THE APPLICATION OF STATISTICAL TECHNIQUES TO PISTON RING WEAR AS INFLUENCED BY GASOLINE ADDITIVES AND JACKET TEMPERATURE

by

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INTRODUCTION

In such a motorized age as we live in today, it is of the utmost importance to lengthen the useful life of the engines supplying us with the conveniences which we enjoy. The elimination of various factors causing uneconomical use through excessive fuel and oil losses, and leading to pronounced power losses, has been the objective of many researchers associated to this field. It is not unreasonable to claim that the disposition of the piston rings, which controls oil consumption and power losses, is a direct measure of engine usefulness and can be used as a reference to indicate when an overhaul is necessary. Therefore, any remedy which would increase the life of the piston rings, that is, to reduce piston ring wear, would aid in the improvement of engine performance and usefulness.

New methods of engine testing and refined methods for detecting wear of piston rings, due to the numerous engine operating variables, have brought about significant changes in automotive design and the fuels and lubricants used for automotive purposes. Nevertheless, engine wear is still considered as an unsolved problem. Verification of previous test results and still more refined methods for testing engines are needed to give the automobile owner a more useful and dependable product.

It is intended that the material contained in this paper will clearly illustrate that statistical techniques offer the most valid methods of design and analysis to the experimental scientist, regardless of the field of research. The application of statistical methods to the study of fuel effects on piston ring wear at low jacket temperatures will provide ample evidence regarding the advantages of these techniques, as well as supplying information concerning the investigation.

PISTON RING WEAR AND MEASUREMENT

The recent amount of research work done with piston ring wear has given an insight to many of the problems associated with engine performance. Numerous investigators have studied the sources and many patterns of piston ring wear. From these results the useful life of engines, in the past few years, has been considerably increased. Power loss and oil consumption, which are largely dependent upon piston ring condition, are used to determine the usefulness of an engine. Therefore the study of all factors causing piston rings to wear represents a field of major importance in engine research.

There are four accepted theories by which piston rings can wear. These processes are friction, abrasion, scuffing and corrosion. Engine manufacturers and oil companies have attacked the wear problem and in many cases have established remedies by which these above mentioned processes have been lessened.

To reduce piston ring wear a method for measuring the wear has to be available. The various methods used are:

1. Physically weighing the rings before and after each test,
2. Measurement of the reduction in length of special marks stamped into the rings before and after use,
3. Determination of the increase of iron content in crankcase oil by chemical means,

4. Radioactive tracer method measuring the increase in intensity of irradiated iron particles worn from the piston rings.

The first three methods are time consuming, based upon weak assumptions, and inaccurate as compared to the fourth method. The advantages of the radioactive tracer method are listed below.

1. Small amounts of wear are easily detected. One milligram of top ring wear will give a counting rate of approximately 45 CPM above a background of 30 CPM with the particular experimental arrangements used (3, p. 530).
2. A continuous recording of wear allows for detection of transient effects.
3. The materials being tested and the number of personnel required to run a wear test are decreased to a minimum. A subsequent reduction in time is also advantageous with respect to the availability of results.
4. Each variable is effectively isolated due to the reduced time of the wear test.

The expensive apparatus required by this method is more than justified when compared to other methods of measuring wear and their respective weaknesses.

RADIATION PROTECTION

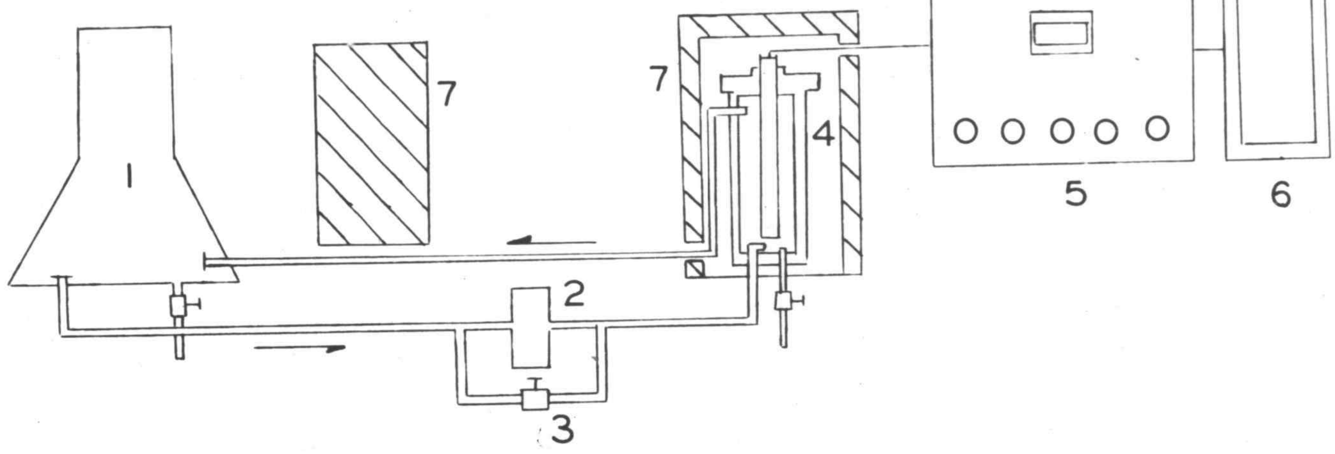
When radioactive materials are used in wear test experiments, there are two immediate systems requiring radiation protection. The first and prime consideration is given to the operator or personnel. The second system is the detecting apparatus which requires protection from stray radiation due to the decay of the irradiated source.

The International Commission on Radiological Protection recommends a maximum permissible exposure, from external sources, of three hundred milliroentgens per five day working week, based upon whole body exposure (6, p. 549). Recent information indicates that this level has not been altered (12, pp. 260-261). During the time interval starting with receipt of the two irradiated rings and engine installation and ending with the completion of engine testing there were no personnel receiving an excess to the above prescribed dosage. The maximum amount of exposure occurred during the period of ring installation and engine reassembly. Film badge dosimeters were worn by both personnel during this period and the resulting bodily exposure was found to be twenty milliroentgens. The time involved during this period was one half an hour. It is noted that the twenty milliroentgens received during this period did not surpass the recommended dosage. Subsequent degrees of exposure were measured on a weekly basis with similar film badge dosimeters. The maximum dosage received during a normal week of operation was twenty milliroentgens.

