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Effects of Using Unleaded and Low-lead Gasoline, and Non-lead Additives on Agricultural Engines Designed for Leaded Gasoline

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I. Background

Due to health concerns from public exposure to lead in automotive exhaust, the Environmental Protection Agency (EPA) undertook a lead phasedown program in the early 1970's to remove lead from gasoline. At that time, refiners used approximately 2.5 grams per leaded gallon (gplg). In 1982 the amount of lead permitted in leaded gasoline was reduced to 1.10 gplg. On March 7, 1985, EPA further reduced the allowable level to 0.50 gplg, effective July 1, 1985 and 0.10 gplg on January 1, 1986. A complete ban on leaded gasoline has been considered for as early as 1988. The Agency has not proceeded with a total ban because of a concern that older engines designed for leaded gasoline may suffer premature valve seat wear if required to use unleaded gasoline exclusively, and a major health effect study of lead exposure required further review.

The Agency determined that 0.10 gplg would be satifactory to protect those older engines, based on testing that had been done in the early 1970's. Results of those tests are summarized in Costs and Benefits of Reducing Lead in Gasoline--Final Regulatory Impact Analysis (EPA-230-05-85-006, February, 1985). Generally, these tests showed that certain engines when operated on unleaded fuel for continuous high speeds, experienced valve seat recession. However, at lower speeds, valve seat recession was greatly reduced. One study showed that between 0.04 and 0.07 gplg would be satisfactory to protect valve seats. Based on this and other studies, EPA concluded that 0.10 gplg would be sufficient to protect exhaust valve seats from recession in engines designed for leaded gasoline.

The farming community expressed a concern that older farm engines designed to operate on leaded gasoline may experience engine damage if operated on low-lead or unleaded gasoline. In response to that concern, Congress required a study to be conducted under Section 1765 of the Food Security Act of 1985 (P.L. 99-198) (Act).

The Act required the Administrator of EPA and the Secretary of Agriculture (USDA) to "jointly conduct a study of the use of fuels containing lead additives and alternative lubricating additives," on gasoline-powered agricultural machinery. The study was to analyze the potential for mechanical problems (including but not limited to valve seat recession) that may occur with the use of other fuels in farm machinery. The Secretary of Agriculture was to specify the types and items of agricultural machinery to be included in the study and all testing of engines was to reflect actual agricultural conditions, including revolutions per minute and loads placed on the engines.

II. Scope of study

The study's overall goals are to determine the risk to engines if gasoline is limited to either low-lead or unleaded and to evaluate alternative additives to lead. The study has a complex design because the relationship between gasoline type and engine durability is a function of both engine design and usage patterns. The primary engine component at risk with a fuel change is the exhaust valve seat. This wears by receding into the cylinder head. If wear is severe enough, the exhaust valve eventually will not seat properly and engine failure will follow. Factors influencing the risk of wear include engine speed (rpm), load, temperature and cylinder head design. Information is needed on all of these factors to assess the risk of engine failure.

Little information was available about rpm and load levels for agricultural equipment under actual use conditions. Further, concern arose that since most of the equipment is not new, the valve seats could have been modified during overhauls so that original equipment specifications would no longer accurately reflect the type of valve seats in use.

The study was divided into three areas: Agricultural machinery testing on engine dynamometers; farm use survey of gasoline-powered equipment; and field measurement of the type of valve seat material in exhaust valve seats in gasoline-powered tractors.

A. Dynamometer Testing

The design of the testing portion of this study was initiated with a letter from EPA on December 6, 1985 to 25 potential commenters from EPA, USDA, the American Farm Bureau Federation (AFBF), tractor manufacturers, university professors, and independent consultants. The letter forwarded a statement of work suggested for the study. Comments were received from most of the recipients of the letter and suggested a wide variety of changes. A meeting was held on January 27, 1986 with all commenters who wished to attend to discuss the program and reach a consensus on engines to test, duty cycles and other details of the test program. Twenty-one commenters attended the meeting. Based on discussions at this session, EPA revised the statement of work and sent it back to the commenters for a final review. Through this procedure and further contacts with engine manufacturers and others, EPA and USDA representatives agreed on a test procedure for tractors, combines, and farm trucks, including the selection of engines and duty cycles.

In addition, EPA decided to include a recreational vehicle (RV) engine in the study because of a concern expressed by RV owners related to potential engine damage while operating these engines on low-lead or unleaded gasoline. EPA developed a duty cycle to be used on the RV engine, after discussions with consultants and original-equipment manufacturers.

Engine testing was performed by the National Institute for Petroleum and Energy Research (NIPER), an independent research laboratory located at Bartlesville, Oklahoma. (See Appendix 6 for information on how to obtain a copy of their report.) Technical advice and oversight were provided by two consultants, Dr. Louis I. Leviticus of the Nebraska Tractor Testing Laboratory, Lincoln, Nebraska and Dr. Ralph Fleming of Energy, Fuels and Engine Consulting Services, Accokeek, Maryland. The consultants commented on the original program design, visited the test facility on several occasions and consulted on major program decisions throughout the study. Their evaluation of the test program is in Appendix 2.

B. Farm Engine-Use Survey

The second area of this study was a survey of the number and use of selected gasoline-powered farm equipment (tractors, combines and trucks). Questions were added to a Farm Labor Survey conducted in July 1986 by the National Agricultural Statistics Service, USDA. (See Appendix 5 for a copy of the survey form and see Appendix 6 for information on how to obtain a copy of the manual that accompanied the questionnaire.) Survey results were related to the results of the dynamometer tests in order to characterize the degree of risk encountered by farm equipment. Highlights of that analysis are included in this report. More extensive analysis of the data may reveal additional information about the use of these engines.

C. Cylinder Head Survey

Valve seat recession is affected by the type and hardness of the material used in valve seats. A field survey of cylinder heads was performed to determine what material (cast iron, soft steel, hard steel or stellite) is in the exhaust valve seats of tractors. Due to overhauls, engines may no longer have valve seats meeting original equipment specifications.

The survey, conducted by the Radian Corporation, Sacramento, California, involved sending an engineer to test cylinder heads removed by eight tractor dismantling and salvage firms located throughout the United States. (See Appendix 6 for additional information on how to obtain a copy of the protocol and quality assurance plan for this survey.)

III. Agricultural Machinery Testing on Engine Dynamometers

A. Test Design

Lead combustion products serve as solid lubricants for some parts of the engine--primarily the exhaust valve seats. Engines designed for leaded gasoline typically have a valve seat geometry designed to prevent excessive accumulation of lead compounds. They may also use valve rotators for this purpose. Valve seat wear appears to be related primarily to engine speed and load.

A tractor duty cycle was designed to reflect a full range of tractor use conditions. The duty cycle had two parts. The first part consisted of 144 hours (16 hours/day) at governed engine speed and loads varying from no load to full power. This cycle was adopted from the cycle used by the Nebraska Tractor Testing Laboratory (SAE J708).1/ The second part consisted of a 56-hour continuous test at governed engine speed and 75% of maximum available power. This segment represents the maximum continuous load that is likely to be placed on these engines, such as pumping irrigation water. The combine engine was tested using the same duty cycle. (See Appendix 3 for a description of the duty cycles.)

The farm truck engine was operated throughout the 200 hours at varying engine speeds (2000-3600 rpm) and loads (25% to 85% of maximum power) representing normal conditions

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1/This cycle has a long history of use in testing the performance of new tractors.

for farm trucks larger than one-ton capacity. The RV engine was operated for 144 hours at varying engine speeds (2000-3600 rpm) and loads (45% to 85% of maximum power) followed by a 56-hour hour steady state cycle (100 HP, which is 52% of maximum power, at 3000 rpm). The farm truck and RV engines were operated for 16 hours on and 8 hours off throughout the tests. (See Appendix 3 for a description of the duty cycles.)

Before each test, the cylinder heads were changed and broken in on the next fuel being tested. Testing was conducted on leaded (1.2 gplg), unleaded, and low-lead (0.1 gplg) gasoline, and gasoline containing non-lead additives.[2/] The principal focus of the testing was to record wear of exhaust valve seats. Valve clearance was set to manufacturers' specifications each time a measurement was taken. In addition, the contractor measured intake valve seat recession, valve stem length, valve guide and stem wear, valve tulip diameter and valve seat angle, valve spring force and height, and other measures of engine wear. Engine performance was monitored and emissions tests were performed on the exhaust gases. After each fuel test, engines were carefully examined for deposits and other conditions that may have resulted from the test. Elemental analyses of the lubricating oils were conducted. Cylinder heads and valve seat inserts were carefully selected to control the hardness of exhaust valve seats.

2/Leaded gasoline in this study contains tetraethyl lead.

Tractor and combine engines usually have solid valve lifters. A valve adjustment is needed in the engines after about every 15 thousandths of an inch of wear and new valve seats are needed after about 125 to 200 thousandths of an inch of wear. While repeated valve adjustments theoretically make it possible to continue operating an engine as valve seat recession occurs, as a practical matter, an engine operator is likely to burn a valve and, thus, require an overhaul of the valve assembly before all of the potential adjustments can be made. This is because valve seat wear gives an operator few clues to the problem until significant damage occurs. There is no increase in engine noise and misfiring and loss of power often are not noticed until after valves or valve seats have burned. Automotive-type engines usually have hydraulic valve lifters so regular valve adjustments are not needed. New valve seats are needed in these engines after about 75 thousandths of an inch of valve seat wear. New valve seats may be obtained by replacing the cylinder head or by machining out the valve seats and installing valve seat inserts.

Proper clearance also must be maintained between valve stems and valve guides. Worn valve stems and guides result in increased oil usage and may cause excessive valve and valve seat wear because the valve does not seat properly. When valve guide clearance increases by more than 2 thousandths of an inch, many manufacturers recommend that the valve guides be replaced or that the valves be replaced by ones with oversize stems.

See Appendix 6 for information on how to obtain a copy of the statement of work used in the study and a detailed description of the engine tests, including fuel and oil specifications, engine rebuilding procedures, recession measurement guidelines, and other test parameters which NIPER was required to follow.

B. Engines Tested

The five farm equipment engines initially selected by USDA were: John Deere "B", Farmall "H" and International Harvester 240 tractors, John Deere 303 cubic inch displacement (CID) combine engine, and a pre-1974 General Motors 292 CID (GM 292) truck engine. The engines, described in Appendix 4, represent a broad range of engine sizes and characteristics. EPA selected the pre-1984 General Motors 454 CID V-8 engine (GM 454) to represent engines used in RVs.

Plans called for purchase of a duplicate of the engine that experienced the most valve seat recession on unleaded gasoline, in order to focus more attention on tests of this engine. The GM 292 truck engine proved most vulnerable and a duplicate was purchased. At the request of the USDA and the American Farm Bureau Federation, a Ford 8N tractor engine also was procured for the study after it was learned that one of the other tractor engines selected did not need to be tested on low-lead gasoline and non-lead additives. Manufacturers' specifications for the John Deere "B", International 240, John Deere 303, and GM 292 engines called for ordinary cast iron cylinder heads without valve seat inserts. Hardness of these valve seats typically ranges from 9 to 25 on the Rockwell C scale.3/ The Farmall "H" was originally equipped with "gray iron" valve seat inserts (Rockwell C scale values of 26-36); the Ford 8N was originally equipped with harder exhaust valve seat inserts (Rockwell C scale 39-43); and the General Motors 454 CID engine was originally equipped with induction-hardened cast iron valve seats (no inserts) with a Rockwell C scale hardness of about 55 specified by the manufacturer.4/ The General Motors 454 and 292 engines are currently being manufactured with induction-hardened cast iron valve seats. All engines were tested with valve seats meeting original equipment specifications except the Farmall "H" and Ford 8N. Since the latter engines may have been rebuilt with different valve seat material, they were tested with ordinary cast iron valve seat inserts (Rockwell C scale value of 17).

C. Dynamometer Testing Limitations

The dynamometer testing portion of this study has a number of limitations. First, budget limitations did not permit testing enough engines to assure statistical reliability. Only one or at most two engines of any given type could be tested. Second, dynamometer tests typically show

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3/Lower numbers indicate softer materials.

4/Hardness of induction-hardened cast iron valve seats typically ranges from 40 to 60 on the Rockwell C scale.

more wear than is found during actual in-use operation of engines. Every attempt was made to make the tests representative of actual in-use conditions, but this was difficult because data on how the engines are used did not exist. Third, because of time and cost restrictions, valve design factors which could affect valve seat wear, such as the presence of valve rotators, were not examined fully. Finally, unforseen engine characteristics such as air/fuel ratios and mechanical problems, which appear to have an effect on valve seat wear rates, were not controlled in the study design.

IV. Results of Dynamometer Testing

A. Tests of Leaded Gasoline (1.2 gplg)

Baseline tests were run on the six original engines using gasoline containing 1.2 grams per leaded gallon (gplg). The duplicate truck engine (GM 292-B) and the additional tractor engine (Ford 8N) were not tested on gasoline containing 1.2 gplg because none of the original engines showed appreciable wear with this fuel.

Table 1 summarizes the maximum rates of valve seat recession (in thousandths of an inch per 100 hours) found while operating the engines on leaded, low-lead, and unleaded gasoline. Except for the GM 454 engine, essentially no valve seat recession was found and no unusual wear occurred on other engine components when leaded gasoline was used. It should be noted that the GM 292-A exhaust valve guide diameter increased by 1.8 thousandths of an inch and that the International Harvester 240 intake valve guide diameter increased by 14.3 thousandths of an inch (probably due to an oil line blockage that was corrected early in the test) which are substantially more than were observed in the other engines. Exhaust valve seat recession is not a problem with gasoline containing 1.2 grams per leaded gallon.

Table 1--Maximum exhaust valve seat recession rates*

Engine	Type of valve seat 1/	Exhaust valve rotators	Leaded 2/ 1.2 gplg	Leaded 2/ 0.1 gplg	Unleaded Intermittent phase 3/	Unleaded Steady state phase 3/	Unleaded Total 2/
			Thousandths of an inch per 100 hours				
John Deere B, run 1	CI	No	0	NT	0	4/19.6	4/4.5
John Deere B, run 2	CI	No	NA	NA	5/5.7	0	6/4.7
Farmall H	CI	No	0	NT	0.7	0	0
International 240, run 1	CI	Yes	1.5	0.5	0	0	0
International 240, run 2	CI	Yes	NA	NA	16.7	44.6	23.5
International 240	CI inserts	Yes	NT	1.0	32.6	83.9	42.5
Ford 8N	CI inserts	Yes	NT	NT	11.8	50.0	15.0
John Deere 303 CID	CI	Yes	0.5	2.0	16.7	69.6	32.0
GM 454 CID	IHCI	Yes	3.0	2.5	20.8	14.3	16.0
GM 454 CID	SS inserts	Yes	NT	NT	11.8	5.4	8.5
GM 292 CID, engine A	CI	Yes	1.0	7/20.0 5.0	2/8/170.4	NA	8/170.4
GM 292 CID, engine B	CI	Yes	NT	1.0	NT	NT	NT
GM 292 CID, engine B	IHCI	Yes	NT	NT	2/5.5	NA	5.5
GM 292 CID, engine B, lighter load 9/	CI	Yes	NT	NT	2/10/106.8	NA	10/106.8

NA denotes "not applicable." NT denotes "no test."

*See figures in Appendix 1 for recession data on individual cylinders.

1/ CI = ordinary cast iron; IHCI = induction-hardened cast iron; SS = soft steel. 2/ Recession based on measurement of cylinder heads before and after each fuel test. 3/ Recession estimates based on valve lash measurements recorded at intervals during each fuel test. This procedure is less accurate than "before and after" measurements. See NIPER report for more information on measurement techniques.

Continued --

Table 1--Maximum exhaust valve seat recession rates*--continued

4/ Recession may have been influenced by improper alignment of rocker arm assembly. 5/ Operated 244 hours. 6/ Operated 300 hours. 7/ Results are for two tests. During the first test (the larger recession rate), the cylinder head gasket failed and may have generated additional heat which contributed to the recession. 8/ Engine could complete only 71 of the scheduled 200 hours due to recession. 9/ Engine was run without the 3600 rpm part of the duty cycle. 10/ Engine was stopped after 88 hours of operation due to recession.

B. Tests of Unleaded Gasoline

All engines procured for this test program were evaluated on unleaded gasoline. Recession data are summarized in Table 1 and Appendix 1, Figures 1-13. Principal findings are as follows.

1. The John Deere "B" tractor engine was tested twice on unleaded gasoline (Appendix 1, Figures 1 and 2). The first test found that one cylinder had 11 thousandths of an inch of recession after 200 hours of operation, all of which occurred during the steady state portion of the test. Examination of the engine after the test showed that the rocker arm was not striking the valve stem tip properly and it was believed that recession was due to this mechanical problem instead of the fuel. This may have caused valve guide diameter wear to increase from 1.0 thousandths of inch for the leaded fuel test to 3.2 thousandths of an inch during the first unleaded test. After properly aligning the rocker assembly, the unleaded test was repeated with a new cylinder head. Both exhaust valve seats experienced some recession after 80 hours, but no additional recession through 200 hours. The test was continued on the intermittent portion of the duty cycle for 100 more hours and no additional recession occurred. Valve guide diameter wear was consistent with the rate observed for leaded gasoline. Valve stem wear increased from 0.2 thousandths of an inch for leaded gasoline to 0.8 thousands of an inch for unleaded gasoline. No

other unusual wear was observed. The John Deere "B" tractor engine may experience a small amount of valve seat recession but should not have problems operating on unleaded gasoline.

2. The Farmall "H" tractor engine did not experience valve seat recession or any other unusual wear while operating on unleaded gasoline and was not tested any further (Appendix 1, Figure 3).

3. The John Deere 303 CID combine engine experienced substantial valve seat recession while operating on unleaded gasoline (Appendix 1, Figure 4). At 144 hours, all cylinders showed recession ranging from 10 to 24 thousandths of an inch. After the steady state portion of the test, total recession ranged from 41 to 63 thousandths of an inch. Valve guide wear increased from a maximum of 0.2 thousandths of an inch on leaded fuel to 1.5 thousandths of an inch on unleaded fuel.

