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ABSTRACT

A radiotracer method has been developed to measure piston ring and cylinder bore wear rates in spark-ignition (SI) engines. The method has sufficient sensitivity to measure ring and bore wear rates in real time during normal operating conditions. This work reports measurements on the rates of break-in and steady-state wear of piston rings and cylinder bores during a variety of engine operating conditions. Results show that piston ring break-in is minimal and that ring wear rates are constant at steady-state engine operation. The key factor affecting ring wear is engine brake mean effective pressure (BMEP). Ring wear behavior is repeatable for a given engine type and between two different engine designs. Cylinder bore wear is dominated by initial break-in, cold-start wear, and changes in operating conditions. Wear of the cylinder bore during steady-state operating conditions is very low when compared to break-in and changes in conditions. Both piston ring and cylinder bore wear rates as measured by the radiotracer method are reasonable when compared with long-term wear observed in vehicle tests.

INTRODUCTION

A radiotracer technique has been developed to measure piston ring and cylinder bore wear rates of SI engines [1]. This method has sufficient sensitivity to provide for the rapid measurement of ring and bore rates in real time and during normal operating conditions. Wear-rate data during normal operating conditions is required before the effects of adverse operating conditions and degraded lubricants can be ascertained. Measurements can then be performed using lubricants with a variety of rheological and additive modifications, as well as contamination from water, fuel and combustion gases.

Published data on ring and bore wear in engines is very limited because of the technical difficulties involved in performing the measurements. Most available wear data involves diesel engines, which typically have higher wear than SI engines due to higher combustion pressures, longer service life, and soot contamination in the lubricating oil. Limited data is available for SI engines, but is usually obtained from vehicle fleet tests. Fleet tests by nature contain many uncontrolled variables. They also require long operating times, high costs, and do not provide information on specific operating conditions. These limitations make fleet studies unattractive when numerous parameters and conditions must be evaluated to predict wear life.

The limited amount of published wear information shows a wide range of wear rates for rings [2–5] and cylinder bores [2, 6, 7] in SI engines. The use of different materials, operating conditions and reporting methods makes it difficult to compare results and predict trends. For example, ring-wear rates are reported to be as low as a few [3], to hundreds [4, 5], to more than a thousand [2] micrograms per hour (μg/h). Additionally, there is no information available on modern engines and lubricant formulations or on the effects of specific operating conditions.

Cylinder bore wear is even more difficult to measure than ring wear because it occurs over a much larger surface area, and the wear rates vary widely at different locations in the bore. Ring wear can be determined by simply measuring mass loss, but bore wear must be determined by careful dimensional measurements at different locations. Bore wear is generally reported as a dimensional change at the maximum point of wear, e.g., μm at top ring reversal, rather than as weight loss. Published data on cylinder bore wear is even more meager than for ring wear. Fleet data suggest that average wear rates at top-ring reversal are in the range of 2 to 20 nm/h in modern engines [6, 7]. The purpose of this work is to determine wear rates under normal start-up and steady-state operating conditions. This information is necessary to provide the baseline needed to evaluate the effects of other variables on ring and bore wear rates.

EXPERIMENTAL

TEST ENGINES AND LUBRICANTS - The primary engine used in these studies was a 1999 GM 3.4-L 60° V6 spark-ignition engine. The top-compression rings were replaced for each of ten radiotracer tests, and the block was replaced twice to incorporate the radioactive tracers at selected areas in the cylinder bores. A second engine type (2000 GM 5.3-L V8) was also employed to determine whether wear trends observed for the 3.4-L engine could be applied to other SI engines. Only ring wear studies were performed with the 5.3-L engine.

Data from two oils is reported (Oil A and Oil E). Two different oils were used to accommodate other aspects of the program not reported in this work. For the purpose of this study, the two oils were expected to perform similarly. Both were fully formulated SAE 5W-30 oils of API SJ quality.

PISTON RING ACTIVATIONS - The top compression rings for the 3.4-L engine have a plasma-sprayed alloy coating on the surface that contacts the bore, the purpose of which is to increase resistance to wear and scuffing. This alloy contains approximately 80% molybdenum. The remainder of the ring is steel. The thickness of the Mo-alloy coating is a minimum of 100 μm, which is sufficiently thick to ensure that only a few percent of the coating will be worn during the engine tests. The total mass of Mo-alloy coating in each set of six activated rings is approximately 1.25 g.

The piston rings were activated by neutron irradiation at the University of Michigan Phoenix Memorial Laboratory. The total quantity of ^{99}Mo in the rings at the start of an engine test was typically eight millicuries (mCi), with a specific activity of 7 μCi/mg of Mo. Piston rings for the 5.3-L engine were of similar design and contained the Mo-based anti-wear coating, but had a larger diameter (96 mm v. 92 mm). In addition, the 5.3-L engine was a V8, and hence eight rather than six top compression rings were activated for that engine study. During the course of this study, 11 ring sets were activated for wear studies. Both new and previously used rings were activated to determine the effect of break-in on the wear rates. The effects of different operating conditions and lubricant properties were measured during some of these tests, which will be the subject of a separate paper. Detailed parameters for the piston ring irradiation process are found in Ref. 1.

CYLINDER BORE ACTIVATIONS - Specific surface locations of the cylinder bores were made radioactive by surface-layer activations (SLA) at AEA Technology of Harwell, UK, and at Forschungszentrum Karlsruhe, Germany. The SLA technique, which involves bombardment of a metal surface with high-energy charged particles from an accelerator, is the only viable method for the activation of blocks. Because of their large mass, neutron activation would produce a very large amount of radioactivity not involved in the wear measurements. Locations at top ring reversal of several cylinders were selected for activation. These areas were selected because they were the highest wearing locations observed in prior engine tests not involving radioactive blocks.

Figure 1 shows the activation locations selected for the initial bore wear study. In this particular test, four locations were activated with 50 μCi each of ^{56}Co, within 10 μm of the surface, by AEA Technology of Harwell (AEA).

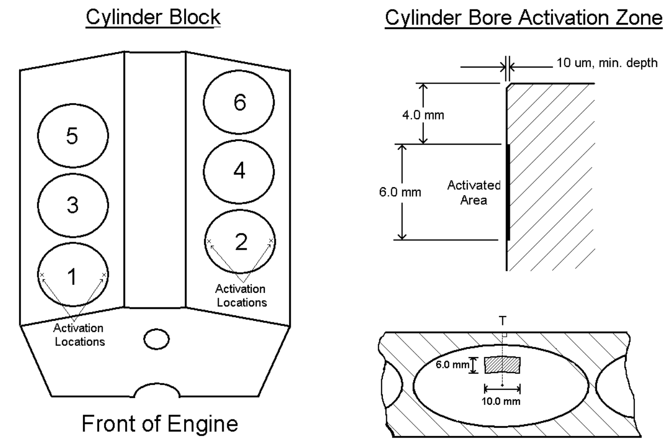

Figure 1. *Schematic diagram of the location of areas activated by AEA in the 3.4-L Cylinder Block A.*

The second block activation was modified somewhat from the first as a result of information obtained from the first study. Figure 2 shows the activation locations selected for the second bore wear study. In this test the activated zone was reduced in area, and only the thrust sides of the bores were activated. Also, cylinders 5 and 6 were selected instead of cylinders 1 and 2, due to field data suggesting that these cylinders were more prone to marginal lubrication during certain operating conditions. Each cylinder was activated with 100 μCi of ^{56}Co, within 10 μm of the surface, by Forschungszentrum Karlsruhe (KFK).

