THE EFFECT OF DETONATION ON PISTON RING WEAR

by

DONEL RUDOLPH OLSON

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APPROVED:

[redacted]

Professor of Mechanical Engineering

In Charge of Major

[redacted]

Chairman of Department of Mechanical Engineering

[redacted]

Chairman of School Graduate Committee

[redacted]

Dean of Graduate School

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INTRODUCTION

The increasing trend in modern automotive engine design is towards higher compression ratios to enable greater horsepower output. The limiting factor on how high compression ratios may go is not as keenly related to design as it is to the fuel which is available to operate these engines. The fact that engine designers are taxing fuels to the limit is evidenced by the fine division between knocking and knock-free engine operation. A thin layer of deposits in the combustion chamber which in effect increases the compression ratio has the deleterious effect of increasing the knocking tendency of the fuel. This knocking or detonation within the combustion chamber is what the average motorist describes as "pinging" or "spark knock" and he notices that it is most pronounced upon acceleration or hill climbing when a maximum amount of power is required from the engine.

Detonation in itself may have several undesirable effects on the automobile engine, but of greatest concern to automobile manufacturers and gasoline suppliers is the psychological reaction the noise causes in the driver. No automobile owner appreciates a noisy engine and whether or not the noise is harmful he will inevitably take measures to quiet it. For this and other reasons there is an extensive research program in progress by automobile manufacturers, oil companies, and private investigators to eliminate or reduce detonation.

One obvious solution seems to be an increase in the octane rating of the fuel, but this in itself is a difficult problem. Furthermore it becomes increasingly difficult the higher the octane rating. The present average research octane number for premium type gasoline is 96 to 97. It is estimated by various sources that by 1960 a 97 octane fuel would not meet the needs of over 50% of the new cars, yet the initial plant investment and subsequent expensive control necessary to increase merely two octane numbers runs into the millions of dollars.

As detonation is recognized to be a serious deterrent to the horsepower race engaged in at present by automobile manufacturers it is somewhat strange that more work has not been done on the physical effects to the engine which detonation may cause. It is recognized in the aircraft industry that detonation is extremely detrimental and if allowed to continue can be a contributing cause of rapid engine failure. Automobile purchasers are interested in buying a car that will last a reasonable period of time and the engine, they consider, is ready for overhaul when piston rings and cylinders are worn to the extent that oil consumption becomes excessive. With this in mind it then seems reasonable that more concern should be given to the physical effect of detonation. Detonation occurs in the combustion chamber so it is readily apparent that any physical effects will be registered on the top of the piston, piston rings and the upper cylinder walls. It is these components of the engine which are the yardstick for determination of engine condition so a study of the physical effect of detonation would be of value in the effort to increase engine power and reduce engine wear.

THEORY OF DETONATION

As far back in history as the beginnings of the internal combustion engine detonation has been the factor which determined the maximum practicable compression ratio. Through the years many different theories have been advanced to explain knock in terms of what takes place prior to detonation, but most theories have been discredited for some reason or another. The theory which is most generally accepted involves a physical interpretation of knock in terms of pressure, temperature and time and has been termed the "autoignition" theory. According to this theory if the end gas is subjected to critical physical conditions autoignition will occur. Miller concludes in his classical work on the problem of detonation, that knock is best explained by a combination of the autoignition theory and the detonation-wave theory (15, p.143). He claims that knock is actually caused by a detonation wave that follows autoignition of the end gas.

The broad mechanism, as opposed to the chemistry, of detonation can be explained quite simply. In studying the sequence of events that leads to the occurrence of knock in a conventional Otto cycle engine, that is, an engine operating with spark ignition and a premixed charge, reference is made to figure 1. A typical plan view of the combustion chamber is shown with the piston near top dead center and the combustion in progress. A flame front has been established at the spark plug and it is burning into the combustible mixture, compressing ahead of it the unburned portion of the combustible air-fuel vapor mixture. The end gas, which is the air-fuel vapor mixture to be burned last, will be compressed to the greatest degree. Under the resultant temperatures and pressures oxidation reactions occur which may lead to spontaneous ignition of the end gas. This spontaneous reaction is identified as detonation and is accompanied by a rapid increase in pressure within the combustion chamber causing the cylinder walls to vibrate or "ping" as though hit with a light hammer.

Three quantities are of major importance in the study of spontaneous ignition reactions. These are pressure, temperature and ignition lag. Ignition lag is the residence time of the mixture at conditions of pressure and temperature prior to spontaneous ignition. The time of ignition delay decreases exponentially as the pressure or temperature increases (1, p.8). If the end gas is consumed by the normal progress of the flame front before the end gas reactions reach the stage of spontaneous ignition, no knock will occur.

An accurate analysis of detonation has been difficult to obtain due to the extreme speed of the knocking reaction.

Photographs of the combustion process which were taken by Miller at speeds of 40,000 and 200,000 frames per second indicate that detonation waves travel at velocities from two to three times the speed of sound (15, p.142).

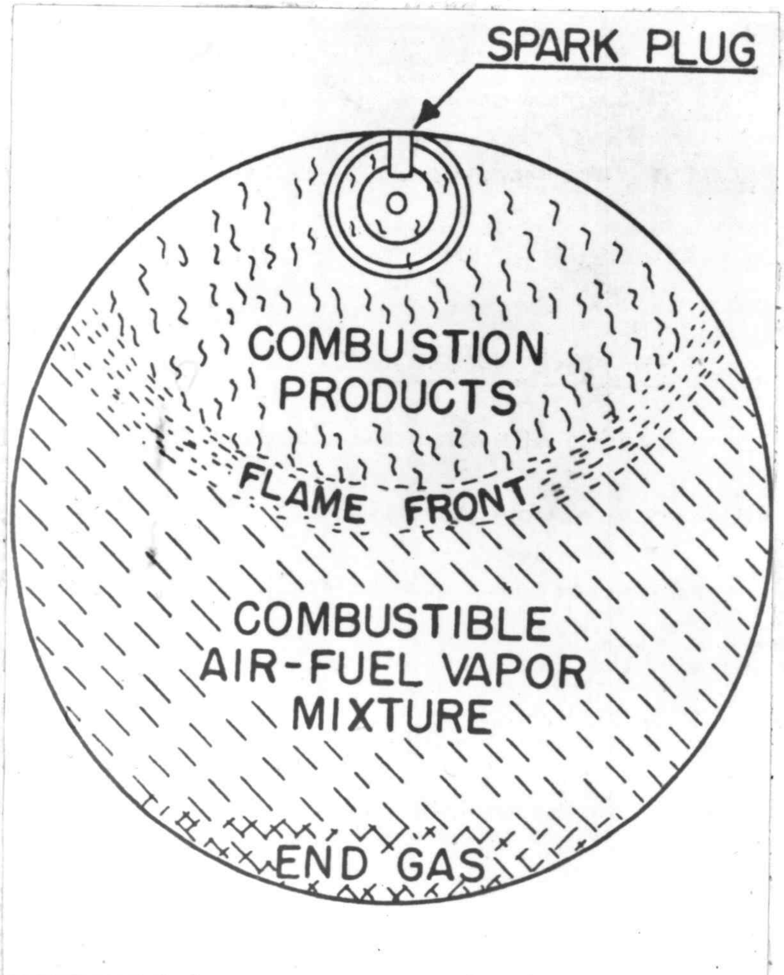


Fig. 1. Plan View of Combustion Process

The chemistry of detonation is extremely complex and most conclusions in this respect are based on theoretical treatment of a limited amount of data. It is known that certain compounds such as ethyl nitrite will greatly increase the tendency to detonate and this seems reasonable to the extent that their presence lowers the general level of self-ignition temperature. Not so easily explained is the effect of nitrous oxide which is a highly endothermic oxygen carrier. By all rules this compound should greatly increase the tendency to detonate, yet it has precisely the opposite effect. It has been known for a long time that lead and thallium, when finely divided and mixed with gasoline, are remarkably effective in suppressing detonation, yet no wholly satisfactory explanation of the chemical process has been given.

Sturgis, in a comprehensive investigation, studied the chemistry of knock and presented some interesting arguments (23, pp.36-39). Closely tied in with knock are the cool and blue flames which appear just prior to detonation. It is reasoned by Sturgis that chemical reactions take place in the fuel preceding knock because: (1) measurements indicate as much as 25 to 40% of the total combustion energy is released before a hot flame appears, (2) cylinder pressure rises abnormally high before knock, and (3) qualitative analysis of end gas has shown the fuel to be oxidized into other products prior to autoignition.

Sturgis goes on to show that the complete burning of a hydrocarbon fuel is a very complex process which does not occur in one step, but by a series of molecule collisions to first form a series of intermediate products. The first product formed by the reaction of a hydrocarbon with oxygen is peroxide, which is very unstable at the high temperatures of the end gas. Peroxide decomposes in two different ways; either by fission of the molecules, to yield two radicals, each radical promoting further oxidation of the hydrocarbon, or by thermal decomposition, which forms the relatively inactive aldehydes, ketones and olefins.

Near the end of the cool flame period the radicals obtained by the fission of molecules chain-react to form an ever increasing number of reactive radicals. This reaction is accompanied by a blue flame and it is theorized by Sturgis that it is this chain reaction which causes knock.

Other theories too numerous to mention have been presented but in general the foregoing theories seem to be the most widely accepted.

PISTON RING AND CYLINDER WEAR THEORY

Wear of cylinders and piston rings will continue to be a problem as long as internal combustion engines use piston rings to seal the piston as it reciprocates back and forth within the cylinder. Wear, as applied to piston rings and cylinders, can be classified as abrasive, corrosive, scuffing or combination thereof. In addition wear may be considered as a gradual phenomenon consisting of smooth deterioration by friction.

Abrasive wear takes place when two surfaces rub together and is accelerated if this rubbing occurs in the presence of abrasive particles. Engine cleanliness, proper choice of ring and cylinder surface material, and proper lubrication are primary factors in reducing or minimizing abrasive wear. Another factor which appreciably affects abrasive wear rate is pressure of the ring against the cylinder wall (6, p.39).

The second type of wear, corrosion, may be due to carbon dioxide and the oxides of nitrogen and sulphur. Corrosive wear consists of the chemical attack of acids on the metal surfaces. While sulphur appears to be one of the greatest factors influencing corrosive wear (6, p.40 and 26, p.138), it is interesting to note that at least one author reports that increasing amounts of sulphur will actually cause a decrease in piston ring wear if the operating temperature is maintained above the dew point of the coolant (19, p.27). Reduction in corrosive wear can be obtained by selection of low sulphur fuels, by selection of lubricating oils with proper corrosion inhibiting additives, and by maintenance of coolant temperatures above the critical level.

