EFFECT OF FUEL-IMPINGEMENT-SURFACE TEMPERATURE ON NOISE, SMOKE, AND POWER OF A COMPRESSION-IGNITION ENGINE

> Thesis for the Degree of Ph. D. MICHIGAN STATE UNIVERSITY Lawrence Richard Daniel, Jr. 1958





This is to certify that the

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### EFFECT OF FUEL-INFINGEMENT-SURFACE TEMPERATURE ON NOISE, SMOKE, AND FOWER OF A COMPRESSION-IGNITION ENGINE

By

Lawrence Michard Daniel, Jr.

### AN ABSTRACT

Submitted to the School for Advanced Graduate Studies of Lichigan State University of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Department of Mechanical Engineering

1958

Approved Louis L. Otto

Lawrence Richard Daniel, Jr.

#### AN ABSTRACT

The intention of this investigation was to determine experimentally the effect of impingement-surface temperature on smoke, noise and power in a compression-ignition engine combustion chamber in which there is combustion-surface fuel impingement.

A regular CFR Cetane engine was modified in such a way that, by use of a directional nozzle, the fuel spray could be directed either toward a combustion chamber wall or out into the open combustion chamber space. The combustion chamber consisted of a small cylindrical space located in the cylinder-head and was offset from the centerline of the bore. An investigation of air-flow in this chamber using paintpatterns and a small paddle-wheel finally led to the development of a combustion surface in the form of a protruding lip in the bottom of the combustion chamber. The fuel was injected onto this lip and the vapors produced thereon were picked up by the currents of air from the compression process.

Spheroidization of the fuel was investigated on the assumption that within the engine a combustion surface might exist on which the fuel would spheroidize rather than spread as a smooth film. It was found that deposit formation on this combustion surface occurred so rapidly at higher surface temperatures that this system would not successfully operate within the temperature range at which spheroidization would seem to be a problem.

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Deposit formation caused increasingly more trouble as the temperature of the impingement surface was increased. It was concluded that the distance between the injector nozzle and the impingement surface was somewhat critical, in that too small a distance would allow diversion of the fuel spray by the deposits prior to its complete spreading on the lip, while too large a distance would allow a large portion of the fuel to autoignite and cause a louder combustion noise.

It was found that the beneficial effect of an impingement surface on noise and smoke increased as the surface temperature increased. At the higher surface temperatures, however, deposits quickly formed and the beneficial effect of the surface was reduced. For this engine it was found that the optimum surface operating temperature was in the neighborhood of 500°F. Above this temperature the smoke became worse, power dropped off and noise tended to increase, depending on the manner in which the deposits formed. Below this temperature both noise and smoke quickly became unreasonable.

The effect of compression ratio on the surface-impingement system in a compression-ignition engine such as this one was similar to that of the normal space-impingement system. For compression ratios between 16:1 and 22:1 it was found that smoke became worse, power increased, and noise decreased as the compression ratio was increased. Higher compression ratios than 22:1 gave excessive smoke.

The original fuel-impingement compression-ignition engine as developed by Dr. J. S. Meurer, known as the M-system combustion chamber, utilizes fuel impingement in a hemispherical combustion chamber and

Lawrence kichard Daniel, Jr.

3.

evaporation of this surface film into a controlled air-swirl. It was concluded that the system originated herein is not a true M-system combustion chamber. In the true M-system the reaction rate is low at the beginning of combustion and increases towards the end of combustion while in this "lip" engine the maximum rate of pressure change occurs nearer the beginning of combustion.

### EFFECT OF FUEL-IMPINGELENT-SURFACE TEMPERATURE ON NOISE, SMOKE, AND POWER OF A COMPRESSION-IGNITION ENGINE

Bу

Lawrence Kichard Daniel, Jr.

### A THESIS

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#### INTRODUCTION

Ever since the early days of the diesel engine. engineers have been concerned with the formation of a combustible mixture within its combustion chamber. While the Otto, or spark-ignition engine, uses the major portion of the intake and compression strokes in which to form a combustible mixture, the diesel has considerably less time to perform this necessary function. In the diesel, or compressionignition engine, the injection of fuel is begun just before the end of the compression stroke only to be terminated a few degrees later in the beginning of the expansion stroke. It could be estimated, therefore, that the diesel has in the order of one-twentieth the time of the spark-ignition engine to form a combustible mixture. This is further complicated by the fact that, while the combustible mixture is completely formed at the time of its ignition in the spark-ignition engine, in the diesel the last portion of the fuel to be injected is sprayed into a zone of combustion, glowing hot from the action of the initial autoignition. The early combustion has already taken full usage of the most readily available oxygen, leaving the last portion of the fuel to burn in a relatively fuel-rich zone. It is mainly the job of the injection system to so combine the fuel and air that this fuel-rich condition, and its attendant formation of smoke, does not occur before the maximum amount of air has been combined with the fuel. This is also the reason why it is said that a diesel engine under full power is smoke-limited and why the richest fuel-air mixture

ratio for a diesel is considerably leaner than that of an otto engine under the same full-power conditions.

During early investigations it was generally accepted that the best mechanism of formation consisted of immediate vaporization and mixing with air as the fuel was injected into the cylinder or combustion space. The control of the combustion reaction was then under the direct influence of the rate of inflow of the fuel. Delay of combustion (ignition delay) caused by a chemical delay characteristic of the fuel was something which had to be put up with and the more that could be done to snorten this delay the better.

During the ignition delay period more and more fuel is being injected into the combustion chamber. Because of this accumulation of fuel when combustion begins, a large amount of the fuel is consumed in a short time causing a high rate of change of pressure. This high rate of change in pressure may shock load some of the engine parts and set them to vibrating, transmitting noise to the surroundings. Because of the heterogeniety of the autoignition process, pressure differences may be set up within the combustion chamber which may be superimposed upon the already vibrating masses. Thus it is that many factors, such as injection processes, natural frequency of the vibrating parts, mass of the varts, and the like, enter into whether or not a fuel knocks in a particular engine. There seems to be no fixed value of rate of change of pressure which differentiates between a knocking and a non-knocking combustion process. Each individual engine design has its own value of rate of change of pressure at which audible knock begins.

It has been found that in the case of the more volatile fuels, smoke increases with decreased ignition delay, while in the case of less volatile fuels this trend is reversed.<sup>1</sup> As the time for the beginning of injection was advanced less smoke was produced.<sup>2</sup> However, if the injection was advanced too far, smoke production was increased because of spray impingement on the combustion chamber surfaces.<sup>3</sup>

Using a "nearly ideal micro- and macro-mixture" formed during the period of ignition lag produced a loud characteristic diesel knock and heavy exhaust smoke.<sup>4</sup> These same investigators found that if, for improving mixture formation, either the spray velocity or the air velocity or both were increased, the combustion noise became louder. If the fuel rate at the beginning of injection was reduced the engine ran smoother, but there was an increase in exhaust smoke.

Throughout this confusion, fuel characteristics were always paramount and any comparison of engine performances without their inclusion was almost useless. In particular, the spark-ignition fuels with their long-delay characteristics were in general eliminated from use in a compression-ignition engine.

All the while the gap between the fuel used in the sparkignition engine and the compression-ignition engine was widening. Autoignition was necessary in one engine while it was highly undesirable in the other. This separation was not too undesirable because that fuel not readily adaptable to the diesel was usually usable in the otto engine. Nevertheless, the production of two distinctly

different fuels is much more expensive than the production of only one, and toward this end a great deal of research has been directed. A true multifuel engine, capable of burning either gasoline or diesel oil, would be eagerly accepted. This engine must have the power and economy of contemporary engines, and it must be quiet and cleanburning like the spark-ignition engine without the necessity of using the highly refined fuel required of this latter type.

In June, 1955 there was presented to the Society of Automotive Engineers an explanation and solution to some of the problems of diesel engine combustion. Dr. J. S. Meurer of Machinenfabrik Augsburg Nürnberg, Nürnberg, Germany presented a paper entitled "Evaluation of Reaction Kinetics Eliminates Diesel Knock" and demonstrated its practical applications with the operation of a highly successful engine. That this engine was quiet and relatively smokeless was witnessed by all. Dr. Meurer's theories have now withstood three years of extensive research by industry.

This engine successfully burned all ruels in the range from gasoline to lube oil and as a result has served as an extreme impetus to research into the realm of multifuel engines. Just recently (October, 1956) there was presented a series of six papers on multifuel engines before the Society of Automotive Engineers National Diesel Engine Meeting. Since all types of fuels can be used in these engines it seems then that the gap between spark- and compressionignition engines has finally closed.

The M-system combustion system, as Dr. Meurer's theory is called, consists basically of fuel impingement on the combustionchamber walls. Prior to the impingement a small portion of the fuel autoignites during its passage from the nozzle tip to the combustion surface. The remaining fuel is deposited as a liquid film on the surface. Here evaporation is delayed as compared with an injection system in which fuel is forced outward into the hot compressed air. This fuel vapor is picked up and consumed in a comparatively orderly manner by a rapid air swirl within the combustion chamber. The temperature of the combustion surface is extremely important in that it controls the rate of evaporation, lip wetting, and fuel cracking. This variable, combustion-surface temperature, is the primary interest of this investigation.

The problem chosen for this investigation is to formulate a satisfactory qualitative analysis of the combustion process for fuelimpingement combustion as the temperature of the impingement surface is varied. Basically it includes an experimental development of a fuel-impingement combustion chamber for a compression-ignition engine and a physical interpretation of the effects of surface temperature on smoke, power, and noise.



#### DELINEATION OF VARIABLES AND DEFINITIONS

In order to successfully investigate the effect of surface temperature on smoke, noise, and power, it is necessary to obtain means to vary and measure each to a certain degree of accuracy dependent upon the magnitude of their variations. Thus, it was considered useful to record such uncontrollable variables as atmospheric pressure and intake-air volume. However, such a small variation existed in the amount of air consumed under varying circumstances, including the variation in compression ratios, that this variable was discounted during calculations.

