Heavy Fuel Composition and Its Influence on the Energy Release in a Medium Speed Diesel Engine

L. Th Collin, S. Dunert and J. Lundgren
Chalmers University of Technology, S-412 96 Göteborg

ABSTRACT

When trying to correlate any combustion model for energy release in a combustion engine many times the influence of the fuel composition on the energy release sequence is not taken into account. Therefore some basic research on the interaction of fuel quality in a medium speed engine, capable of burning low quality fuels, could be of interest.

This paper describes a long term project, the aim of which was to try to clearify how different hydrocarbon structures in a fuel could influence the energy release in a medium speed diesel engine. As the fuel composition is built up from several thousands of different hydrocarbon molecules, it has been assumed that the accuracy in the measurements must be built up in a way looking after not only percent but even promille or still lower concentrations of some components. That will correspondingly ask for high accuracy in the measurement, in the analysis and in the realization of the tests.

The test engine has been a three-cylinder medium speed engine with a bore of 250 mm and a stroke of 300 mm, where one cylinder has been used as a measuring device. The chemical analysis is based upon gas chromatography, where we in most cases have been forced to distil the heavy fuel before the analysis, as the gas chromatography does not enable any analysis of heavier hydrocarbons than C_{40}. In a distillation column we have been able to divide given fuels in different sections and test not only the basic fuel but also the different sections produced. In addition to normal pressure and temperature measurements we have also been able to analyse the exhaust as to NO_x, HC, CO and CO_2.

As a result of the investigation we could define that the energy release is very strongly influenced by the composition of the fuel as to hydrocarbon molecules, chain configurations and concentrations.

Test Engine Description

The engine, which has been used as an experimental engine, is a four stroke medium speed engine from NOHAB, type F10, delivered during the early seventies. The engine has been upgraded to the later version type F20 and was then supplied with larger plunge diameters and new cam profiles in order to enable a higher lifting capacity of the fuel plunger. The cam profiles used could be easily adjusted and could be exchanged and modified with a rather large freedom. The engine is more directly described in Table 1. To enable more detailed studies and to minimize the consumption of fuel to be tested, one cylinder adjacent to the output flange and the flywheel has been chosen as a test cylinder and has been instrumented accordingly. On the flywheel a device has been built, which gives a pulse for every degree of crank angle. The short connecting shaft between the test cylinder and crank angle indicator hopefully eliminates any deviations due to torsions. The engine has been extensively instrumented and the sensors are connected partly to a data logging equipment, partly to the instrumentation in the control room. For every crank angle degree the combustion pressure, the injection pressure and the needle lift were registered and once per full 360° rotation the air consumption, the scavenging pressure, the exhaust gas temperature and the pump rack position were recorded. Of course, the position of the UDP is to be defined with very high accuracy, especially if you would extend the data treatment further than what is reported here.

The exhaust gases from the test cylinder are passing a special mixing flange before they are mixed with the exhaust from the other cylinders. In such a way the emission from only the test cylinder could be analysed in emission instrumentation. The concentration of NO_x, HC, CO, CO_2 and O_2 were determined and are also registered. The schedule for the instrumentation is given in Figure 1.

Fuel Supply System

To be able to test different fuels, the fuel supply to the test cylinder is most essential. It has been fitted out with separate fuel supply, according to three different alternatives, given in Figure 2.

A) Fuel could be supplied from four different fuel tanks, each of 2000 litre, all fitted out for not too viscous fuels.
B) Fuel from four different barrels of each 200 litre, which all could be pre-heated so that heavy oil could be used.
C) Fuel from a small vessel of 2.5 litre in-

stalled just before the fuel pump and which could be connected just during the measuring sequence. The fuel could be pre-heated so that all kinds of heavy fuels could be utilized.

Those three different alternatives give a possibility to run both long time testing and tests where the test fuel is available only in limited quantities. The alternative C) has been used mostly, and has proved to be the most practical system when it comes to handling special fuels. The comparison of the results from continuous service with one fuel and with the same fuel in the test vessel proves that the volume is sufficient to get steady state as the pressure development and the emissions are identical. In order to save fuel of the tested kind the engine is started on a common fuel and run up to a certain output rpm level and when that one is achieved and steady state is reached, the fuel system on the test cylinder is switched to the test fuel during the measuring sequence. This procedure makes it possible to study a fuel at quite a number of different load situations without using too much of the same.

Fuel Analysing Equipment

The basic thought and the ambition in this work is to find out if and how the fuel composition will influence the energy release in the cylinder. The analysis of the fuel has been based upon gas chromatography through which not only the hydrocarbon molecules could be defined but also the structure of the chains could be indicated. The gas chromatograph is fitted out with a capillar column and a flame ionization detector. It is also completed with a computer which governs the proceeding and handles the result. Hydrocarbons from C_1 to C_{40} could be analysed. If still heavier chains should be involved, the fraction up to 550°C BP will be separated in a vacuum destillation and analysed. An IR-spectrometer is used to complete the results from the chromatograph when defining the different chain types.

Not only the analysis of the fuel and its composition could explain the energy release development. The way in which they have been composed, i.e. the variation in concentration between the different groups of hydrocarbons, could influence the proceedings. In order to be able to study that and how a certain boiling point interval in the fuel influences the activity in the combustion chamber, a destillation column has been produced in order to produce fuel, with a very narrow boiling point interval. The destillation unit, which is of packed column type, has been built within our department. It is working under vacuum and has a length of 2 meter. Through the vacuum it is possible to distil oil with high boiling points and residuals. The long column makes it possible to achieve a good separation. The apparatus could run continuously or batchwise. Through the gas chromatograph we could then get sufficient information about the composition of the distilled product. The handling procedure of the fuels is given in Fig. 3.

