AN ABSTRACT OF THE THESIS OF

Reuben William Peterson for the _MS_ in _Mech Engineering._

Date thesis is presented _June 4, 1953_.

Title _THE EFFECT OF OPERATING VARIABLES ON PISTON RING WEAR AS DETERMINED BY RADIOACTIVE TRACERS._

Abstract approved _Prof. Professor._

The problem of engine wear has been the object of research by engine manufacturers and oil companies for many years. Modern internal combustion engines are limited in economical service life by ring and cylinder bore wear. Most engines require overhaul because oil consumption becomes excessive and power loss becomes considerable, both factors being due to ring and cylinder wear. It is believed that through research the major causes of this wear can be determined and methods developed to reduce it to the point where present-day engines will require no overhaul in the service life of the automobile itself.

It is generally accepted by authorities on this subject that wear of rings and cylinder walls occurs by four processes; namely, friction, abrasion, corrosion, and scuffing. Of these processes, the phenomena of corrosive wear appear to be most controversial. For this reason, this test was directed toward investigating wear under corrosive conditions. The principal variables selected were fuel sulfur content and engine water jacket temperature. Sulfur contents of 0.0%, 0.3%, and 0.75% over the range of jacket temperatures from 110 F to 180 F were chosen to yield results of practical value. The 0.0% sulfur fuel actually contained about 0.01%. The other mixtures were obtained by adding carbon disulfide to the fuel. The 0.0% to 0.3% covered the range of commercial fuels and the 0.75% was chosen to determine the relative increase in wear with abnormal sulfur in the fuel.

The radioactive tracer method was selected as the most convenient and advanced method for wear measurements. The two compression rings from the one-cylinder, 2.7 hp Lauson engine used in the test were irradiated in the Oak Ridge National Laboratory nuclear reactor. Special equipment was constructed to transport and handle the rings. After the rings were installed and the break-in run completed, the engine was operated at five jacket temperatures in the range given for each fuel sulfur content.

The results were presented in graphical form. Wear rate versus cylinder jacket temperature was plotted for each fuel sulfur content.
Reuben William Peterson Abstract, page 2

At lower temperatures, the 0.75% fuel caused nearly four times the wear with the sulfur free fuel. The ring wear increased nearly ten times as the jacket temperature was reduced from 160 F to 110 F with 0.75% sulfur content. The no sulfur curve showed that there is an optimum oil viscosity at which minimum friction wear occurs. A comparison of the no sulfur curve with the sulfur curves indicated that at higher temperatures, the oxides of sulfur formed combine with the oil film and reduce friction wear or mild scuffing wear.

It was concluded from the test that corrosion is an important wear process at low temperatures and with sulfur present in the fuel. Conditions such as these would be found in start-stop short run service. Corrosive wear can be virtually eliminated by increasing jacket temperatures to the 150 F to 170 F range. This is possible in long haul service and corrosive wear does not appear to be an important process in this type service. Temperatures above this range can cause increased friction wear or possibly mild scuffing if the proper lubricating oil is not used.
THE EFFECT OF OPERATING VARIABLES
ON PISTON RING WEAR
AS DETERMINED BY RADIOACTIVE TRACERS

by

REUBEN WILLIAM PETERSON

A THESIS
submitted to
OREGON STATE COLLEGE

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1954
APPROVED:

Redacted for privacy
Professor of Mechanical Engineering
In Charge of Major

Redacted for privacy
Chairman of Department of Mechanical Engineering

Redacted for privacy
Chairman of School Graduate Committee

Redacted for privacy
Dean of Graduate School

Date thesis is presented  June 4, 1953

Typed by Jane J. Bower
ACKNOWLEDGMENTS

The author is particularly grateful to the Standard Oil Company of California for making this investigation possible by sponsoring him with a Research Fellowship at Oregon State College.

The Department of Mechanical Engineering at Oregon State College and the author would like to express their gratitude to the Atlantic Refining Company for granting permission to use the radioactive piston ring wear test method which they originated and patented. The California Research Corporation was very generous with helpful information from their own experiences with the radioactive ring method. The Shell Oil Company Research Department also contributed information on corrosion testing and worthwhile suggestions for further study. This type of cooperation between industry and educational institutions is a large factor in the progress of our colleges and universities.