No specific correction concerning the effect of atmospheric pressure on smoke and noise is known and although recorded, this variable was also discounted during calculations. Incidentally, the pressure variation for the entire time of testing was no greater than two per cent.

Low engine speed will produce the most pronounced diesel knock. Since the CFR diesel which was to be used in this investigation was regulated at 600 rpm, it was decided to use this speed. In order to eliminate another variable it was decided to maintain this as the only speed used during the tests.

Considerable disagreement exists in the literature regarding the effectiveness of the various smoke-measuring devices. Since reproductivity, continuous reading, and only comparative results were necessary, it was decided to construct a device suitable for this



investigation. The indications obtained therefrom ranged from 6.1 to 1.3 when the exhaust changed from what might be considered a "rather dark" to a "clear" condition. The density of exhaust smoke is therefore somewhat proportional to the smoke-meter readings.

Two methods were chosen for comparing noise. A tape-recorder was most useful for audio-comparative results over a period of time but this could not be incorporated on a written page. A commercial noisemeter was used for direct readings in decibels and these values were listed under the "Noise" heading on the data sheet.

In a normal engine the fuel may come into contact with the combustion surfaces. Because of this it was decided to start the range of the lip temperatures as near to that of a normal combustion chamber surface as possible. This would be in the order of 350°F and higher. The upper limit of the temperatures would depend upon the progress of the investigation.

Compression ratios of 28.5:1 down to 16:1 would be all that were necessary. Lower than 16:1 would certainly produce a noisy condition and the higher ratios are conducive to smoke formation. The main investigation was actually centered in the range of 18:1.

All variables which could be controlled were made constant. This included intake air (150°), coolant temperature (212°), and fuel rate (10 ml./min., in general). The fuel rate was set at a condition which produced heavy smoke in some cases while in others the exhaust was relatively clear. Because this system of combustion has previously been shown to be effective with most internal-combustion engine fuels,



only one type of fuel was used for most of the tests, a commercial

diesel fuel, Cetane #42 minimum.

In the description of the place of injection, the following nomenclature is used:

- Sleeve-impingement or sleeve-injection. Injection onto the sleeve and lip immediately adjacent to the nozzle.
- Lip-impingement or lip-injection. Injection somewhere out on the lip at one-half inch along the lip from the sleeve unless otherwise noted. The distance between the impingement surface and the nozzle tip is somewhat greater than in the case of sleeve-injection.
- Space-impingement or space-injection. Injection so that there is no impingement on any combustion surface. This implies injection toward the passage between the cylinder and the lip and sleeve assembly.

The liner is that portion of the combustion chamber which has been forced into a hole bored in the cylinder head.

The mouth-insert is that machined part which is used in the bottom of the liner to control the flow of air and/or gases to and from the cylinder space. It serves a secondary purpose of keeping the sleeve and lip assembly in place.

The compression-ratio plug is that machined part which is inserted in the top of the liner. It serves as a means of closing the combustion chamber and of varying the compression ratio by the use of different sizes of plugs. In the case of the regular, unmodified CFR Cetane engine the compression-ratio plug is that part which is normally used to change the compression ratio. This latter arrangement is more

elaborate than that of the modified engine but it operates in essentially the same manner.

When the word "scale" is used, it indicates the force in pounds exerted by the torque arm of the dynamometer. Since the engine rpm is constant, the scale readings are a direct indication of the power produced.

The nozzles used in the injector for this investigation consisted of the normal pintle-type nozzle with which the CFR engine is regularly equipped and a multiple-orifice nozzle in which all except one of the orifices were closed. This latter arrangement supplied a method by which the direction of injection could be enanged, consisting essentially of rotating the nozzle in the injector or rotating the injector in its mounting in the engine. The orifice diameter was 0.0118".

The oscilloscope pictures were obtained by seven different exposures. In each case the time variable began on the right and moved to the left. The ordinate of the top two curves was pressure and that of the bottom two was the rate of change of pressure, or dp/dt. The top and bottom curves pertain to the engine under firing conditions while the center two curves are for the motoring condition. Pips appear at 13°BTDC and 13°ATDC. Approximately at the two and at the four centimeter lines up from the center are seen horizontal traces. The bottom trace represents 578 psi while the top trace represents 1057 psi, each measured from the center. No scale is set up for the rate diagram but its value can be obtained by use of a constant which is derived in the Appendix D.



The different types of lips are described as:

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Low-temperature lip - lip and sleeve assembly using no insulation between it and the liner.

- Intermediate-temperature lip lip and sleeve assembly using annular grooves, or spaces, as an insulation method.
- High-temperature lip lip and sleeve assembly using asbestos as an insulation between it and the liner.

The term "combustion chamber" refers to that separate chamber, apart from the space immediately above the piston, into which the fuel is injected. It is that volume enclosed by the lip and sleeve assembly above the mouth-insert and below the compression-ratio plug.

### PRESENTATION AND DISCUSSION OF RESULTS

#### GENERAL RESULTS

### Effect of Impingement Surface

Table I and Figures 1, 2, and 3 show very clearly the effect

of varying the place of injection from space to lip to sleeve, re-

spectively. This variance was obtained by attaching a flexible fuel

### TABLE I

### COMPARISON OF THREE PLACES OF INJECTION. INTERMEDIATE-TEMPERATURE LIP AND SLEEVE ASSEMBLY WITH BOTTOM OF LIP INSULATED FROM MOUTH-INSERT BY ASBESTOS, COMPRESSION RATIO 18 1/2:1, FUEL RATE 10 ML./MIN.

	Space	Lip	Sleeve
Injection Advance, °BTDC	21	21	21
Noise	75.0	74.5	73.7
Smoke Density	5.5	3.8	4.0
Power (Scale)	9.5	9.7	9.3
Lip Temperature, °F	830	640	580
Maximum Pressure, psi	1,060	980	<i>9</i> 10
Average Maximum Hate, psi/sec.	203,000	162,000	81,400
Picture Number	1	2	3
Average Maximum Kate, psi/sec. Picture Number	203,000 1	162,000 2	81,400 3



- Time

Figure 1. Pressure-Time and Rate-Time Relationships, Motoring and Firing, for Space-Injection at 18<sup>1</sup>/<sub>2</sub>:1 Compression Ratio. Pips at 13°BTDC and 13°ATDC. Surface Temperature of Combustion Chamber, 83°F. Injection Commences 21°ETDC




Figure 2. Pressure-Time and Rate-Time Relationships, Motoring and Firing, for Lip-Injection at 10<sup>1</sup>/<sub>2</sub>:1 Compression Ratio. Fips at 13°BTDC and 13°ATDC. Impingement-Surface Temperature 640°F. Injection Commences 21°BTDC.





Figure 3. Pressure-Time and Rate-Time Relationships, Motoring and Firing, for Sieeve-Injection at 18%:1 Compression Ratio. Pips at 13° BTDC and 13° ATDC. Implement-Surface Temperature 580°F. Injection Commences 21° BTDC.



line to the injector and rotating the injector assembly while the engine was in operation. The three pictures are taken consecutively with very little time lapse between them.

Figure 4 is a set of motoring curves used to determine the effective compression ratio throughout the tests. These curves were obtained by motoring the unmodified CFR Cetane engine at various compression ratios. From these it can be seen that the compression ratio of the first three pictures, as indicated by the second curve from the top on each, is in the order of 18 1/2:1.

The magnitudes of the maximum combustion pressure in Figures 1, 2, and 3 were 1,060, 980, and 910 psi, respectively, and the maximum of the average rates of pressure change were approximately 203,000, 162,000, and 81,400 psi/sec, respectively. The first set of readings was taken from the maximum of each of the top curves and the second set from the maximum of the average trace, or mean, of the bottom curves. Thus, in the case of rate curves with a large number of fluctuations, the average ordinate is used rather than the maximum of any one fluctuation. It can be plainly seen by the pressure-time curves that the rate of change of pressure during the combustion process is greater in space-injection than in lip-injection which, in turn, has a greater rate than sleeve-injection. Care must be taken not to confuse the two calibration marks, one at 13°BTDC and the other at 13°ATDC, with pressure variations.

The second curve from the bottom is the motoring rate-time curve. Its only purpose is comparative.



-Time

Figure 4. Motoring Compression Pressure Diagrams for Unmodified CFR Cetane Engine at 16.6, 18.1, 19.9, 22.1, 24.9 and 28.5:1 Compression Ratio. Pips at 3/9ETDC and 19/9ATDC.



The amount of noise produced by space-injection and lipinjection, 75.0 and 74.5, respectively, would probably preclude their acceptance as commercial machines. A noise reading of 74.5, in general, separates the realm of general quietness and noisiness herein. This is, of course, relative and might not be similarly judged by another observer.

Reducing the injection advance for space-injection would quiet the engine but with a reduction in power and increase in smoke. A comparable change for lip-injection would produce the same changes as in the case of space-injection. Tests showed that an injection advance which would quiet the engine to an acceptable level would reduce the power of both space-injection and lip-injection into the range of the power produced by sleeve-injection while in neither case was the exhaust as clear as in the latter. The investigation was, therefore, mainly centered around sleeve-injection.

Note that there is a row in Table I under the heading of Lip Temperature. The lip temperatures for space-, lip-, and sleeveinjection are listed as 830°F, 640°F, and 580°F, respectively. All three temperatures are measured by a thermocouple placed in the center of the lip. For space-injection no cooling film of fuel is impinged on the lip so the temperature recorded under this condition is naturally nigher than for lip- or sleeve-injection. For lip-injection, the fuel comes into contact with the lip over the outer half, or less, of lip area, so at least part of the lip is insulated and cooled by the fuel film and its vapors. The temperature listed for lip-injection



is therefore less than for space-injection. Sleeve-injection implies injection onto the sleeve and lip immediately adjacent to the nozzle. Only a very short distance of intervening space separates the nozzle from the lip. The fuel spreads onto a much larger portion of the lip than in the case of lip-injection; therefore, the recorded lip temperature is the lowest of the three temperatures listed. Note that the names for the last two types of injection, lip- and sleeve-, correspond to the first place of impingement of the fuel after leaving the nozzle.

