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MASTER

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U.S. Department of Energy
Division of Fossil Fuel Utilization
Washington, D.C. 20545

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Attention: Mr. John Fairbanks

AC03-79ET15450

Gentlemen:

Third Quarterly Technical Progress
Report on "Synfuel Modified Diesel"

Please find enclosed the Third Quarterly Technical Progress
Report on the Cummins Synfuel Modified Diesel Program for the
period of October, 1981 to December 31, 1981.

Respectfully submitted,

Roy Kamo
Executive Director - Advanced
Program Development

R.Kamo-50165/pw

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Enclosures

APPROVED:

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DOE/ET/15450--T2/

THIRD QUARTERLY PROGRESS REPORT
SYNFUEL MODIFIED DIESEL

Prepared By:

Cummins Engine Company
Columbus, Indiana

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Under Contract With

U.S. Department of Energy
Division of Fossil Fuel Utilization
Washington, D.C.

REPORT FOR PERIOD

October 1, 1981 through December 31, 1981

SYNFUEL MODIFIED DIESEL

Summary

Yanmar's effort was directed toward: (1) heat release analysis of SRC-II fuel in a prechamber diesel, and (2) improving the particulate trap to obtain reliable and consistent particulate concentration from a prechamber engine burning SRC-II blend fuel. Yanmar also disassembled the engine to check for excessive wear and deposits; none were found. Komatsu has started to obtain spark assisted data on the baseline engine. Although 100% SRC-II fuel was not attempted, spark assist has made significant contribution to the combustion of 50% SRC-II blend or less. Competitive fuel economy was also obtained with 50% SRC-II blend. Thus, it was shown that spark assist can improve the operating range of blended SRC-II fuel. The major problems are: (1) spark plug cracking, and (2) engine failure due to rough and knocking combustion in the marginal operating range with surface discharge spark plug. The location of the spark plug in the combustion chamber and its timing was found to be quite important. Conventional electrode gap spark will be tried; and if no breakage is encountered, 100% SRC-II fuel will be attempted.

Introduction

Cummins Engine Company of Columbus, Indiana, has proposed a two-year program to the U.S. Department of Energy (Division of Fuel Utilization) to test three diesel engines operating on coal derived liquid fuels and compare the results with standard diesel fuel oil No. 2; namely, (1) prechamber diesel, (2) dual fuel diesel (direct injection), and (3) spark assisted diesel engines. The proposed diesel combustion chambers to be investigated are shown in Figure 1.

The three types of diesel engines to be tested were to be modified in three forms; namely, (1) conventional water-cooled, (2) waterless-uncooled, and (3) adiabatic (uncooled). Because of limited funds, the first year's work covered only the conventional water-cooled prechamber diesel engine and the spark assisted prechamber diesel engine.

Objective

The objectives of this program are:

"To test the conventional water-cooled prechamber diesel engine and the spark assisted prechamber diesel engine operating on standard diesel fuel No. 2 and SRCII coal derived liquid fuel for performance and emissions. Fuel properties are shown in Table 1. Performance data shall include fuel consumption, ignition qualities, cold start, and output. Emissions shall include nitrogen dioxide, unburned hydrocarbons, carbon monoxide, smoke, and particulates. Particulates shall be checked for mutagens. Other pertinent and standard forms of diesel engine test data will be gathered during the course of this investigation".

Work Schedule

Cummins Engine Company, Inc. (prime contractor) and the two subcontractors (Yanmar Diescl, Ltd. and Komatsu, Ltd.) sat down and formulated a plan which will be executed during the course of the first year program. The work plan is shown in Table II.

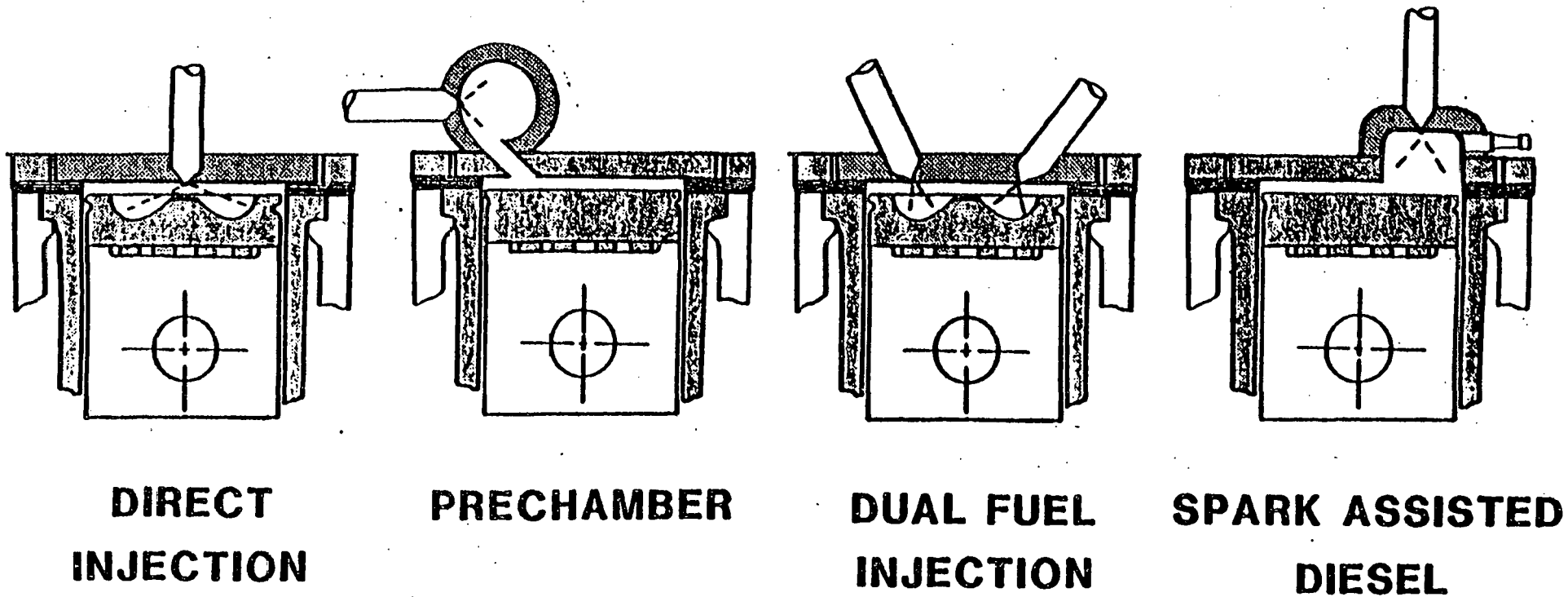


FIGURE 1. DIESEL COMBUSTION CHAMBERS TO BE INVESTIGATED ON SYNFUEL MODIFIED DIESEL PROGRAM

TABLE I
COMPARISON DIESEL Vs. SYNTHETIC FUELS

FUEL PROPERTY	DIESEL FUEL	SRC II MIDDLE DISTILATE	SHALE
<u>PHYSICAL AND CHEMICAL PROPERTIES</u>			
ENERGYCONTENT BTU/LB GROSS	19,200	17,102	19,365
GRAVITY 60°F.	33	12.4	38.2
SPECIFIC GRAVITY 60/60 °F	.86	.983	.834
VISCOSITY	2.85	3.87	2.72
POUR POINT	-35	-65	- 5
FLASH POINT	167	175	178
CETANE NO	45-50	22	45
HYDROGEN/CARBON	1.75	1.24	1.86
- AROMATICS	36	79.1	30.5
- SATURATES	62	14.4	67.7
- OLEFINS	20	6.5	1.8
<u>ELEMENTAL ANALYSIS</u>			
- SULFUR	.29	.31	.07
- NITROGEN	.2-.4	1.0	.024

Progress

I. Yanmar Diesel Engine Co., Ltd.

A. Third Quarter Work

The work conducted by Yanmar Diesel Engine Co., Ltd. during the third quarter was:

1. Heat release analysis of the cylinder pressure diagrams obtained during the second quarter engine testing.
2. Fabrication and improvising of particulate sampling system.
3. Measurement of carbon particulates.

B. Discussion of Yanmar Work

Heat release analysis was performed on pressure diagrams obtained during the second quarter engine testing. Various blends of SRC-II (0%, 26%, 49%, 72%, and 90%) at various loads and speeds were analyzed. The heat release analysis for the case of coolant water temperature increase, inlet air temperature increase, inlet boost pressure increase, and for cetane improvers was made. The particulate sampling trap has been constructed and improvised. Preliminary carbon particulates data are reported.

1. Analysis of Cylinder Pressure Diagrams

Cylinder pressures measured using a kistler #6121 transducer were averaged over 100 cycles and loaded into an Ono Sokki made combustion analyzer for computation of characteristics such as ignition delay periods, the rates of pressure rise, and the rates of heat release.

Figures 2 through 5 show how the rate of heat release changed with increases in SRC-II content under the following four conditions:

At 1200 rpm; 3 and 10 kg/cm²

At 1800 rpm; 3 and 12 kg/cm²

These tests were run with the fuel injection timings optimized for each condition, and under the same conditions as the cylinder pressure diagrams reported in the Second Quarterly progress report. Vertical broken lines seen in these figures indicate the crank angle at which dynamic fuel injection began.

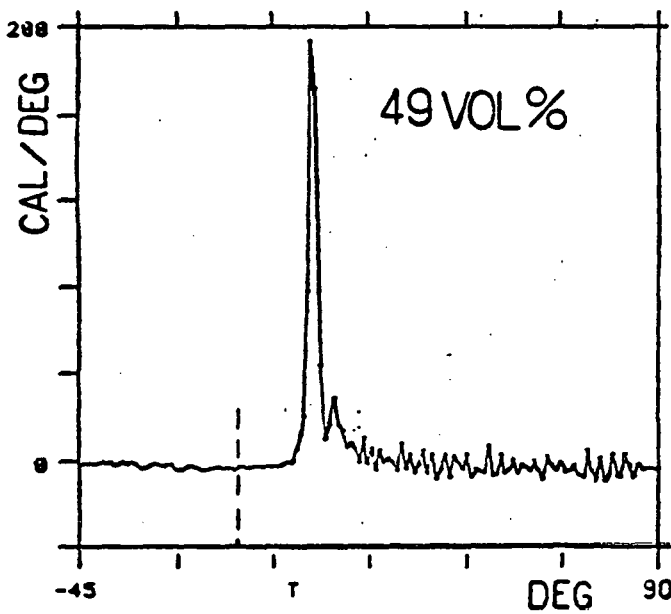
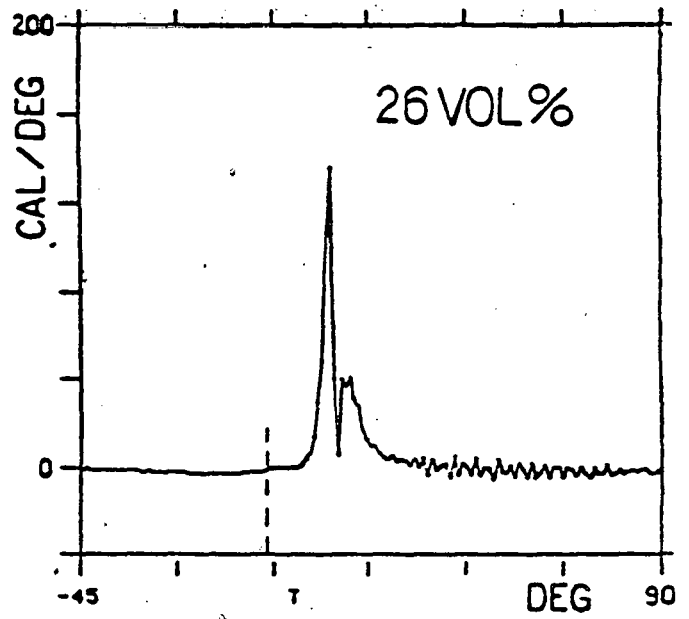
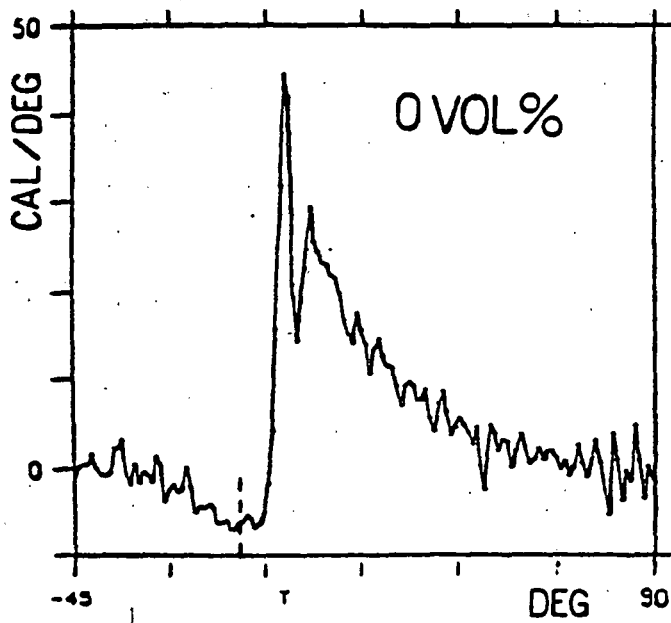