The author expresses his sincere appreciation to M. Popovich, Major Professor and Chairman of the Mechanical Engineering Department, for his excellent guidance and tireless efforts in promoting this project. To other staff members who contributed information and assistance, the author expresses his thanks. The author is also grateful to the Engineering Experiment Station for purchasing the equipment and supplies necessary for the project.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>THEORY OF RING AND CYLINDER WEAR</td>
<td>3</td>
</tr>
<tr>
<td>Friction</td>
<td>3</td>
</tr>
<tr>
<td>Abrasion</td>
<td>3</td>
</tr>
<tr>
<td>Corrosion</td>
<td>4</td>
</tr>
<tr>
<td>Scuffing</td>
<td>5</td>
</tr>
<tr>
<td>WEAR TEST METHODS</td>
<td>6</td>
</tr>
<tr>
<td>THE RADIOACTIVE RING METHOD</td>
<td>8</td>
</tr>
<tr>
<td>OBJECTIVES OF THIS TEST</td>
<td>10</td>
</tr>
<tr>
<td>APPARATUS</td>
<td>12</td>
</tr>
<tr>
<td>RADIATION SAFETY</td>
<td>19</td>
</tr>
<tr>
<td>PROCEDURE</td>
<td>23</td>
</tr>
<tr>
<td>RESULTS</td>
<td>27</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>34</td>
</tr>
<tr>
<td>RECOMMENDATIONS</td>
<td>36</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>38</td>
</tr>
</tbody>
</table>
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Test Engine and Auxiliary Equipment</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>Radioactivity Measuring Equipment</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>Radioactive Ring Shipping Container</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>Piston Shielding Jig and Ring Handling Tools</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>Radiation Safety Instruments</td>
<td>17</td>
</tr>
</tbody>
</table>
THE EFFECT OF OPERATING VARIABLES
ON PISTON RING WEAR
AS DETERMINED BY RADIOACTIVE TRACERS

INTRODUCTION

The effect of operating variables on engine wear; specifically, piston ring and cylinder wear, has been the objective of exhaustive research by engine manufacturers and oil companies for many years. The useful life of present-day engines is largely determined by power loss and oil consumption, both caused by ring and cylinder wear. The life of the bearings and other moving parts is possibly twice that of rings and cylinders. This indicates that in order to lengthen the economical service life of modern engines, the objective of research must be to find the major causes of this wear and ways of reducing it. To realize the importance of prolonging engine life and reducing fuel and oil consumption, one needs only consider the motorized age in which he lives.

A great deal of progress has been made toward this objective and some important facts have been discovered. Engine manufacturers have approached the wear problem with research directed toward improved engine design. Oil companies have been developing new lubricating oils to combat wear. This research has been carried on in accurately controlled laboratory dynamometer tests and full-scale
field service tests; both equally important in the progress made thus far. Advanced research and correlation and verification of previous research are greatly needed. The numerous operating variables that could affect ring and cylinder wear give relatively unlimited opportunities for further research.
THEORY OF RING AND CYLINDER WEAR

The processes by which wear of rings and cylinders occurs in internal combustion engines are complex. However, authorities on this subject generally agree that wear occurs by the following processes: (1) Friction (2) Abrasion (3) Corrosion (4) Scuffing.

**Friction.** Wear by friction is the cutting or deform-
ing action of the ring passing over the cylinder wall surface. Irregularities on each surface will cut or deform the other surface at the points of contact where the oil film is penetrated. This action will actually remove the irregularities and increase the contact area thus improving the load-carrying ability of the surfaces. During the break-in period this type of wear is desirable, but after the surfaces fit properly it should be brought to a minimum. It is probable that surface finish, material properties, and oil viscosity are the major factors in friction wear. The surface finish governs the number of irregularities in the surface. Hardness of the materials affects the depth of surface penetration by irregularities and hence, the amount of cutting. Oil viscosity determines how close the two surfaces approach each other or how small an irregular-
ity will penetrate the oil film and cut the other surface.

**Abrasión.** By abrasive wear is meant the friction wear caused by foreign particles between the rubbing
surfaces. These particles may be brought in with the intake air or carried in the lubricating oil. Well-designed oil and air filters reduce this type of wear but under adverse atmospheric conditions some particles may still find their way into the engine. It is reasonable that, in addition to the factors affecting friction wear, the quantity, size, shape, and hardness of the particles affect abrasive wear. Unlike friction wear, the harder surface will wear more because the abrasive particles embed themselves in the softer material.