The third type of wear, scuffing, is a result of metal-to-metal contact and usually is characterized by an abnormally high rate of material removal. It is generally believed that scuffing can occur only in the presence of a breakdown in the oil film, and under conditions of speed and pressure sufficient to generate surface temperatures high enough to permit momentary welding of materials in localized areas. While proof of this theory is somewhat complex it is generally considered that reduction in scuffing wear is related primarily to the material structure of mating parts (6, pp.40-41). While reduction in unit pressure will reduce scuffing tendency it is a tantamount fact that the use of narrower rings will also improve scuff resistance by providing for more rapid heat transfer from the ring face.

The last type of wear, friction, is a deforming action which takes place as the ring passes over the cylinder wall. The squashing down or cutting off of surface irregularities has the effect of increasing surface contact area and thereby reducing unit pressure. Friction wear is most pronounced during break-in of an engine and is desirable during this time to the extent that an eventual better match will be obtained between cylinder and piston ring. Reduction of friction wear is primarily related to surface finish, oil viscosity, and material properties.

The mechanism of wear which takes place during detonation is probably a combination of friction and scuffing. As has already been pointed out, when detonation occurs the pressure in the combustion chamber rises markedly. This increase in pressure is transferred from the piston to the rings and results in a higher pressure between piston rings and cylinder wall. It is theorized that this increase in pressure and accompanying pressure fluctuation is sufficient at times to break through the protective oil film and allow momentary scuffing to take place. If the pressure is not sufficient to cause the ring to break through the oil film, wearing of the metal will at least be hastened through the friction process.

There is still the question among many authorities whether cylinder lubrication should be classified as boundary layer or hydrodynamic. It is suggested by one investigator that lubrication between a piston ring and cylinder is partially hydrodynamic and partially boundary, (27, p.40). There is hydrodynamic lubrication during the time when relative velocity between the cylinder and ring is high and boundary lubrication at the ends of each stroke. If this theory is correct it is evident that boundary lubrication exists at the time of most severe pressure rise in the combustion chamber. Due to the relative low strength of the oil film there should be a decided tendency towards scuffing during detonation.

WEAR TEST METHOD

To detect operating conditions which cause wear within an engine it is necessary to have an accurate means of wear measurement. Conventional wear test methods in which attempts are made to measure the change in dimension of engine parts or the amount of iron in the crankcase oil by chemical means are long, costly and subject to certain inaccuracies. Discussion of conventional wear test methods is given in any of several other papers (20, p.1; 12, p.7 and 19, p.7). In contrast, the radioactive tracer method of wear measurement, because of its sensitivity and continuous operation without engine rebuild, is shorter and cheaper with better accuracy. Utilizing the rapid response to changes in wear rate, it is possible, using the radioactive method, to study transitory wear phenomena which cannot be measured by conventional methods.

The radioactive method consists, in general, of activating a standard piston ring in the Atomic Energy Commission's nuclear reactor at either the Oak Ridge National Laboratory or the Brookhaven National Laboratory and installing the activated ring in the test equipment. As the ring wears, radioactive particles enter the lubricating oil and flow past a sensitive geiger tube thus enabling a determination of the amount of wear which has taken place.

A complete description of the radioactive wear method is given in several previous papers (26, pp.133-144; 12, pp.8-10; 19, pp.7-9; 10, p.1 and 20, pp.2-5). A detailed description of the apparatus used in this work for determining wear rate is reported in a later chapter.

OBJECTIVES OF THIS TEST

At least one company has made a limited investigation of the effect of detonation on piston ring wear as specifically pertains to automotive, light service type engines (10, pp.2-3). Investigations showed that there was an alarming increase in wear rate with merely trace knock conditions under controlled laboratory tests. Other work done in the field by the same company with Chevrolet automobiles operating under intermittent knocking conditions likewise resulted in wear increase with knock, but to considerably lesser degree.[1]

One of the objectives of this investigation is to obtain a comparison to the previous work mentioned. Other objectives are;

. . . to obtain a quantitative analysis of the effect of detonation,

. . . to investigate wear rates caused by detonation at various compression ratios, and

. . . to correlate wear rate with an increase in the time rate of pressure change within the combustion chamber.

1. Personal correspondence with Atlantic Refining Company, Philadelphia, Penn. Oct. 13, 1955.

APPARATUS

The engine used for this test was an ASTM-CFR knock testing unit specifically designed for knock testing of fuels. It is a single cylinder engine of continuously variable compression ratio with dimensions as follows:

Compression ratio	4 to 10
Bore, inches	3.25
Stroke, inches	4.50
Displacement, cu. inches	37.33

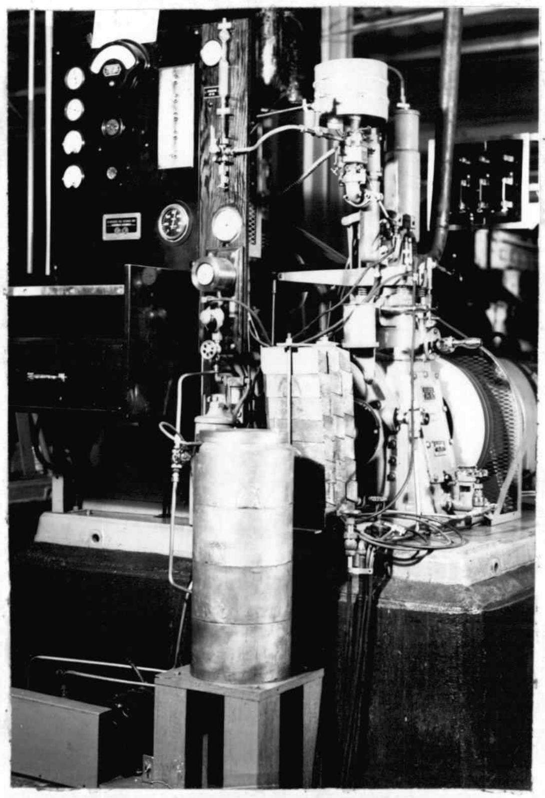


Fig. 2. Engine Test Stand

A synchronous motor connected to the engine with a multiple belt pulley arrangement was used to absorb the developed power and hold engine speed constant at 900 rpm. The amount of power which was developed by the engine was not calculated because such information would have little value in a relative comparison test such as this work encompasses. It was important that load remain constant for a given set of conditions and also be easily reproduced. It was assumed that such was the case as throttle opening was fixed and speed remained essentially constant with no fluctuation during a test run.

An evaporative cooling system equipped with a water cooled condenser coil above the coolant level was used, to maintain cooling water temperature at 212°F.

The adjustable level four bowl carburetor which is standard equipment for the knock testing unit was replaced with a single bowl Tillotson downdraft carburetor. The Tillotson carburetor was entirely adequate for the scope of this work. The only control necessary was maintenance of a constant air-fuel ratio for all conditions. This was easily accomplished with a needle valve adjustment. Intake air was passed through a positive type filter, which consisted of two layers of flannel cloth, to alleviate the possibility of dust entering with the intake air and affecting the results. The air-fuel ratio was set and periodically checked by use of a Hayes exhaust gas analyzer.

A gravity flow fuel system was used for dependability and fuel was blended by volume using the burets and flasks pictured in figure 3.

Temperature of the air-fuel mixture was determined by a chrome-alumel thermocouple inserted in the intake manifold. Ambient temperature was checked with a mercury in glass thermometer.

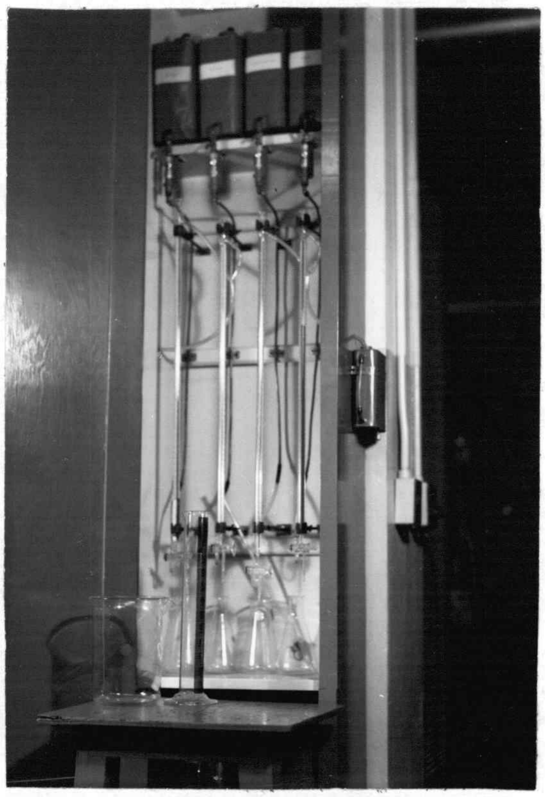


Fig. 3. Fuel Measuring Equipment

Pressure fluctuations within the combustion chamber were determined with a mechano-electrical pressure transducer developed in the Massachusetts Institute of

Technology laboratory by C. S. Draper and Y. T. Li. Pressure acting on a diaphragm is converted into mechanical compression of a hollow cylindrical column. Resistance-wire strain gauges bonded to the hollow column convert the mechanical strain into an electrical signal. Figure 4 shows a cross-section view of the pick-up at a diameter. Adequate cooling for the pick-up is secured by supplying filtered air at a pressure of three to five psi.

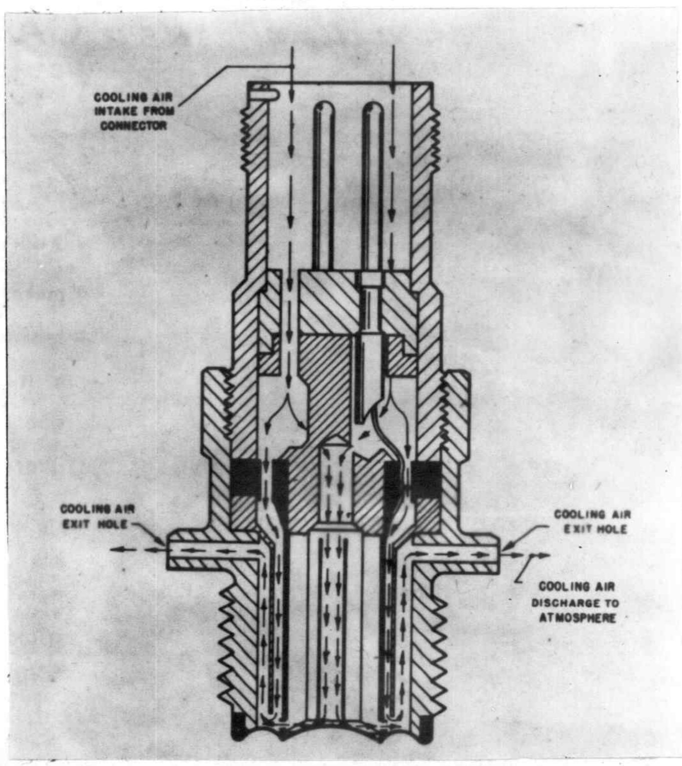


Fig. 4. Cross-section of Pressure Pick-up

The most unusual feature of this pressure indicator is the double catenary diaphragm construction. Construction details of the pick-up may be seen in figure 5. The hollow cylindrical column terminates at the junction of the two catenary surfaces. This construction feature allows the diaphragm to be in tension at all times thus achieving structural rigidity yet permitting a very flexible diaphragm.