FIG. 2. CHANGES IN RATE OF HEAT RELEASE - 1
 BMEP 3 KG/CM²/1200RPM

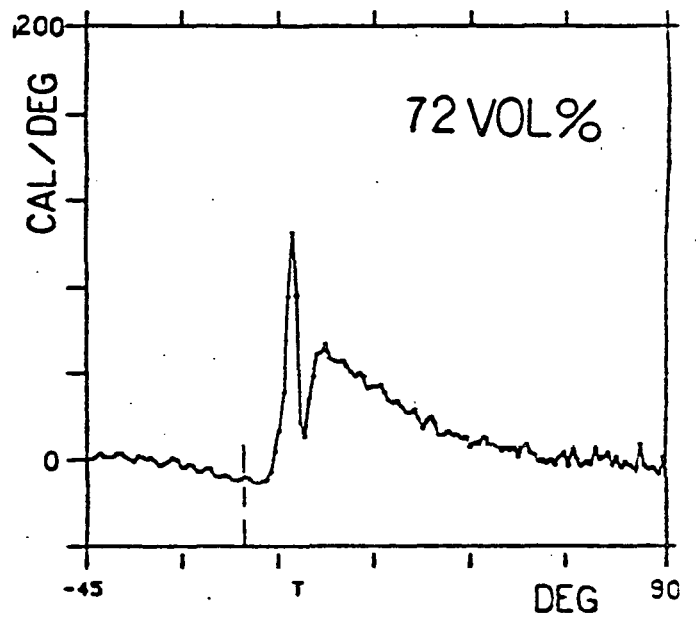
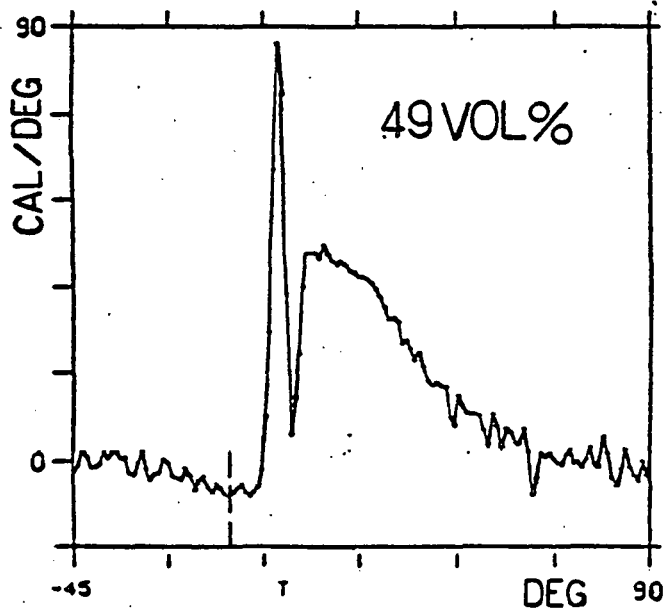
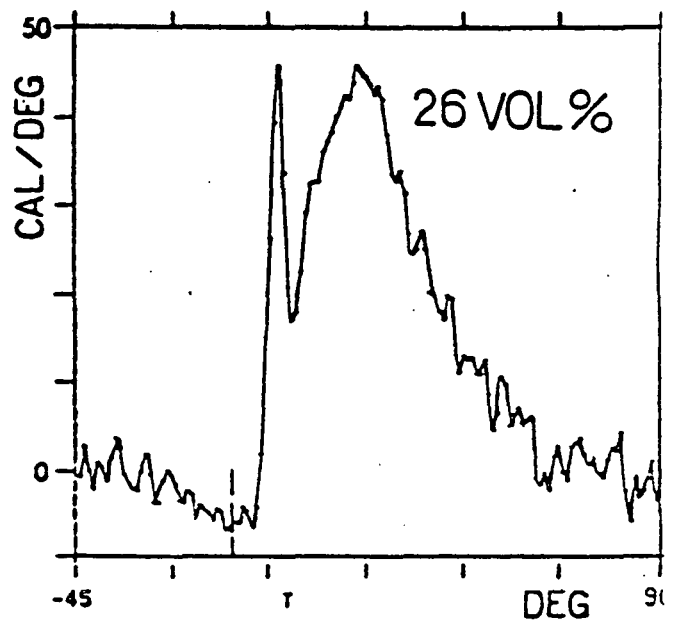
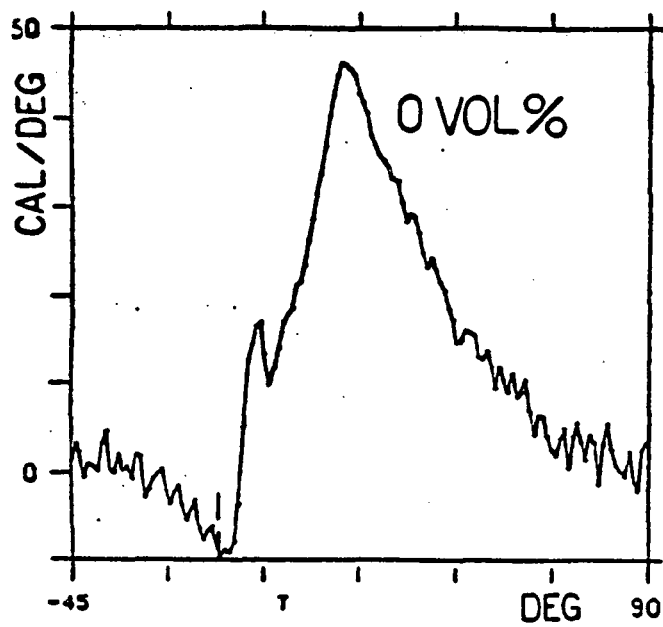


FIG 3. CHANGES IN RATE OF HEAT RELEASE - 2
 BMEP 10KG/CM²/1200RPM

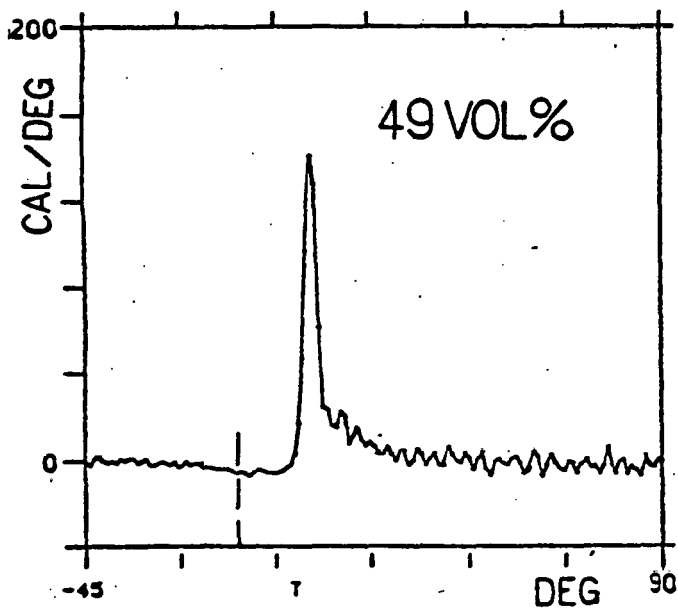
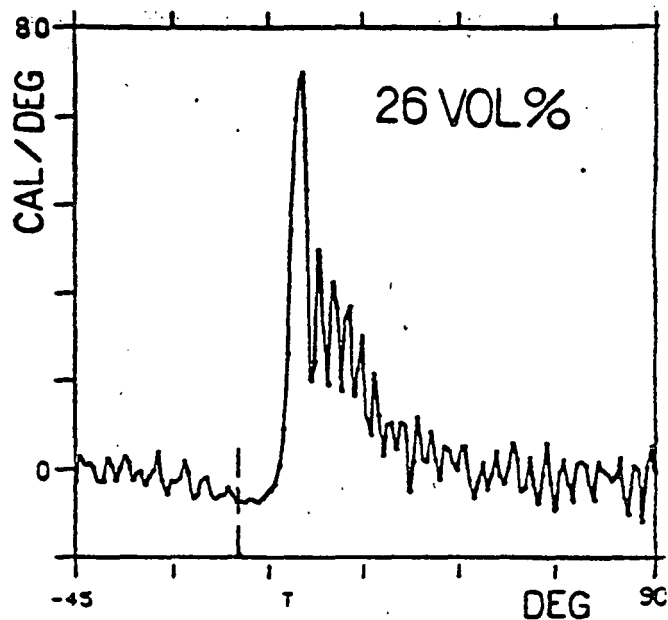
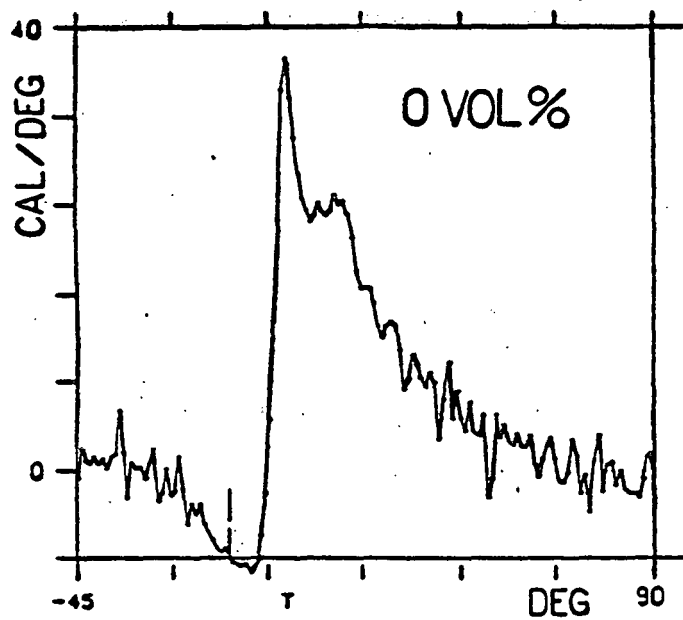