The test fuels, treated as just described, or untreated, are then tested in the engine. In order to be able to define small deviations from the normal fuel, a stable and easily handled engine unit is desirable. Sometimes one-cylinder units are preferred, but the engine earlier described has some given advantages. The experiences gained could be directly transferred into similar engine types. Problems experienced in running engines could be reproduced more directly and the energy release sequence at a fuel recommended for use in service offers reliable examples for how a "good" oil in the cylinder should behave.

Test Procedures

During the years passed, well defined routine for the execution of the test has been developed. Very high degree of repetitivity has been achieved through extreme accuracy regarding temperatures in the engine, the running-in and warming-up procedures and calibration of sensors. Several hundreds of tests have been run and have given us a reliable background. The achieved repetitivity is based upon extensive knowledge of the temperature development in the engine and in the laboratory, where the engine is placed during the tests. The temperature in parts of the engine, the scavenging air temperature and the fuel temperature will influence the results. The temperature in the laboratory changes during the run as the engine is a heat source of importance. The air temperature and air moisture are influenced during the running. To reach a steady state you need a number of hours running. The knowledge reached within the field during the past years has made it possible to lay out the test so that the time could be limited and the variation very small.

Test Result Accuracy

As an example of the results achieved and the way in which the results are presented we refer to Fig. 4, where the engine has been running at 750 rpm at a normal distilled fuel but at different loads, 100 %, 75 %, 50 %, and 25 % of full output. At the lower part of the diagram you will see the pressure as a function of the crank angle degree, above that the time derivate of the pressure development, the fuel amount per crank angle degree and the fuel pressure. On the upper part the energy release per degree crank angle as well as a totally integrated released energy is drawn. You could see how the energy release is influenced by the load and that the lower load gives a very high intensity in energy release after a delay, which is far longer than in the higher load sequencies. The development from a partly diesel knock to a more regular combustion could be easily seen. Of course the variation in energy release and delay time depends upon the temperature in the combustion room due to the load and to the injection pressure, which also influences the average droplet size of the fuel drop in entering the combustion space.

In order to achieve diagrams of this type we have to study not only one cycle but a number of cycles. The results are based upon measurements for each crank angle degree done during 100 cycles. The readings are then the basis for average calculations and it is the average for those hundred cycles which forms the data which have been plotted in the previous diagram. With the data handling routine we could study for example

the standard deviation at different angles and find out what kind of confidence we would have in the given values.

We have found that plotting of the data is more efficient than studying a large number of figures in tables. The eventual deviations between different lines are easier recognized than the deviations in figures. This is exemplified in Fig. 5, where the results from the seven repeated tests at 750 rpm and 42 % load are given. They are all plotted in the same diagram above each other and you could see that the variations are merely depending upon the one degree distance between the readings than a lack of consistency in the readings. The load 42 % has been chosen as a reference load, right through our investigation, as the sensitivity in energy release seems to be at maximum there, possibly due to the combustion chamber configuration in our engine.

Fuel Investigations Approaches

There are a number of different methods through which the influence on the energy release from the fuel composition could be studied. Usually the number of parameters in the fuel could be reduced. That could be carried through in two ways.

You could distil a narrow fraction from a fuel with a rather wide boiling point interval. In such a way you will get a fuel with a reduced number of hydrocarbon chains to analyse. That means that a more safe analysis could be made.

Another way is to add to a well known fuel amounts of a fuel consisting of a few defined singular hydrocarbon chains.

With those methods you could study the chosen distillate interval or the singular hydrocarbons influence on the energy release when the test is done with or without the well defined hydrocarbons.

If you have a fuel consisting of a large number of hydrocarbons, it could be investigated in a more schematic way. Heavy fuel for example, that shows principle differencies in paraffin concentration, and the amount of branched chains are rather well characterised in a chromatogram without any need for a detailed analysis.

In the following, some examples of those methods and the penetrating possibilities of the test equipment will be shown. The examples show the possibilities of the different approaches and what the present test equipment could achieve. The examples are:

1. A wide range distillate, WRD, is divided in four volumetric equal parts with gradual increasing boiling temperature interval but with some overlapping.
2. A fuel with a narrow boiling point interval is prepared with different singular hydrocarbon chains.
3. Heavy fuels of different types, but without further treatment.

The Handling of the Wide Range Distillate

The WRD was divided in the distillation column in four equal large parts. Test were run both with the original wide range distillate and the different distillated parts. The specification of the wide range distillate is given in Table 2. Through the gas chromatograph the boiling point intervals could be defined. As could be seen from the table the samples 2 and 3 have a rather similar composition. In Fig. 6 the chromatogram for the wide range destillate and destillate one to three and four are given. As could be seen from Fig. 7 and Fig. 8 there is a well recognizable difference between the different fuel batches. The heaviest part of the wide range has the shortest ignition delay and the lightest distilled part has even longer ignition delay than the original wide range distillate. The composition also influences the amount of energy, which is released during the first ten to twenty degrees of the combustion, which in turn influences the maximum pressure as well as the exhaust temperature, as the energy release delay shortens the possible expansion after combustion.