4. The International Harvester 240 tractor engine was tested three times on unleaded gasoline. The first test showed no valve seat recession (Appendix 1, Figure 5). We subsequently found that the cylinder head used was among the hardest of the heads purchased for the tests. It was decided to test the engine a second time using a cylinder head at the softer end of the hardness range of heads available. Substantial valve seat recession (43-49 thousandths of an inch) occurred on two of the valve seats (Appendix 1, Figure 6). About one-half of the recession occurred during the 56-hour steady state portion of the test cycle.

Further investigation of the cylinder heads after the tests were completed revealed that the hardness of the metal in the seat area was essentially the same for both heads. Differences in wear in the International 240, therefore, were not due to differences in hardness of the valve seats. Evaluation of the data revealed that the air/fuel ratio was much higher during the test that exhibited valve seat recession even though the engine was set to the manufacturer's specifications (Table 2). The higher air/fuel ratio may have contributed to the valve seat recession since a leaner mixture would cause higher exhaust temperatures. After the test was completed, the carburetor was cleaned and the air/fuel ratio returned to its original level.

A third unleaded test was performed on the engine using exhaust valve seat inserts. The inserts were of about the same hardness as the valve seats in the first two unleaded tests on this engine. Appendix 1, Figure 7 shows that no recession occurred during the first 80 hours but then occurred very rapidly. After 144 hours of variable loads, recession ranged from 16 to 47 thousandths of an inch and then rose to 63 to 94 thousandths of an inch during the final 56 hours of steady state operation. The air-fuel ratio did not rise during this test. This test suggests that engines with valve seat inserts are more susceptible to recession than engines without inserts when the valve seats are of equal hardness.

Table 2--Average emissions and air-fuel ratios by engine and test fuel

Engine and fuel	CO 1/	HC 2/	NOx 3/	Air-fuel ratio
	Percent	ppm	ppm	
John Deere B				
1.2 gplg	5.3	3,303	679	13.0
Unleaded				
Run 1	9.3	3,202	202	10.9
Run 2	6.0	3,605	847	12.2
Farmall H				
1.2 gplg	5.1	3,544	1,008	13.0
Unleaded	4.2	2,187	1,116	13.4
International 240				
1.2 gplg	5.1	3,133	817	12.7
Unleaded				
Run 1	5.7	2,358	925	12.5
Run 2	2.1	1,338	1,380	14.3
Inserts	4.6	2,022	NA	12.9
0.1 gplg				
No inserts	6.3	2,606	868	12.3
Inserts	5.6	2,104	NA	12.5
John Deere 303 CID				
1.2 gplg	4.9	3,610	1,212	12.7
Unleaded	4.6	1,951	1,305	13.0
0.1 gplg	6.3	2,612	738	12.2
DuPont additive 4/	5.2	2,033	NA	12.7
Standard "PowerShield" additive 5/	7.3	2,482	NA	11.8
Ford 8N				
Unleaded	5.5	2,933	NA	12.5
GM 454 CID				
1.2 gplg	2.0	1,726	1,950	14.0
Unleaded				
No inserts	2.5	930	1,802	13.8
Steel inserts	3.4	813	NA	13.4
0.1 gplg	2.5	1,090	1,868	13.9
Standard "PowerShield" additive 5/	3.0	891	NA	13.6

Continued--

Table 2--Average emmissions and air-fuel ratios by engine and test fuel--continued

Engine and fuel	CO 1/	HC 2/	NOx 3/	Air-fuel ratio
	Percent	ppm	ppm	
GM 292 CID, engine A				
1.2 gplg	3.8	2,356	1,339	13.4
Unleaded	4.3	1,006	1,119	13.1
0.1 gplg				
Run 1	3.0	1,597	1,696	13.7
Run 2	3.9	1,182	NA	13.2
DuPont additive 4/	3.8	1,054	NA	13.3
Standard "PowerShield" additive 5/	2.7	1,205	1,924	13.6
GM 292 CID, engine B				
Unleaded				
IHCI 6/	3.9	1,436	1,398	13.1
Lighter load 7/ . . .	3.9	1,222	NA	13.2
0.1 gplg	5.2	1,416	NA	12.7
Concentrated "PowerShield" additive 8/	4.9	2,865	NA	12.7

1/ Carbon monoxide.
2/ Hydrocarbons.
3/ Nitrogen oxides.
4/ 200 pounds of additive per 1,000 barrels of gasoline.
5/ 250 pounds of additive per 1,000 barrels of gasoline.
6/ Induction-hardened cast iron exhaust valve seats.
7/ Engine was run without the 3,600 rpm part of the duty cycle.
8/ 1,000 pounds of additive per 1,000 barrels of gasoline.

Valve train inspection data show that exhaust valve guide wear was up to 2.2 thousandths of an inch without inserts and up to 8.7 thousandths of an inch with inserts compared to a maximum of 0.9 thousandths of an inch with leaded fuel and no inserts.

5. Tested with ordinary cast iron valve seat inserts, the Ford 8N had up to 17 thousandths of an inch of valve seat recession after 144 hours, and 17 to 29 thousandths of an inch of recession after 200 hours, a significant amount of wear (Appendix 1, Figure 8).

Two cylinders may have had above-normal valve guide wear based on comparisons with the leaded fuel tests on the other engines (the Ford 8N does not have a leaded-fuel baseline test since none of the original engines tested showed appreciable wear with this fuel).

6. The GM 292-A CID truck engine, when tested on unleaded fuel with ordinary cast iron valve seats, experienced the highest rate of recession (Table 1 and Appendix 1, Figure 9). In fact, the test had to be terminated after 71 hours due to fear that the engine would be severely damaged by excessive valve seat recession. Exhaust valve guide wear increased but not substantially more than found in the leaded test.

A duplicate engine, GM 292-B, was tested with the harshest portion of the duty cycle (3600 rpm) deleted. The wear rate was reduced by 40 percent, but the test still had to be terminated after 88 hours due to excessive valve seat recession

(Appendix 1, Figure 10). Subsequently, the GM 292-B engine was tested with induction-hardened cast iron exhaust valve seats, and experienced 11 thousandths of an inch of recession after 200 hours (Appendix 1, Figure 11). However, there was a greater change in exhaust valve guide diameter (a maximum of 4 thousandths of an inch versus 1.8 thousandths of an inch for leaded fuel) during this test. Valve length was reduced by up to 8 thousandths of an inch compared to increases of up to 4 thousandths of an inch for leaded fuel.

7. The GM 454 recreational vehicle engine was tested with induction-hardened cast iron valve seats. All cylinders showed significant recession, ranging from 14 to 30 thousandths of an inch after 144 hours. Total recession increased slightly to a maximum of 34 thousandths of an inch after the steady state portion of the test (Appendix 1, Figure 12). The induction hardening process for the GM 454 affects the valve seats to a depth of about 50 thousandths of an inch. Rapid wear would be expected after the induction-hardened portion of the valve seat is worn away. Exhaust valve guide wear increased from a maximum of 1 thousandths of an inch using leaded fuel to 4.6 thousandths of an inch while operating on unleaded fuel.

A second test on unleaded fuel was conducted using soft steel "XB" valve seat inserts (Rockwell C scale value of 42) designed for moderate-duty use. This test also showed valve seat recession but it was much less; 17 thousandths of an inch after 144 hours with little recession during the final steady state portion of the test (Appendix 1, Figure 13). Maximum exhaust valve guide wear of 1.7 thousandths of an inch occurred compared to 1 thousandths of an inch on leaded fuel.

8. Summary of Results on Unleaded Gasoline.

Engines operated at low speeds (e.g., John Deere B, rated at 1250 rpm; and Farmall H, rated at 1650 rpm) should have little or no problem operating on unleaded gasoline, regardless of the type of valve seat material. Engines which operate at medium rpm (e.g., International 240 and Ford 8N rated at 2000 rpm) are likely to experience significant valve seat recession unless they are used only for light-duty tasks or have hard steel valve seat inserts. Engines operated under heavy-duty steady state conditions may experience 2-4 times more recession than engines operated under a wider range of load conditions.

Farm equipment engines operating at higher speeds (e.g., John Deere 303 CID, rated at 2500 rpm) which have ordinary cast iron valve seats probably will experience considerable valve seat recession. Based on the tests of the GM 292 and GM 454 CID engines, we concluded that automotive-type engines of the type tested, when operated under conditions represented by the duty cycles used in these tests, are extremely susceptible to valve seat recession when they have ordinary cast iron valve seats. Furthermore, the tests on the GM 454 showed that engines could experience considerable recession even if they are equipped with induction-hardened cast iron valve seats which are still being installed in new vehicles. Based on tests of the GM 454, soft steel inserts also are vulnerable with unleaded fuel although wear rates appear to be lower than for induction-hardened cast iron seats. Unleaded gasoline also increases valve guide wear and may increase valve stem wear.

Factors other than the lead content of fuel also affect valve seat recession, probably because of heat differences. Higher air/fuel ratios appear to increase valve seat recession. Engines with valve seat inserts appear to be more susceptible to valve seat recession than engines with equally hard integral cylinder head seats. The use of valve rotators also may increase recession.

C. Tests of Low-lead Gasoline (0.1 gplg)

Four of the original six engines showed significant recession on unleaded gasoline and, therefore, were tested on gasoline containing 0.1 gplg. The John Deere 303, the International 240 (with and without valve seat inserts) and the GM 454 engines all operated satisfactorily on 0.1 gplg (Table 1 and Appendix 1, Figures 14, 15, 16, and 17).

Other parameters measured showed no changes for the International 240. Compared to leaded fuel, maximum valve guide wear increased from 1.0 thousandths of an inch to 2.0 thousandths of an inch in the GM 454 and from 0.2 thousandths on an inch to 1.2 thousandths of an inch in the John Deere 303.

The GM 292-A experienced significant recession after 91 hours (Appendix 1, Figure 18). Since the head gasket failed at about that time, and may have contributed to the valve seat recession, it was decided to retest the GM 292-A engine and the duplicate GM 292-B, engine on this fuel.[5/] One of the engines showed no increase in wear compared to the leaded test. The other engine showed slightly more recession in one cylinder. Overall, little recession occurred in these subsequent tests (Appendix 1, Figures 19 and 20). Under good operating conditions, most farm engines probably will experience little or no valve seat wear using 0.1 gplg gasoline.

However, 0.1 gplg appears to be at or near the minimum level needed by most of these engines when they are properly maintained and operated under conditions similar to the duty cycles tested, unless other forms of valve seat protection are used (such as non-lead additives or more wear-resistant seat materials).

The technical specialists who worked on this study believe that excessive heat may contribute significantly to valve seat recession. The head gasket failure and differences in air/fuel ratios observed in this study are two of many

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[5/]The exact time that the gasket failure started to occur is not known because it did not cause an abrupt change in the engine's behavior or in the performance measures being monitored, such as power, engine temperature and emissions. One of the consultants on the project (Dr. Ralph Fleming) examined the test data and engine characteristics to determine if the gasket failure caused the recession, and reported that a conclusive determination could not be made.

factors that could cause excessive heat that may not be detected by operators in everyday engine operations. An improperly maintained engine might experience excessive valve seat recession even when high concentrations of lead are in the gasoline, but good engine maintenance is especially important when using gasoline containing only 0.1 gplg or less of lead.

D. Tests of Non-lead Additives[6]

Two proprietary additives were evaluated in the test program.[7] An additive manufactured by Lubrizol Corporation (Lubrizol) was tested on the John Deere 303, GM 454 and GM 292 A and B engines. The second additive, produced by E.I. duPont de Nemours and Company (DuPont), was evaluated on the GM 292-A and the John Deere 303 engines.

Table 3 and Appendix 1, Figures 21-25, summarize the rates of exhaust valve seat recession found while operating the engines on the Lubrizol and DuPont additives.

1. Test Results Using the Lubrizol Additive

Three formulations of the Lubrizol additive were tested.

6/Products containing tetraethyl lead to be added by the consumers were not evaluated because we would expect the same results as with the leaded-fuel tests that were conducted.

7/Additives were selected for testing in this program if the manufacturers indicated to EPA a desire to have their products tested and they provided data to EPA which showed that their products had the potential for reducing valve seat recession when used with unleaded gasoline.

Item	Unleaded gasoline	DuPont additive	Lubrizol additive: Modified "PowerShield"	Lubrizol additive: Standard "PowerShield"	Lubrizol additive: Concentrated "PowerShield"
	Pounds per 1,000 barrels of gasoline				
Additive treat rate		1/200	250	250	1,000
	Thousandths of an inch per 100 hours				
John Deere 303 CID					
Intermittent phase	3/16.7	2/4/4.2	2/5/15.0	3/7.6	NT
Steady state phase	3/69.5	NA	NA	3/60.7	NT
Total 2/	31.5	NA	NA	20.0	NT
GM 292 CID					
Engine A 2/	170.4	22	6/120	7/130	NT
Engine B 2/	NT	NT	NT	NT	0.5
GM 454 CID					
Intermittent phase 3/	20.8	NT	NT	3.5	NT
Steady state phase 3/	14.3	NT	NT	7.1	NT
Total 2/	16.0	NT	NT	4.5	NT

*See figures in Appendix 1 for recession data on individual cylinders.

NA denotes "not applicable" because the test was not completed.
NT denotes "no test."

1/ About double the concentration normally recommended by DuPont. 2/ Recession based on measurement of cylinder heads before and after each fuel test. 3/ Recession estimates based on valve lash measurements recorded at intervals during each test. This procedure is less accurate than "before and after" measurements. See NIPER report for more information on measurement techniques. 4/ Test terminated after 48 hours due to a problem not related to the fuel. 5/ Test terminated after 80 hours when NIPER was notified that the additive was not properly manufactured. 6/ Test terminated after 64 hours due to excessive valve seat recession. 7/ Test terminated after 84 hours due to excessive valve seat recession.

The first, a modified version of a product Lubrizol sells under the trade name "PowerShield" had little effect on valve seat recession. Lubrizol, subsequently, notified NIPER that the product had not been properly formulated and asked that "PowerShield" be tested. "PowerShield" was tested at the manufacturer's recommended concentration of 250 pounds per 1,000 barrels of gasoline. For the GM 454, recession was about comparable to that found using 1.2 gplg and 0.1 gplg. However, compared to unleaded gasoline, "PowerShield" slightly reduced but did not stop wear in the other two engines tested (John Deere 303 and GM 292-A) (Table 3 and Appendix 1, Figures 21, 22, and 23). Valve guide wear was above normal with "PowerShield" (based on the test using 1.2 gplg gasoline) in the John Deere 303 (3.3 thousandths of an inch compared to 0.2 thousandths of an inch with leaded).

"PowerShield" was tested in one engine (GM 292-B) at a concentration of 1,000 pounds of additive per 1,000 barrels of gasoline (four times the level normally recommended for the product). Valve seat recession was stopped (Appendix 1, Figure 24). Valve stem wear was slightly greater than was observed for both leaded and unleaded gasolines.

The "PowerShield" additive caused deposits to form in the combustion chamber of the engines. Engine deposits increased when the "PowerShield" concentration was quadrupled. Combustion chamber deposits can increase an engine's octane requirement, but it is not clear from this testing whether the deposits seen would significantly alter octane requirements or have any other effects on the engines.

"PowerShield" at the 250 pounds of additive per 1,000 barrels of gasoline also caused oily black deposits to form on intake runners, but the implications, if any, are not known. This occurred in both the GM 292-A and John Deere 303 engines and to a lesser extent in the GM 454.

Examination of lubricating oils revealed substantially higher levels of sodium in the oil after running the engines on "PowerShield." Two of the engines also had elevated levels of phosphorus and the engine that ran on "PowerShield" at 1,000 pounds of additive per 1,000 barrels of gasoline had much larger quantities of sulfur in the oil.

2. Test Results Using the DuPont Additive

Two engines (John Deere 303 and GM 292-A) were tested on the DuPont additive at about twice the concentration normally recommended by the manufacturer. The test on the John Deere 303 was terminated after only 48 hours due to a problem with the engine's cooling system. At that point, essentially no valve seat recession was occurring. However, 48 hours was not long enough to yield meaningful results.

The DuPont additive reduced valve seat recession in the GM 292-A engine, although, at 22 thousandths of an inch per 100 hours, wear was st ll excessive (Table 3, and Appendix 1, Figure 25). The additive caused deposits to form in the engine. A large amount of hard, sticky deposits was found on the intake valves. One intake valve was unable to close completely and was beginning to burn. Inside the combustion chamber, a glaze deposit had formed on valve surfaces. The full implications of these deposits, including the potential for eliminating them, are not known.

Examination of the lubricating oils revealed substantially higher levels of phosphorus after running engines on the DuPont additive.

3. Summary of Additive Testing

The DuPont additive, at about twice the concentraton normally recommended by the manufacturer, provided some degree of protection against valve seat recession. At the manufacturers recommended concentration, Lubrizol's "PowerShield" reduced recession. At four times the concentration normally recommended by the manufacturer, Lubrizol's "PowerShield" stopped recession in the one engine tested. Both additives produced engine deposits which raised unanswered questions. The DuPont additive increased the amount of phosphorus in the lubricating oil. "PowerShield" also increased the amount of sodium, sulfur, and phosphorus found in the lubricating oils. Nevertheless, although further product development work is essential, the additives may have potential as substitutes for lead.

V. Results of the Farm Engine-Use Survey and Cylinder Head Survey

The National Agricultural Statistics Service, USDA conducted a survey of farmers to learn how many gasoline-powered tractors, combines, and large trucks are in use on farms and how much they are used. The survey was conducted in July 1986. The questionnaire is in Appendix 5. (See Appendix 6 for information on how to obtain a copy of the manual that accompanied the questionnaire.)

At that time, farmers operated a total of 4.4 million tractors, of which 1.8 million were gasoline powered and 2.6 million were diesel powered. The gasoline-powered tractors, which average 26 years of age, were used an average of 250 hours in 1985. The amount of use varies with the size of the tractor (Table 4). Further, tractors with low annual hours of operation tend to see more light duty use (Table 5) than tractors that are used more.

