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TRANSACTIONS (TM)

COMBUSTION STUDIES AND ENDURANCE TESTS ON LOW IGNITION QUALITY FUEL OILS

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Combustion Studies and Endurance Tests on Low Ignition Quality Fuel Oils

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SYNOPSIS

Fuel oil quality, in particular heavy fuel oil, but also distillate fuel oil and marine diesel oil, has deteriorated considerably with time. The main reason for this is the increased use of secondary refining processes. Present fuel specification standards and some proposed standards give ample scope for further deterioration. It has been evident for some time that fuel oils with lower ignition quality are entering the market. Early tests indicated that fuels with low ignition quality could cause severe damage unless engines were modified to reduce for example ignition delay. In order to assess the situation and find designs suitable for future fuels with even lower ignition quality, a series of tests was run on two engine types. One of the engines has a bore of 320 mm and a maximum speed of 800 rev/min, the other 220 mm and 1200 rev/min. A range of fuels with different ignition quality, ie with CCAI values from 840 to 950, presuming that CCAI is an indicator of fuel oil ignition quality, was used. The effect the different test oils had on the combustion process in general and on the ignition delay and pressure rise ratio in particular was studied using a fully computerised measuring system in combination with software developed for the purpose. The test results indicate that engines having load-dependent temperature-control systems are fully capable of efficiently burning fuel oils with CCAI numbers up to 875 with few or no difficulties. With refinements to the temperature-control and fuel-injection systems the limit can be pushed upwards. Designs for fuels having CCAI numbers in the region of 900 and above are more complicated, but available when and if they are needed.

BACKGROUND

In the late 1970s and early 1980s the main emphasis in our diesel engine development testing was on securing reliable operation under all operating conditions on fuels with high viscosity and density and with high carbon residue, asphaltene, sulphur, vanadium and sodium content.

A systematic and continuous analysis of the predicted changes in refinery processes and of fuel oil blending practices combined with a continuous follow-up of characteristics of fuel delivered is used to assess the present situation and to predict future changes. A valuable source to back up information from other more sporadic publications, from oil companies and from installations has been Ref. 1.

From 1982 on it was possible to trace a trend towards density/viscosity ratios providing reduced ignition quality when determined with the Shell CCAI formula. In some bunker ports very high density/viscosity ratios were occasionally reported.

It had also become evident that aromatic diluents have to be used for the viscosity adjustment of thermally cracked residues in order to get a stable blend. In fact, at least one oil company had already pointed this out in 1977. It has also long been known that aromatics have low ignition quality.

Publication of the CCAI formula in 1983[2] linked this knowledge to the generally available density and viscosity values and has proven adequate for the ranking of the ignition quality of heavy fuel oils. One weak point for practical use is the sensitivity to error in the determination of density. Other methods for the ranking of ignition quality published later[3,4] either do not add much to the accuracy or are far more complicated.

H. Sjöberg was awarded the degree of Technician (Mechanical Engineering) by the Vasa Technical School in 1957. In the same year he joined the Wärtsilä Vasa factory, working first in the Production Engine Test Department and then in the New Design Department. In 1959 he was appointed Manager of the Diesel Laboratory, a position he still holds. Mr Sjöberg has been responsible for the development testing of five new diesel engine types.

FUEL STANDARDS AND QUALITY RECOMMENDATIONS

The BS MA 100:1982, the recently published CIMAC recommendations regarding requirements for heavy fuels for diesel engines (1986) and the ISO proposed fuel grades (1983) all recognise the need to determine the ignition quality, but have not included it because of the lack of a suitable method.

The above standard, recommendation and proposal contain fuel grades with ample scope for density/viscosity ratios

Table I: CCAI for different heavy fuel grades

BS	*CIMAC*	*ISO*	*Maximum* *Viscosity* (cSt at 50 °C)	 *Density* (kg / m^3)	*CCAI*
M8	H45	RMH 45	500	991	850
	K45		500	1010	869
M9	H55	RMH 45	700	991	846
	K55		700	1010	865
M7	H35	RMH 35	380	991	852
	K35		380	1010	871
M6	F25	RMF 25	180	991	861
M5	D15	RMD 15	80	991	871
			50	991	878
M4	B10	RMB 10	40	991	881
	A10	RMA 10	40	975	865

The CCAI value has been calculated on maximum viscosity and maximum density for each fuel grade, but if for example a M5, D15, RMD15 is delivered with maximum density and a lower viscosity, say 50 cSt at 50 °C instead of the maximum 80 cSt at 50 °C, the CCAI value would rise from 871 to 878.

giving high to very high CCAI numbers (see Table I). It is worth noting that one of the distillate fuel grades covered by ISO also allows very high density/viscosity ratios and consequently a high CCAI value (see Table II). The possibility of degradation in the quality of marine diesel fuels in general is illustrated in Table III.

Table II: Distillate fuels

BS	*ISO*	*Maximum Viscosity* (cSt at / 50 °C)	*Maximum Density* (kg / m^3)	*CCAI*
	DM-A	4.7	900	837
		(1.3)	900	887
M2	DM-B	8.4	900	822
M3	DM-C	10.4	920	836

ISO DM-A, if delivered with maximum density and minimum viscosity, would produce a high CCAI value.

Table III: Comparison between 1970 and 1982 standards

Property		*BS 2869: 1970 B 2*	*BS MA 100: 1982 M 3*
Density at 15 °C (kg / l)	max		0.920
Viscosity at 40 °C (cSt)	max	13	14
Conradson carbon (% by mass)	max	1.2	2.5
Flash point closed (°C)	min	66	60
Water (% by vol)	max	0.25	0.30
Sediment (% by mass)	max	0.05	
Ash (% by mass)	max	0.02	0.05
Sulphur (% by mass)	max	1.8	2.0

This comparison between the 1970 and 1982 British standards for two similar fuels shows that the scope for quality deterioration has increased. Maximum CCR and ash have more than doubled. Maximum density in M3 is set sufficiently high to accommodate cat cracked distillates (cycle oils). BS Class B2 was widely used as a norm for marine diesel oil quality in the 1970s.

Table IV: Test fuel oils

Fuel	*Viscosity* (cSt at 50 °C)	*Density* (kg / l at 15 °C)	*CCAI*
E-POR I	753	0.9828	837
POR 650	680	0.9850	840
	660	0.9878	844
E-POR III	608	1.014	871
	809	1.005	859
	665	1.010	866
Shell SFF-7	670	1.007	863
	882	1.017	870
	746	1.017	872
SL 50	546	1.033	891
EP 85	181	1.024	893
E-POR IV	155	1.014	885
	212	1.039	907
	173	1.026	896
SL 80	350	1.060	922
	384	1.050	911
CCS	143	1.078	950

Some fuels of nominally the same grade were deilvered in several batches having different properties. The SSF 7 was analysed at two different laboratories. The first values were obtained from Shell.

DETERMINING THE LIMITS FOR ACCEPTABLE IGNITION QUALITY

None of the organizations that have published the various methods for determining fuel oil ignition quality have defined acceptable limits. This has been considered the task of engine manufacturers, and rightly so.

Wärtsilä Diesel considers it necessary for their diesel engines to be capable of running trouble-free on all 'normal' fuels available in the market place, but also to be able to digest considerable deviations from 'normal' with the basic design, and even extreme deviations from 'normal' without serious breakdowns with automatic or manual changes to systems and/or engine operation parameters.

Engine users should be informed about possible limitations.

Although Wärtsilä Diesel takes an active part in more general and scientific research projects ('Engine damage criteria', Nordforsk; 'Heavy fuel utilization project', Nordforsk; 'Combustion of residual fuel oils', AERE Harwell; 'Assessment of residual fuels', Lloyd's Register of Shipping, and some smaller projects), it has proved necessary because of the sometimes substantial and rapid changes in fuel quality to do some less scientific research, where the aim has been to find engine specific approaches quickly.