Other precautions taken during the engine testing operations were as follows:

1. Oil-resistant gloves were worn by the operator whenever disposing of contaminated oil or working on engine parts and apparatus.
2. Disposable towels were used for cleaning tools, oil spillage, and hands after the periods of operation.
3. Frequent checks were made on hands and clothing using a RCL Mark 11 Model 10 portable geiger counter suitable for detecting small amounts of radioactive contamination.
4. A Tracerlab SU-1F Portable Radiation Survey Meter was periodically used to measure radiation levels in the vicinities of the test apparatus and engine exhaust (6, p. 563). There were no traces of contamination in the area surrounding the engine exhaust.

To protect the instrument detecting the irradiated iron particles in the external oil system, it was necessary to place shielding between the engine and the wear detecting instrument. Sufficient shielding consisted of an interlocking brick wall constructed of lead with a thickness of six inches. An additional one inch thick lead casing enclosed the sensing well housing the detecting instrument. With the instrument exposed to the test engine a reading of 6000 counts per



1 LAUSON H-2 OIL TEST ENGINE
2 OIL CIRCULATING PUMP
3 BY-PASS (REGULATES OIL FLOW)
4 SENSING WELL ENCLOSING GEIGER TUBE
5 TRACERLAB PRECISION RATEMETER
6 ESTERLINE-ANGUS RECORDER
7 LEAD SHIELDING

Fig. 1. Schematic Diagram of Radiation Detecting and Recording Apparatus.

minute (CPM) was observed. With the shielding properly placed the instrument gave a reading of 100 CPM. Normal background prior to receipt of the irradiated rings was 50 to 60 CPM. The shielding employed was considered adequate for this investigation.

APPLICATION OF STATISTICAL TECHNIQUES

An engine is a complicated apparatus. Its operating characteristics and performance are affected by many variable factors. These factors have been the subject of a considerable measure of study in the field of engine research.

New methods are necessary to study and ultimately eliminate the undesirable factors. Interactions occurring between these factors require powerful methods of analysis to differentiate between real effects and experimental error. It is equally important to compare the effects various products have upon engine performance. Statistical techniques offer the most economical designs of experiments (16, pp. 531-538). When used to analyze data the significant differences in these factors are readily determined and the accuracy with which real effects are distinguished from experimental error is greatly increased.

It is not unreasonable to state that all experimental results are subject to error. It is also quite common that conclusions are drawn from totally inadequate data. An ill designed experiment, based upon only a few observations, can end with the acceptance of almost any hypothesis. By solely inspecting data and using inductive reasoning, one cannot reveal the true state of affairs. But by using statistical methods, it is possible to produce information concerning the confidence with which conclusions are drawn from data and, in turn, reduce the chances of making wrong decisions.

Consider, as an example, that a test has been run using two engines of the same design to investigate the effects that two blends of fuel have upon piston ring wear. The results indicate that one blend causes slightly more wear than the other blend at a given set of engine operating conditions. There are two alternatives the experimenter can take in publishing his results. He may consider that the results obtained are only applicable to similar tests, thereby not committing himself to results found in actual usage. Secondly, due to the closeness of results (data), he may consider that there would be no significant difference in wear from these two blends upon actual field applications.

In both cases he has not provided information concerning either the reproduction of his test data or the conditions with which he has utilized inductive reasoning, regarding the distinction between true results and experimental error. It is not necessarily true that the same two fuel blends would give the same results when tested again or in another pair of engines. However, by incorporating a statistical design, the results of the investigation are somewhat different. The experimenter can analyze his data in such a manner that only a great amount of evidence not rejecting his hypothesis will result in a faithful acceptance of the hypothesis being tested.

It is the objective of statistical techniques to furnish information regarding the general case based upon sufficient evidence supplied by a particular application. When a hypothesis is tested there are two possible types of errors that can, and are, frequently made (8, pp. 45-53). The first type of error involves rejecting a true hypothesis. In statistics, the probability of committing this type of error, a Type I error, is termed the level of significance. As an example, the five per cent significance level implies that five per cent of all possible samples drawn from a population will lead to the rejection of a hypothesis if it is true.

The question arises why a zero per cent significance level is not used, thus eliminating the mistake of ever rejecting a true hypothesis. This uncovers the other type of error. A Type II error is defined as the acceptance of a false hypothesis. The experimental accuracy used in testing hypotheses governs the control of this type of error. It is noted that the use of a zero per cent significance level would lead to the acceptance of any hypothesis whether it be true or false.

As the sample size is increased, or the amount of information concerning a specific hypothesis is increased, the probability of committing a Type I error is reduced. Of course, the hypothesis being tested has to be a true hypothesis. If a false hypothesis is tested, the chances of making a Type II error will be reduced due to the increase in the amount of experimental evidence. The increase in sample size is not the only way to reduce both types of error. If the variation of the observations within a population (variance) is decreased, both types of error are also reduced. Reduction of the variance is obtained through experimental technique.

A summary of the above discussion is offered to simplify the meanings of both types of error and the factors governing their control.

1. For the same sample size the reduction in significance level, Type I error, will cause an increase in the probability of committing a Type II error.
2. A greater difference between the true value and the assumed value will decrease the probability of committing a Type II error if the significance level and sample size remain unchanged.
3. By either increasing the sample size or reducing the population variance, or a combination of both, the probability of committing both types of error is reduced.
4. The improvement in experimental technique tends to reduce the probability of accepting a false hypothesis if the significance level remains unchanged.

The discussion of the two types of errors involved in statistical analysis and the means for reducing the probability of committing them is presented as a linkage between the design of the experiment and the validity in using statistical methods to analyze data. After collecting data from any type of experiment, there are always assumptions involved in the methods of analysis. In the field of materials, stresses are assumed to be proportional to strain, materials are assumed to be homogeneous, and so forth.

Similarly, it is assumed that samples are randomly distributed in the statistical analysis (5, pp. 17-21, and 8, p. 54). The meaning of randomization is that no guidance is used in obtaining the samples. A random sample contains observations, all of which have equal opportunity of being drawn. It can be seen that in a wear test some of the important factors affecting wear are themselves affected by the wearing process. The cylinder liner material affects piston ring wear, and in turn the wearing of the rings causes the cylinder liners to wear. The variations owing to the wear of these components must be distributed in such a manner that the results are not biased by their effects.