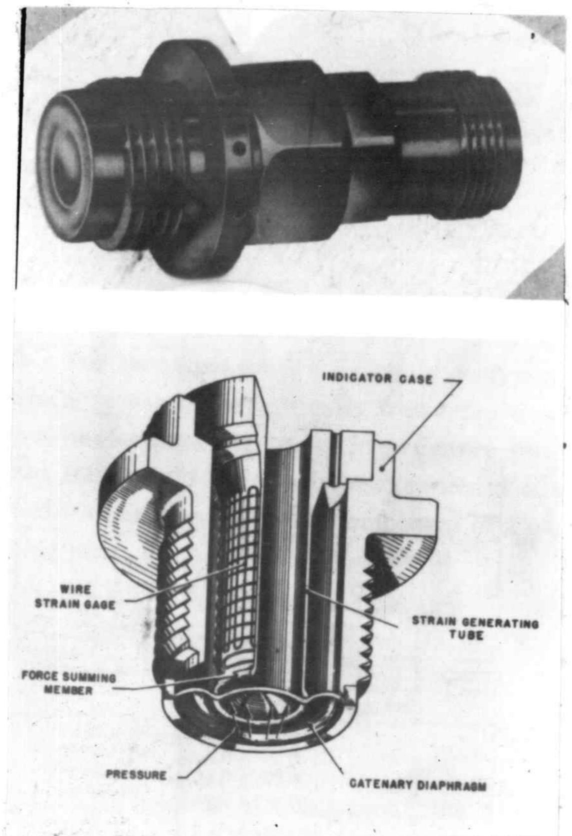


Fig. 5. External View and Construction Features of Pressure Pick-up

The two 1000 ohm strain gauges mounted in the pressure pick-up comprise two arms of a Wheatstone bridge. The other two arms of the Wheatstone bridge are housed in the control box which serves the dual purpose of supplying power to the pressure pick-up and amplifying the resultant signal. The amplified signal is then fed either into an oscilloscope to obtain a pressure-time trace on the screen or, as done in this work, the signal is passed through a suitable arrangement of condensors and resistance to obtain a differentiated trace on the oscilloscope screen. Arrangement was made so that either the pressure-time or the dp/dt trace could be viewed. It was concluded, however, that the differentiated trace was best for the purposes of this work.

Fig. 6. Oscilloscope and Polaroid Land Camera

A Tektronix cathode-ray oscilloscope, type 535, equipped with a differential, high-gain, calibrated dc preamp, type 53D plug in unit was used for final acceptance of the signal from the pressure pick-up. A Fairchild polaroid Land camera was utilized in recording the trace on the oscilloscope screen. The oscilloscope with camera attached for recording the trace is shown in figure 6 and figure 7 shows the combination power supply-amplifier, differentiating box and oscilloscope connected in series. More is said about the photography technique in a later chapter.

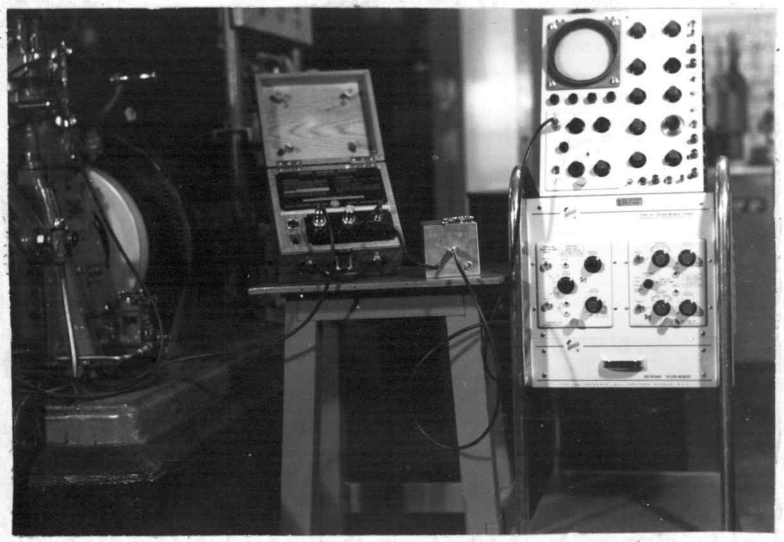


Fig. 7. Pressure Pick-up
Circuit

A schematic flow diagram of the wear measuring apparatus is shown in figure 8. As wear of the activated ring takes place the radioactive particles enter the lubricating oil and are circulated with the oil past the sensitive geiger tube immersed in the lead shielded container. The geiger tube measured the activity of the oil and an RCL Mk 13 Mod 1 scalar performed the counting operation. The signal from the scalar was differentiated by a Tracerlab Ratemeter to give counts per minute (cpm). A millivolt signal was then fed from the Ratemeter to a Brown Continuous

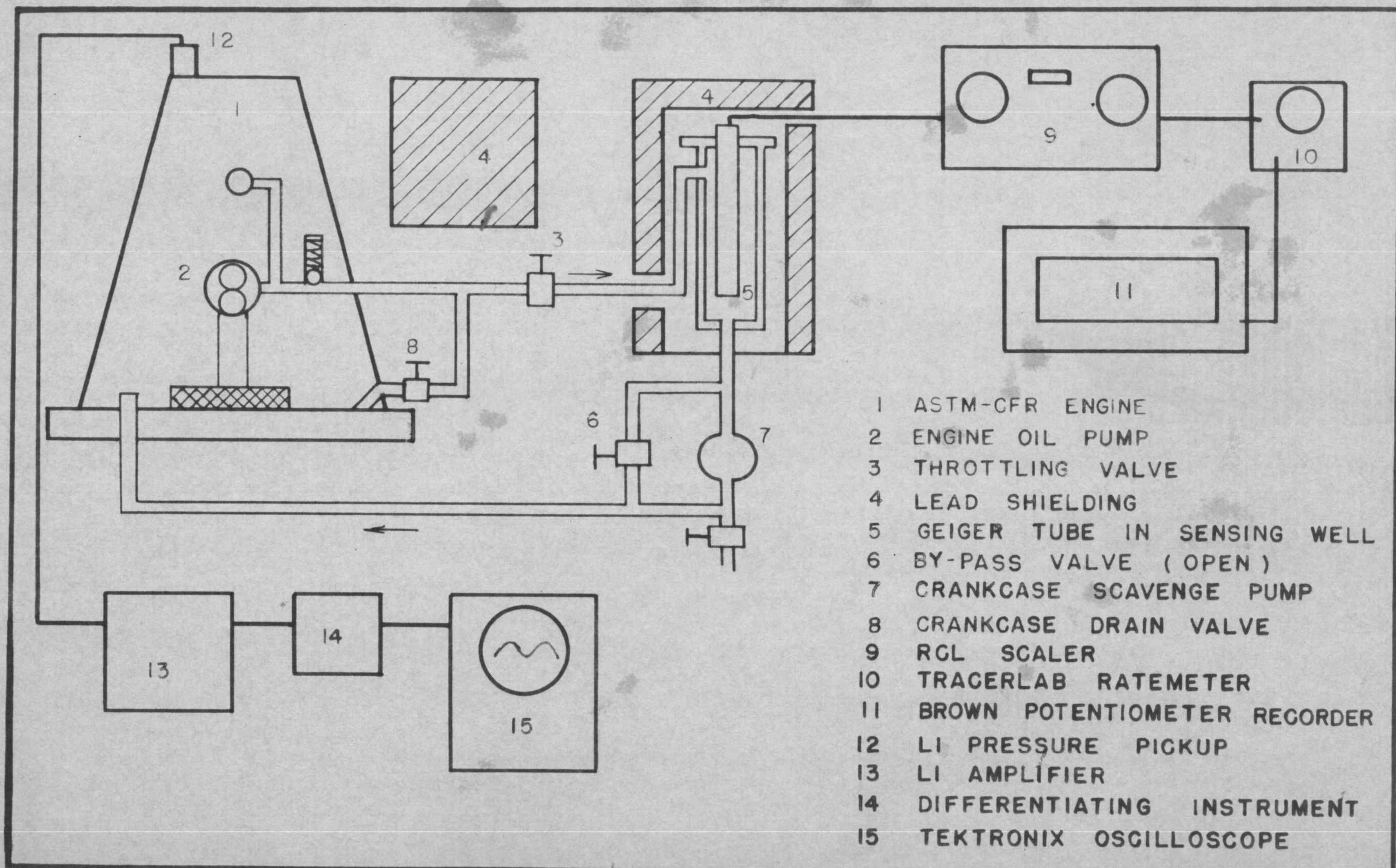


Fig. 8. Schematic Diagram of Oil and Recording Circuits

Balance Potentiometer recorder to obtain a record of cpm against time. The recorder chart was calibrated in degrees Fahrenheit so conversion had to be made to cpm. With this done the recorder maintained a continuous record of oil activity in cpm. A photograph of the scalar, ratemeter and potentiometer is shown in figure 9.

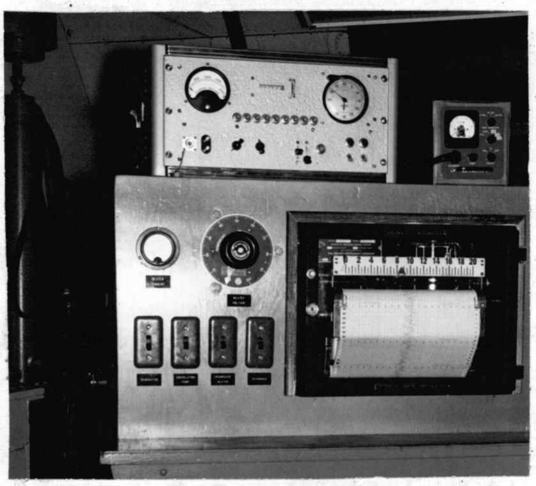


Fig. 9. Recording Apparatus

In addition to a one inch lead shielding around the sensing well six inches of lead was placed between it and the engine to reduce the background count.