## Warm-Up Requirement and Deposit Formation

Table II, a warm-up run on the high temperature lip with lip-

#### TABLE II

# ENGINE WARM-UP DATA, USING HIGH-TEMPERATURE LIP AND SLEEVE ASSEMBLY, LIP-INJECTION, COMPRESSION RATIO 18 1/2:1, INJECTION ADVANCE 18° BTDC, FUEL RATE 10 ML./MIN.

Time After Start (Lin)	Smoke Density	Power (Scale)	Lip Temper- ature, °F	Noise
3	3.6	7.2	535	74.ċ
12	5.8	7.3	790	75.3
24	5.9	მ <b>_</b> 2	630	74.6
36	5.6	8.5	630	74.6
48	5.8	7.9	750	74.9
72	5.0	9.1	745	74.3
78	5.3	8.3	720	74.7



injection, is indicative of the variations encountered in this investigation. To be particularly noted is the trend of the lip temperatures, first increasing to a maximum (790°) followed by a reduction in temperature and occasionally by another increase. This is understandable when it is considered that the lip is initially clean and therefore uninsulated from the hot gases. This lip, because it was designed to run at high temperatures, was very susceptible to early deposit formation. Consequently, the deposits quickly formed, diverting the spray before it thoroughly impinged on the lip, and reduced the cooling effect of the liquid fuel. This loss of cooling effect, combined with the clean uninsulated surface of the lip, allows the heat of the combustion gases to quickly penetrate the lip and raise its temperature. Eventually deposits do form on the lip and their insulating value succeeds in lowering the temperature of the lip, hereafter to fluctuate somewhat, depending upon the amount of deposits remaining on the lip.

For the lower temperature lips less trouble is encounted by deposits and therefore, the cooling action of the fuel spreading out and forming a thin cover is the controlling factor. The only sure indication of impingement of the fuel on the lip is obtained by changing the place of injection. May decrease in the temperature indicates better impingement on the lip since the thermocouple is located in its center. No appreciable increase in temperature when the direction of injection has been changed from lip or sleeve to space indicates that deposits have built up and caused diversion prior to complete impingement.



Noise depends on the manner of diversion and the time of injection, the earlier and the less dispersed injections producing the louder diesel knock. Snoke depends to a large extent on the control which the lip exercises on the fuel, a well spread out highly dispersed injection producing a minimum of snoke.

### Comparison with Standard CFR

Although Figure 5 was taken using a different pressure pickup (different calibration) than was used for the rest of the investigation, it is included herein for its general interest. This picture was taken of the events occurring under standard conditions in an unmodified CFR diesel engine at a compression ratio of 18 1/2:1. Since the fuel rate, and power, were different than in the circumstances under which all the other pictures were taken, no quantitative comparison can be made. In particular, it should be noticed that the large-ranged fluctuations of the rate of pressure rise vs. time diagram are absent as compared with Figures 1 and 2. This is due to the pintle-type of injector used, while the remaining pictures are indicative of the behavior of an orifice-type nozzle. The preceding statement was verified by use of an orifice-type nozzle in place of the pintle-type in the regular CFR engine. The orifice-type nozzle evidently delivers fuel in such a manner as to induce large, almost instantaneous, variations in the rate of pressure rise. Referring again to Figures 1, 2, and 3, we see that a controlled condition such as sleeve-inpingement can considerably reduce both the magnitude of the fluctuations of the rate of pressure rise and their mean value.



---- Time

Figure 5. Pressure-Time and Rate-Time delationships, Motoring and Firing, for Unmodified CFR Cetane Engine © 183:1 Compression Ratio. Pips at 13° BTDC and 13° ATDC. Injection Commences 13° BTDC.



#### Impingement Effect in Standard CFR

The data shown in Table III was taken on the regular CFR Cetane diesel using a pintle-type nozzle. The information desired

### TABLE III

DATA ON REGULAR CFR CETANE ENGINE, WITH AND WITHOUT INSULATED STAINLESS STEEL CAP ON COMPRESSION-RATIO PLUG AS COMPRESSION RATIO IS CHANGED FROM 22.1:1 TO 15.3:1 AND BACK TO 22.1:1. INJECTION ADVANCE 13°BTDC, FUEL FLOW 9 ML./MIN.

	Insulated Stai On Compressi	nless Steel Cap on-Ratio Plug	Standard Co Ratio	ompre <b>ss</b> ion- Plug
Compression Ratio	Power (Scale)	Smoke Density	Power (Scale)	Smoke Density
22.1:1	10.0	4.1	10.3	4.6
19.9:1	10.0	3.0	10.5	3.6
18.1:1	9.9	3.0	10.5	2.7
16.6:1	10.0	2.3	10.3	2.2
15.3:1	9.7	2.3	10.0	2.1
16.6:1	9.6	2.5	10.1	2.3
18.1:1	9.5	3.1	10.3	2.6
19.9:1	9.6	3.0	10.1	3.1
22.1:1	9.4	4.1	10.1	3.6

here was to determine the effect of providing a hot surface for the fuel to impinge upon in case it was successful in traversing the combustion chamber without complete evaporation. This is accomplished by attaching a stainless steel disk insulated by asbestos to the compression-ratio plug. It was found that this surface attained an average temperature of the order of  $\delta 00^{\circ}$ F while the bare plug averaged approximately  $360^{\circ}$ F.



Actually, none of the M-system principles (Appendix A) are applied here because (1) the amount of fuel autoigniting is not limited, (2) oxidation does not begin gradually, and (3) little or no controlled evaporation delay is introduced by this system. All injected fuel, except that which might impinge on the far surface is free to evaporate as rapidly as possible with little control over permissible pressure rise. It is nevertneless interesting to note the effects.

Graph I indicates the trends of smoke and noise vs. compression ratio. In each case, with and without the insulater cap, the trend was toward more power during the compression ratio reduction than during the compression ratio increase. This can be explained when it is noted that the runs started at a night compression ratio and progressed to the lower compression ratios. This was followed immediately with a set of runs taken as the ratios were increased. For this latter set it was necessary to reheat the engine components to a temperature compatible with the higher compression ratios. This represents a loss in availability of the fuel for useful work. Although it seemed at the time that a sufficient waiting period had elapsed, the graph snows otherwise. This is brought up here because it is wished to emphasize the time involved for equilibrium conditions to be achieved. Twohour warm-up periods were not unusual.

An explanation of the smoke trend is necessary. Note that there is less smoke at the lower compression ratios. Elliot<sup>2</sup> has explained that "short ignition delay generally increases smoke production



because a larger portion of the fuel is injected into an inflamed mixture. Under these conditions the production of locally overrich regions is favored and thermal decomposition is more likely to occur." This is obviously what happened here for as the compression ratio is increased the ignition delay is certainly decreased.

The uninsulated plug shows more power than the insulated plug. This is at least partially due to a poorer volumetric efficiency with the insulated plug. Another very important factor is time of combustion and rate of pressure rise. The tape recorder revealed more noise for the bare uninsulated plug. This indicates a larger rate of pressure rise which, if occurring just after TDC, would probably produce more power than that produced by a gradual pressure rise.

Another concurrence with the statement that decreased ignition delay produces more smoke is shown in the range of compression ratios less than 19:1. Here the smoke is worse for the hotter condition dictated by the insulated cap.

In order to confirm or deny the smoke trends existing in Table III and Graph I, a rerun was made over the entire range of usable compression ratios. This information is snown in Table IV and its plotted form is given in Graph II. Again, the insulated plug gave Less power than the uninsulated plug at all compression ratios, and again there was somewhat of a cross-over in the smoke trend at a compression ratio of approximately 20:1 with the insulated plug producing more smoke at the lower compression ratios than the uninsulated plug. A possible explanation could be that at the lower compression ratios the insulated plug provides a higher ambient temperature into which



### TABLE IV

## DATA ON REGULAR CFR CETANE ENGINE, WITH AND WITHOUT INSULATED STAINLESS STEEL CAP ON COMPRESSION-RATIO PLUG AS COMPRESSION MATIO IS CHANGED FROM 28.5:1 TO 13.4:1. INJECTION ADVANCE 13°BTDC, FUEL RATE 9 ML./MIN.

	Insulatea Stai On Compressi	nless Steel Cap on-Ratio Plug	Standard Co Ratio	ompression- Plug
Compression Ratio	Power (Scale)	Smoke Density	Power (Scale)	Smoke Density
28.5:1	8 .4	6.0	8.6	5.9
24.9:1	9.2	5.0	9.5	5.4
22.1:1	9.7	4.0	10.3	4.2
19.9:1	10.1	3.6	10.5	3.7
18.1:1	10.1	3.1	10.5	2.7
16.6:1	10.0	2.4	13.4	2 .4
15.3:1	9.8	2.3	10.2	2.1
13.4:1	9.4	2.0	9.6	2.0

the fuel is injected thereby reducing the ignition delay and producing more smoke. At the higher compression ratios, obtained in this engine by drastically shortening the length of the combustion chamber, the predominant influence could possibly now be the impingement of the fuel onto the immediately adjacent compression-ratio plug, with the insulated cap providing the hotter surface for more efficient fuel vaporization and combustion. This would indicate that impingement upon the less-hot uninsulated plug delayed evaporation a sufficient time to foul the combustion pattern. The anomaly at the highest compression ratio shown could very easily be due to a misreading.



#### Effect of Higher Lip Temperature

Table V is a comparison of space-, lip-, and sleeve-injection for a higher temperature lip than was used to obtain Table I and

	Space	Lip	Sleeve
Injection Advance, °BTDC	15.5	15.5	15.5
Noise	76	75	74
Smoke Density	5.0	5.2	4.3

10.4

855

9.8

710

9.2

690

Power (Scale)

Lip Temperature, °F

#### TABLE V COMPARISON OF THREE FLACES OF INJECTION. HIGH-TEMPERATURE LIP AND SLEEVE ASSEMBLY, COMPRESSION RATIO 18 1/2:1

Figures 1, 2, and 3 and at a smaller injection advance. The same general trends existed for noise and smoke with the exception that lip-injection seemingly produced a smokier condition for the hotter lip. In general, however, the noise was lower and there was less smoke for impingement than for non-impingement. This lip and sleeve assembly gave much difficulty with quick deposit formation, so it could quite possibly be that a diversion of the impinged spray was the cause of this apparent trend to slightly more smoke for lip-impingement.