About 42 percent of gasoline-powered farm tractors are used exclusively in light duty tasks and, therefore, have little risk of valve seat recession if operated on unleaded gasoline. The other 58 percent of tractors see some medium and heavy uses which potentially make them vulnerable to excessive valve seat wear if fueled with unleaded gasoline, unless they are low-rpm engines, have hardened exhaust valve seats, or are protected by a fuel additive.

Table 4--Distribution of gasoline-powered tractors by size and hours of use, 1985

Annual hours of use	Number of tractors	Average horsepower
20-49	213,784	31
50-99	324,146	34
100-149	321,520	38
150-249	350,372	43
250-499	303,857	46
500-749	141,992	49
750-1499	84,884	49
1,500 or more	33,160	54
All tractors	1,773,715	40

Table 5--Annual use of gasoline-powered tractors, 1985

Annual hours of use	Percentage distribution of use			
	Irrigation pumping	Hard use	Medium use	Light use
20-49	0.35	8.61	25.48	65.55
50-99	0.05	9.15	30.08	60.71
100-149	0.44	9.99	33.92	55.64
150-249	0.42	12.26	34.29	53.03
250-499	0.17	14.37	36.77	48.68
500-749	0.41	16.80	40.45	42.34
750-1,499	0.27	18.72	43.22	37.79
1,500 or more	0.16	23.00	43.54	33.31
All tractors	0.29	12.08	33.91	53.72

Farmers operate 271,000 gasoline-powered combines that average 19 years of age. On average, each combine harvested 220 acres of grain in 1985. Combines, like tractors, see a skewed use distribution (Table 6). All combine engines receive hard use and are likely to experience excessive valve seat recession if they have cast iron valve seats and are operated on unleaded gasoline.

About 750,000 gasoline-powered trucks larger than 1-ton capacity are used on farms. They average 19 years of age and were driven an average of 3,800 miles in 1985. Over half of the trucks were driven less than 2,000 miles (Table 7). Trucks receive a range of light to hard uses. Data are not available that would more precisely characterize this use although, on average, it is thought to be represented by the duty cycle specified for the tests conducted by NIPER.

The Radian Corporation conducted a survey of tractor dismantling operations to determine the type of material in tractors' valve seats. (See Appendix 6 for information on how to obtain a copy of the protocol and quality assurance plan for this survey.) An eddy-current test was used to identify stellite valve seats and steel/cast iron seats. A chemical test (for the presence of chromium) was then used to distinguish between valve seats made of steel and cast iron. Data were obtained from eight establishments located throughout the United States. This survey is subject to large sampling and measurement errors and the data have not been fully

Table 6--Distribution of number of gasoline-powered combines by number of acres harvested, 1985

Number of acres harvested	Number of combines
1-99	101,641
100-199	69,159
200-299	32,418
300-399	24,446
400-499	13,793
500-999	22,594
1,000 or more	6,294
All combines	270,345

Table 7--Annual miles of farm trucks

larger than 1 ton rated capacity, 1985

Total annual miles driven	Number of trucks
0-1,000	254,805
1,001-2,000	145,783
2,001-3,000	81,896
3,001-4,000	42,568
4,001-5,000	74,053
5,001-10,000	96,361
10,001-20,000	32,341
20,001 or more	5,955
All trucks	733,762

examined at this time. A preliminary analysis suggests that 33 percent of all gasoline-powered tractors may have hard valve seat inserts. These would not be vulnerable to valve seat recession with unleaded gasoline. The remaining 67 percent of the tractors have cast iron inserts or have seats that were machined into the cast iron heads. These tractors are potentially vulnerable to valve seat recession with unleaded fuel if the engines are operated under medium-duty and/or heavy-duty conditions.

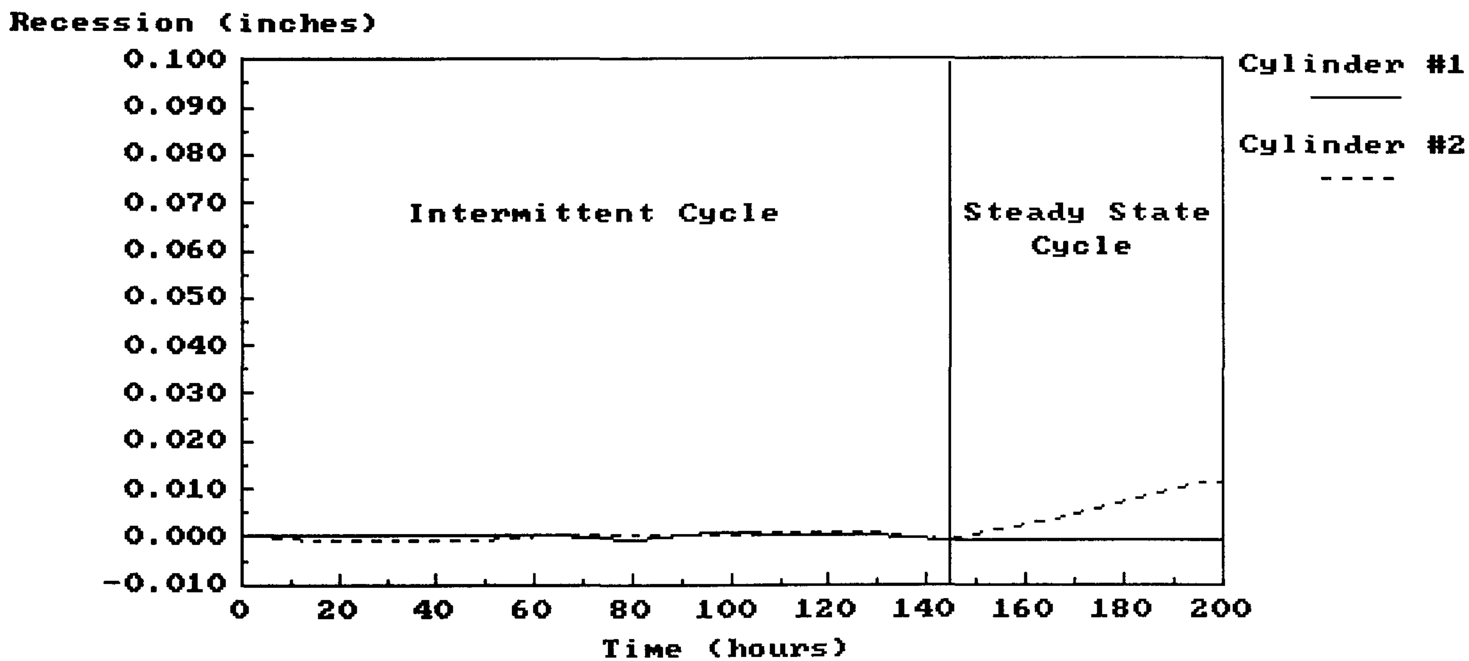
While hundreds of thousands gasoline-powered engines on tractors, combines, trucks and other large farm equipment face no risk of damage if fueled with unleaded gasoline, hundreds of thousands of others need lead or an effective substitute if they are to continue in their present uses without needing an engine overhaul.

Appendix 1

Exhaust Valve Seat Recession by Cylinder

Figure 1

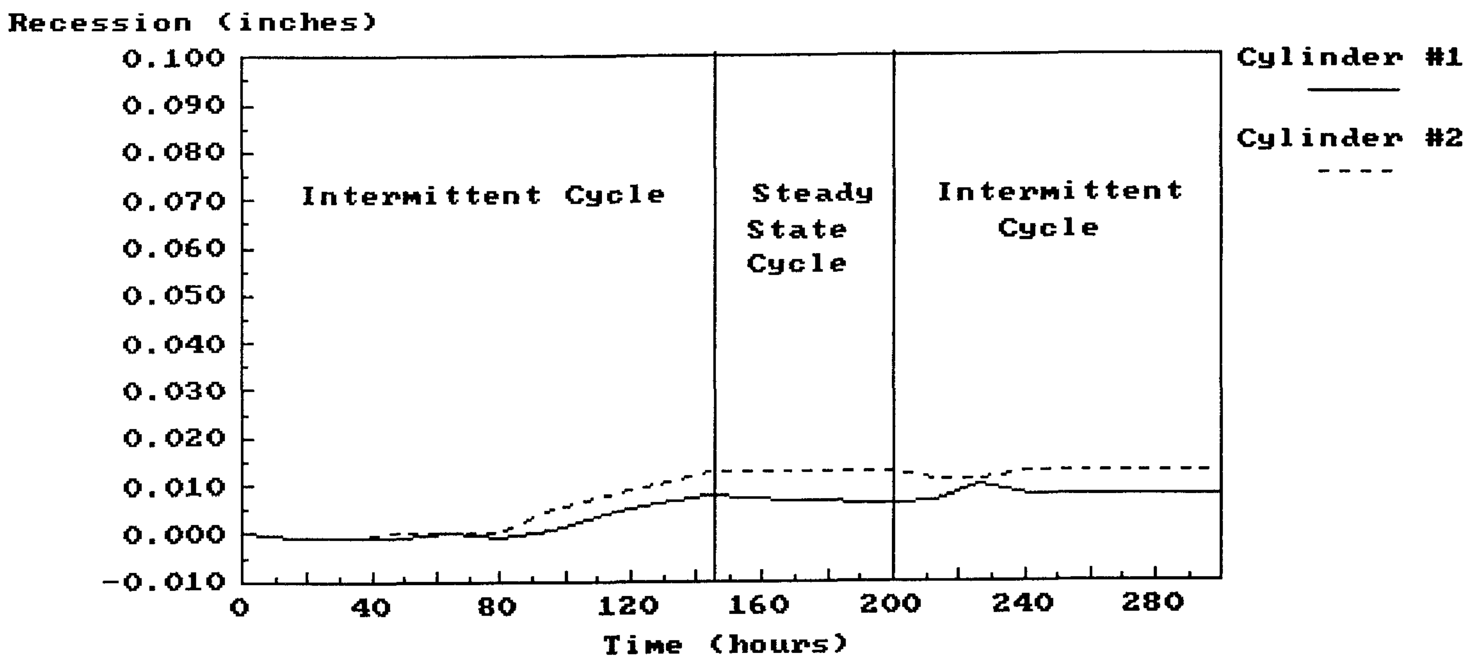
Exhaust Valve Seat Recession
John Deere B, unleaded fuel, run 1
cast iron valve seats



See text for description of duty cycle

Figure 2

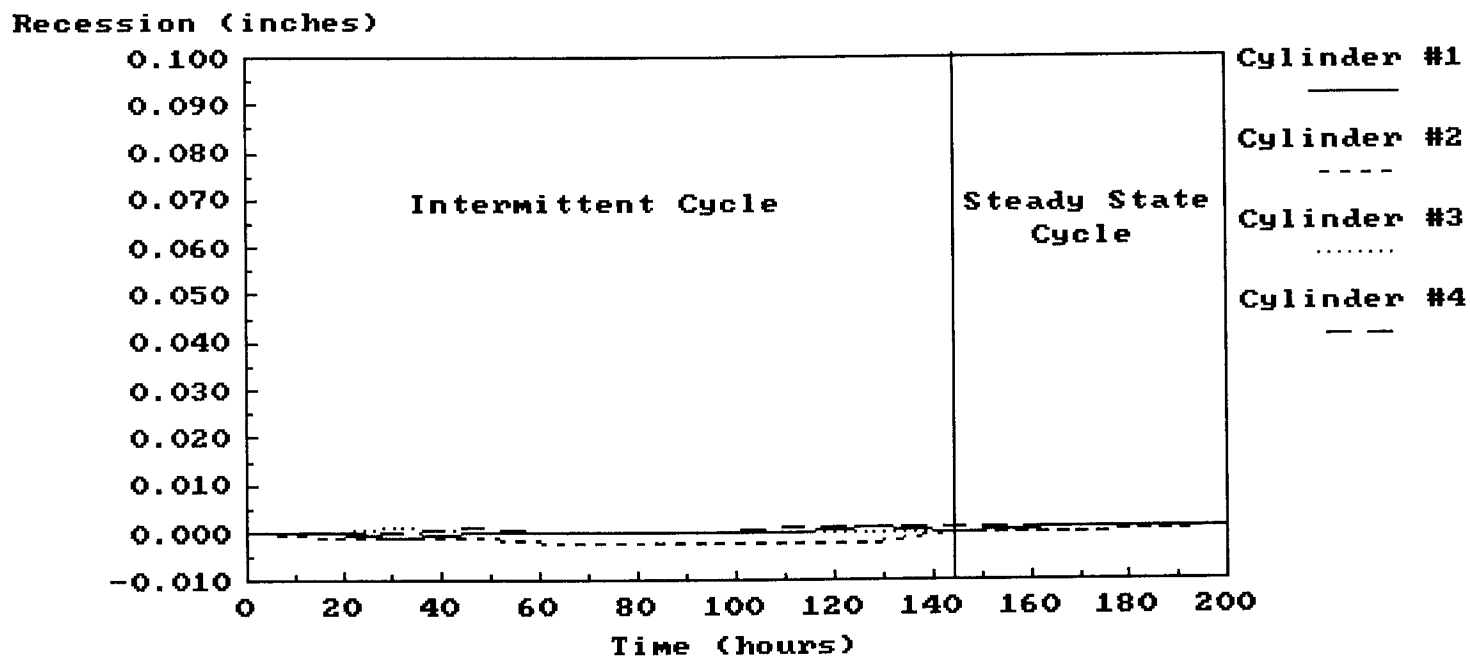
Exhaust Valve Seat Recession
John Deere B, unleaded fuel, run 2
cast iron valve seats



See text for description of duty cycle

Figure 3

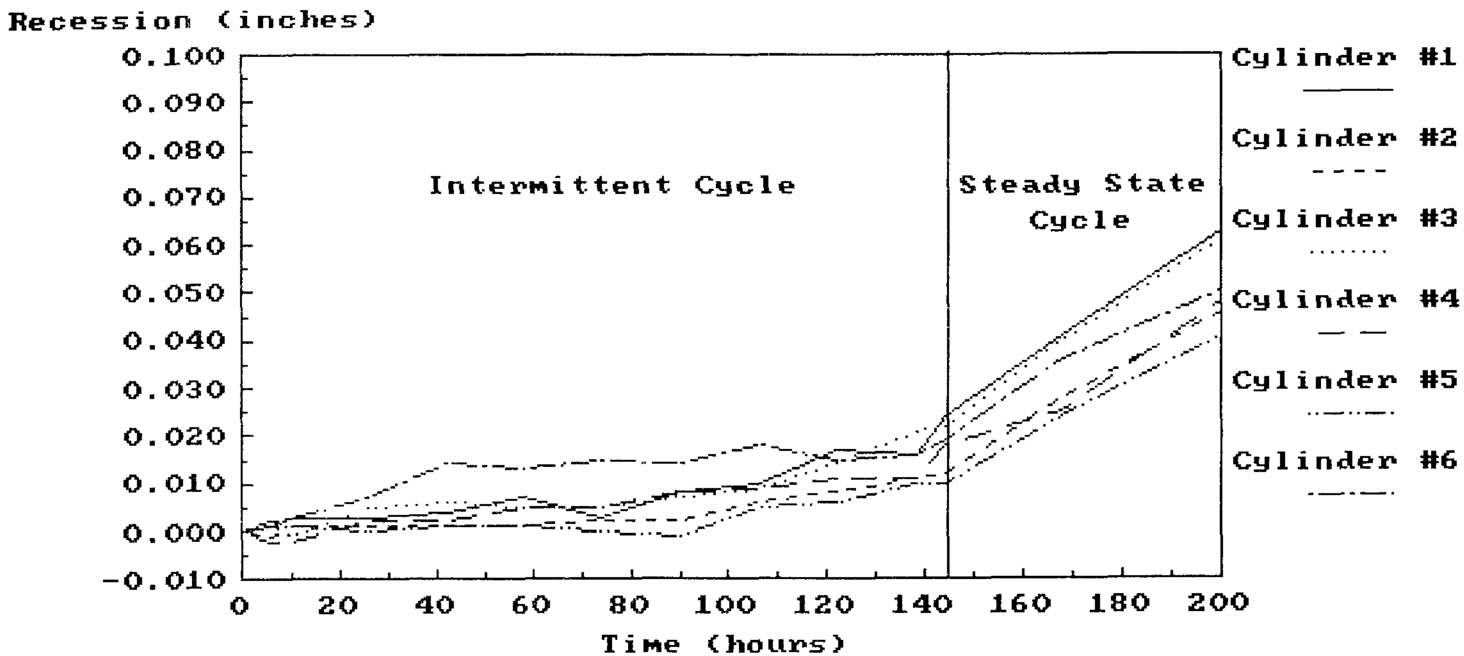
Exhaust Valve Seat Recession
Farmall H, unleaded fuel
cast iron valve seats