Preparing of a Narrow Test Fuel with Singular Hydrocarbons

Through mixing the defined fuel, as given in Table 3, with given amounts of different singular hydrocarbons, the influence of that doping could be studied in the energy release. This fuel was prepared with a short paraffin (n-hexane), with a cyclic paraffin (cyclohexane), with a cyclic aromat (p-xylene) and a long paraffin (hexacosane). The three first hydrocarbons are wellknown from the gasoline production, where they are used to control the anti-knocking ability of the fuel. They are easily found in the market and we thought it interesting to investigate their influence in a diesel engine. The paraffin chains of nearly double length could be expected to react more easily than the original fuel, why this combination was of interest. The mixing of the different components are given in Table 4.

As a result of those tests, which are indicated in Fig. 9, 10 and 11, you could find that the fuel prepared with enhexan, cyclohexane and p-xylene, followed the expected development with an increased ignition delay. Figure 9 is an enlargement of the ignition derivate directly giving the different ignition delays compared with the original test fuel, indicated as A. In Fig. 10 and 11 the variations with the different concentrations of hexocosane shows a gradual increase in ignition ability, which proves that the longer paraffin chains are more willing to react than even the basic fuel, containing rather large proportions of hexadecane, which is the normalized fuel for cetane number one hundred.

Through this investigation it is directly proved that, if a heavy fuel and even a residual contains generous amounts of straight paraffin molecules, its ignition ability should be good and the starting-up of the combustion would be secure, irrespective of the remaining part of the fuel.

Heavy Fuels

It is known that heavy fuels of similar viscosity and density will show different behaviour during the combustion. We have exemplified this in three heavy fuels, numbered no 1 to 3, where the viscosity is around 1000 cSt at 15 centigrades and a density between .97 and .98.

The oils are of two different types. HF 1 is a straight run product containing a large percent of paraffins with a lower carbon number of ten, which you see in Fig. 12 where the gas chromatography diagrams are indicated for the

four different fuels. HF2 and 3 are visbreak oils with lower carbon number around 5 and which has a boiling point at 36°C. The concentration of paraffins is far lower, just as visbreaking works in a way to cut off the long straight hydrocarbon chains. HF3 shows a still lower concentration of paraffins in the higher boiling off points. The fourth heavy fuel, HF4, is not an ordinary fuel, but is a product which is left after a catalytic cracking, a so called cycle oil. The characteristic for such a product is high density, low viscosity and cyclic and chain hydrocarbons. At catalytic cracking the straight hydrocarbon chains are broken up to branched ones. This indicates that the reaction willingness will be poor for the remaining part. The different hydrocarbon concentrations and chain forms influence are indicated in the pressure diagrams. The fuel, HF1, which has a highest concentration of paraffins is the one which clearly has the lowest ignition delay. When the number of branching off is increased in HF2 and HF3, their delay in reaction is more and more pronounced. It is from the slow energy release directly visible, that only a minor fraction of the fuel has been well prepared for the oxidation to start (Diagram 13).

In Fig. 15, CO and NO_x concentrations of the different fuels during tests are indicated. To the right in the diagram you have the HF1 fuel which, compared with the normal fuel we are running continuously, gives an increased CO and NO_x concentration. Both those two concentrations are stable. When we go from the basic fuel to HF2 and HF3, we could see that the NO_x concentration increases and then goes down again, and that the CO concentration increases slowly to a more stable value during the full utilization of the fuel in question. The NO_x peaks at the beginning and the end of the test period indicates that when the HF2 and HF3 are mixed with normal fuel they go through a period when the energy release intensities are increased, creating a higher peak pressure and a higher temperature and thus a higher NO_x temperature. But when the final remains of the basic fuel have been utilized and the non-diluted fuel comes into the system, the reaction has disappeared. Even in the short test lay-out for making this emission analysis the variation in the combustion process through mixing different fuels is directly visible.

The catalytical cracking has, compared with the three others, a still longer ignition delay, but when the ignition happens, a very large amount of fuel has been prepared and are close to reaction. The time derivate of the energy release will then be extremely high, which could be easily seen from Fig. 14. The very high concentrated intensity depends on the narrow fraction of hydrocarbons of which the fuel consists, which also indicates that a fuel burning in a normal way should have a certain minimum spread in the sizes of the hydrocarbon chains.

Water Emulsions

It has been said at several occasions that fuel injection or water emulsion would diminish the problems when using heavy fuels. A wisbreak fuel, HF5, has been used as a basis for a test where the emulsion has been created around 12 % water. As could be seen in Diagram 16, the energy release has changed to some extent. The water mixture indicates a quicker starting-up of the energy release and that a larger amount of fuel has been prepared for reaction before the ignition starts. The water emulsion gives a higher first pressure derivate, but without changing the ignition delay. The later part of the combustion seems anyhow not to be too much influenced by the water addition.