Corrosion. Corrosive wear is, as the name implies, a chemical process. It is a result of acid attack of metal surfaces by certain products of combustion of fuel or of contamination or oxidation of the lubricating oil. Any acid-forming substance can cause this type of wear, but it appears that sulfur and its acids are the major offenders. The corrosive wear tests that have been conducted indicate that the cylinder wall temperature is the critical factor. Other factors that could affect corrosive wear are oil film thickness, oil alkalinity, cylinder pressures and temperatures, and material composition. Oil film thickness could affect corrosion by acting as a protective covering which hinders the acid particles from contacting the metal surface. Oil alkalinity could retard corrosion by neutralizing the acids before they reach the metal. Cylinder wall temperatures could influence the
chemical reaction rate, increasing it as the temperature rises. But more important, they could affect the amount of condensation on the walls, and hence the quantity of acid causing the corrosion.

**Scuffing.** Scuffing is wear caused by the welding of points on the two surfaces and subsequent tearing away of the welded junctions. High surface temperatures and clean metallic contact are the main factors that initiate scuffing. Any oil film, of course, will aid in preventing scuffing by separating the surfaces. Once the surface is roughened by scuffing, wear rates will be high because of friction wear. Scuffing is critical during break-in since there are high temperatures and thin oil films between the surfaces. High temperatures, pressures, rubbing velocities and distortion also add to the possibility of scuffing. Higher viscosity lubricants provide a film which is more difficult to penetrate thus hindering scuffing. Dust or any other abrasive particles present greatly aggravate scuffing. Considerable work has been done on metal coatings and finishes to prevent scuffing. The exact properties that make such materials resistant to scuffing have not been very well determined.
WEAR TEST METHODS

One of the most difficult problems to circumvent in engine wear research is that of measuring the small quantities of iron involved to determine the effect of any set of operating conditions. The three methods used at present are:

1. Physical measurement of rings and cylinder bore.
2. Chemical analysis of lubricating oil for iron content.
3. Radioactive piston rings.

The first method requires very long and, consequently, expensive periods (above 500 hours) of operation to obtain wear measurable with micrometers, dial indicators, and feeler gages. Over such long periods of time, it is hard to maintain constant conditions, thus making the isolation of variables and reproducibility of results difficult. Also, differences in material composition and surface finish between the same type of engines affect wear, further complicating the evaluation of wear data.

The second method yields results in shorter periods of operation (about 100 hours) which eliminates many of the problems encountered in the first method. Laboratory analysis of oil samples is necessary and sampling procedure is critical. Oil changing, and accounting for iron lost due to oil consumption are also problems but can be solved.
without much difficulty. It is also necessary to assume that the iron worn from other engine parts is of negligible quantity which is entirely reasonable. The third and most recently developed method is the use of radioactive rings on the piston. Since special Geiger counters can detect radioactive iron in the lubricating oil in concentrations as low as one part per million accurately, wear rates under set operating conditions can be established in as little as 12 hours. Thus, variables can be isolated and the same engine used to obtain all the data necessary for the determination of the effect of one variable on wear. The disadvantages of the expensive radiation measuring instruments required and the precautions necessary to protect personnel from radiation hazards are more than offset by the time and money saved in operation. The Atomic Energy Commission has made the irradiation of piston rings convenient and inexpensive since the development of the isotopes division at the Oak Ridge National Laboratories. The use of this method yields results only on ring wear, but, since the rings are exposed to the same conditions as the cylinder walls, the ring wear is an excellent index of the effect of operating variables.
THE RADIOACTIVE RING METHOD

This method was originated by Atlantic Refining Company in 1940. At that time it was somewhat impractical, mainly because the only source of radioactive materials was from the cyclotron. The characteristic short life and weak activity of most isotopes produced in a cyclotron were the principal reasons. Since the war, the availability of irradiation service from the reactor at Oak Ridge has rendered this method a greatly improved means of measuring engine wear.

The method consists of irradiating a standard piston ring in the reactor for one month to bring it to a relatively high level of activity. Actually, only one atom in a billion becomes the radioactive iron isotope, Fe$^{59}$. The ring is then installed in the engine with special tools. Then as the ring wears under the set conditions, the radioactive iron particles are carried into the lubricating oil. Periodically, samples of oil are drained from the crankcase and a very sensitive immersion type geiger counter is used to determine the activity of the oil. By comparing this activity to that of a standard solution of known iron content, the quantity of ring iron in the oil sample can be calculated. The total amount of oil in the engine and the rate of oil consumption must be known to complete the calculation of total iron worn from the ring.
The engine is operated under a certain set of conditions until the rate of increase of total ring iron in the oil becomes constant, thus establishing a definite wear rate. A more detailed description of these procedures and calculations is given later in the report.
OBJECTIVES OF THIS TEST

