THE EFFECTS OF LOW SUMP TEMPERATURES AND ENGINE STARTING ON PISTON RING WEAR

by

HENRY THOMAS MEADOR

A THESIS

submitted to

OREGON STATE COLLEGE

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1956

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 April 27, 1956

Typed by Genevieve S. Erickson

ACKNOWLEDGMENT

The author wishes to express his sincere appreciation to M. Popovich, Assistant Dean of the School of Engineering. As Major Professor, his patient guidance and sound advice contributed immeasurably to the conduct of these experiments. The author is also indebted to J. R. Kellog and R. Johnson for their assistance in repairing and maintaining the test apparatus and to the Engineering Experiment Station for furnishing the necessary materials for the tests.

TABLE OF CONTENTS

THE EFFECTS OF LOW SUMP TEMPERATURES AND ENGINE STARTING ON PISTON RING WEAR

INTRODUCTION

The primary factor which governs the useful life of an internal combustion engine is wear. In turn, the rate at which wear occurs in an engine is dependent on the effectiveness of lubrication. As engine design progresses toward higher power ratings and better efficiencies, lubrication problems become increasingly acute. In keeping with the recent pace in engine design, the activity in lubrication research has been accelerated considerably in the last few years.

The most satisfactory test of a lubricant lies in the measurement of the rate at which metal is removed from the critical surfaces of an engine due to wear. Results of such tests are more informative when actual service conditions are duplicated. Preliminary investigations are usually carried out on a laboratory scale. If further information is required field tests, sometimes involving fleets of automobiles and trucks, are performed.

It has been estimated that 85 per cent of the engine overhauls performed are necessitated by wear on piston rings and cylinder walls (16, p.2). This wear manifests itself in four ways:

(1) Friction, in which irregularities in surfaces

sliding against each other exert a cutting action which tends to level out these irregularities.

(2) Abrasion, in which an abrasive material is introduced between the sliding surfaces.

(3) Corrosion, in which chemical reactions result in the removal of material.

(4) Scuffing, which is believed to be caused by welding and subsequent tearing off of metal in areas where distortion, insufficient oil film, and high temperatures occur.

Through the study of the effects of operating variables on engine wear rates, the oil refiner endeavors to develop better lubricants. These, in turn, will improve engine performance and reduce repair and replacement costs for automobile and truck owners.

METHODS OF WEAR MEASUREMENT

There are three basic types of tests used to determine engine wear rates under specific operating conditions (15, pp.1-3). The first method involves the direct measurement of the dimensions of the particular parts being investigated. The measurements are made prior to testing and again at the end of the running period. However, the duration of such a test will be dictated by the precision with which the dimensions may be determined. Obviously, if the maximum precision is to 0.001 in., the running time must be sufficient to produce at least that much wear. Cylinder and piston ring wear rates are usually such that 500 hours or more may be required to produce measurable amounts. Duplication of results is also difficult. Even though all affected parts are replaced, slight variations in hardness, finish, mechanical fit, and break-in process affect the wear rate appreciably. In general, the direct measurement method leaves a great deal to be desired with respect to time and precision.

The second method involves the chemical analysis of the lubricant for metallic content. As little as 0.1 part of iron per million may be detected by this method, and in the range of 5 to 100 parts per million, quantities may be measured with an accuracy of 5 to 10 per cent. Tests of

50 to 100 hours will usually produce sufficient wear for measurement. It is not necessary to dismantle the engine after each test so mechanical factors such as surface finish and break-in have little or no effect as variables. The method also lends itself well to field testing. However, there is one detrimental factor in that there is no way of knowing with certainty from which part of the engine the iron was worn.

The third method was developed about 1940 by the Atlantic Refining Company. It consists of a technique for measuring engine wear through the use of radioactive tracers (1, pp.138-140; 11, pp.1-5; 15, pp.1-2; 19, pp.2-3; 23, pp.1-6; 25, pp.4-39). Since this was the method employed in the tests conducted by the author, it is appropriate that a more detailed description be given.

When an iron engine part, for example a piston ring, is bombarded with neutrons in a nuclear reactor, some of the iron atoms are transformed to the heavier isotope Fe^{59}, which is radioactive. The number of atoms transformed is dependent on the flux density in the pile and the length of time the ring is subjected to bombardment. This relationship is expressed mathematically as:

$$\text{specific activity} = \frac{16.4\sigma IF(1-e^{-0.693t/T_{\frac{1}{2}}})}{A}$$

where F = neutron flux per cm^2 per sec.

σ = activation cross section in barns.

A = atomic weight of element.

t = irradiation time.

$T_{\frac{1}{2}}$ = half life of isotope.

I = isotopic abundance.

The activation cross section of an element is a measure of its affinity for neutrons. The term $(1-e^{-0.693t/T_{\frac{1}{2}}})$ is called the "build-up" factor. The build-up of radioactivity is very nearly logarithmic and eventually a point will be reached at which the rate of activation is equal to the rate of decay. This is the "saturated activity" of the element for the particular value of neutron flux involved. For practical purposes irradiation for about 5 half-lives is used where maximum activation is required. In this time the radioactivity has reached about 99 per cent of the saturation level. Fe^{59} has a half-life of 46.3 days. Piston rings for use in engine wear tests are usually irradiated for 30 days (Oak Ridge reactor), so their activity, upon removal from the reactor, is a little over one third the saturated activity. Such a ring contains about one atom of Fe^{59} per billion stable atoms.

Immediately upon removal from the pile the activity of the ring begins to decrease due to decay. In 46.3 days the specific activity is one-half the value it was when irradiation ceased. By multiplying the maximum activity by the decay factor, $e^{-0.693t/T_{\frac{1}{2}}}$, where t in this case is the time since removal from the pile, the activity level at any later time may be determined. It is important that decay be considered when making comparative wear-rate tests.

With the radioactive ring installed, the engine is then run under the desired conditions. Particles of iron worn from the ring are carried to the engine sump by the lubricating oil. By measuring the activity level of the contaminated oil, the wear rate may be determined, since the activity is directly proportional to the number of Fe^{59} atoms present.

For the measurement of activity, extremely sensitive devices have been developed. The one most commonly used in wear testing is the Geiger tube. This tube has a high voltage impressed across it and the ionization of the gas within the tube, caused by beta and gamma radiation, triggers a discharge which registers on a radiation scaler as a "count". The counts per minute (CPM) are, then, proportional to the amount of radioactive material present.

If a sample of oil from the engine sump is drawn and a Geiger tube is immersed in this sample, the activity level registered may be compared with the value obtained with a sample containing a known amount of irradiated iron. In this way quantitative measurement may be obtained. The extreme sensitivity enables accurate measurement of as little as 10 micrograms of iron (1, p.138).

In many investigations relative wear rates are sufficient. In other words, the change in wear rate, produced by changes in certain running conditions, is the information sought. In such cases it is more convenient to obtain activity measurements by continuously circulating the oil through a sensing well containing a Geiger tube.

The radioactive tracer method not only allows testing time to be reduced to 6 to 10 hours per run, but also permits the variation of running conditions at any time during the test. The introduction of this method for wear testing has opened up an extensive field for research. Oil companies and engine manufacturers have intensified their research considerably, but an immense amount of work remains to be done.

PISTON RING WEAR

The most critical wear conditions in an internal combustion engine usually occur in the cylinders. A small amount of wear causes oil consumption to increase, fouling of plugs, contamination of crankcase oil, and loss of power. Lubrication of cylinders is complicated by the very nature of the processes occurring within them. The maintenance of an oil film in the upper part of the cylinder is deterred by combustion and the accompanying high temperatures and pressures. Abrasives enter the system as dust in the intake air and deposits which have broken loose from combustion chamber surfaces. Acids formed from combustion products in a cold engine and the halogen compounds often used in leaded fuels are corrosive. The starting of a cold engine is often accompanied by the introduction of raw fuel which dilutes the oil on the cylinder walls and piston rings. These are just a few of the factors which make the total elimination of wear an impossibility.

By testing engines for wear under various operating conditions, the types of oil giving the best lubrication for given service conditions may be determined. Furthermore, the weaknesses of fuels and lubricants are pointed out to the refiner in his work to produce better products.

OBJECTIVES OF TESTS

Theories concerning engine warm-up procedure are many and varied. Some maintain that initial warm-up is not important as long as enough time is allowed for oil to reach all parts of the engine and loads are kept low until the engine reaches its normal operating temperature. Others advocate a no-load warm-up until the water temper-gauge indicates that cylinder walls are up to normal operating temperatures (about 180°F water temperature). Still others believe oil sump temperatures of about 140°F should be reached before loading an engine.

The purpose of the first series of tests was to determine the effect of sump temperature on piston ring wear. Originally it was intended to include temperatures as low as 35°F, however, due to the lack of refrigerating equipment capable of maintaining low temperatures, it was decided to vary temperatures from about 60°F to 180°F. The test was designed to show not only the variation of wear with sump temperature, but also the optimum sump temperature for the particular engine tested.

The purpose of the second series of tests was to determine the wear rates under the conditions prevalent in the operation of automobiles. These tests simulated:

1. Start and stop driving, as might be

encountered in delivery vehicles.

2. Short drives with long lay-over periods, typical of operation to and from work.
3. Light loading with short warm-up, as would be the case where the operator avoided rapid acceleration and lugging of a cold engine.

DESCRIPTION OF APPARATUS

The engine on which the tests were performed was a Lauson, 2-5/8 in. by 2-3/4 in., single cylinder, four stroke cycle, type H-2 Oil Test engine rated at 4.3 hp at 2400 rpm (fig. 1). A 3 phase, 60 cycle, 220 volt electric motor, rated at 3 hp, was used for starting and loading the engine.