FIG. 4. CHANGES IN RATE OF HEAT RELEASE -3
 BMEP 3KG/CM²/1800RPM

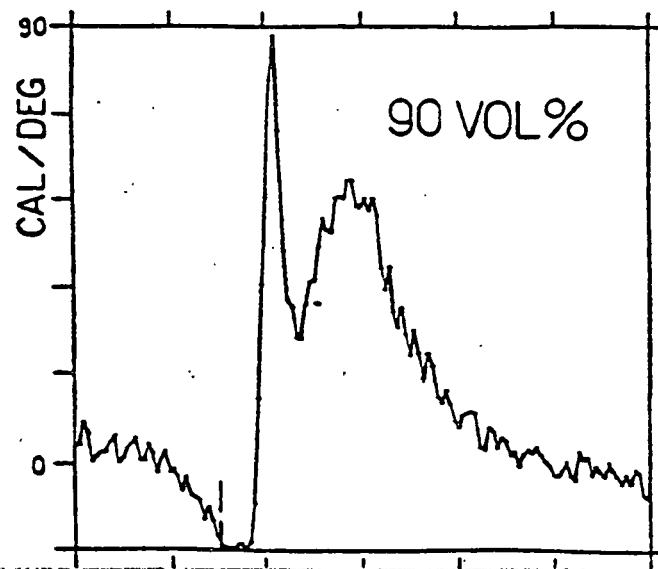
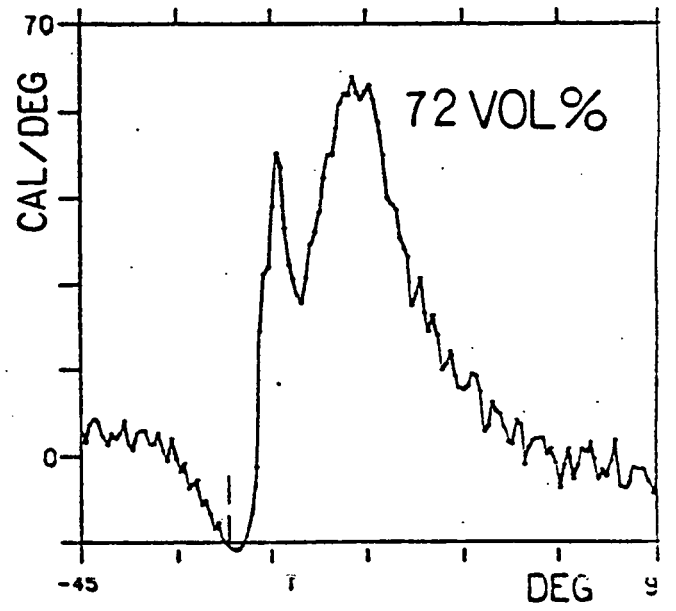
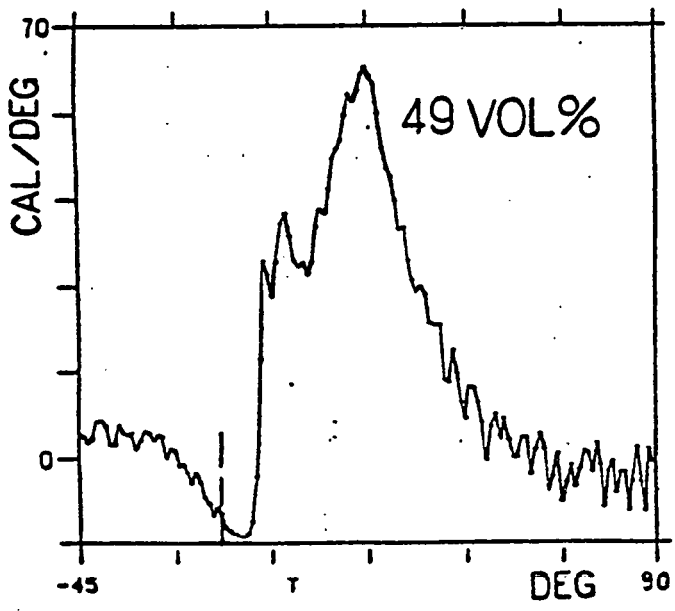
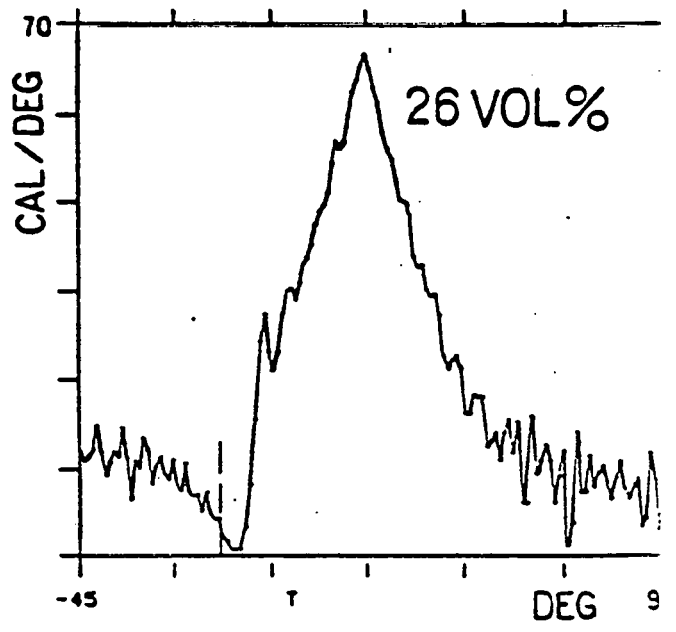
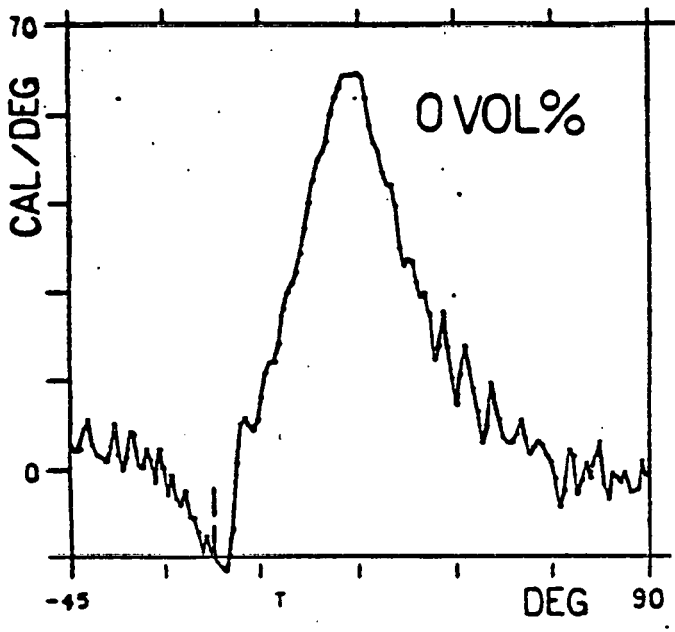


FIG.5. CHANGES OF RATE OF HEAT RELEASE-4
 BMEP 12 KG/CM²/1800RPM

In any of load and speed combinations, the ignition delay period tended to increase with increases in SRC-II content, and, as a result, premixed combustion, in other words, uncontrolled combustion became predominant. This then led to a steep rise of cylinder pressure and hence a high probability of diesel knock, as well as an increase in NOx concentration.

The ignition delay period and the rate of pressure rise are plotted against SRC-II content in Figure 6, where it can be observed that the influence of SRC-II was more significant at lower loads. Here, the peak values of the rate of heat release were taken to produce the curves given in Figure 6.

Also shown in Figure 7 is how the rate of heat release curve changed its shape with a change in each of the intake temperature, the boost pressure, the coolant temperature, and the quantity of cetane improver added. Obviously, the most significant effect was by the use of cetane improver.

2. Particulate Trap

A simplified version of the particulate trap was constructed to a drawing previously provided by Cummins. Photo 1 shows its external view, and Figure 8 is its schematic layout.

It was found, after a short run, that the system should be slightly modified to allow particulate measurements to be properly made over the entire load and speed range. The modifications were as follows:

- The transfer tube happened to be as long as 1900 mm due to a torturous installation of the system, thus resulting in a need to heat up the gas flow to the dilution tunnel by utilizing a part of the by-pass exhaust gas so as to prevent a gas temperature drop.
- An electric heater was fitted all around the dilution tunnel to maintain the filter temperature constant at 52°C even during low load operation.
- In an attempt to increase exhaust flow, the transfer tube was installed with its probe opening right at the minimum cross-sectional position of the dilution nozzle. The idea was to accelerate gas flow by a thereby created greater pressure drop. Reference was made to the GM design on this arrangement.

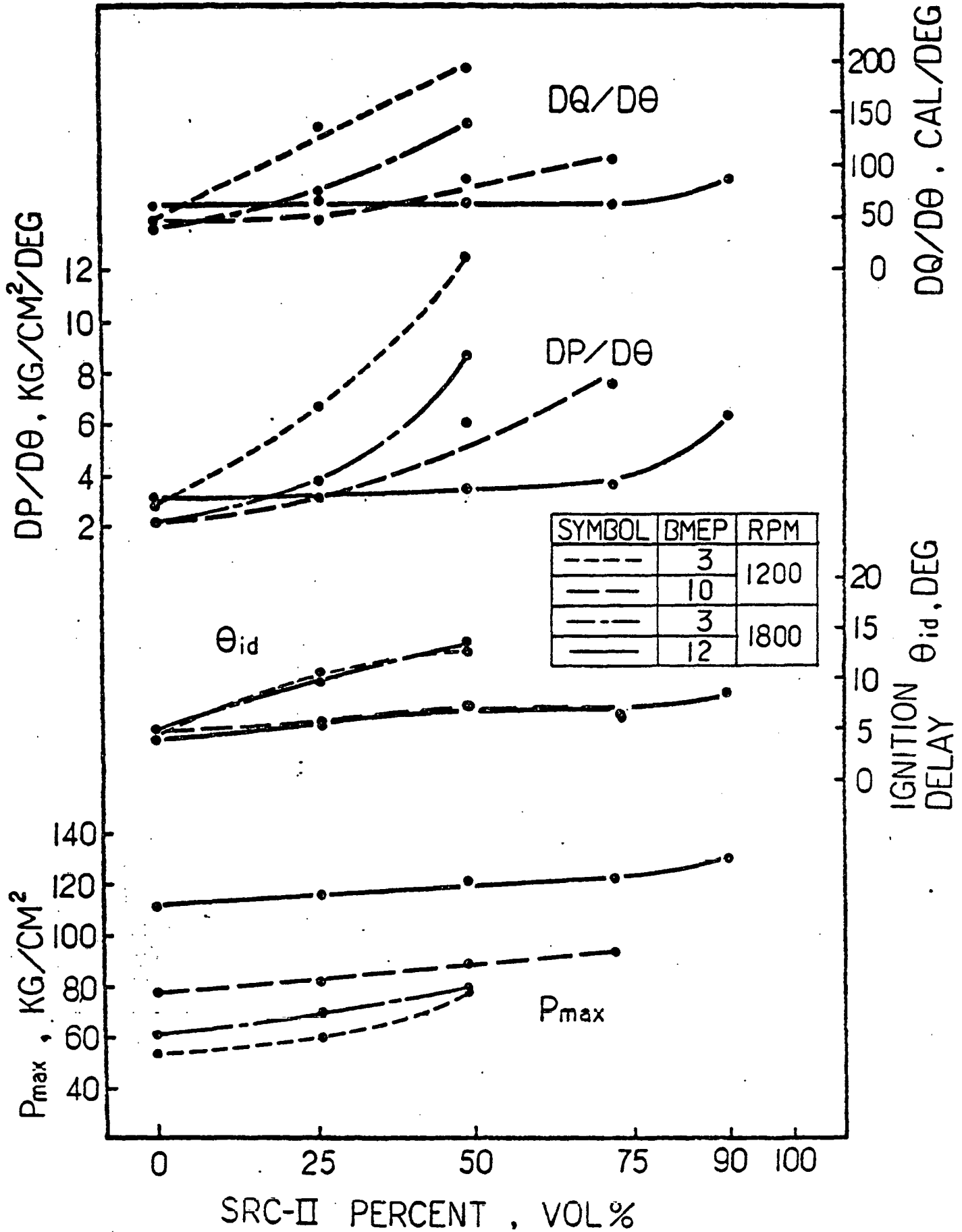
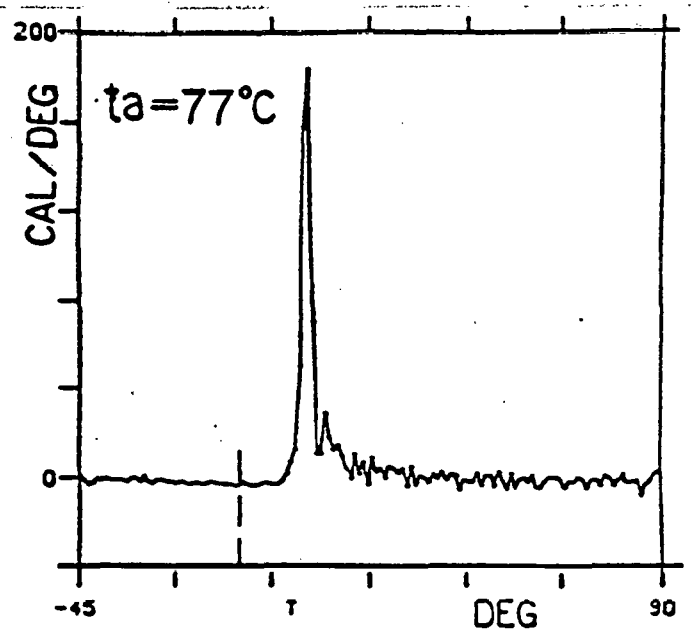
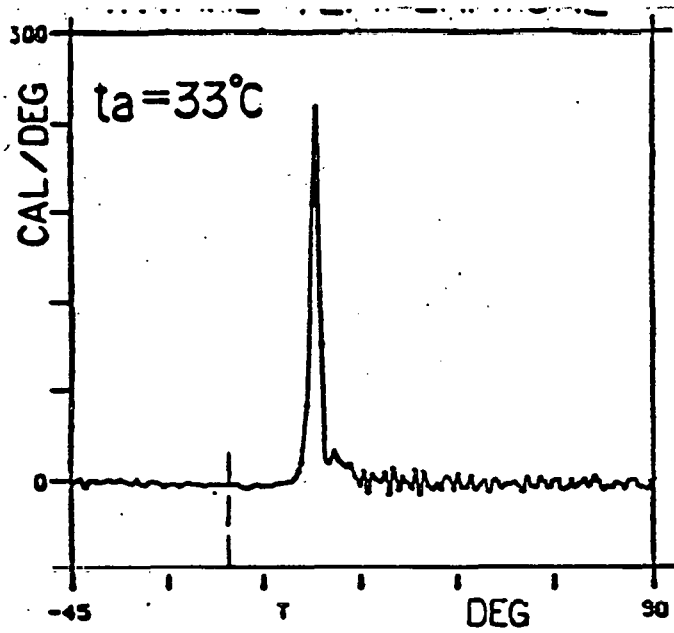
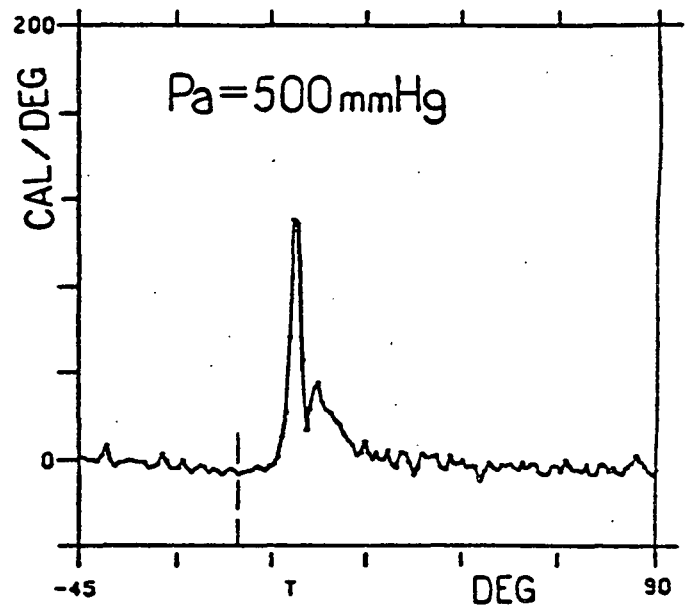
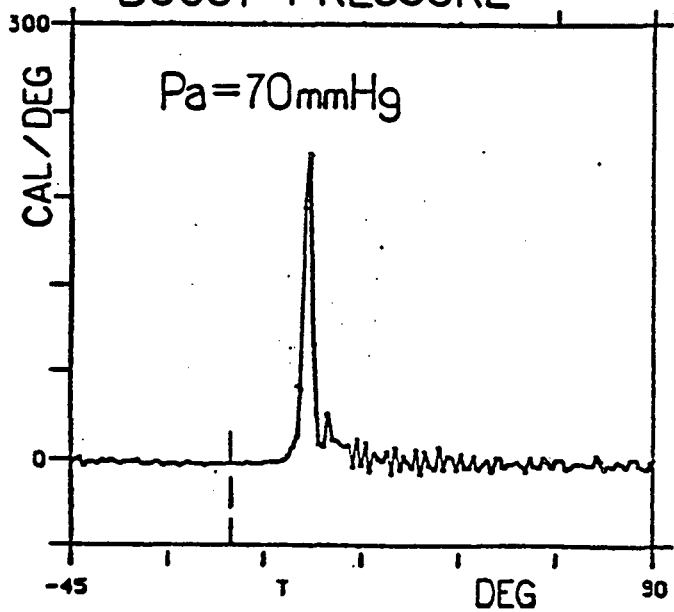