Of the four processes discussed in the theory, wear due to corrosion appears to be the most controversial and more information is needed. A survey of previous research shows that little work has been done on wear rates with various fuel sulfur contents and cylinder wall or jacket temperatures. For this reason, it was decided to hold all other conditions constant while varying fuel sulfur content and jacket temperature. The results could then be plotted as wear rates versus jacket temperature for each fuel sulfur content. Fuel sulfur contents of 0.0%, 0.3%, and 0.75% and jacket temperatures from 110 F to 180 F were selected. The range from 0.0% to 0.3% covers commercial fuels. The 0.75% sulfur content was chosen to determine the relative increase in wear with abnormal sulfur content. The sulfur-free fuel gave a corrosion-free basis for determining the effect of corrosive wear alone. Actually, the sulfur-free fuel contained about 0.01% sulfur.

The radioactive ring method was chosen as the most advanced and convenient means for obtaining the wear measurements in this test. Also, it was desired to initiate the relatively new radioactive tracer method at Oregon State College to progress in the field of engine research. As much data as possible were obtained on operating procedures and techniques to help in further
research. The tracer method gives almost unlimited possibilities for further engine wear research.
APPARATUS

The engine used for this test was a Lauson 2-5/8 in. by 2-1/2 in., 4-cycle type LF 822. The engine was loaded by a dc generator connected to heating coils capable of dissipating the engine's 2.7 hp at 1800 rpm. A gravity flow fuel system was used for dependability. Cooling was accomplished by a heat exchanger supplied with city water. The engine was equipped with a water pump and control valve to circulate and control the flow of cooling water through

Fig. 1. Test Engine and Auxiliary Equipment.
the jacket and heat exchanger. Control valves on the exchanger supply and engine system were manipulated in such a manner that the water temperature rise through the engine was about equal at the various jacket temperatures. An external oil sump shown under engine was used to facilitate sampling and temperature control. The "power stat" at the left supplied current through the ammeter shown to a heating coil wrapped around the oil sump. About four amperes through a 12 ohm coil were necessary for the maximum oil temperatures used. A right-angle mercury-in-glass thermometer indicated the sump temperature. The sump was so constructed that the oil was drained down to exactly the same level each time samples were taken, thus leaving the same quantity of oil in the engine for operation while measuring the radioactivity of the sample. A gage glass on the sump was marked at a level corresponding to a known initial weight of oil. Then, by weighing the sample each time, the oil loss could be determined. The sample weight was approximately two-thirds of the total weight of oil in the engine.
Fig. 2. Radioactivity Measuring Equipment.

The picture above shows the containers and instruments that were used for determining the activity of the oil samples. The glass cylinder on the right is the oil sampling cylinder. Inside it, supported and centered by a specially constructed frame, is the immersion type geiger counter. The center cylinder is for washing the counter and was filled with white gasoline. The one on the left is the standard solution cylinder with its top and bottom counter centering rings. The instrument on the right is a RCL Mk 13 Mod 1 scalar that actually performs the counting operation. The standard solution cylinder was filled to nearly the same level as the oil sampling cylinder to expose
the counter surface geometrically the same each time an activity count was taken. Before the test was started, fresh oil was put in the sampling cylinder and a count taken. This was the background count and was subtracted from all oil sample activity counts. The standard solution was not in the vicinity of the counter when counting oil samples because it affects the background. The background count varies over long periods so the value subtracted was actually an average of several counts. The counting time used was three minutes which gave a good average count and still did not require the oil being out of the engine for excessive time.

Fig. 3. Radioactive Ring Shipping Container.

For shipping the irradiated rings a special container shown at right above was made. It surrounds the rings with
two inches of lead. The step construction eliminates any cracks through which radiation could travel. Studs and wing nuts hold the lid securely on the base. Handles were provided on the lid for removal. The box at left contained the lead container during shipment. It was made of double thicknesses of three-quarter inch plywood and assembled by gluing and wood screws. The frame on the top was for shipping cards. The container design had to be approved by the Bureau of Explosives. Approval of this container is shown by the permit number on the lid. The shipping weight was about 85 pounds.

Fig. 4. Piston Shielding Jig and Ring Handling Tools

The above picture was taken looking from the back side of the jig. The operation of placing the rings on
the piston was shielded by the two inch thick lead bricks shown and observed through mirrors. This prevented unnecessary exposure to the body but did not protect the hand and forearm. The tool at left is a commercial ring expander with long handles. The tool on the right is an ordinary ring compressor, also with long handles. The piston was carried and placed in the engine with the second tool.

