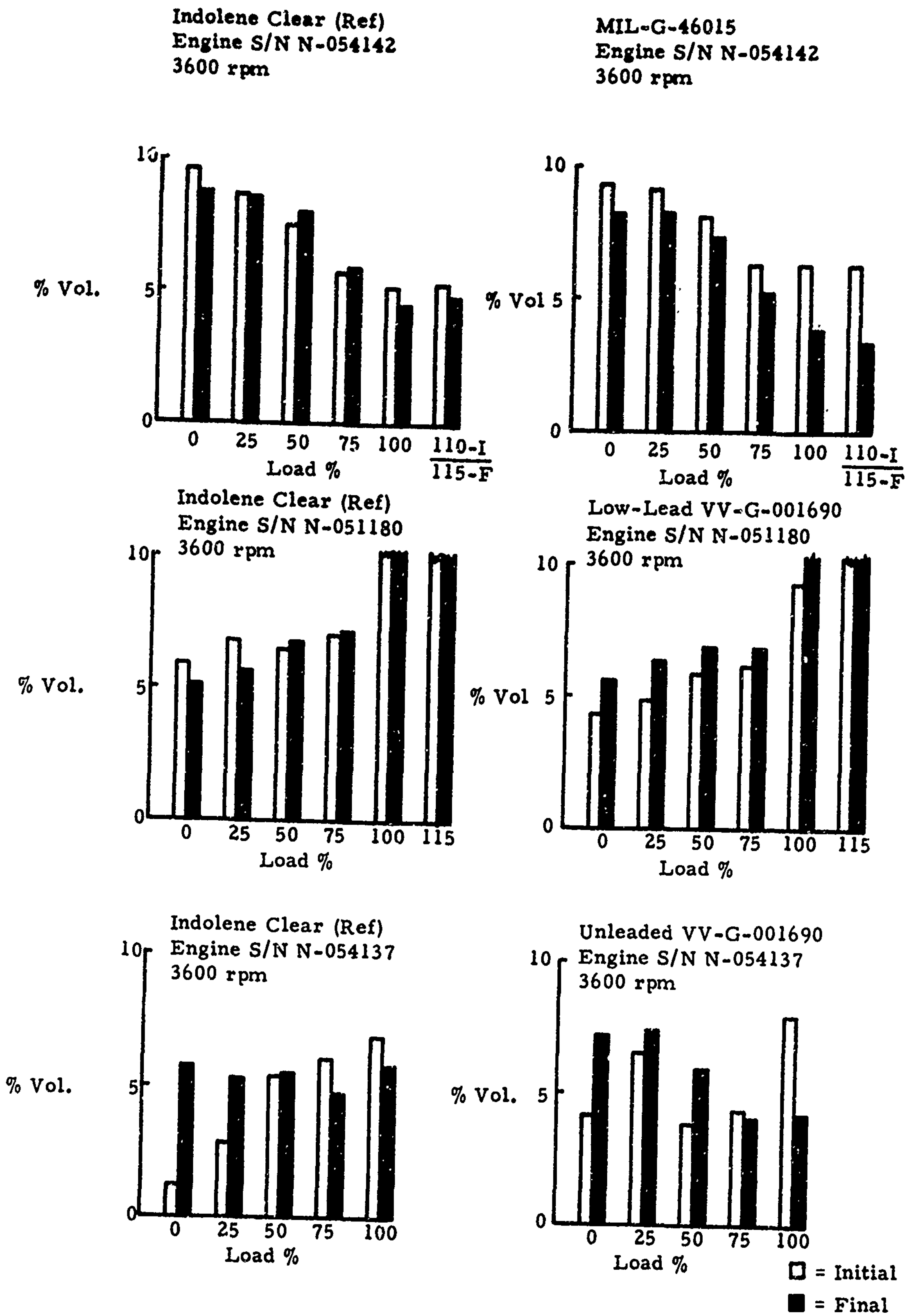

FIGURE D-2. MIL STD 1.5-kW GENERATOR SETS–125-HOUR ENDURANCE TESTS CARBON MONOXIDE (CO) EMISSIONS PATTERNS

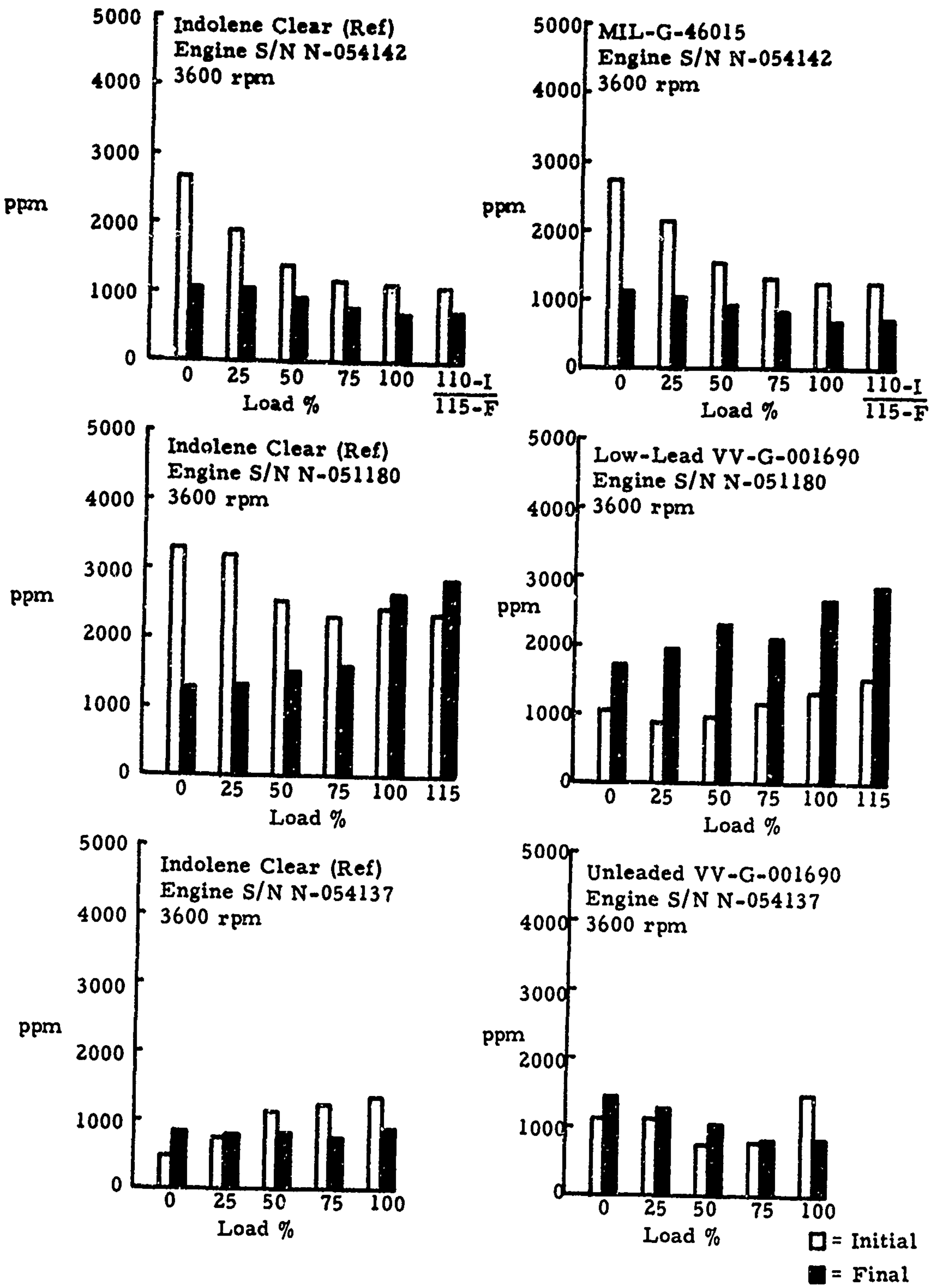

FIGURE D-3. MIL STD 1.5-kW GENERATOR