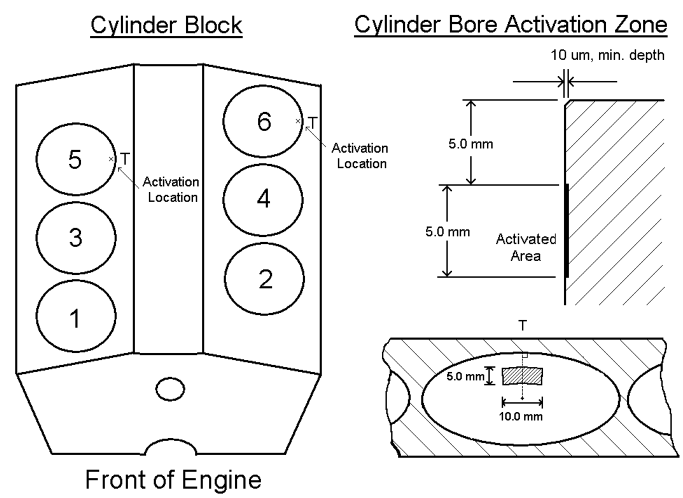

Figure 2. *Schematic diagram of the location of areas activated by KFK in the 3.4-L Cylinder Block B. Activations were on the thrust side (T) only.*

There is always a concern that the procedures used to produce the radiotracers may change material properties and affect wear rates. The technique of SLA has been studied thoroughly in this regard. Under typical activation conditions changes in chemical and metallurgical properties of the activated area are insignificant [8]. While less detailed analysis has been performed regarding the effect of low levels of neutron exposure on wear rates, other investigators have performed wear studies on rings having at least ten times the neutron fluence as those used in these studies [9]. In addition, wear values obtained in this study have been found to be reasonable when compared with data obtained from fleet studies, as described in later sections.

DATA ACQUISITION AND ANALYSIS - Both ring and bore wear data are obtained by measuring the accumulation of radioactive wear debris in the lubricating oil. An external oil pump is used to circulate oil from the sump through a chamber around a high-resolution γ-ray detector. For piston ring wear measurements, initial testing verified that nearly all the radioactive wear debris is entrained in the oil, and only a small amount is transferred to the mating component, deposited in the engine, or trapped in the filter. Some experimenters have shown that, after engine break-in, it is possible to perform this type of short-term wear testing without oil filtration [9]. For cylinder bore wear, break-in and changes in operating conditions cause the majority of wear, and the rate of debris removal by the filter can significantly affect measured wear rates. Care must be taken to minimize the amount of residual radioactive wear debris in the oil when attempting to measure steady-state bore wear rates.

Typically, the system collects data for 30 to 60 seconds to create a γ-ray spectrum. The specific γ-ray peaks of interest in the spectrum are then integrated and the background subtracted. The net count rates are decay-corrected to a reference time using the half-lives of the associated radionuclides. This information is stored along with the appropriate engine parameters (e.g., engine speed, engine manifold vacuum, oil sump temperature, and coolant temperature). Then, a new spectrum is collected and this procedure repeats continuously while the engine is running.

The decay-corrected count rate in each spectrum is used to calculate the total amount of material worn. This calculation is determined by using the detector efficiency to calculate the total amount of radioactive debris in the engine oil and then comparing that value to the total amount of radioactivity in the irradiated components. If the radioactivity is not distributed uniformly as a function of depth worn, a correction factor based on the actual depth distribution is also included. Results are plotted in terms of mass or thickness worn, depending on the desired output. At the conclusion of each day, the oil and filter are changed, and the engine is flushed and filled with fresh oil for the next day. This minimization of accumulated radioactivity in the oil improves wear measurement sensitivity. Oil and filter samples are assayed off-line for radioactive content. At the conclusion of each ring test, the engine is disassembled and the rings are measured for radioactivity remaining. Detailed information concerning the setup, calibration, and operation of the radiotracer wear measurement system are found in Ref. 1.

RESULTS AND DISCUSSION

PISTON RING WEAR MEASUREMENTS –

<u>Wear Data Test Sequences</u> - Results of typical ring wear measurement sequences taken on the first and seventh days of a test are shown in Figures 3 and 4. Point-to-point fluctuations in the data represent statistical uncertainties in individual measurements. Linear fits to the data at constant engine operation yield average wear rates for a given condition and an uncertainty in the overall measurement, which is determined by the uncertainty in the slope of the fitted line.

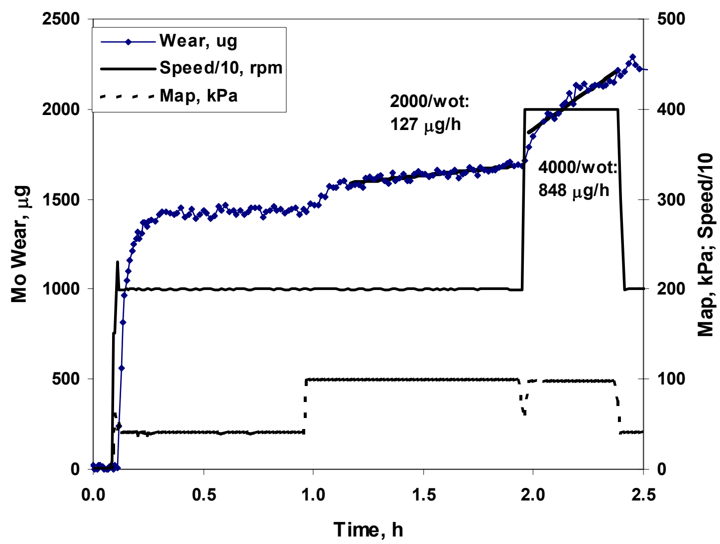

Figure 3. *Wear of molybdenum (Mo) from piston rings (micrograms, μg) during initial ring break-in and at wide-open throttle (wot) during the first day of Test B.*

These plots show features that are consistently observed in ring wear measurements, namely: i) an initial, rapid amount of wear observed during the first engine start-up after ring installation, ii) a smaller increase in wear during subsequent engine starts, iii) an abrupt change in the slope of the wear rate when engine operating conditions are changed, and iv) a constant wear rate slope as long as operating conditions are held constant.

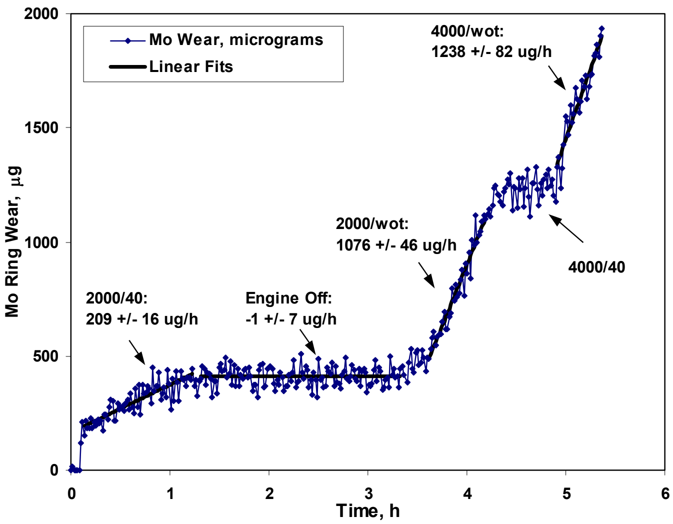

Figure 4. *Wear of Mo from piston rings on the seventh day of Test A as a function of different engine operating conditions (speed, rpm / manifold vacuum, kPa).*

Another common feature of the tests is that the steady-state measurements made immediately after the initial high-wear ring break-in (e.g., Fig. 3; 2000/wot) have wear rates lower than obtained during repeated subsequent measurements. In fact, if a less aggressive wearing condition were run, such as idle conditions, the wear rate would appear to be negative. This is due to the removal of a small fraction of the wear debris generated during initial break-in by the oil filter. To reduce the influence of this effect, no steady state data generated prior to the first oil change is included in the engine speed/load map results, and several high-load conditions are run prior to the first oil change to expedite ring break-in and initial debris removal. In general, the oil filter contains 10-20% of the total radioactive debris at the first oil change. By the end of a given test, the cumulative debris in the oil filters represents about 5% of the total wear. Because this contribution is small and is primarily attributed to the break-in process, specific corrections for the collection of wear debris in the filter are ignored.