Fig. 5. Radiation Safety Instruments.

The instrument on the left above is a minometer sold by the Victoreen Instrument Company. Inserted in the minometer is a pocket ionization chamber. An ionization chamber ready for use is shown in the center. The minometer and pocket chamber measure the dosage from gamma and x-rays. A charge is placed on the chamber and as the
radiation ionizes the gas in the chamber the charge leaks off. After a period of time, the amount of discharge is measured by the minometer on a scale calibrated in roentgens. The instrument at right is a RCL Mark 11 Model 10 portable geiger counter. It is used for detecting small amounts of radioactive contamination. It does not measure dosage, but is useful in examining clothes, tools, hands, etc, for contamination.
RADIATION SAFETY

The use of radioactive materials raises the problem of protecting operating personnel from the physical hazards of harmful radiation. Even though the radiation from the rings is not extremely dangerous, it cannot be ignored. With some reasonable precautions and special handling equipment, the danger is virtually eliminated. The physiological effects of radiation are rather complex and new information is being compiled all the time. The figures stated in this report are mostly Atomic Energy Commission (AEC) specifications from the AEC isotopes catalog. There is a great amount of information on this subject that could be included here; however, only the data that are essential in this type of work will be discussed.

The unit used to define radiation dosage is the roentgen and is based on the ionizing effect of the radiation on a gas. The types of radiation from the rings are beta and gamma rays. To determine physical dosage, both radiations can be considered the same and measured in the same units. The accepted safe level of dosage is 0.1 r (roentgen) per 8-hour day or 0.3 r per week of either type of radiation. The dosage can be measured conveniently with pocket ionization chambers in conjunction with a minometer or pocket dosimeters. A portable geiger counter is also helpful in detecting contamination but does not
give indications of dosage. A survey meter is an excellent instrument for both detection and dosage indication but is expensive. Use of ionization chambers with the minometer and a portable geiger counter is quite satisfactory for protection of personnel.

Beta rays are easily stopped by most material but gamma rays are very penetrating and several inches of lead are required to effectively stop them. For this reason, personnel should be shielded from the rings as much as possible to minimize the dosage when handling the rings or working around the engine. The beta rays or particles constitute a hazard only if ingested into the body or absorbed through the skin because their penetrating power is low and their path in air is short. Even though the activity of the oil is low, skin contact should be avoided. To eliminate any possibility of absorption into the body, rubber gloves should be used because skin contact is almost inevitable regardless of how carefully the oil is handled. Of course, direct handling of the rings is extremely dangerous. In general, the best protection from any type of radiation is distance since intensity decreases as the square of the distance.

To give more specific information on this subject, some actual measurements made during this test will be given. Two rings weighing 9.5 grams each were shipped in
a lead container and arrived at the test site at a level of activity that produced a dosage rate of 4 r/hr at a distance of six inches. This allowed an exposure of six minutes at one foot while installing the rings. One minute per ring was ample time for placing the rings on the piston held in a special jig. Installing the piston and rod in the engine took two minutes. For additional safety, one person performed the first operation and another the second.

After the piston was placed in the engine, a full day elapsed before the rod was connected to the crankshaft and the engine made ready for operation. During the two hours necessary for last assembly, 0.02 r were measured by ionization chambers on the wrists of both hands. The shielding provided by the cylinder block reduced the dosage considerably. During this same day, the standard solution containing 200 mg of the iron was made. At the end of this day the wrist chambers registered 0.05 r or half the safe daily dose. The special tools for this work were constructed such that the hands were one foot away from the radioactive material. The whole operation was entirely safe because the specified dosage is based on whole body exposure and those measured were to the hands and forearms.

After the engine was in operating condition, measurements were taken around the engine to determine the safe time in this vicinity. At an average radius of four inches
around the engine cylinder and head, the dosage rate was 0.1 r/hr. During the first day of operation the dosage measured by wrist and shirt pocket chambers was 0.04 r in 16 hours. Succeeding days showed less exposure as the engine required less attention. Ionization chambers placed adjacent to the standard solution and typical oil samples containing about 6 mg of radioactive iron showed about 0.003 r/hr.

Disposable paper towels were used to wipe up any oil drops around the engine or sampling containers. Hands and shirt sleeves were checked repeatedly for any trace of contamination and none was detected. Because of the rings in the engine, it was necessary to be at least 30 feet away when checking hands or clothes. In the vicinity of the engine the geiger counter read 1000 to 2000 counts per minute. A reverse flow muffler was used on the exhaust system to trap any contaminated solids. To check exhaust, a porous paper was placed at the muffler outlet to somewhat filter the gases. No contamination was detected at this point.