Consider an experiment is run to determine the effects fuel sulfur has upon piston ring wear. Without a statistical knowledge, the experimenter may reason that the fuel samples should be tested in an order of increasing fuel sulfur contents. This would eliminate any carry-over effects from one sample to the next since it is already known that fuel sulfur does cause piston rings to wear. What has not been taken into consideration by the experimenter is that the piston ring does not necessarily function in the same manner between successive tests. It may be the case that during the first few tests that the ring wear is sufficient to cause both crankcase dilution and oil losses. By the time the last test is run, the measured wear rate will be a combination of fuel sulfur effects, abrasive particles from previous tests, and improper lubrication of the cylinder walls. The conclusion from this experiment would indicate a significance in wear rate differences between high and low sulfur content fuels. It would be most embarrassing to the experimenter to discover that the wear rate of the lowest sulfur content fuel, run after the experiment, was greater than the wear rates observed during the experiment for possibly the next two lowest sulfur content fuels. Not only would this prove embarrassing, but a complete loss in time and materials would be the consequence of this improper design.

Some of the advantages are not readily apparent when statistical methods are used to investigate minor factors contributing to wear. Still, it is not known if these minor factors affecting wear interact under certain conditions. Statistical analysis considering such a problem, can determine whether or not these minor factors interact. It is just as important to know what factors cause wear as well as those which do not cause wear.

It is the intent of the complete discussion presented above to show some of the advantages statistical techniques can offer by using proper designs and correctly analyzing data. The randomization of tests is one of the most important stipulations in an investigation as has been shown. To gain the maximum amount of correct information possible from an investigation, one must have both a clear knowledge of statistics and that of the subject matter field. The designing of tests is quite critical; the actual running of the tests is no more than anti-climatic.

Reference has frequently been made to the analysis of data. One might expect that the methods require high powered mathematics. Actually, all that is required is algebra and the use of a desk calculator to simplify the computations. In the statistical analysis a number of tools are used. No one would expect to employ a single method to obtain all the answers to a problem. A combination of these tools, such as analysis of variance, new multiple range test, and the single degree of freedom are used together to fulfill the objective of the statistical application; to give information about the general case using sample data.

In this investigation, statistical techniques were used to study the effects various gasoline additives have upon piston ring wear at high and low jacket temperatures. A two factorial experiment was statistically designed based upon the following assumptions:

1. The set of irradiated piston rings used in the experiment were representative samples of normal piston rings.
2. The condition of engine parts, especially of the piston rings, would not change enough throughout the entire experiment to alter the effects the various fuels had upon piston ring wear.
3. The amount of oil loss through consumption and leakage during each of the four replications is negligible.
4. Four replications would be sufficient to obtain representative data.
5. Four hours of engine running per fuel sample would be sufficient to obtain a representative wear slope.
6. The method for agitating the fuel samples after mixing in the additives would give a homogeneous blend.

In this experiment the data were analyzed using a randomized block design for the analysis of variance. The new multiple range test was used to rank the fuels according to their respective wear rates at both jacket temperature conditions. The single degree of freedom was then used to test two specific hypotheses. Calculations for these methods of analysis are included in the Appendix. The information regarding the results of these tests are discussed in the Test Results and Conclusions.

OBJECTIVES

The purpose of this study is actually twofold. Although there has been much work done in the past few years in the field of engine research, there is still much to be done in advancing the testing procedures. Refined methods for engine testing will both educate the experimenter and yield more reliable results.

In this investigation, various fuel blends were tested at both high and low jacket temperatures to study their effects upon piston ring wear. Previous research work has indicated that fuel sulfur is the main cause of wear, by corrosive action, at low jacket temperatures. By comparing the wear rates of the fuels containing additives to the wear rate of the base fuel, all of which contain the same amount of sulfur, the effects not due to sulfur on piston ring wear can be determined. The amount of sulfur in the fuel and the concentrations of additive mixtures all simulate typical regular gasolines currently being marketed.

It is of equal importance to develop new methods for engine wear tests. The second objective of this study is to illustrate that statistical techniques offer the best available method for the design of an experiment and the analysis of data. To fulfill this second objective, the wear test investigation will furnish information necessary to present a valid illustration.

APPARATUS

The two irradiated compression rings were standard equipment of the Type H2, single cylinder, Lauson Oil Test engine used in this experiment. Engine load was created by overspeeding a three phase, sixty cycle, 220 volt, Type K, G. E. Motor rated at three horsepower. Generated power was fed through two Type JP-1, G. E. Instrument Current Transformers and recorded by a Type CD-15, AC-DC, G. E. Recording Wattmeter.

The lubricating oil was heated by three 500-watt Weigand heater bars located in the base of the Lauson engine. Current was supplied by a 110 volt Powerstat transformer. The amount of current supplied to the heater bars was indicated by an ammeter located in the instrument panel.

Lubricating oil was drawn out of the engine sump with a Brown-Sharpe gear type pump driven by a Type A, 1/6 hp, Delco AC Motor. A by-pass valve around this pump was used to regulate the flow of oil. Vacuum and pressure gages located on either side of the oil pump permitted an accurate control of the oil flow.

Fuel was supplied to the engine in a gravity flow arrangement from three 5-gallon cans. The fuel lines were connected to a three way inlet, one way outlet, Weatherhead valve. The air-fuel ratios were indicated during the tests by an Elliott Carbumeter. Periodic orsat gas analyses were taken to check the accuracy of the Elliott instrument.

Oil temperature was taken by a thermocouple placed at the point where the oil was drawn from the engine crankcase. This temperature was recorded on a Brown Continuous Balance Potentiometer recorder.

To eliminate any abrasive particles or dust from entering the engine, a flannel cloth air filter arrangement was placed over the air intake of the carburetor.

A standard equipment reflux vane, located in the top of the engine cylinder housing, was used to maintain a constant 212°F jacket temperature. Steam was produced from the water in the jacket and then condensed upon rising to the city-water cooled reflux vane. It was necessary to modify the external apparatus supplied with the engine to obtain a constant 120°F jacket temperature. Water was pumped by a 3/4 size, Deming centrifugal pump, driven by a Type SEO, 1/4 hp, Dunlap motor, and through a counterflow water heat exchanger. Upon leaving the heat exchanger, the water was raised to a level equal to the top of the condenser housing and was forced into the full-length water jacket housing. By controlling the flow of cooling water being circulated through the counterflow heat exchanger, the 120°F jacket temperature was maintained. Capillary probes indicated the temperatures of water both entering and leaving the jacket. A recording of the water temperature made on a Wilson-Maeulen Continuous Line Mechanical Lever Recorder was used to indicate constant conditions.