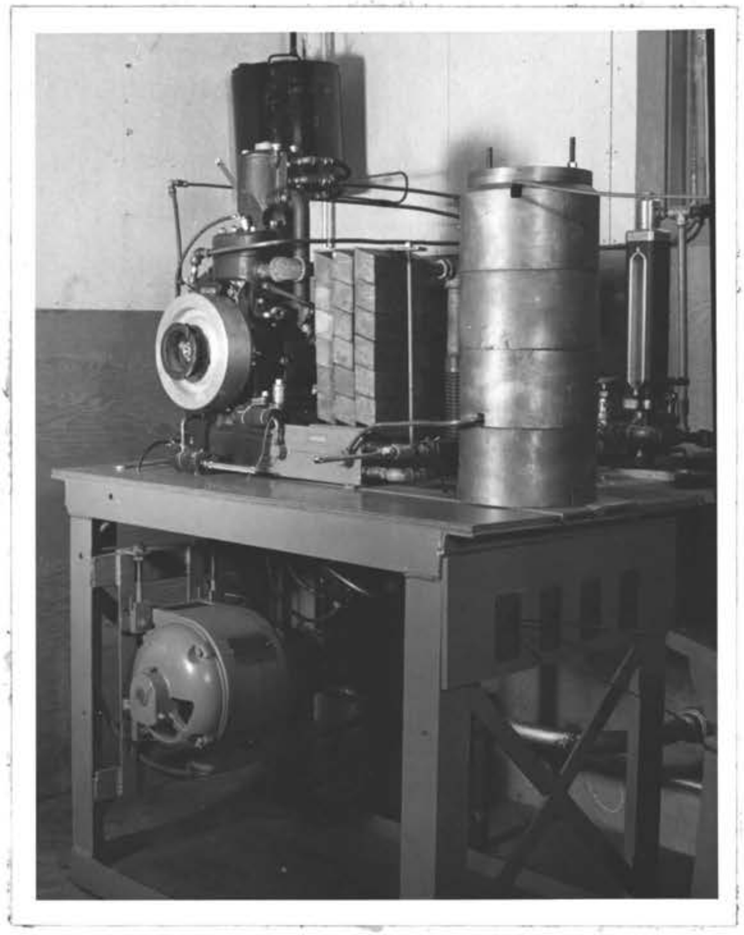

Fig. 1 Engine test stand with sensing well.

Drive was through triple V-belts with a 1 to 1 pulley ratio. By overspeeding the motor (over 1800 rpm) it behaved as an induction generator and thus loaded the engine. Generated power was fed back into the 220 volt service lines through a watt-hour meter. Engine output was determined by timing the speed of rotation of the meter disc. The speed of the engine was controlled by a governor which was connected to the throttle. Fuel was supplied from a five gallon gravity tank.

The engine was equipped with a reflux condenser for cooling. Jacket temperatures did not vary more than $1^{\circ}F$ once the engine was warmed up, since the reflux system maintained the coolant in the reservoir at its boiling point. Water was used as the jacket coolant and city water was circulated through the condenser coils. Mercury-in-glass well thermometers indicated jacket water temperatures at both inlet and outlet.

A 110 volt electric heater, controlled by a Powerstat transformer, was located in the engine base for heating the lubricating oil. The oil was circulated through the sensing well by a gear pump driven by a 110 volt, 1/4 hp motor. Suction was taken at a point above the bottom of the sump to prevent the oil level from dropping too low while the pump was running. A mercury-in-glass well thermometer, located in the suction line near the engine, indicated sump temperature. A heat exchanger for cooling the oil was installed in the return line between the sensing well and the engine. Piping for the cooling water was arranged so that city water could be either chilled or used directly. The chilled water line contained a copper coil which was immersed in an ice bath. Cooling water temperature was measured by a mercury-in-glass thermometer installed in the inlet side of the heat exchanger. Water flow rates were measured on parallel-connected Fischer-Porter rotameters.

Iron-constantan thermocouples were installed on the suction and return oil lines near the engine and on the water inlet of the oil cooler. These, together with another thermocouple for measuring room temperature, were connected to a four-station Brown "Electronic" Potentiometer recorder. The sensing well consisted of a cylindrical chamber with an immersion type Geiger tube inserted through an oil-tight gland. The chamber was enclosed within an outer cylinder of lead, one inch thick, to prevent stray radiation from affecting the counting. To further prevent background effects, a six-inch wall of interlocking lead bricks was placed between the engine and the sensing well.

An RCL Mk 13 Mod 1 Scaler was used to supply high voltage to the Geiger tube and record radiation counts.

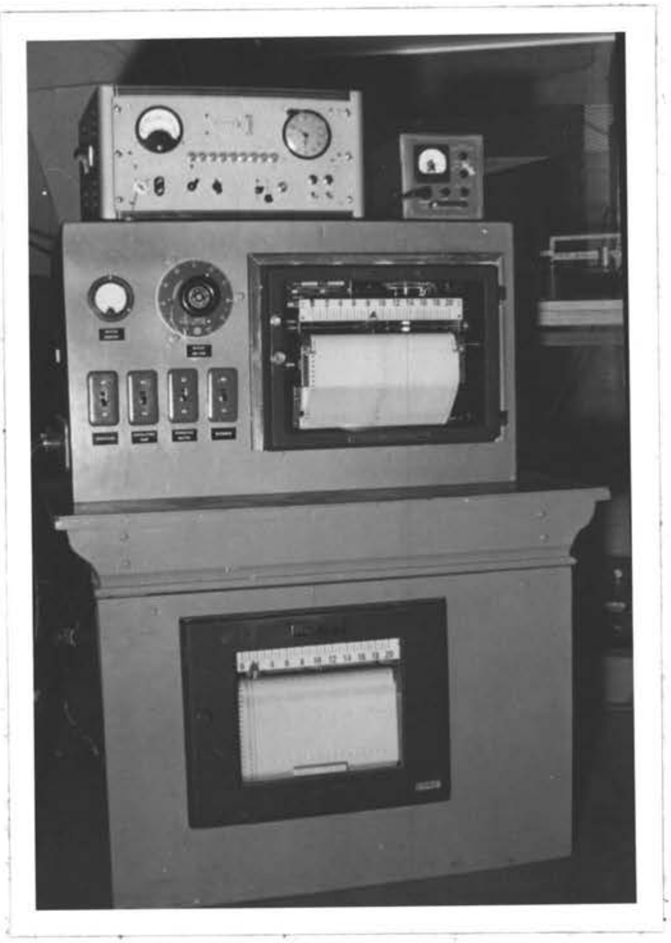

Fig. 2. Control panel and radiation counting components

The scaler had been modified so the second, fourth, and eighth counting stages fed into a Tracerlab Ratemeter. The millivolt output of the ratemeter was taken to a Brown Continuous Balance Potentiometer recorder. In this way the activity level of the oil was continuously recorded on a chart.

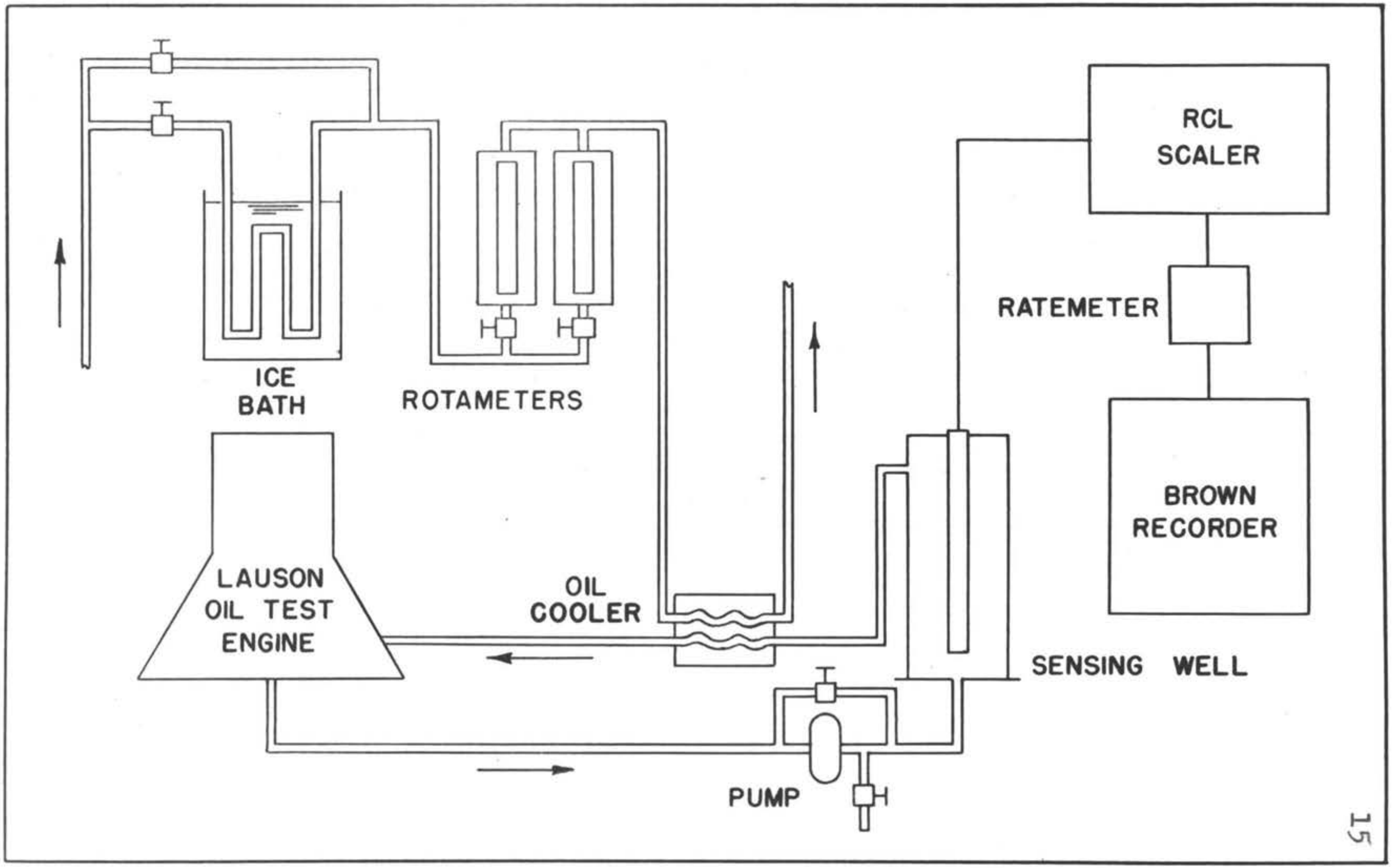

FIG. 3. SCHEMATIC DIAGRAM OF TEST APPARATUS.