Considering the overall operation, it was completely safe. Some precautions taken were possibly unnecessary but nevertheless wise. Any precaution that would reduce exposure, even though already below the safe limit, was considered worth while.
PROCEDURE

After obtaining proper authorization through the Atomic Energy Commission and Federal Bureau of Explosives, two standard compression rings for the Lauson engine were sent to the Oak Ridge National Laboratory for irradiation. Also, six 200 mg segments of the ring material were irradiated with the rings for use as standards of radioactivity. Eight weeks elapsed from shipment to receipt of the rings and standards. The standard solution was made by dissolving one of the segments in a 1 to 12 sulfuric acid solution and then diluting 1 to 20 to reduce the activity count. The final solution was then comparable in iron content to the oil samples. The rings were installed in the engine with the special tools described in the preceding chapter. The fuel with various sulfur content was made by mixing carbon disulfide with sulfur free white gasoline. The lubricating oil used was an ASTM reference oil. The constant conditions held were as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>50%</td>
</tr>
<tr>
<td>Speed</td>
<td>1800 rpm</td>
</tr>
<tr>
<td>Oil Sump Temp</td>
<td>155 F</td>
</tr>
<tr>
<td>Lube Oil</td>
<td>ASTM D-7-48</td>
</tr>
<tr>
<td>Fuel</td>
<td>White Gas + CS₂</td>
</tr>
<tr>
<td>Ignition Timing</td>
<td>25° BTDC</td>
</tr>
<tr>
<td>A/F Ratio</td>
<td>13.5 to 1</td>
</tr>
<tr>
<td>Intake Temp</td>
<td>85 F</td>
</tr>
</tbody>
</table>
Since new rings were used and the cylinder walls were honed, a break-in run was necessary. This period of operation was continued until the activity count of the oil indicated a normal wear rate had been established. After changing oil, the regular runs with no-sulfur fuel were started, setting the high jacket temperature of 180°F first, and successively 160°F, 145°F, 130°F, and 110°F. The engine was run a minimum of five hours before taking the first oil count on any condition to eliminate the effect of the previous conditions. Ring iron wear was measured at two and three hour intervals depending on the wear rate. A running plot of ring iron in the oil versus hours was kept during each run. Four points in a straight line were set as the requirement to establish the wear rate usually over a period of 12 hours or more. This process was repeated for each fuel sulfur content. When the fuel was changed, a considerably longer time was allowed for the conditions to take effect. Also, the oil was changed after each run to eliminate the possibility of dirty oil affecting wear.

It was necessary to correct for iron loss due to oil consumption. This was accomplished by assuming that all the oil lost during an interval contained the same quantity of iron as the oil at the end of that interval. This is a close approximation because the oil lost by the rings
contains a higher concentration of ring iron than the oil in the sump due to its proximity to the wear region. Thus, assuming a higher-than-average iron concentration for the interval is justified. Total oil quantity was fixed at the time of taking the first sample for each run by filling the oil sump to a predetermined mark on the sump gage glass. Then, with constant oil temperature, oil consumption was found with sufficient accuracy by the decrease in weight of successive oil samples. The last factor considered was the radioactive decay of the standard solution. This is necessary because the half life of Fe$^{59}$ is only 47 days. Radioactivity counts on the standard solution were taken at one day intervals at the beginning of the test. Using these values and the half life of 47 days, a semi-log plot of counts per minute per mg (cpm/mg) versus days was constructed to provide the standard activity count for the rest of the test. This curve was based on the theoretical exponential decay of radioactive materials and conveniently plots a straight line on semi-log graph paper.

Applying the previously mentioned factors, the total ring iron in the oil was calculated in the following manner.