A specially constructed lead container was used for shipping the rings. It surrounded the rings with two inches of lead to maintain a safe activity level. Total shipping weight of the lead container and enclosing plywood box was 92 pounds.

An ordinary ring expander was modified and adapted with long handles to place the active ring on the piston.

The piston and connecting rod assembly was held with a long handled aluminum clamp and forced up into the lubricated cylinder. The chamfered edges of the cylinder served to compress the rings.

Radiation level in the vicinity of the engine was measured with a Tracerlab SU-1F Portable Radiation Survey Meter. This instrument gives readings of milliroentgens per hour to facilitate rapid calculation of dosage rates. An RCL Mark 11 Model 10 portable geiger counter was used in examining used oil, tools etc. for radioactive contamination.

RADIATION SAFETY

The subject of radiation safety has been covered quite extensively in the reports of previous work at Oregon State College (12, pp.21-24) and other literature contains an ever increasing amount of safety information. Therefore it is not felt there would by any value in repeating that which has been investigated so fully, but the safety problem will be summarized and a few calculations as pertains to this work will be given.

The legal limit of radiation exposure as set by the Atomic Energy Commission (AEC) is 300 milliroentgens per week. The activity level of the ring upon removal from the reactor was 10,000 milliroentgens per hour at a distance of nine inches. With special tools the ring was handled at a distance of approximately 18 inches while installing it on the piston. At this distance a week's dosage would be obtained in approximately seven minutes. It took two or three minutes to remove the piston ring from the lead shipping container, place it on the piston and insert the piston in the cylinder. During this operation the major portion of the body was protected by working behind two inches of lead shielding. The heavy cast iron cylinder and head assembly reduced the activity level to about eight milliroentgens per hour at a distance of one foot so the radiation hazard was slight as long as extended exposure immediately adjacent to the engine was avoided.

PROCEDURE

It was necessary to modify the lead shipping container which was used in previous work here at Oregon State College for the larger diameter ring of the ASTM-CFR engine. The modified design was approved by the Federal Bureau of Explosives and permission was subsequently given by the AEC to use the radioactive ring. One compression ring was sent to the Oak Ridge National Laboratory to be irradiated for one month. The active ring was received during the first week of January and installed in the engine using long handled tools and other necessary precautions.

Operating conditions held constant throughout the entire testing program included:

Speed	900 rpm
Jacket temperature	212 F
Fuel	Blend of iso octane and n-heptane
Oil	Heavy duty SAE 30
Air/fuel ratio	13 to 1
Inlet air/fuel mixture	145 F
Oil sump	150 F

Tests were made at compression ratios of 6.0, 7.0, 8.0, 5.0, and 5.5. The spark timing was held constant for each series of tests at a given compression ratio, but it was necessary to retard the spark for each successively higher compression ratio. Respective spark settings were 20°, 10°, 7°, 26°, and 24° BTDC.

As a complete set of new rings had been installed it was necessary to make a preliminary break-in run. This was accomplished by operating the engine for approximately ten hours at a compression ratio of 6.0 and then at each successive compression ratio for about two hours each. This allowed approximately 20 hours of break-in and as the wear rate became essentially constant during the last several hours it was assumed that normal wear was taking place. A non-detergent SAE 20 W oil was used for the break-in run.

After completion of the break-in run the oil was drained from the engine and replaced with a heavy duty SAE 30 oil. The oil was changed periodically throughout the test series to limit the amount of radioactive contamination.

The general procedure was similar for each compression ratio. Approximately two hours of operation were necessary to obtain equilibrium conditions prior to each run. The oil temperature, which was controlled by an immersion type heater, and the oil pressure, were extremely critical. The volume of oil which flowed past the geiger tube was dependent on both temperature and pressure, thus a slight deviation in either would affect the record of relative wear rate.

As it was desired to obtain the relative wear rate under knocking conditions as compared to non-knocking conditions, it was necessary to first obtain a reference wear rate by operation under non-knocking normal combustion conditions. This was accomplished by first operating the engine on 100% iso octane[2] for a period of time long enough to obtain an indicative wear rate, usually about five to six hours. The fuel blend was then changed to allow trace knock while all other conditions were held constant. After the wear rate became well defined again the fuel blend was changed to allow light knock and so on until data had been recorded for conditions of non, trace, light, medium, and heavy knock at a constant compression ratio. It was desired to operate continuously at a given compression ratio until a record of all conditions of knock had been established, but as this entailed from 20 to 30 hours of continuous operation it was sometimes necessary to divide a series into two or three 10 to 15 hour periods.

Photographs of the oscilloscope trace showing the time rate of pressure change in the combustion chamber were taken for each condition with the polaroid camera described in the chapter on apparatus.

2. In the case of a 6.0 compression ratio 95% iso octane was used.

Pressure-time traces were originally photographed for compression ratios of 6.0 and 7.0, but later in the testing program it was decided that a dp-dt trace enabled a better comparison of knocking conditions. Subsequent traces were differentiated and knock conditions were duplicated at compression ratios of 6.0 and 7.0 to finally obtain the dp-dt traces shown in the results. The photographs were obtained by opening the shutter of the camera, manually triggering the oscilloscope trace and closing the shutter of the camera. This method produced a picture of a single trace and by retriggering at different vertical positions a series of traces could be photographed. The camera is constructed so that two pictures per frame can be obtained. A maximum number of three traces per picture thus allowed six traces to be made for each camera setting. An important feature of the polaroid camera is that only a one minute wait is necessary between time of taking the picture and obtaining the finished, developed product.

Classification of knock condition was done both by ear and by observation of the oscilloscope trace.

The above procedure was followed for each compression ratio. Several runs were made in an effort to satisfactorily reproduce results, and after analyzing the data reruns were made of all points in question.

The relative wear rate for each condition was determined by the slope of a line drawn through the recorder trace. The recorder trace occurs as a zig-zag line because the decay of radioactive iron takes place in a random manner. In order to make a relative comparison of wear rates it was necessary to correct the recorded rate for the decrease in activity of the radioactive iron. Considering that radioactive decay is a probability process in which rate of decay is proportional to the number of unstable nuclei present at any time the following equation can be derived: (12, pp. 27-28)

(1) $N = N_o e^{-\lambda t}$

Where: N = number of unstable nuclei at time t

λ = the decay constant

N_o = the number of atoms at zero time

From (1), the time $t_{\frac{1}{2}}$ for the number of atoms to fall to one-half of any given value (the half life) is:

(2) $t_{\frac{1}{2}} = 0.693/\lambda$

For the radioisotope of iron which has a half-life of 46.3 days, λ from (2) is 0.01495 and equation (1) becomes:

(3) $K = N/N_o = e^{-0.01495t}$

Where: K = decay correction factor

N = number of unstable nuclei at time t

t = time in days from determination of N_o

N_o = number of atoms at zero time

For this test zero time was taken as the day the ring came out of the reactor (12-27-56) and N_o was equal to 1.0 at this time. All data were then corrected to the same activity level by the relationship:

(4) $R_1 = R_o/K$

Where: R_1 = corrected wear rate in cpm/hr

R_o = uncorrected wear rate in cpm/hr as determined from the recorder chart

K = decay correction factor

Oil was measured to determine how much consumption took place during an oil drain interval. It was found there was no measurable consumption so no further correction of wear rate was necessary.

The corrected wear rates were plotted against knock condition to give a graphical record of the effect of detonation on piston ring wear.

RESULTS

Results of this investigation are presented in graphical and tabular form on the following pages. The bar graphs show the wear rate obtained at a given knock condition for each compression ratio. Under trace and light knock conditions wear, in all cases, is greater than for non-knocking conditions. Increasing knock intensity caused a corresponding increase in wear for compression ratios of 5.5, 6.0, 7.0, and 8.0. Highest wear rates were obtained for these compression ratios when detonation was most severe, and in the case of a 6.0 ratio the relative increase over non-knocking conditions reached 226%.

Knock condition was largely determined by observation of the dp/dt trace or the pressure-time trace, but auditory comparisons were also made. Under trace knock conditions a very light "pinging" could be heard intermittently. Light knock was audible all the time, but probably could not be heard, for instance, by the driver of an automobile. Medium knock was clearly audible several feet from the test stand and actually caused a decided vibration of the engine. Heavy knock was considerably louder than an automobile owner would allow for any period of time. The magnitude of pressure fluctuation within the combustion chamber was sufficient to mildly shake the engine test stand and the vibration could be felt through the concrete floor.

Typical, uncorrected wear rate traces for a compression ratio of 5.5 are shown in figure 19.

TEST RESULTS

ASTM-CFR Engine, Constant Load, A/F-13.0, Jacket Water-212 F,
Intake Mixture-145 F, Oil Sump-150 F, Fuel-Blend of Iso Octane & N-Heptane

Compression Ratio	Percent Iso Octane	Knock Condition	Recorded Slope Increase Minutes For 50F	Uncorrected Wear Rate Increase CPM/HR	Date	Decay Correction Factor K	Corrected Wear Rate Increase CPM/HR	Relative Wear Rate Increase %	Average Wear Rate Increase %
			Spark Setting-26° adv.						
5.0	100	non	260	0.461	2-9-56	0.515	0.896	100	100
5.0	100	non	200	.60	1-23-56	.67	.896	100	
5.0	75	trace	215	.559	2-9-56	.515	1.082	121	121
5.0	75	trace	165	.728	1-23-56	.67	1.085	121	
5.0	65	light	180	.667	1-23-56	.67	.993	111	111
5.0	60	med	420	.267	2-10-56	.51	.522	58	
5.0	60	med	360	.333	1-25-56	.655	.510	57	57.5
5.0	50	heavy	360	.333	1-25-56	.655	.510	58	57.5
5.0	50	heavy	420	.267	2-10-56	.51	.522	58	
			Spark Setting-24° adv.						
5.5	100	non	240	0.500	2-7-56	0.535	0.935	113	
5.5	100	non	255	.47	1-28-56	.62	.758	91	100
5.5	100	non	255	.47	1-20-56	.70	.672	81	
5.5	100	non	240	.50	2-8-56	.525	.952	115	
5.5	80	trace	190	.632	1-28-56	.62	1.02	123	123
5.5	80	trace	185	.648	1-27-56	.635	1.02	123	
5.5	75	light	140	.857	1-21-56	.69	1.24	150	150
5.5	70	med	155	.775	1-30-56	.605	1.28	155	173
5.5	70	med	145	.828	2-8-56	.525	1.575	190	
5.5	60	heavy	100	1.20	1-30-56	.605	1.985	240	251
5.5	60	heavy	105	1.14	2-8-56	.525	2.17	262	
			Spark Setting-20° adv.						
6.0	95	non	72	1.67	1-14-56	0.765	2.18	100	
6.0	90	trace	48	2.5	1-14-56	.765	3.27	150	
6.0	85	light	44	2.73	1-14-56	.765	3.57	164	
6.0	80	med	32	3.75	1-14-56	.765	4.90	225	
6.0	75	m-heavy	30	4.0	1-14-56	.765	5.23	240	
6.0	70	heavy	22	5.45	1-14-56	.765	7.12	326	
			Spark Setting-10° adv.						
7.0	100	non	210	0.572	1-16-56	0.74	0.770	100	
7.0	95	trace	130	.923	1-16-56	.74	1.245	162	
7.0	90	light	115	1.042	1-16-56	.74	1.408	183	
7.0	85	med	110	1.090	1-16-56	.75	1.470	191	
7.0	80	heavy	70	1.715	1-16-56	.74	2.310	300	
			Spark Setting-7° adv.						
8.0	100	non	90	1.33	1-18-56	0.715	1.865	100	
8.0	92	med	60	2.0	1-18-56	.715	2.80	150	