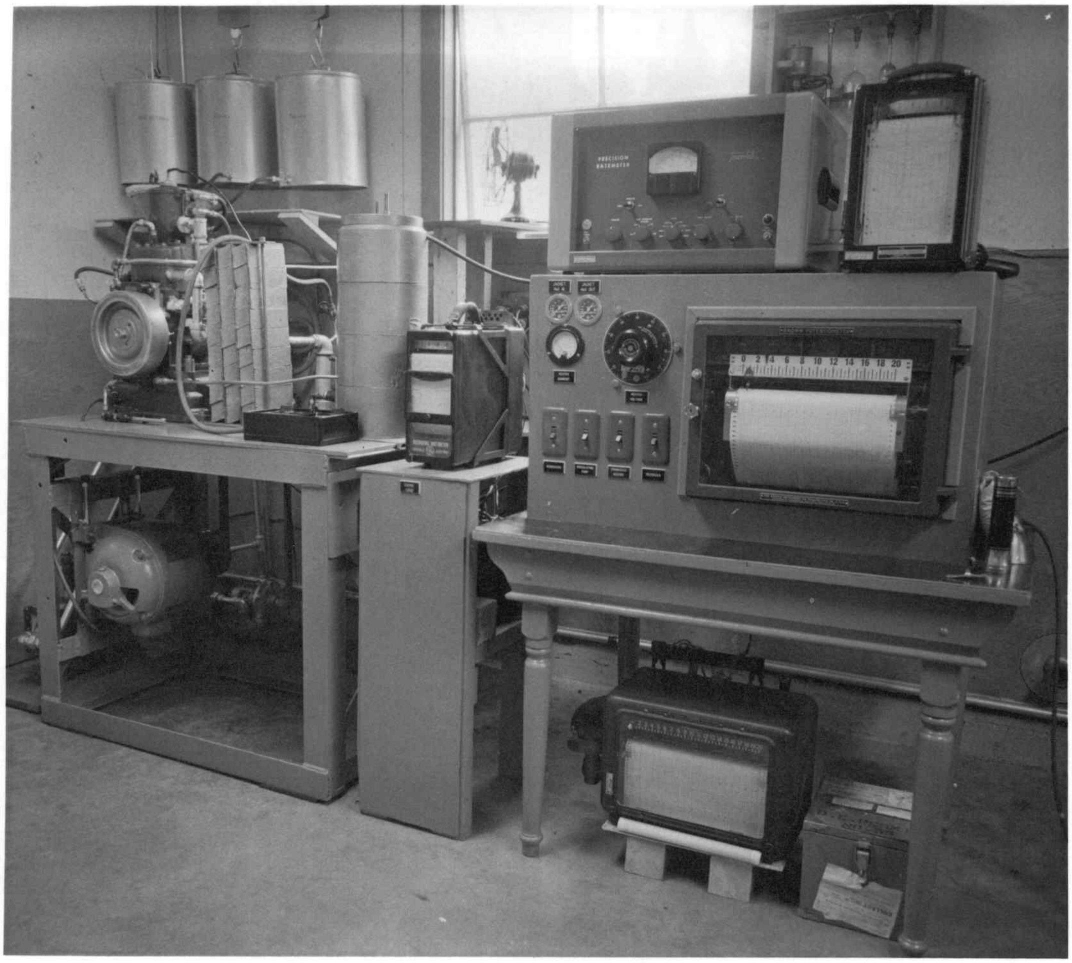


Fig. 2. Experimental Wear Testing Facilities.

A thermocouple probe from this instrument was inserted through the top of the condenser housing and placed in the center of the jacket at a depth of two inches of circulation of the jacket water.

The oil, after leaving the external oil pump, was forced upwards in a swirling motion, around a Type GC1K Geiger Mueller Counter tube, through a brass sensing well. The oil was then returned to the engine crankcase. A Type SC-34A Tracerlab Precision Ratemeter supplied high voltage to the geiger tube. Impulses caused by ionization of the geiger tube gases were received by the ratemeter and in turn amplified to register the radiation or iron content intensity of the oil. A Model AW Esterline-Angus Graphic Ammeter Recorder was connected to the ratemeter to record the oil intensity and thus file permanent records of the piston ring wear.