CONCLUSIONS

The intention with this report is to prove that it is possible to trace the influence in a given combustion room from variations in the fuel composition. The engine chosen for the investigation is a medium speed engine of a size useful for off-shore used engines, smaller vessels and power generation. The variations could be regarded as small. If you anyhow consider that large variations in most cases are eliminated through development work in laboratories, and that we in the first line are looking for causes, for disturbances in the service, we are looking for influences of a rather small magnitude. If we assume that an engine of the type we have investigated here gives running troubles after one year, we have to consider that one year might be equal to 5000 working hours. In one hour the engine has been running 60 x 750 rpm, which is the same as 22500 combustion processes in the cylinder for every hour. During the 6000 hours running time not less than 135 million working strokes will be experienced. It is obvious that if any disturbance has an accumulating effect, even extremely small variations causing accumulations of any type could be disastrous. That is one of the main considerations why we have tried to keep a very high level of accuracy through the test. The target in the longer perspective would be to find out what is delaying or what is speeding up the reaction so that to a given fuel, simple automatic modifications could be made and/or additives could be given to help the fuel to react in the normal way for which the engine is designed. Even in the slightly longer perspective this approach would indicate what kind of artificial or synthetic fuel should be produced and what kind of hydrocarbon chains then would be preferred.

The work reported here has been carried through with support from the Swedish Board of Technical Development and some assistance from the Swedish Ship-building Association for which support we are most grateful.

Table 1 Description of the experimental motor with brake

Engine type: 4-stroke medium speed direct injected diesel engine built by NOHAB, Sweden, type F10 1970 modified to F20 1982

Number of cylinders	3
Cylinder bore (mm)	250
Piston stroke (mm)	300
Max continuous rating (kW/cyl)	130
Speed (RPM)	750
B mep (MPa)	1.46
Max combustion pressure (MPa)	12.00
Air charging pressure (MPa)	0.15

Turbocharger: BBC VTR 160 WP
Brake: Carl Schenk WS 450 eddy current brake

Table 2 Specification of WRD

boiling point interval	240 - 400°C
boiling point 50%	360 °C
molecule range	$C_{12}H_{24}$ - $C_{32}H_{66}$
average weight of molecule	282
H/C ratio	1.80
composition:	
paraffines	54.5 %
aromatics	21.0 %
naftenes, olefines and others	24.5 %

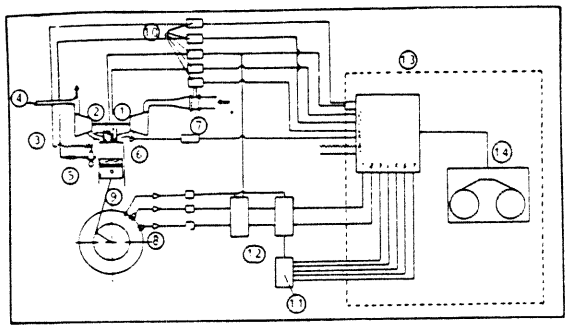

Figure 1. Plan of instrumentation

1 Cyl.press.	8 Crank angle
2 Needle lift	9 Top dead center
3 Delivery line press.	10 Logic unit, signals
4 Exhaust emissions	11 Logic unit,triggpulses
5 Pump rack pos.	12 Logic unit, start/stop
6 Scavenging air press.	13 A/D converter
7 Air flow	14 Tape recorder

Table 3 Specification of testfuel

boiling point interval	213 - 255 °C
boiling point, 50%	227 °C
molecule range	$C_{10}H_8$ - $C_{15}H_{35}$
average weight of molecule	175
H/C ratio	1.92
composition:	
paraffines	56.0 %
aromatics	24.7 %
naftenes, olefines and others	19.3 %

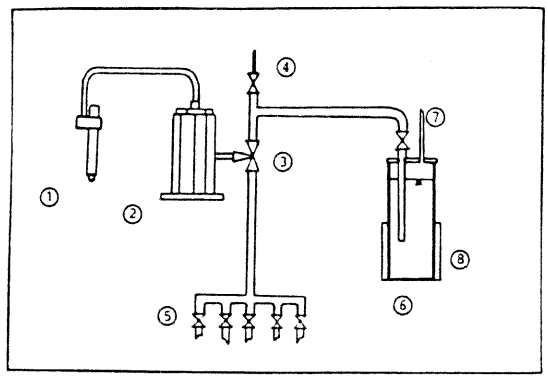

Figure 2. Fuel delivery plan

1. Fuel nozzle	5. Fuel tank conn.
2. Fuel pump	6. Test vessel
3. 3-way valve	7. Conn. for pressuriz.
4. Air vent	8. Heating tape

Table 4 Testfuel

A	Testfuel		
B	Testfuel	+ 10 %	n-hexan, C_6H_{14}
C	Testfuel	+ 10 %	cyklohexan, C_6H_{12}
D	Testfuel	+ 10 %	p-xylen, C_8H_{12}
G	Testfuel	+ 5 %	($C_{26}H_{54}$ - $C_{27}H_{56}$)
H	Testfuel	+ 10 %	(- " -)
I	Testfuel	+ 25 %	(- " -)
J	Testfuel		