Initial, Cold-Start, and Warm-Start Ring Break-in Wear - Table 1 shows the total initial break-in wear of the six rings as a function of ring wear history and operating conditions for the 3.4-L engine. The wear values are also plotted in Figure 5. All of these tests involve a block that had been previously subjected to a break-in schedule and operated in feasibility wear studies. Test D is not reported due to a loss of data at the start of the test, and Test J involved a different type of engine. Results show that the rings have a small but variable amount of initial break-in wear which is independent of ring wear history and engine speed between 650 and 2000 r/min. The average amount of initial ring break-in represents only about 0.15% of the 1.25 g of Mo-alloy coating on the six rings. The first five tests (A-F) were performed using worn-in rings to minimize the time required to break in the ring pack. Test G used worn-in rings in the odd cylinders and new rings in the even cylinders to determine differences between new and worn-in rings. In this particular test the total amount of ring wear was significantly higher than previously observed. However, post-test measurements of individual ring wear showed no difference between new and worn-in rings. Thus, the higher wear rate in Test G was attributed to random variation and not due to the use of new rings in the even cylinders. Subsequent tests employed new rings only. Initial break-in wear of the new rings (Tests H, I, and K) are similar to values obtained for the worn-in rings from Tests A, B, C, E, and F. These trends indicate that new and previously worn-in rings have similar initial break-in wear.

Table 1. *Total initial break-in wear after engine assembly versus ring condition and operating parameters.*

Test	Ring Condition	Speed / map	Init. Ring Wear, µg
A	worn-in	1500/40	1875
B	worn-in	2000/40	1750
C	worn-in	650/40	1125
E	worn-in	2000/40	938
F	worn-in	1500/40	2500
G	1/2 new	2000/40	4250
H	new	2000/40	1000
I	new	2000/40	375
K	new	2000/40	2750
		Average	1800
		Std. Dev.	1200

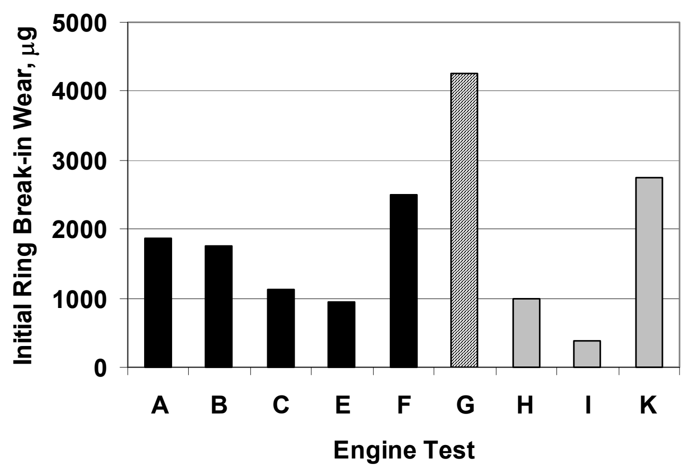

Figure 5. *Total initial top ring break-in wear for each engine test (six rings). Black bars represent tests with worn-in rings, and gray bars represent tests with new rings. Test G involved half new and half worn-in rings.*

The first few data points in Figure 4 show the typical break-in response of the ring pack at engine "cold-start" after an overnight shutdown, but without engine disassembly/reassembly. Cold-start wear values are usually between 0 and 200 µg. (This is in contrast to the average initial break-in wear of 1800 μg, measured immediately after engine assembly, as reported in Table 1.) At an average of 100 μg per cold start, half the total Mo-alloy surface would be removed after about 6,000 engine starts. Removal of half the total alloy may be considered the approximate point at which the alloy is worn completely through at one point on the ring. This estimate is based on the measured circumferential variation in alloy thickness (typically about 30%; Appendix A) and anticipated nonuniform circumferential wear. (Circumferential wear of rings in heavy-duty diesel studies is twice as high at the gap as opposite the gap [10].)

Other cold-start data [5] reported on top and second cast-iron compression rings in a four-cylinder SI engine without engine disassembly show an average start-up wear of 100-200 μg/ring, or 400-800 μg total, over a 20-min period. This is roughly an order of magnitude higher than the start-up wear observed in these tests. This difference may be due to the improved wear resistance of the Mo coating used in this engine compared to engines with uncoated rings.

To determine whether the time duration of the engine-off condition has any effect on start-up wear, the engine was run at steady-state operating conditions until a constant ring wear rate was reached. Then, the engine was shut down for a short period (1-3 minutes) and restarted at the same operating condition five times. This procedure was performed at both the 2000 rpm / 40 map and 650 rpm / 40 map conditions. Results of this test are shown in Figure 6. Typical 100-μg wear is observed for cold start-up, followed by a constant wear rate at the 2000/40 condition. No deviations in the wear rate are observed for the five short shutdown sequences. When the test condition is switched to 650/40 a small decrease in the wear rate is observed, as expected. Once again no deviations in the wear rate are observed for the short shutdown periods at idle. These tests suggest that shutdown and start-up in itself is not responsible for the wear generated at initial cold engine start. Two possible factors involved in cold-start are the temperature of the block, and the draining of lubricant from the ring/bore interface during overnight shutdown. Further studies will help determine the mechanism of this cold-start wear. The lack of wear at warm-start is encouraging for proposed schemes of automatic engine shut-off during warm idle to improve fuel economy.

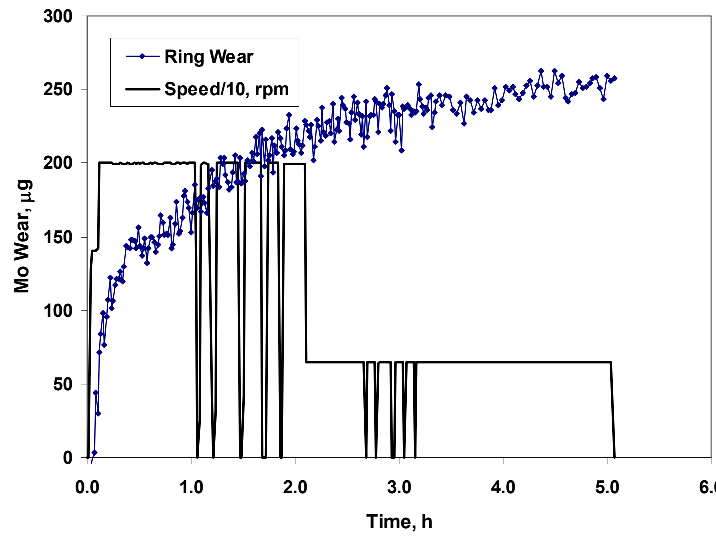

Figure 6. *Break-in wear at cold start-up and warm start-up at 2000 and 650 r/min.*

<u>Ring Wear at Different Steady State Engine Operating Conditions</u> - As shown in Figures 3 and 4, the ring wear rate changes with different engine operating conditions, but the wear rate is constant at each given steady state condition. There may be a small step increase in the wear rate when conditions are changed, after which a new constant wear rate is established.

Over the course of the 11 ring wear studies reported in this work; a large number of measurements were made at each of the four steady state operating conditions evaluated. Each reported value is determined after the initial ring break-in process is complete, and the oil has been changed to remove the break-in wear debris. As shown in Figure 4, the engine steady state measurement sequence typically starts at idle (650 r/min; 40 kPa manifold absolute pressure), which has the lowest wear rate. The sequence progresses through several conditions of increasing power output, eventually reaching the most severe test condition (4000 r/min; wide-open throttle). This procedure ensures the best overall detection sensitivity because the low wear-rate conditions require a lower residual oil activity than the high wear-rate conditions.