After some sporadic tests on fuels with different ignition qualities (as determined by the CCAI value) in 1983, and with reference to some experience from installations, the diagram in Fig. 1 was made available to our customers together with some recommendations. Some of the comments given to customers together with this diagram are as follows: 'For engines without pre-heating before starting, and with cooling systems without a temperature increase at low loads, CCAI levels above 830 should be avoided. Misfiring and rough

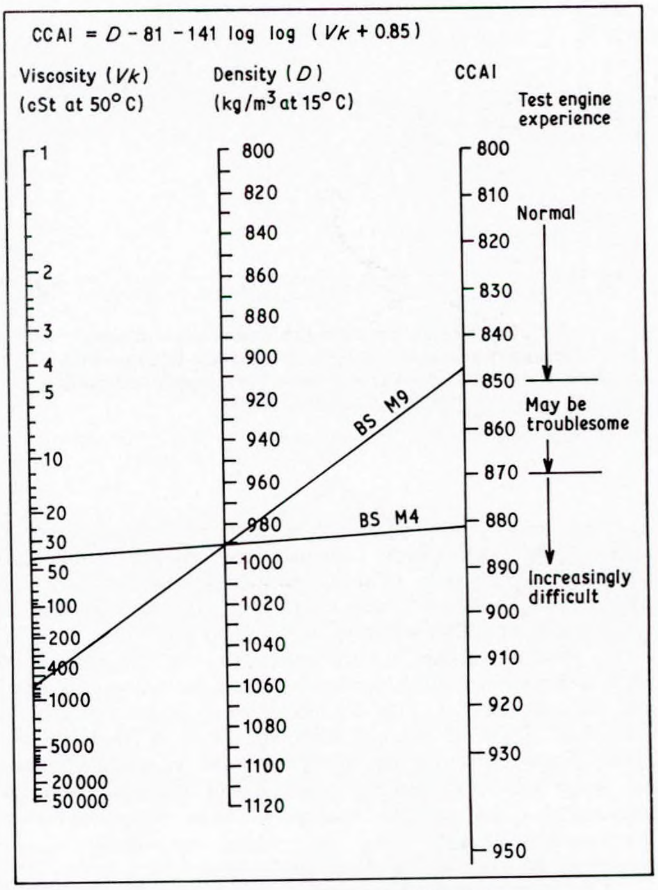

FIG. 1: Diagram made available to Wärtsilä customers in 1983

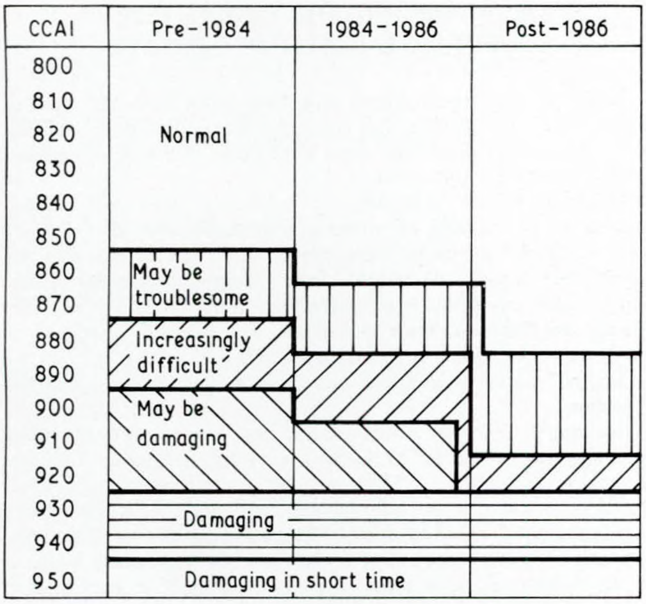

FIG. 2: Current and predicted response of Wärtsilä Vasa 22HF to the fuel oil CCAI value

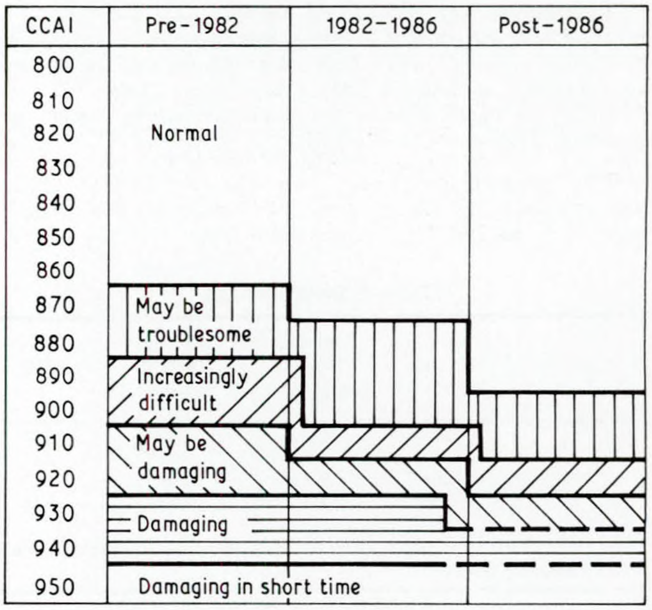

FIG. 3: Current and predicted response of Wärtsilä Vasa 32 to the fuel oil CCAI value. Vasa 32 is less sensitive than Vasa 22HF. Test results indicate that there is potential, if and when needed, for further improving the Vasa 22HF

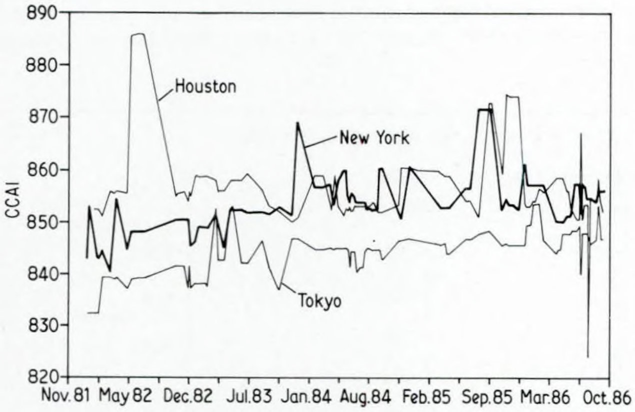

FIG. 4: CCAI values of fuels from Tokyo (steady increase), Houston (generally between 850 and 860 with occasional peaks) and New York (approaching 860 with occasional peaks).

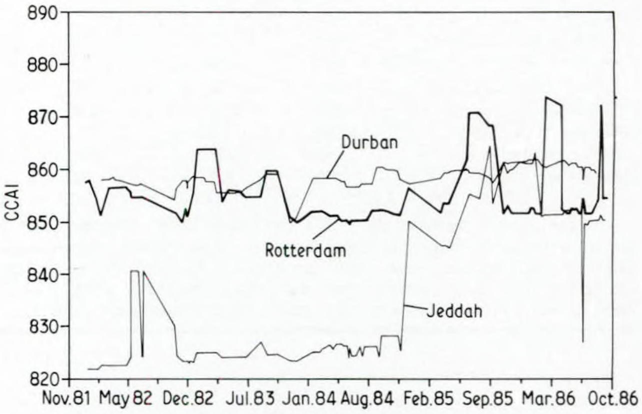

FIG. 5: CCAI values of fuels from Jeddah (820-830 with some peaks until 1984 when a jump to 850-860 occured), Durban (slowly increasing at the 860 level) and Rotterdam (generally between 850 and 860 but lately some peaks above 870)

operation may otherwise occur at low inlet air temperature and/or low raw water temperatures during start and idling'...'Engines with efficient pre-heating before start and with a load-dependent temperature-control system may operate satisfactorily on fuels with CCAI values up to 870.'

In 1984 and 1985 a more systematic test programme on fuels with different CCAI values was run on two engine types and the diagrams in Figs 2 and 3 were made available to customers. Some of the test fuels are listed in Table IV. E-POR IV was chosen as the fuel for a series of endurance tests run under different operating conditions in order to assess the situation and find designs usable for future fuels with even lower ignition quality. Such fuels appear sporadically on the market, as indicated in Figs 4 and 5.

A fully computerised measuring system like that in Fig. 6 was used in combination with in-house software developed for the purpose.

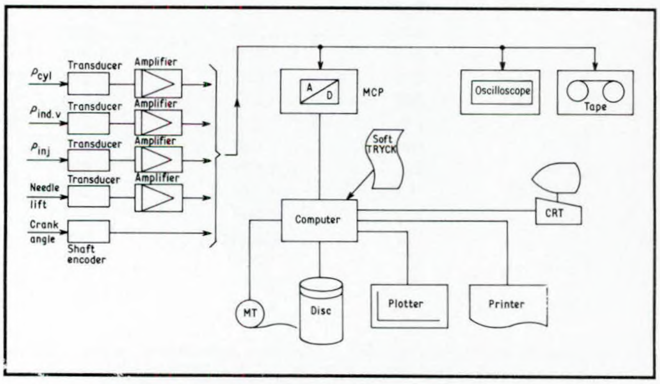

FIG. 6: Layout of measuring system used for combustion studies

SPECIFICATION OF MEASURING AND DATA ACQUISITION EQUIPMENT

Transducers

The following transducers were used: piezoelectric Kistler type 6001 (p_{cyl}, $p_{ind.v}$) including cooling adapters with the cylinder pressure transducer flush with combustion chamber wall; piezoelectric Kistler type 6201 (p_{inj}); inductive display transducer (needle lift); and an optical shaft encoder, Leine & Linde type 6306, 360 pulses/rev + reference mark (crank angle).

Amplifiers

A Kistler type 5001 charge amplifier with a Vibrometer type 100-TR1/A 100 kHz carrier frequency bridge.