Fuel A-D charge air temperature 35°C

Fuel G-J charge air temperature 20°C

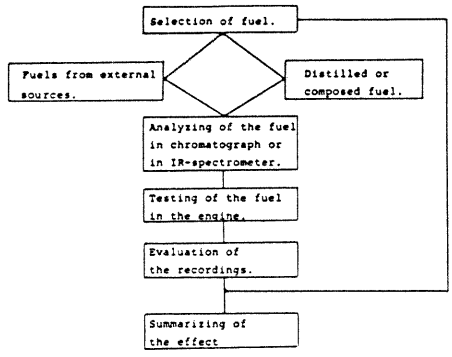

Figure 3. Plan of test procedure

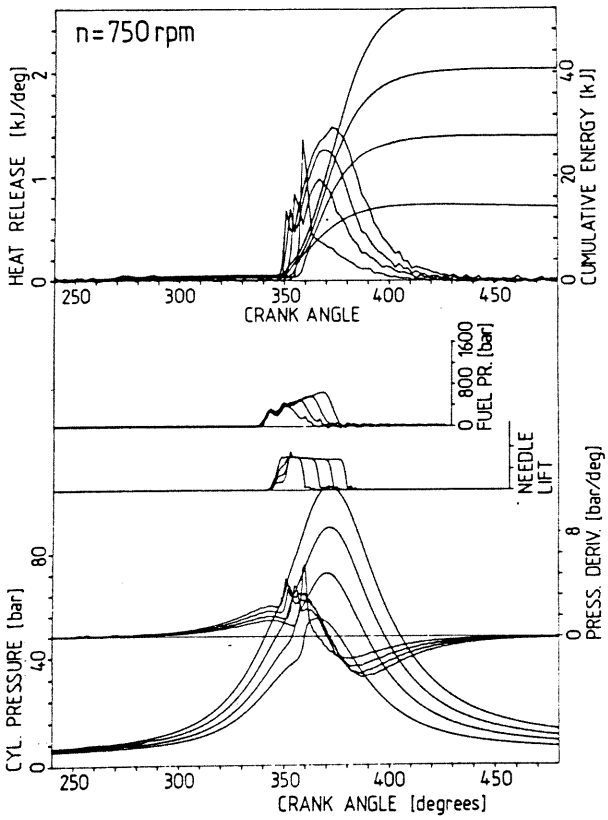

Figure 4. Load sequence, 25,50,75 and 100% load

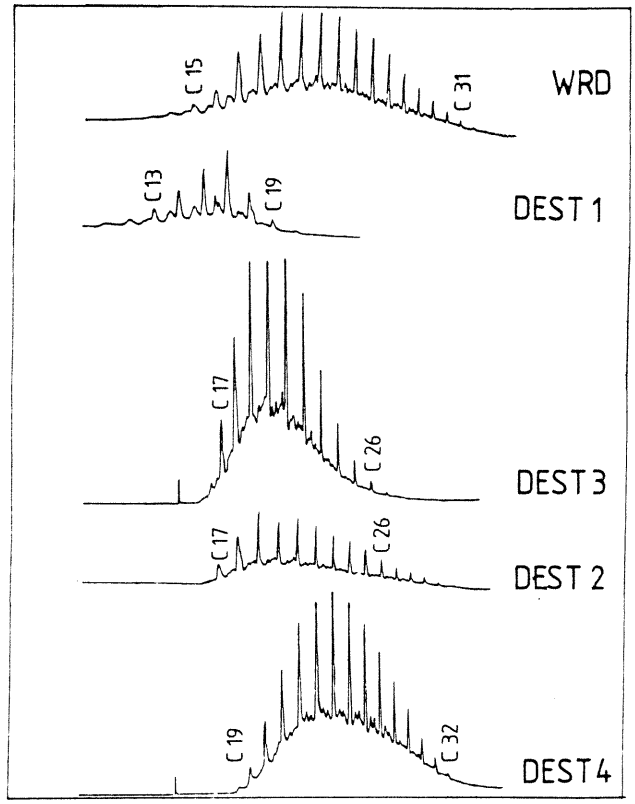

Figure 6. Chromatograms of WRD and its fractions

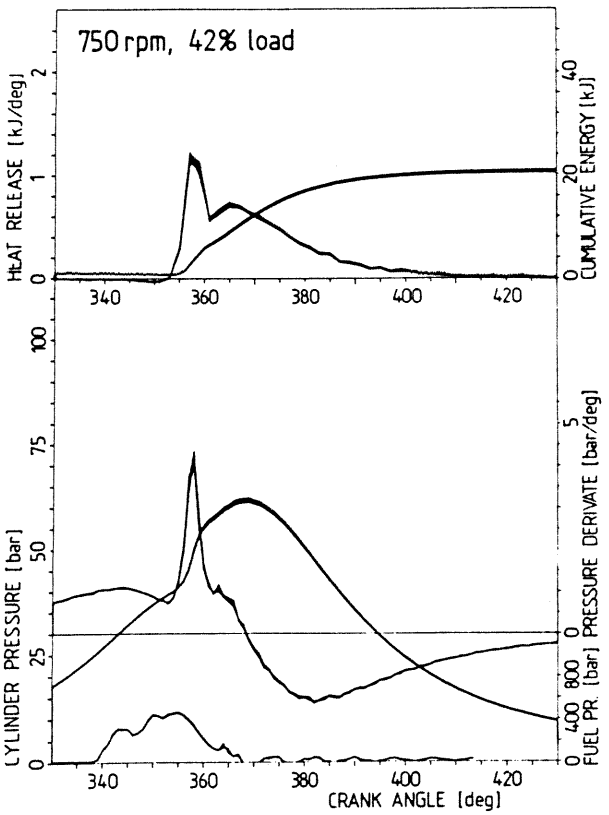

Figure 5. Confidence test. 7 runs in 1 hour.