Figures 7-10 show all individual wear rate measurements for both oils at each operating condition as well as the average value for all measurements at each condition. Average wear rates for the individual oils, averages for each condition, and statistical uncertainties are reported in Table 2.

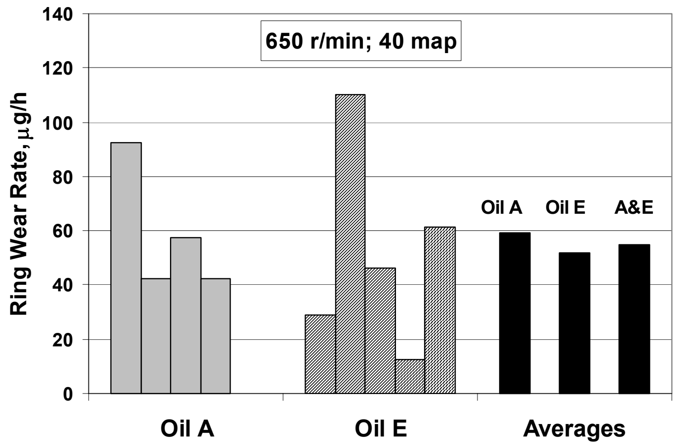

Figure 7. *Ring wear rate at 650 r/min and 40 kPa map for Oils A and E.*

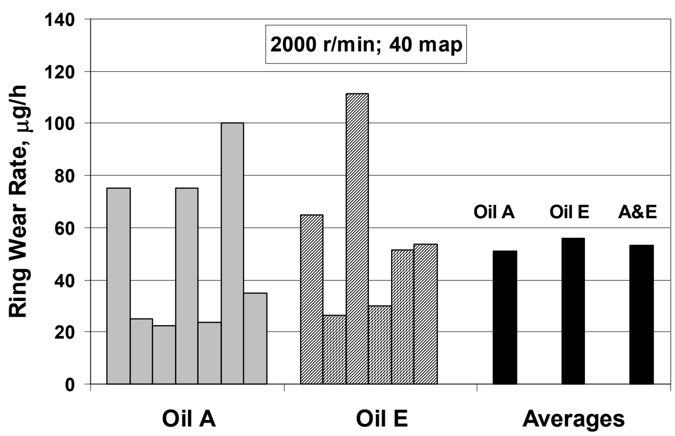

Figure 8. *Ring wear rate at 2000 r/min and 40 kPa map for Oils A and E.*

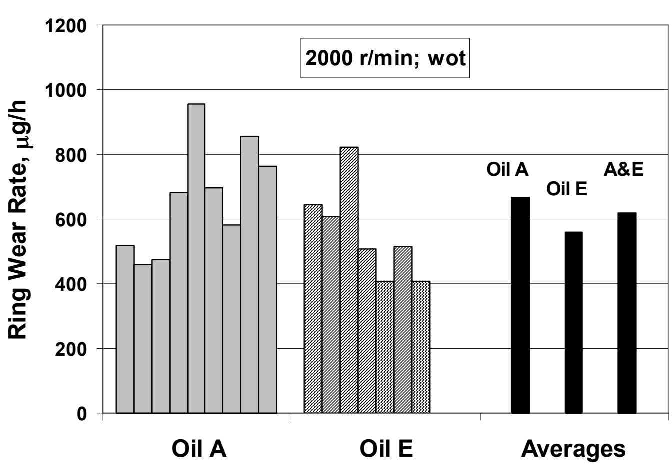

Figure 9. *Ring wear rate at 2000 r/min and 100 kPa map (wide open throttle) for Oils A and E.*

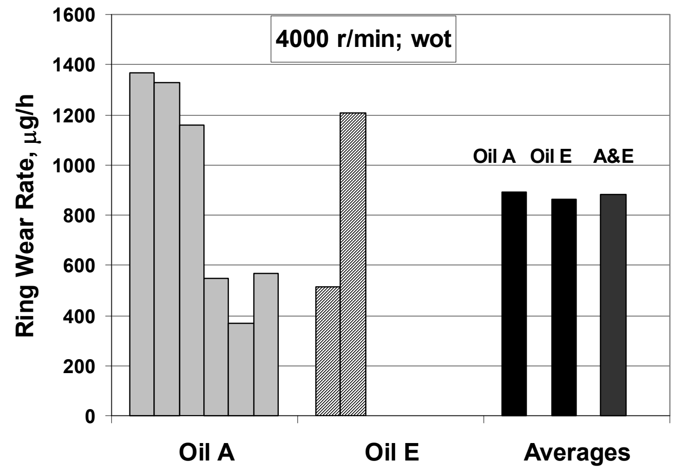

Figure 10. *Ring wear rate at 4000 r/min and 100 kPa map (wide open throttle) for Oils A and E.*

Table 2. *Average wear rates for individual oils and operating conditions and statistical parameters.*

Operating Condition, speed / map	Ring Wear, μg/h: Oil A	Ring Wear, μg/h: Oil E	t-Test p-value	Avg. Wear, μg/h	Std. Dev, μg/h
650/40	59	52	0.76	**55**	30
2000/40	51	56	0.76	**53**	30
2000/wot	665	559	0.21	**619**	166
4000/wot	890	883	0.94	**883**	419

Within each operating condition there is a substantial variation in the wear rate from measurement to measurement. This variation is much larger than the uncertainty of the value or the variation in the wear rate during the test interval. Figure 11 shows an example of the consistency of the wear rate during prolonged steady-state operation. Because of the long operating time involved, the uncertainty in the slope of the line is only ±1 μg/h. It is also evident that the wear rate does not vary significantly from the linear increase over the entire 3.5-h steady-state test period. Thus, the observed test-to-test variations in Figures 7-10 are due to other uncontrolled variables in engine operation. Figure 11 indicates that the variation is not the sensitivity of the measurement method or short-term variations in engine-related variables. Some possibilities that may cause the wear-rate variation are differences in inlet air temperature and humidity, engine oil temperatures, and orientation of each ring gap in its cylinder bore, all of which can vary from one day to the next. Further studies are being conducted to determine the influence of operating variables other than speed and load on ring wear rates.

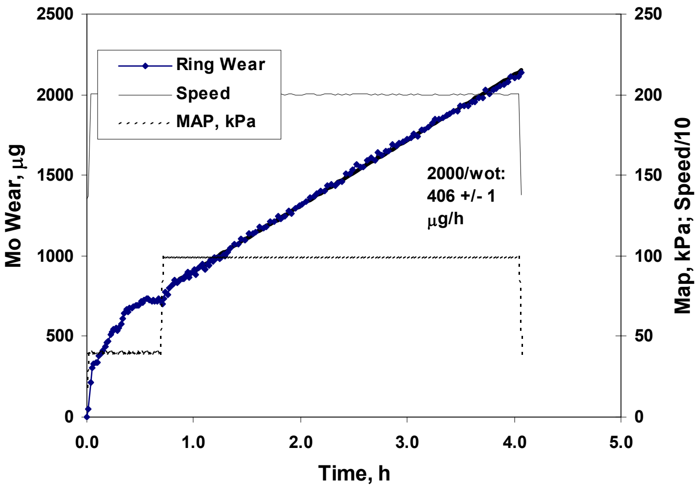

Figure 11. *Wear of Mo from piston rings during an extended operating period at 2000 r/min and wide-open throttle.*

An overview of Figures 7-10 indicates that there are no obvious differences between Oils A and E. Indeed, it was expected that these oils should behave similarly, since they were both SAE 5W-30 of API SJ quality. Table 2 shows relevant statistics relating to this comparison. The t-Test p-values reported for each condition represent the two-sample student's t-test assuming equal variances between the two sets of data. Each p-value can be interpreted as the probability that there are no differences in wear performance between the two oils, and that the observed difference in means between the two sets is due only to chance. The relatively high p-values observed for each condition support the hypothesis that the oils have the same wear performance. For example, one might require a 95% probability before accepting that there are differences between the two oils. This would require a p-value less than 0.05. Thus, there is no statistical justification to treat these oils differently, and all subsequent discussions refer to data from both oils.