SAFETY MEASURES

The currently accepted maximum permissible dosage of radiation is 7.5 milliroentgens per hour for an 8 hour day and 5 day week, or a total of 300 milliroentgens per week (3, pp.56-57). The only times the daily maximum of 60 milliroentgens was approached was during installation of the rings and when repair work necessitated removal of the cylinder head.

The rings were shipped from Oak Ridge National Laboratory in an approved lead container. Calculation indicated the maximum daily dosage would be received in 11 min. if the rings were at a distance of 1 ft. from the unshielded body. The total elapsed time, from removal of the rings from the shipping container to completion of installation, was about 6 min. For installation, the piston was held in a clamping device in front of which a 2 in. thick barrier of lead bricks was erected for a body shield. The tongs, ring expander, and ring compressor were fitted with extension handles about 1 ft. long. When the engine was reassembled a survey showed the radiation intensity to be 7.5 milliroentgens per hour at a distance of about 8 in. from the engine.

During the conduct of the work every effort was made to observe recommended precautions and handling techniques to eliminate danger to personnel. Contaminated oil and oily rags were kept in covered metal containers. Rubber gloves were worn whenever contaminated materials were handled. Pocket ionization chambers were worn while in the laboratory. A Victoreen minometer was used to charge these and read the amount of radiation dosage. An RCL Mark 11 Model 10 Portable Geiger Counter was used to examine tools, rags, gloves, hands, etc. for contamination. A Tracerlab SU-1F Portable Radiation Survey Meter was used regularly to measure the level of radiation in the working area.

Contaminated solids were removed from the exhaust gases by a muffler and from crankcase gases by a trap in the breather line. Surveys were made from time to time to assure that no contaminated gases were being discharged to the atmosphere.

TESTING PROCEDURE

When installation of the rings and reassembly of the engine were completed, a wear-in run was made. Previous tests on the engine indicated about eight hours would be required to properly seat the rings. SAE 10 oil and automotive ethyl gasoline were used. The engine was run at 1800 rpm under no load for seven and one-half hours and then a third load was applied for the remaining half-hour by increasing speed to 1815 rpm. Oil temperature was allowed to increase naturally to its normal operating value of about 130°F. Readings of the scaler and ratemeter were taken every twenty minutes to check their operation.

Throughout the testing a change from one type of oil to another was accompanied by flushing for one hour at no load. A regular commercial flushing oil was used. The engine was allowed to drain overnight before refilling. The amount of oil required for the crankcase and sensing well ($5\frac{1}{2}$ quarts) was measured with a graduate as the system was filled. The amount drained was similarly measured to check consumption. At no time during the testing was the difference enough to be significant. Each group of tests were run on both SAE 20 and SAE 10-30 oil of the same brand.

In the first series of tests only the sump temperatures were varied. Load was held constant at two-thirds, speed at 1850 rpm, jacket temperature at 212°F, timing at 23°BTDC, and air-fuel ratio at 13 to 1. Automotive ethyl gasoline was used for fuel. Runs of ten hours duration were made with the sump temperature at 60°F, 90°F, 120°F, 150°F, and 180°F. These temperatures were controlled by adjusting the rate of flow of water in the oil cooler or the current to the electric sump heater, depending on which was required. The engine was started two hours prior to the testing period in order to establish equilibrium conditions. During the test, readings of engine speed, power output, scaler counts, and the temperatures of oil, jacket water, oil cooler circulating water, and ambient air were taken every twenty minutes.

In the second series of tests, where driving conditions were simulated, the procedure was quite different. Again tests were performed using both SAE 20 and SAE 10-30 oil. One-half hour prior to the starting of a run the radiation counting instruments and oil circulating pump were started. This was done in order to minimize the effects of settled particles on the count rate. The engine was then started and allowed to warm up for two minutes before applying the load. In all cases the oil was allowed to warm up naturally. The controlled variables were the lengths of the running and lay-over periods. Where lay-over periods were ten minutes the recorders and oil pump were not turned off. For longer periods the pump was started one-half hour prior to starting the engine and the recorders were started and stopped with the engine.

Reference runs were made at one-third load to determine the wear rate under continuous running conditions. These were designated as "type A" runs. Similar tests at two-thirds load were called "type B" runs. In both types readings were taken at intervals of ten minutes for eight hours.

In the start and stop runs, simulating conditions under which delivery vehicles operate, the running periods were thirty minutes and lay-over between these was ten minutes. These were designated "type C" and "type D" with loads of one-third and two-thirds respectively. Instruments were read every five minutes and the duration of the tests was six hours.

"Type E" runs, designed to simulate driving to and from work, were at one-third load. They consisted of morning and evening runs of thirty minutes duration for five consecutive days. Here too, readings were taken every five minutes while operating.

RESULTS

A section of the chart trace for the wear-in run showing high starting wear is reproduced in Fig. 6. The results of the series of tests in which sump temperatures were varied are shown graphically in Fig. 4 and in tabular form in Table I. Although the differences in wear rates at various temperatures were not great, the tests did show a definite trend. The lowest rates (4.34 CPM/hr for SAE 20 and 2.74 CPM/hr for SAE 10-30) were obtained when the sump temperature was 150°F. Wear rates increased at temperatures both above and below that value. In all the tests in the series the wear rate was greater when SAE 20 oil was used than with SAE 10-30. Data from the runs at 60°F was inconclusive due to inability to maintain the sump temperature constant. The important point is that the effect of varying sump temperatures was slight.

The results of the series of tests in which driving conditions were simulated are shown graphically in Fig. 5 and in tabular form in Table II. Sections of the charts are reproduced in Figs. 7 through 14. Wear rate values for the type B reference runs (continuous run at two-thirds load) were taken from the runs at 120°F sump temperature in the first series of tests since the average sump temperature in type A runs was very nearly 120°F.

The data indicated the wear rate was greatest in the start-stop runs C and D. In the type C runs the wear rate was 14.67 CPM/hr with SAE 20 oil and 17.25 CPM/hr with SAE 10-30. In all other runs wear rate with SAE 10-30 was less than with SAE 20. In the intermittent, short runs (type E) the wear rate was 11.62 CPM/hr with SAE 20 oil and only 4.75 CPM/hr with SAE 10-30.

A few tests on an ethylene glycol synthetic oil were attempted but were inconclusive in that indicated wear rates were erratic.

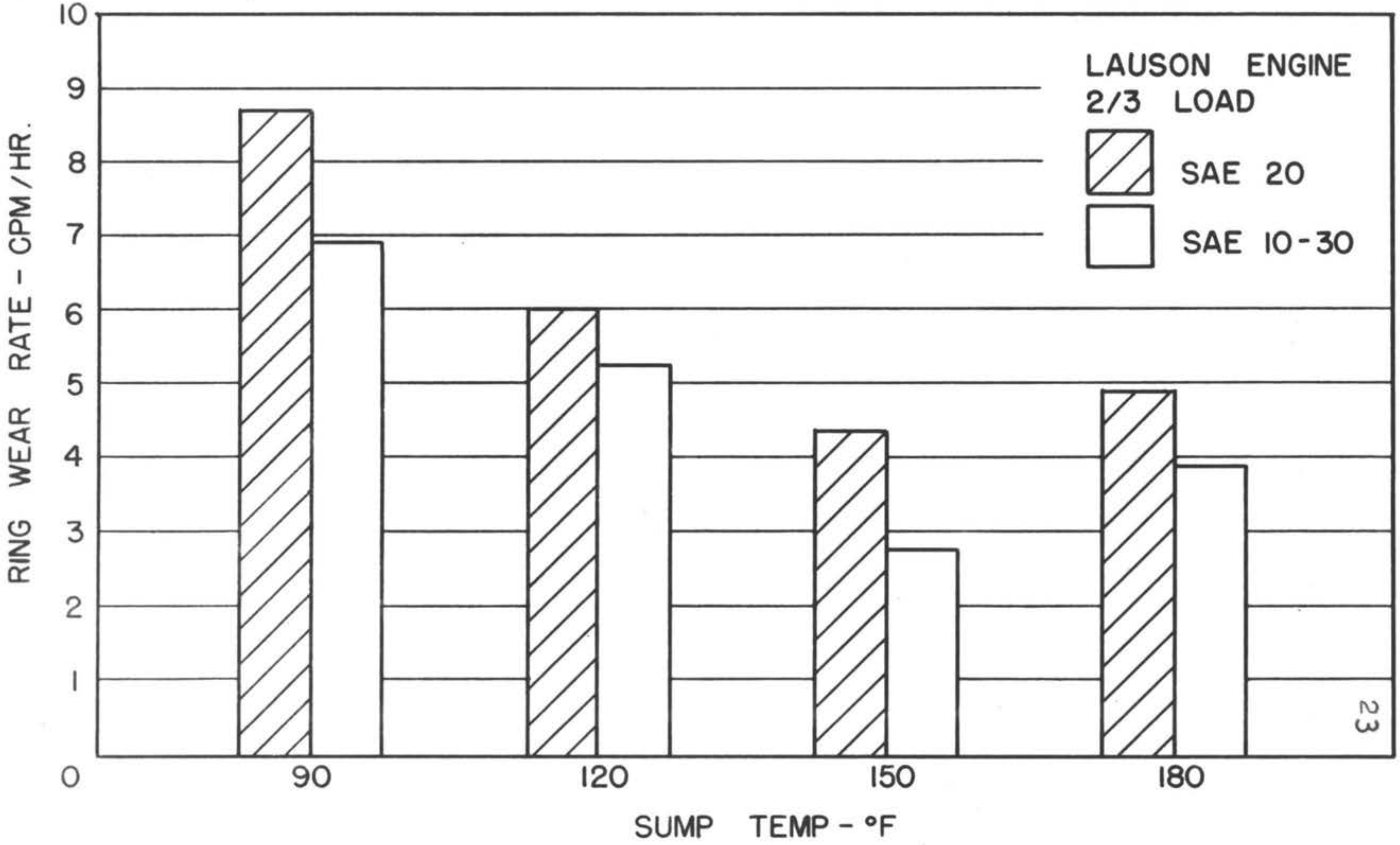

FIG. 4. EFFECT OF SUMP TEMPERATURE ON PISTON RING WEAR.