Data acquisition

This was conducted using a Hewlett–Packard type HP 2250 measuring and control processor, a Hewlett–Packard HP 1000M, including peripherals (disc, MT-unit, CTR, etc.), and the Wärtsilä Vasa Factory program TRYCK for data acquisition, analysing and post-processing.

Other instruments

These included a Tektronix type 7623A (signal monitoring) oscilloscope and a Racal type Store 7DS (analogue, safety-copy) tape recorder.

Test engines

One 12V22HF and one 4R32 engine were used.

Engine characteristics, Wärtsilä Vasa 22HF

Cylinder bore	220 mm
Piston stroke	240 mm
Rated speed	900-1200 rev/min
Rated load	145-175 kW/cyl
Cylinder numbers	4, 6, 8 in-line 8, 12, 16 Vee
Fuel spec.	BS MA 100:1982 Class M9

Engine characteristics, Wärtsilä Vasa 32

Cylinder bore	320 mm
Piston stoke	350 mm
Rated speed	720-800 rev/min
Rated load	405-410 kW/cyl
Cylinder numbers	4, 6, 8, 9 in-line 12, 16, 18 Vee
Fuel spec.	BS MA 100:1982 Class M9

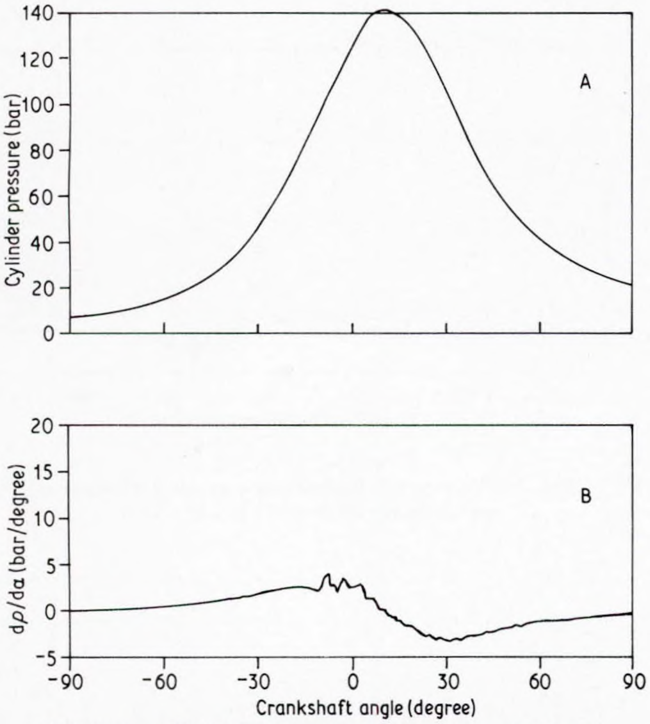

FIG. 7: Vasa 32. The combustion process is smooth at rated load and speed on POR 650 (CCAI ≈ 840)

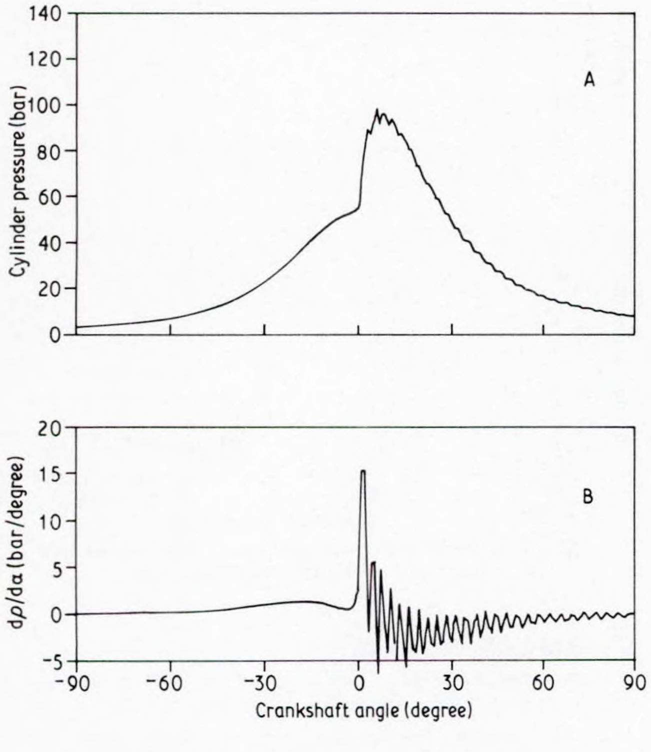

FIG. 8: Vasa 32. E-POR IV reveals its nature at part load. Combustion is rough and dp/dα is high

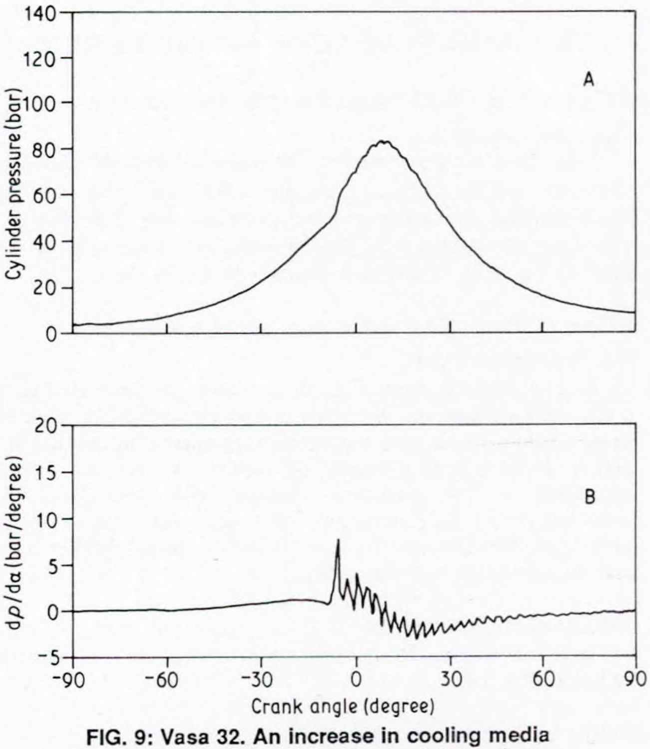

FIG. 9: Vasa 32. An increase in cooling media temperature induced by the load-dependent temperature-control system improves ignition and combustion of E-POR IV at part load

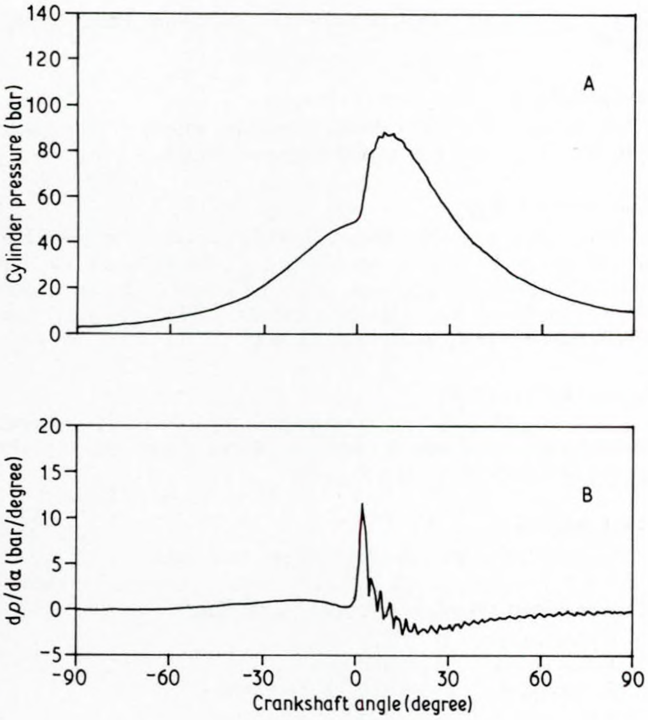

FIG. 10: Vasa 22HF. Performance at rated speed and part load on POR 650 (CCAI ≈ 840)

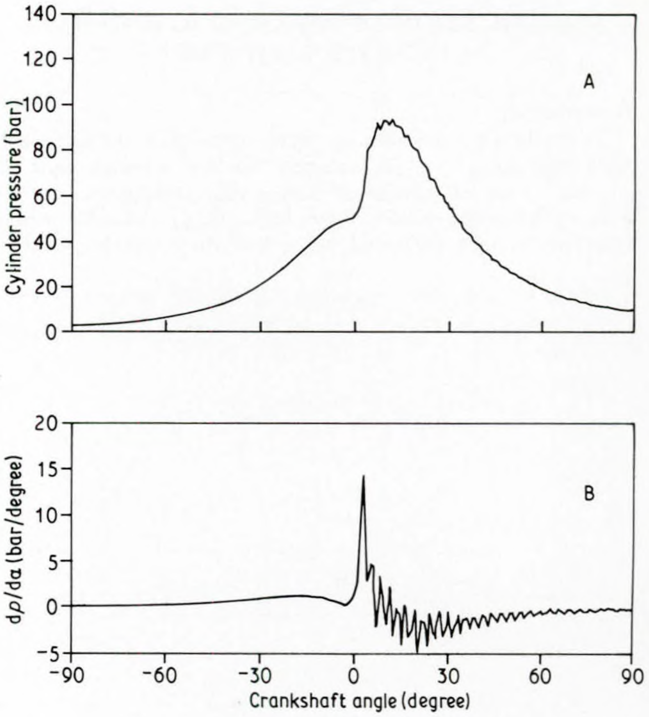

FIG. 11: Vasa 22HF. Performance at rated speed and part load on Shell SSF7 (CCAI ≈ 870)

TEST RESULTS

Combustion studies

Figures 7 to 12 give examples of diagrams obtained with the measuring and data acquisition system described in Fig. 6. Figures 10-12 show the behaviour of three different fuels at part load in a 12V22HF engine.