In particular it should be noted that the trend in power is different, and is less for impingement than for non-impingement. Had a larger injection advance been used, this could have been to a large



extent modified such that sleeve- or lip-impingement would produce almost as much power as space-impingement when all three were operating under ideal conditions of injection advance. Note also the trend of scale readings in Table I which were taken at a constant injection advance of 21°BTDC. This latter data indicates that perhaps the optimum injection advance for sleeve-impingement is greater than 21° for this particular lip and sleeve combination.



## EFFECT OF LIP TEMPERATURE AND INJECTION ADVANCE AT CONSTANT COMPRESSION RATIO

#### 1. Low Lip Temperature.

Table VI is a comparison of two places of injection (sleeve and space) for three types of lip and sleeve combinations with the engine operating at two injection advances. The three types of lip and sleeve combinations are used to control the temperature of the impingement and non-impingement surfaces. The two injection advances are intended to compel operation under conditions more favorable for space-injection, 11°, and more favorable for sleeve-injection, 21°. These are not necessarily optimum conditions under any of the circumstances tested. For each lip and sleeve combination these data were taken as quickly as possible after equilibrium conditions had set in and before an appreciable amount of deposits had formed. Headings were first taken for space-impingement followed by a quick rotation of the injector to produce sleeve-impingement. The sequence was then repeated as a check. It was important to note that the deposits formed by sleeve-impingement were swept clean and oxidized during the spaceimpingement operation.

The aforementioned formation of deposits does not in any way preclude the successful use of an impingement surface but it does indicate that this variable has become pronounced during the reduction of smoke and noise.

COIM	ARISON OI COMPRESS	F TWO I SION IM	TLACES (	DF INJE 1/2:1,	CTION F( FUEL H	OK THRE ATE 10	HI. TYPE	S OF LI N.	.R.			
				Η	ype of 1	ip ard	Slecv	e Insul	ation			
	<b>1</b>	No Insu wedi	lating um			Annu Spa	lar ces		Annu <sup>]</sup> Asbe	Lar Spe estos 1	aces wit Inder Li	प् व
jection Advance, "BTDC	7		5				5		я		21	
ace of Injection	Sleeve	Space	Sleeve	Space	Sleeve	Space	Sleevc	Space	Sleeve	Space	Sleeve	Space
Noise	1, 17	74.8	74.8	0.77	74.1	74.9	75.1	75.9	73.7	1, 17	73.6	75.0
Smoke Density	ی. ح	<b>0</b> • 9	ر. ک	<b>لا ،</b> لا	<del>ر</del> ک	<b>د.</b> ارا	3.7	4 •2	4.9	5.7	3.6	5 .4
Power (Scale)	0° 6	6•6	10.2	10 <b>.</b> 4	9 <b>•</b> 6	10.6	10.5	ų. ų	- <b>-</b> • :0	0•6	9.7	4° 6

TABLE VI

-

>590

>1110

Lip Temperature, °F



Graph III is a plot of the events occurring using the lowest temperature, or non-insulated lip and sleeve assembly. An interesting set of events occurred. First, the lip temperature increased as injection was changed from sleeve to space, a larger increase occurring at the larger injection advances. This is natural since larger pressures would be created when more of the combustion occurs in the vicinity of or prior to top-dead-center. For the ll° injection advance more power is available for space- than for sleeve-impingement because the low temperature impingement surface delays evaporation of the impinged fuel until too late in the cycle for efficient usage, while injection into the hot compressed air is timed more nearly correct for good power output. A reversal of this tendency would occur for the 21° injection advance, if the sleeve were hot enough to supply ample vaporization during the time of fuel impingement. The sleeve and lip are evidently too cold here for this to happen, so again the power trend is for more power for space-injection.

The noise trend is what might be expected, louder combustion for space-injection than for sleeve-injection. Even though the sleeve has not been successful in producing comparable power, it has accomplished its purpose of controlling the rate of combustion.

The smoke trend is probably the most interesting and requires more explanation. Note that at ll° injection advance the trend is toward more smoke for space-injection than for sleeve-injection and that this trend is reversed at 21° injection advance. First, a long mixture time for space combustion is necessary for minimum shoke,

thus point four is better (less smoke) than point two because the injection advance is considerably greater here. Next, for a cold sleeve and a long mixture time, impingement delays combustion so long that a smokier condition exists, thus point four is better than point three. Since the cold sleeve is a definite controlling factor points one and three are about the same with three being understandably better because of the time involved. The general trend for this cold lip and sleeve combination is therefore: for small injection advances more smoke in the non-impingement condition; for large injection advances more smoke in the impingement conditions.

#### 2. Intermediate Lip Temperature.

Graph IV represents a plot of the variations occurring using the intermediate-temperature lip, as the place of injection is varied from the sleeve to space. Even though the expected trends exist for the data as recorded, a careful study of the operating conditions indicates that certain corrections should be made here.

The first correction would produce very little change. It is noted that the lip temperature for sleeve-injection is greater, 590°F, than in the case of the better insulated lip on the right on Table VI, 570°. It is quite possible then that diversion by deposit formation was beginning to occur. Depending upon the magnitude of diversion and its nature, there might be a change in smoke, noise, or scale readings. The unusually high value for noise, 75.1, for sleeve-injection definitely confirms either a diversion or a skipping action. The correction for noise and temperature should therefore be in the manner


shown as corrected (1). No indication of the direction of corrections necessary for smoke and power is apparent. This was an occurrence, not infrequent, which does not destroy the utility of the data.

It was shown earlier that fuel impingement on a surface under controlled conditions did in fact decrease smoke production markedly. This was somewhat true, even for the normal CFK diesel operating at the higher compression ratios with an insulated cap on the compression ratio plug. It seems apparent then that the increase in smoke produced as the place of injection is changed from lip to space is not here compatible with the preceding statement. Subsequent checks showed that any impingement whatsoever on any of the lips used, except the coldest at a large injection advance, definitely reduced the **amount** of smoke even though noise and power were not necessarily changed in any specific direction or perhaps not changed at all. Therefore, in this case, it is nighly probable that the corrections (2) should be made.

The power trend is as expected. At ll° injection advance, space-injection produced more power than sleeve-injection. At 21° injection advance, sleeve-injection produced more power than spaceinjection.

3. High Lip Temperature.

Graph V, a plot similar to that of Graphs III and IV, shows the events occurring under a hotter condition, this time with the same sleeve insulated with annular grooves as used to obtain Graph IV but with asbestos insulation between the lip and the mouth-insert molaing

the lip and sleeve assembly in place. The trends are typical and well formed.

Lip temperature rises for both injection advances as the place of injection is changed from sleeve to space. Power correspondingly increases as the place of injection is changed from sleeve to space for ll° injection advance but decreases for 21° advance. Smoke, at both injection advance angles, is worse for space injection than for sleeve injection. Noteworthy is the noise increase at ll° injection advance, 73.7 for lip to 74.1 for space. This relatively small increase can be explained by considering the temperature which the lip and sleeve assembly and the space have at this time. Understandably the sleeve controls the noise for the sleeve-impingement condition and this explains the 73.7 Late injection into hot surroundings (space-impingeme.t) decreases ignition delay thereby producing smoke, and this decrease in ignition delay explains the 74.1 That smoke is produced is verified by the space smoke reading of 5.7.

# EFFECT OF LIP TEMPERATURE AND COMPRESSION RATIO AT OPTIMUM INJECTION ADVANCE FOR SLEEVE-IMPINGEMENT

A comparison of the preceding information obtained on the three lip and sleeve assemblies is not necessarily valid, although typical, partially explainable, variations do exist. In none of the previous cases have the optimum conditions of injection advance been sought out. Because of this it is much more revealing to investigate sleeve-impingement for each lip and sleeve assembly under optimum conditions of injection advance as the compression ratio is changed. This was done, and the data presented in Tables VII, VIII, and IX are the results of this investigation. This information is shown corrected and in graphical form in Graphs VI, VII, and VIII.

The information which is required to plot these graphs was obtained through a long series of time-consuming runs in which the optimum injection advance was obtained for each compression ratio. This required a thorough warm-up followed by sufficiently long runs at each injection advance to allow equilibrium conditions to set in. At all times it was necessary to be exceptionally careful that deposit formation had not altered too greatly the required impingement pattern.

#### 1. Low Lip Temperature.

Table VII represents the data obtained using the low-temperature lip at compression ratios of 16:1, 18 1/2:1 and 22:1. Although the injection advance at the 16:1 compression ratio is slightly misleading, the trends of the variations are in general correct. As the compression



#### TABLE VII

COMPARISON FOR SLEEVE-IMPINGEMENT AT THREE COMPRESSION RATIOS FOR LOW-TEMPERATURE LIP AND SLEEVE ASSEMBLY FUEL RATE 10 ML./MIN.

Compression Ratio	16:1	18 1/2:1	22:1
Injection Advance, °BTDC	21	21	19 1/2
Noise	74.9	74 .8	74.5
Smoke Density	4.2	4.8	5.6
Power (Scale)	9.7	10.0	10.0
Lip Temperature, °F	390	410	480

ratio increases power increases, smoke gets worse, noise decreases and lip temperature increases. Note that injection advance remained constant for the two lower compression ratios and then became less at this higher compression ratio. The general trend consisting of smaller injection advances for higher compression ratios is correct. A cneck of the original data sheet revealed a note to the effect that the injection advance for the l6:1 compression ratio run was "noise limited" which indicated that the engine was knocking considerably, and it seemed advisable not to further increase the injection advance. This was a case of audio misinterpretation. Thus, a logical correction at the lower compression ratio would be to increase the injection advance, the power, the noise, and the lip temperature, slightly, and to decrease the smoke indication. These corrections are shown in approximate, but nevertheless considered, amounts on Graph VI.