See text for description of duty cycle

Figure 4

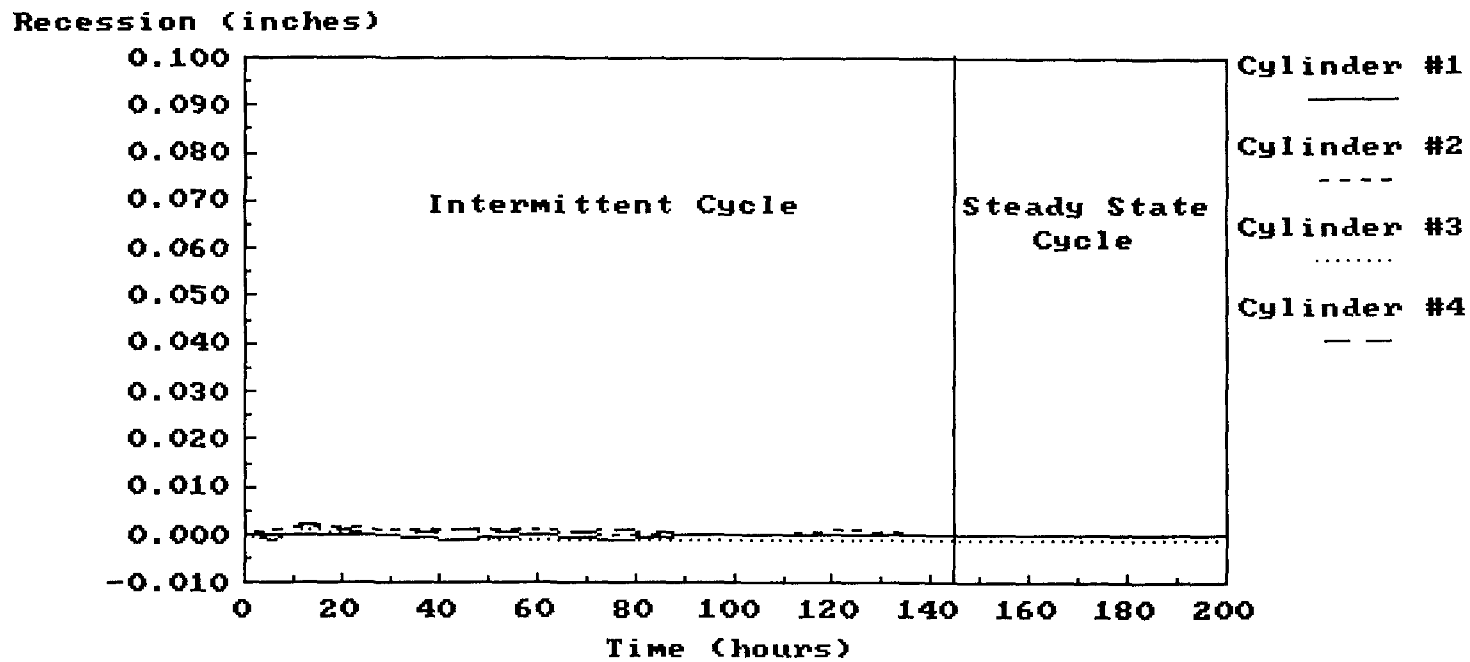
Exhaust Valve Seat Recession
John Deere 303 CID, unleaded fuel
cast iron valve seats



See text for description of duty cycle

Figure 5

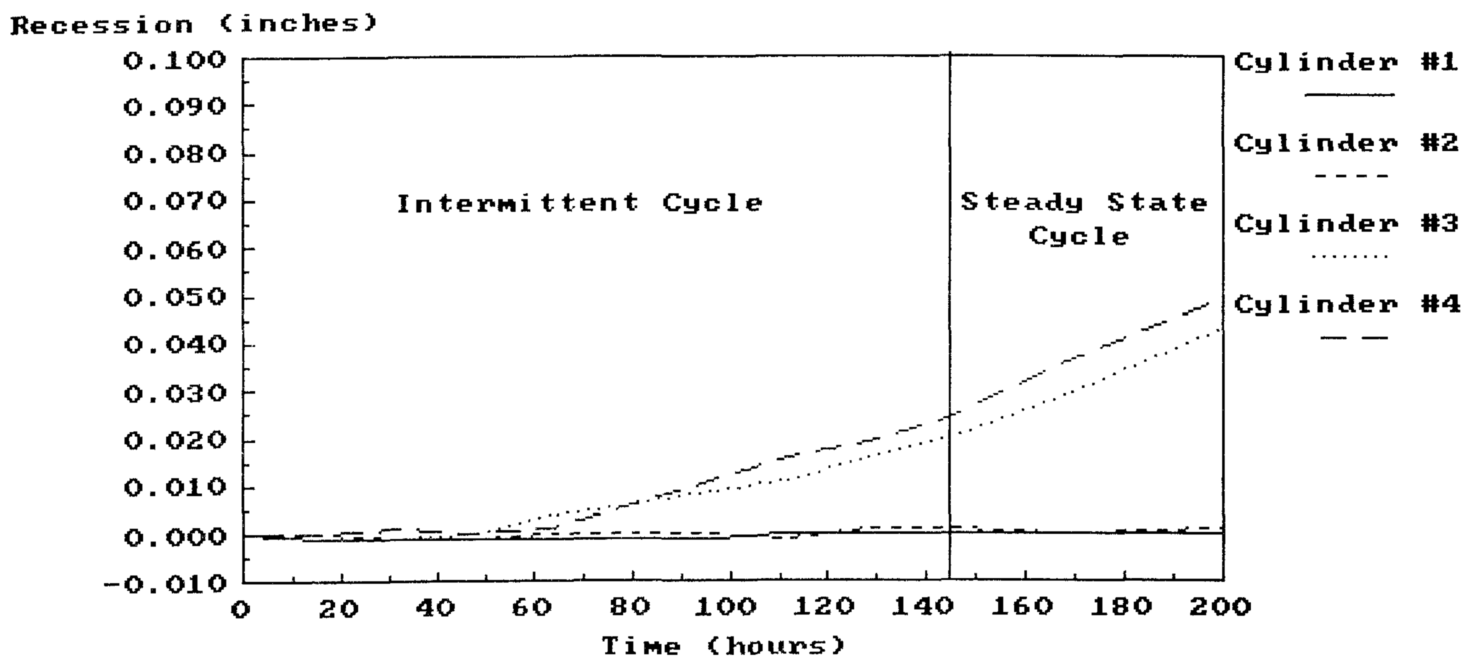
Exhaust Valve Seat Recession
IH 240, unleaded fuel, run 1
cast iron valve seats



See text for description of duty cycle

Figure 6

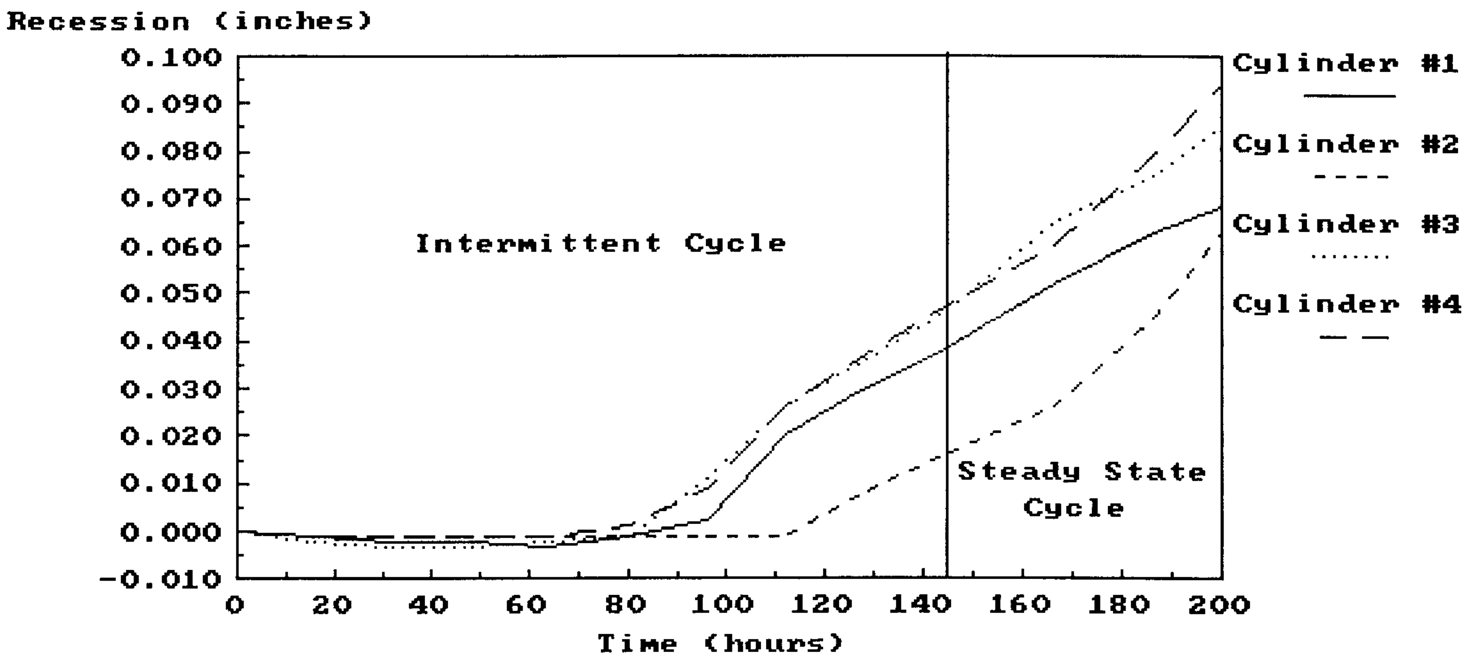
Exhaust Valve Seat Recession
IH 240, unleaded fuel, run 2
cast iron valve seats



See text for description of duty cycle

Figure 7

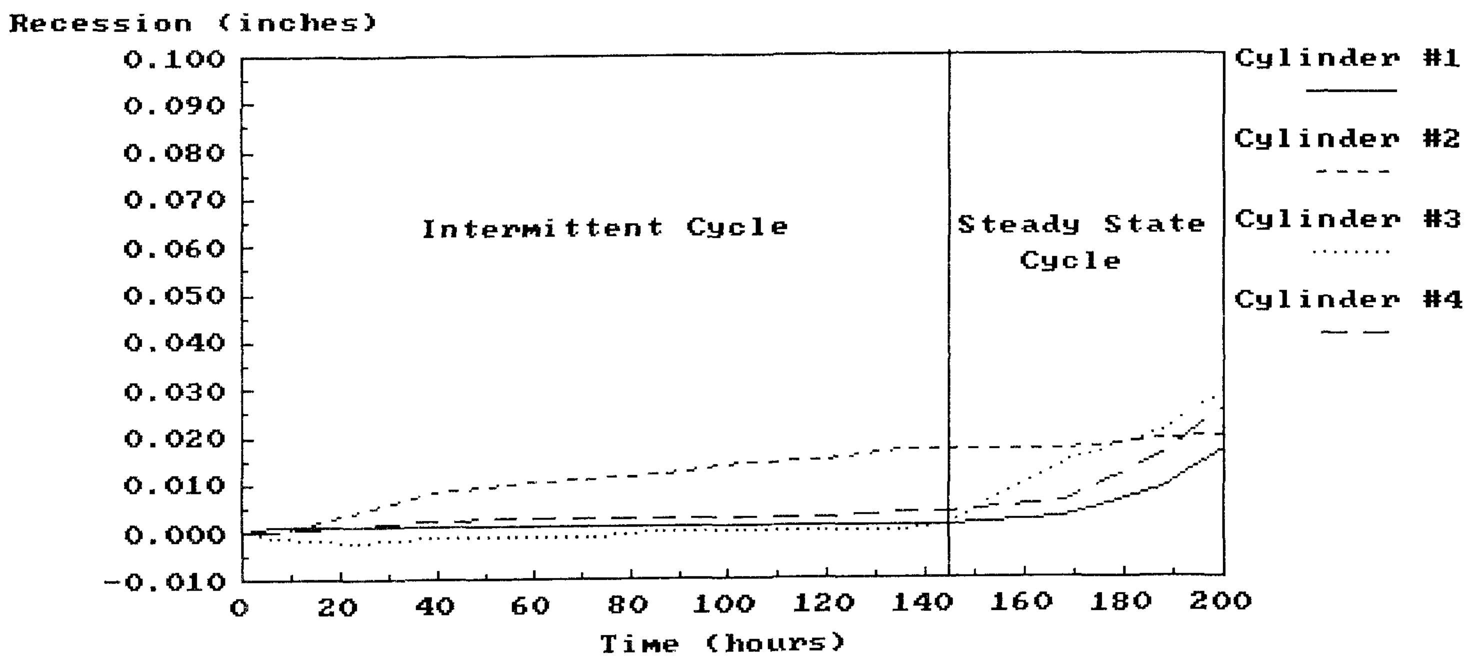
Exhaust Valve Seat Recession
IH 240, unleaded fuel, run 3
cast iron valve seat inserts



See text for description of duty cycle

Figure 8

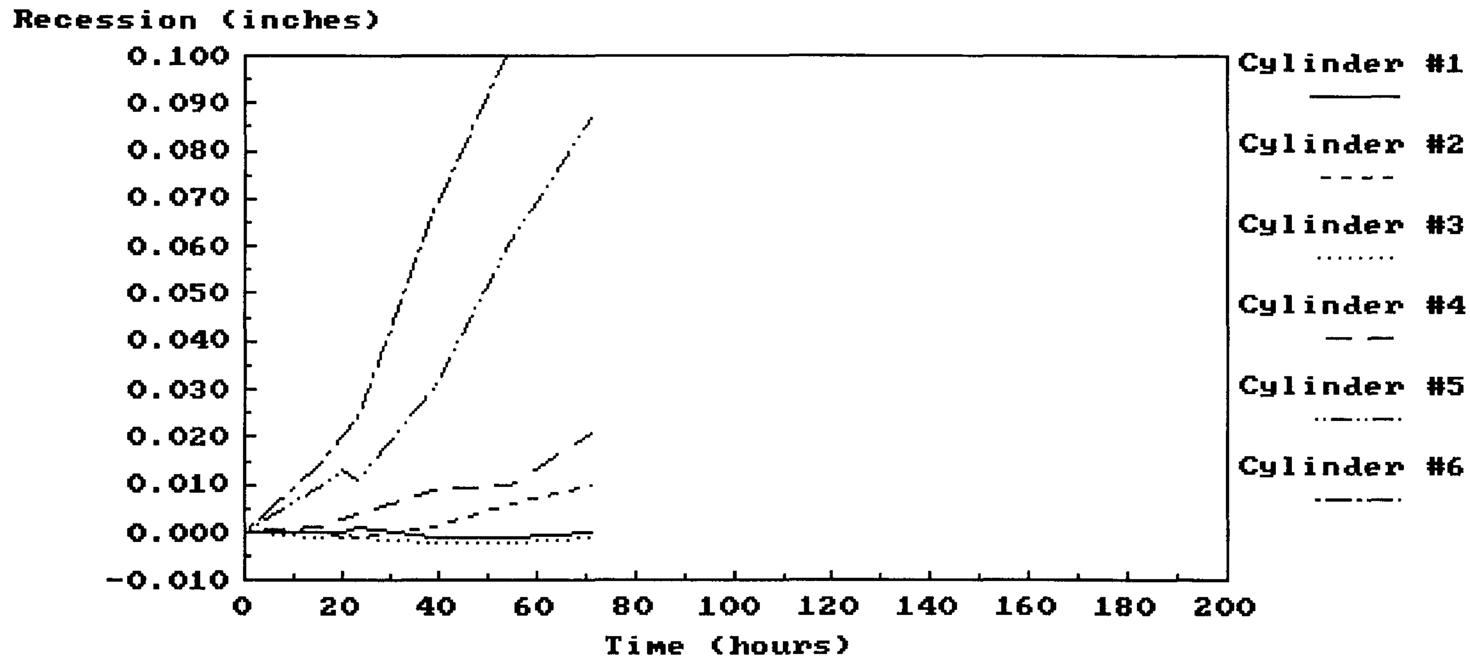
Exhaust Valve Seat Recession
Ford 8N, unleaded fuel
cast iron valve seat inserts



See text for description of duty cycle

Figure 9

Exhaust Valve Seat Recession
GM 292-A, unleaded fuel
cast iron valve seats

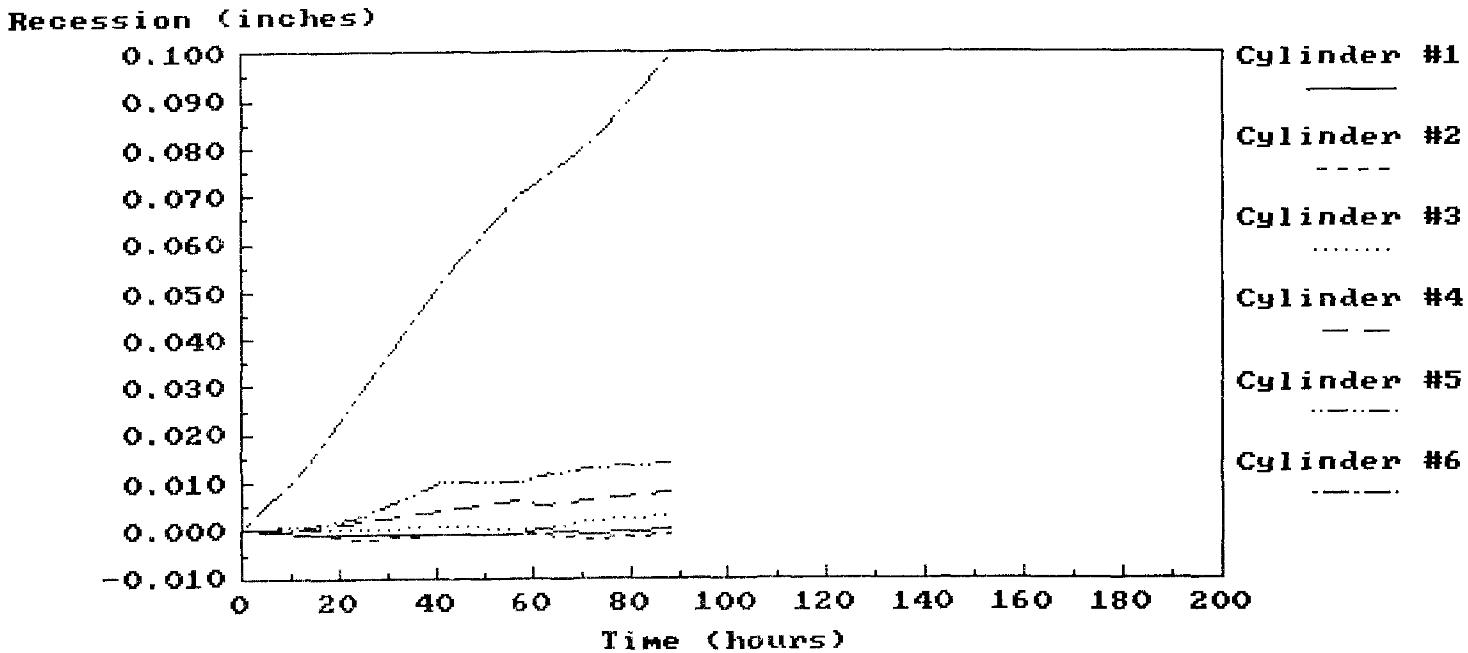


Test terminated at 71 hours due to excessive recession.
Total recession on cylinder # 6 is 0.131 inches.