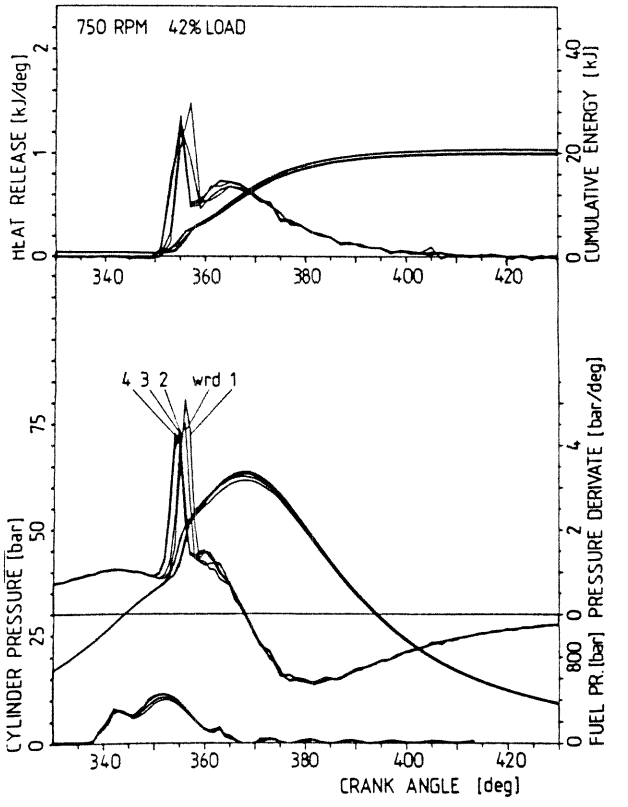

Figure 7. Pressure development and energy release of WRD and its fractions

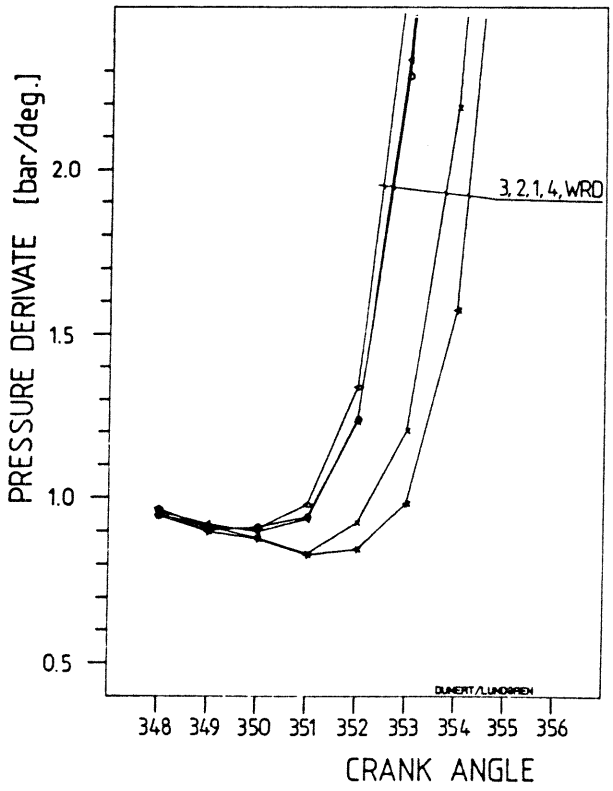

Figure 8. Pressure derivate of WRD and its fractions around the ignition point

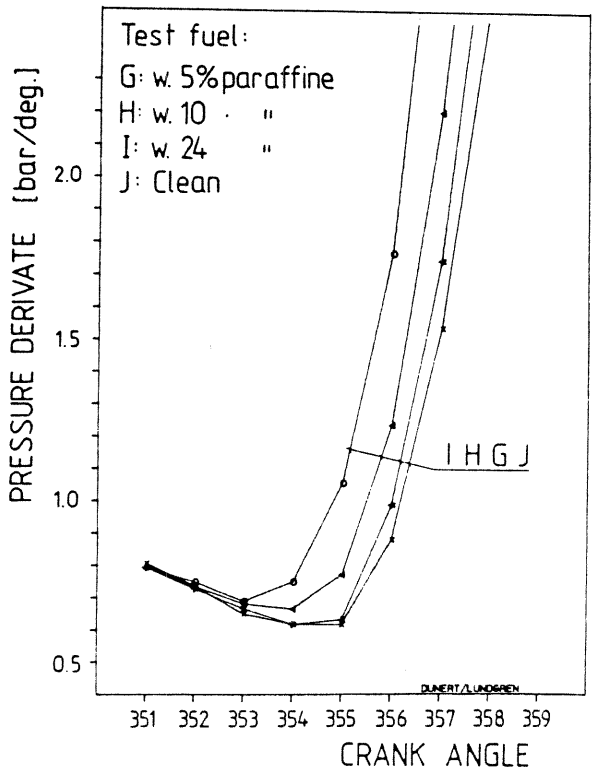

Figure 9. Pressure derivate around the ignition point