FIG. 6. CHANGES IN P_{max} , θ_{id} , $DP/D\theta$, $DQ/D\theta$



BOOST PRESSURE



COOLANT TEMPERATURE

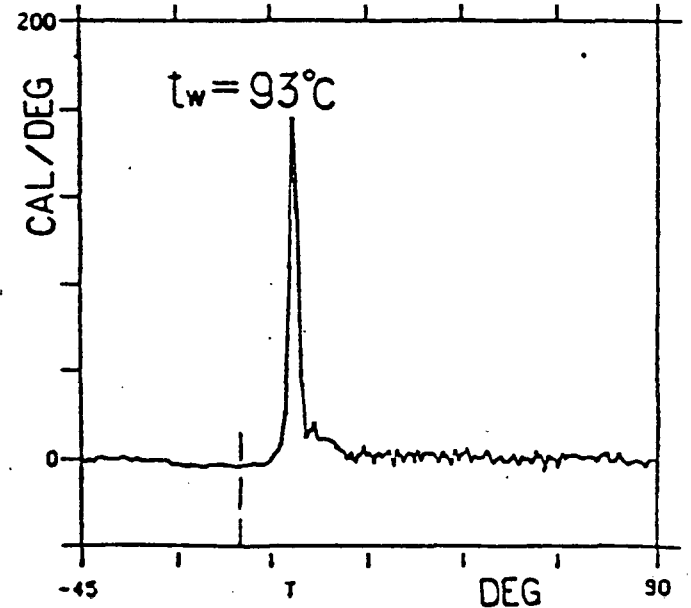
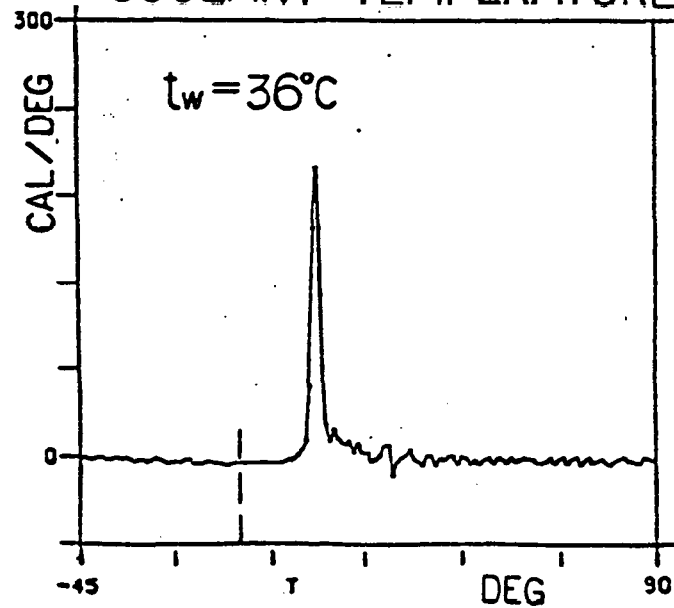


FIG 7. CHANGES IN RATE OF HEAT RELEASE-5

CETANE IMPROVER

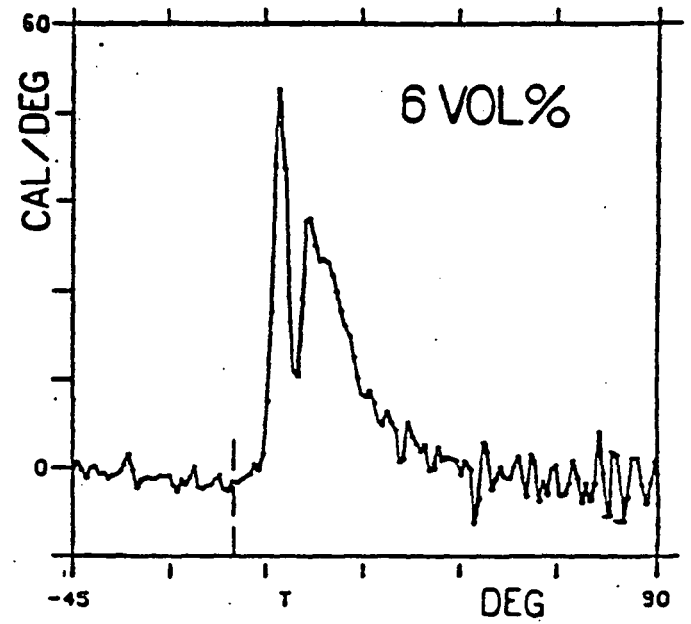
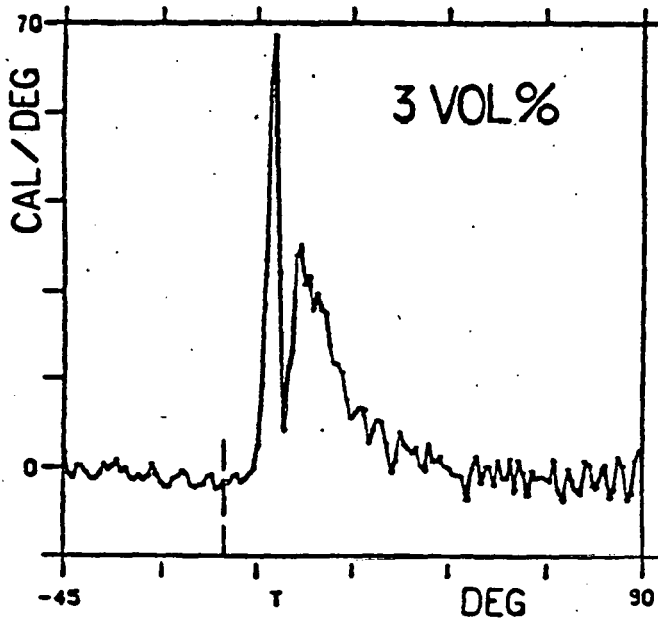
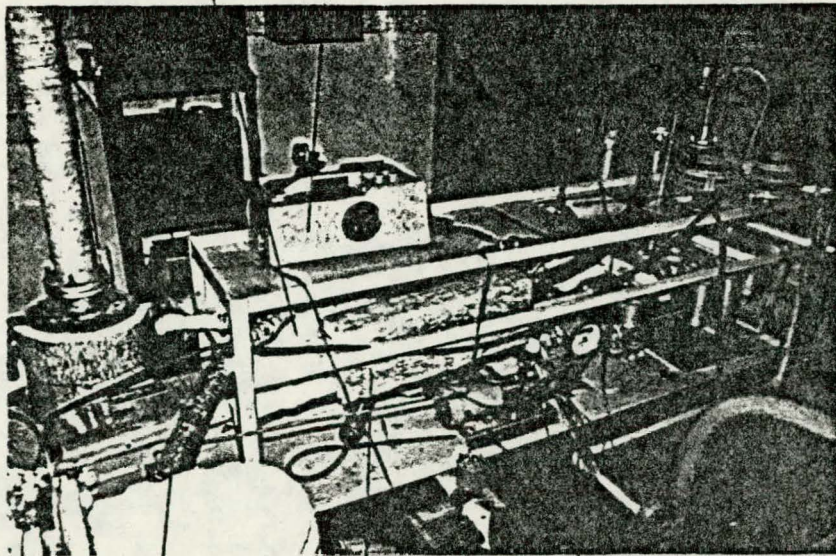


FIG. 7 (CONT'D)