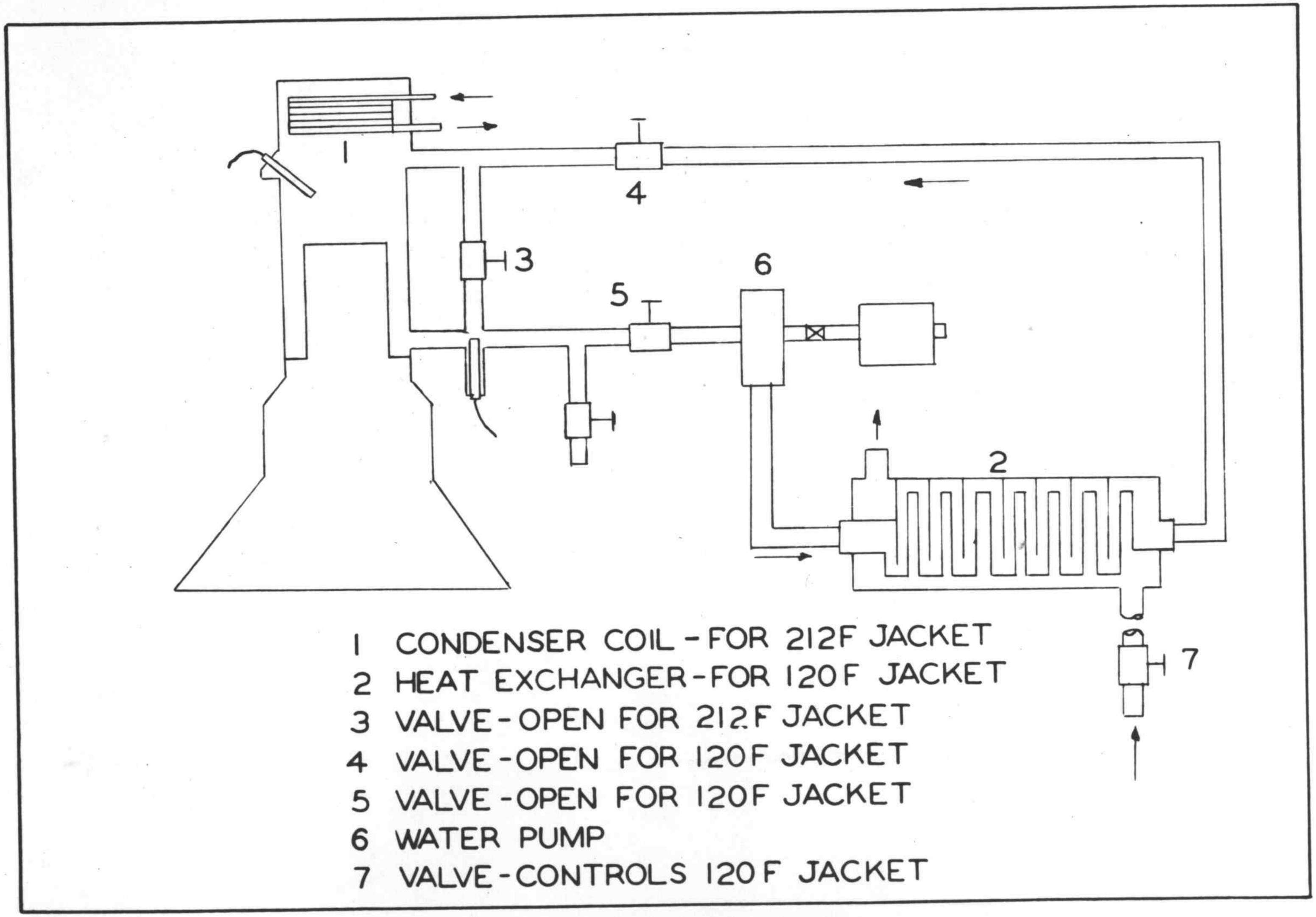


Fig. 3. Engine Cooling Systems.

TESTING PROCEDURE

After the rings had been installed in the engine and the engine reassembly completed, a break in period of nine hours indicated a constant wear rate. Iso-octane fuel and SAE 20W oil were used during this pretesting period. Operating conditions of the engine during break in were as follows: 212°F jacket temperature, full throttle, 160°F oil temperature, and a 13.0 to 1 air-fuel ratio.

The statistical design of the tests required that no radical changes in engine operating features be made once the testing began. For this reason all apparatus were doubly checked before starting the first replication. It was presumed that four replications would provide an adequate amount of information while eliminating any errors introduced in the operating features. The order with which samples were tested and the operating conditions for each test was determined from a random sampling numbers table (8, p. 509). A total of forty test runs, consisting of four hours per test or one hundred and sixty engine hours, comprised the experiment from which useful data were obtained.

Previous work at Oregon State College has indicated that a period of six to eight hours is required to obtain a constant wear rate (10, p. 19, and 11, p. 20). With improved apparatus, refined operating methods, and by running successive fuel samples without stopping the engine, it was predicted that the time could be reduced to four hours per test and still obtain representative wear rates. Continuous engine operation between successive fuel samples was achieved by using three fuel tanks, in a gravity flow arrangement, connected to a common fuel valve.

During the tests, one container would supply the engine with a fuel sample while the second container was disconnected from the system. Ample time was allowed in the four hours between each test to carefully clean the disconnected container of any residual fuel and to fill it with the next sample to be tested. The third fuel tank contained iso-octane, and it was necessary to only refill it occasionally. Iso-octane was used during the engine warmup periods and transition periods between the samples requiring a change in jacket temperature.

A brief discussion of the fuel blends included in this investigation merits attention at this point. Mixing of the compounds to the base fuel was done in a down draft hood since all but one of the mixtures contained toxic lead. After obtaining the desired mixture ratios, each of the fourteen gallon blends was agitated for a period of not less than two hours. The final mixture ratios used in this study were:

Tricresyl phosphate	1cc plus 3cc Motor Mix per gal. of base fuel
Motor Mix	3cc per gallon of base fuel
Motor Plus	3cc per gallon of base fuel
Aviation Mix	3cc per gallon of base fuel
Base fuel	no additives

The above concentrations were chosen to approximate the amounts encountered in typical fuels. The sulfur content of the base fuel was determined by the standard Sulfur Lamp test (18: Method 5201.5). The sulfur content, by weight, is 0.095 per cent. The most recent information published on motor gasolines (2, pp.2 and 28) indicates that the average sulfur contents of regular gasolines are 0.063 per cent and 0.075 per cent for the nation and the Pacific Northwest (Western Washington and Western Oregon), respectively. This illustrates that the base fuel used in this experiment was similar to the typical marketed fuels. The similarity is based upon the sulfur contents since other fuel constituents have a comparatively small effect on piston ring wear at jacket temperatures where corrosive wear is predominant. Recommended instructions for handling the toxic fluids were followed throughout the mixing processes. Each of the remaining quantities of the blends were again agitated prior to being used.

The conditions maintained during the actual testing were:

Jacket temperature	120°F	212°F
Air-fuel ratio	13.2 to 1	13.2 to 1
Oil temperature	160°F	160°F
Indicated engine load	1.8 kw	1.8 kw
Engine speed	1880 rpm	1880 rpm
Ignition timing	23°BTDC	23°BTDC

TEST RESULTS

From the analysis of variance table shown in the Appendix, the results of the four general hypotheses tested are as follows:

1. The hypothesis is accepted. The operating features of the engine and the amount of wear of parts did not significantly change during the experiment. In other words, the amount of excessive wear other than fuel effects is negligible.
2. The hypothesis is rejected. The fuels do not have the same effect upon piston ring wear. This indicates that the difference in composition of the additive compounds produced different rates of wear.
3. The hypothesis is rejected. The result of changing the jacket temperature from 120°F to 212°F, or vice versa, is a significant change in the wear rates produced by using the various fuels.
4. The hypothesis is rejected. This indicates that interaction does exist between the five levels of fuel and the two levels of jacket temperature. A constant difference is not maintained for each of the five fuels between the two jacket temperature conditions.

The above results are general and are not sufficient to provide the necessary information concerning the individual fuel blends. For this reason, the new multiple range test was used to rank the fuels with respect to their mean wear rates based upon four observations. The calculations and tabulated results of this test are shown in the Appendix. The results of this investigation are as follows:

At the 212°F jacket temperature operating condition:

1. The difference in wear rates between the fuels containing the following additives are significant.

   A. Motor Plus and Aviation Mix

   B. Motor Plus and Base fuel

   C. Motor Plus and Tricresyl phosphate

2. The differences in wear rates of all the remaining combinations of fuel blends is not significant at the 212°F jacket temperature.

At the 120°F jacket temperature operating condition:

1. The difference in wear rates between the fuels containing the following additives is significant.

   A. Motor Mix and Tricresyl phosphate

   B. Motor Mix and Motor Plus

   C. Motor Mix and Aviation Mix

   D. Motor Mix and Base fuel

   E. Base fuel and Tricresyl phosphate

   F. Base fuel and Motor Plus

2. The differences in wear rates of all the remaining combinations of fuel blends is not significant at this operating condition.