EVALUATION OF SOME OF THE RESULTS

Effect of the CCAI value on cylinder pressure rise ratio (dp/dα)

There is a clear correlation between an increased CCAI and increased dp/dα, both at constant speed (see Fig. 13) and when running according to the propeller law (see Fig. 14). The level of dp/dα is higher at very low load than at high load but the slope of the curve remains about the same.

Effect of the CCAI value and ignition delay on the expansion curve

As can be seen from Fig. 15 (cylinder pressure at different crankshaft positions), the fuels with higher CCAI generally cause higher maximum combustion pressures in particular at partial loads. The pressure difference is less at 30 and negligible at 60 crankshaft degrees after the TDC. The conclusion is that none of the test fuels used caused prolonged combustion in spite of quite large differences in ignition quality and ignition delay.

Effect of engine speed

Reduced engine speed does not reduce the pressure rise ratio (see Fig. 16).

Effect of increased cooling media temperatures

The effect of increased charge air, cooling water and piston cooling oil temperature on ignition delay when running on low ignition quality fuels is very marked (see Fig. 17).

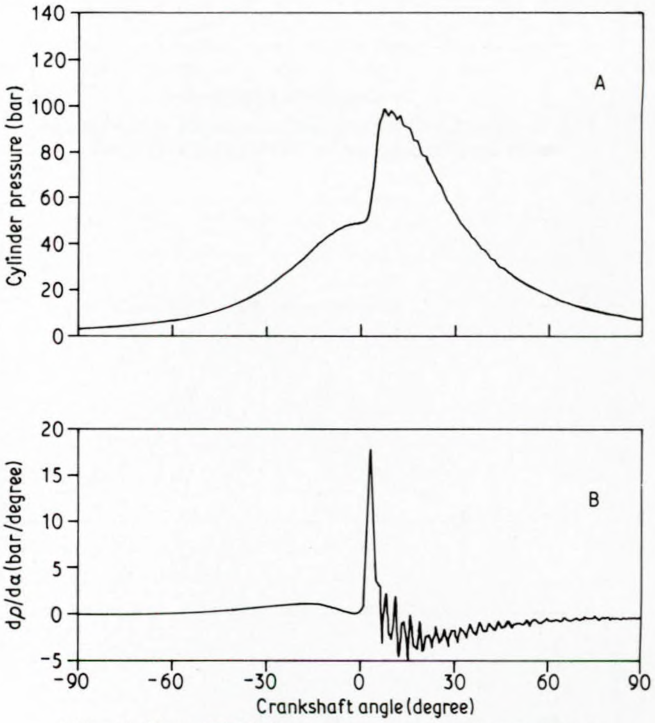

FIG. 12: Vasa 22HF. Performance at rated speed and part load on E-POR IV (CCAI ≈ 900)

Cycle-to-cycle variations

Low ignition quality fuels appear to cause considerably bigger cycle-to-cycle variations than 'normal' fuels (see Fig. 18). The cycles having the highest dp/dα may be the damaging ones. The 'one shot' approach (oscilloscope + camera) may be very misleading as may a consistent mean value approach.

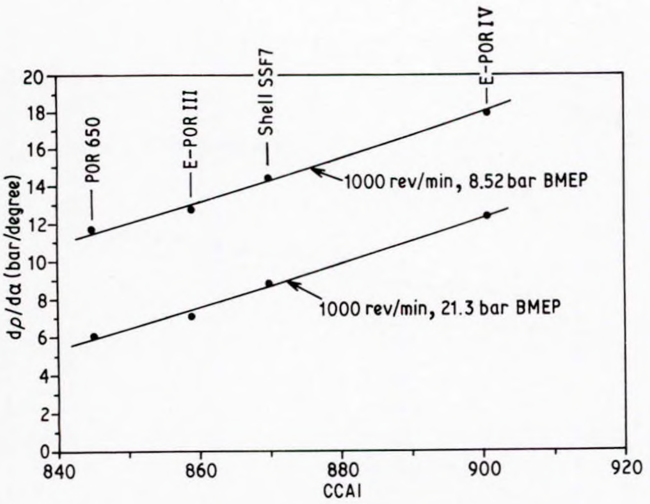

FIG. 13: Vasa 12V22HF, constant speed 1000 rev/min, $dp/d\alpha = f(\text{CCAI})$ at 21.3 and 8.5 bar

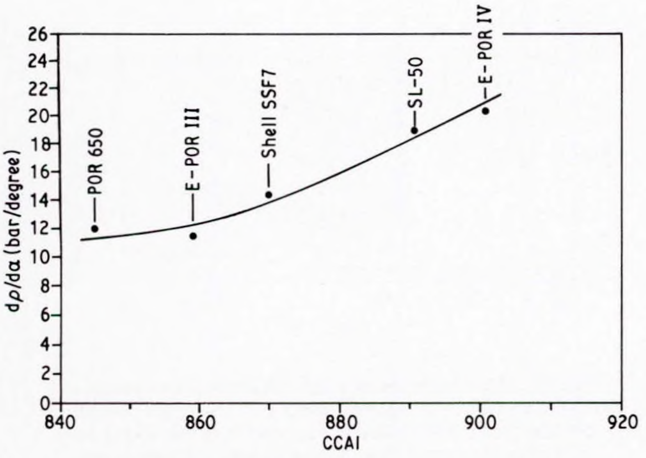

FIG. 14: Vasa 12V22HF, propeller law, 34% load, $dp/d\alpha = f(\text{CCAI})$ at 700 rev/min and 10.4 bar BMEP

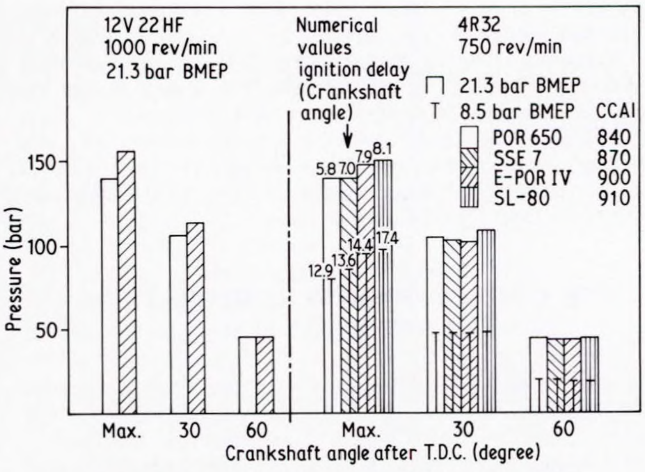

FIG. 15: Cylinder pressure at different crankshaft positions. There is no difference in combustion pressure at 60 crankshaft degrees after the TDC

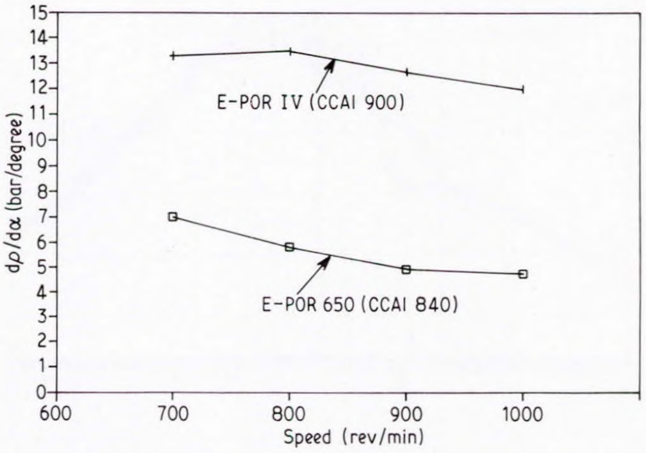

FIG. 16: Vasa 12V22HF, $dp/d\alpha = f(\text{speed})$ at constant fuel rack position, BMEP = 21.3 bar at 1000 rev/min