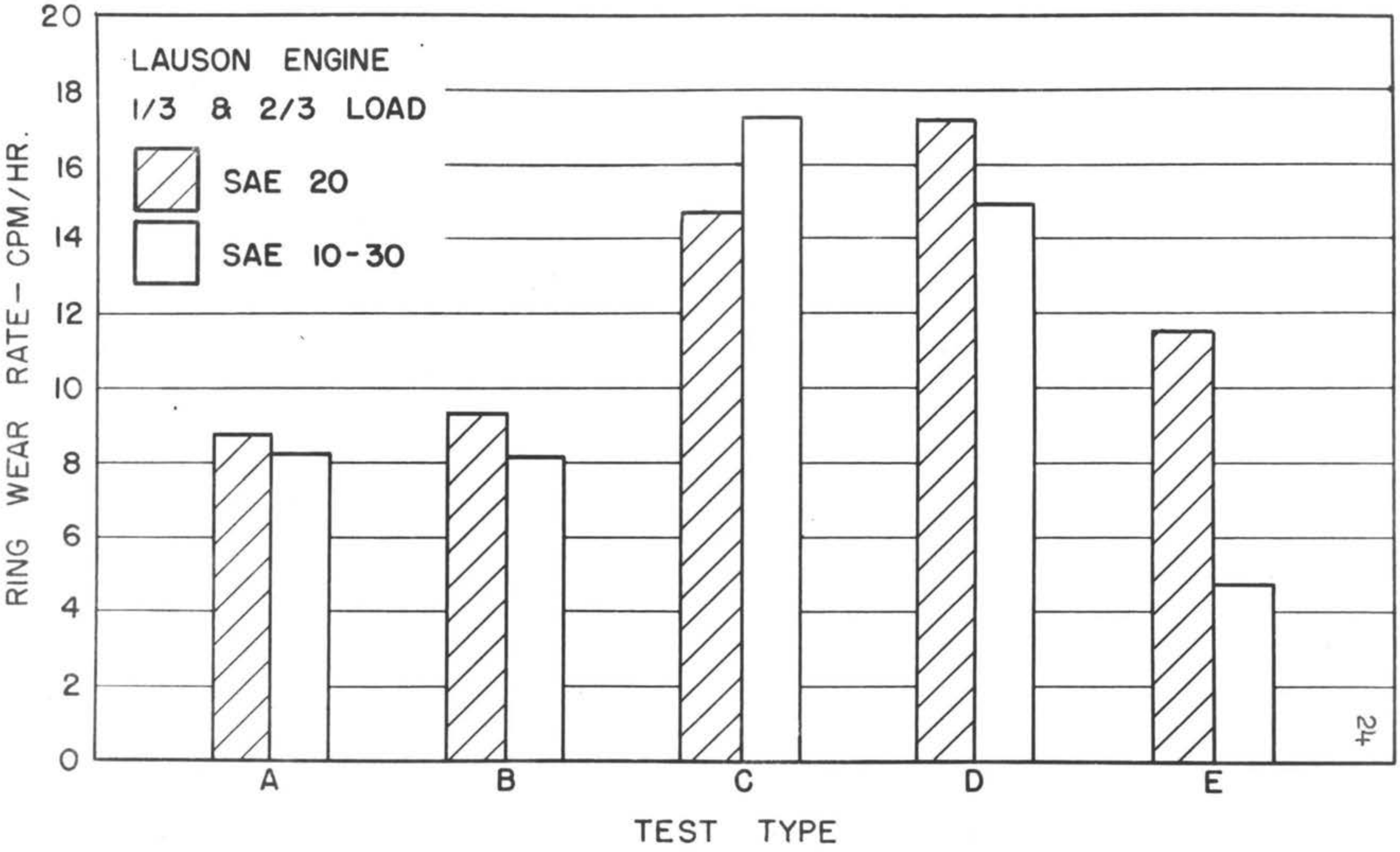

FIG. 5. PISTON RING WEAR RATES → SIMULATED DRIVING CONDITIONS.

TABLE I

TEST OF EFFECTS OF LOW SUMP TEMPERATURES ON PISTON RING WEAR

Lauson Engine, 2/3 load, "ethyl" fuel, jacket 212^{o}F

K = Decay factor = $e^{-0.693t/T_{\frac{1}{2}}}$

t = Time elapsed since start of tests, days.

$T_{\frac{1}{2}}$ = Half-life of isotope (Fe^{59}) = 46.3 days.

R_o = Uncorrected wear rate, CPM/hr.

R = Corrected wear rate = R_o/K, CPM/hr.

Sump Temp ^{o}F	SAE Oil Grade	t days	K	R_o CPM/hr	R CPM/hr
180	20	0	1.000	4.88	4.88
	10-30	9	0.874	3.40	3.89
	10-30	14	0.811	3.44	4.24
	10-30	47	0.495	1.66	3.36
150	20	1	0.985	4.28	4.34
	10-30	11	0.848	2.32	2.74
	10-30	15	0.799	2.15	2.69
120	20	6	0.914	5.49	6.00
	10-30	16	0.787	4.13	5.25
90	20	7	0.901	7.84	8.70
	10-30	19	0.752	5.20	6.90

TABLE II

PISTON RING WEAR RATES UNDER
SIMULATED DRIVING CONDITIONS

Lauson Engine, "regular" fuel, jacket 212°F

K = Decay factor = $e^{-0.693t/T_{\frac{1}{2}}}$

t = Time elapsed since start of tests, days.

$T_{\frac{1}{2}}$ = Half-life of isotope (Fe^{59}) = 46.3 days.

R_o = Uncorrected wear rate, CPM/hr.

R = Corrected wear rate = R_o/K, CPM/hr.

Test Type A - 1/3 load continuous run reference test.
B - 2/3 load continuous run reference test.
C - 1/3 load stop-start test.
D - 2/3 load stop-start test.
E - 1/3 load intermittent, short run test.

Test Type	SAE Oil Grade	t days	K	R_o CPM/hr	R CPM/hr
A	20	57	0.427	3.74	8.76
	10-30	73	0.336	2.80	8.35
B	20	6	0.914	5.49	6.00
	10-30	16	0.787	4.13	5.25
C	20	59	0.414	6.06	14.67
	10-30	66	0.373	6.44	17.25
D	20	60	0.408	7.02	17.21
	10-30	67	0.369	5.52	14.95
E	20	61-65	0.390	4.53	11.62
	10-30	68-72	0.351	1.67	4.75

Note: R for type B tests must be multiplied by 1.55 to correct for change in recorder due to alteration of ratemeter.

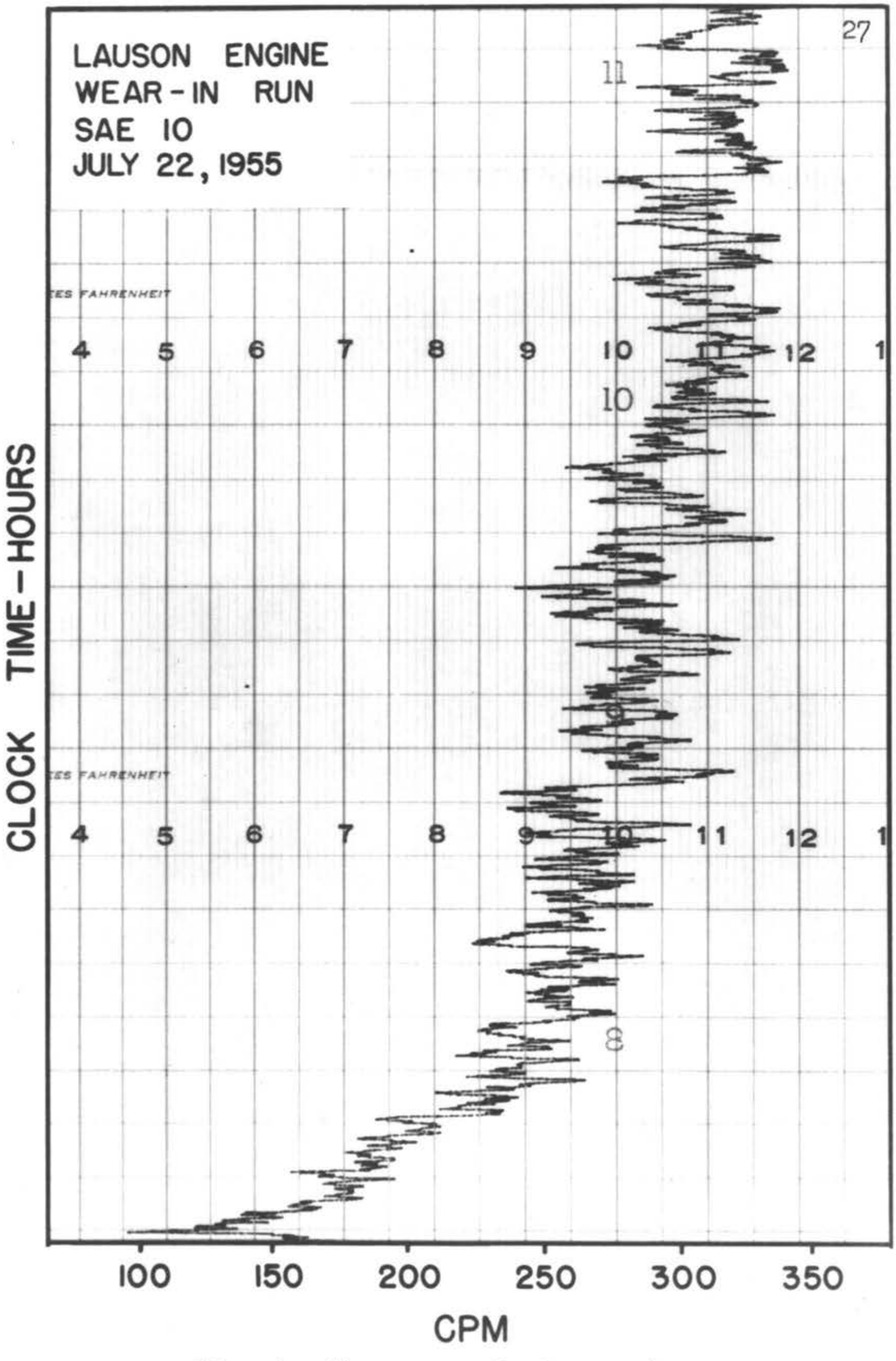

Fig. 6. Wear record of wear-in run.