Dilution Nozzle CO₂ Meter



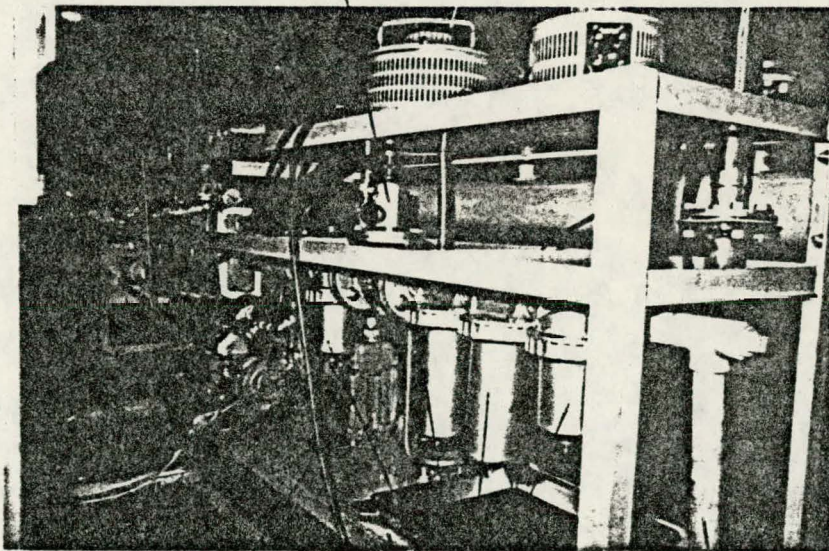
Filter Holder

Transfer Tube

Heat Exchanger

Vacuum Pump

Pressure Regulator



Gas Meter

Air Filter

Compressed Air

PHOTO.1 EXTERNAL VIEW OF PARTICULATE SAMPLING SYSTEM

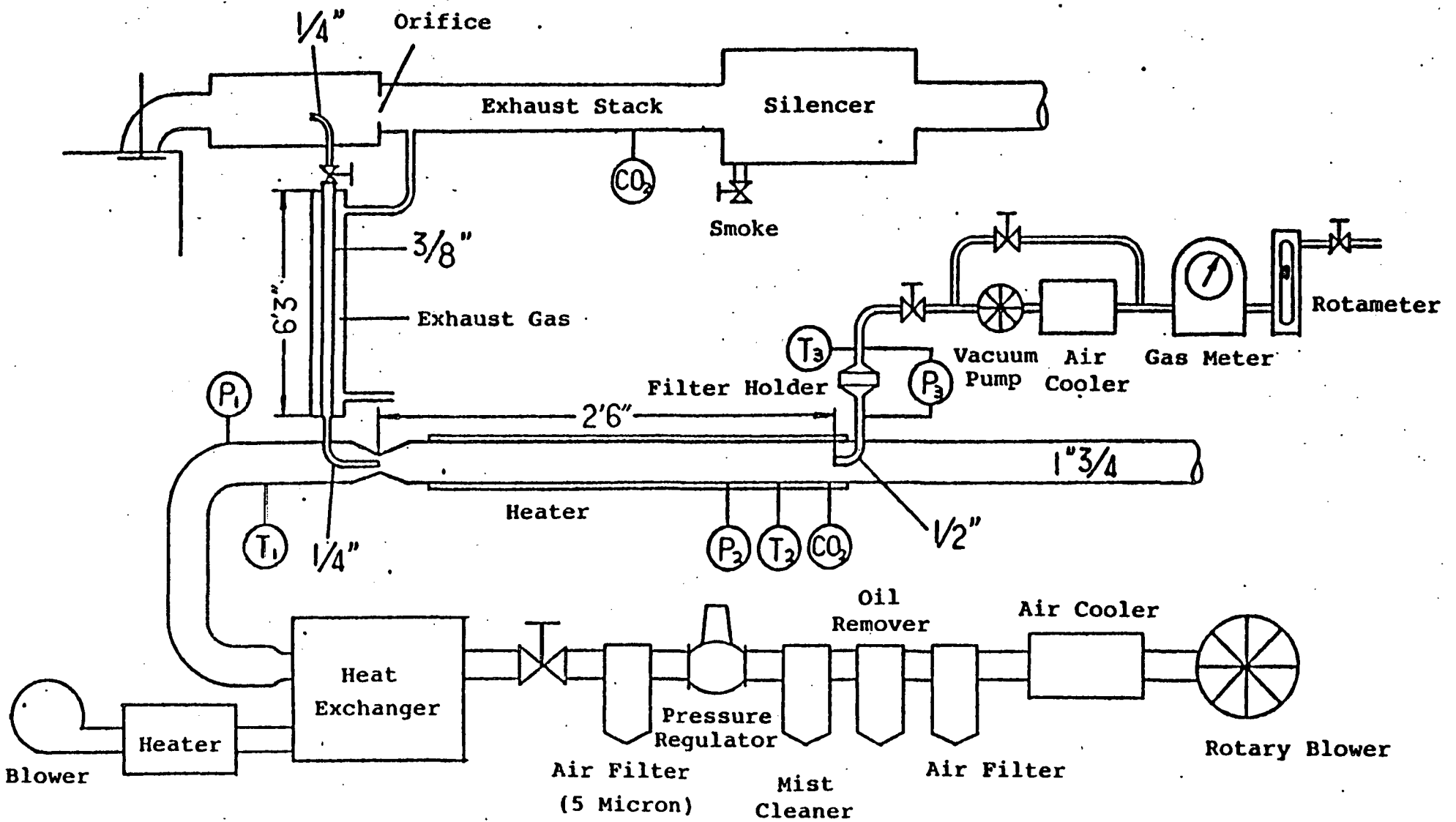


FIG.8 PARTICULATE SAMPLING SYSTEM

- A by-pass circuit and an air cooler were provided downstream of the vacuum pump for adjustment of sample gas quantity as well as for control of the temperature of sample gas flowing into the gas meter.

During sampling at the BMEP of 3 kg/cm^2 at 1800 rpm using a blend containing 49 vol. % SRC-II as a fuel, diesel knock took place and the prechamber tip was chipped off, causing the piston, liner, exhaust valves, and pressure transducer to be seriously damaged. Testing, therefore, was discontinued; and this report only covers test results each for #2 diesel fuel and its blend with 49 vol. % SRC-II.

Particulate concentrations are plotted in Figure 9 against these two kinds of fuels. Here, dilution ratios were as follows:

<u>Dilution Ratio</u>	<u>Load and Speed</u>
2	3 kg/cm^2 at 1200 and 1800 rpm
10	10 kg/cm^2 at 1200 rpm
10	12 kg/cm^2 at 1800 rpm

The particulate concentrations are expressed by the weight per cubic meter sampled at 0°C and 760 mm Mercury, and under the following conditions:

Sample gas flow rate: 1.0 to $3.0 \text{ Nm}^3/\text{hr}$
Sample gas weight: 10 to 30 mg
Sampling time: 1.0 to 3.0 hrs.

The exhaust gas flow rate in Figure 9 means a total volume of gas exhausted from the engine per minute.

3. Wear of Critical Components

The piston, liner, and piston rings were dimensionally checked, where they had not been subjected to damage caused by the prechamber failure, to determine their wear after 250 hours of running with varying levels of SRC-II content. Results indicated the wear of these components was well within measuring tolerances.

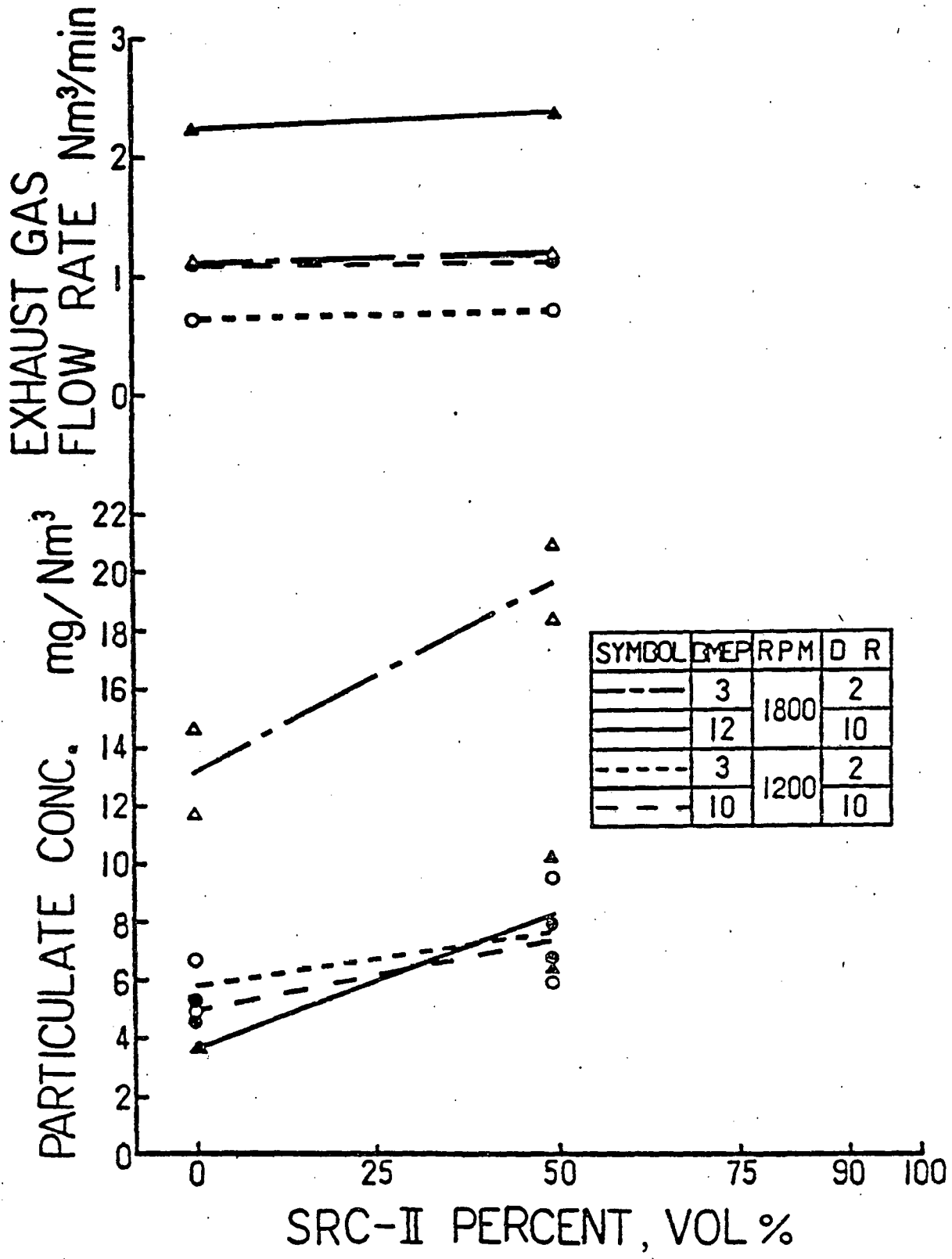


FIG.9 PARTICULATE CONCENTRATIONS

II. Komatsu, Ltd.

A. Third Quarter Work

The work conducted by Komatsu, Ltd. during the third quarter included the following:

1. SRC-II fuel blends of 50% and 75% (by volume) were tested with the base engine without spark assist. Engine operation was unstable and rough in spite of injection advance.
2. Spark assist engine tests were made with 50% SRC-II fuel blend to determine improvements in engine operating range.
3. Optimum location and timing of spark assist were determined for 50% SRC-II fuel blend.

B. Discussion of Komatsu Work

1. Extension of Baseline Test

After the baseline test without spark assist and with standard diesel fuel No. 2, two series of tests was made with 50% and 75% (by volume) of SRC-II fuel blended with diesel fuel No. 2. Although it was possible to run the engine by advancing the injection timing (standard 20°BTDC static, advanced to 30°BTDC), the engine operating condition was very rough and unstable and the base engine test of SRC-II 75% fuel was abandoned. When the cylinder head of the engine was removed, it was found that the pistons and the swirl chamber hot plugs were found damaged as shown in Figure 10. The damaged parts were replaced by new ones and spark assist engine tests were started.

2. Spark Assisted Engine Tests

The layout of the spark assist arrangement is shown in Figure 11. Surface discharge type spark plugs of three different length electrodes, as shown in the figure, were prepared. The reason for the choice of the surface discharge type was its relative invulnerability to carbon fouling because of its self-cleaning effect by surface spark discharge. The first test condition was chosen as follows:

Injection timing: 20°BTDC (static)
Length of the spark plug: The longest one (C in the figure)
Spark Timing: Variable (adjusted for best torque)
Fuel: SRC-II 50%

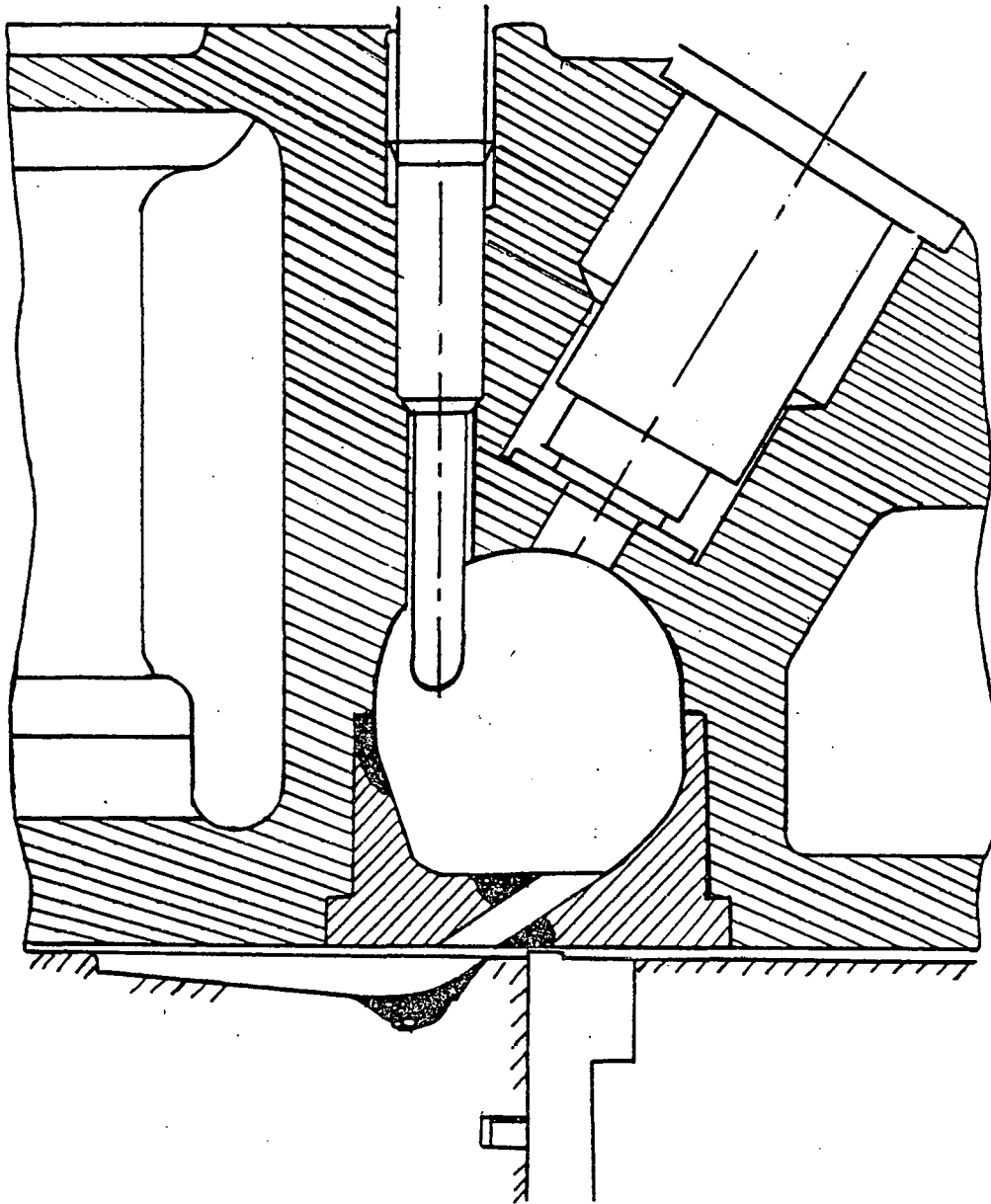


Figure 10. Damaged parts of combustion chamber.
Indicated by black.
(Refer to photograph 1 and 2.)