Field service ring wear data are available on the 3.1-L predecessor to the 3.4-L engine [4]. Although the primary effort in that work was to identify the extent of engine degradation with M85 fuel, baseline ring wear was measured using gasoline fuel only. Combined top ring wear after about 19,000 miles of city and highway driving was 50 mg. This translates to a wear rate of about 100 µg/h assuming an average speed of 40 mph. This is in good agreement with the rate of about 55 µg/h for the two light-load conditions measured in this work. The field tests were also subject to multiple cold starts and lubricant degradation that may cause the field tests to have a somewhat higher rate than that found in dynamometer measurements at steady-state conditions.

Table 3 lists engine-operating parameters at each test condition and the linear correlation between each parameter and the observed wear rates. Both BMEP, brake mean effective pressure, and power provide an excellent correlation with the wear rate, with speed providing a lower correlation factor. Since power is proportional to the product of speed and BMEP, and its correlation is no better than BMEP alone, the key factor affecting the wear rate is engine BMEP. Figure 12 plots the correlation between BMEP and wear, and includes the uncertainties in the wear data. This result is in excellent agreement with radiotracer ring wear data on a diesel engine [10], which show that ring wear is independent of speed at maximum fueling, when plotted against BMEP. It should be noted, however, that measurements at a wider range of BMEP values would be better to determine the exact correlation between ring wear and BMEP.

Table 3. *Correlations between engine operating parameters and ring wear for all 3.4-L engine tests, and estimated time until ring coating wear-through.*

Operating Condition, speed / map	Speed, r/min	BMEP, kPa	Power, kW	Avg. Wear, µg/h	Std. Dev, µg/h	Est. Time Until Wear Through, h
650/40	650	133	2.5	55	30	11,400
2000/40	2000	203	11.9	53	30	11,800
2000/wot	2000	906	51.5	619	166	1,000
4000/wot	4000	961	108.1	883	419	700
R-sq. fit	**0.69**	**0.95**	**0.94**			

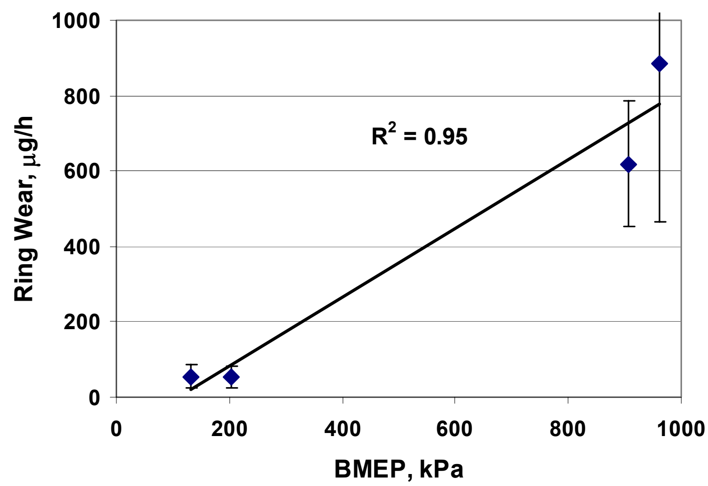

Figure 12. *Correlation between piston ring wear and brake mean effective pressure, BMEP. Error bars represent observed 1-σ variations in the wear measurements.*

Table 3 also lists the estimated time until the coating begins to wear through, based on the assumption that this may occur when about 50% of the total coating is removed. These results indicate that there is little concern for ring wear under typical light-load operating conditions, but ring wear may become an issue under sustained high-load conditions.

Ring Wear with Different Engines - It is useful to determine whether the trends of ring wear observed in this study are characteristic only for the 3.4-L engine or can be applied to other engine families. To that end, ring wear studies similar to those performed on the 3.4-L engine were preformed on the 5.3-L engine. This engine was selected for comparison because the top compression rings also had a Mo-alloy coating similar to the 3.4-L engine.

A comparison of the average wear rates for the four test conditions is shown in Figure 13. Although there are some significant differences in absolute wear rates, the overall trend toward much higher wear rates at higher loads is evident. Uncertainties for the 3.4-L engine data in Fig. 13 are the same as plotted in Fig. 12 and listed in Table 3. Uncertainties for the 5.3-L engine are less well known because of fewer (1 to 4) measurements at each condition.

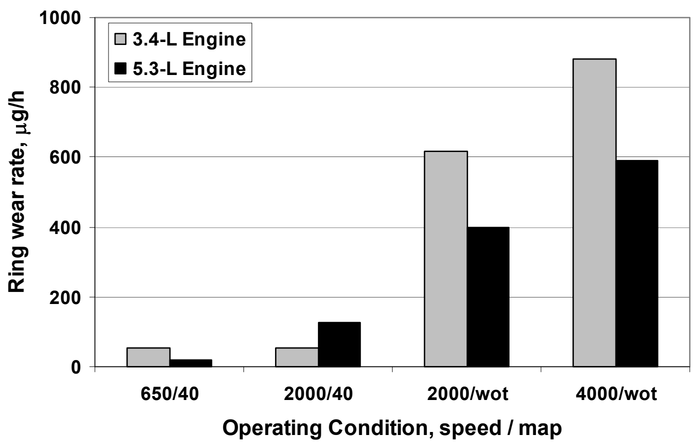

Figure 13. *Comparison between wears rates of the 3.4-L engine and the 5.3-L engine.*

Because the previous analysis showed that BMEP could explain the majority of variation in wear with engine conditions for the 3.4-L engine, BMEP data from the 5.3-L engine were calculated.

Figure 14 shows the resultant correlation between BMEP and piston ring wear. This data shows that 83% of the variations in ring wear at different operating conditions and with two engine designs can be explained by the change in piston BMEP alone. A similar calculation using power output resulted in a coefficient of variation of only 0.67. Hence for SI engines as well as diesel engines, the controlling factor in piston ring wear appears to be BMEP.

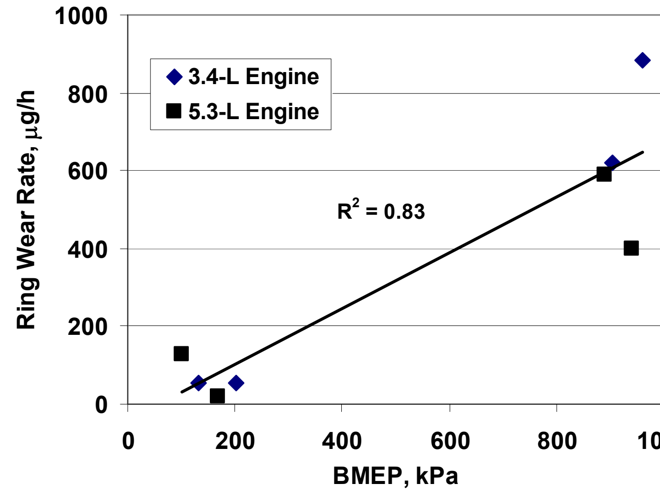

Figure 14. *Relationship between piston brake mean effective pressure and piston ring wear rates for the two engines evaluated in this study.*

CYLINDER BORE WEAR MEASUREMENTS -

Wear Data Test Sequences - Wear data test sequences for cylinder bores were similar to those already described for piston rings. It should be noted that bore wear is reported in thickness rather than mass. The wear thickness or depth represents the average thickness worn over the activated areas as shown in Figures 1 and 2. The absolute value of reported bore wear rates is thus highly dependent on the surface area activated.