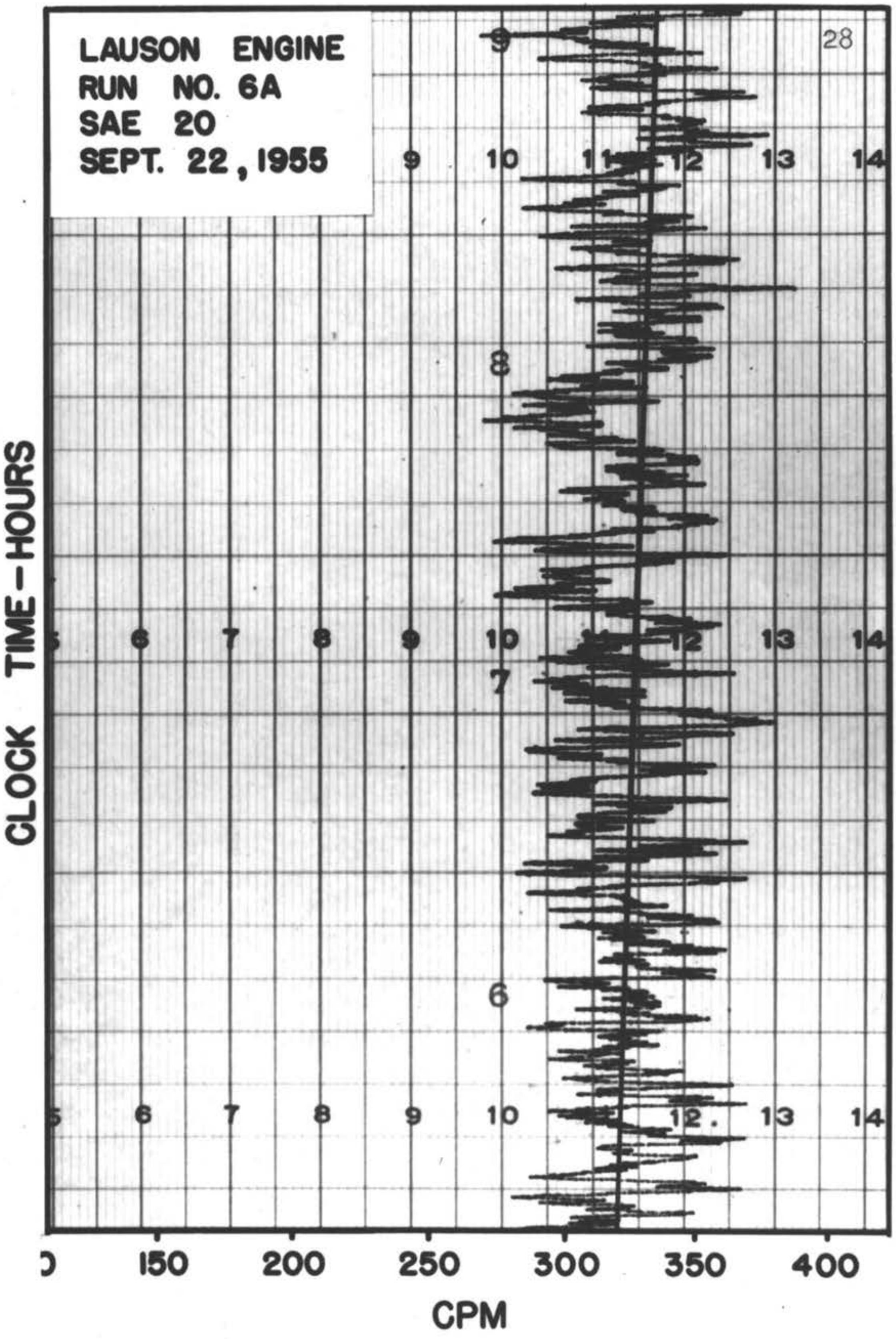

Fig. 7. Wear record of reference run.

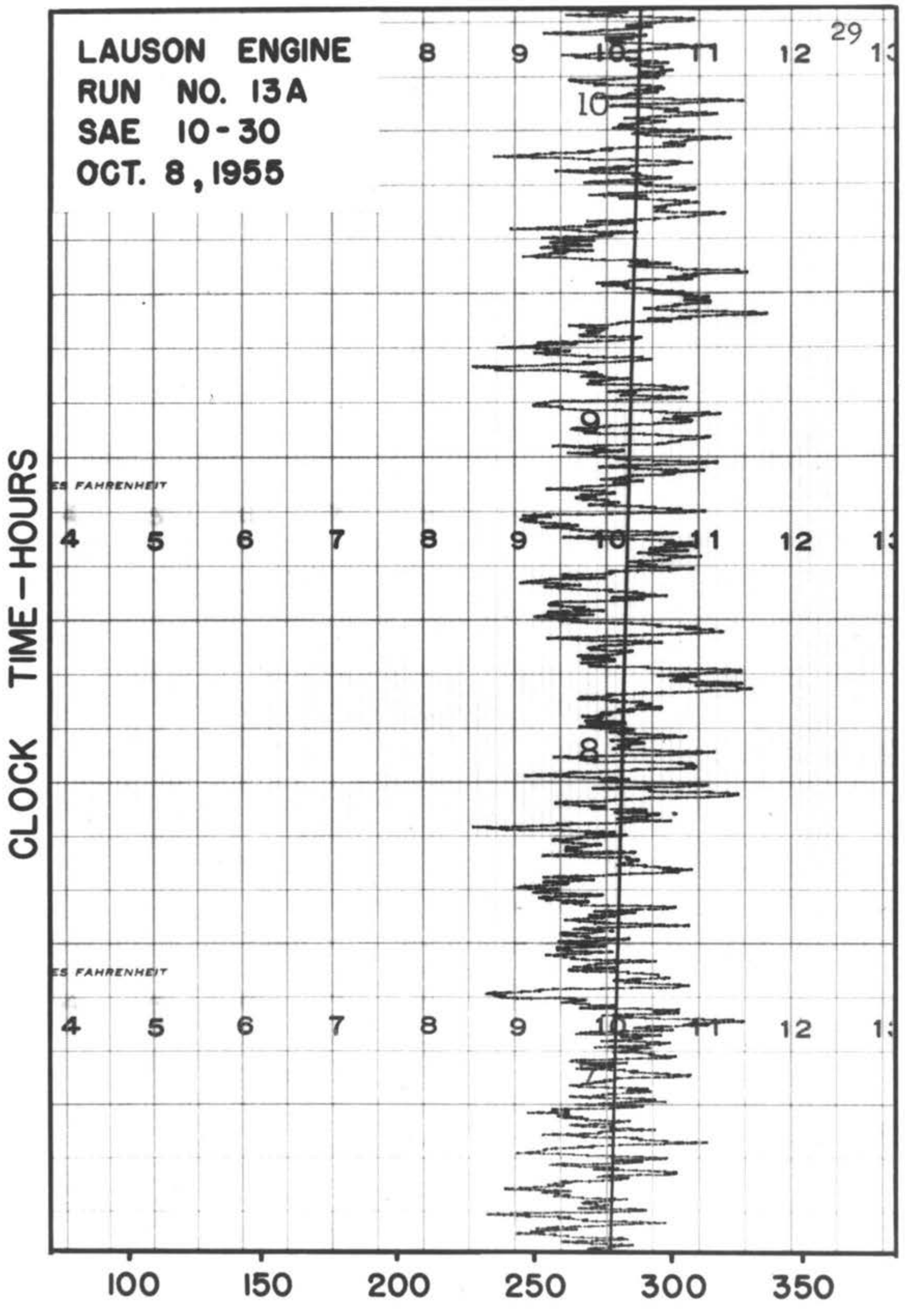

Fig. 8. Wear record of reference run.