SETS—125-HOUR ENDURANCE TESTS UNBURNED HYDROCARBONS (HC) EMISSIONS PATTERNS

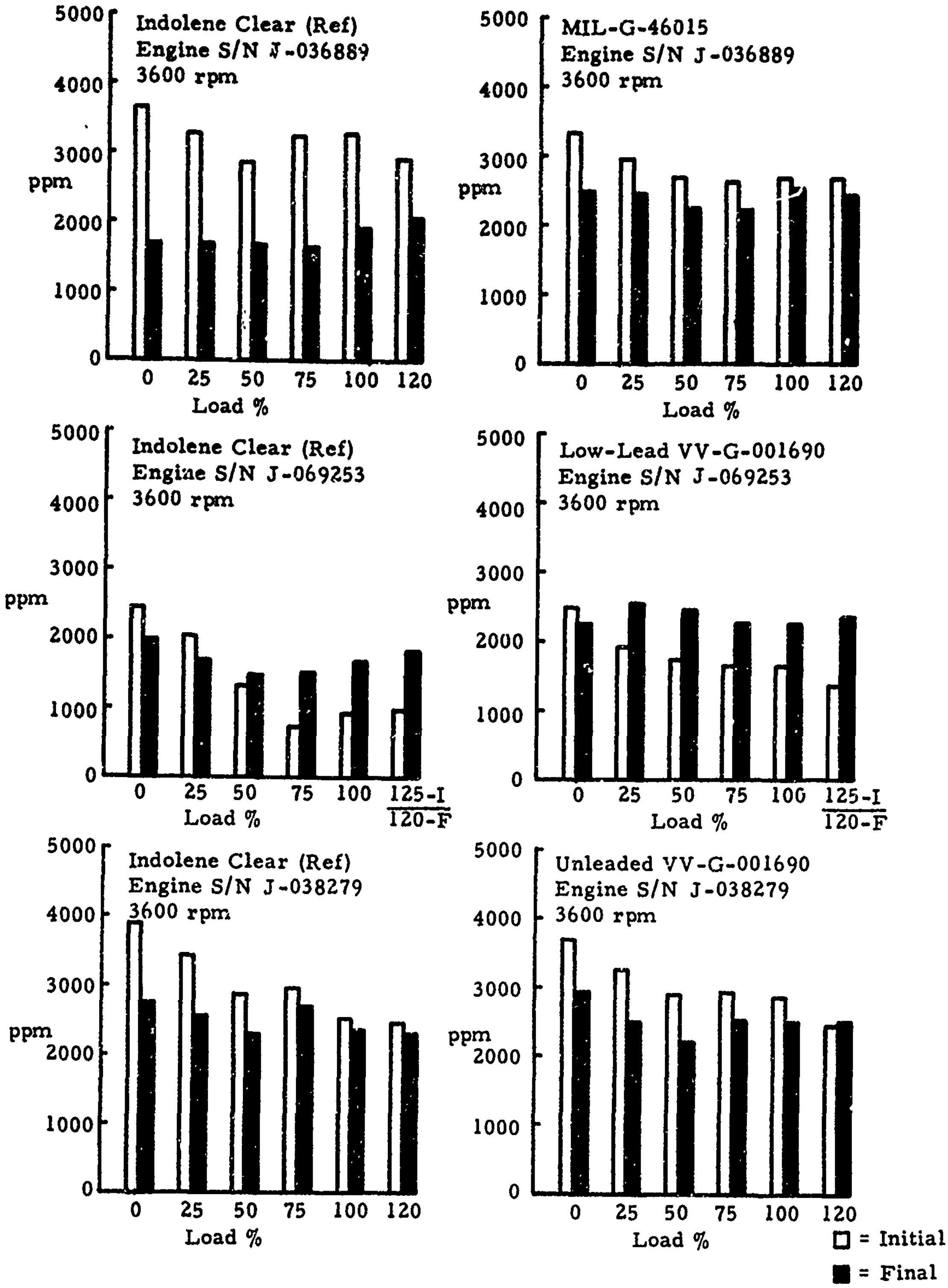

FIGURE D-4. MIL STD 3.0-kW GENERATOR SETS–125-HOUR ENDURANCE TESTS UNBURNED HYDROCARBONS (HC) EMISSIONS PATTERNS