Specific examples of wear data will be presented when break-in and steady-state measurements are described. In general, bore wear behavior is substantially different than ring wear. Most bore wear occurs during initial break-in, cold starts, and when changing from one operating condition to the next. Cylinder bore steady-state wear rates are very low compared to the wear generated during these other conditions.

Initial, Cold-Start Bore Break-in Wear - Figure 15 shows the initial break-in wear for Block A. An initial break-in of about 100 nanometers (nm) was observed for the 2000 r/min; 40 map condition. The subsequent increase in load to wide-open throttle generated an additional 800 nm of wear in less than an hour. The wear rate then abruptly dropped by a factor of 20. Figure 16 shows the second day of similar testing following a flush and refill with Oil E. Once again, an initial 100 nm of wear was observed at start-up at the 2000/40 conditions. Once the cold-start break-in was complete, the wear rate at steady-state conditions was only 3±1 nm/h. Similarly, the change to wide-open throttle generated about 20 nm of wear, followed by a steady-state rate of 19±10 nm/h. Results from the third day, shown in Figure 17, show even smaller values for each break-in and steady-state condition, even though the engine operating parameters were identical to the first two days. This wear behavior is quite different than that observed for the piston rings, and is much more difficult to quantify because break-in by its nature is highly variable and continuously diminishes in magnitude with testing time.

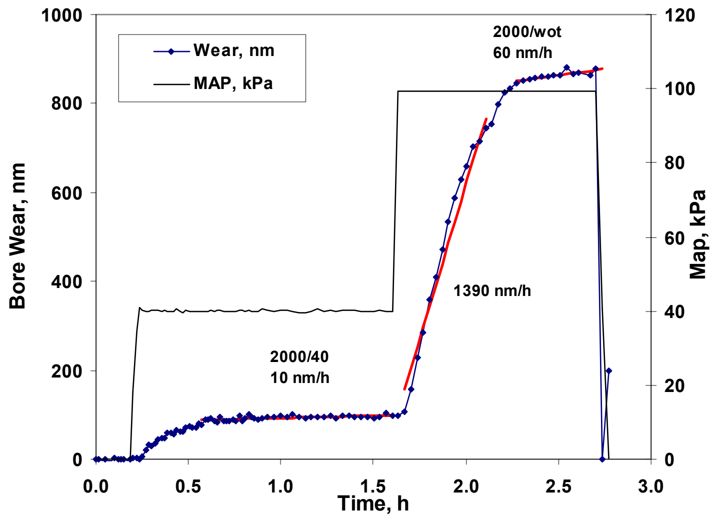

Figure 15. *Wear of iron from the Cylinder Block A (nanometers, nm) during initial break-in at 2000 r/min.*

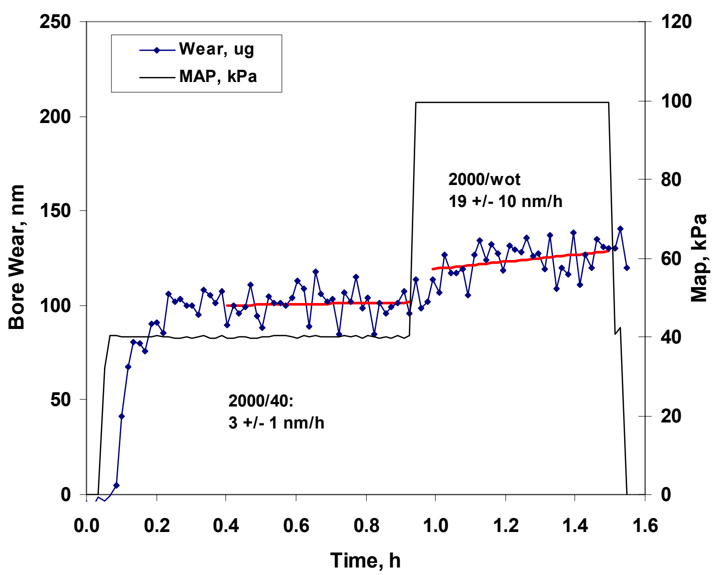

Figure 16. *Wear of iron from the Cylinder Block A at 2000 r/min during the second day of testing.*

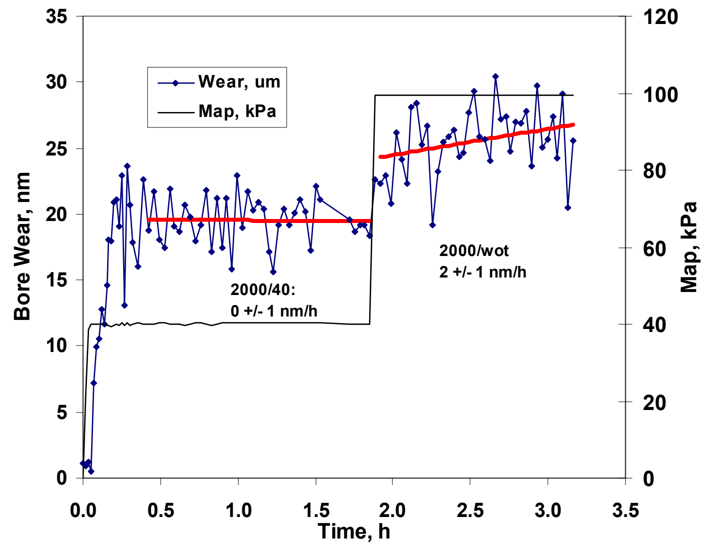

Figure 17. *Wear of iron from the Cylinder Block A at 2000 r/min during the third day of testing.*

Figure 18 shows the initial break-in wear for Block B. There is about 25 nm of initial wear, which is eventually removed by the filter over the next hour of operation. Subsequent testing the next day (Fig. 19) showed only a 10-nm cold-start break-in. Initial operation at 2000/wot (Fig. 20) revealed less than 5-nm of additional break-in when the load was increased. This result is quite different from the initial break-in of Block A, which showed about 1000 nm of break-in wear before wearing conditions stabilized. There were some small differences in the activation locations between the two blocks, but none of the differences was significant in terms of expected break-in wear behavior. Although there are only two block break-in data sets to compare thus far, the wide variability of break-in wear has also been observed in camshaft wear tests [9].

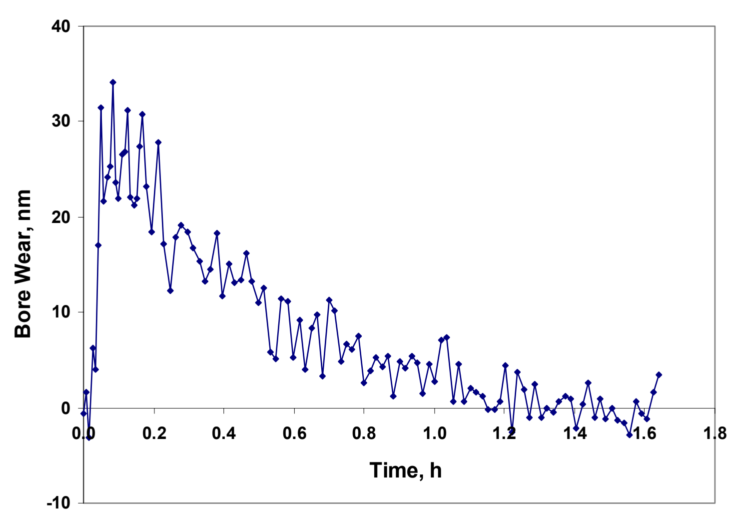

Figure 18. *Wear of iron from the Cylinder Block B during initial break-in at 2000 r/min; 40 map.*