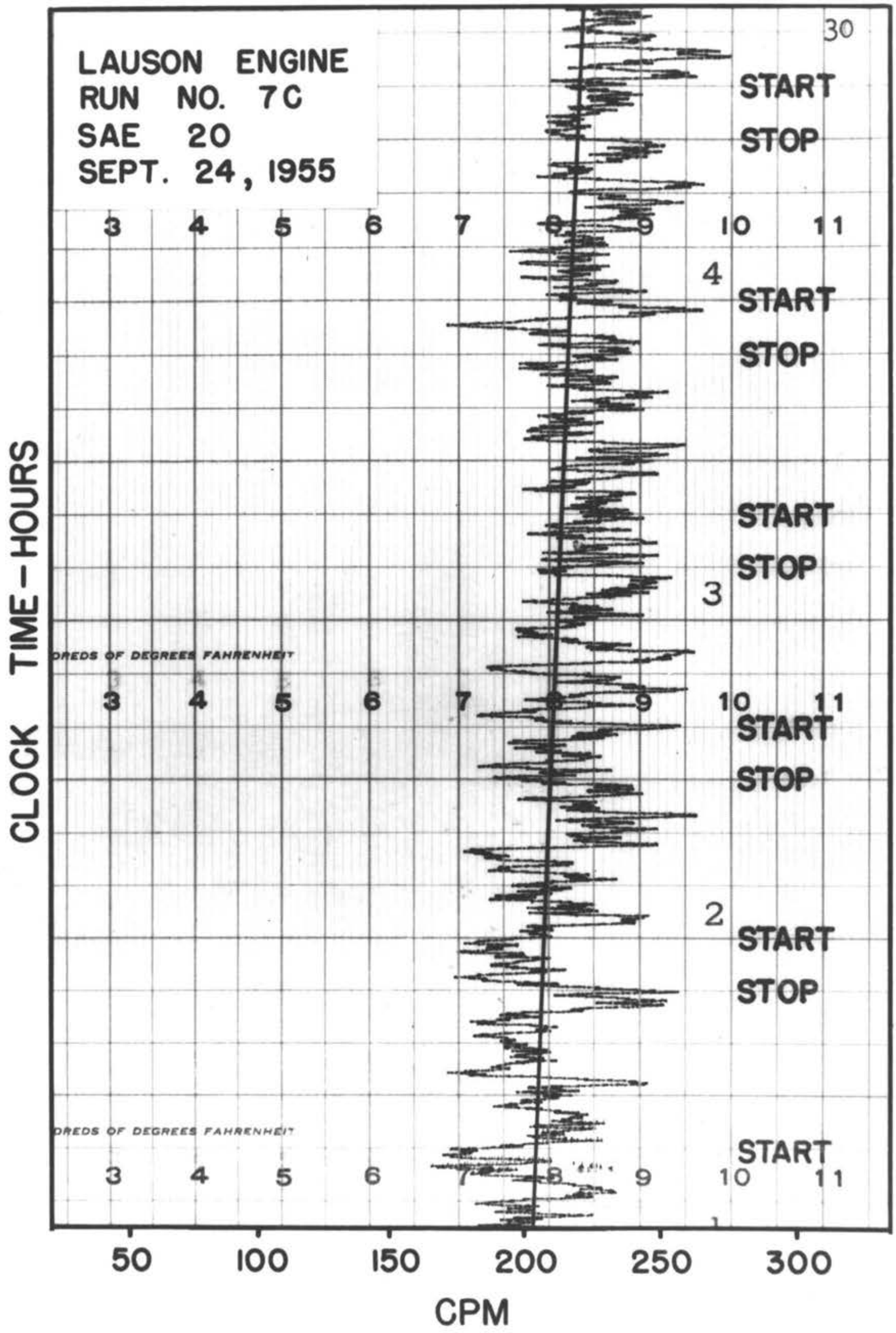

Fig. 9. Wear record of start-stop run.

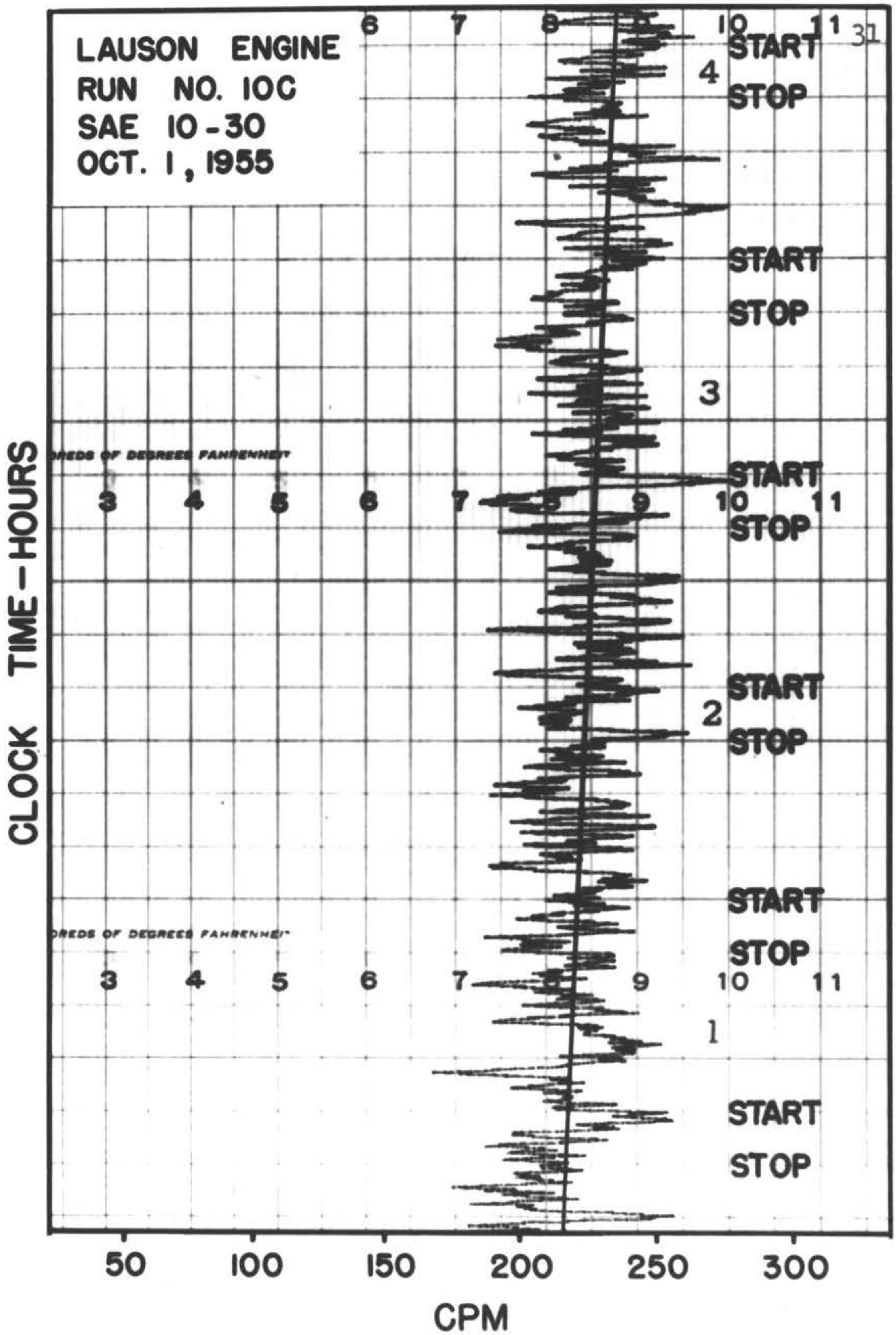

Fig. 10. Wear record of start-stop run.

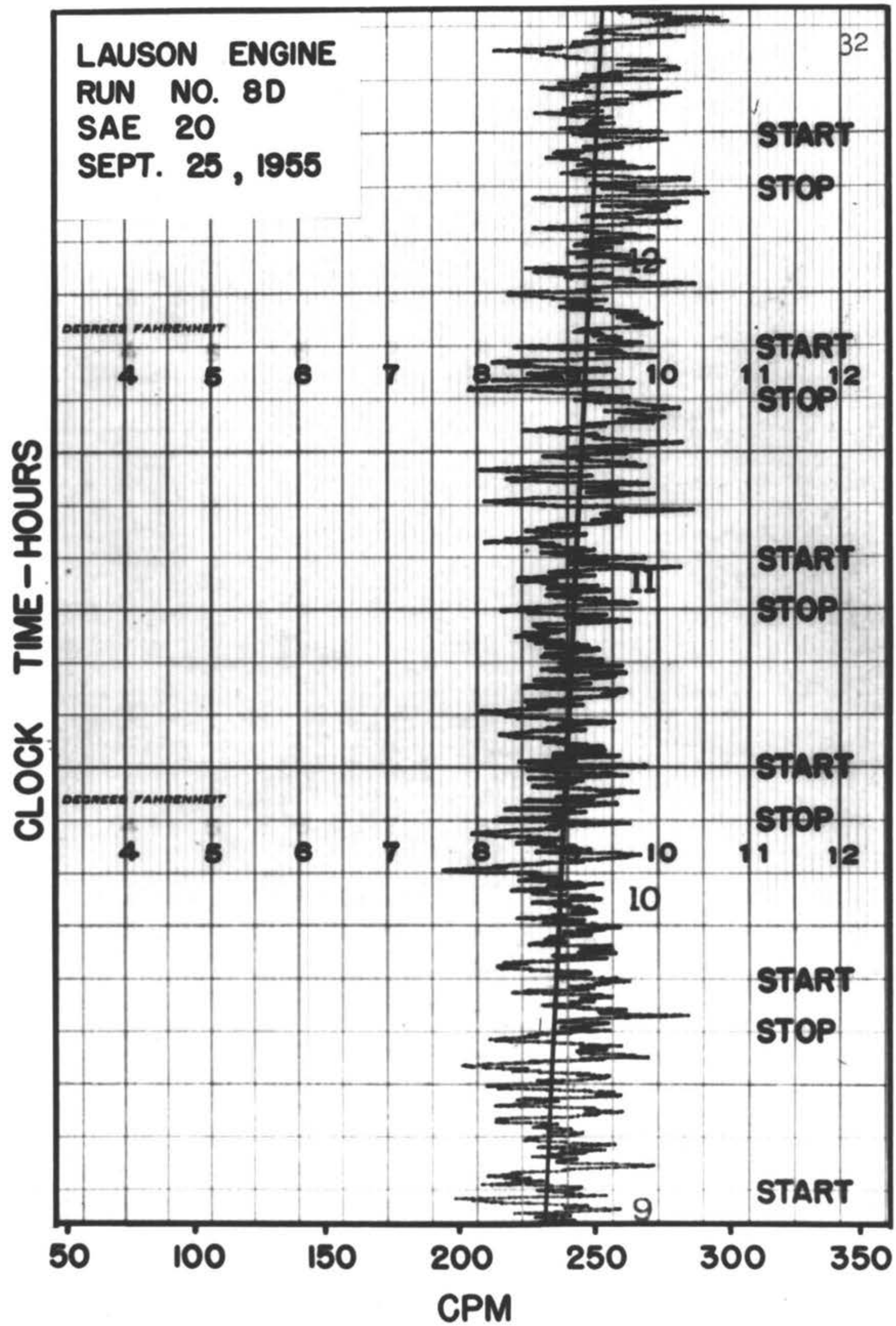

Fig. 11. Wear record of start-stop run.