See text for description of duty cycle

Figure 10

Exhaust Valve Seat Recession
GM 292-B, unleaded fuel
cast iron valve seats
lighter duty cycle

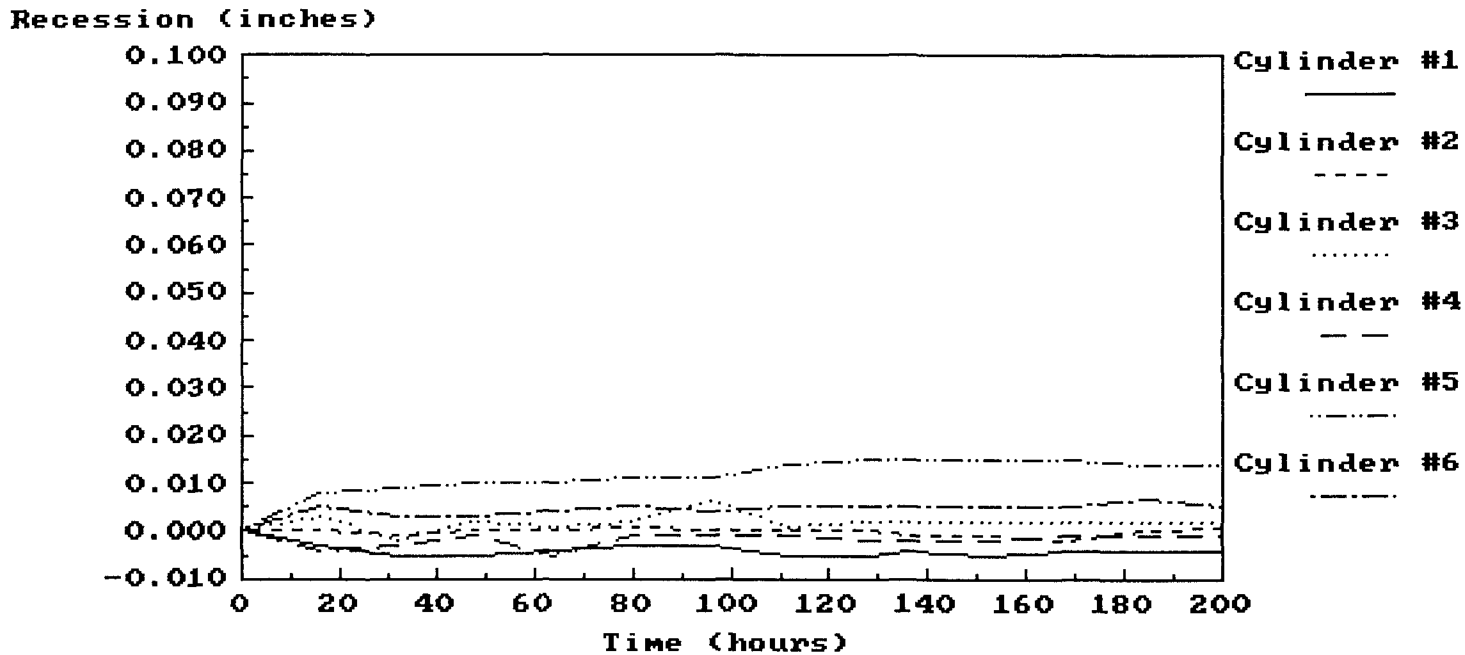


Duty cycle changed to eliminate the 3600 rpm portion of the cycle. Test terminated at 88 hours due to excessive recession. Maximum recession, 0.099 inches.

See text for description of duty cycle

Figure 11

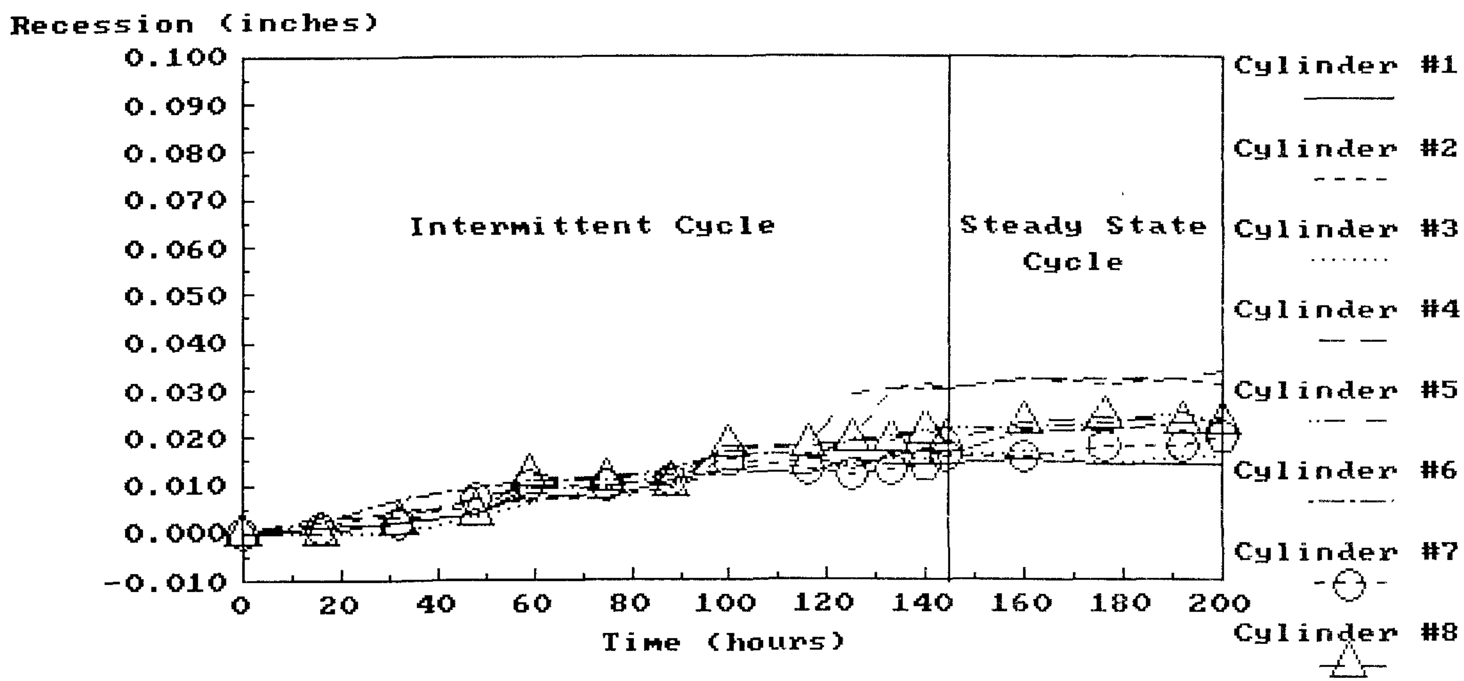
Exhaust Valve Seat Recession
GM 292-B, unleaded fuel
induction-hardened cast iron valve seats



See text for description of duty cycle

Figure 12

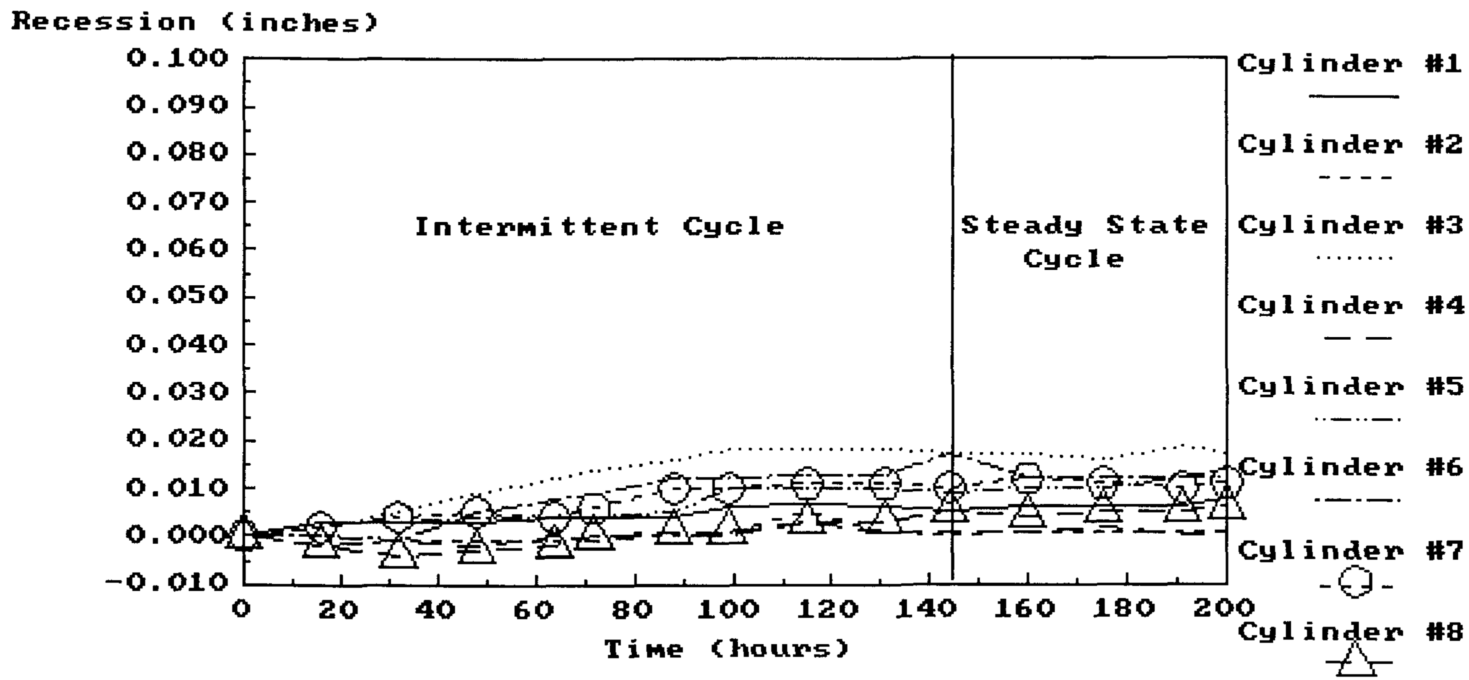
Exhaust Valve Seat Recession
GM 454, unleaded fuel
induction-hardened cast iron valve seats



See text for description of duty cycle

Figure 13

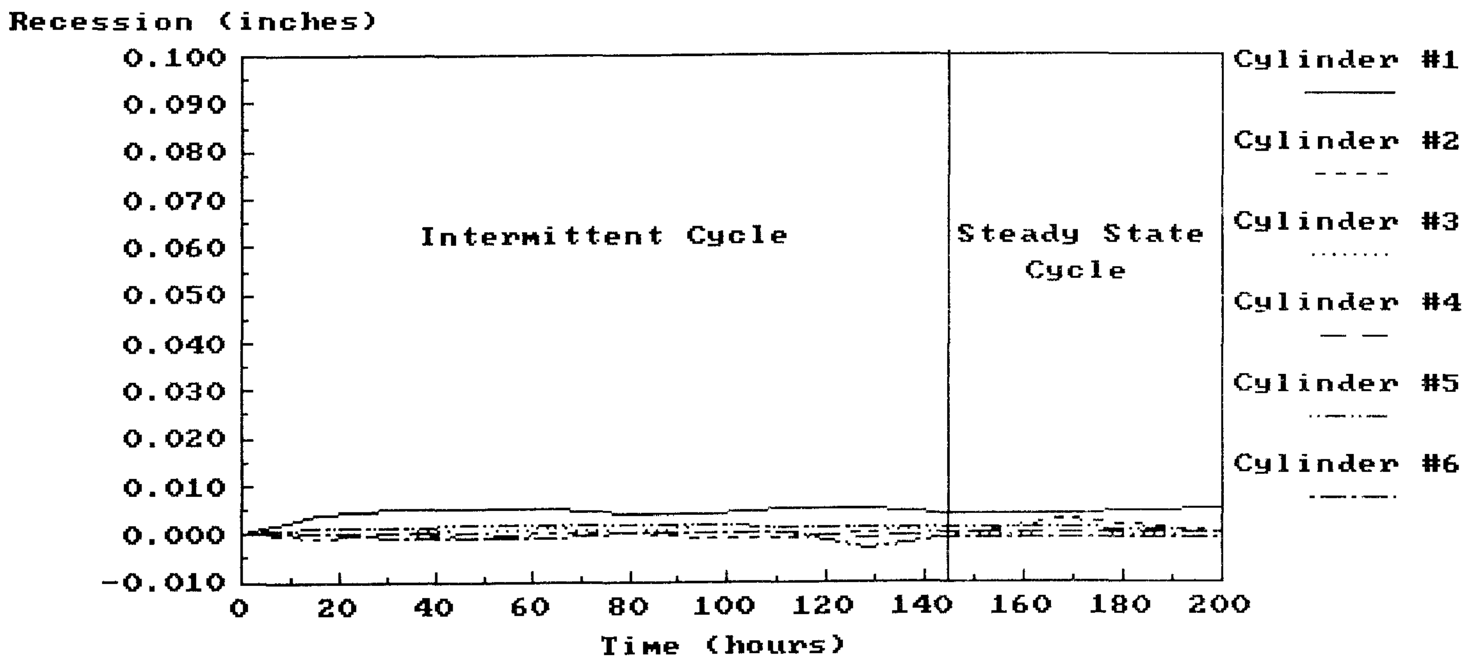
Exhaust Valve Seat Recession
GM 454, unleaded fuel
steel valve seat inserts



See text for description of duty cycle

Figure 14

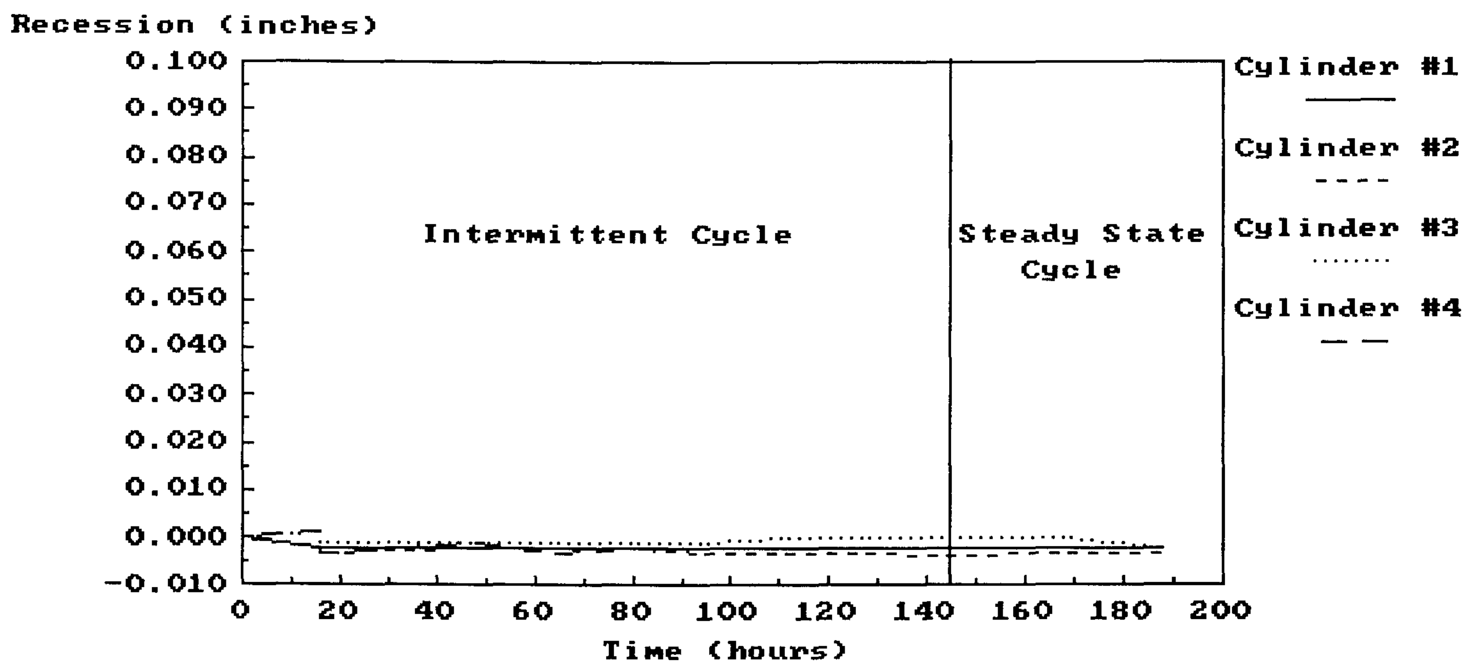
Exhaust Valve Seat Recession
John Deere 303 CID, 0.10 gplg
cast iron valve seats