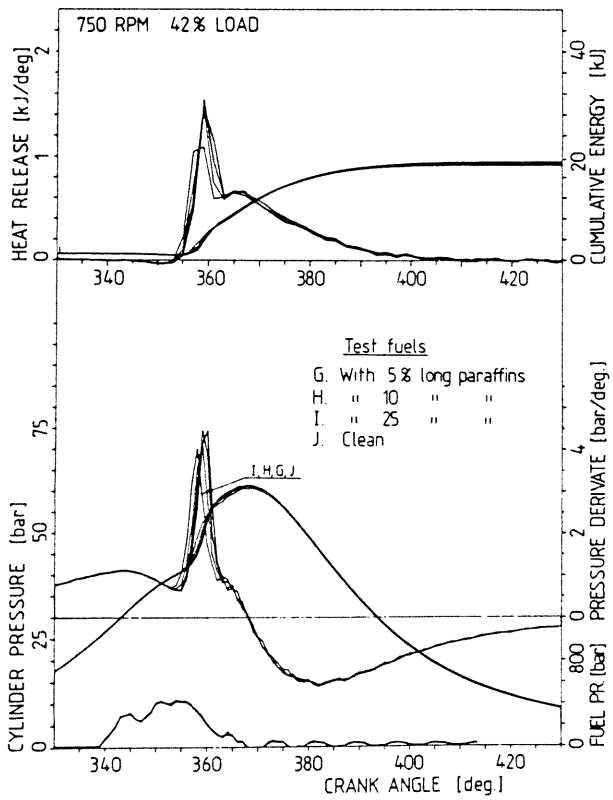

Figure 10. Pressure development and energy release for prepared test fuels

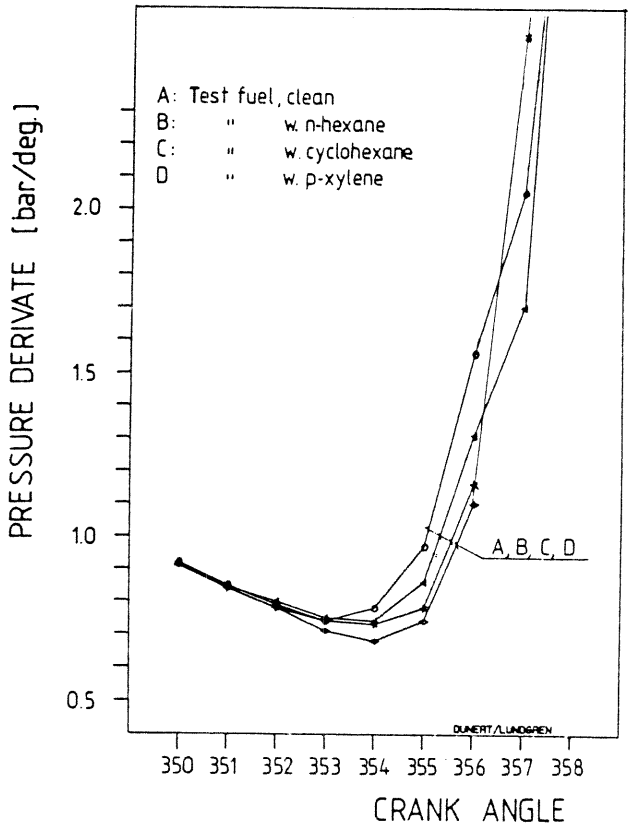

Figure 11. Pressure derivate around the ignition point

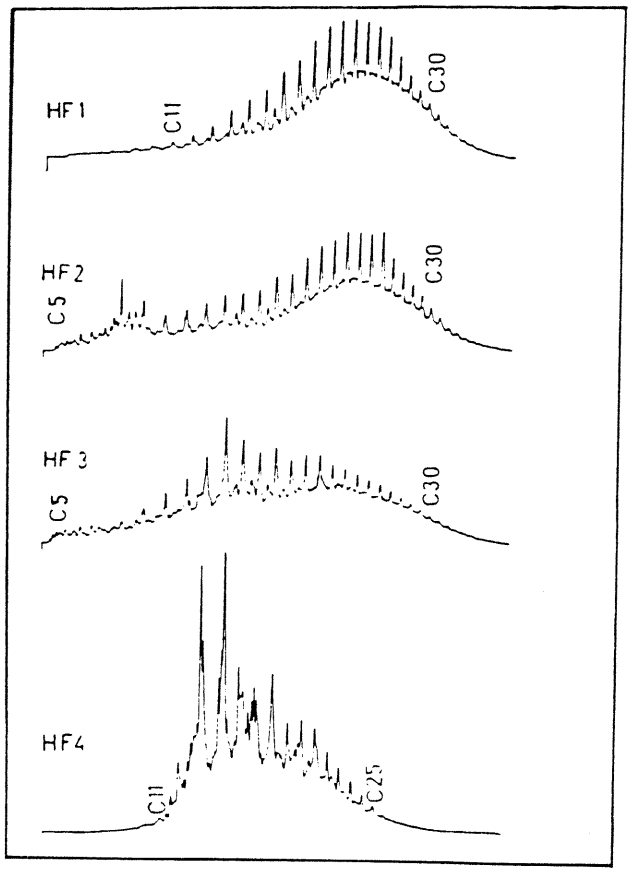

Figure 12. Chromatograms for heavy fuel HF1-4. Every peak designate a certain hydrocarbon