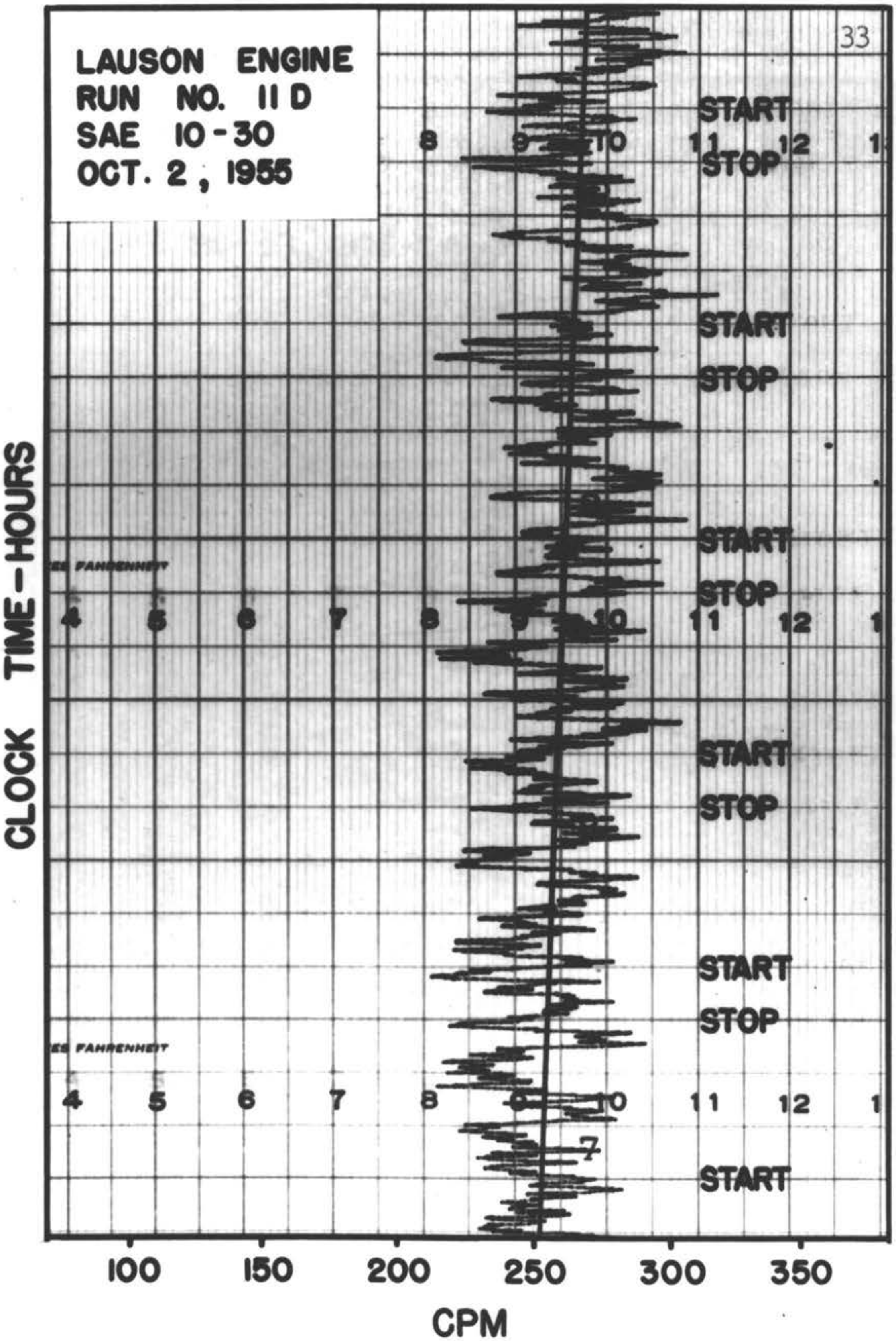

Fig. 12. Wear record of start-stop run.

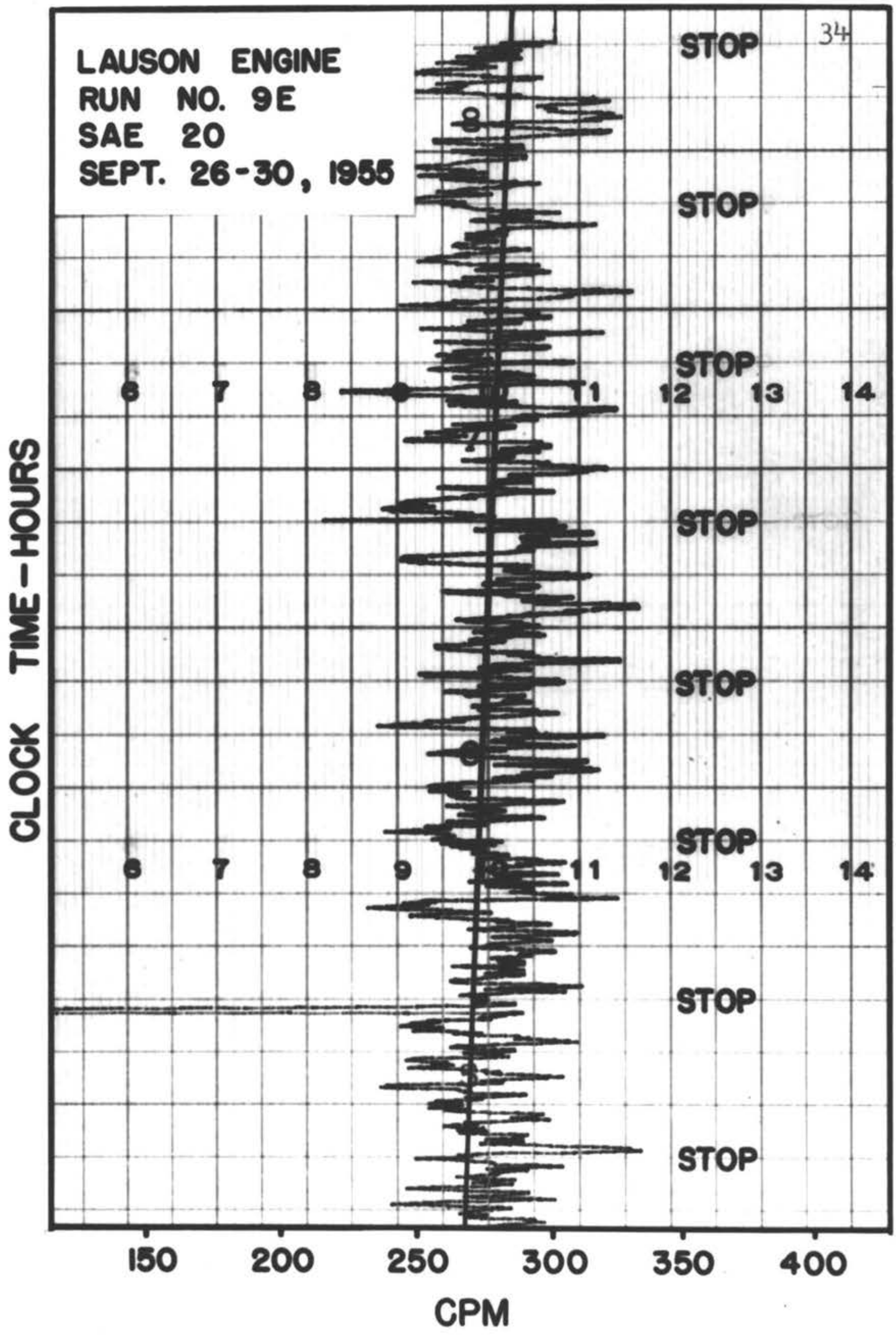

Fig. 13. Wear record of cold start run.

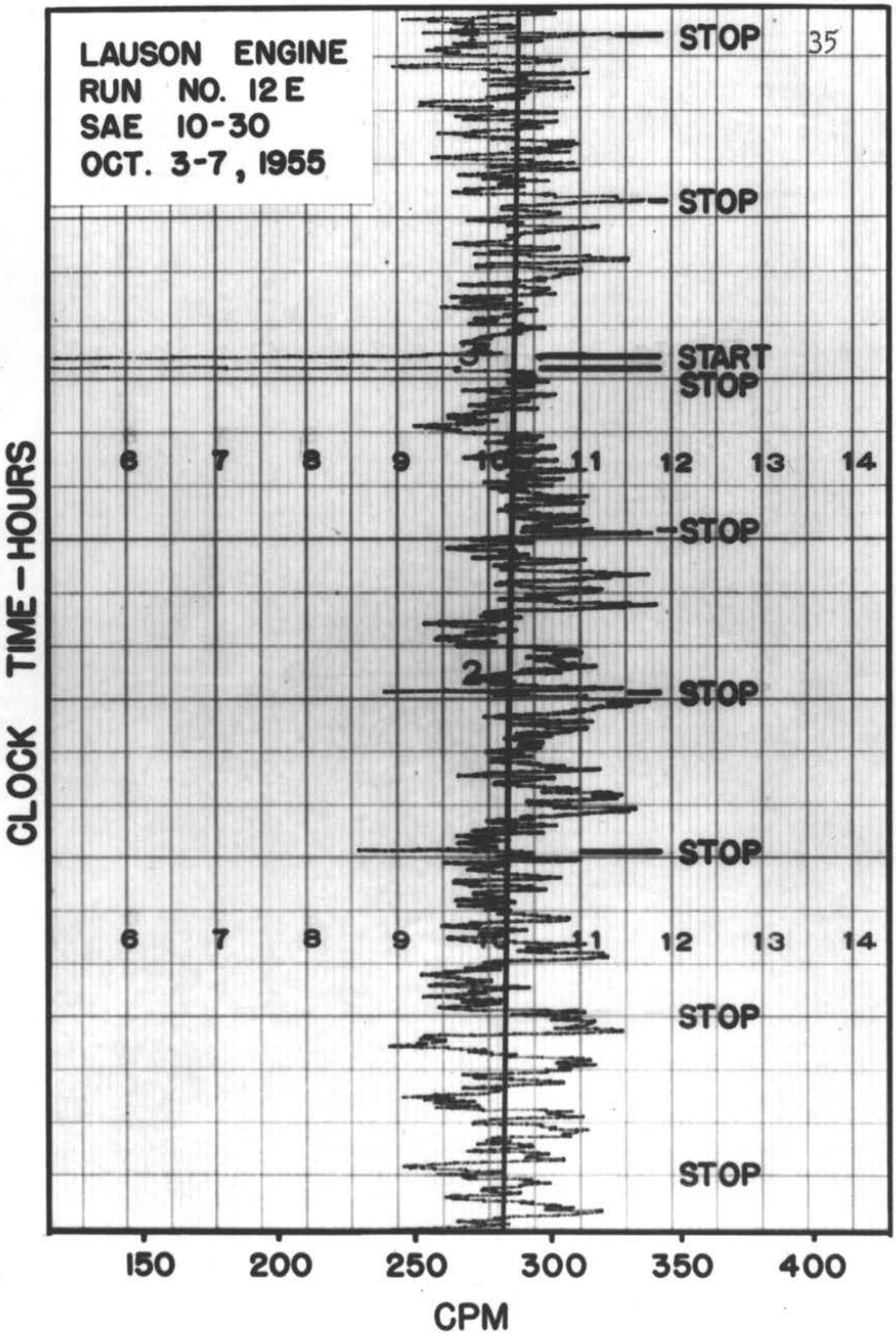

Fig. 14. Wear record of cold start run.