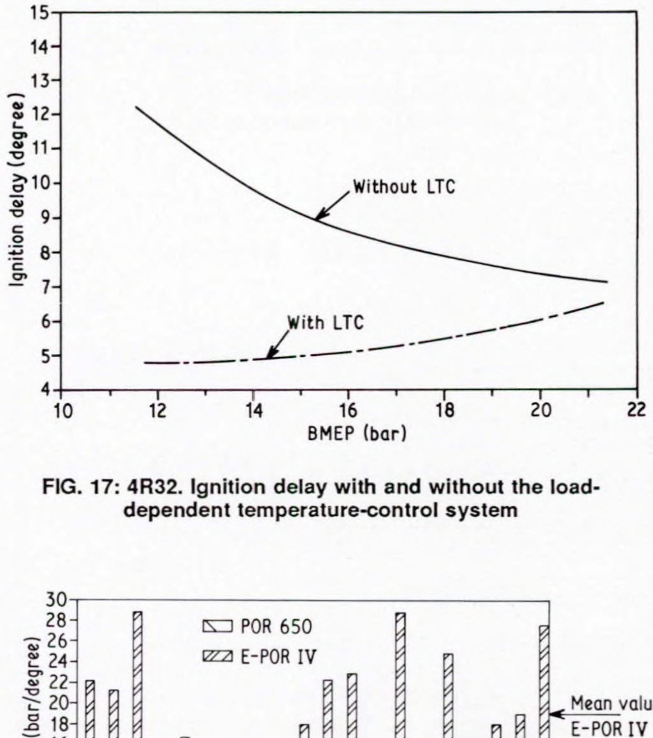

FIG. 17: 4R32. Ignition delay with and without the load-dependent temperature-control system

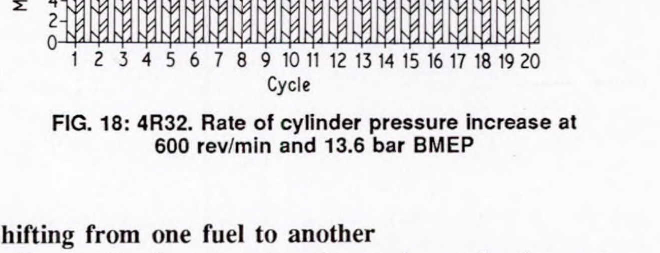

FIG. 18: 4R32. Rate of cylinder pressure increase at 600 rev/min and 13.6 bar BMEP

Shifting from one fuel to another

Figure 19 illustrates the change in combustion pattern when shifting from POR 650 to E-POR IV.

Starting difficulties

The test fuel SL 50 with a CCAI of 890 caused starting problems with the 220 mm bore engine, but these were overcome by increased pre-heating of the engine. With the 320 mm bore engine similar difficulties appeared using SL 80

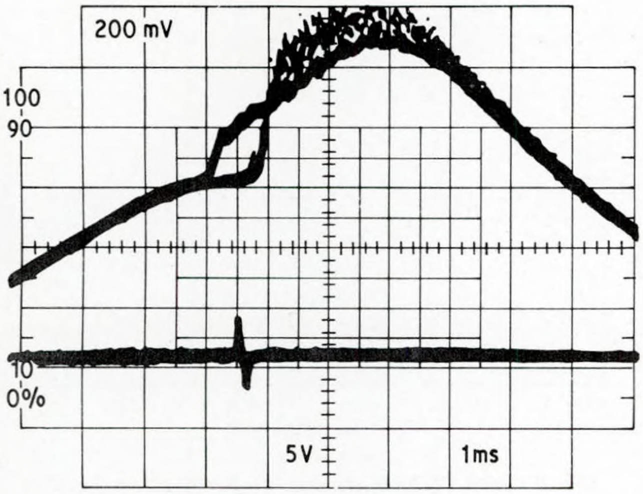

FIG. 19: Effect of shifting from POR 650 to E-POR IV

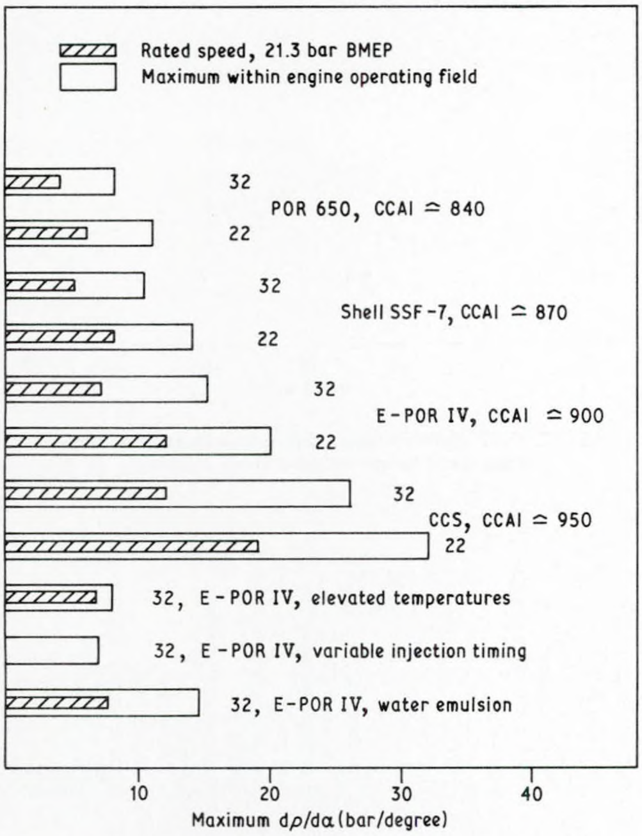

FIG. 20: Rate of cylinder pressure increase with different fuels and operating conditions

fuel with a CCAI of 911. None of the engines could be started using the CCS with a CCAI of 950.

DAMAGE

In endurance tests broken piston rings were experienced with fuels having CCAI values of 900 and above. The CCS fuel, CCAI 950, damaged cylinder components in a matter of hours.

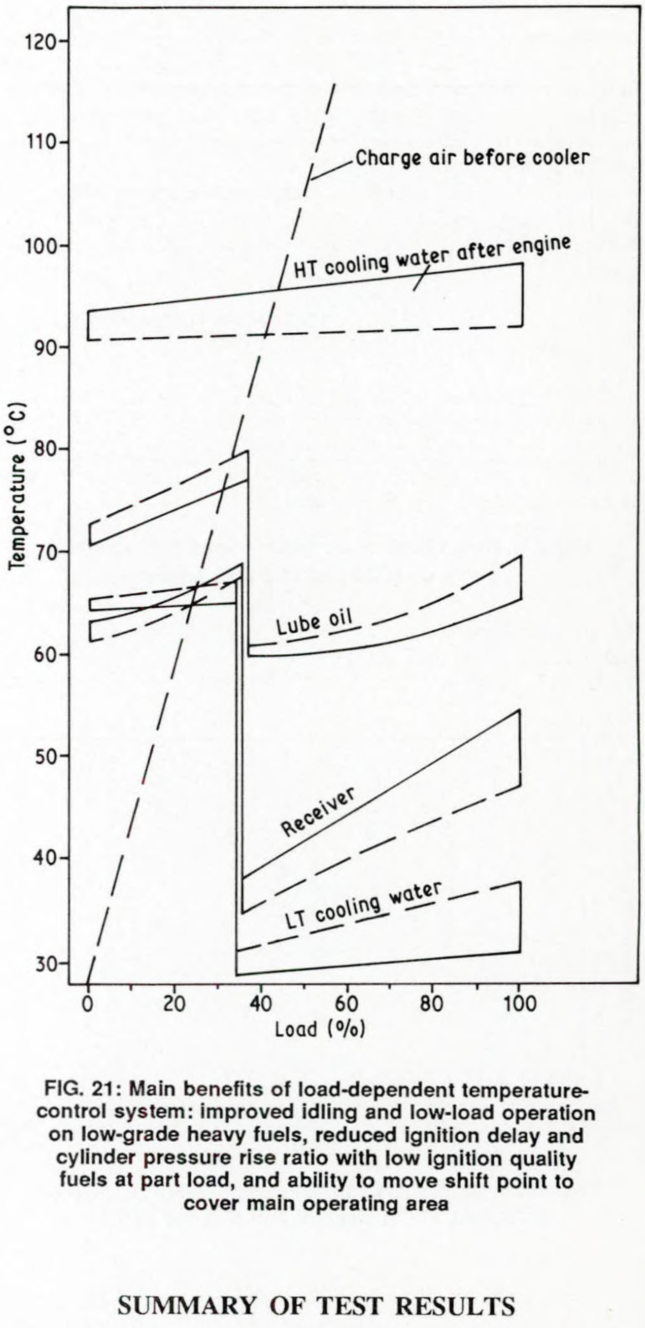

FIG. 21: Main benefits of load-dependent temperature-control system: improved idling and low-load operation on low-grade heavy fuels, reduced ignition delay and cylinder pressure rise ratio with low ignition quality fuels at part load, and ability to move shift point to cover main operating area

SUMMARY OF TEST RESULTS

Figure 20 gives a general and qualitative summary of some of the test results. It may appear that the smaller engine is less tolerant to low ignition quality. This is not because a smaller engine per se is less tolerant. The reason is that the smaller engine and its systems were less developed to digest low ignition quality fuels at the time the tests were run. The difference between the two engines has in fact provided valuable information about possible ways to improve the ability to digest low ignition quality fuels.