## 2. Intermediate Lip Temperature.

Table VIII represents the data obtained for the intermediatetemperature lip at the same three compression ratios used earlier.

### TABLE VIII

# COMPARISON FOR SLEEVE-IMPINGEMENT AT THREE COMPRESSION RATIOS FOR INTERMEDIATE-TEMPERATURE LIP AND SLEEVE ASSEMBLY. FUEL RATE 10 ML./MIN.

Compression Ratio	16:1	18 1/2:1	22:1
Injection Advance, °BTDC	20	19	18
Noise	73.8	74.1	74.1
Smoke Density	4.7	4.2	5.2
Power (Scale)	9.5	10.1	10.2
Lip Temperature, °F	465	460	535

Note that the lip temperature was higher, the noise was less and the intensity of smoke was greater at 16:1 compression ratio than at 18 1/2:1 compression ratio. This same effect was noted while running the highest lip temperature used in this investigation. On occasions when the engine was producing an unusual amount of noise, the smoke would begin to increase, noise would decrease, and the lip temperature would rise. Inspection invariably revealed diversion of the fuel spray by the deposits. It was concluded that the deposits were sufficiently arranged, suitably hot, and caused early enough diversion to produce an injection similar to space-injection, while the hot ambient temperature of the surroundings suitably reduced the delay



period to increase smoke and quietness. High compression ratios notably reduced noise and increased smoke for this same reason.

Inspection of the deposits on the lip after the lowest compression ratio run revealed a "crinkly" deposit which was "diverted a little to the right". This then could most easily produce the condition mentioned earlier; more smoke, less noise and a nigher temperature. Probable corrections are incorporated in Graph VII and again the indication is more power, worse smoke, less noise, and higher lip temperature as the compression ratio is increased.

3. High Lip Temperature.

Table IX represents the variations occurring when a modified intermediate-temperature lip is used and shows the effect of a higher

#### TABLE IX

# COMPARISON FOR SLEEVE-IMPINGEMENT AT THREE COMPRESSION RATIOS FOR INTERMEDIATE-TEMPERATURE LIP AND SLEEVE ASSEMBLY WITH BOTTOM OF LIP INSULATED FROM MOUTH-INSERT BY ASBESTOS. FJEL RATE 10 ML./MIN.

Compression Ratio	16:1	18 1/2:1	22:1
Injection Advance, °BTDC	20	18	16
Noise	74.4	74.2	74.2
Smoke Density	4.2	4.7	5.5
Power (Scale)	9.0	9.1	9.4
Lip Temperature, °F	570	675	645



temperature. This lip and sleeve assembly is similar to the intermediate-temperature lip except that asbestos insulation is used between the bottom of the lip and the mouth-insert holding the lip and sleeve assembly in place.

Again a correction to the observed data is in order even though the same general trends exist here as for the other two lips. The lip temperature is greater at the intermediate compression ratio than at the highest compression ratio. The original data sheet shows that a relatively long time was required to establish equilibrium conditions which indicates that deposits might have formed. Data taken later at a larger injection advance also points to a lower temperature. No other change is indicated. Consequently, Graph VIII indicates the same trends as the other lip and sleeve assemblies with more power, worse smoke, less noise and higher lip temperature as the compression ratio is increased.

#### 4. Highest Lip Temperature.

Considerably more data was obtained than is presented here. In particular, much information was obtained with a high-temperature lip and sleeve assembly which was completely insulated by asbestos. This lip operated at temperatures ranging from 700°F for sleeve injection (a very short while only) to 1050°F for space injection. Deposits built up so quickly that reliable runs could not be made.

In an effort to limit the deposit formation somewhat, the asbestos insulation between the lip and the mouth-insert was replaced by foundry cement, a commercial "plastic iron". This lip, although



running cooler, was also plagued with deposits. Some impingement was obtained and these results indicated a high noise level, medium smoke, and medium power.

## 5. Deposit Effect on Smoke Density

The smoke density readings for sleeve-injection at 21° injection advance and at 18 1/2:1 compression ratio onto a clean combustion surface, as taken from Graphs III, IV, and V, are 5.0, 3.7, and 3.6 for three lip temperatures in order of increasing temperature. A similar set of readings, as taken from Graphs VI, VII, and VIII, at 21°, 19°, and 18° injection advance at the same compression ratio taken after the combustion surface nad been covered with a considerable amount of deposits as a result of a long period of running is 4.8, 4.2, and 4.7, respectively. A comparison would then be 5.0 vs 4.8, 3.7 vs 4.2, 3.6 vs 4.7. This rather clearly indicates again the effect of the higher temperatures and their attendant deposit formation, even though some of the improvement may be due to injection advance.



### GENERAL COMPARISONS

A comparison of smoke, noise, and power at the different lip temperatures should provide qualitative design information. In order to successfully show the trends, it is necessary to use a specific compression ratio rather than averages of the three ratios investigated, since averages would tend to nullify or at least lessen the characteristic variables. Since noise is higher at the lower compression ratio and smoke is worse at the higher compression ratio, the 18 1/2:1 compression ratio will be used.

Graph IX is a plot of the variables, smoke, noise and power, as the lip temperature is increased from 400° to 600°. An area, rather than a point, has been plotted in order to indicate the variations which should be considered. This area is based on the experience of some 150 hours of engine operation. Considering the lack of information obtainable in the literature and the nature of the investigation, these values still might be within too small a range.

Nevertheless, certain significant trends are apparent. As lip temperature increases the power available first increases and then decreases. The indication is that the maximum is reached somewhere between 400°F and 500°F lip temperature. The trend of the variation for both smoke and noise indicate that an optimum might exist in the neighborhood of 500°F.

Figures 6, 7, and 8 were taken of runs at the three temperatures just discussed: 410°, 450°, and 600°, respectively. They rather



Figure 6. Pressure-Time and Rate-Time Relationships, Motoring and Firing, for Fuel-Impingement System at 189:1 Compression Ratio. Impingement-Surface Temperature h10°F. Injection Commences 21 BDDC.



- Time

Figure 7. Fressure-Time and date-Time Relationships, Motoring and Firing, for Fuel-Impingement System at 183:1 Compression datio. Impingement-Surface Temperature 160°F. Pips at 13°ETDC and 13°ATDC. Injection Commences 19°BTDC.



- Time

Figure 8. Pressure-Time and date-Time Relationships, Motoring and Firing for Fuel-Impingement System at 18%:1 Compression Ratio. Impingement-Surface Temperature 600°F. Fips at 13°ETDC and 13°ATDC. Injection Commences 10°ETDC.



clearly show the noise trend, or combustion roughness, with the intermediate temperature seemingly more smooth.

Thus it has been shown for a surface-impingement system such as this at a constant compression ratio of  $1\delta$  1/2:1, that a combustion surface temperature exists for which best power can be obtained almost simultaneously with minimum noise and smoke intensity. As the compression ratio is increased from 16:1 to 22:1, it has been found that more power, more smoke, and higher impingement-surface temperatures are produced along with less noise. At higher compression ratios than this the smoke was considered unreasonable.



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Graph I. Compression Latio vs Smoke Density and Power for Kegular CFK Cetane Engine, With and Without Insulated Cap on Compression-Ratio Plug, as Compression Ratio is First Decreased and Then Increased. Fuel Rate 9 ml./min. Injection at 13°BTDC.





Graph II. Compression Ratio vs Smoke and Power for Regular CFR Cetane Engine, With and Without Insulated Cap on Compression-Ratio Plug. Fuel Rate 9 ml./min. Injection at 13°BTDC.



21° INJECTION ADVANCE Place of Injection Place of Injection Sleeve Space Sleeve \_\_\_77 76 75 74 73 Smoke Density 2 (3) 5 (4) Г -----3 2 1 Power (Scale) 10 - -----9 Lip Temperature 700 600 500 400 300

Graph III. Effect of Sleeve- and Space-Injection on Noise, Smoke Density, Power and Lip Temperature Using Low-Temperature Lip and Sleeve Assembly.



## 11° INJECTION ADVANCE



# Graph IV. Effect of Sleeve- and Space-Injection on Noise, Smoke Density, Power and Lip Temperature Using Intermediate-Temperature Lip and Sleeve Assembly.



## 11° INJECTION ADVANCE

21° INJECTION ADVANCE

Place of Injection

# Place of Injection

Sleeve	Space	Noise	Sleeve	Space
		77		
		76		
		7],		
		73		
		12		
		Smoke Density		
		Ľ		
		<b>_</b>		
		2		
		רביים ביים ביים ביים ביים ביים ביים ביים		
· -		•		
		Power (Scale)		
		9		
F		8		
				. 1
	-			
		Lip Temperature		
		700		
		600		
		500		
		<u>гоо</u>		
		300		

Graph V. Effect of Sleeve- and Space-Injection on Noise, Smoke Density, Power and Lip Temperature Using Intermediate-Temperature Lip and Sleeve Assembly (Asbestos Insulation Between Lip and Mouth-Insert.)












Density, Power, Lip Temperature and Injection Advance for Intermediate-Temperature Lip and Sleeve Assembly at Best Power. Fuel Rate 10 ml./min.





Graph VIII. Compression Ratio vs Noise, Smoke Density, Power, Lip Temperature, and Injection Advance for Intermediate-Temperature Lip and Sleeve Assembly (Asbestos Insulation between Lip and Mouth-Insert) at Best Power. Fuel Rate 10 ml./min.





Graph IX. Lip Temperature vs Noise, Smoke Density, and Power at Best Power. Compression-Ratio 18 1/2:1, Fuel Rate 10 ml./min.



#### SUMMARY AND CONCLUSIONS

The intention of this investigation was to determine the effect of impingement-surface temperature on smoke, noise, and power in a fuel-impingement compression-ignition engine combustion system.