Fig. 10. Tabulated Test Results

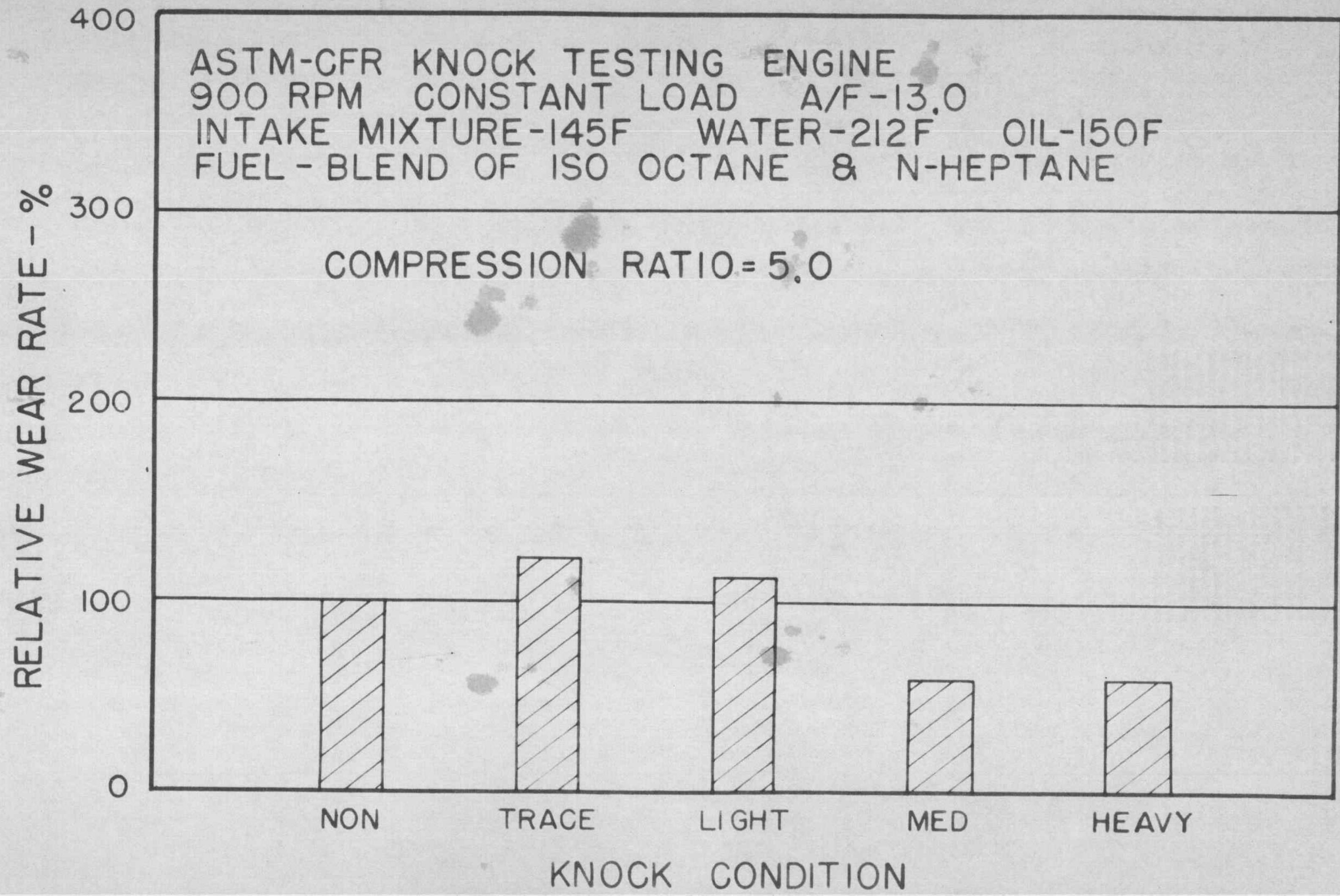


Fig. 11. Wear Rate for a Compression Ratio of 5.0

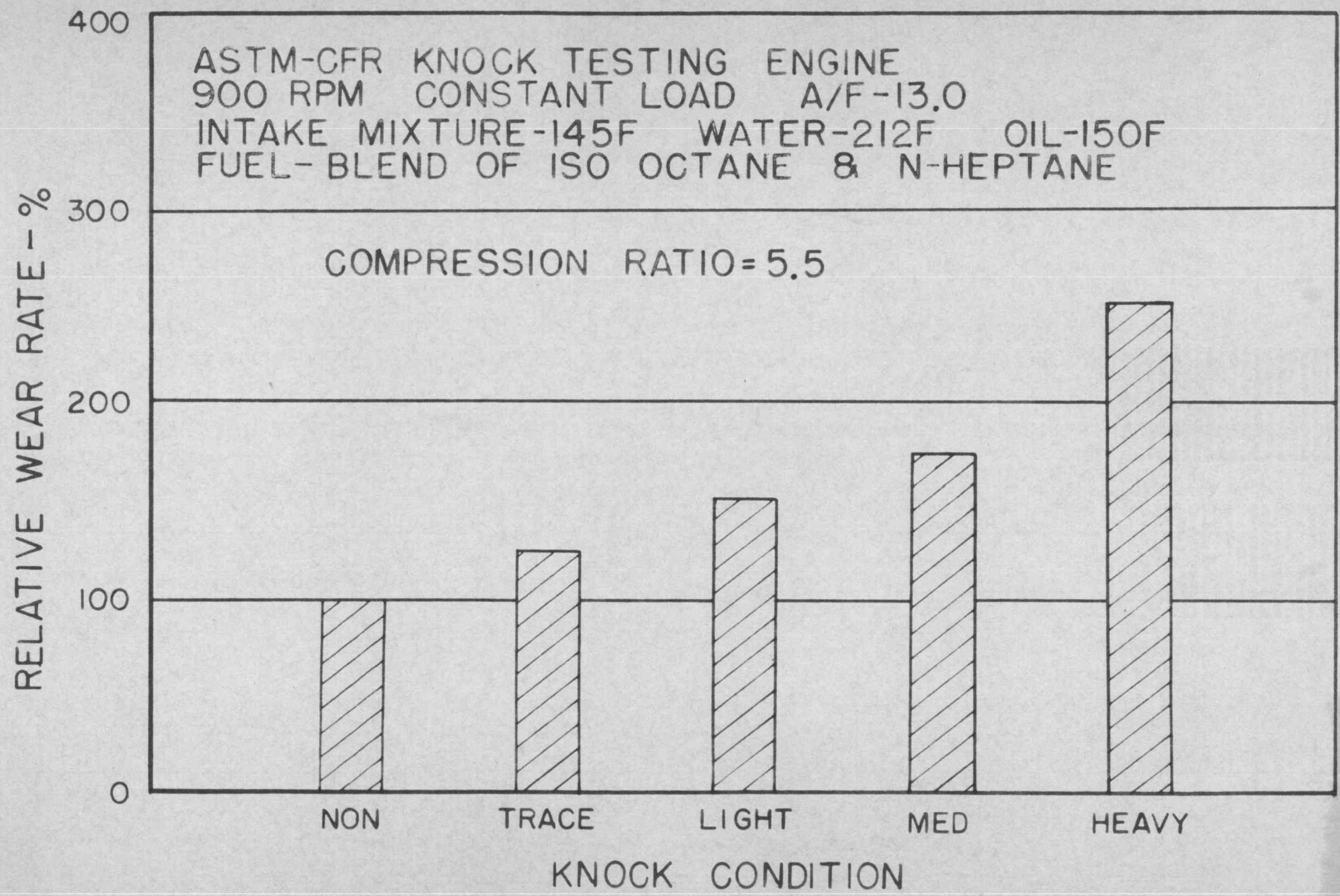


Fig. 12. Wear Rate for a Compression Ratio of 5.5

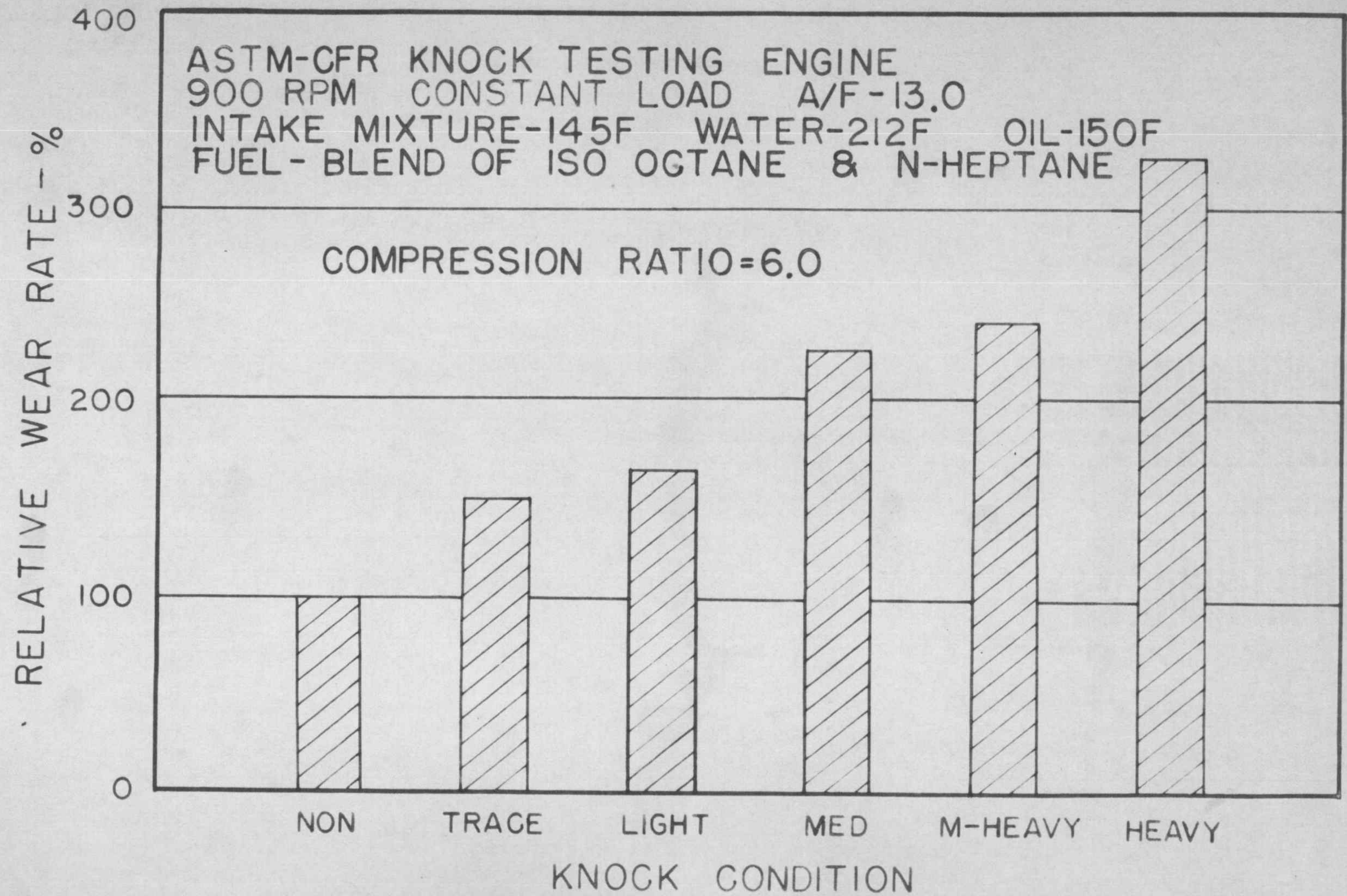


Fig. 13. Wear Rate for a Compression Ratio of 6.0

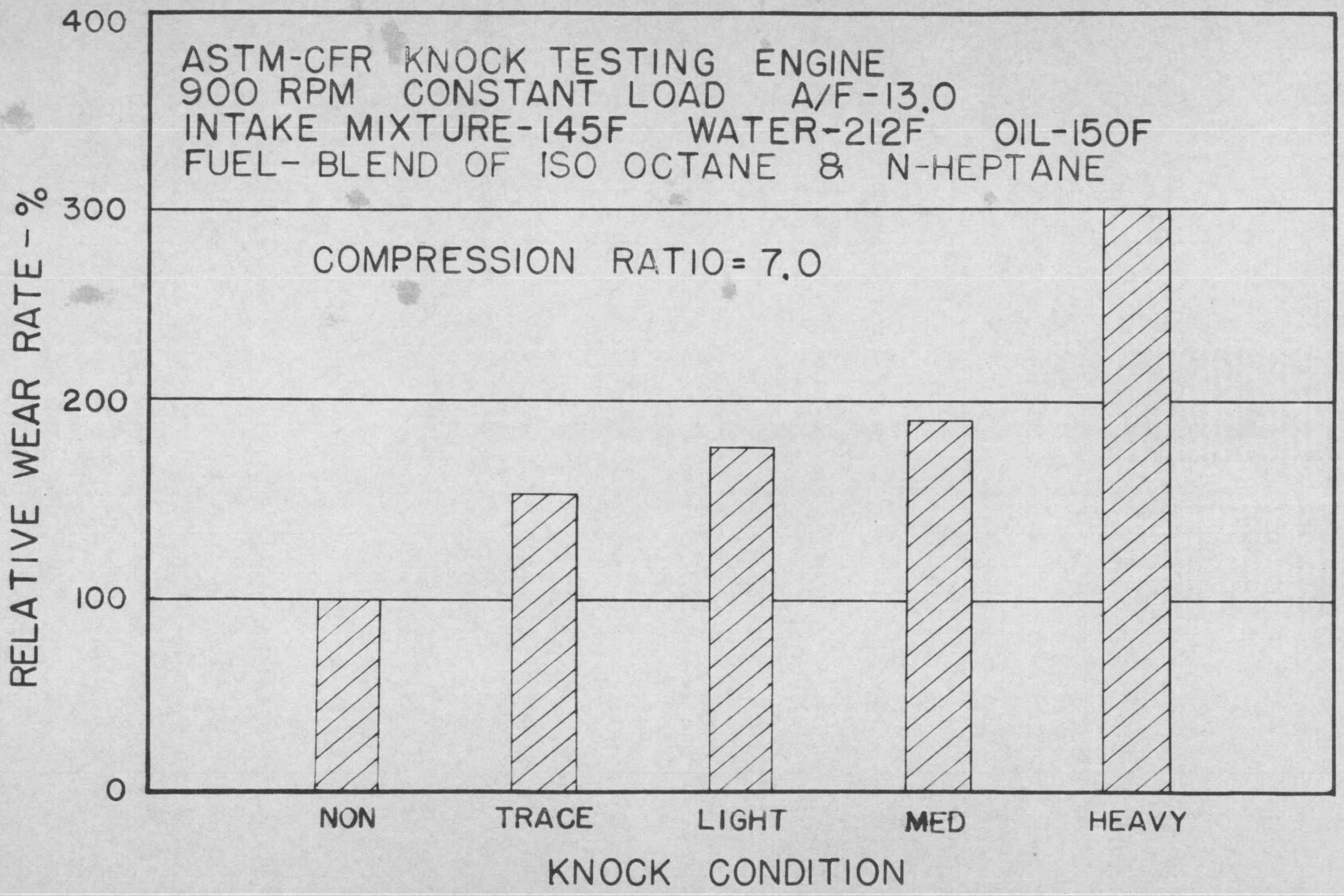
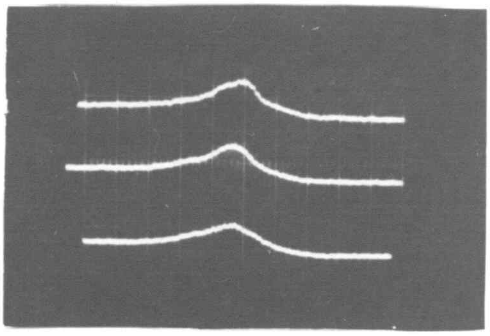


Fig. 14. Wear Rate for a Compression Ratio of 7.0

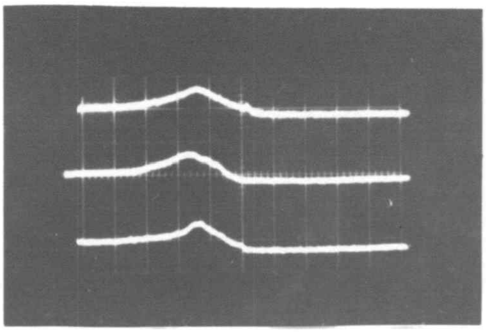
KNOCK INTENSITY PHOTOGRAPHS

OSCILLOSCOPE TRACES SHOWING THE TIME RATE OF PRESSURE CHANGE IN THE COMBUSTION CHAMBER