THE LOAD-DEPENDENT TEMPERATURE-CONTROL SYSTEM

Wärtsilä Diesel was confronted with the need to improve fuel ignition in diesel engines in the early 1960s. At that time the embryo of the present load-dependent temperature-control system (LTC) was formed, the aim being to secure reliable starting and low-load operation on icebreaker engines with the combustion and scavenge air supply from outside the engine room. Then it was not the low ignition quality of the fuel but the sub-zero inlet air temperatures resulting in low compression end temperatures that called for improvement.

At the end of the 1970s when a marked reduction in heavy fuel quality occurred because of the increased use of secondary refining processes (cracking), the LTC was further developed and refined in order to secure efficient low-load operation on low-grade heavy fuels.

The LTC has proved an efficient tool for reducing the potential problems when burning low ignition quality fuels. Figure 21 shows the function of the simplest variant of the system.

CONCLUSIONS

The CCAI is a simple and sufficiently accurate tool for the evaluation of heavy fuel oil ignition quality. Engines must be able by basic design and by automatic or manual changes to systems and/or engine operation parameters to cope with rather large deviations from 'normal' fuel quality parameters, as such deviations occur in bunkers sporadically and with unpredictable frequency

An automatic load-dependent temperature-control system that as far as possible maintains high-load thermal conditions at all loads and speeds solves most of the problems with rather low ignition quality fuels.

If and when a more general reduction in fuel oil ignition quality occurs, there are means available to improve operating characteristics, for instance by making changes in the fuel injection system.

ACKNOWLEDGEMENTS

The author is indebted to Wärtsilä Diesel for permission to publish this paper. He also thanks his colleagues in the Product Development Department at the Vasa Factory for their contributions to and assistance in performing the tests and preparing this paper.

The contents of this paper reflect the views of the author and do not necessarily coincide with those of Wärtsilä Diesel.

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Discussion

A. A. WRIGHT (Lloyd's Register of Shipping): The author is to be congratulated on the presentation of a paper which not only extends the range of discussion on the subject of ignition performance from the viewpoint of an engine builder but also provides factual information regarding engine performance.

However, reference to Fig. D1 would indicate that aspects of HFO ignition performance problems have, in essence, been 'designed out' of the current engine types produced by the author's company if a CCAI value of 880 is taken to be the limit of satisfactory operation. Certainly in my experience from the analysis of many thousands of fuel oil samples, combinations of viscosity and density that would give CCAI values in excess of 880 would be extremely rare for fuels supplied as comforming to BSMA 100 Classes M6 to M12 or, less precisely, IFO 180 and above. However, this is far from the case with the lower viscosity grades such as those confoming to the BSMA 100 Class M4 specification. In such cases the imposition of density limitations below those required by fuel treatment equipment may well be the only practical approach.

The test performance results given in the paper add further weight to the use of the CCAI formula as a means of ranking the ignition performance of fuels, particularly the more viscous grades. I would add to this, but at the other end of the fuel grade range, in that it has become clear from my experience of marine gas oils, BSMA 100 Class M2, that a very close relationship between CCAI and the more established ignition characteristics of cetane index, IP 364, exists as shown in Fig D2.

As with all indicators of performance it is often the exceptions which are perhaps of greater interest and the CCAI is no exception. For example, I have experienced two cases of apparent inconsistances with fuels used in slow-speed engines operating under normal conditions and with CCAI values, 855 and 860, as used both before and after the event without difficulty, which caused particular ignition problems in service. I would therefore be most interested to know if the author has any information regarding similar cases of poor ignition performance not indicated by the magnitude of the CCAI value? Furthermore, since a particular CCAI value can be arrived at through widely differing combinations of viscosity and density values it would also be of interest to learn of any variations in performance found with fuels of nominally similar CCAI values but with substantially different density values.

As a further point I would ask the author's, as representing an engine builder, whether he would now consider that the CCAI value, in addition to ranking ignition performance, has been shown to fulfil the stated requirements of the various published and draft marine fuel oil specifications for an ignition performance parameter? In which case it would seem that a CCAI value of 880, which would not be unduly restrictive on current fuel supplies, for the BSMA 100 Classes M6 to M12, for example, would be a reasonable value that could be adotpted for those grades.

Dr G. J. HAWKSLEY (Southampton Institute of Higher Education): I should first like to congratulate the author on a very well presented paper. It represents a great deal of careful, methodical work and I thank him for making this very useful information available.

Peak rate of pressure rise is now beginning ro receive the recognition it deserves. It gives a good indication of rough combustion, engine noise and, as Mr Sjöberg demonstrates, the potential for damage to cylinder components.

Whilst we may appreciate the value of rate of pressure rise as a criterion, its estimation from cylinder pressure diagrams is very difficult. This is partly due to the cycle-by-cycle variations shown in Fig. 18 of the paper. However, the difficulty is compounded by the superimposed ripple over the peak of the cylinder pressure diagrams. These ripples appear to be caused by pressure waves running to-and-fro across the cylinder and their magnitude appears to depend on the violence of the combustion.

Mr Sjöberg's results agree with my own findings that the highest rates of pressure rise are normally associated with part-load operation, at least in high-speed engines. The rate of pressure rise depends, amongst other things, on the pressure and temperature at injection and these are themselves dependent on engine speed and load. It is already very difficult to predict the rate of pressure rise and the introduction of fuel quality as an extra variable makes life more difficult still. Relationships such as Fig. 13 will clearly be very useful in developing mathematical models of the combustion process.

R. J. CLEMENTS (Shell Seatex): I should like to compliment the author on the very clear way in which the has presented a considerable amount of data. As a result, I found his paper most interesting. It is always gratifying when the result of a test programme of this magnitude is so positive and enables engines to accept a wider range of fuels as indicated by Figs 2 and 3.

For Shell, it is also very pleasing that the concept of CCAI, introduced by Messrs Zeelenberg, Fijn van Draat and Barker in their paper to CIMAC in 1983, has been shown to have a positive value to indicate the guidelines for acceptable running of fuels in these engines, now and in the near future.

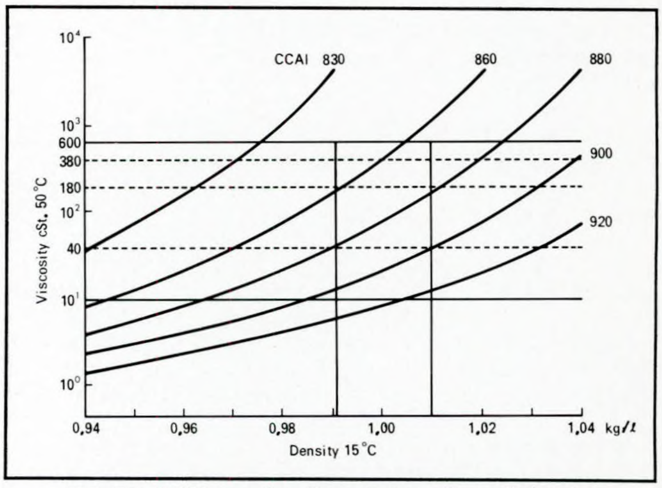

FIG. D1: CCAI as a function of viscosity and density

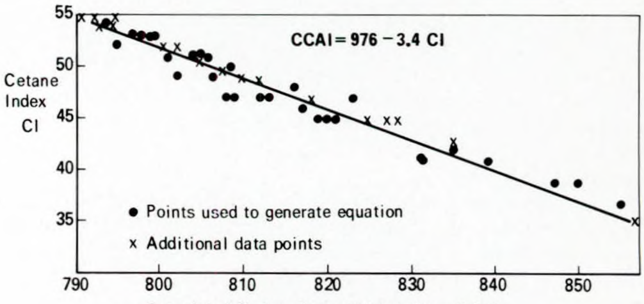

FIG. D2: Relationship between CCAI and CI

Mr Zeelenberg has asked for the following comment to be made on his behalf.