A fuel-impingement system for a compression-ignition engine was successfully constructed and tested. The system, commonly called M-system, operated in the manner described by its originator, Dr. J. S. Meurer of Machinenfabrik, Augsburg-Nürnberg, Nürnberg, Cermany. (See Appendix A.) Certain pertinent information pertaining to its behavior was obtained in addition to the original object of the investigation.

Spheroidization of the fuel spray at high surface temperatures was investigated. It was found that the engine did not operate in a sufficiently high temperature range for which spheroidization would seem likely. (See Appendix C.)

Air swirl in an inclined cylindrical chamber, offset from the centerline of the cylinder bore, was investigated by means of paintpatterns and a small paddle-wheel. (See Appendix B.) It was found that the direction of swirl in the offset chamber could be successfully controlled by various mouth-insert configurations and by use of a shrouded intake valve; however, no method was obtained which would produce a high-rate continuous unidirectional swirl within the chamber. It was concluded therefrom that the predominant air-flow was up one side of the chamber and down the other. A protruding lip on the down-



stream side would therefore provide a surface on which to impinge the fuel and from which the on-rushing air could pick up the vapors for combustion.

The protruding lip was in all cases attached to a stainless steel sleeve. The various sleeves used were cylindrical in nature, their outside diameters and configurations being such that various means could be used to insulate the assembly from the liner into which it was fitted.

The place of fuel impingement was varied by using a modified multi-hole orifice-type nozzle in which all holes were closed except one. This produced a directional nozzle, the angle of fuel flow being at 75° with the axis of the nozzle. Thus the place of injection could be changed by rotating the injector about its longitudinal axis.

After running the engine, inspection of the deposit formation indicated that the fuel was spreading onto about one-half of the lip surface in a relatively long narrow path. Occasionally it indicated a flow off of the lip and onto the piston. Because of this, it is felt that a specially designed nozzle would be a definite aid to the fuelimpingement system as described herein. By this means the longitudinal flow of fuel could be reduced and the area of the fuel impingement could be increased thus allowing more effective use of the lip surface.

Better results could most possibly be obtained by use of a hemispherical or cylindrical combustion surface with injection in the latter case in a circumferential direction. Thus the fuel will have little tendency to skip, or be diverted off into space. In any skip-



ping, or diversion action the fuel will be forced to return to an impingement surface.

Throughout the entire investigation of the fuel-impingement system the formation of deposits on the impingement surface was a critical item. Deposit formation altered the amount of smoke and noise produced and the amount of power developed. Ironically, these variations were not always repetitive nor always in the same direction. Deposit formation occurred in a shorter time at the higher temperatures. No long successful runs without diversion by deposits were made at higher surface temperatures than 600°F.

It was found that the beneficial effect of a fuel-impingement surface increased as the surface temperature increased. At the higher surface temperatures, however, deposits quickly formed and the effectiveness of the surface was reduced. For this engine, with all things considered, it was found that the optimum surface operating temperature was in the neighborhood of 500°F. Above this temperature the smoke became worse, power dropped off and noise tended to increase, depending on the manner in which the deposits formed. Below this temperature both noise and smoke quickly became unreasonable.

The effect of compression ratio on the surface-impingement system was exactly similar to its effect on a space-injection system. As the compression ratio was changed from 16:1 to 22:1 the power and the smoke intensity increased while the noise level decreased. At higher compression ratios than this the smoke was considered unreasonable.



The results obtained from this particular engine design indicate that an optimum distance should exist between the nozzle orifice and the impingement surface. Too small a distance will allow quick diversion of the fuel by deposit formation while too large a distance does not properly limit the amount of fuel subject to autoignition in space. This latter occurence will produce excessive noise and more smoke.

It was of particular importance to note that any impingement whatsoever on the combustion surface, even its furthermost edge, did in fact reduce the smoke formation markedly while little change was affected in power and noise (depending, of course, on injection advance). Although the amount of fuel autoigniting is not changed appreciably when the place of injection is changed from the far edge of the lip to space, it seems most probable that the rate of combustion of the remaining fuel is quickly brought under control by surface impingement. In the case of space-injection the fuel injected after autoignition begins is injected into a high temperature zone created by burning vapors, and for this last portion the ignition delay is sufficiently shortened that combustion starts before a chemically correct mixture can form. The production of a fuel-rich zone and its accompanying smoke is therefore enhanced. For surface combustion the last portion is spread on to a hot lip which quickly controls the rate and type of evaporation. The combustion rate is therefore controlled sufficiently to allow progressive consumption of all the vapors.

Use of gasoline in an engine of this nature is not precluded



because of its lower spheroidizing temperature (higher volatility). In a properly designed chamber the fuel will never leave an impingement surface for long, and will therefore be held under its control. Thus the desired evaporation and gradual mixing of the fuel with air will be accomplished. That portion of the fuel which has autoignited earlier will then provide the ignition source for the remaining fuel which has been deposited on the impingement surface. The noise level will therefore be low since the amount of fuel autoigniting is very small.

It is concluded that the system originated herein is not a true M-system as set up by its originator. In the true M-system the reaction rate is low at the beginning of combustion and increases toward the end of combustion, while in this "lip" engine the rate-time diagrams reveal the maximum rate of pressure change to occur nearer to the beginning of combustion. The controlling effect of the "lip" nevertheless exists and less smoke and noise is produced at comparable power.



A PPENDIX

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#### APPENDIX A

## M-SYSTEM THEORY

The rules set up by Dr. Meurer in the development of his engine which so successfully combats noise and smoke are:

- 1. Limit to a minimum the portion of the fuel involved in autoignition.
- 2. Allow the fuel to oxidize gradually.

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3. Mix the fuel with the hot air fast enough to affect a stoichiometric air-fuel ratio before ignition starts and make sure that no more fuel is mixed at any time than can burn with a permissible pressure rise.

Regarding Rule 1, it is obvious that the reasoning here is to limit the rate of pressure rise in the beginning of combustion. Allowing the combustion chamber to become full of the combustible mixture prior to autoignition will aggravate the knocking tendency of the engine.

Rule 2 needs more explanation. In the M-system engine the fuel is injected from a nozzle located in the cylinder head into a hemispherical combustion chamber located in the central portion of the top of the piston. The injector and combustion chamber are so located that the fuel leaving the injector will spread on to the hemisphere before much intervening space has been traversed. It is during this transportation that Rule 1 is accomplished.

Because of the nature of the evaporation from the hot combustion surface (the air and/or the combustion gases are even hotter)



the fuel evaporates more slowly than when in the air and at least part of the time in a zone deficient of oxygen. This process, controlled and slowed down by the surface temperature, allows the accomplishment of Rule 2.

Dr. Meurer has cited references and has shown by the results obtained with his engine that "evidently the ignition point is influenced by the mechanism of mixture formation, being low (or earlier) for vapors formed by heating fuel droplets with hot air, and high (or later) for vapors formed by heating fuel in the absence of any appreciable amount of air and subsequent diffusion in air."

Rule 3 says "mix the fuel with the hot air fast enough to affect a stoichiometric air-fuel **ratio** before ignition starts and make sure that no more fuel is mixed at any time than can burn with a permissible rate of pressure rise."

According to the explanation for Kule 2, we find that the vapors do not show an extreme tendency to autoignite, at least not in the time allotted. After formation of a combustible mixture there will be a tendency to await ignition by the flaming particles formed during the accomplishment of Hule 1. Now if the combustible mixture or burned gases are progressively removed from the impingement surface the fresh vapors formed underneath can be made ready for combustion in a controlled manner. This leads to a controlled combustion state rather than the extreme thermal advance caused by spraying fuel into extremely hot compressed air. It is this last rule that provides for the reduction of smoke production. Likewise, the controlled rate of



formation of a stoichiometric air-fuel ratio combats an extreme rate of pressure rise, and its consequent knock, during the latter phases of combustion.

In order to obtain the rate of mixing dictated by Rule 3, Dr. Meurer has used an intake-induced swirl and superimposed on this the squishing action of the close approach of the piston to the cylinder head to produce an even higher rate of rotation of compression air in the hemispherical combustion chamber. This type of action is shown in Appendix B, Figure 6.

Primary variables upon which the success of this system depends are swirl rate and surface temperature, the latter of which comprises the subject of this research.



# APPENDIX B

# DEVELOPMENT OF COMBUSTION-CHAMBER CONFIGURATION

In a fuel-impingement combustion system the necessary vaporization of the fuel is accomplished by the combined action of the hot impingement surface and the even hotter compression air. Either these vapors must be removed from the vicinity of the impingement surface and later mixed with air for combustion, or the combustion takes place in the vicinity of the surface and the burned gases must be removed prior to the combustion of the vapors being formed underneath. Any return of the burned gases to the zone of mixing or zone of combustion tends to richen the mixture relatively in fuel and thereby cause smoke. No autoignition can take place in that part of the vapors closest to the impingement surface because the necessary mixing with air has not taken place.

Indiscriminate highly turbulent mixing is not desirable in that it is necessary to remove the vapors or the combustion gases in a controlled manner such that smoke formation is not too great. If the vapors are held under the control of the cooler surface, and thereby mostly unaffected by the higher gas temperatures until sufficient air is in the vicinity for complete combustion, the uncontrolled thermal advance which leaves behind a carbon skeleton (smoke) can be eliminated. Positively controlling the manner in which the air passes over the vaporization surface can also control the rate of



pressure rise by limiting the amount of mixture available for combustion at any one time.

It is necessary then to direct the air into the vicinity of the injection surface in a controlled manner. Since swirl had been used in the parent design as set up by its originator, it was decided to try to adapt the equipment available here to such a system.

The M-system, as this process is called, incorporated its combustion chamber in the top of the piston. Because of the difficulties involved in obtaining temperature readings from a reciprocating mass it was decided for this investigation to develop a combustion chamber in the cylinder head of the existing engine.

The literature revealed several methods of ascertaining information on air-flow in a compression-ignition engine.  $^{5,6}$  None of these were completely satisfactory so two of them were used with certain modifications. In both publications a statement was made to the extent that, once established, a strong swirl persisted doggedly. This was the beginning of the development of the lip combustion chamber.