See text for description of duty cycle

Figure 15

Exhaust Valve Seat Recession
IH 240, 0.10 gplg
cast iron valve seats

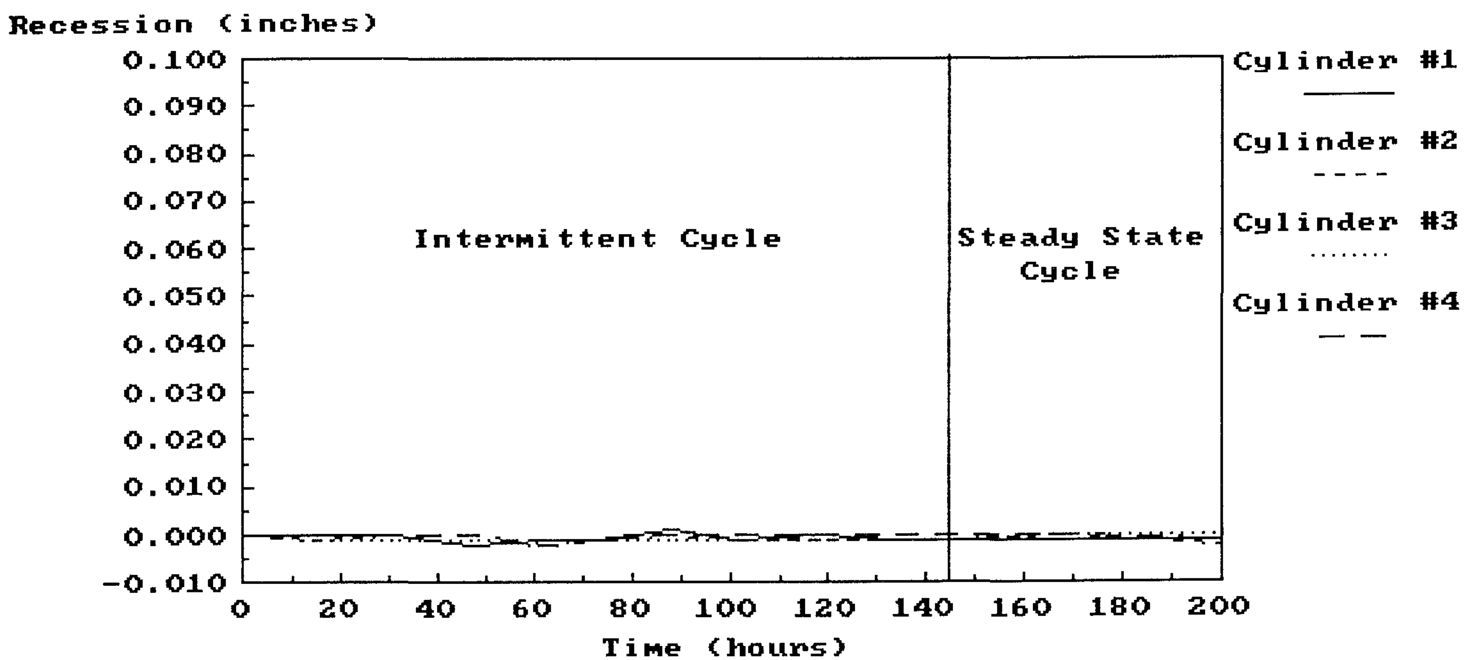


Test terminated at 188 hours due to broken crankshaft

See text for description of duty cycle

Figure 16

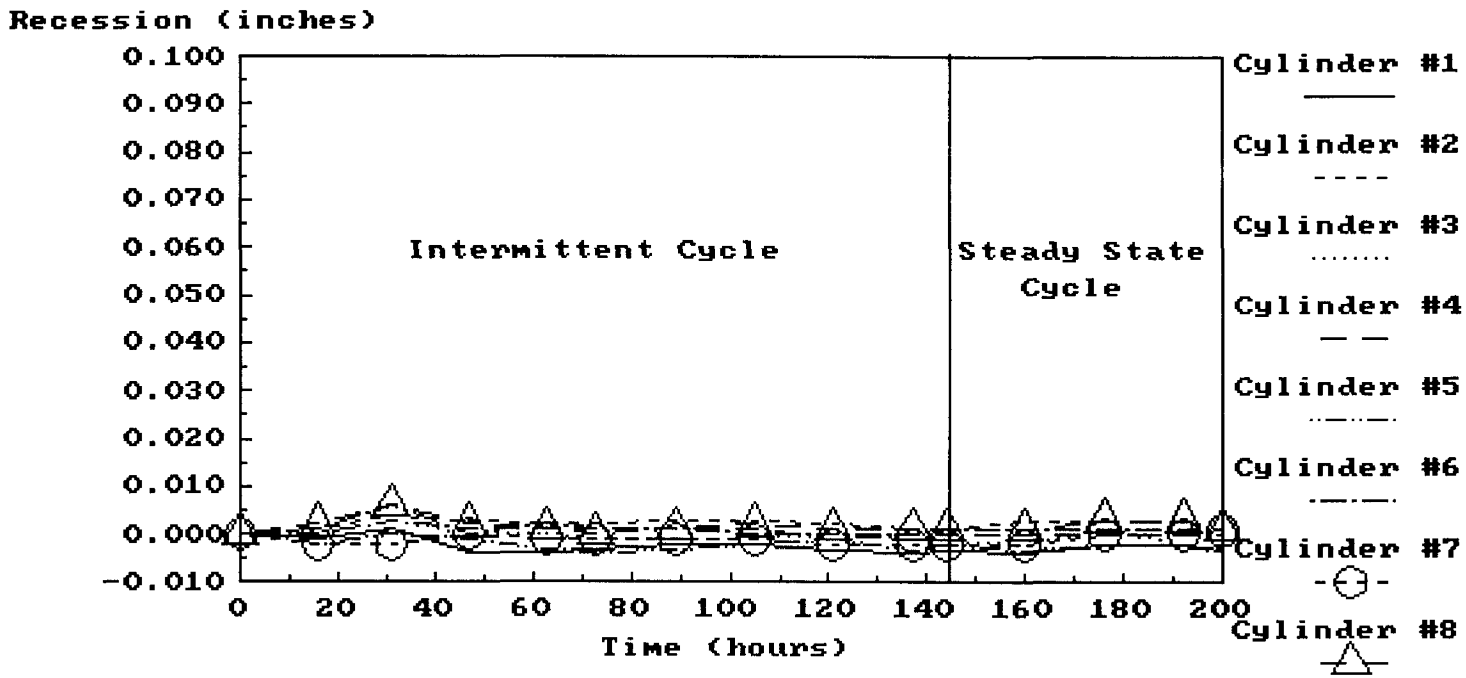
Exhaust Valve Seat Recession
IH 240, 0.10 gplg
cast iron valve seat inserts



See text for description of duty cycle

Figure 17

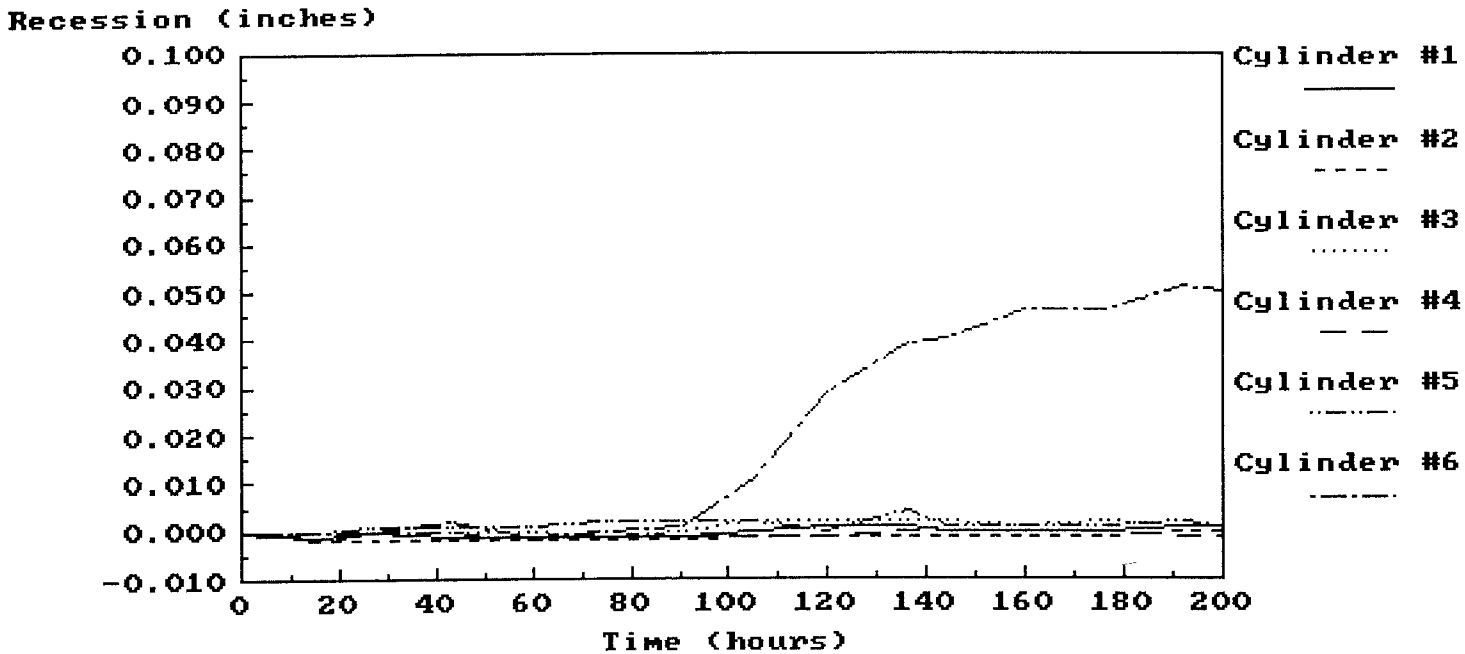
Exhaust Valve Seat Recession
GM 454, 0.10 gplg
induction-hardened cast iron valve seats



See text for description of duty cycle

Figure 18

Exhaust Valve Seat Recession
GM 292-A, 0.10 gplg, run 1
cast iron valve seats

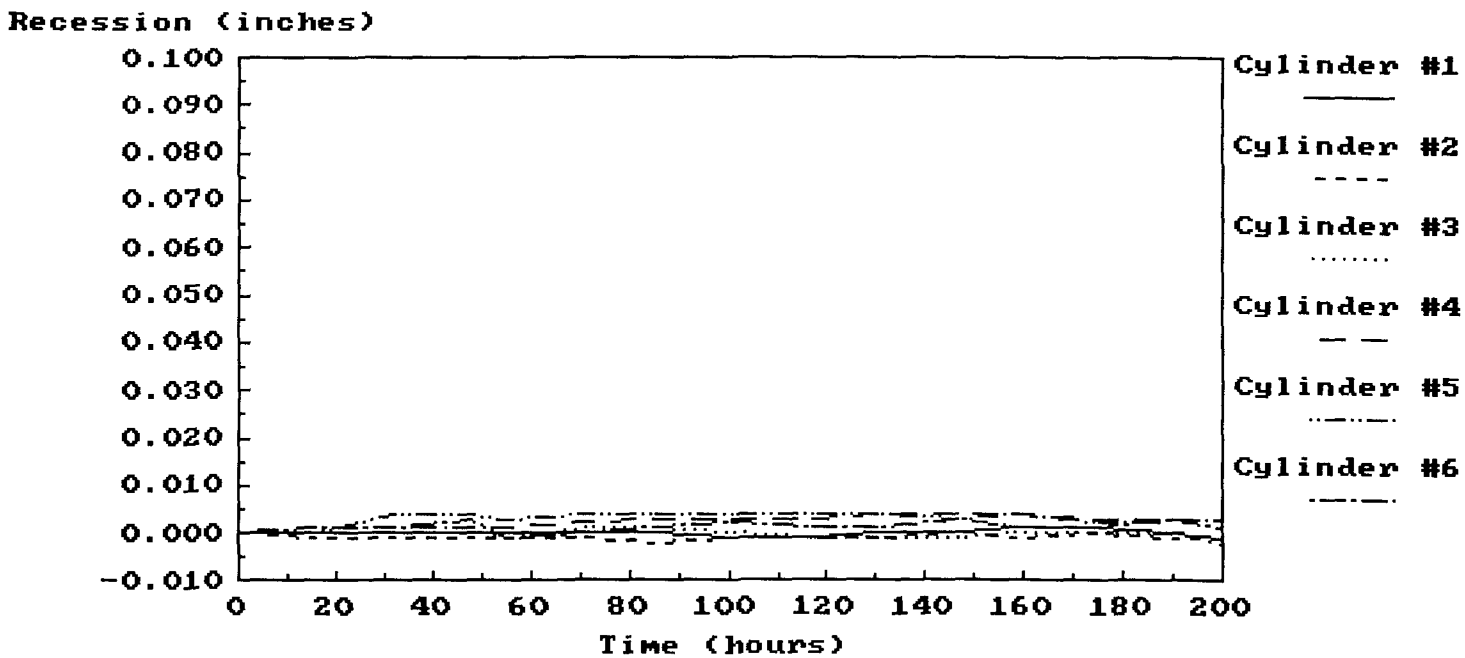


Cylinder head gasket replaced at 120 hours

See text for description of duty cycle

Figure 19

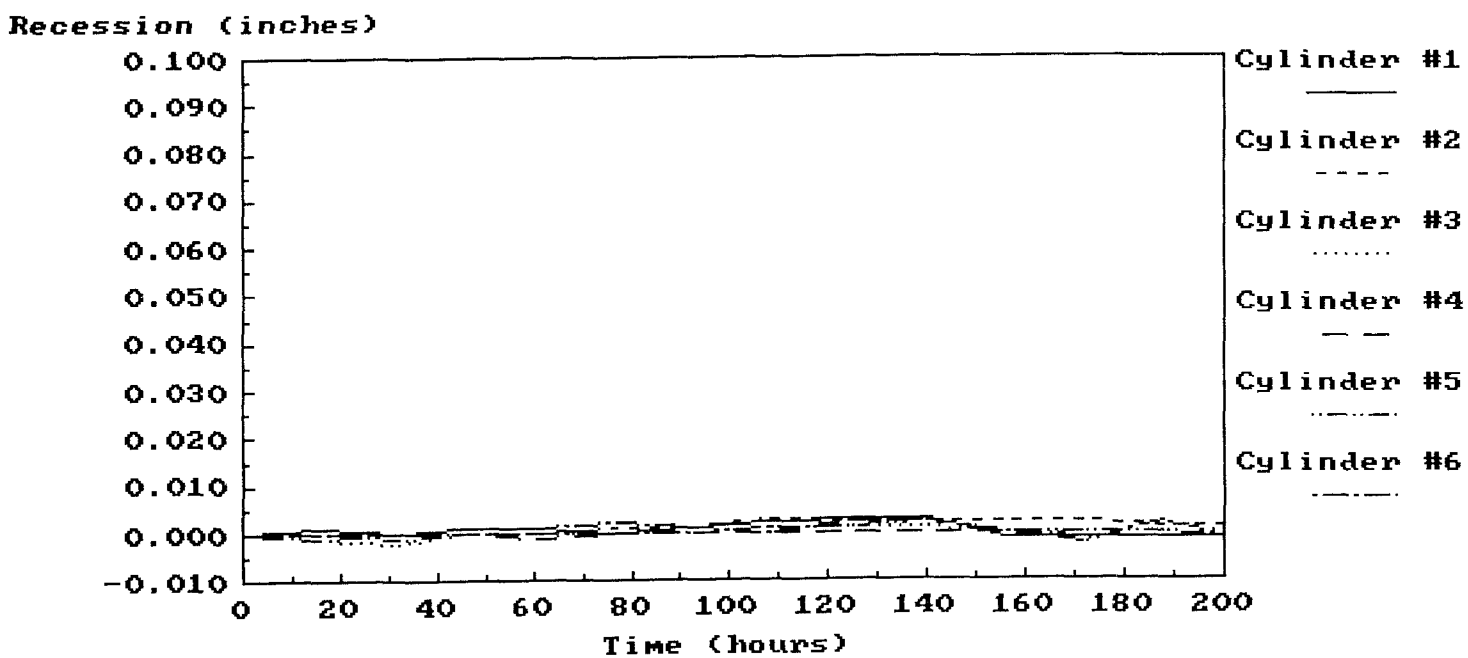
Exhaust Valve Seat Recession
GM 292-A, 0.10 gplg, run 2
cast iron valve seats



See text for description of duty cycle

Figure 20

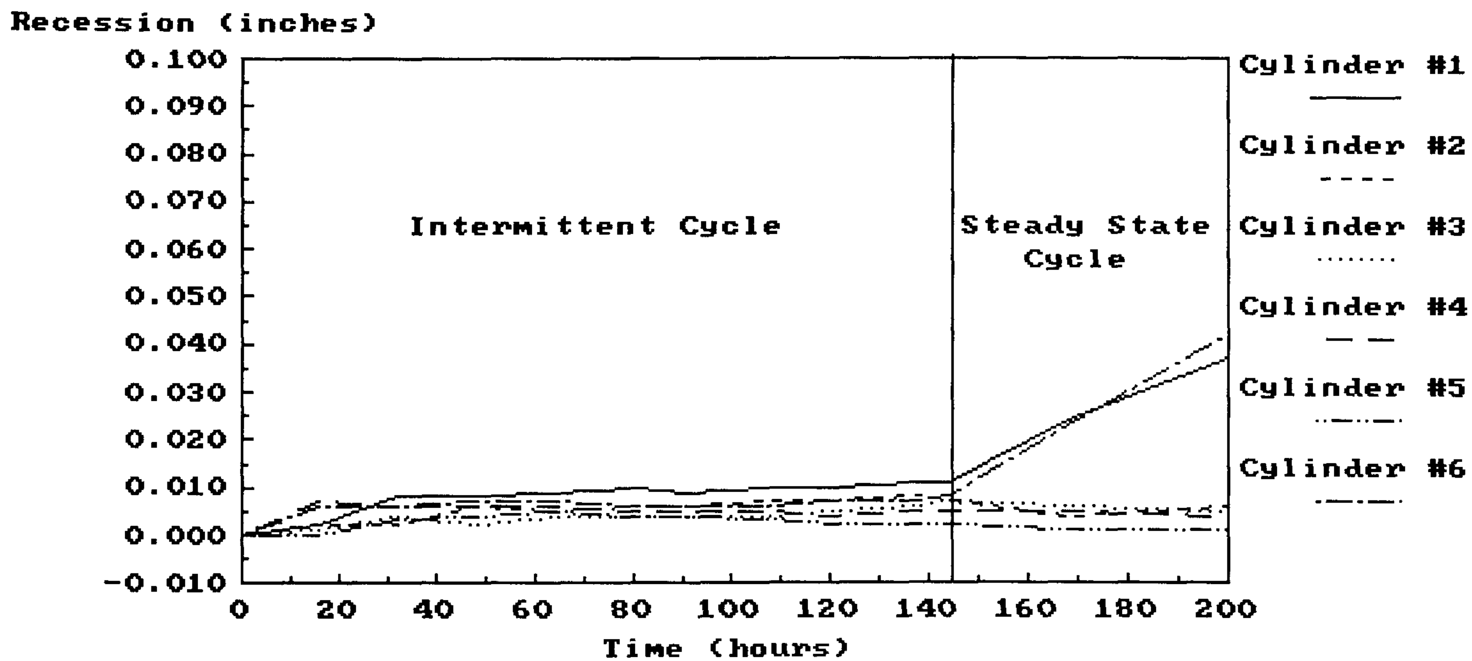
Exhaust Valve Seat Recession
GM 292-B, 0.10 gplg
cast iron valve seats