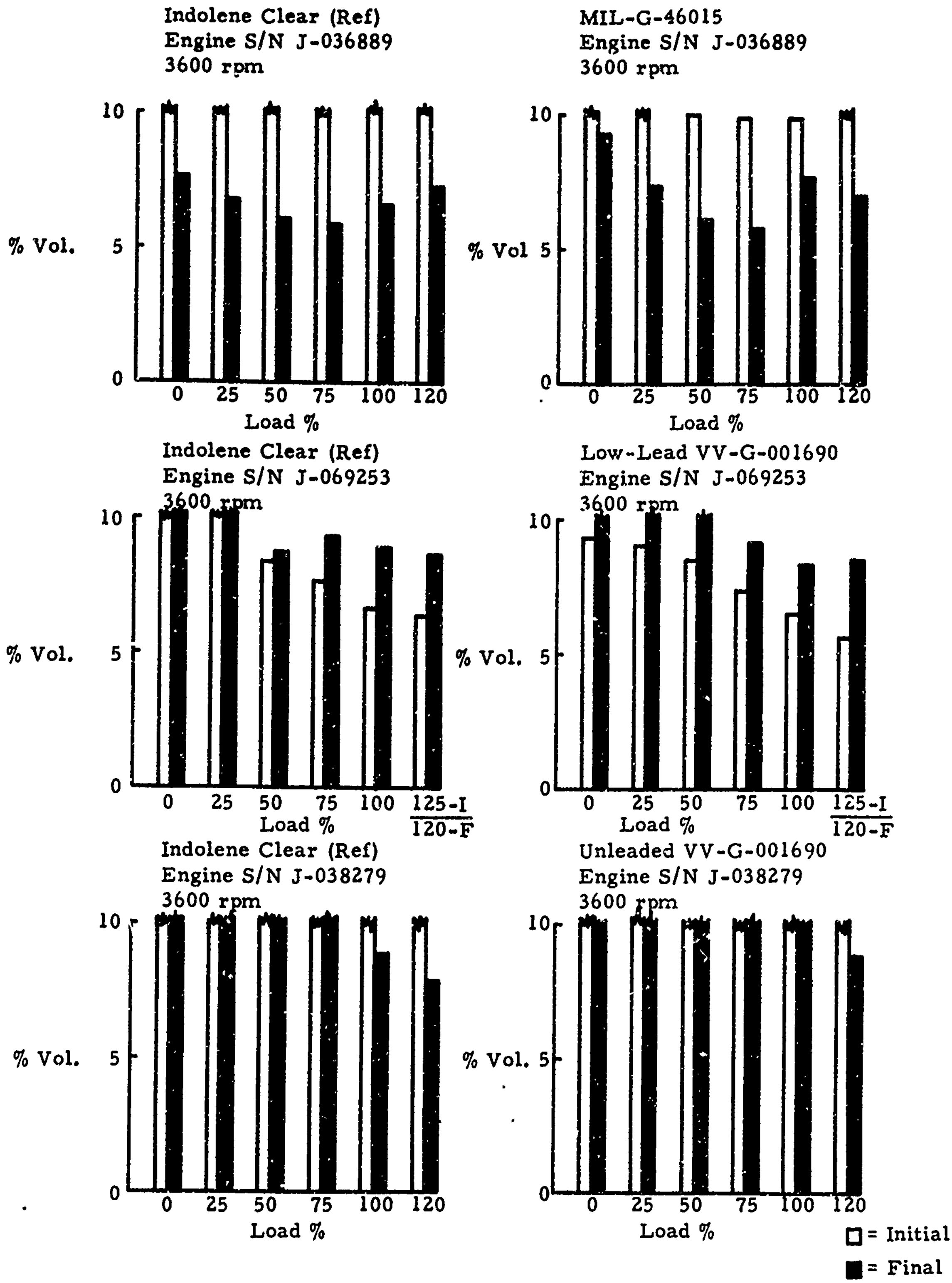

FIGURE D-5. MIL STD 3.0-kW GENERATOR SETS–125-HOUR ENDURANCE TESTS CARBON MONOXIDE (CO) EMISSIONS PATTERNS

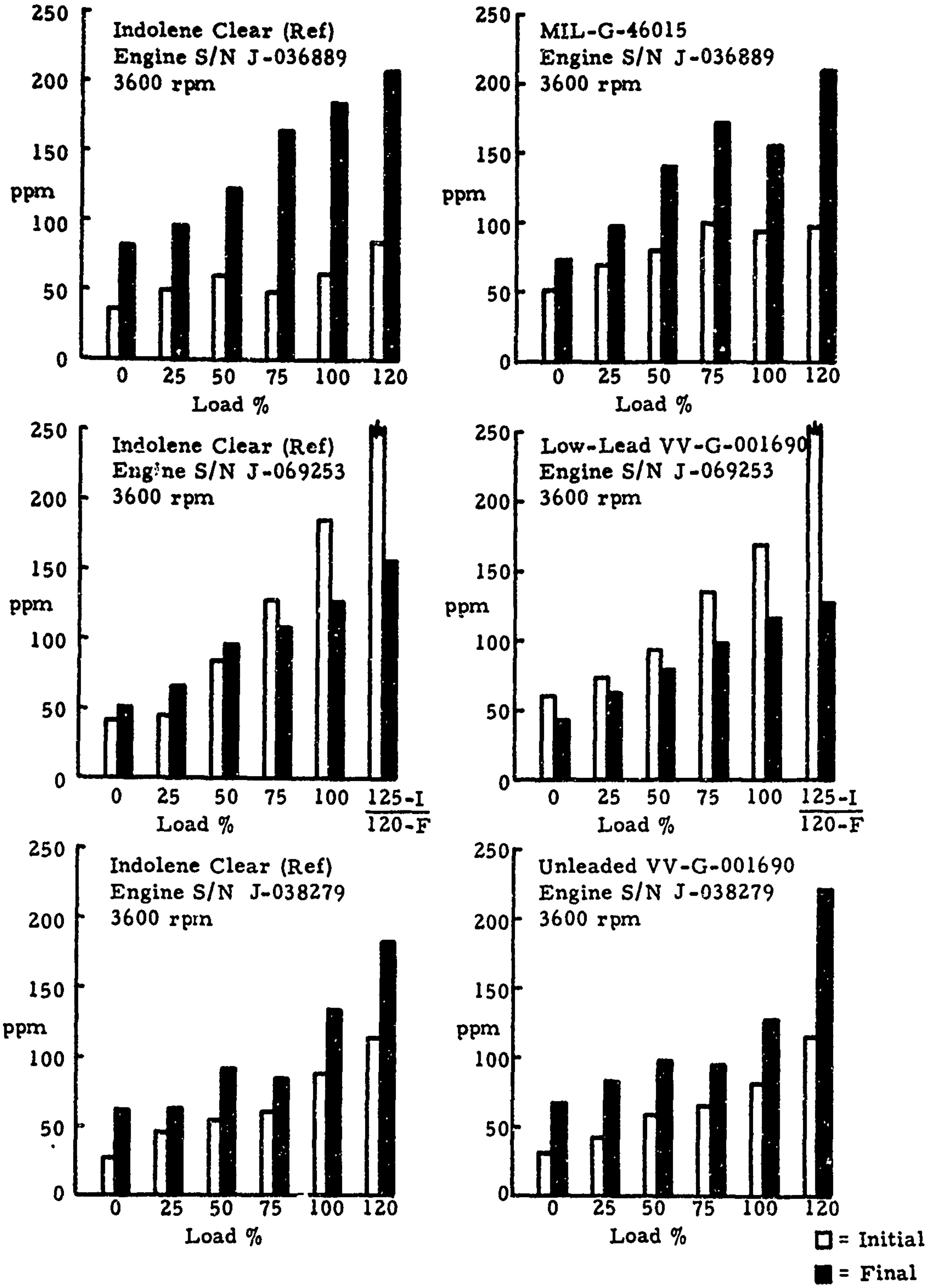