The values of CCAI were not intended to be absolute but are only approximations with a certain spread. It is, however, reassuring that so very few fuels are outside the expectation limits. The very regular correlation between dp/dα, in our terminology the combustion hardness, versus CCAI is better than we experienced, probably due to the use of fuels of a very similar volatility. In the KSLA study we sometimes noticed different behaviour: fuels with similar CCAI but high volatility eveporate more during the ignition delay period resulting in a larger pre-mixed charge and a distinctly higher dp/dα on ignition. Pure residual fuel can be combusted under those conditions without danger.

I should like to present some comments from another colleague Mr Ives who, from the operator's viewpoint, welcomes the use of CCAI by engine manufacturers.

Previous engine trials and energy audits undertaken by Shell Seatex on Shell Group vessels have shown a wide variation in results, attributed in part to different fuel ignition qualities which in turn can be correlated to different CCAI values.

Our own experience indicates that engines respond to CCAI values in different ways depending on the individual engine combustion characteristics and load conditions such as cylinder temperature, cylinder compression ratio and fuel injection parameters. We believe that there may be variations between engines of the same type caused by the above operating conditions which again shows that the use of CCAI can only be an approximation and not an absolute guide.

We would support the comments made by the author concerning the relationship between engine operating parameters and ignition quality and their influence on fuel savings. We have found fuel injection parameters, in particular fuel injection temperature, to be of significant importance in promoting an efficient combustion process. In this respect therefore we would like to ask the author if he has made any studies relating ignition quality to a change in fuel injection viscosity at vaying loads with either normal or high CCAI fuels

Dr G. K. BARNES (BP Research Centre): I should also like to thank the author for presenting an interesting paper. I have a question on the content of the paper, together with a comment on marine fuel ignition quality.

The author suggests, rightly in our opinion, that the onus is on the engine builder to define acceptable limits for the ignition quality of fuels to be used in his engine: this will presumably be based on a maximum rate of pressure rise. Would he therefore care to comment on the maximum rate of pressure rise acceptable in Wärtsilä engines? The inference is ~15 bar/degree from Fig. 14, assuming the maximum CCAI value of 875 quoted in the synopsis.

Since a reference is made to early BP work, it may be of interest to know the latest stage of BP work in this area. In 1984, we published a paper describing the use of a modified CFR engine to measure quality of residual fuel (Ref. 3 in the paper). This parameter is termed ignition number because although the reference fuels used in the procedure are the same as in cetane number measurement of distillate fuels, the engine operating conditions are sightly different. However, the two parameters are essentially the same. We also suggested that a good prediction of ignition number, termed calculated ignition index (CII), could be obtained from density and viscosity.

Since then, we have shown, in collaboration with a major marine engine manufacturer, that the modified CFR engine does rank fuels in the same order as a full size marine engine (the same fuels are currently being investigated by a second major manufacturer). The CFR procedure requires 2 litres of sample and takes ~1 hour to rate: repeatability is ±1 number. We have also further developed the predictive equation to include a viscosity term measured at any temperature (previously, viscosity was required at 100 °C), and validated the equation using over 80 marine service fuels from a variety of sources.

Finally, we have a laboratory technique, based on thermogravimetry/differential thermal analysis (TG/DTA), which has also been shown to correlate well with measured ignition number.

The results of this work are to be the subject of a paper at the forthcoming CIMAC conference.

In summary therefore:

1. BP have a reliable and rapid test method for measuring the ignition quality of residual marine fuel oils using a modified CFR engine. The ignition number value obtained is comparable with distillate fuel cetane number. A reliable procedure is essential for specification purposes, and for rating fuels in cases of dispute.
2. A predictive equation is also available, allowing the calulation of ignition quality from density and viscosity, data readily available to the Chief Engineer.

G. A. WATERS (Gamlen Chemical Co. (UK) Ltd): On page 2 of the paper it is stated that 'for engines without preheating before starting and with cooling systems without a temperature increase at low loads, CCA1 levels above 830 should be avoided. Misfiring and rough operation may occur…'.

First there are very few engines with air preheating at present, although I admit trials with them have been successful, and secondly I have not seen a fuel with a CCA1 below 830 for a very long time. For example, a 'normal' 180 cSt at 50 °C fuel with a density of 0.985 will give a rating of 856. On first assessment these figures would give no cause for concern.

Gamlen Marine have carried out substantiative tests, in both the laboratory and the field, to establish the effects of conditioning fuel with poor combustion characteristics, and have found success in improving both combustion and deposit modification. Have Wärtsilä considered testing treatments?

The paper has relied on one method of determining combustion quality. There are others which contribute to the overall picture, and although they are considered inaccurate in laboratory terms, they are all we have. For example, Conradson Carbon Residue which has been included in BS MA 100.

A. E. SWINDEN (BP Marine International): I would like to express my thanks to Mr Sjöberg for a comprehensive and yet easily understood presentation of this most important topic. It is nice to see that someone is actually squirting fuels into a diesel engine and monitoring what happens, rather than telling us what a computer predicts will happen! I hope other engine builders will publish similar useful work.

I have three questions. First, can Mr Sjöberg give us some additional characteristics of the CCS (cat-cracker slurry) fuel which caused the severe engine damage. Mr Sjöberg infers that this was the result of high aromaticity. Whilst CCS is highly aromatic, it invaribly is also high in metals (notably aluminium and silicon) and hence ash content. To what extent did the latter characteristic influence the condition of the cylinder components?

Secondly, it is one thing to say that a very carefully maintained engine operated by Wärtsilä staff can satisfactorily burn fuel of quality X. In practice, engine conditions will vary from good to not so good. What effect does this have and how will it change the type of fuel rating given in Figs 2 and 3 of the paper?

Thirdly, manufacturing tolerances presumably influence the combustion severity of an engine, particularly when all tolerances conspire to be to maximum and minimum values. Has Wärtsilä examined the ignition and combustion variability of ostensibly identical engine builds?

Author's reply

The discussion following the presentation was very informative. There seems to be some confusion regarding the terms 'ignition quality' and 'combustion quality', which may not necessarily be the same. Our interpretation of the terms is that ignition quality controls the sequence from the start of fuel injection to approximately the point of maximum cylinder pressure, whereas combustion quality controls the sequence on the expansion curve.

Whether CCAI, CI, CII, ignition number, cetane number or any other parameter is used in fuel standards as an ignition performance parameter, it is obvious that different engines will react in different ways to fuels with the same ignition performance. This is the case in various grades with many of the other fuel properties specified in fuel standards, eg sulphur, vandium and carbon residue. Engine builders will have to specify what their engine can cope with in terms of ignition quality.

Mr Wright is probably right when he claims that CCAI values in excess of 880 are extremely rare for IFO 180 and above at present. Figures 4 and 5 in the paper suggest that fuels with CCAI values in excess of 870 do appear on the market from time to time. The CCAI values in the figures are probably underestimated because it has been assumed that the maximum density reported is linked to the maximum viscosity reported, which may not always by the case. It may well be that the peak CCAI fuels account for some 'inexplicable' breakdowns or even for breakdowns believed to be caused by cat fines, these being sure fingerprints of highly aromatic diluents.

We have encountered cases where ignition performance did not match the CCAI value. Although the numbers of observations are too few to draw firm conclusions from, it seems that each particular engine type has a cylinder temperature level threshold at the time of fuel injection start, below which the ignition performance may be poorer than is indicated by the CCAI value. In an engine with a poor temperature control system a situation like this may arise, for instance at low ambient air temperature and/or low seawater temperatures, causing low charge air temperatures. Another parameter that seems to offset the 'normal' ignition performance/CCAI ratio is the fuel droplet size, in particular close to the temperature threshold.

The test fuel matrix did not contain fuels with similar CCAI values but with substantially different density values. No doubt it would have been very interesting to find out if such fuels behave differently. However, the main objective of our work was to find engine-specific ways of pushing the acceptable CCAI limit upwards safely.

Only a few ignition quality investigations covering such fuels have been found in our files.[1-4] It seems quite difficult to draw any firm conclusions from the results reported, possibly because of the wide range of test methods used. For example, Ref. 1 measured the combustion pressure in the indicator valves using a heavily damped measuring system, a conclusion drawn from the published pressure diagrams.

Tables DI, DII and DIII indicate that fuels with different density and approximately the same CCAI value perform in a similar way, while Tables DIV and DV show different behaviour.