See text for description of duty cycle

Figure 21

Exhaust Valve Seat Recession
John Deere 303 CID, Lubrizol "PowerShield"
cast iron valve seats

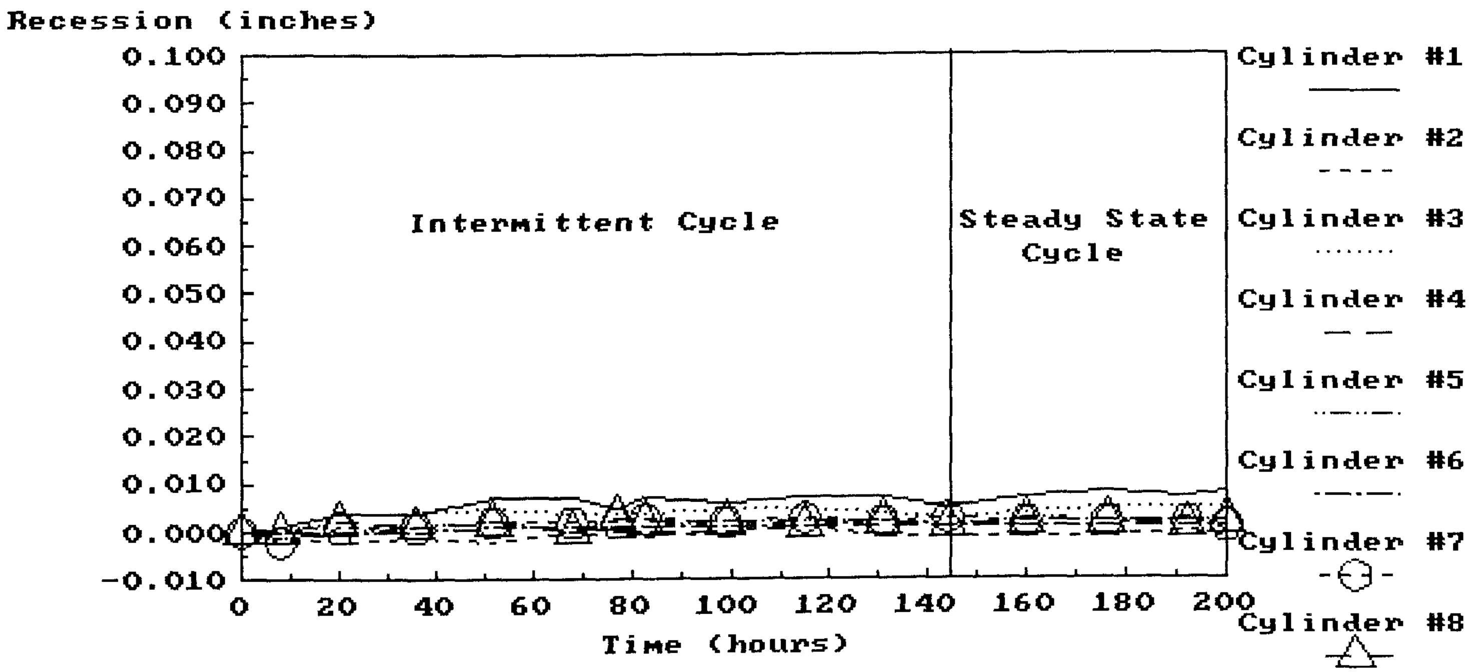


"PowerShield" additive used at 250 pounds per 1,000 barrels of gasoline

See text for description of duty cycle

Figure 22

Exhaust Valve Seat Recession
GM 454, Lubrizol "PowerShield"
induction-hardened cast iron valve seats

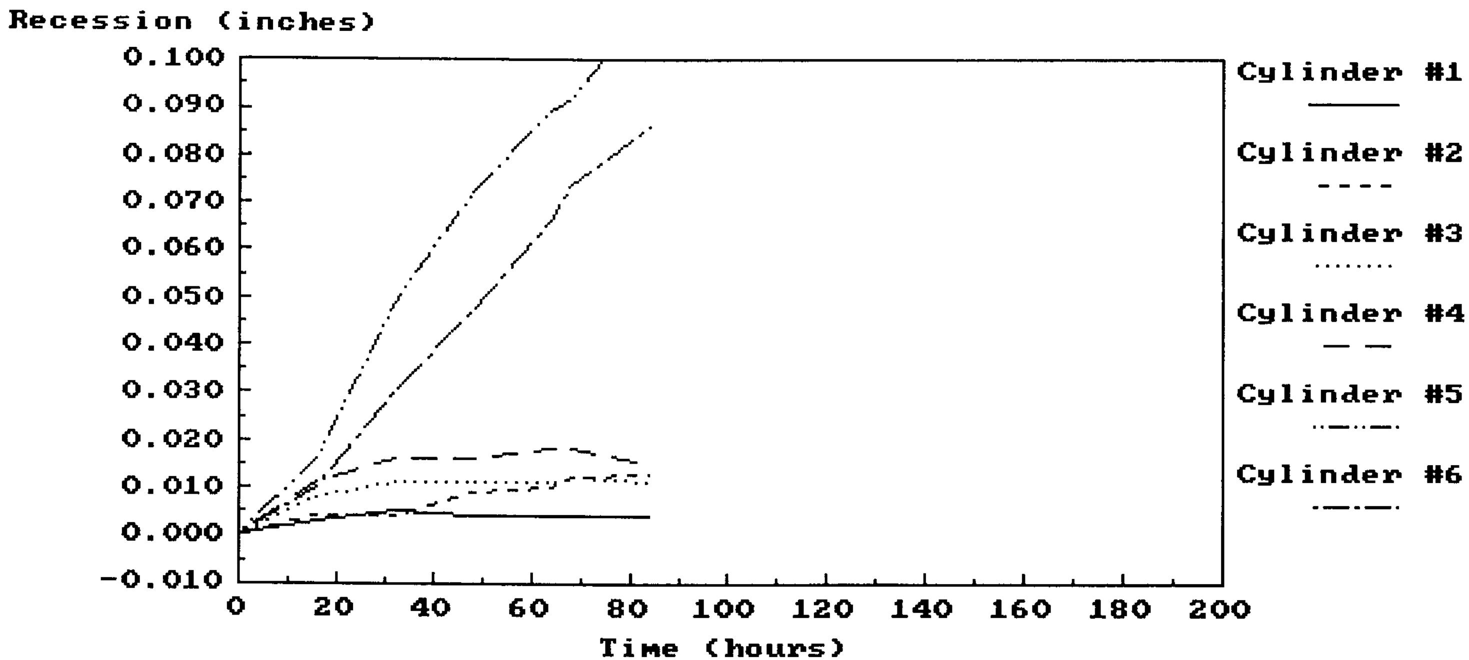


"PowerShield" additive used at 250 pounds per 1,000 barrels of gasoline

See text for description of duty cycle

Figure 23

Exhaust Valve Seat Recession
GM 292-A, Lubrizol "PowerShield"
cast iron valve seats



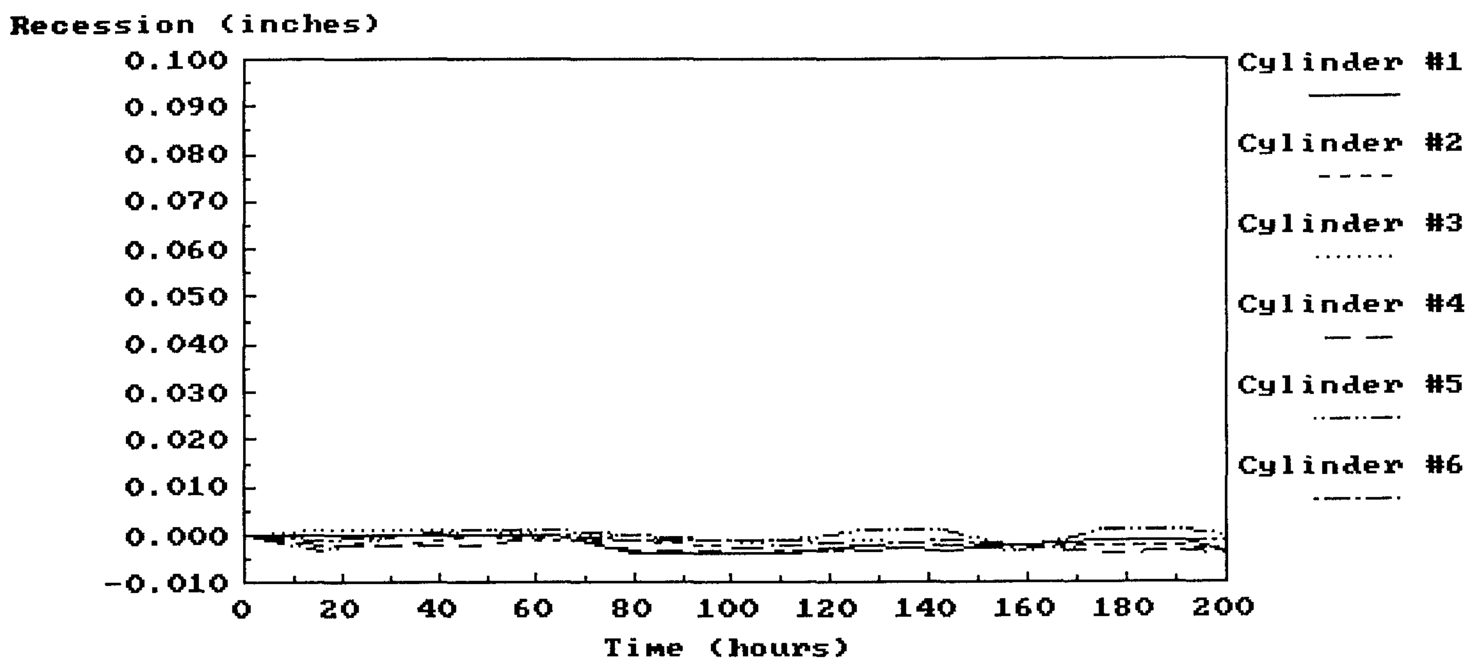
"PowerShield" additive used at 250 pounds per 1,000 barrels of gasoline

Test terminated at 84 hours due to excessive recession.
Maximum recession, 0.112 inches.

See text for description of duty cycle

Figure 24

Exhaust Valve Seat Recession
GM 292-B, Lubrizol Concentrated "PowerShield"
cast iron valve seats

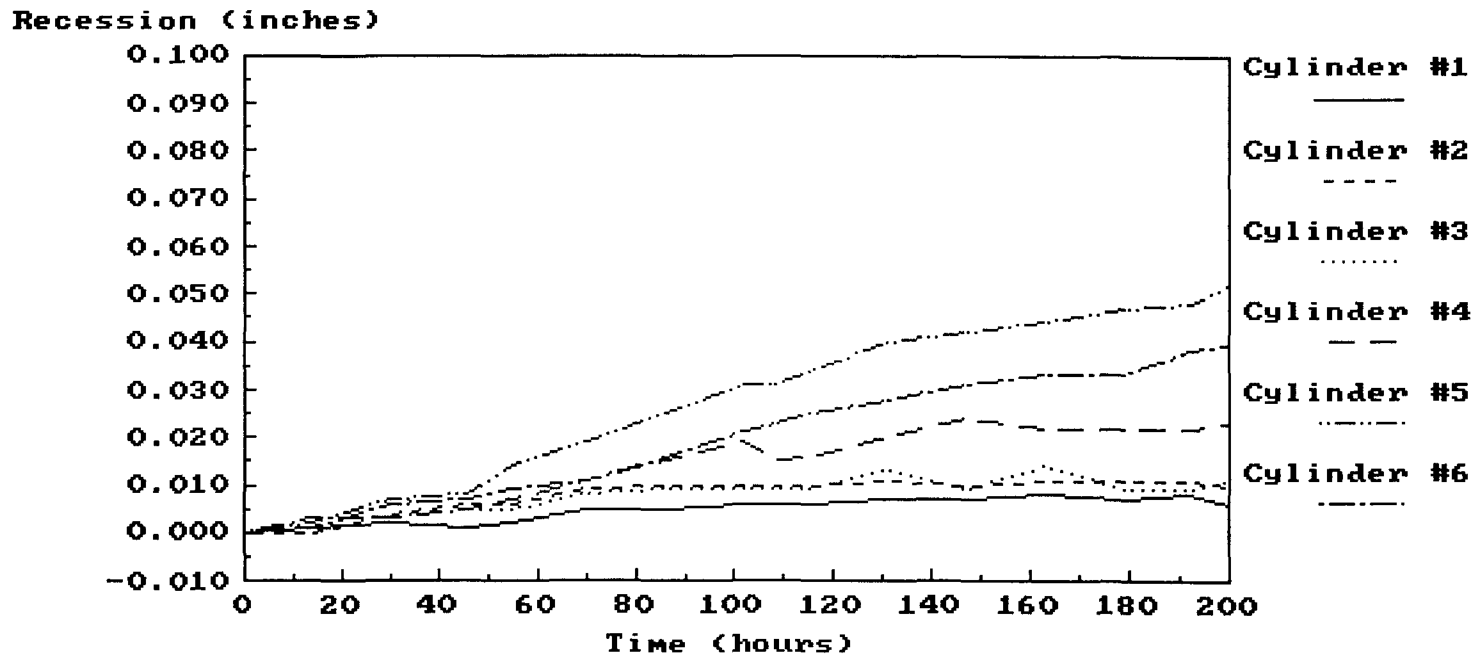


"PowerShield" additive used at 1,000 pounds per 1,000 barrels of gasoline

See text for description of duty cycle

Figure 25

Exhaust Valve Seat Recession
GM 292-A, DuPont Additive
cast iron valve seats



DuPont additive used at 200 pounds per 1,000 barrels of gasoline

See text for description of duty cycle

Appendix 2

Consultants Evaluations of Engine Testing Performed by NIPER

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Energy, Fuels and Engine Consulting Services

March 2, 1987

Mr. Richard G. Kozlowski
Director, Field Operations and Support Division
EN-397F
U. S. Environmental Protection Agency
Washington, DC 20460

Dear Mr. Kozlowski:

The purpose of this letter is to provide comments on the testing program involving agricultural engines that was conducted by the National Institute for Petroleum and Energy Research (NIPER) at Bartlesville, Oklahoma. The final report resulting from that study is entitled "Effect of Low Levels of Lead and Alternative Additives to Lead on Engines Designed to Operate on Leaded Gasoline". In order to put my comments into perspective, some background information on the overall study will be given.

Background

During the latter part of Calendar Year 1985, a proposed test plan was developed by the Environmental Protection Agency (EPA) in cooperation with the U. S. Department of Agriculture (USDA). That test plan was reviewed and commented on in December 1985 by representatives from various engine manufacturers, universities, government agencies, organizations representing the farmers and other interested parties. An EPA/USDA meeting was held in January 1986 with members of the various reviewing groups to discuss the development of the testing program. The contractor was under contract to do the work by early summer of 1986 and actual engine testing was begun in June 1986. The draft final report was delivered to EPA for review in January 1987.

Because of a variety of different equipment configurations ranging from two to eight cylinder engines, laboratory modifications were necessary to accommodate the various engines. Some engines required pressurized cooling systems, while others operated at atmospheric pressure. Some older engines used in the study had carburetor systems that were inherent y poor in their ability to control air-fuel ratios. Procedures for determining valve seat hardness and recession during the accumulations had to be developed by the contractor.

Several factors unrelated to the fuels being tested, resulted in setbacks of the experimental schedule. They included: failures of dynamometer equipment; mechanical failures of engines; and an unusual amount of rainfall in the vicinity of the contractor site which flooded the laboratory.

Performance of Contractor

The contractor has done an excellent job in conducting the testing program and executing the various tasks on a reasonable time schedule, considering the short lead time for setting up the experiments and the many setbacks that were beyond the contractor's control. The quality of the data is as good as could be expected, considering the limitations on the budget and the number of engines available for testing. The methods developed for determining valve seat hardness and recession during the accumulation of hours were adequate for the purposes of the study. The valve seat recession measurements taken during the accumulation of hours were backed-up by bench inspections of the cylinder heads. The bench measurements were made before the start of the accumulation of hours on the engines and after the completion of each test by an independent certified automotive mechanic. This was an excellent method for confirming the accuracy of valve seat recession measurements because the two separate measurements were made totally independent from each other.

The testing program was well conceived with a representative cross section of engine types being incorporated into the testing. The chosen engine duty cycles were good in that they served to show valve seat recession as a function of fuel type for some engines, while other engines showed no valve seat recession with any of the fuels. In general, the contractor performed well in executing the experimental testing in a timely fashion and produced a technical report that provides useful data on the effect of gasoline lead levels and alternative additives to lead on valve seat recession in engines that were originally designed for leaded gasoline. However, at no fault of the contractor, EPA or USDA (because of budget constraints), it would have been helpful to have had more engines in the testing program. This aspect will be discussed further in the following section.

Adequacy of the Test Data

The data from the program are adequate for the purposes of the study with the exception of two areas. One area relates to the question of whether or not lead at 0.10 gram per gallon in gasoline is adequate to prevent valve seat recession in all of the engines tested. The Ford 8N engine was not tested on 0.10 gram per gallon leaded gasoline, therefore, no data are available to determine if 0.10 gram per gallon leaded gasoline would prevent valve seat recession in this engine. The GM 292 engine showed significant valve seat recession in one cylinder with 0.10 gram per gallon leaded gasoline. Because a head gasket failure occurred mid-way through the accumulation of hours on this first test, the engine was rebuilt and retested and 10 thousands of an inch recession was noted for one valve seat. A duplicate GM 292 engine was tested later in the program with no observed valve seat recession. Although a head gasket failure occurred in the first test, the engine was repaired at 120 hours and the test was continued to 200 hours. Valve seat recession continued after the head gasket replacement at 120 hours. Although the rate of valve seat recession was lower after the head gasket replacement than that just prior to the head gasket failure, there appears to be no basis for throwing out this test result. The overall results from the GM 292 engine tests for 0.10 gram per gallon leaded gasoline are mixed. Further engine testing is required to determine whether or not 0.10 gram per gallon leaded gasoline will provide adequate protection against valve seat recession in the GM 292 engine.