To determine whether or not sulfur is the main cause of wear at the lower jacket temperature operating condition, the single degree of freedom is used to test the hypothesis that the wear rate of the base fuel is equal to the average wear rate of the four blends of fuel containing the various additives. The calculations for this test are shown in the Appendix. The results of this test indicate that the hypothesis is accepted; the average wear rate of the four fuels containing additives is not significantly different from the wear rate of the base fuel at the 120°F jacket temperature. This indicates that fuel sulfur is the main cause of piston ring wear at low jacket temperatures, based upon four fuel blends containing the most popular additives commercially marketed.

It has been observed that certain blends produce wear rates that are significantly different from others. This was shown in the new multiple range test. To determine whether the fuels containing additives, as a group, possess any significant quality, either good or bad from a wear standpoint at the 212°F jacket temperature, would be of interest. This is also accomplished by using the single degree of freedom, as shown in the Appendix. The hypothesis tested is that the average wear rate of the four fuels containing additives is equal to the wear rate of the base fuel. This hypothesis is accepted and it is concluded that the blends containing additives do not possess any significant quality, neither favorable nor undesirable, from a wear standpoint.

CONCLUSIONS

The analysis of variance results indicate that there is no replication effect. This was one of the original assumptions considered in the design of the experiment. Since there is no replication effect the following assumptions have been verified.

1. The variable effects of the different fuels upon piston rings are not affected by the changing conditions of the many engine parts also subject to wear.
2. The method of agitating the fuel blends gave homogeneous mixtures.
3. Four replications were sufficient to obtain valid data based on four hours per test run.

The results of the analysis of variance also indicate, by the presence of the interaction term, that the fuels do not cause the piston rings to wear in the same manner between the two operating conditions. One would expect a result such as this. It would also be expected that the change in jacket temperatures would produce a significant difference in the wear rates. This has been shown by the third hypothesis tested in the analysis of variance.

It was necessary to use the new multiple range test to discover which of the fuels possessed the qualities causing the interaction term. It was previously shown that the average wear rate of Motor Plus was greater than any other fuel at the higher jacket temperature. The results of this test indicate that the relation existing between the wear rates of Motor Plus and Motor Mix is one of no significant difference. Yet, the difference between Motor Mix and the other fuels is not significant either. The position of the Motor Mix additive could be in the same class as the Motor Plus additive or in the same class as the other fuel blends. It may even be in a group by itself. Only further experimental evidence will clarify the situation. Previous work at Oregon State College (10, p. 30) has indicated that the differences in Motor Plus and Motor Mix wear rates are small when compared to the very small wear rate of the Aviation Mix additive. It appears from these results that the wear rates of the fuels increase as the content of the ethylene dichloride scavenger is increased. Aviation Mix and of course, the base fuel contain no ethylene dichloride; the Tricresyl phosphate mixture, Motor Mix and Motor Plus each contain one theory of ethylene dichloride (4, p. 8). It may be that the phosphorus constituent of Tricresyl phosphate helped to lower the wear rate, as compared to the Motor Mix additive. Motor Plus contains one-tenth of a theory more of ethylene dibromide than Motor Mix and Tricresyl phosphate, which contained an equal amount of Motor Mix as the former. It is speculated that this constituent caused the increased wear rate. Since it has already been shown that an interaction term exists, it would be unreasonable to expect that the same conditions or explanation of results would hold for the 120°F jacket temperature operating conditions.

It was mentioned in the preceding paragraph that the position of the Motor Mix additive, at the higher jacket temperature, was not clear. It might have belonged to one of two groups, or it may constitute a group of its own. When the engine was operated at the lower temperature condition, the wear rate of this additive was found to be in a class of its own. This was also determined from the new multiple range test. It has a wear rate significantly higher than any of the other fuel blends. Another very recent investigation substantiates the placement of this type additive when operating at low jacket temperatures (1, p.81). Yet, this does not indicate that the Motor Mix additive belongs to any certain group in the 212°F temperature conditions. Only an increased sample size can produce a correct answer.

The Tricresyl phosphate type of fuel produces a significantly different wear rate than the base fuel at the low operating temperatures. It is only possible to speculate that the phosphorus compound reduces the amount of piston ring wear at this condition. It is known that acids composed of phosphorus are quite corrosive to metal surfaces. It is also possible that these acids are formed at the low jacket temperatures due to the presence of liquid water which has been condensed and deposited on the cylinder walls. There are many theories supporting this type of action (13, pp. 39-44, and 15, pp. 216-221). The possibility that these phosphorus compounds prevent other acids from reaching the metal surfaces cannot be excluded. This would have to be studied in another experiment where the amounts of this additive were varied with different amounts of fuel sulfur, assuming that fuel sulfur is the main cause of corrosive wear.

No explanation if offered with respect to the action involving the Motor Plus additive at the low operating condition. Another series of tests would have to be designed to study the characteristics of this additive at low operating temperatures. It is the result of this investigation that the Motor Plus additive gave a significantly lower wear rate than that of the base fuel.

It has also been shown that the Aviation Mix additive could possibly be a member of two groups, or make up a group of its own. As it was brought out for the Motor Mix additive for the higher jacket temperatures, only more evidence can clearly determine the effects this type of additive has upon piston ring wear at the lower jacket temperatures.

Previous research work has indicated that sulfur is highly regarded as the main fuel constituent causing wear at cylinder wall temperatures where water is formed on the metal surfaces (14, p. 27, and 1, p. 81). From the individual degree of freedom, with the results of the lower operating temperature, substantiate this theory. It is the conclusion that fuel sulfur, as encountered in these typical fuels, is the main cause of wear at the lower operating temperatures.

It is also concluded, from the results obtained in the 212°F jacket temperature tests, that the fuels containing additives possess no significant qualities, from a wear standpoint, different from the base fuel. This statement is not entirely unreasonable, since none of these additives are intended, primarily, as wear reducers. They are intended, essentially, as combustion chamber deposit modifiers (7, p. 93 and 9, p. 666). But any gasoline additive, before being marketed to the public, must conform to a number of specifications. One of these specifications is to cause no damage to engine parts, which would naturally include piston ring wear. Therefore, the conclusions seem to be quite reasonable.

A review of this presentation should clearly indicate the many advantages possessed by an experiment using statistical techniques. The use of a factorial design in this experiment illustrated three distinct advantages.

1. Economy is established in effort and experimental material.
2. Interaction between factors is easily detected.
3. The conclusions reached are more general.