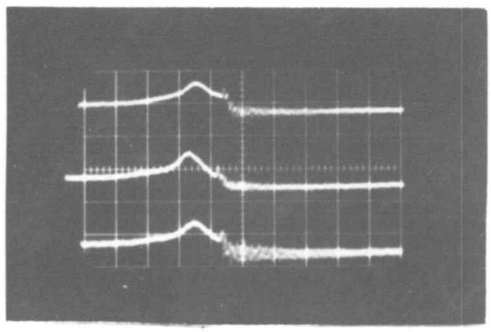
COMPRESSION RATIO = 5.0



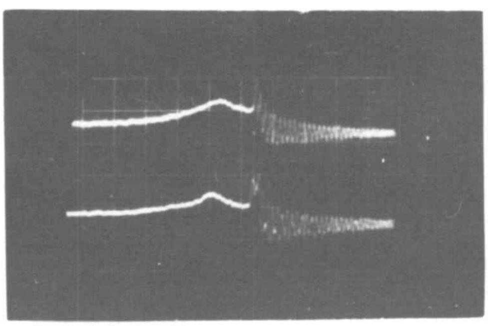
NON KNOCKING



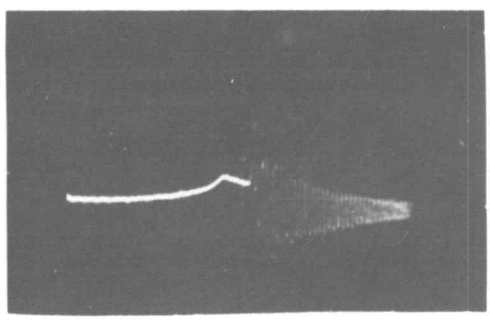
TRACE KNOCK



LIGHT KNOCK



MEDIUM KNOCK



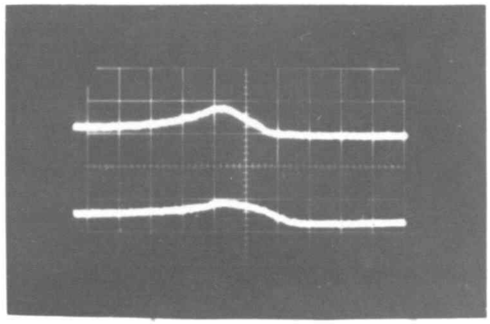
HEAVY KNOCK

Fig. 15. Detonation Traces for a Compression Ratio of 5.0

KNOCK INTENSITY PHOTOGRAPHS

OSCILLOSCOPE TRACES SHOWING THE TIME RATE OF PRESSURE CHANGE IN THE COMBUSTION CHAMBER

COMPRESSION RATIO = 5.5



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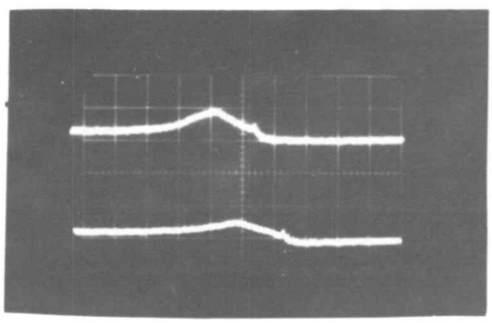