The centerline location of the valves in the available engine precluded a center location of the combustion chamber and the compromise solution was an offset as shown in Figures 9 and 10. The piston side of the combustion chamber was to be as near the center of the cylinder as possible and the edge of the chamber was to pass tangent to the injector tip. If a directional nozzle were used this would allow tangential injection of the fuel onto the walls of the chamber.











Elementary calculations indicated that suitable compression ratios (30:1 down to 16:1) could be obtained easily with a one inch diameter combustion chamber. Still other calculations revealed that a cast iron wall thickness of 3/16" would provide an adequate factor of safety, so a  $1 \frac{3}{8}$  hole was bored as close to the values as practical. The edge of this hole was so located that upon insertion of the liner the fuel leaving the injector nozzle would lay on almost circumferentially. A cast iron liner of such oversize dimensions as to provide a tight press fit was made and forced into place. A combustion-chamber plug was machined and a heavy steel plate was provided with holes in order that it might serve as a bridge to hold the plug in place. These parts and other obvious ones required for successful assembly of the combustion chamber are shown in Figures 11 and 12. The compression ratio could then be changed by adding washers on top of the plug. Later during the overall investigation it was found expedient to change the form of these plugs rather than use the washers, and these plugs are shown in Figure 13.

Since the original device to change the compression ratio was no longer operative, it was laid away and this space was used as indicated in Appendix D.

A series of tests were then begun in which aluminum paint was daubed onto the piston in sufficient amount to form globules. The engine was quickly assembled without the intake and exhaust pipes. Motoring was begun as soon as possible and after a few minutes the engine was shut down and the head removed. The first attempts gave a

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Fig. 11. Compression-Ratio Plug and Tie-Down Bolt




Fig. 12. Modified CFR Cetane Engine. Note Tie-Down Bolt of Figure 11.





Fig. 13. Compression-Ratio Flugs



faint visual history of the path of the air. This was considerably improved by the addition of drops of black paint, a good example of which is shown in Figures 14 and 15.

By using a shrouded intake value the direction of rotation of the air swirl could be easily changed, depending on the direction in which the shroud allowed the incoming air to enter the cylinder. The value used had a 180° shroud and is shown in Figure 16.

When an abundance of paint was used, a clear indication of the path of the air up into the combustion chamber was shown. This path indicated an abrupt change in flow of the air on one side or the other of the combustion chamber proper. In an attempt to smooth out the flow an insert was developed and placed into the bottom of the combustion-chamber liner. This insert was then ground away in such a manner that the paint pattern indicated that a relatively smooth transition was obtained as the air was forced from the space between the piston and head and up into the combustion chamber. The original form of the insert, sometimes called a mouth-insert, is shown at the bottom of Figure 17 and its final form inserted into the liner is shown in Figure 18. A combustion-chamber plug, or compression-ratio plug, as it is sometimes called, is shown in the top of Figure 17.

Note here that the direction of swirl was counter-clockwise as viewed from below and that the combustion-chamber plug in the upper left-hand portion of the picture indicates the same rotation. The attempt here was to scoop up into the pocket the air flowing at the outer periphery of the cylinder and to allow that air passing nearer the center to go on by.



Fig. 14. Piston and Block. Paint-Pattern of Air-Swirl





Fig. 15. Cylinder Head. Paint-Pattern of Air-Swirl





Fig. 16. Shrouded Intake Valve





Fig. 17. Compression-Ratio Flug and Original Mouth-Insert Prior to Grinding





Fig. 18. Mouth-Insert Inserted into Liner. Compare with Fig. 15 (no insert) and Fig. 17



Later on during the project it was found that the air utilization of the engine was inadequate. This led to a new investigation of air motion within the combustion chamber. Since the paint-pattern method gave every indication of a well-directed air motion, it was decided that perhaps its velocity was insufficient for enough of the air to be provided in the proper place during the short time available for combustion. In order to ascertain the velocity of swirl within the combustion chamber a paddle-wheel device was fabricated and installed in one of the combustion chamber plugs. (See Figure 19.) The shaft and plug had an almost airtight but yet relatively friction-free fit. A small roller thrust bearing was used to provide freedom from axial movement. Upon motoring the engine the paddle-wheel device indicated that the total swirl during one cycle of the engine was less than one revolution. It seemed logical, therefore, that the low swirl rate was responsible for the poor air utilization of the engine.

Several other shapes of insert were then tried, each having its own particular postulate in order to obtain sufficient swirl. These inserts, shown in Figure 20, attempted to do such things as allow the air to enter tangentially and spirally or to bodily transport the intake-induced swirl into the combustion chamber. Some produced results comparable with the original design and others were worse.

It became apparent that the intake-induced swirl was somewhat destroyed during the time it was being forced into the offset combustion chamber. This was doubtless due in part to the counter effects of the squish (squeezing action) occurring in the small clearance space as the piston approached the top center position.





## Fig. 19. Paddle-Wheel Used for Determining Air Rotation





### Fig. 20. Various Mouth-Inserts



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The best design turned out to be one in which the squish action was reduced by relieving the top of the piston in the form of an inverted cone with its apex in the vicinity of the combustion chamber mouth and using an insert which would allow smooth transition from the clearance volume above the piston to the combustion chamber. Even this was considered inadequate.

As can be seen from Figure 21(a) the air generally tends to enter the combustion chamber mainly from three sides. It was considered possible that air entering tangential to the piston circumference on one side might somewhat cancel that entering from the other side with a result that the predominant air-flow direction was at an angle with the head. (See Figure 21(b)). If this was correct, then a combustion chamber shaped like Figure 21(c) would allow the air to enter in a somewhat vertical direction and leave in a more horizontal direction. If the direction of injection were changed from tangential to the combustion chamber in the circumferential direction, to downward and tangential in the axial direction, then this would provide the action necessary for controlled air motion. A compromise solution for the particular configuration available here is shown in Figure 21(d). That this solution was adequate is verified in the main portion of this thesis.





Fig. 21. Schematics of Combustion Chamber Air-Flow in Modified CFR Diesel.



# APPENDIX C

## SPHEROIDIZING TENDENCIES

Part of the investigation of the fuel-impingement combustion system consisted of an attempt to determine what happened when the fuel in the form of small droplets was spread on the hot combustion surface.

It is known that when water is dropped on a hot stove that the droplets seem to dance for quite some time without any sensible evaporation. What would happen under conditions in which the droplets were shot onto the hot surface in the form of a fine spray in a very nearly tangential direction? Would the same phenomenon occur causing the fine spray to be delayed in its evaporation? Would this be different at atmospheric conditions than at high temperature and pressure?

The M-system theory is based on the assumption that the fuel is "slicked on" to the combustion surface and does not leave it as a liquid. The spheroidization of the droplets, or Leidenfrost phenomenon as it is sometimes called, could very well limit the maximum temperature under which the impingement surface could perform. Above this temperature the fuel would be more susceptible to the action of the air on all sides and thus the combustion process would revert to something similar to that of the normal diesel in which the fuel is injected into space rather than on an impingement surface. This would probably decrease the ignition delay such that more smoke would arise. The investigation into the Leidenfrost phenomenon



# proceeded as follows:

First, fuel was dropped upon a hot-plate as the temperature was progressively raised. On an inclined surface the Leidenfrost or spheroidizing action apparently occurred between 580°F and 620°F while on a horizontal plate it began between 680°F and 710°F. The rate of evaporation seemed faster on the inclined plate where the scrubbing action as the droplet moved across the plate was more apparent.

This test was followed by impingement of the fuel by the injector nozzle onto the same hot-plate still at atmospheric pressure. Visual inspection under stroboscopic light indicated at least some wetting of the surface between 690°F and 780°F but the area became progressively smaller at the higher temperatures.

High speed movies, in the order of 6,000 to 7,500 frames per second, were used in an attempt to further define the temperature at which spheroidizing would take place. Even these did not suitably stop the action such that a complete visual analysis could be made. However, the pictures shown in Figure 22 are a sequence, at 535°F, which definitely indicates that wetting action is taking place. Figure 23, taken at 793°F, shows a definite bouncing tendency of the latter portion of injection.

Finally, high speed stills, at 1/20,000 sec., taken by means of the stroboscopic light, revealed that wetting occurs at 480°F while spheroidizing is progressively more visible at 780°F than at 645°F. (See Figures 24 through 32.) It should be noted here that at 480°



Fig. 22. High-Speed Movies of Fuel Impingement on Surface at 535°F, at 6000 Frames per Second.





Fig. 23. High-Speed of Fuel Impingement on Surface at 793°F, at 7500 Frames per Second.








Fig. 26. Fuel Impingement on Surface at 780°F (Close-Up), Just After Completion of Injection, 0.00005 Second.









Fig. 29. Fuel Impingement on Surface at 645°F (Close-Up), Just After Completion of Injection, 0.00005 Second.







Fig. 32. Fuel Impingement on Surface at 480°F (Close-Up), Just After Completion of Injection, 0.00005 Second.



(Figure 32), there is seemingly no difference between the zones of impingement and non-impingement. The liquid here is spread thin and has not picked up the glare of the strobe light.

In considering the effect of the temperature of the hot gases of the combustion zone, it was concluded that possibly the only appreciable effect was an increase in rate of evaporation of the globules formed by spheroidization.

The literature reveals some information of the effect of pressure on the rate of film boiling. This can be considered here because when the rate of film boiling is high and the film is thin, spheroidizing occurs. This information indicates that as the pressure increases the maximum rate of heat transfer through the film is much greater and the temperature differential between the mass of the fluid and the surface is less at this maximum rate than it was at the maximum rate at the lower pressure. It is just after this maximum rate of heat transfer occurs that spheroidization takes place.

Absolute values have not been obtained but there is every indication that some spheroidization does occur at the higher lip temperatures of the order of 645°F and up.