FIGURE D-6. MIL STD 3.0-kW GENERATOR SETS—125-HOUR ENDURANCE TESTS OXIDES OF NITROGEN (NO_X) EMISSIONS PATTERNS

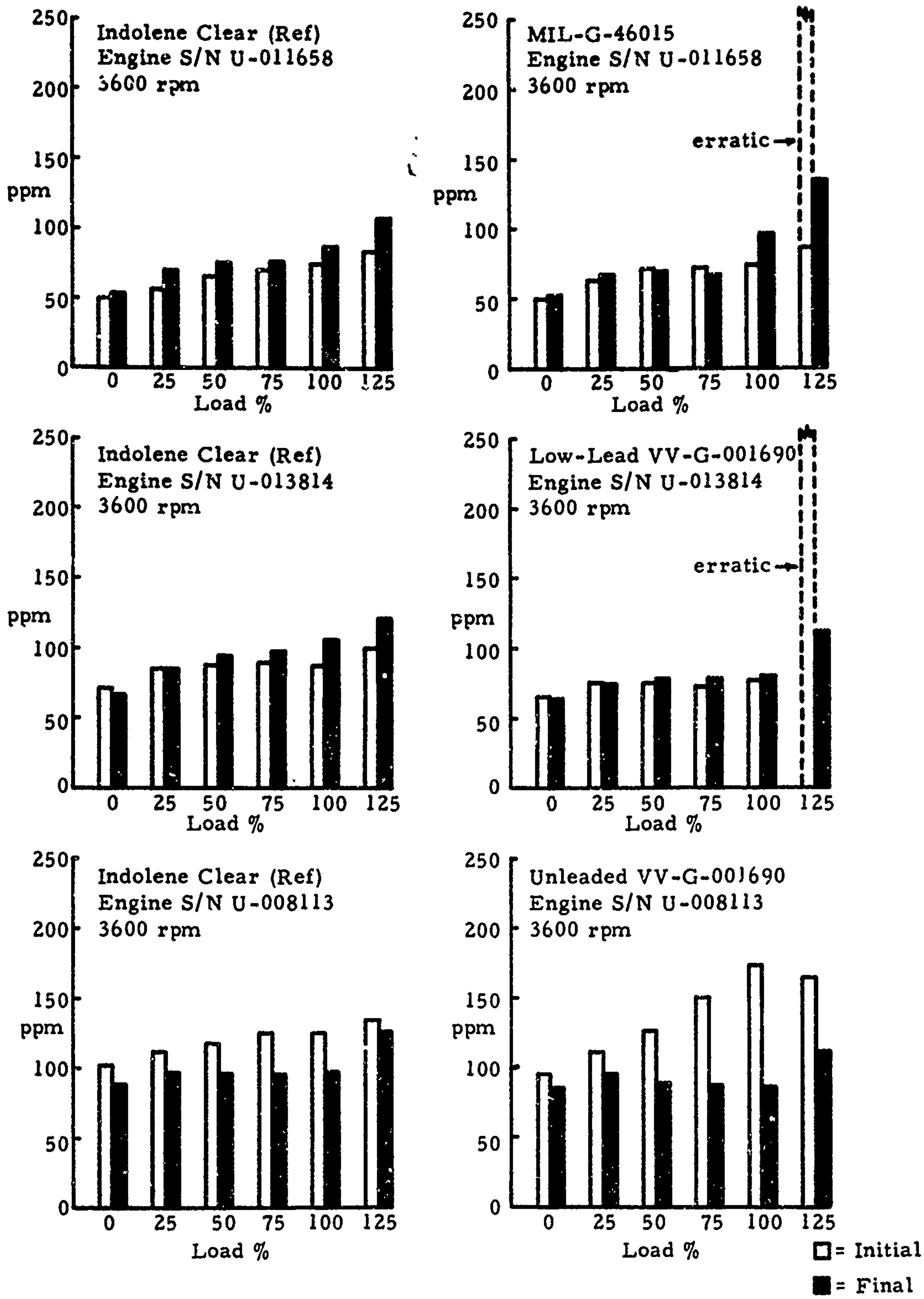

FIGURE D-7. MIL STD 10-kW GENERATOR SETS–125-HOUR ENDURANCE TESTS OXIDES OF NITROGEN (NO_X) EMISSIONS PATTERNS