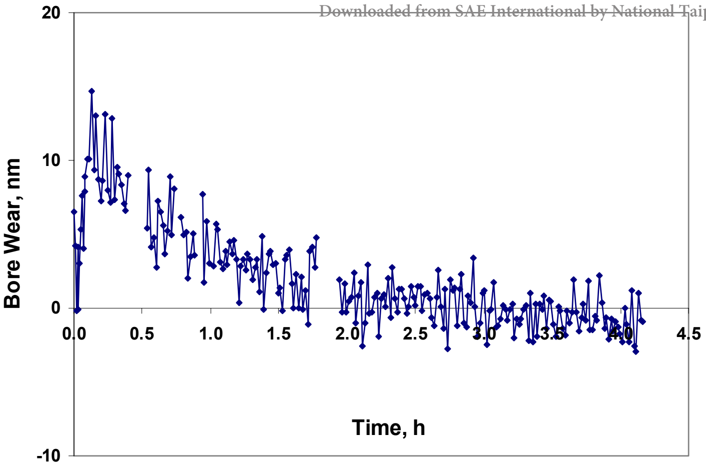

Figure 19. *Wear of iron from the Cylinder Block B during the second day at 2000 r/min; 40 map.*

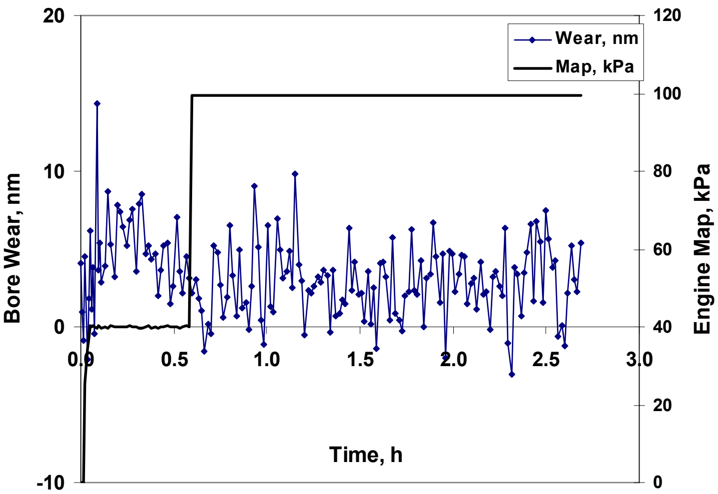

Figure 20. *Wear of iron from the Cylinder Block B during initial operation at 2000 r/min; 100 map.*

Cylinder Bore Wear at Different Steady State Engine Operating Conditions - Table 4 lists steady-state wear rates at the four different operating conditions for each block. As with break-in, these results are in sharp contrast to the patterns observed for ring wear. In general, measured rates are very low and highly variable. The variability probably relates to the fact that the majority of bore wear occurs during a break-in or cold-start process. Some steady-state values may be higher than others if the break-in had not yet been completed. Numbers may also be low if a significant break-in had just occurred, and the oil filter was still removing some of the previously generated wear debris. The key result of this data is that once initial and cold-start break-in is complete, the wear rate of the cylinder bore is very low, even at high-speed and high-load conditions.

Table 4. *Cylinder bore rates observed for different blocks and operating conditions.*

	Block Wear Rate, nm/h			
Condition	**650/40**	**2000/40**	**2000/wot**	**4000/wot**
Block A	0.7 -0.6 0.2	3.1 0.1 2.6 -0.3	2 2.4 1.1	12.5 11.6
Block B	0.6 0.6 0.04 0.1	0.8 5.4 -0.4 0.1	-0.1 -0.1	-0.3
Avg.	**0.2**	**1.4**	**1.1**	**7.9**
Std.	**0.5**	**2.1**	**1.2**	**7.1**

Comparison between Cumulative Piston Ring and Cylinder Bore Wear - Figure 21 plots the cumulative wear of the two bore wear tests and two representative ring wear tests. Ring wear has been converted from mass to thickness by a conversion factor of 11 μg/nm of wear. This factor is determined by dividing the average mass of Mo in the ring activations of 1.1 g by the minimum specification thickness of 0.10 mm for the Mo-sprayed coating on the rings.

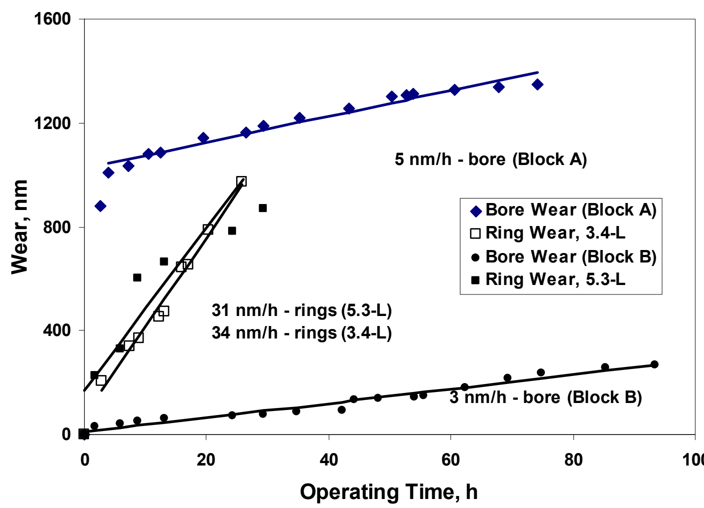

Figure 21. *Comparison of overall piston ring and cylinder bore wear rates, reported for all testing conditions.*

This plot shows the similarity in wear rates between the two different bore wear tests once break-in is complete. Even though individual operating conditions were different for each day, the overall wear rate was consistently about 4 nm/h for each cylinder bore test. Similarly, each ring test averaged about 32 nm/h for the wear rate. It is also evident that break-in wear can be an important factor for bore wear, while it is insignificant for ring wear.

Comparison to Conventional Bore Wear Data - Although no prior data exists on bore break-in wear, information does exist on wear of the cylinder bore at top-ring reversal for vehicles involved in field studies. One such test involved a 1997 3.0-L L81 V6 Cadillac Catera. This vehicle was operated for 12,000 miles under ordinary driving conditions, followed by 16,000 miles of simulated taxi service without an oil change. The oil used was a 5W-30 GF-2 quality, and three quarts of makeup oil were added during the 16,000-mile test. Bore wear was determined by obtaining a surface map of cylinder bore cylindricity using a PAT Equipment Incometer. Cylinders #1 and #6 were measured at 5-degree intervals around the bore circumference at 1-mm increments from the deck face. Average axial profiles of the deviation from cylindricity are shown in Figure 22. A positive deviation from the 0-mm axial distance indicates the presence of wear. These results show an average amount of wear at top-ring reversal of 8 μm (a change from –8 to 0 μm), with little difference between the two cylinders. Assuming an estimated average speed of 25 mph, the average wear rate would be 7 nm/h. This is in excellent agreement with the observed average rate of 4 nm/h for the two bore wear studies reported herein. Since the activated areas are somewhat wider than the ring reversal area, the average wear rate is expected to be somewhat lower than the actual wear at top-ring reversal. It is also of interest to note that there is additional wear at the oil ring reversal point, which occurs 9-mm from top ring reversal. This is the distance between the top compression and oil ring grooves in the piston. Incometer data also revealed that the wear around the bore circumference does not show an increased wear rate at either the thrust or anti-thrust regions. Incometer measurements were also performed on the cylinder blocks used in the radiotracer wear studies. Wear patterns were not discernable. This negative result is expected, as the highest amount of wear (Block A) was only about one micrometer.