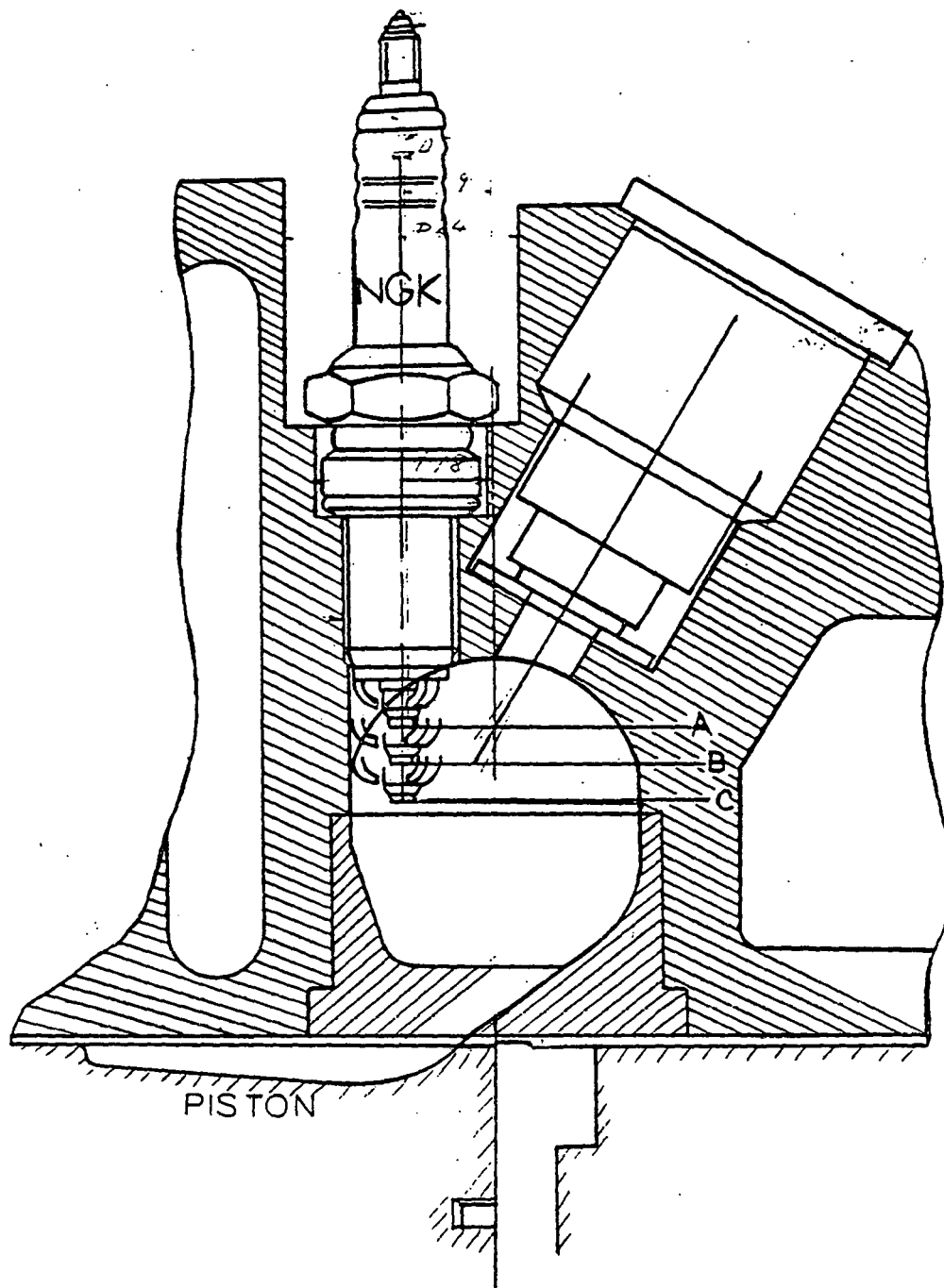


Figure 11. Arrangement of spark assist diesel.
(Surface spark discharge type plug.)

Lost ceramic sleeve

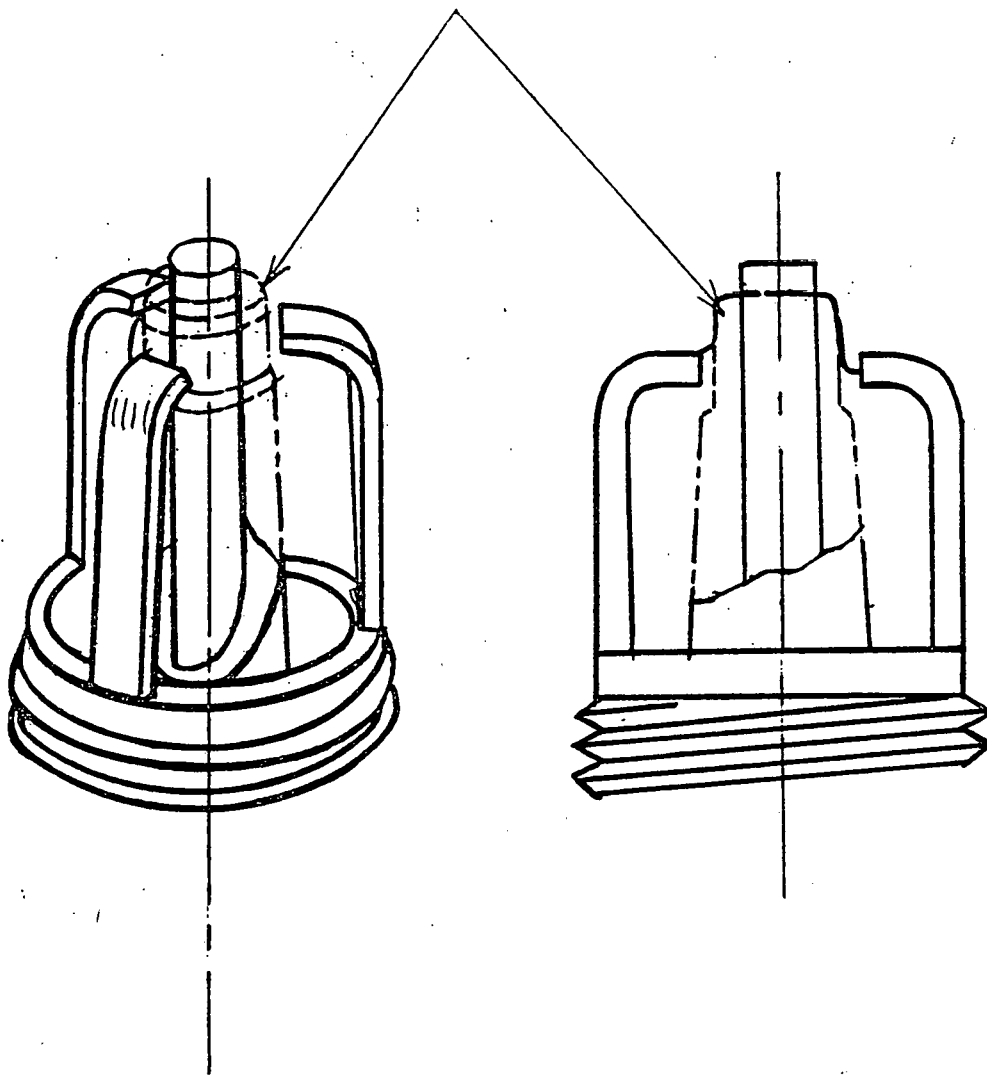


Figure 12. Broken spark plug.
(Refer to photo 3.)

The main purpose of this test condition was to see how much the operating range can be expanded by spark assist (it was impossible to run the engine above 2500 rpm as shown in the second quarter report (Figure 13)).

In the middle of the test, a sudden increase of blow-by was observed; and the engine was stopped for inspection. The cause was found that a ceramic sleeve of a central electrode was broken, as shown in Figure 12; and the ceramic fragments damaged the cylinder liner surface. The cause of the breakage of the spark plug is now under close inspection by the plug manufacturer (NGK). After this breakage, the test was tried by the shorter electrode spark plugs (A and B in Figure 11); but the effect of spark assist was not observed for all engine speeds. The obtained data before the breakage are shown in Figures 13, 14, and 15. The conclusion at the moment is as follows:

- The spark assist is effective to control the long ignition delay of the SRC-II 50% fuel. This is shown in Figures 13 and 14. Long ignition delay and severe combustion pressure rise (middle row) are modified to smooth pressure rise (lower row) by spark assist.

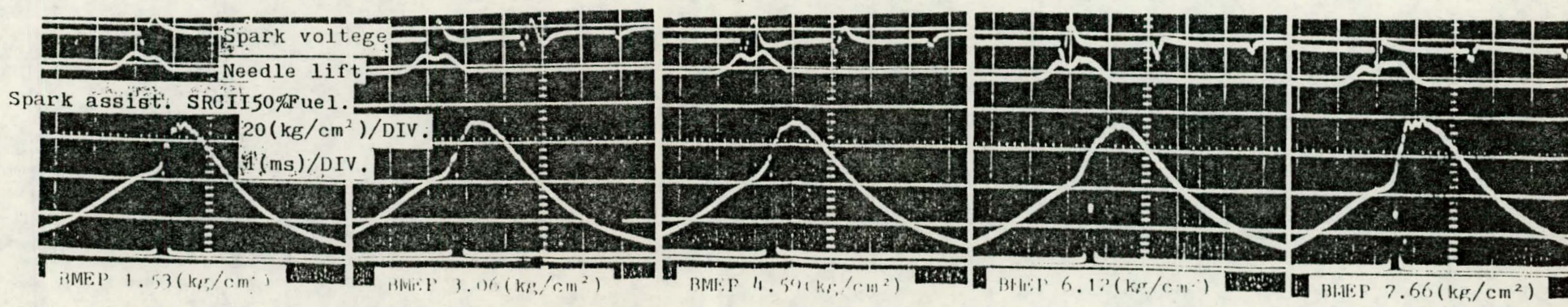
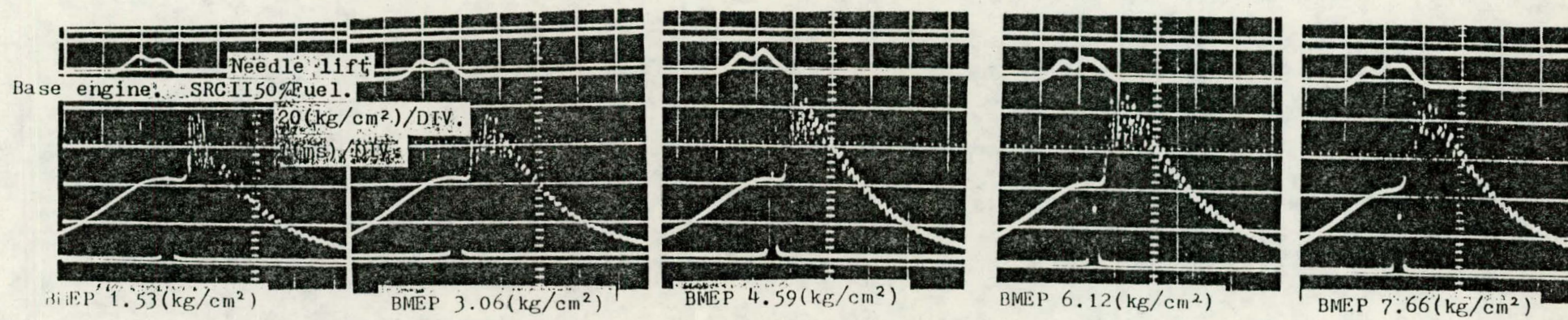
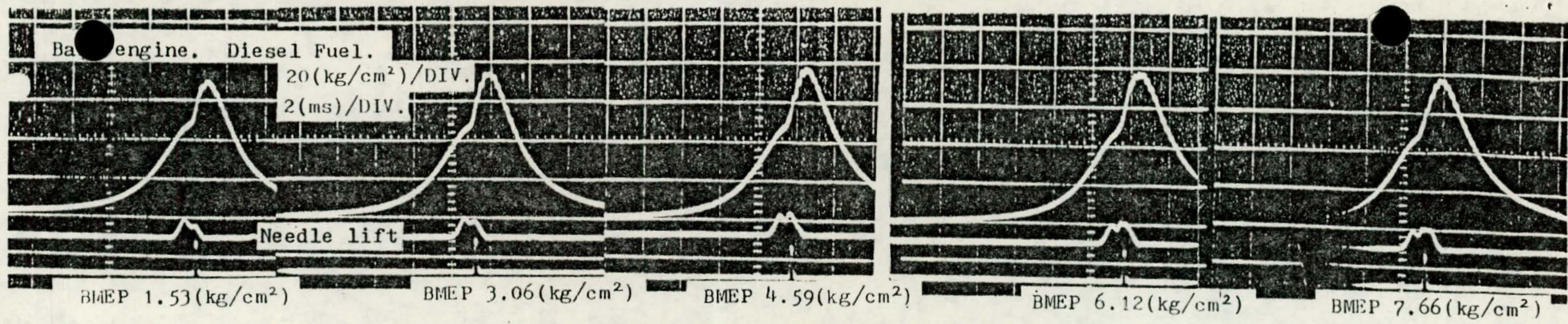
3. Optimum Spark Location

Spark timing and location in the combustion chamber are critical for effective spark assistance. This comes from the observed fact that effective spark timing range relative to injection timing was very narrow and that only one spark location (C in Figure 11) was effective among the three.