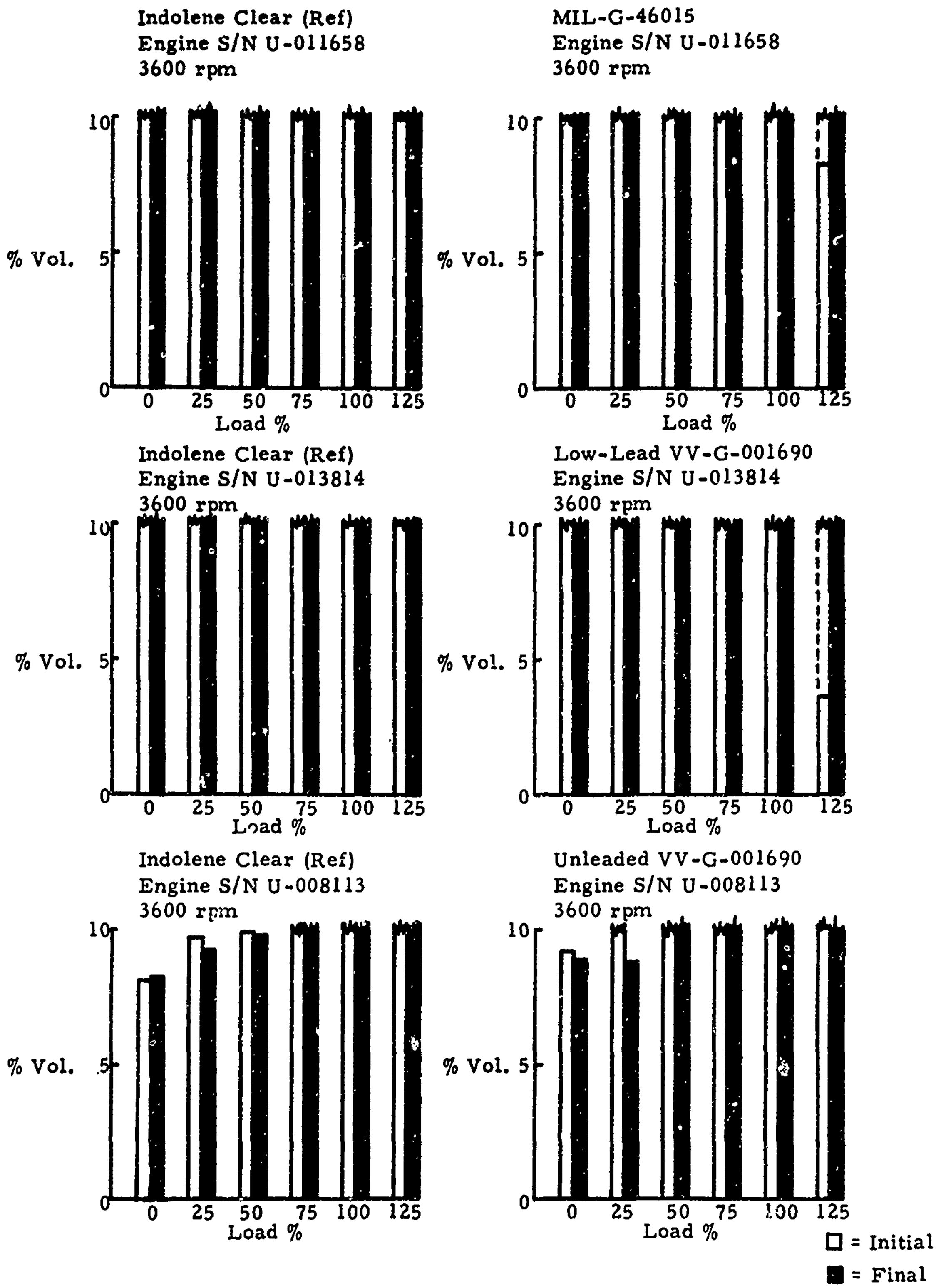

FIGURE D-8. MIL STD 10-kW GENERATOR SETS—125-HOUR ENDURANCE TESTS
CARBON MONOXIDE (CO) EMISSIONS PATTERNS

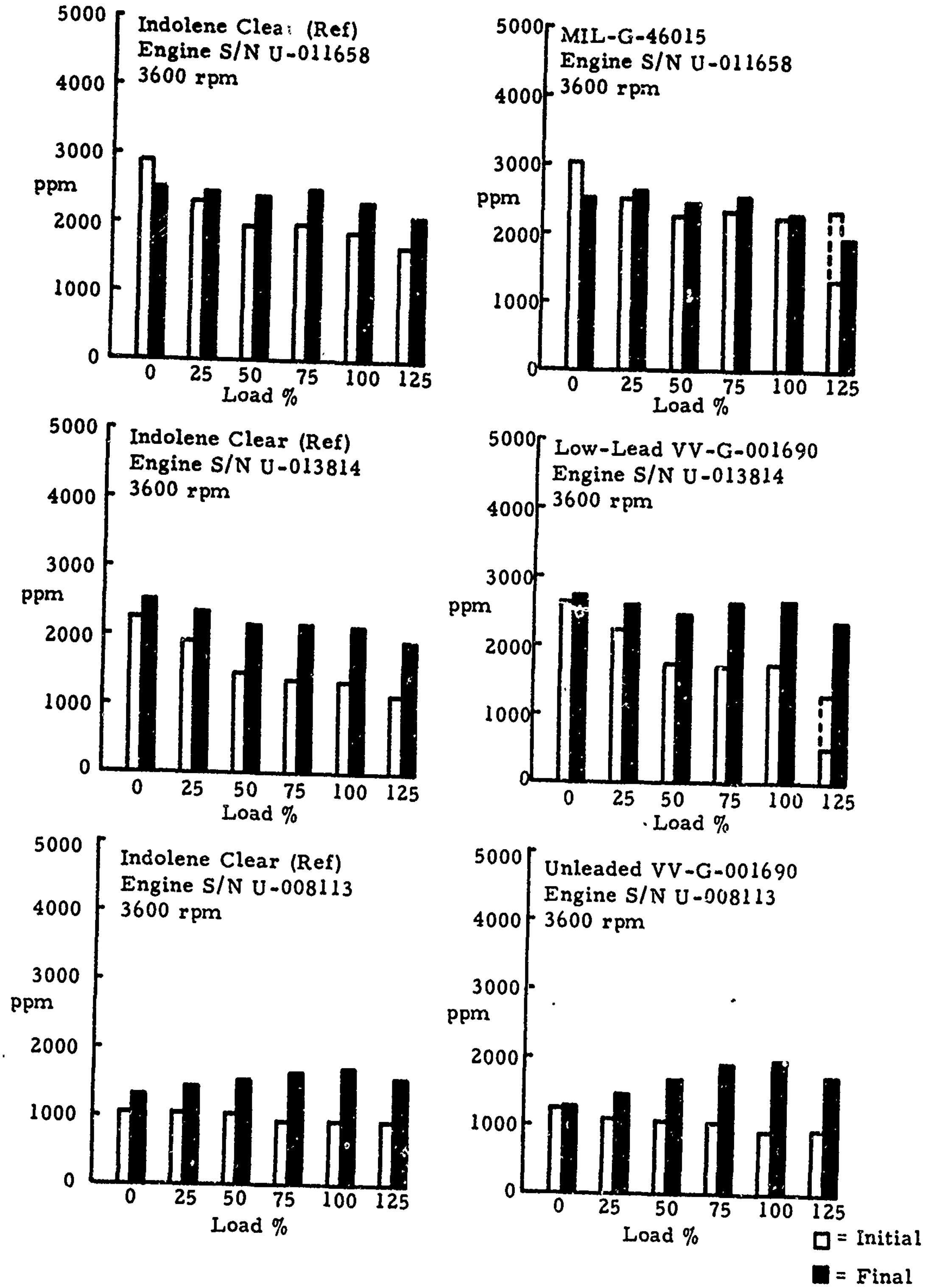

FIGURE D-9. MIL STD 10-kW GENERATOR SETS—125-HOUR ENDURANCE TESTS
UNBURNED HYDROCARBONS (HC) EMISSIONS PATTERNS

TABLE D-I. ENGINE-TO-ENGINE INITIAL EMISSIONS REPEATABILITY—1.5-kW GENERATOR SETS INDOLENE CLEAR REFERENCE FUEL

(Dry Gas Analyses)