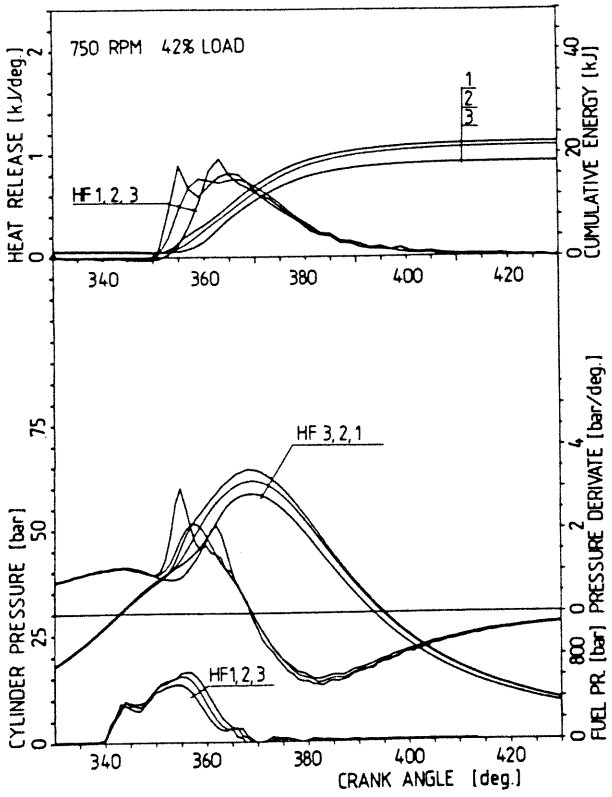

Figure 13. Pressure development and energy release for HF1 - HF3

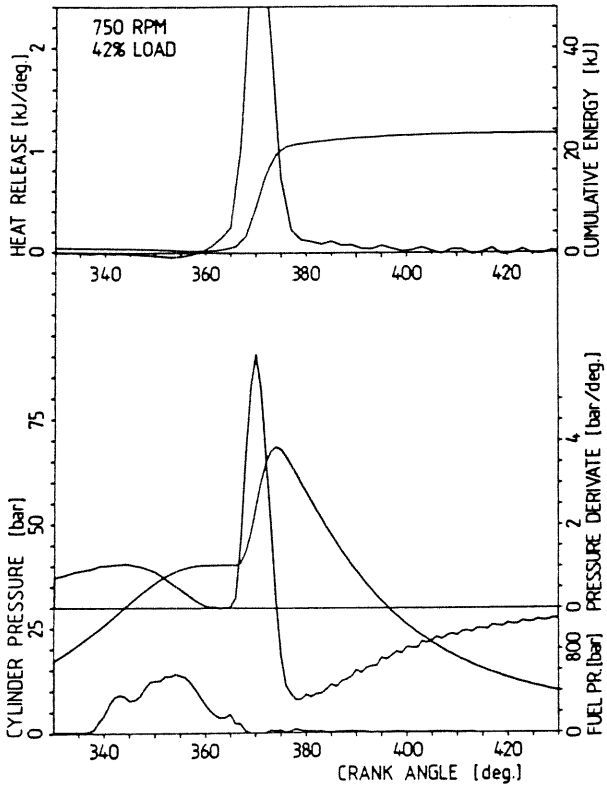

Figure 14. Pressure development and energy release for HF4

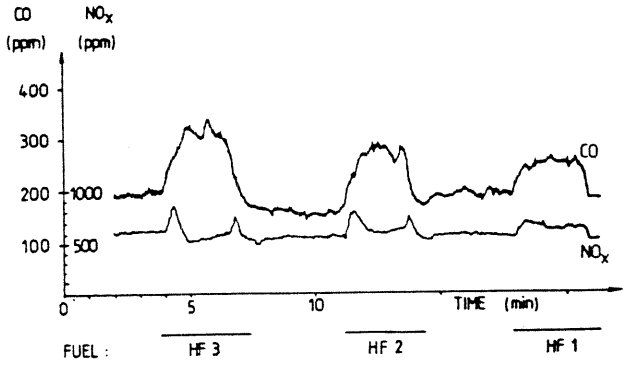

Figure 15. Emission graph for HF1 - HF3

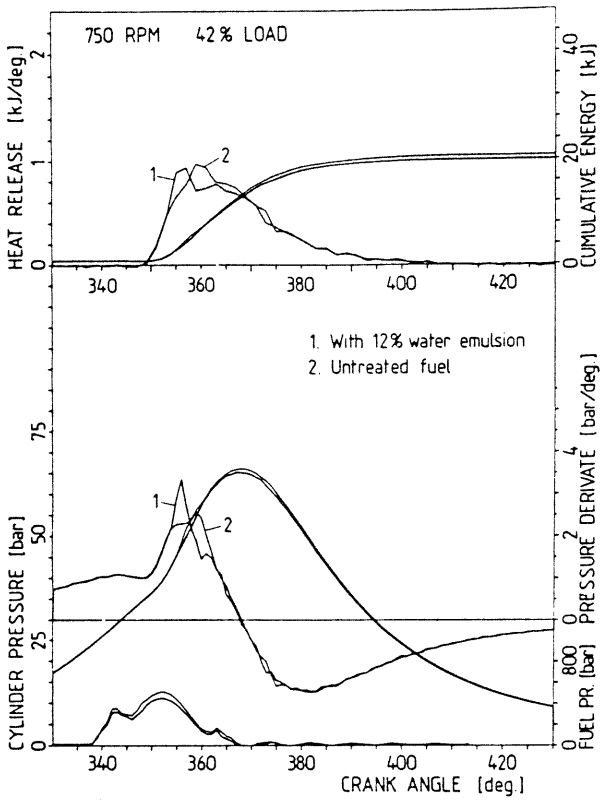

Figure 16. Pressure development and energy release for a visbreaked fuel