4. Spark Plug Reliability Problem

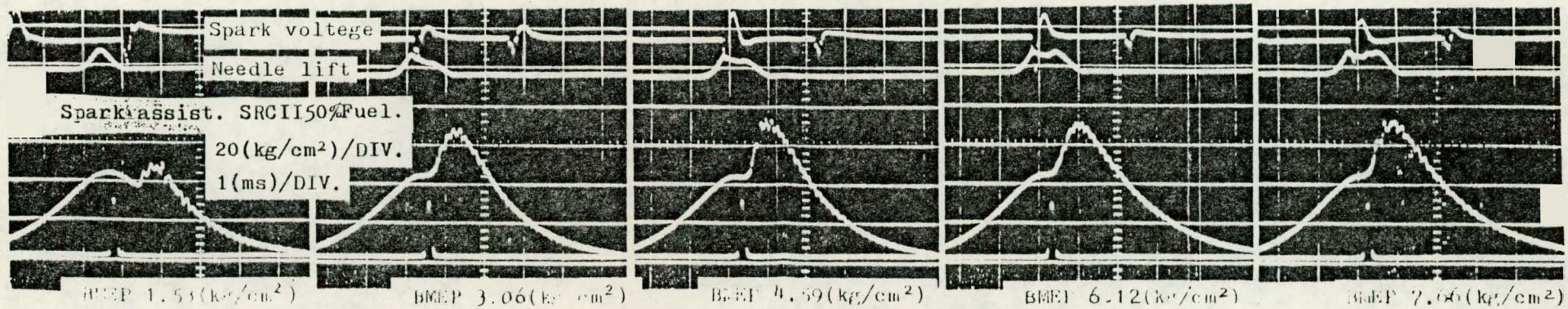
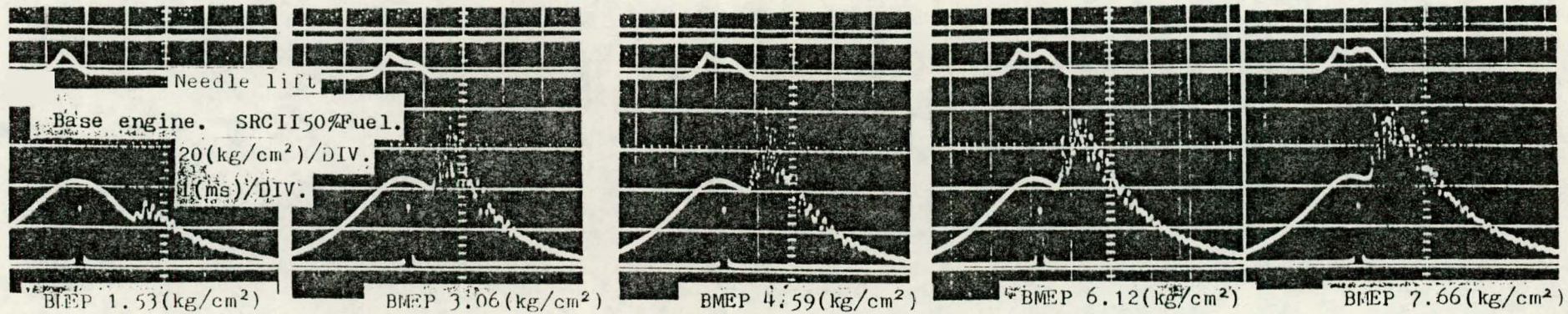
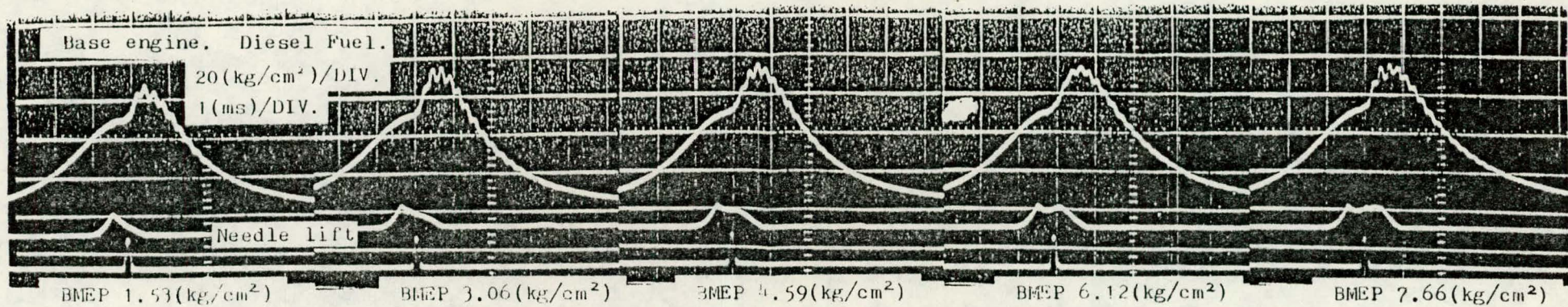
The spark plugs (surface discharge type) prepared for the spark assisted diesel for SRC-II test could not endure more than ten-minutes operation. Thus, the surface discharge type was abandoned and another type spark plug (conventional type with long electrode) as shown in Figure 16 was made.

An investigation report was received on broken spark plugs by the plug manufacturer (NGK). Close-up photographs of the broken spark plugs are shown in Figure 17. Two modes of breakage were found, one is the breakage at the root of the ceramic sleeve of the central electrode possibly caused by an excessive mechanical vibration of the central electrode; the other is the breakage at the tip of the ceramic sleeve caused by a spark penetration through the ceramic sleeve. The breakage of the electrode itself of the No. 2 cylinder is considered to be a secondary breakage by the first mode breakage.



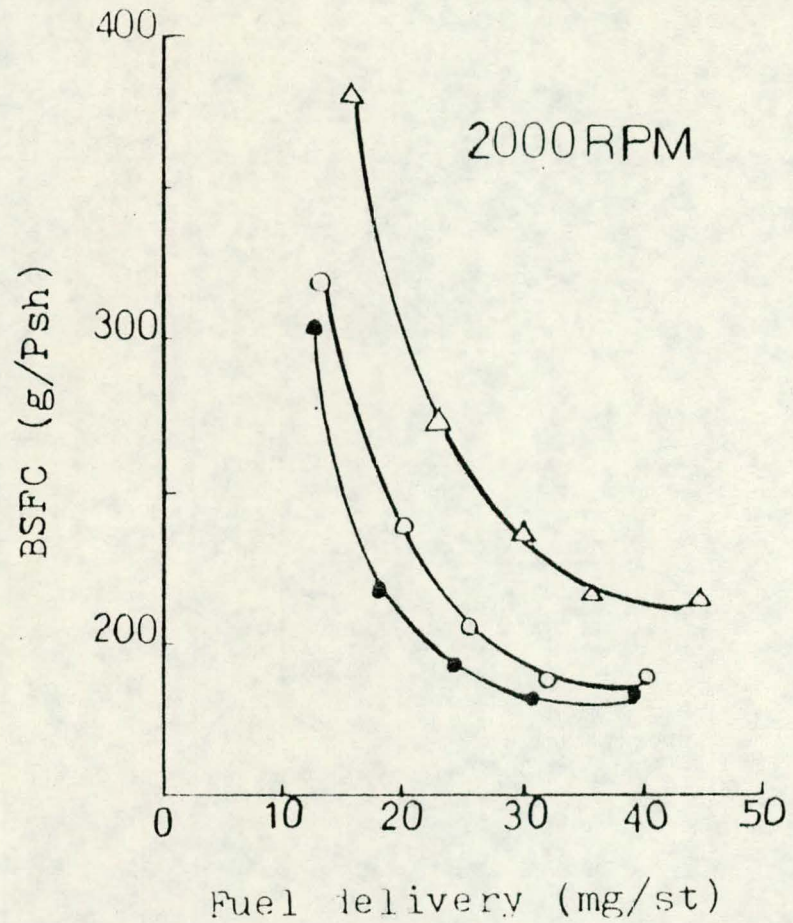
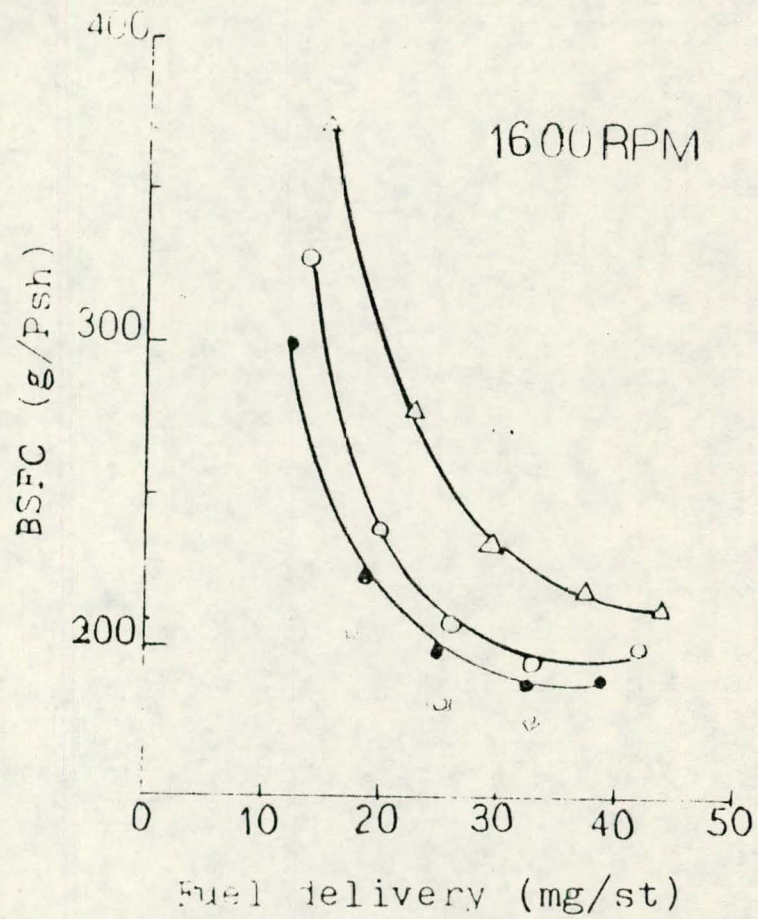
Engine speed: 1900rpm