CONCLUSIONS

The first series of tests indicates that, while sump temperature does have an effect on piston ring wear rate, the effect is small within the range of 90°F to 180°F. The effects of other variables, such as jacket temperature and oil viscosity, have been shown to be much greater (6, pp.1-4; 12, pp.1-7; 13, pp.29-47; 23, pp.1-6). From Fig. 4, however, it may be concluded that a considerable deviation from the optimum sump temperature will result in significant wear. Within the temperatures investigated, the viscosity of the oil was such that splash lubrication was not deterred to any extent and the oil presumably reached cylinder wall temperature soon after it was deposited there.

The second series of tests indicates that, under continuous running, the wear rate is only slightly affected by increasing load. This is probably not true when overloading is involved. Wear rates are considerably increased during stop and start running. This is to be expected since cylinder walls cool off and oil drains from the surfaces while the engine is stopped. The tests indicated the wear rate under start-stop conditions was approximately twice that under continuous operation.

The tests also indicate that, under heavy loads, the

SAE 10-30 oil performs better than SAE 20. Under light load conditions the difference in the performance of the two oils is not so great and, under start-stop conditions, the SAE 20 oil may even be better.

The magnitude of the wear rate in intermittent, short period running (type E) was much less than expected. It is believed that the wear rates under such conditions should be higher than for stop-start driving since temperatures are such that condensation and, consequently, corrosive wear would be greater than in stop-start operation. However, a comparison of the wear rates for the two oils used in this test show a definite supremacy in SAE 10-30 oil where cold starts and short runs are involved.

It is believed that the conclusions drawn as a result of these tests must be tempered somewhat by factors which may have introduced inaccuracies. Briefly, these were as follows:

(1) Three times during the first series of tests the engine was dismantled to clean out lead deposits in the combustion chamber and carbonaceous deposits on the intake valve and its seat. These deposits caused loss of power and an erratic wear rate. At the end of the first series of tests the valves and valve guides were replaced and the seats were ground. Subsequently "regular" gasoline was used instead of ethyl.

(2) During the second series of tests the ratemeter and recorder occasionally failed to indicate the same counting rate as the scaler. Investigation showed that the ratemeter was designed for a higher voltage supply than it was receiving from the scaler. Incorporation of a separate power supply and modification of scale selection gave a higher millivolt output for the recorder. The ratemeter and recorder were then recalibrated.

(3) When the radioactive rings were received they had considerably less activity than those received in previous shipments. Also, due to the repair work, the tests were not completed until eighty-seven days after the rings were removed from the pile. This is nearly two half-lives. The first half-life had elapsed by the time the second series of tests were begun.

(4) A certain amount of "slugging" of iron particles occurred throughout the tests causing the recorder trace to wander. This, plus the inherent breadth of the trace, made determination of its overall slope somewhat arbitrary. Accuracy of the slope is particularly important in the latter parts of a test because of the greater influence of the decay factor.

RECOMMENDATIONS

The radioactive piston ring method for wear testing is a powerful research tool providing it is properly applied and equipment functions satisfactorily. In order that future investigators may possibly profit from the author's experiences, the following recommendations are offered:

(1) It is believed that the "slugging" of iron particles could be reduced by taking the suction for the counting system from the lowest point in the crankcase. There would be no danger of lowering the oil level in the sump if the system were kept full and free from leaks.

(2) The oil capacity of the system should be kept at a minimum and the sensing well should be no larger than is necessary for the free passage of oil.

(3) Some type of dissipative load, such as a direct-current generator and resistor bank would be more desirable than the three-phase induction generator used in these tests.

(4) The use of modified radiation counting equipment should be avoided if possible.

(5) A long half-life isotope, such as Co^{60} should be used for calibration of the counting system. A small quantity of such a material could be mounted on a probe

and introduced into the sensing well through a plugged hole in the top. This would allow periodic checking of the system.

BIBLIOGRAPHY

1. Application of radioactive tracers in the petroleum industry. Lubrication 43:133-144. 1955.

2. Atomic Industrial Forum and Stanford Research Institute. Atomic energy - the new industrial frontier. Proceedings of a meeting, April 4-5, 1955, at San Francisco, California. 254p.

3. Bradford, John R. Radioisotopes in industry. New York, Reinhold, 1953. 309p.

4. Braendel, Helmuth G. Design features affecting wear. Paper presented at the society of automotive engineers summer meeting, June 6, 1950, at French Lick, Indiana. 9p.

5. Braendel, Helmuth G. Engine wear from scuffing. Paper presented at the society of automotive engineers summer meeting, June 6, 1950, at French Lick, Indiana. 7p.

6. Brenneke, A. M. and A. J. Weigand. Piston rings and the wear problem. Paper presented at the society of automotive engineers west coast meeting, Aug. 13-15, 1951, at Seattle, Washington. 4p.

7. Ellis, J. C. and J. A. Edgar. Wear prevention by alkaline lubricating oils. Paper presented at the society of automotive engineers summer meeting, June 1-6, 1952, at Atlantic City, New Jersey. 12p.

8. Forman, Albert J. Industrial applications of electronic equipment in the automotive industry. Tele-tech and electronic industries 13:62-77. Jan. 1954.

9. Gavlin, Gilbert, Edwin A. Swire, and Sam P. Jones, Jr. Pour point depression of lubricating oils. Industrial and engineering chemistry 45:2327-2335. 1953.

10. Hundere, A., G. C. Lawrason, and B. B. Baber, Jr. Piston ring wear and scuffing with arctic lubricants. Report of Southwest Research

Institute. San Antonio, Southwest Research Institute, Feb. 1954. 37p.

11. Jackson, H. R. Laboratory and field wear tests using radioactive tracers. Paper presented at the society of automotive engineers summer meeting, June 1-6, 1952, at Atlantic City, New Jersey. 5p.

12. Jackson, H. R. <u>et al</u>. Some phenomena of engine wear as revealed by radioactive tracer technique. Paper presented at the society of automotive engineers national fuels and lubricants meeting, Nov. 1, 1951, at Chicago, Illinois. 7p.

13. Johnson, Linwood Eugene. The effect of oil viscosity on piston ring wear as determined by radioactive tracers. Master's thesis. Corvallis, Oregon State College, 1955. 52 numb. leaves.

14. Joint Fire and Marine Insurance Committee on Radiation. Report. Jan. 1951. 12p.

15. Kavanagh, F. W. Engine wear - comparison of radioactive wear and field measurements. Paper presented at the society of automotive engineers summer meeting, June 1-6, 1952, at Atlantic City, New Jersey. 5p.

16. Kunc, J. F., D. S. McArthur, and L. E. Moody. How engines wear. Paper presented at the society of automotive engineers summer meeting, June 1-6, 1952, at Atlantic City, New Jersey. 9p.

17. Manov, George G. The availability of radioisotopes and their application to petroleum and automotive research. Paper presented at the society of automotive engineers national fuels and lubricants meeting, Nov. 1, 1951, at Chicago, Illinois. 15p.

18. Miller, J. A. and H. F. Galindo. The case for synthetic lubricants in winter operation of automotive engines. Paper presented at the society of automotive engineers national fuels and lubricants meeting, Nov. 6-7, 1952, at Tulsa, Oklahoma. 12p.

19. Moore, C. C. and W. L. Kent. Wear measurements by physical, chemical or radioactivity methods. Paper presented at the society of automotive engineers summer meeting, June 1-6, 1952, at Atlantic City, New Jersey. 3p.

20. Murray, Raymond L. Introduction to nuclear engineering. New York, Prentice Hall, 1954. 418p.

21. Pennington, John W. Piston ring and cylinder wear in diesel engines. Paper presented at the society of automotive engineers national tractor and diesel engine meeting, Sept. 7-9, 1948, at Milwaukee, Wisconsin. 14p.

22. Peterson, Reuben William. The effect of operating variables on piston ring wear as determined by radioactive tracers. Master's thesis. Corvallis, Oregon state college, 1954. 39 numb. leaves.

23. Pinotti, P. L., D. E. Hull, and E. J. McLaughlin. Application of radioactive tracers to improvement of automotive fuels, lubricants, and engines. Paper presented at the society of engineers national passenger car, body, and production meeting, March 8-10, 1949, at Detroit, Michigan. 6p.

24. Raviolo, Victor G. Critical lubrication areas in an engine. Paper presented at the society of automotive engineers summer meeting, June 1-6, 1952, at Atlantic City, New Jersey. 9p.

25. Southwest Research Institute. Report of symposium on piston ring wear with arctic lubricants, March 8-9, 1954, at San Antonio, Texas. 171p.

26. Stansfield, R. and J. G. Withers. The correlation of lubricating oil engine test procedures. Paper presented at the society of automotive engineers national fuels and lubricants meeting, Nov. 6-7, 1952, at Tulsa, Oklahome. 12p.

27. Tammaro, A. The potential contribution of the automotive industry to the field of atomic energy. Paper presented at the society of automotive engineers annual meeting, Jan. 11, 1955, at Detroit, Michigan. (abstracted in SAE journal

63:32. May 1955).

28. Vacuum Oil Company. Sludges in engine oils. Engineering memorandum 1024. Automobile engineer 45:202. May 1955.

29. Wuerz, Oscar W. Corrosion is a major cause of wear in engine cylinders. Automotive industries 111:60-61. Aug. 1, 1954.

30. Zisman, W. A. Engineering possibilities of synthetic lubricants. Paper presented at the society of automotive engineers national fuels and lubricants meeting, Nov. 6-7, 1952, at Tulsa, Oklahoma. 17p.