The advantage of checking assumptions in this type of design is also rather evident. Since all conclusions have been based upon the assumptions made in the test, it is only justice that they be verified in some fairly systematic manner before the confidence with which conclusions are made, is presented.

The accuracy with which the results of this investigation have been founded are all based upon the five per cent significance level. These results can be applied to other engines with reasonable accuracy. The accuracy with which these results can be substantiated will depend upon the knowledge of statistics and the subject matter field possessed by the other investigators.

RECOMMENDATIONS

It should be noted that the paper presentation does not represent a complete study of wear at low jacket temperatures. There have been no remedies studied, which would be designed for reducing the low jacket temperature wear. The results of this test indicate that both the Motor Plus and Tricresyl phosphate additives do not contribute to piston ring wear, as compared to the other fuels, where corrosive wear is expected to occur. The following recommendations are offered, with respect to these two additives, for advance study:

1. Design of a two factorial experiment to study the effects of the phosphorus compound on ring wear at low jacket temperature operating conditions. The two factors would be the quantities of phosphorus compound and fuel sulfur.
2. Design of a three factorial experiment to study the effects phosphorus compounds have on piston ring wear at low jacket temperatures when mixed with various antiknock compounds. The three factors would be the phosphorus compound, antiknock compounds, and fuel sulfur.
3. Design of a three factorial experiment to study the effects of phosphorus compounds on ring wear when mixed with different antiknock compounds of variable concentration in the fuel. The three factors would be the phosphorus compound, antiknock

fluids, and the quantities of antiknock fluids in the fuel.

4. Design of a two factorial experiment to study corrosive wear actions with the Motor Plus antiknock compound. The two factors would be the concentrations of Motor Plus and sulfur in the fuel.

It would also be of interest to make a survey of the gasoline additives sold in service stations. The additives referred to are those additives claimed to reduce wear, increase engine power and performance, prevent any gumming action in the fuel, and to have other desirable features. A number of experiments could be designed using these additives. Especial interest would be their effects upon piston ring wear:

1. At different jacket temperatures.
2. At various engine load conditions.
3. Over a range of oil temperatures, using different types of oil.
4. With fuels containing different amounts of sulfur.

The Lauson engine, with slight modifications, and the test apparatus used in this experiment, would provide excellent testing conditions. Since the Lauson is a single cylinder, there would be no interaction effects from other cylinders such as fuel distribution and differences in power and other losses. Of course, the results from a single cylinder engine test could be compared to the results of a multi-cylinder engine test.

Another study which would be of extreme importance would be engine starting effects on piston ring wear. It was observed in this study that starting wear was much more critical than the wear produced in the constant condition testing. Various loading conditions, using different types of lubricating oils, could be applied to the engine from a cold start. This would simulate conditions of automobile owners who drive very short distances periodically, such as to and from work.

Recent sources of information indicate that use of the two-stroke engine, in the fields of marine, aeronautical, and automotive application, has increased in the past few years (17, p. 265). European automotive manufacturers have found a market, in this country, for their two-stroke cycle, engine operated products. Two-stroke, spark ignition engines, produced by the leading manufacturers of outboard motors in this country, are in wide use. It is also believed that the military use of this type of engine, for aeronautical purposes, will increase with advanced study and increased development in performance. A comparison between cylinder bore and piston ring wear in the two- and four-stroke engines would be a great benefit in the sense of broadening the knowledge in this field.

As a basis or foundation for comparison between the two-stroke and four-stroke engines, one would most likely test two engines capable of creating the same power. One such aspect would be a comparison between the ratios of wear, resulting from different operating conditions, to initial or first cost of the engines. An economical outlook would be of considerable importance in this comparison. In the above mentioned comparison, such mechanical relationships as piston size, piston speed and travel, and cylinder pressures would influence the amount of wear, and would have to be taken into consideration.

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APPENDIX

RADIOACTIVE DECAY CORRECTIONS

The half life of the irradiated iron piston rings is approximately forty seven days. It was necessary to correct the observed wear rates to a common intensity level. A value of unity was chosen for the first test of the first replication, 1-10.

The code used for testing purposes and computations was:

Jacket temperature	120°F	212°F
Motor Plus	1	6
Aviation Mix	2	7
Motor Mix	3	8
Base fuel	4	9
Tricresyl phosphate	5	10

The order with which the samples were tested in each replication due to the randomization of the tests was:

Replication	Fuel Samples									
1	10	4	3	9	8	6	5	7	1	2
2	9	3	8	4	5	6	1	2	7	10
3	7	5	4	9	3	2	1	6	8	10
4	5	1	8	3	4	7	2	6	9	10

WEAR RATES

Sample	Observed Value	Corrected to 1st Rep.	Corrected Value	Correct to 1-10	Correct Wear Rate	Totals	Mean
1-1	25.0	1.000	25.0	0.958	26.1		
2-1	24.6	0.955	25.75		26.9		
3-1	22.0	0.910	24.18		25.2		
4-1	21.0	0.868	24.18		25.2	103.4	25.8
1-2	27.0	1.000	27.0	0.9565	28.2		
2-2	20.0	0.948	21.1		22.1		
3-2	25.4	0.915	27.76		29.0		
4-2	22.2	0.791	28.04		29.3	108.6	27.2
1-3	34.5	1.000	34.5	0.995	34.7		
2-3	30.5	0.935	32.63		32.8		
3-3	33.3	0.882	37.75		38.0		
4-3	30.0	0.807	37.17		37.4	142.9	35.7
1-4	31.2	1.000	31.2	0.9975	31.3		
2-4	27.4	0.928	29.54		29.6		
3-4	26.0	0.892	29.13		29.2		
4-4	25.0	0.803	31.13		31.2	121.3	30.3
1-5	22.0	1.000	22.0	0.9649	22.8		
2-5	24.0	0.9545	25.14		26.0		
3-5	20.6	0.925	22.27		23.1		
4-5	25.0	0.865	28.90		30.0	101.9	25.5