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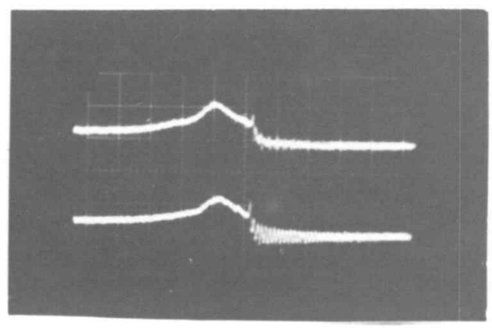

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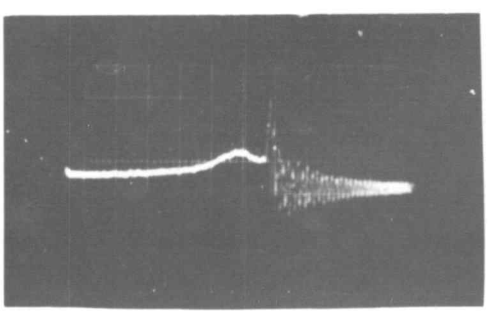
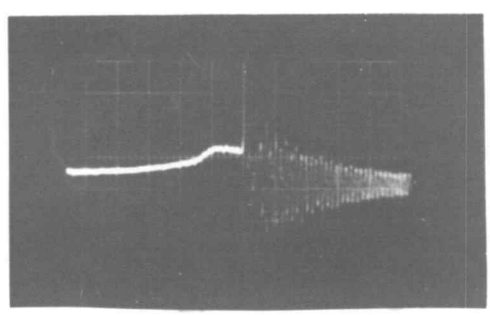


MEDIUM KNOCK



HEAVY KNOCK

Fig. 16. Detonation Traces for a Compression Ratio of5.5

KNOCK INTENSITY PHOTOGRAPHS

OSCILLOSCOPE TRACES SHOWING THE TIME RATE OF PRESSURE CHANGE IN THE COMBUSTION CHAMBER

COMPRESSION RATIO=6.0

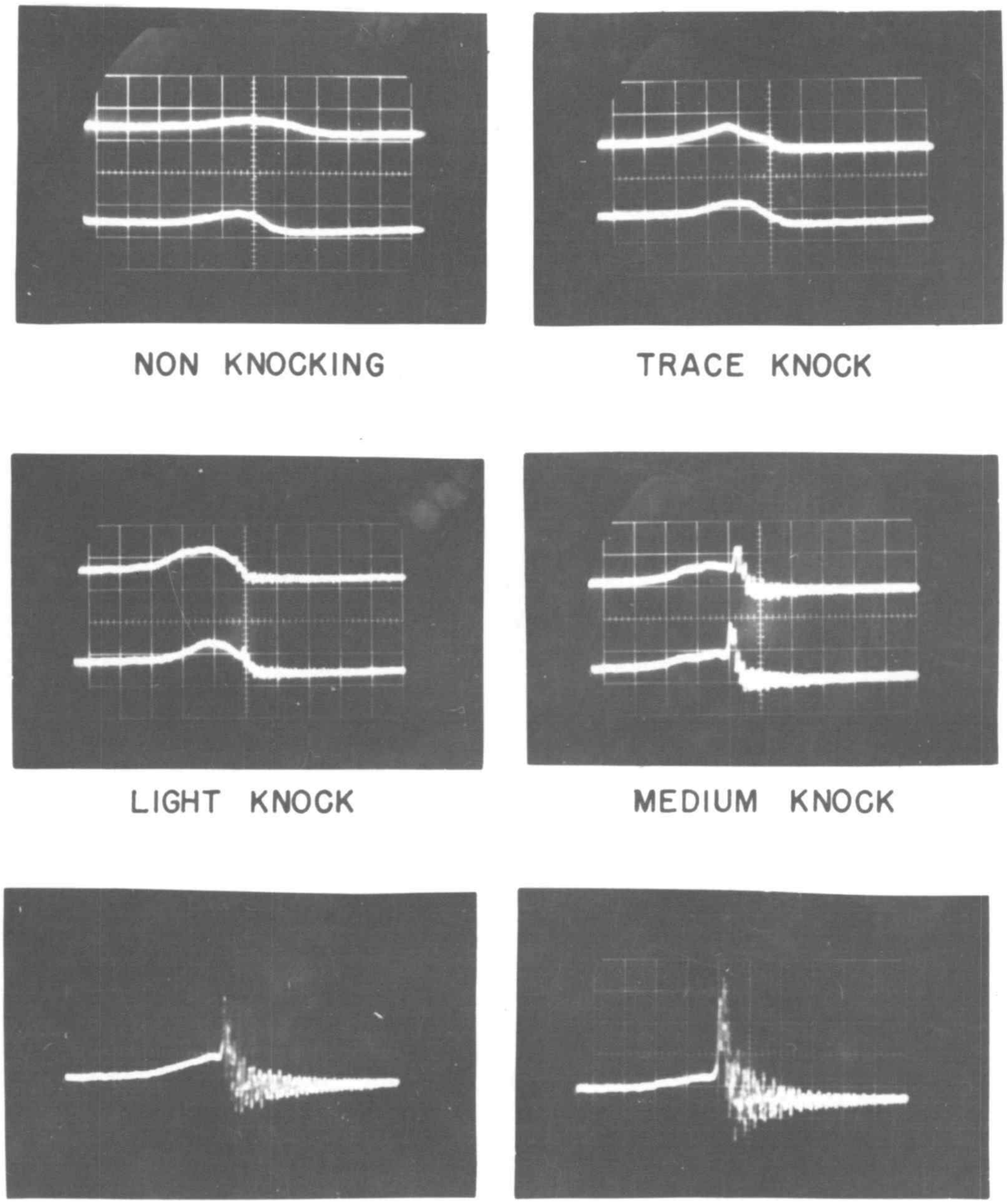
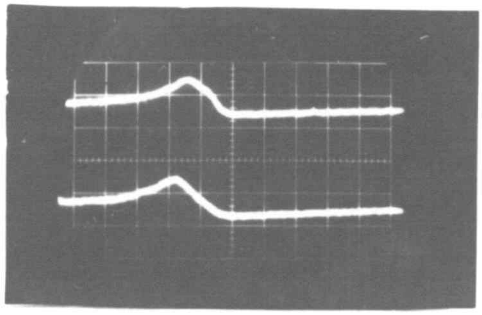