Let:  
W = Total weight of oil in engine at time of first sample  
w = Weight of sample taken  
C = Radioactivity count of sample taken, cpm  
Cs = Radioactivity count of standard solution from curve, cpm/mg  
RI = Total iron worn from the rings, mg.
Then at first sampling,
\[ RI = \frac{W \times C}{w \times C_s} \]

At intervals 1, 2, 3, etc,
\[ RI_1 = \left[ \frac{W}{w_1} \times \frac{C_1 + (w-w_1) \times C_1}{C_1} \right] \frac{1}{C_{s1}} \]
\[ RI_2 = \left[ \frac{W}{w_2} \times \frac{C_2 + (w-w_1) \times C_1 + (w_1-w_2) \times C_2}{C_2} \right] \frac{1}{C_{s2}} \]
\[ RI_3 = \left[ \frac{W}{w_3} \times \frac{C_3 + (w-w_1) \times C_1 + (w_1-w_2) \times C_2 + (w_2-w_3) \times C_3}{C_3} \right] \frac{1}{C_{s3}} \]

Applying \( C_{s1}, C_{s2}, C_{s3} \), etc to all the terms in the brackets is not exactly correct but the decay is so slight and the oil consumption is so small, being less than one percent of the total oil, that the error is negligible over the short intervals used. At low wear rates the calculations can be simplified by using the first calculation at each interval without sacrificing accuracy. Now by plotting \( RI, RI_1, RI_2, \) etc versus time in hours, the slope of the curve or wear rate in mg ring iron per hour can be determined.
RESULTS

The results of this test are shown graphically on the following page. It can be seen that with 0.75% sulfur in the fuel ring wear increases nearly ten times as the jacket temperature is reduced from 160 F to 110 F. At the low temperature, wear is increased nearly four times by adding 0.75% sulfur to the fuel. With only 0.3% sulfur it is still nearly twice the wear with sulfur free fuel. The three curves appear to converge to a minimum wear rate at 160 F indicating that the effect of sulfur is eliminated. This checks well with previous research at other laboratories. The Atlantic Refining Company, from their test results, believe that at this point the cylinder wall temperature is at the dew point of the combustion products. Below this temperature, condensation of water vapor on the cylinder walls will occur; condensing larger quantities of vapor as the temperature decreases. Since the oxides of sulfur are present in the combustion products, it is probable that they combine with the water vapor to form highly corrosive acids that attack the cylinder walls and rings. Above the dew point, no condensation will occur and the acids do not attack the metal surfaces. If condensation of the acid on the surfaces is the major cause of corrosive wear, the wear should be constant above the dew point. This is borne out quite well by the curves, and
EFFECT OF FUEL SULFUR ON TOP RING WEAR

2-5/8 x 2-1/2 one-cylinder Lauson engine
REO-7-48 oil 155F sump 1800 rpm 1/2 load

Oregon State College Laboratory

LEGEND:
- 0.01% S
- 0.30% S
- 0.75% S

WEAR RATE FROM TOP TWO RINGS - MG/HR

0.00
0.75
0.50
0.25

110 120 130 140 150 160 170 180
JACKET WATER OUTLET TEMPERATURE - °F
it appears that condensation is necessary to cause corrosion of the metal. The wear above the dew point, then, must be caused by friction and abrasion.

Another possible explanation of this wear phenomenon has been considered in this test. It is quite probable that the sulfur in the fuel is oxidized to its anhydrous acids during combustion of the fuel. The gas could then be adsorbed by the ring and wall surfaces and also could combine with the oil film. Then, with this anhydrous acid layer on the metal surfaces, the presence of water would immediately start corrosion. The cylinder jacket temperature could be the main factor in determining whether any water is present. At higher wall temperatures, the water would be driven off the surfaces or out of the oil film, thus inhibiting corrosion. At lower temperatures, water would be allowed to remain and combine with the anhydrous acid layer and corrosion would take place.

The Shell Oil Company in recent tests has effectively reduced corrosive wear by the use of alkaline lubricating oils. Their objective was not to prevent the acids from forming but to cover the metal surfaces with a protective layer that would neutralize the acids before they reached the ring and wall surfaces. Their tests were highly successful. However, these tests did not indicate whether the acids were formed in the process of combustion and then condensed on the rings and walls or whether the anhydrous
acid is present in an adsorbed layer in the metal surfaces awaiting the presence of water vapor to start corrosion.

A result of this test that supports the adsorbed layer explanation is the reduction of high temperature wear by higher fuel sulfur content. It is conceivable that sulfur, being a high pressure additive in its free state and in certain organic compounds, could, in the absence of water, reduce friction and abrasive wear. The sulfur compounds formed during combustion could combine with the oil film to effectively form a high pressure additive that would reduce friction wear under this mild scuffing condition. This data shown on the curve could be in error due to the low wear rates, but this is unlikely because the points are quite consistent.