WEAR RATES

Sample	Observed Value	Corrected to 1st Rep.	Corrected Value	Correct to 1-10	Correct Wear Rate	Totals	Mean
1-6	17.2	1.000	17.2	0.9851	17.5		
2-6	17.1	0.932	18.34		18.6		
3-6	15.6	0.884	17.64		17.9		
4-6	16.5	0.768	21.50		21.8	75.8	19.0
1-7	12.8	1.000	12.8	0.9616	13.3		
2-7	13.5	0.941	14.35		14.9		
3-7	9.35	0.931	10.05		10.4		
4-7	9.50	0.824	11.53		12.0	50.6	12.6
1-8	19.4	1.000	19.4	0.9876	19.6		
2-8	14.0	0.939	14.91		15.1		
3-8	14.8	0.8791	16.84		17.0		
4-8	10.2	0.825	12.36		12.5	64.2	16.0
1-9	16.7	1.000	16.7	0.992	16.8		
2-9	13.3	0.954	13.98		14.1		
3-9	11.4	0.895	12.77		12.9		
4-9	12.7	0.752	16.89		17.0	60.8	15.2
1-10	15.0	1.000	15.0	1.000	15.0		
2-10	12.0	0.9022	13.3		13.3		
3-10	11.1	0.8664	12.82		12.8		
4-10	15.0	0.7475	20.07		20.1	61.2	15.3

REPLICATION TOTALS

	1	2	3	4
1	26.1	26.9	25.2	25.2
2	28.2	22.1	29.0	29.3
3	34.7	32.8	38.0	37.4
4	31.3	29.6	29.2	31.2
5	22.8	26.0	23.1	30.0
6	17.5	18.6	17.9	21.8
7	13.3	14.9	10.4	12.0
8	19.6	15.1	17.0	12.5
9	16.8	14.1	12.9	17.0
10	15.0	13.3	12.8	20.1
	225.3	213.4	215.5	236.5

TREATMENT TOTALS

A	1	2	3	4	5	T_b
B						
1	103.4	108.6	142.9	121.3	101.9	578.1
2	75.8	50.6	64.2	60.8	61.2	312.6
T_a	179.2	159.2	207.1	182.1	163.1	

G is 890.7

ANALYSIS OF VARIANCE CALCULATIONS

Preliminary Calculations

Type of Total	Sum Squares of Totals	No. Totals Squared	Observations per Total	Sum Squares per Obs.
Grand	793,346.49	1	40	19,833.66
Replication	198,672.15	4	10	19,867.22
A	160,109.71	5	8	20,013.71
B	431,918.37	2	20	21,595.92
AB	87,872.95	10	4	21,968.24
Observation	22,154.65	40	1	22,154.65

Analysis of Variance

Source of Variation	D.F.	Sum of Squares	M.S.	F	d.f.
Replication	3	33.56	11.19	1.977	3 & 27
A	4	180.05	45.01	7.952	4& 27
B	1	1762.26	1762.26	311.4	1 & 27
AB	4	192.27	48.07	8.493	4 & 27
Error	27	152.85	5.66		
Total	39	2320.99			

The critical regions, using the five per cent significance level, are, F is greater than:

Replication:	2.9604
A:	2.7278
B:	4.2100
AB:	2.7278

NEW MULTIPLE RANGE TEST CALCULATIONS

The mean wear rates of the various blends are ranked according to increasing magnitudes.

	5	1	2	4	3
120°F	25.48	25.85	27.15	30.32	35.72
	7	9	10	8	6
212°F	12.65	15.20	15.30	16.05	18.95

$$S_y = (s^2/n)^{1/2}$$

The error mean square is 5.66 and n is equal to 4.

$$S_y = 1.1895$$

g:	2	3	4	5
Tabulated values :	2.905	3.05	3.135	3.205
SSR :	3.456	3.628	3.730	3.812

The twenty comparisons between blends are shown in tabulated form on the following page.

g	Varieties	Difference in Mean Wear Rates	SSR	Conclusion
5	3 - 5	10.24	3.812	Significant
4	3 - 1	9.87	3.730	Significant
3	3 - 2	8.57	3.628	Significant
2	3 - 4	5.40	3.456	Significant
4	4 - 5	4.84	3.730	Significant
3	4 - 1	4.47	3.628	Significant
2	4 - 2	3.17	3.456	Not Significant
3	2 - 5	1.67	3.628	Not Significant
2	2 - 1	Do Not Test		Not Significant
2	1 - 5	Do Not Test		Not Significant
5	6 - 7	6.30	3.812	Significant
4	6 - 9	3.75	3.730	Significant
3	6 - 10	3.65	3.628	Significant
2	6 - 8	2.90	3.456	Not Significant
4	8 - 7	3.40	3.730	Not Significant
3	8 - 9	Do Not Test		Not Significant
2	8 - 10	Do Not Test		Not Significant
3	10 - 7	Do Not Test		Not Significant
2	10 - 9	Do Not Test		Not Significant
2	9 - 7	Do Not Test		Not Significant

Note : Comparisons between varieties contained within a subgroup that has a non-significant range are not necessary.

SINGLE DEGREE OF FREEDOM

Treatment Number	Totals-CPM/4 hours
1	75.8
2	50.6
3	64.2
4	60.8
5	61.2
6	103.4
7	108.6
8	142.9
9	121.3
10	101.9

First Hypothesis : The wear rate of the base fuel is equal to the average wear rate of the other four fuels for the lower jacket temperature condition.

Second Hypothesis : The wear rate of the base fuel is equal to the average wear rate of the other four fuels for the higher jacket temperature condition.

Table of Multipliers

	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9	M_{10}
Q_1^2	0	0	0	0	0	1	1	1	-4	1
Q_2^2	1	1	1	-4	1	0	0	0	0	0

Q^2 = (Sum of M x Totals)^2/ n(Sum of multipliers, M, squared)

Q_1^2 is equal to 10.082, and Q_2^2 is equal to 0.9245.

$F = Q^2 / 5.66$ Error M. S. from the analysis of variance is equal to 5.66

F_1 is equal to 1.78, and F_2 is equal to 0.163. Both F-tests have the same critical region, that is, F is greater than 4.2100. Therefore both of the above hypotheses are accepted.

STATISTICAL SYMBOLS

d.f. Number of degrees of freedom of a statistic or a parameter.

g The number of treatment means in a group.

n Number of observations per sample or the number of replications.

s^2 The variance of a sample.

u The mean of the observations in a sample.

A One of the factors in a factorial experiment.

AB The interaction between factors A and B of a factorial experiment.

B The second factor in a factorial experiment.

F A statistic which follows the F-distribution.

G The grand total.

M A multiplier used in obtaining a single degree of freedom of the sum of squares.

MS Mean square.

Q^2 A single degree of freedom of the treatment sum of squares.

S_y The standard error of the mean.

SS Sum of squares.

SSR The shortest significant range.

T_a Sum of the observations belonging to a particular level of the factor A of a factorial experiment.

T_b The same as T_a, except for factor B.

T_r Sum of observations per replication in a randomized block test.