When the engine was tested under various conditions, it was found that lip temperatures of 600°F and above gave extreme difficulty due to deposit formation. Just as smoke formation limits the useful power of a diesel so does deposit formation limit the useful temperature of the lip. Because deposit formation precluded continuous operation at 645°F and above, it was decided that this portion of the problem is a matter for future investigation.



## APPENDIX D

## EQUIPMENT AND CALIBRATION

It was decided to use a regular CFR Cetane engine as the fundamental unit for the investigation. Since this engine is standardized and is universally used in research projects, it would be easy to duplicate and check the results in other localities. Using such standardized equipment would allow a comparison procedure rather than direct measurement of absolute variables.

This engine in its standard form is shown in the two schematics of Figure 33. In this form it used a pintle-type nozzle. After modification the engine can be pictured as shown in the two schematics of Figure 34. Here a directional orifice-type nozzle was used, having been obtained by the modification of a multi-hole orifice-type nozzle. The spray cone of this nozzle prior to modification had an included angle of 150°. Closing off all except one hole produced a directional flow, the angle of injection at 75° with the centerline. Fotating the injector in its mounting, therefore, allowed changes in direction of injection. The combustion chamber liner (a cylindrical tube) was so placed that the extension of the original injector mounting hole allowed the injector to be located in such a position that a directional nozzle could "lay on" the fuel either on the liner in a circumferential spiral direction upwards or on the liner and lip in an almost axial direction downwards.





Side View

Fig. 33. Schematic of Regular CFR Diesel





End View



Fig. 34. Schematic of Lodified CFR Diesel



In order to provide a surface to which to attach the lip as shown in Figure 21(d) of Appendix B, and also to provide a means for varying the temperature of this lip, a set of stainless steel sleeves were used which would allow the use of varying means of insulation between themselves and the liner. Figure 35(a) shows a sleeve installed in a liner with the compression-ratio plug in place on top and the mouth-insert necessary to control the gas and air inflow and outflow in its place at the bottom of the liner. This mouth-insert also serves to dissuade movement of the lip and sleeve assembly. Figure 35(b)shows a sleeve with annular grooves used as an insulating medium. It also indicates the general dimensions used on all the sleeves. A sleeve of sufficiently small outside diameter to allow installation of a 0.020" asbestos sheet between it and the liner was also used during the investigation. Figure 35(c) shows various views of the lip and its dimensions. Figure 36 is taken of one of the lip and sleeve assemblies actually used. The irregular hole in the sleeve was required in order to insert the injector nozzle. The wires attached to the lip are remnants of the thermocouple which was used to measure lip temperature.

The CFR engine was belted to a constant speed electric motor which could also be used as a dynamometer. The engine was held to 600 rpm plus 1/2 rpm at full power to minus one rpm when motoring. No change in rotational speed was considered necessary since in diesel combustion noise is more prominent at the slower speeds. Since the electric motor served only as an absorber or driver with no method of





(c) Dimensions of Lip

Fig. 35. Dimensions of Lip and Sleeve Installation





Fig. 36. Low-Temperature Lip and Sleeve Assembly



determing torque it was necessary to install a torque arm and scales as a measuring device. The very nature of a diesel giving heavy impulses to the crankshaft required the necessity of adding more damping than was available in the scales. This was successfully supplied by an aircraft-type automotive shock absorber.

Noise was measured and compared in two ways. During the early part of the investigation a direct comparative procedure consisting of a tape-recorder was used to judge the effectiveness of any changes. This was quite successful; however, it was felt that a method should be available for presenting this information in a visual form. This was successfully done by means of a General Hadio Company Sound-Level Meter. This meter measured in units of decibels. A fast and slow response was available and due to the large noise variation during each cycle, only the slow response was used. The B weighting scale was used only because it was recommended as a good general range. Any of the other weighting scales could have been used with the same amount of relative accuracy.

A visual record of the pressure-time sequence within the cylinder is always desirable in any combustion investigation. Here an SLM Quartz Pressure pick up and a combination pre-amplifier and calibration unit, the Piezo-Calibrator, were used as input to a Hewlett-Packard Model 130A Oscilloscope. This pick up was installed through the cylinder-head water-jacket and flush with the head. It was as centrally located as possible, diametrically opposed to the mouth of the modified combustion chamber. This placed the pick up, the intake



and exhaust valves, and the mouth of the combustion chamber in a fourleaf clover arrangement. (See Figure 15 in Appendix B.) Horizontal external-calibration marks were obtained by a grounding circuit consisting of a copper brush mounted on a stationary bracket and two copper contacts to ground mounted on the flywheel. These marks provided visual notice of 13°BTDC and 13°ATDC. They have no significance in the vertical direction.

The Piezo-Calibrator is constructed in such a way that the voltage generated by the pickup can be applied to a resistor. The current generated will be directly proportioned to the pressure rate, i.e., the rate of change of pressure with respect to time, or dp/dt. The resulting voltage across the resistor is measured, itself a measure of dp/dt, and is displayed on an oscillograph. This then provides the rate-time information which is a visual indication of the combustion process. The calibration marks at 13°BTDC and 13°ATDC appear on this diagram also.

A Polaroid Land Camera has been adapted to the oscilloscope to record the traces aforementioned. In this paper these traces are arranged such that the firing, or combustion, pressure-time diagram is on top, its rate-time diagram on the bottom, the motoring pressuretime diagram is second from the top and its rate-time diagram second from the bottom. Two horizontal lines also show up, and these are described in the explanation which follows. Although the oscilloscope traces from left to right, the photographic equipment reverses this, and the trace in all oscilloscope pictures is from right to left. It



should also be noted that occasionally, as in the combustion rate-time curve in Figure 1 in Presentation and Discussion of Data, one of the calibration marks fails to register.

Calibration of the SLM pickup consisted of using a dead-weight tester to impose a specific pressure on the pickup. It was found, using the oscilloscope settings necessary to produce appropriate diagrams, that one cm. corresponded to 305 psi. Calibration lines at 578 psi and 1157 psi were superimposed on the diagrams and these will be seen at approximately two and four centimeters up from the center horizontal axis.

In order to determine the rate of pressure rise, dp/dt, it was first necessary to determine a pressure calibration factor. This is obatined from the following:<sup>7</sup>

$$K = 2.7 \frac{(R) \times (DV)}{P} = M H Cb/psi$$

where 2.7 is potentiometer voltage x 10

R is range setting (capacitance)

DV is dial setting (or potentiometer percentage)

P is pressure applied

The rate of change calibration factor is then

$$Kr = \frac{K \times Resistance}{10^{12}} = volts/psi/sec$$

where Resistance is the resistance across which potential is applied =  $10^5$  ohms. So Kr =  $\frac{2.46 \times 10^5}{10^{12}}$  = 2.46 x 10<sup>-7</sup> volts/psi/sec.



The oscilloscope vertical scale was 0.05 volts per centimeter so each centimeter variations of the dp/dt trace represented 203,000 psi per second.

The relative measure of smoke density was obtained by means of a General Electric exposure meter intended for use with a Polaroid Land camera. This light-meter was inserted into a downstream projection of an elbow in the exhauster system connected to the engine. Approximately eight feet above, also in the exhauster system, and in another projection at an elbow, a Ken-rad 150 watt, 130 volt Par 38 Projection Spot-light provided the intensity for measurement. (See Figures 37 and 38.) The exhauster system provided sufficient suction under maximum power output, 0.4 inches of water at the upper elbow, to keep both the exposure meter and the spotlight swept clean by air entering small holes appropriately placed. These holes were shielded to preclude entrance of any appreciable amount of external light.

The readings on a General Electric exposure meter such as this increase as the intensity of the light reaching it increases. As used here these readings would be somewhat inversely proportional to the density of the smoke between it and the source of light. It was, therefore, decided to use as an indication of the density of smoke produced by the engine and measured by the light-meter the amount (3 - x) where x is the light-meter reading. This is the number entered under the heading of Smoke Density in the Tables and Graphs. A clear exhaust would therefore give a Smoke Density in the order of 1.3 while an exhaust darkened by the recommended fuel rate for the CFR at intermediate compression ratios would show a Smoke Density of 6.0 or more.





Fig. 30. Schematic of Smoke-meter





Fig. 37. Schematic of Smoke-Meter



It was found that Chromel-Alumel thermocouples were necessary to withstand the high temperatures and other abuses of this investigation. No commercial thermocouples were immediately available which could be easily installed in a combustion chamber so hand fabrication was resorted to. The thermocouple wires were led through rifle-drilled holes in the liner to the appropriate recording places. A pressure tight seal was obtained as shown in Figure 39 in which a thermocouple is shown attached to the sleeve. The thermocouple was silver soldered to the place for which the temperature was desired.



Fig. 39. Installation of Thermocouple

An L and N No. 8657-C portable, double range, Potentiometer Indicator, with manual reference junction (cold junction) compensation was used to determine thermocouple potential. The thermocouple was


connected directly to the potentiometer without use of extension leads. A general view of this equipment, taken while in operation, is shown in Figure 40. The scales can be seen in the upper left background. The lower portion of the smoke-meter extends just below the black air-intake conduit from the rotary air-meter. The air-intake heater is connected to the other end of the black air-intake conduit. The potentiometer for measuring the thermocouple potential is in the center foreground and the CFR console is on the left. The oscilloscope, calibrator, and camera are on the right. The ladder was used for access to the smoke-meter spot-light. At the very bottom, between the potentiometer and the oscilloscope table, is the sound-meter.

The high-speed still-photographs were taken with the aid of a General Radio Company Strobotac, Type 648-A, and Strobolux Type 631-B1. These were connected to the pressure-operated switch on the fuel injector of the engine. The fuel injector was mounted on a table next to a small hot-plate and a fuel line was run to it. (See Figure 41.) By varying the spring rate on the switch, the stroboscopic light was made to flash at the desired time within the fuel delivery cycle. This explains how the still-pictures presented in Appendix C were obtained.

Moving pictures were taken by means of a 16 mm. 100' Wollensok Fastax camera at 6000 to 7500 frames per second.

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Fig. 40. General View of Modified CFR Diesel and Associated Equipment.







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