Fig.13 Comparison of combustion pressure diagram



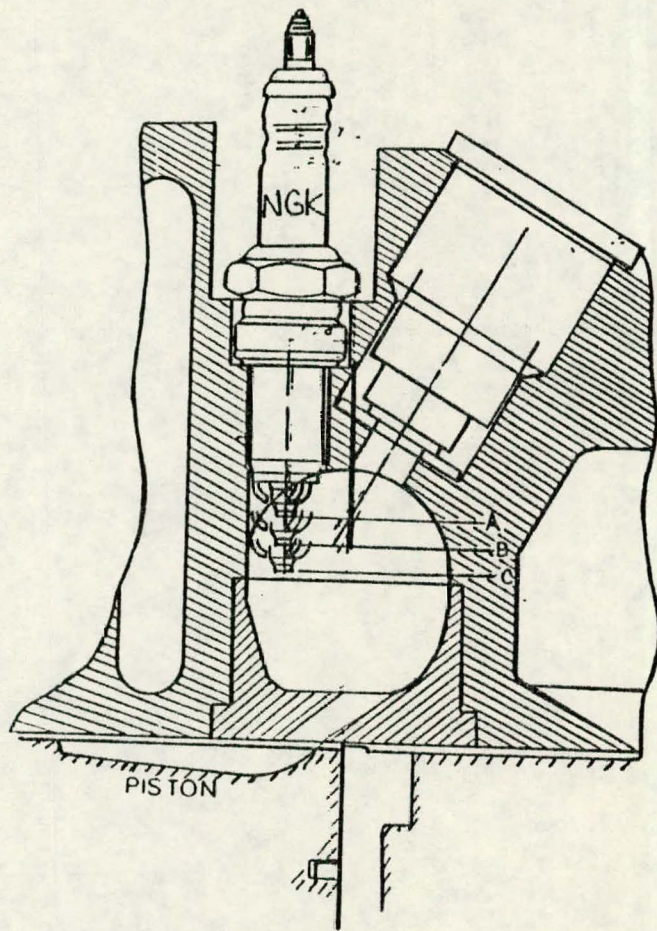
Engine speed: 2000rpm

Fig.14 Comparison of combustion pressure diagram

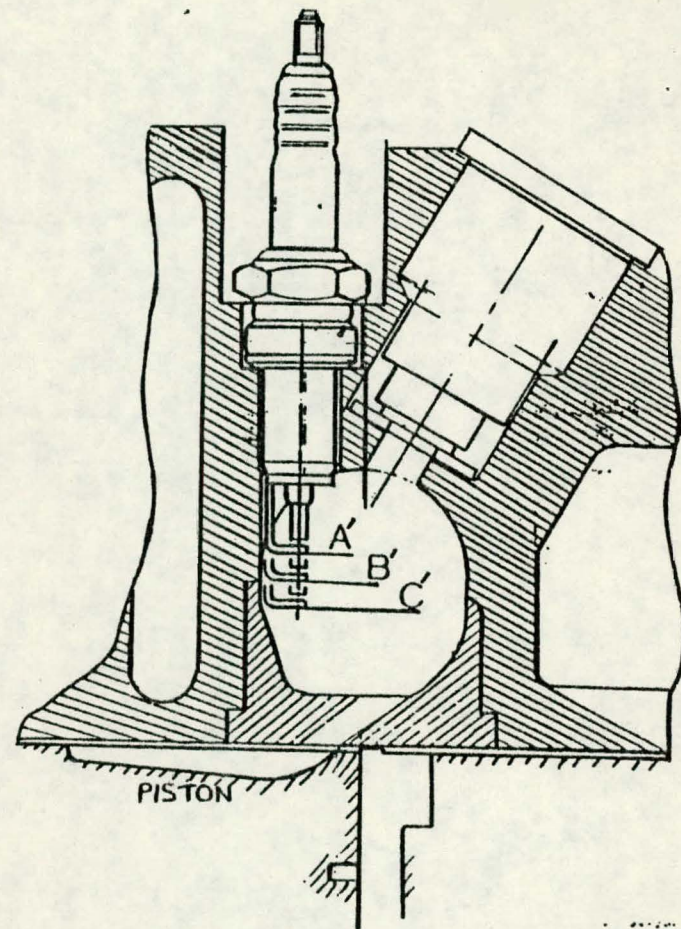
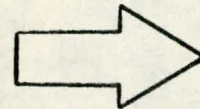


- △—△ Base engine. SRCII 50% Fuel.
- Spark assist. SRCII 50% Fuel.
- Base engine. Diesel Fuel.

Figure 15. Comparison of specific fuel consumption
(Difference of heat content is not corrected.)



(a) Surface discharge type
(Broken)

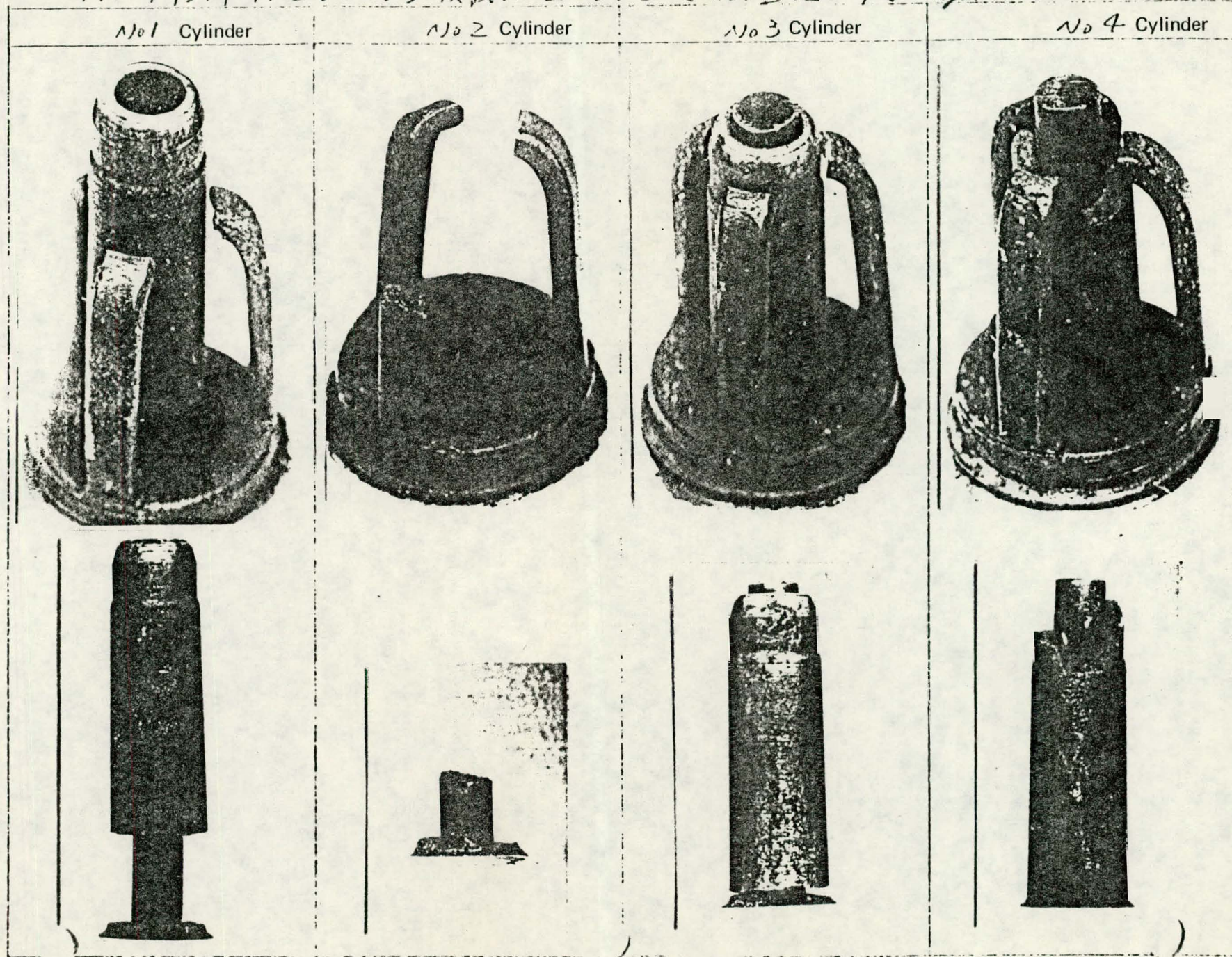


(b) Conventional type with long electrode
(Newly made)

Fig 16. Two types of spark plugs

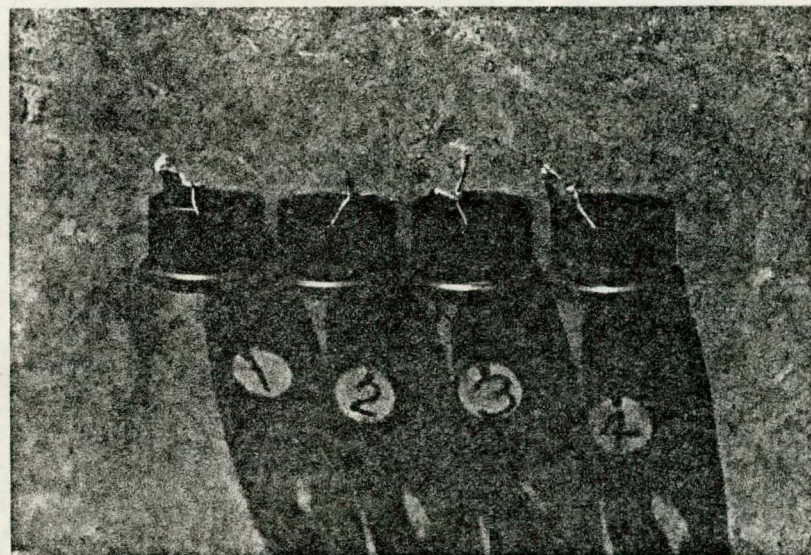
FIG. 17 BROKEN SPARK PLUGS

スノー7アシストターボエンジン 供試の L1234C (電極長 12mm) (Length of electrode 12mm)

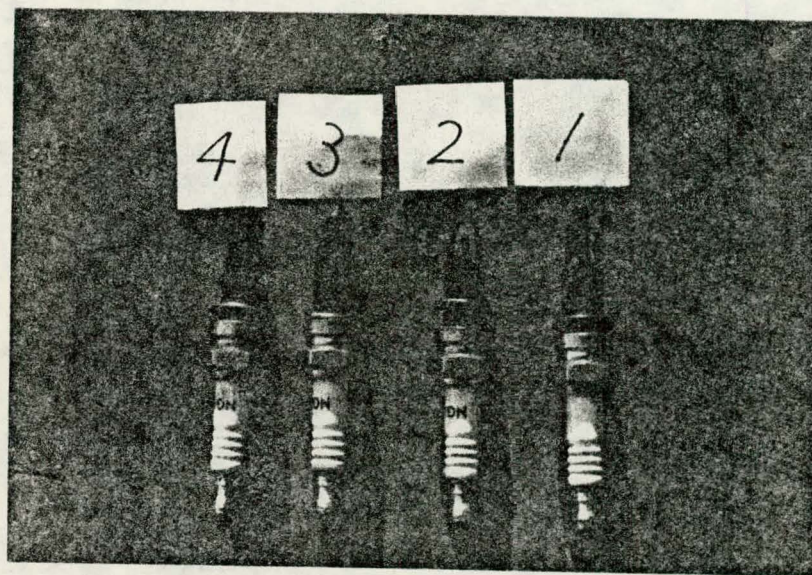




Photograph 2



Photograph 3



Photograph 4

Conclusions

The third quarter work by Yanmar and Komatsu begins to shed some light on the combustion aspects of SRC-II fuel in a prechamber and a spark assisted prechamber diesel engine. From the data obtained thus far on this program, it can be concluded that:

1. Some form of modification to the contemporary diesel engine or to the fuel will be required to burn SRC-II coal derived fuel oil.
2. Major factors which can improve the combustion of SRC-II fuel oil in a contemporary diesel engine are:
 - A. Fuel blending
 - B. Cetane improver
 - C. Spark assist
 - D. Hotter inlet air temperature
 - E. Hotter cooling water temperature
 - F. Faster injection timing
3. When proper operation with SRC-II fuel is obtained, trade-off of BSFC with emissions is quite comparable with diesel fuel No. 2 when correction is allowed for lower heating value of the SRC-II fuel.
4. Spark assist definitely contributes to the improvement in combustion of SRC-II coal derived fuel oil.

Future Work

The last and final quarter work on this program is approaching and the work scheduled in Table II will be completed to fulfill our contractual obligations.

Yanmar will:

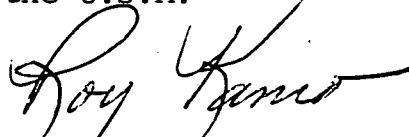
1. Continue particulate measurements on the remainder of diesel fuel No. 2 and SRC-II blends.
2. Check "mutagens" in particulates of standard diesel fuel and SRC-II.
3. Make noise measurements with SRC-II fuel.

Komatsu encountered unforeseen difficulty with their spark electrode breakage problem. It is still expected that Komatsu will complete their work task by March, 1982. Specifically, their remaining work is:

1. Complete performance and emissions data by using the longest conventional spark plug with 50% SRC-II fuel blend.

2. 100% SRC-II will also be attempted with spark assist.
3. Obtain particulates and "mutagen" data with spark assist.
4. Noise measurements.

It may be difficult to obtain mutagen data in Japan. In such event, the particulate samples will be sent to Cummins; and the mutagen tests will be performed in the U.S.A.



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