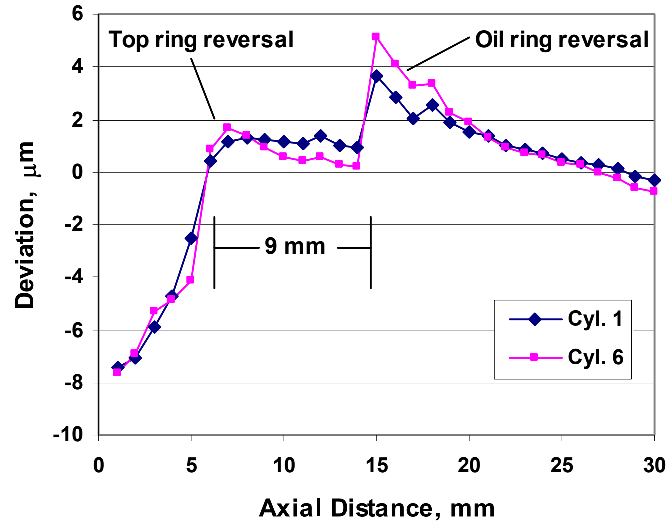

Figure 22. *Deviation from cylinder bore cylindricity averaged over all angles for a vehicle under extended oil drain testing.*

Data is also reported in the literature for bore wear at top-ring reversal in a wide variety of vehicles that were operated for long distances [7]. These data have been replotted in Figure 23. Assuming an average speed of 25 mph, the average wear rate is 2.8 nm/h. This data also shows a wide engine-to-engine variability in total wear, which is unrelated to oil quality. Thus, the reported rates of 3 and 5 nm/h in this study are quite reasonable in reference to data from long-term field tests.

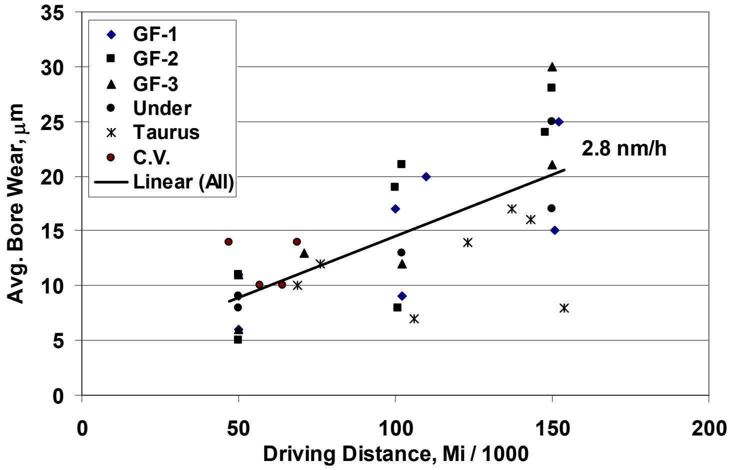

Figure 23. *Average bore wear at top ring reversal for a variety of Ford vehicles having various levels of mileage accumulation [7]. This study also involved extended oil drain service and different levels of oil quality. Each data set labeled GF-1, GF-2, and GF-3 employed that respective classification of oil run in a 3.0-L Windstar taxi fleet. The "Under" designation represents the same type of fleet using a GF-1 oil with 20% under treatment of additives. Data from other vehicles included seven 3.0-L Tauruses and four 4.6-L Crown Victorias (C.V.). The average wear rate for all vehicles was calculated for comparison to data in this work assuming an average speed of 25 mph.*

CONCLUSIONS

A radiotracer technique has been developed to measure real-time piston ring and cylinder bore wear in spark-ignition engines. This work reports the measurement of ring and bore wear rates during break-in and as a function of engine speed and load. This information is needed to provide a baseline for the determination of the effects that environmental conditions and oil quality have on engine wear. Specific test results from the V6 engine tested here show that for:

PISTON RING WEAR -

1. Initial break-in after engine assembly does not depend on whether the rings had been used previously, and removes an average of only 0.15% of the Mo-alloy coating, or 1800 μg for the six rings. Start-up wear with the engine at room temperature averages only 100 μg for the six rings per start-up. There is no measurable start-up wear when the engine is warm from prior operation.

2. The ring wear rate is constant at a given steady-state operating condition and changes to a different constant rate when the conditions change. There is no significant increase in wear during the transition between different speeds and loads.

3. The key factor affecting the rate of ring wear is engine brake mean effective pressure, BMEP. At light loads (BMEP of 200 kPa) the total ring wear rate is about 50 μg/h, and at high loads (BMEP of 1000 kPa) the wear rate is about 750 μg/h. At constant BMEP, a change in engine speed has little effect on ring wear.

4. Wear rates observed in these dynamometer tests correlate well with cumulative ring wear data from fleet service data on a similar engine type.

5. Ring wear measured with a different engine type (5.3-L V8) shows similar break-in behavior and displays the same correlation with BMEP as with the 3.4-L V6 engine.

CYLINDER BORE WEAR -

1. Cylinder bore wear at top-ring reversal is substantially different than ring wear. Most bore wear occurs during initial break-in, cold starts, and during transients between one operating condition and the next. Cylinder bore wear at steady-state conditions is very low compared to the wear generated during these other events.

2. There is a substantial variation in the amount of break-in wear between different blocks of the same type.

3. Measured bore wear rates at steady-state operating conditions are very low and vary depending on the extent of break-in. Once initial and cold-start break-in is complete, the wear rate of the cylinder bore is very low, even at high-speed and high-load conditions.

4. Overall cylinder bore wear after initial break-in averages about 4 nanometers per hour at top ring reversal. This is in good agreement with conventional bore wear data, which shows similar long-term wear rates.

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APPENDIX A

UNIFORMITY OF MOLYBDENUM COATINGS ON PISTON RINGS - To assess the uniformity of the Mo coatings on the rings, several rings were measured for ^{99}Mo radioactivity as a function of angle from the ring gap. This was accomplished by measuring the change of the 140-keV γ-ray peak intensity as the ring was rotated slowly past a gap in lead shielding. Ref. 10 provides a detailed description of the experimental apparatus used to perform these measurements. Figure A1 shows the relative intensity of the γ-ray count rate as a function of ring angle for three different rings. These results indicate that portions of the ring can have a coating thickness 30% below the average, and the coating distribution pattern varies randomly from one ring to the next.

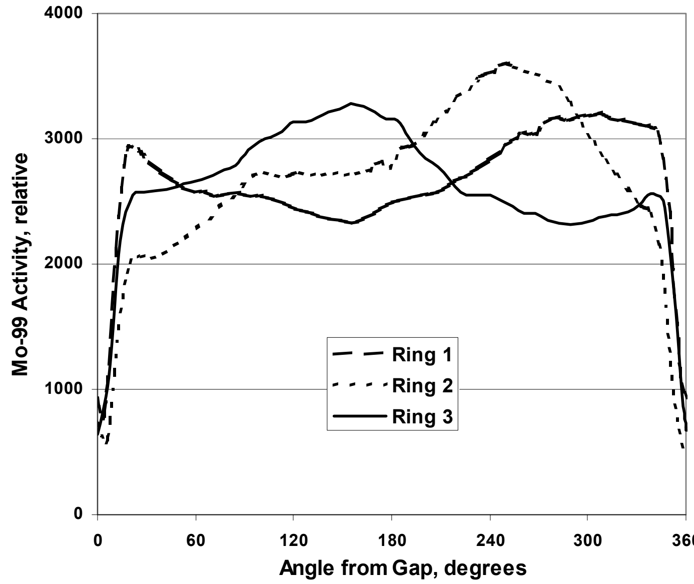

Figure A1. *Relative amount of ^{99}Mo radioactivity versus ring gap angle for three different rings.*