The second area which needs further study is alternative additives. One additive (additive "D") tested in the current program showed good results when blended at a concentration of 1,000 pounds of additive to 1,000 barrels of gasoline. However, the lubricating oil wear metals analyses for the additive "D" test showed increased concentrations of iron, chrome, sodium and molybdenum when compared to other fuel tests with the same GM 292 engine. These results indicate the need for longer term engine durability testing with the additive to determine any adverse effects on the engine such as deposit formation in the engine or increased wear. Since the additive contains sodium and possibly other metallic elements, an assessment should be made to determine if the use of the additive might result in potential degradation of air quality.

Recommendations for Future Work

Should additional engine testing be considered in the future, I suggest that additional studies be done on alternative additives as a method for preventing valve seat recession. In addition to identifying additives that successfully prevent valve seat recession, once an additive has been shown to be effective, further work would be needed to determine any detrimental effects the additives might have on the engine.

If further testing is done, I recommend that a larger number of engines be tested to account for engine-to-engine, test-to-test, and day-to-day variability. In addition, changes in uncontrolled engine variables such as air-fuel ratio may influence valve seat recession. The experimental tests just completed indicate that a larger number of engines is required to give conclusive results.

An example illustrating the need for a larger number of engines is the International Harvester 240 engine used in the current study. The first test with unleaded gasoline showed no valve seat recession. A repeat test with a slightly softer cylinder head showed exhaust valve seat recession in two cylinders. At this point, one might conclude that the softer cylinder head was responsible for the valve seat recession in the repeat test. However, subsequent inspections to determine the hardness of the cylinder head material near the individual valve seats indicated that the observed valve seat recession in the repeat test probably was not due to differences in hardness between the two cylinder heads. It was also noted that the engine's air-fuel ratio (uncontrolled variable) was significantly leaner for the repeat test which could have contributed to increased valve recession. A third test was run on this engine using unleaded gasoline with cast iron valve seat inserts which resulted in exhaust valve seat recession in all of the cylinders. In the third test, the average daily air-fuel ratio was similar to the first test. The variation in test results for a given system suggests the need for replicate testing for each engine/fuel combination in the testing program.

It is recognized that it is impractical to run every engine type in the overall population. However, once a given set of engines is selected for testing, replicate testing of each engine setup and fuel is highly desirable. In many cases, it is impractical to run enough engines and tests to provide statistically significant results. However, a compromise situation may be appropriate for providing a basis for good engineering judgments. For a test program such as the one just completed, three tests is the minimum number of replicates which would give reasonable confidence in the data. This could be done in two different ways. One way would be to repeat the same test three times on the same engine. The second way would be to run three identical engines simultaneously. Should further testing be considered in the future, I strongly recommend that replicate testing be done to increase confidence in the resulting data.

One way to reduce test—to—test and day—to—day variability, and possibly reduce the number of engine tests required to provide conclusive results, is to control air—fuel ratio. First, one would have to determine the normal operating air—fuel ratio for each operating mode and the variation of air—fuel ratio within each mode for each given engine. Then the air—fuel ratio would be controlled (by means of a special laboratory apparatus) at its "average" value throughout the accumulation of hours on each test. The air—fuel ratio would be controlled at a different value for each operating mode corresponding to the normal air—fuel ratio characteristics of the engine.

Since most of the engines tested showed a problem with valve seat recession on unleaded fuel, an assessment should be made to compare the relative cost and practicality of retrofitting cylinder heads with hardened valve seats to using alternative additives or using 0.10 gram per gallon gasoline. This assessment should take into account the total number of engines in the field, the number of engines that have potential for a valve seat recession problem, etc.

Summary

In summary, the contractor has done an excellent job in conducting the experimental work and completing the project in a reasonable time frame. The data from this program are of significant value and should be published in a form such that anyone in the public domain can obtain a copy of the report. In addition, the contractor should be encouraged to publish the results of the study in an engineering society technical paper. Should any future testing be contemplated, I recommend that additional work be done on alternative additives to lead. An assessment should be done to determine the cost and practicality of retrofitting cylinder heads with hardened valve seats. Also, replicate engine tests should be considered to better account for test—to—test variability.

Should there be any questions about these comments, please do not hesitate to give me a call.

Sincerely,

Ralph D. Fleming

Ralph D. Fleming
Consultant

cc:
Jerry Allsup, NIPER
John Garbak, EPA
Gerald Grinnell, USDA

REPORT

Assessment of the testing program conducted by NIPER on selected gasoline engines.

Louis I. Leviticus
Nebraska Tractor Testing Laboratory.

March 25, 1987.

1. I want to compliment NIPER, and in particular Mr. Allsup and his staff, for a job well done under severe time constraints. The work was carried out with competence and integrity. The only criticism I have is the fact that the oil analysis was not carried out exactly as in the original plan of work.

2. One of the great limitations of this project has been the fact that not enough engines of each type could be evaluated. It is quite clear from the hardness measurements that considerable variation exists between heads. This variation may be the result of manufacturing processes or may be due to different sources for the heads or inserts used. Hence, tests of the statistical significance cannot be applied in this study.

3. Although the results obtained may be debatable from a statistical significance viewpoint, they nevertheless provide a good insight into the problems encountered when operating an engine, designed for leaded fuel use, on unleaded fuel and with additives.

4. In general, the results tend to show that the combustion chamber temperature may be a major contributor to the phenomenon of recession of valve seats below a certain critical hardness value. Higher combustion chamber temperatures can occur due to a variety of reasons:

a. High loads.
b. Inadequate cooling (dirty radiator, slipping belts, blocked passageways in the engine etc.).
c. Lean fuel mixtures (High A/F ratio).
d. Ignition problems (Timing, Fouled spark plugs).
e. Carbon or other deposits in the combustion chamber.

5. It cannot be determined with certainty from the data what the critical seat hardness is. This would seem to depend upon the engine characteristics and, possibly, on the way the engine is used and maintained.

6. Engine speed may not be a factor by itself~~, but,~~ coupled with a high load and/or a lean mixture an increase in engine speed may lead to earlier recession. This is a judgement call. The study was designed to simulate the operation of engines under normal conditions. It accomplishes that purpose. However, several questions remain unanswered concerning what exactly causes recession.

7. The results tend to show that at 0.1 gplg none of the engines suffered from excess recession. A definite conclusion cannot be reached however since one of the engines did show excessive recession after head gasket failure. Since the test did not examine the harshest possible operating conditions, one cannot conclude that 0.1 gplg will protect all engines under all operating conditions.

8. The data from the additive tests, limited as they were, do not warrant their recommendation, at this stage, as a replacement for lead. This conclusion is based on the following reasons:

a. It appears that there is, as yet, uncertainty about the correct cocentration of some of the additives. I may point out that it is possible that different engines might require different concentrations of an additive.

b. The recommended concentrations, for the additives tested, showed that the engines were not completely protected against recession.

c. An examination of the effect of the additives on emissions was inconclusive.

d. The oil analysis showed that when additives were used, the Sodium content usually increased drastically. The sodium is apparently introduced to the oil through the additive. Since the formulation of the additives is proprietary the composition of the compound in which sodium occurs is not known.

e. The oil and exhaust gas analysis did not include checking for sulphur compounds. Sulphur in the exhaust gases can cause damage to the engine and exhaust parts since they are mixed with Hydrocarbons and water vapor and may form acids; the sulphur compounds in the oil can cause damage in certain engines since they attack certain metal compounds. It is very difficult to determine which engines would be affected, since this depends upon:

.. Engine combustion characteristics, which can vary with engine design and operating conditions.

.. Different oils contain different additives which may react differently with sulphur compounds.

.. Metal alloys used in the engine. There are examples of manufacturers warning the users against certain oils, containing a molybdenum compound, which releases a sulphur compound in the oil. This compound then combines with water to create an acid, which attacks certain alloys used.

f. The nature of the deposits found and their long-term influence on the engine were not determined.

g. The only fuel additive combination, which did not cause recession was tested on one engine only.

9. Recommendations for future testing.

The additives should be tested and evaluated further in order to:

a. Determine the correct concentration(s) to be used.

b. Investigate whether the concentrations should differ for different engine makes.

c. Determine the composition of the exhaust gases and their influence, if any, on the various engine components.

d. Determine the influence on the composition of engine oils and the influence of the compounds on the oil quality and on alloys used in various engines.

Louis I. Leviticus
Nebraska Tractor Testing Lab

Appendix 3

Duty Cycles Used in Engine Tests

Duty cycles were developed to represent conditions normally encountered by farm tractors, combines and large trucks, and by recreational vehicles. Each engine was operated on its specified duty cycle until 200 hours were accumulated on each test fuel.

Tractors and Combines

The duty cycle for tractor and combine engines consisted of two parts--an intermittent portion covering 144 hours of operation and a steady-state portion covering 56 hours. The intermittent part is consistent with the duty cycle (SAE J708) used for many years by the Nebraska Tractor Testing Laboratory to test the performance of new tractors. The steady-state part was selected to represent the maximum continuous load that is likely to be placed on these engines, such as pumping irrigation water.

Intermittent Part--Each engine was run through six power settings with the engine speed controlled by the governor per manufacturers' specifications as follows until 144 hours were accumulated (16 hours on 8 hours off per day):

a. 85% of dynamometer torque obtained at maximum power--40 minutes

b. Zero dynamometer torque at rated rpm--40 minutes

c. 42.5% of dynamometer torque obtained at maximum power--40 minutes

d. Dynamometer torque at maximum power--40 minutes

e. 21.25% of dynamometer torque obtained at maximum power--40 minutes

f. 63.75% of dynamometer torque obtained at maximum power--40 minutes

Steady-State Part--Each engine was run at governed speed and 75 percent of maximum torque around the clock until 56 hours were accumulated. After 24 hours, the engines were shut off for 2 hours for valve seat recession measurements and service checks.

Farm Trucks

The engines were to be operated 16 hours on and 8 hours off per day on the following duty cycle until 200 hours were accumulated for each fuel.

a. 85% of maximum power (available at 3,000 rpm) at 3,000 rpm--40 minutes

b. 45% of maximum power (available at 3,000 rpm) at 3,000 rpm--40 minutes

c. 45% of maximum power (available at 2,500 rpm) at 2,500 rpm--40 minutes

d. 25% of maximum power (available at 2,000 rpm) at 2,000 rpm--40 minutes

e. 85% of maximum power (available at 3,600 rpm) at 3,600 rpm--40 minutes

Recreational Vehicles

The recreational vehicle test called for the engine to be on 16 hours and off 8 hours per day until 200 hours were accumulated for each fuel. The engine was operated in both intermittent and steady-state modes.

Intermittent Part--The engine was operated in six speed and power settings as follows until 144 hours were accumulated:

a. 85% of maximum power (available at 3,000 rpm) at 3,000 rpm--40 minutes

b. 45% of maximum power (available at 2,000 rpm) at 2,000 rpm--40 minutes

c. 85% of maximum power (available at 3,600 rpm) at 3,600 rpm--40 minutes

d. 45% of maximum power (available at 2,500 rpm) at 2,500 rpm--40 minutes

e. 45% of maximum power (available at 3,000 rpm) at 3,000 rpm--40 minutes

f. 85% of maximum power (available at 2,500 rpm) at 2,500 rpm--40 minutes

Steady-State Part--During the steady-state part of the cycle, the engine was run at a setting that produced 100 horsepower (52 percent of maximum power) at 3,000 rpm until 56 hours were accumulated.

Appendix 4

Engines Tested

1. John Deere "B" tractor; 2-cylinder I-head engine; rated at 24 horsepower at 1,250 revolutions per minute (rpm); 4 11/16" x 5 1/2" bore and stroke, 190.4 cubic inch displacement (CID). The engine was originally equipped with ordinary cast iron cylinder heads with a hardness of 9-25 on the Rockwell C scale. The tractor was manufactured between the 1930s and 1952. Similar tractors were manufactured until about 1960.
2. Farmall "H" tractor; 4 cylinder I-head engine; rated at 24 horsepower at 1,650 rpm; 3 3/8 x 4 1/4" bore and stroke. The engine was originally equipped with "special gray iron" valve seat inserts having a hardness of 26-36 on the Rockwell C scale. The tractor was manufactured between the 1930s and 1953. Similar tractors were built until about 1958.
3. For "8N" tractor; 4-cylinder L-head engine; rated at 23 horesepower at 2,000 rpm; 3 3/16" x 3 3/4" bore and stroke, 119.7 CID. The engine was originally equipped with valve seat inserts having a hardness of 39-43 on the Rockwell C scale. The tractor was manufactured between 1947 and 1952.
4. International Harvester 240 tractor; 4 cylinders; rated at 27 horsepower at 2,000 rpm; 3 1/8" x 4" bore and strokes, 122.7 CID. The engine was originally equipped with an ordinary cast iron cylinder head with a hardness of 12-23 on the Rockwell C scale. The tractor was manufactured

between 1958 and 1962. Similar tractors were built until 1978.

5. John Deere 95 303 CID 6-cylinder combine engine; rated at 80 horsepower at 2,500 rpm. The engine was originally equipped with ordinary cast iron cylinder heads with a hardness of 9-25 on the Rockwell C scale. The engine was manufactured between about 1960 and 1974. A 4-cylinder version of this engine also was used in combines and tractors, and a 3-cylinder version was used in tractors.
6. Pre-1974 Chevrolet 292 CID 6-cylinder truck engine; rated at 115 horsepower at 4,000 rpm. Prior to 1974, the engine was equipped with ordinary cast iron cylinder heads. The engine is still in production but now has induction-hardened cast iron exhaust valve seats. The engine also has been used in combines and other agricultural equipment.
7. Pre-1984 General Motors 454 CID 8-cylinder recreational vehicle engine; rated at 210 horsepower at 4,000 rpm. The engine has always been manufactured with induction-hardened exhaust valve seats.

Appendix 5

Farm Engine-Use Survey Form

Form Approved
O.M.B. Number 2060-0137
Expiration Date 1/31/87

Additional information about gasoline-powered farm equipment used on your operation is needed by the USDA's Office of Energy to develop fuel policies related to lead content in gasoline.

17a Did you use any **GASOLINE-POWERED** tractors, combines, or trucks *(larger than 1 ton capacity)* on your operation last year?

Office Use
700

[ ] **YES** [ ] **NO** - *Go to Item 18*

17b What **GASOLINE-POWERED** tractors, combines, and trucks did you use on this operation during 1985?
(DO NOT INCLUDE DIESEL POWERED EQUIPMENT.)

Gasoline Tractors Used 20 or More Hours During 1985, Beginning With the One Used Most / **Percentage of Time Used During 1985 2/**

Tractor	Manufacturer	Office Use	Year of Manufacture 1/	PTO Horsepower	Year Engine Last Overhauled	Total Hours Used in 1985	Pumping Irrigation Water %	Other Hard Uses %	Medium Uses %	Light Uses %	
# 1		701	702	703	704	705	706	707	708	709	100
# 2		710	711	712	713	714	715	716	717	718	100
# 3		719	720	721	722	723	724	725	726	727	100
Others					728 Number	729	730	731	732	733	100

Gasoline Combines and Cornpickers Used During 1985, Beginning With the One Used Most

Combine/ Cornpicker	Manufacturer	Office Use	Year of Manufacture 1/	Rated Horsepower	Year Engine Last Overhauled	Total Acres Harvested in 1985
# 1		734	735	736	737	738
# 2		739	740	741	742	743
Others					744 Number	745

Gasoline Trucks Larger than 1 Ton Capacity Used During 1985, Beginning With the One Used Most

Truck	Manufacturer	Office Use	Year of Manufacture 1/	Engine Size (cu. in.)	Year Engine Last Overhauled	Total Miles Driven in 1985	Rated Capacity (tons)
# 1		746	747	748	749	750	751 • — —
# 2		752	753	754	755	756	757 • — —
# 3		758	759	760	761	762	763 • — —
Others					764 Number	765	

1/ For rented, leased, or borrowed equipment, enter "98" for year of manufacture and report only manufacturer name, total hours and percent of time used, and acres harvested or miles driven in 1985

*2/ **Other Hard Use:** Plowing, Disking, and other high RPM, heavy engine loads*
***Medium Use:** Baling with PTO, chopping silage, rotary mowing, and other high RPM, moderate engine loads*
***Light Use:** Harrowing, planting, cultivating, raking, hauling, spreading manure, and other low to medium RPM, light engine loads*

18. Do you own any diesel-powered tractors?

Number
766

Appendix 6

How to Order Additional Documents Referred to in this Report

The following documents, referred to in this report, are available in EPA docket Number EN-87-03. Copies may be obtained by writing to Control Docket Section (LE-131A), Environmental Protection Agency Gallery 1, West Tower, 401 M Street, S.W., Washington, D.C. 20460. Telephone (202) 382-7548. The docket may be inspected between 8 a.m. and 4 p.m. on weekdays. As provided in 40 CFR Part 2, a reasonable fee may be charged for photocopying.

1. Effects of Low Levels of Lead and Alternative Additives to Lead on Engines Designed to Operate on Leaded Gasoline, Final Report. Report by the National Institute for Petroleum and Energy Research (NIPER) on results of engine tests performed for this study (193+ pages).
2. Statements of work covering work performed by NIPER.
   - A. Effects of Low Levels of Lead and Alternative Additives to Lead on Engines Designed to Operate on Leaded Gasoline. Covers tests of leaded and unleaded gasoline performed during fiscal year 1986 (10 pages).
   - B. Study of the Effects on Leaded Engines of Alternative Additives to Lead. Covers tests of non-lead additives performed during fiscal year 1987 (12 pages).
3. Quality Assurance Project Plan for Engine Testing Work Performed by NIPER (23 pages).

4. <u>Interviewers Manual for Gasoline-Powered Farm Equipment Survey.</u> Survey conducted by the National Agricultural Statistics Service, USDA during July 1986 (7 pages).
5. <u>Survey Protocol and Quality Assurance Plan for Field Measurement of Exhaust Valve Seats in Gasoline-Powered Tractors</u>. Survey conducted by the Radian Corporation during September 1986 (84 pages).