Load, % rated	Engine S/N	NO, ppm	NO_x, ppm	CO, %	CO_2, %	HC, ppm
0	N-054142	40	45	9.6	8.4	2666
	N-051180	57	63	6.0	11.0	3325
	N-054137	80	87	1.3	11.9	515
25	N-054142	57	60	8.7	9.0	1892
	N-051180	68	76	6.8	10.5	3209
	N-054137	106	99	2.8	11.6	774
50	N-054142	75	80	7.5	9.8	1397
	N-051180	102	108	6.5	10.6	2564
	N-054137	103	99	5.4	10.1	1118
75	N-054142	110	112	5.7	10.9	1193
	N-051180	124	134	7.0	10.5	2318
	N-054137	122	131	6.0	10.9	1221
100	N-054142	150	155	5.2	11.2	1160
	N-051180	68	68	10.0	8.0	2413
	N-054137	117	120	5.9	10.2	1355
110	N-054142	160	170	5.4	11.0	1108
115	N-051180	60	62	10.0*	7.5	2393
–	N-054137	(No overload data—circuit breaker opened)				

*Above the calibrated range of the meter.

TABLE D-II. ENGINE-TO-ENGINE INITIAL EMISSIONS REPEATABILITY—3-kW GENERATOR SETS INDOLENE CLEAR REFERENCE FUEL

(Dry Gas Analyses)

Load, % rated	Engine S/N	NO, ppm	NO_x, ppm	CO, %	CO_2, %	HC, ppm
0	J-036889	27	37	10.0+*	7.1	3676
	J-069253	38	41	10.0+	8.3	2423
	J-038279	25	28	10.0+	6.7	3900
25	J-036889	37	50	10.0+	7.3	3239
	J-069253	42	44	10.0+	8.4	2013
	J-038279	37	45	10.0+	7.0	3419
50	J-036889	50	60	10.0+	7.4	2881
	J-069253	70	85	8.4	10.6	1031
	J-038279	45	54	10.0+	7.5	2848
75	J-036889	41	49	10.0+	6.6	3258
	J-069253	124	128	7.6	10.0	763
	J-038279	62	60	10.0+	7.2	2988
100	J-036889	55	62	10.0+	7.0	3279
	J-069253	181	185	6.6	10.4	950
	J-038279	83	88	10.0+	7.9	2537
120†	J-036889	67	85	10.0+	7.3	2938
125	J-069253	257	285	6.4	10.9	962
120†	J-038279	117	114	9.9	8.6	2445

*Above the calibrated range of the meter.
†Maximum available before circuit breaker opened.

TABLE D-III. ENGINE-TO-ENGINE INTITIAL EMISSIONS REPEATABILITY–10-kW GENERATOR SETS INDOLENE CLEAR REFERENCE FUEL

(Dry Gas Analyses)

Load, % rated	Engine S/N	NO, ppm	NO_X, ppm	CO, %	CO_2, %	HC, ppm
0	U-011658	40	50	10.0+*	7.5	2902
	U-013814	66	71	10.0+	8.3	2248
	U-008113	98	102	8.1	9.9	1054
25	U-011658	50	57	10.0+	7.6	2322
	U-013814	78	85	10.0+	8.1	1895
	U-008113	112	112	9.7	9.2	1054
50	U-011658	57	65	10.0+	7.5	1985
	U-013814	83	88	10.0+	7.9	1473
	U-008113	120	119	10.0	8.9	1033
75	U-011658	62	70	10.0+	7.4	1998
	U-013814	84	90	10.0+	7.8	1355
	U-008113	120	125	10.0+	8.7	946
100	U-011658	68	75	10.0+	7.4	1870
	U-013814	86	90	10.0+	7.6	1338
	U-008113	125	125	10.0+	8.6	951
125	U-011658	76	82	10.0+	7.5	1677
	U-013814	95	100	10.0+	7.7	1150
	U-008113	132	134	10.0+	8.4	957

*Above the calibrated range of the meter.

TABLE D-IV. EFFECT OF CATALYTIC CONVERTER ON MIL STD 1.5-kW GENERATOR SET EXHAUST EMISSIONS*

(Dry Gas Analyses)

Engine S/N: N-054137 *Engine Speed: 3600 rpm*

Converter: Engelhard PTX-3 Purifier

Load, % rated	Sample tap†	Fuel									
		Indolene Clear (Reference)					Unleaded VV-G-001690				
		NO, ppm	NO_X, ppm	CO, %	CO_2, %	HC, ppm	NO, ppm	NO_X, ppm	CO, %	CO_2, %	HC, ppm
0	A	80	87	1.3	11.9	515	78	80	4.1	11.5	1157
	B	40	41	0.1	6.2	90	41	41	0.1	7.5	129
25	A	106	99	2.8	11.6	774	94	96	4.7	11.4	1142
	B	46	47	0.1	7.6	129	51	52	0.1	8.4	139
50	A	103	99	5.4	10.1	1118	75	77	3.8	7.7	782
	B	55	58	0.2	8.6	118	66	66	0.1	9.0	129
75‡	A	122	131	6.0	10.9	1221	81	85	4.3	7.6	795
	B	61	71	0.2	10.2	91	72	72	0.1	10.2	107
100‡	A	117	120	6.9	10.2	1355	117	117	7.9	10.2	1492
	B	60	64	0.2	11.2	65	62	65	0.2	12.1	43
		(No overload data–generator circuit breaker opened)									

*Prior to 125-hour endurance test.
†A = converter inlet; B = converter outlet.
‡Converter required fan-cooling to prevent overheating.