Fig. 17. Detonation Traces for a Compression Ratio of 6.0

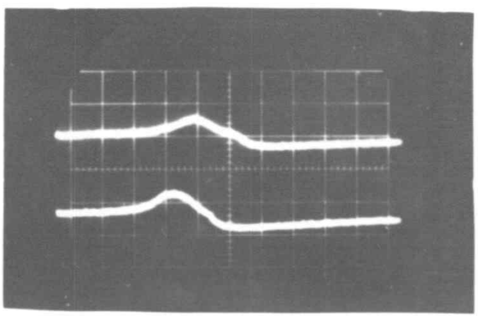
KNOCK INTENSITY PHOTOGRAPHS

OSCILLOSCOPE TRACES SHOWING THE TIME RATE OF PRESSURE CHANGE IN THE COMBUSTION CHAMBER

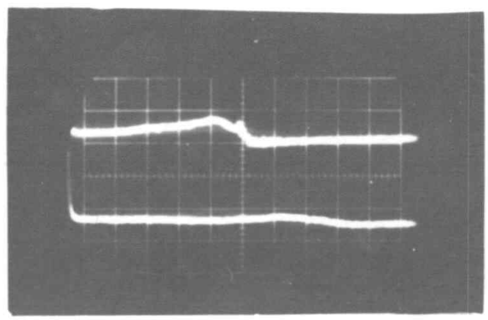
COMPRESSION RATIO = 7.0



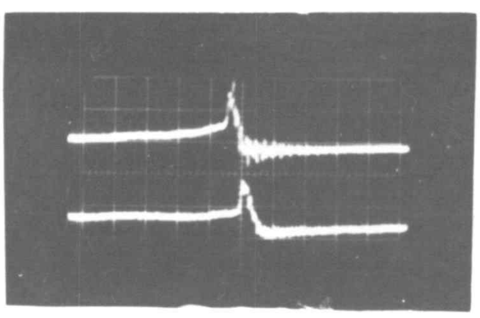
NON KNOCKING



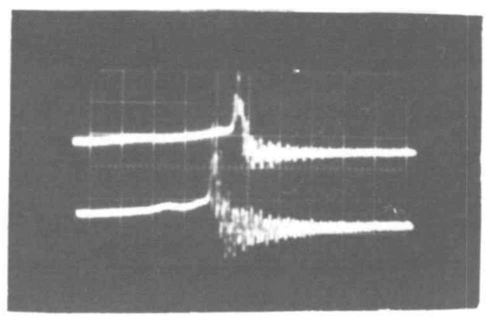
TRACE KNOCK



LIGHT KNOCK



MEDIUM KNOCK



HEAVY KNOCK

Fig. 18. Detonation Traces for a Compression Ratio of 7.0

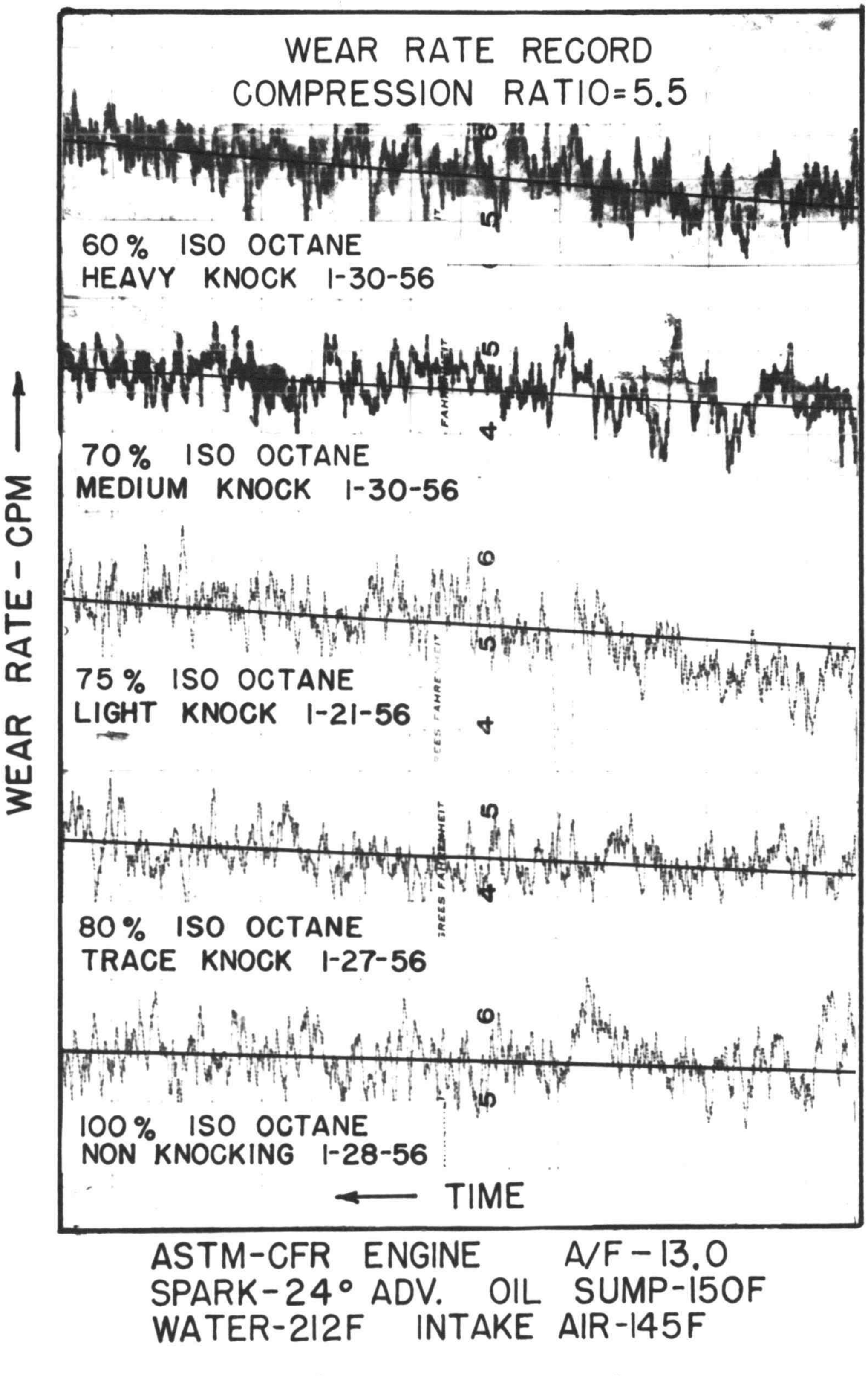


Fig. 19. Wear Rate Record for a Compression Ratio of 5.5

DISCUSSION OF RESULTS

To establish the validity of results the following factors must be considered. A deviation in diametrical size from a true bore will appreciably affect results when the nature of the testing program entails a variable compression ratio. It must be remembered that to change the compression ratio of the ASTM-CFR engine it is necessary to raise or lower the integral head and cylinder assembly. A change in compression ratio then means that the piston is working in a different portion of the cylinder profile. Several reruns were made at a compression ratio of 5.0 in an effort to explain the decrease in wear with increasing knock intensity above trace knock conditions. Resulting wear rates were consistently similar so the physical condition of the cylinder was investigated to obtain some reason for the apparent discrepancy.

The cylinder taper may be seen in figure 20. The profile shown was taken after the testing program, but a rough check at the beginning of this investigation gave, in general, the same profile. It may be seen that the cylinder had a groove which extended around the circumference to a depth of 0.0035 inches. This groove, it is reasoned, served to contain a reserve of oil.

Maximum wear in a cylinder takes place just below the top dead center position of the piston. The reason for this is related to the boundary lubrication which exists when relative velocity is low and to the pressure on the piston which is a maximum at this time. If by some means or another a thick film of lubricant is produced on the cylinder wall in the area where maximum wear normally takes place, wear will be greatly reduced. Herein lies the explanation for a decreasing wear rate with increasing knock intensity at a compression ratio of 5.0. The radioactive ring at this compression ratio should be exhibiting maximum wear just below the groove in the cylinder wall. This is essentially what happened when the combustion pressure was normal or slightly more than normal, but as the pressure increased markedly the effect was to wedge the excess oil, which has accumulated in the groove, down between the cylinder wall and the piston ring, thus affording hydrodynamic lubrication. The overall result was to decrease the amount of scuffing which would otherwise have taken place. At compression ratios of 5.5, 6.0, 7.0 and 8.0 maximum wear was taking place above the groove in the cylinder wall thus nullifying the wedging effect.

The relatively high wear rates obtained at a compression ratio of 6.0 as compared to the other compression ratios is probably a result of wear carry-over effect. H. R. Jackson *et al.* reports that approximately five to ten hours of engine operation is necessary to obtain a normal wear rate after a high wear rate has once been established (10, p.3). The test at a compression ratio of 6.0 was the first series after the break-in run so it is possible that break-in was still not completed. The effect of this consideration on the results is of minor consequence as the wear carry-over would merely tend to reduce the relative percentage increase in wear with increasing knock intensity.

As a final consideration in this discussion the reproducibility of results will be examined. Detonation is a chemical reaction which is dependent on pressure, temperature, time, fuel composition and probably several unknown factors. To assume that all these conditions can be exactly reproduced is absurd. An exact blend of fuel produced different knock intensity on succeeding days, even though there was no noticeable change in other conditions. To complicate the problem even further knock intensity varied from cycle to cycle under identical conditions. A series of knock photographs might show a time rate of pressure change which varied from trace knock to medium knock classification. The dp/dt traces were of considerable help in reproducing results. Each combustion cycle could be flashed on the screen and the rapidity of repetition enabled an average trace to be observed. It was therefore a somewhat simple process to determine if previous knock intensities were being reproduced.

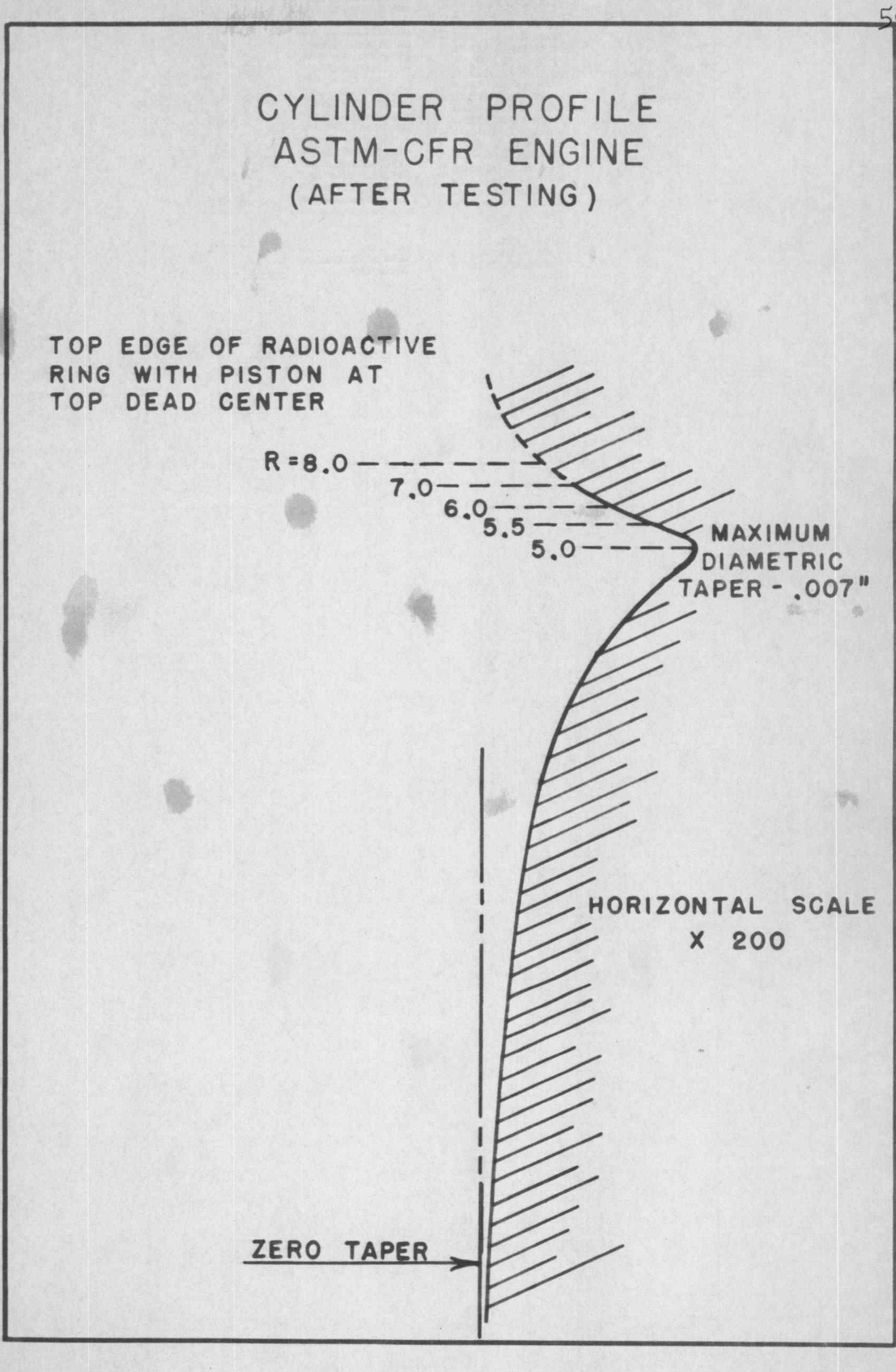


Fig. 20. Cross-section Through the Cylinder Wall

CONCLUSIONS

With due consideration to the assumptions set forth in the preceding section it can be concluded that detonation within the combustion chamber results in a marked wear increase. The magnitude of this wear increase is proportional to the intensity of detonation, and may amount to more than three times the normal wear rate. It appears that the relative damage becomes more pronounced as the compression ratio is increased although in making this conclusion it must be remembered that an increase in compression ratio alone will increase the normal combustion pressure and thus cause a higher wear rate.

RECOMMENDATIONS

An evaluation of the testing procedure and related technique points up several modifications which might be made in a similar research project. Foremost is the necessity of working with an engine having a true bore. As was pointed out in the discussion of results an irregular cylinder bore is undesirable.

Secondly, it would be advisable to obtain some means for assuring a constant volume flow of lubricating oil through the sensing well. For the test set-up used in this investigation the volume of oil flowing through the sensing well was dependent upon both the oil temperature and the oil pressure. If a calibrated orifice was placed in the oil line an accurate control of volume could be obtained by maintaining a constant pressure drop across the orifice.

Adapting the ASTM-CFR engine to radioactive wear measuring apparatus has opened the door to countless avenues of research here at Oregon State College. Quite by accident it was observed that a commercial grade of ethyl gasoline caused a considerably higher wear rate than the pure blends of iso octane and n-heptane used in this investigation. This fact suggested the project of an evaluation of the effect of gasoline additives on piston ring wear.

It would be interesting to compare the results of this work with a similar test conducted on the cetane fuel rating engine. Detonation in a diesel engine is considerably different than in a spark ignition engine, yet it is similar in that it is the cause of rapid pressure rise and pressure fluctuation.

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