The no-sulfur curve should show friction and abrasive wear at any point. The slight dip in the curve indicates an optimum oil viscosity for best lubrication. Even though the oil sump temperature was held constant, the oil film on the cylinder walls would rapidly approach the wall temperature thus changing its viscosity. The comparatively sharp rise in this curve above 160°F was checked twice, as shown by the two points, and seems to be correct. However, it is possible that the non-additive reference oil used has inferior lubricating qualities at higher temperatures where a heavy duty oil with high pressure additives and high viscosity index would not. This high temperature wear
increase is evident in the 0.3% and 0.75% curves, also. Reduced viscosity apparently increases friction and abrasive wear.

The curves on the following page are typical of the running plot of data that was kept during the test. The break-in wear curve is particularly interesting. The extremely high wear rate is caused by scuffing as the ring and wall surface irregularities are cut away. The engine appeared to be broken in at eight hours running, but this was misleading. The runs immediately following were erratic and good data were not obtained until a number of hours more operation. Typical wear rate determination plots are shown by the other two curves. The first section of the curves shows the residual effects disappearing and the last section, the wear rate being established. In some cases, more time was required to eliminate the residual effects. It was also found that it was necessary to fill the sump with fresh oil at the start of each run to obtain consistent activity counts. This could be due to high iron concentrations and foreign particles from previous runs affecting the wear. Also, the accuracy of the geiger counter decreases with higher iron concentrations and there is a possibility of foreign matter in the oil reducing the activity count of the oil by shielding the iron particles.
TYPICAL CURVES FOR WEAR RATE DETERMINATION

2-6/8 X 2-1/2 one-cylinder Lauson engine
REG-7-48 oil 155°F pump 1600 rpm 1/2 load
Oregon State College Laboratory

IRON FROM TWO TOP RINGS IN OIL - MG

0 2 4 6 8 10 12 14
TIME - HOURS

LEGEND:

△ Break-in 150°F jacket 0.0% sulfur
○ 150°F jacket 0.5% sulfur
□ 110°F jacket 0.75% sulfur
In general, the results were quite satisfactory. The points fell on a smooth curve better than expected with the exception of the 0.3% - 130 F, 145 F points. The discrepancy of these points was not serious, however. The reproducibility was shown by the two points at 0.75% - 145 F and 0.0% - 180 F.

Many more theories on ring and cylinder wear too numerous to discuss here are listed in the Bibliography as SAE papers.
CONCLUSIONS

It can be concluded from this test that corrosion is an important wear process at low jacket temperatures with sulfur in the fuel. Conditions such as these are found in field service in start-stop short run driving. Commercial fuels contain between 0.1% and 0.2% sulfur and in this type of service average engine jacket temperatures are usually quite low. In long haul work in which the engine becomes thoroughly warmed, corrosive wear is eliminated and only friction and abrasive wear exist.

The no-sulfur curve shows that jacket temperature does not have a very important effect on friction and abrasive wear. The variation detected can be attributed to the change in oil viscosity on the cylinder walls with jacket temperature. The increase in wear above 160°F probably demonstrates the need for additives in lubricating oils. The non-additive reference oil used in this test apparently did not have the best high temperature lubricating qualities.

The test definitely proves that there is an optimum jacket temperature for wear reduction using commercial fuels. It appears that the range from 150°F to 170°F water jacket is ideal for the Lauson engine. This quantitative result from the Lauson engine can be applied to other engines with reasonable accuracy because the conditions
affecting dew point and condensation are comparable.
RECOMMENDATIONS

The results of this test pointed out several outstanding subjects for further research. Most important, is the effect of sulfur reducing wear as discussed in the results. Information on this subject would be valuable, not so much for the wear reduction, but in determining what state the sulfur is in at the higher temperatures and how it contacts the metal surfaces. For these tests, a radioactive cylinder sleeve would be very helpful but would greatly complicate the problem of radiation safety.

More work should be done on wear trends with sulfur-free fuel over the range of cylinder jacket temperatures. First, the effect of oil viscosity should be more thoroughly investigated by holding oil sump and jacket temperatures equal over the range of jacket temperatures. Also, the qualities of heavy-duty oils and commercial additives could be determined under the same conditions.

An investigation of the effect of engine load on wear under corrosive conditions would provide helpful information to the first-mentioned recommendation. Since engine load affects cylinder temperatures and pressures, more could be learned about the driving forces that cause acid attack of the metal. It is quite probable that friction wear would vary with load, also. Then it would be necessary to investigate corrosion-free conditions under each load.
This would supply more data on friction wear which would be useful in the second recommendation.


7. Jackson, H. R. Laboratory and field wear tests using radioactive tracers. Paper presented at society of automotive engineers summer meeting, June 1-6, 1952, at Atlantic City, New Jersey. 9p.