TABLE D-V. EFFECT OF CATALYTIC CONVERTER ON MIL STD 3-kW GENERATOR SET EXHAUST EMISSIONS*

(Dry Gas Analyses)

Engine S/N: J-038279 *Engine Speed: 3600 rpm*

Converter: Engelhard PTX-3 Purifier†

Load, % rated	Sample tap‡	Fuel: Indolene Clear (Reference) NO, ppm	NOx, ppm	CO, %	CO_2, %	HC, ppm	Fuel: Unleaded VV-G-001690 NO, ppm	NOx, ppm	CO, %	CO_2, %	HC, ppm
0	A	25	28	10.0+**	6.7	3900	28	31	10.0+**	6.8	3677
	B	14	25	6.2	4.3	2775	13	25	6.3	3.8	2660
25	A	37	45	10.0+	7.0	3419	35	41	10.0+	7.2	3258
	B	20	28	6.7	4.0	2145	22	28	6.8	4.2	2123
50	A	45	54	10.0+	7.5	2848	52	58	20.0+	7.7	2904
	B	28	38	6.7	4.2	1646	26	36	6.8	4.3	1790
75	A	62	60	10.0+	7.2	2988	60	64	10.0+	7.5	2923
	B	32	40	7.1	4.4	1618	31	40	7.4	4.5	1925
100	A	83	88	10.0+	7.9	2537	79	81	10.0+	8.0	2845
	B	54	61	6.9	5.2	1505	52	59	7.3	5.2	1965
120††	A	117	114	9.8	8.6	2445	114	115	10.0+	8.6	2450
	B	62	73	6.5	5.7	1398	71	77	6.5	5.7	1512

*Prior to 125-hour endurance test.
†Converter on 8-foot extension of exhaust tailpipe to prevent overheating.
‡A = converter inlet; B = converter outlet.
**Above calibrated range of meter.
††Maximum available overload before generator circuit breaker opened.

TABLE D-VI. EFFECT OF CATALYTIC CONVERTER ON MIL STD 10-kW GENERATOR SET EXHAUST EMISSIONS*

(Dry Gas Analyses)

Engine S/N: U-008113 *Engine Speed: 3600 rpm*

Fuel: Indolene Clear (Reference) *Converter: Engelhard PTX-4 Purifier*

Load, % rated	Sample tap†	Converter on 8-Foot Extension of Exhaust Tailpipe NO, ppm	NOx, ppm	CO, %	CO_2, %	HC, ppm	Converter on 15-Foot Extension of Exhaust Tailpipe NO, ppm	NOx, ppm	CO, %	CO_2, %	HC, ppm
0	A	97	97	8.7	9.6	1393	87	80	9.4	9.3	1269
	B	18	20	3.75	12.4	245	58	61	6.2	6.2	735
25	A	112	112	9.7	9.1	1042	103	103	9.6	9.0	1107
	B	50	50	4.4	12.5	225	70	72	6.8	6.3	656
50	A	‡	‡	‡	‡	‡	111	112	10.0	9.0	1032
	B	‡	‡	‡	‡	‡	44	48	6.4	8.0	559
75	A	‡	‡	‡	‡	‡	115	115	10.0**	8.4	1009
	B	‡	‡	‡	‡	‡	47	51	6.7	7.8	550
100	A	‡	‡	‡	‡	‡	‡	‡	‡	‡	‡
	B	‡	‡	‡	‡	‡	‡	‡	‡	‡	‡

*Prior to 125-hour endurance test.
†A = converter inlet; B = converter outlet.
‡No emissions data available due to converter overheating.
**Above calibrated range of meter.

TABLE D-VII. EFFECTS OF CAPACITOR DISCHARGE IGNITION SYSTEMS ON EXHAUST EMISSIONS* OF 1.5- AND 3-kW MIL STD GENERATOR SETS

(Dry Gas Analyses)

Load, % rated	Ignition system	Fuel									
		Unleaded VV-G-001690					Indolene Clear (Reference)				
		NO, ppm	NO_x, ppm	CO, %	CO_2, %	HC, ppm	NO, ppm	NO_x, ppm	CO, %	CO_2, %	HC, ppm
Engine S/N: N-054137 (1.5-kW Generator) C-D System: Fairbanks-Morse Engine Speed: 3600 rpm											
0	Std	65	65	7.2	9.8	1435	70	70	5.8	10.4	852
	C-D	80	82	6.1	11.0	1335	72	72	6.5	10.6	1393
50	Std	92	96	6.0	10.8	1024	95	97	5.5	10.6	821
	C-D	130	135	5.4	11.6	1150	119	130	4.5	11.7	1066
100	Std	195	199	4.2	12.0	823	126	143	5.8	10.5	871
	C-D	105	106	8.4	9.8	1424	95	99	8.2	9.5	1447
Engine S/N: J-038279 (3.0-kW Generator) C-D System: Fairbanks-Morse Engine Speed: 3600 rpm											
0	Std	53	68	9.6	7.5	2923	53	61	10.0+	7.2	2780
	C-D	51	58	10.0	8.1	3143	49	52	9.9	8.2	3128
50	Std	78	97	10.0+	8.1	2205	82	90	10.0+	8.1	2301
	C-D	89	94	9.0	9.0	2699	58	60	10.0+	7.8	3075
100	Std	116	129	9.6	8.5	2494	127	134	8.9	9.0	2371
	C-D	138†	100	9.4	9.2	2743	106	125	9.1	9.4	2846

*After 125-hour endurance tests. No catalytic converter.
†Emissions very erratic and would not stabilize. Values shown are estimated averages.