I consider the CCAI a good candidate for marine fuel oil specifications. It is simple to use, and although it may not rank all residual fuels correctly it certainly does so for the vast majority. A CCAI value of 870 would probably be more reasonable than 880. CCAI 870, if applied to BS MA 100: 1982 fuels, would limit the maximum density of M4 to 0.981 g/ml at maximum viscosity. M6 to M9 maximum density would not be affected at all. M10, M11 and M12 (no density limit in the standard) would be limited to 1.008, 1.012 and 1.015 mg/l, respectively. CCAI 870 would still cause

Table DI: Engine test, 60% load (Ref. 1)

Fuel no.	6	1	4	3	5
density (kg/l at 15 °C)	0.972	0.980	0.990	0.991	1.007
CCAI	838	842	848	862	877
$dp/d\alpha$	2.9	2.9	3.3	4	4

Table DII: Bomb tests (Ref. 2)

Fuel no.	7	1	6	5
Density (kg/l at 15 °C)	0.966	0.992	0.976	0.989
CCAI	828	833	846	850
Ignition delay (ms)	0.6	0.75	1.25	1.15

Table DIII: Engine tests (Ref. 2)

Fuel no.			6B		5	
Density (kg/l at 15 °C)			0.978		0.989	
CCAI			854		850	
Test no.	p_e (bar)	Speed (rev/min)	Ign. delay (ms)	$dp/d\alpha$	Ign. delay (ms)	$dp/d\alpha$
1	18	750	0.88	8.4	0.88	5.7
2	10	750	1.55	20.0	1.44	19.2
3	10	559	1.79	18.0	1.79	10.9
4	4	750	1.88	8.2	1.77	6.3
5	4	354	2.35	6.8	2.11	4.9

Table DIV: Engine tests (Ref. 3)

Fuel no.	A2	A1	V1
Density (kg/l at 15 °C)	0.954	0.960	0.970
CCAI	824	833	827
Ignition delay (ms)	4.1	4.6	6.0

Table DV: CFR engine tests (Ref. 4)

Fuel no.	D2	D3096
Density (kg/l at 15 °C)	877	971
CCAI	835	840
Ignition delay (ms)	0.53	0.89

Table DVI: Catalytic cracker slurry oil

Density at 15 °C	1.078 kg/l
Viscosity at 50 °C	143 cSt
at 100 °C	11.5 cSt
Flash point	118 °C
Pour point	6 °C
Sulphur content	2.4%
Carbon residue (Conradson)	7.6%
Ash content	0.11%
Aluminium	214 mg/kg
Silicon	294 mg/kg
CCAI (Shell)	950

difficulties in engines without a sufficiently high cylinder temperature at the moment of fuel injection.

An alternative to CCAI would be the CII published by BP. The calculation is based on the same parameters as the CCAI calculation. In their Warsaw CIMAC paper,[5] BP extended the equation to include a temperature term T, allowing the viscosity at any temperature between 50 and 100 °C to be used:

$$\mathrm{CII} = (270.975 + 0.1038T) - 254.565D + 23.708 \log_{10} \log_{10} (V_T + 0.7)$$

where D is the density (kg/l at 15 °C), V_T is the kinematic viscosity (cSt at any temperature between 50 and 100 °C), and T is the temperature (°C between 50 and 100 °C).

This equation is more complicated to use than the CCAI equation (Fig. 1 in the paper), but both equations would be easy to solve with a small programmable calculator.

Dr Hawksley's opinion that peak rate of pressure rise is beginning to recieve the recognition it deserves is appreciated.

Peak rate of pressure rise certainly gives a good indication of engine noise, but the countrary is also true. Experienced engineers are able to limit the pressure rise ratio to a safe level in our engines by adjusting the inverse cooling system set point while listening to the engine.

It is certainly difficult to estimate peak rate of pressure rise from cylinder pressure diagrams. Pressure diagrams measured at indicator valves are useless. Pressure transducers flush with the combustion chamber wall must also be applied very carefully in order to avoid 'false' ripples. The measuring system must be carefully designed to ensure that the pressure diagram is as true as possible. The associated software must be properly developed, and the digital processing calls for huge computer capacity. Even the definition of pressure rise ratio needs some thought, since different definitions have been used by different investigators.

Our findings are that the compression temperature at injection, at least when using normal compression ratios, is much more important than cylinder pressure for the rate of pressure rise.

Mr Clements put forward comments from two of his colleagues. Dr Zeelenberg's comments are appreciated. One of the reasons for the good correlation between $dp/d\alpha$ in our case may be that, with the inverse cooling system in use, our engines are operated well above the in-cylinder temperature threshold at fuel injection discussed in the reply to Mr Wright. If Dr Zeelenberg's term 'pure residual fuel' refers to atmospheric residue from mainly paraffinic light crude containing no cutter stock, I agree with his statement that they can be combusted without danger. They are the best residual fuels and can produce smoother ignition and combustion than certain distillate fuels, but they can no longer be obtained easily as bunkers.

There is no doubt that different engines respond to CCAI values for the reasons mentioned by Mr Ives, and a few more. However this is also the case for all other ignition quality parameters. A certain cetane number gives a certain ignition delay in the CFR engine, but it would be astonishing if the same ignition delay was found in all types of production engine (or indeed any).

Reference 6 measured pressure rise ratios of 11 bar/CA with a CN 30 fuel in an engine with an aluminium piston and 8 bar/CA when a ceramic-coated piston of the same geometry was used in the same engine under the same test conditions.

With a CN 50 fuel the difference was even greater: 9 bar/CA with the aluminium piston and 5 bar/CA with the ceramic-coated piston.

I fail to see why more should be demanded of an ignition peformance parameter for heavy fuels (CCAI or CII) than can be demanded of the cetane number for distillate fuels.

We have run tests on heavy fuels with fuel injection viscosities between 5 and 50 cSt with 'normal' CCAI fuels. No significant differences in engine performance were found up to 40 cSt. Fuel injection pressure of course increases as the viscosity increases and this to some degree counteracts the tendency of higher viscosity to produce larger fuel droplets. The results of the test have enabled us to increase injection viscosity from 10-14 cSt to 16-24 cSt and consequently to reduce the fuel pre-heating temperature by some 20 °C. This conserves energy and reduces the risk of thermal breakdown with high viscosity fuels.

Dr Barnes is correct in his assumption that at present a pressure rise ratio of 15 bar/CA is used to define acceptable limits for the ignition quality of the fuels used in our engine types 22HF and 32.

However, any damage from high pressure ratios in an engine is due largely not only to the magnitude of the pressure rise ratio but also to the engine design. Different engine designs vary widely in their ability to withstand high pressure rise ratios without damage and in the type of damage that occurs. For example, in one of our older engine types with light metal pistons, 15 bar/CA would lead to piston damage. The nodular cast-iron pistons with forced skirt lubrication in the 22HF and 32 are far more resistant.

Whether CCAI, CII or ignition number is used as an ignition quality parameter, engine manufacturers will have to specify what their different engine types can accept and in the long run design their engines to digest all but some very exceptional fuels occurring as bunkers.

It is interesting to note the very good repeatability of ±1 ignition number with the BP modified CFR engine. Reference 7 claims that multiple CFR engine ratings have yielded scatters as high as ±4 cetane numbers. The good repeatability may be attributable to the 100 °C inlet air temperature used by BP rather than the standard 65.5 °C.

When Mr Waters quotes from the paper he omits the determining factors for misfiring and rough operation on fuels with CCAIs below 830. The sentence continues '... at low inlet air temperatures and/or low raw water temperatures during start and idling'. In cold weather automotive, truck and heavy vechicle engines often have starting problems and suffer from rough running and white smoke emission on distillate fuels with CCAI values below 800.

Although fuels with CCAI values below 830 are becoming rare, they still exist and certainly did so in 1983 when the recommendation was written. BP, for example, used six residual fuels with CCAIs ranging bewteen 783 and 826 in their CFR engine work published in 1984.[8] Residual fuels bunkered in Jeddah (Fig. 5 in the paper) had CCAI values below 830 to the end of 1984.

Wärtsilä Diesel has from time to time considered testing of fuel additives but decided to develop the engine to operate properly without them.

As the ignition quality of residual fuels continues to deteriorate (Figs 4 and 5 in the paper), there may be a need for ignition improvers to be used in engines not developed for low ignition quality fuels. Ignition improvers are used on a fairly regular basis for automotive fuels.

The paper is not concerned with the combustion quality of fuels but with ignition quality, which may not be the same thing. We have failed to find any correlation bewteen Condarson Carbon Residue and ignition quality and have found only an uncertain correlation bewteen CCR and combustion quality in our engines.

Mr Swinden asks for some additional characteristics of cat cracker slurry fuel.

The slurry used in our tests was originally acquired to study the influence of cat fines on engine component wear. As can be seen in Table DVI, the slurry contained 214 ppM Al and 294 ppM Si. We found it very difficult to keep the cat fines in suspension in the pre-heated fuel; they settled at the bottom of the tank in a very short time. In the work covered by the paper, the slurry was clarified and contained less than 10 ppM cat fines, so their influence on the condition of the cylinder components can be excluded.

As long as the inverse cooling system works properly, and it is very reliable, the only thing that will reduce acceptable ignition quality is fuel nozzle deterioration, which causes improper fuel atomization resulting in increased fuel droplet sizes.

We have not found that manufacturing tolerances influence the ignition process in our engines. Tests have been carried out in cylinders close to wear limits, way beyond the manufacturing tolerances.

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