



## PAPER NO.: 198

# The effects of a changing oil industry on marine fuel quality and how new and old analytical techniques can be used to ensure predictable performance in marine diesel engines

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**Abstract:** This paper reviews how marine fuels have changed over the last ten years, the effects on the reliable operation of ships' prime movers, how our research and Development efforts have increased our understanding of the root causes and the measures that can be taken to reduce the risk of machinery problems or even breakdown, to a minimum

It briefly reviews the effects of changes to refinery configuration necessary to meet the ever-increasing demands for automotive, domestic and industrial heating fuels. This in turn has changed the way marine fuels are sourced.

It reviews a number of real incidents where fuels that apparently fully met ISO 8217 specifications, have

caused significant damage to compression ignition engines or given rise to serious operational problems.

It reviews the analytical techniques used to identify the root causes of the problems. In particular it reviews a relatively new technique, the FIA, for assessing the ignition and combustion characteristics of residual fuels and how, based on our R&D activities, the data obtained from this technique relates to engine derived data.

Finally the paper discusses residual fuel oil stability, i.e. how some proprietary methods of assessing stability can give very misleading results, and how in some instances, particularly with low sulphur fuels, normal blending rules do not seem to apply.

## INTRODUCTION

Each year more than 200 million tons of bunker fuels are sold into the marine market globally. In the majority of cases the fuel is supplied in accordance with the ISO 8217 Standard.

ISO 8217 attempts to define fuels that will be suitable for use in marine boilers and diesel engines. It includes tables of property limits and clauses that try to control the composition of the fuels. Regrettably, the Standard has a number of key deficiencies. These can result in the supply of fuels, which, while apparently meeting the requirements of the Standard, are nevertheless totally unfit for purpose. Two key deficiencies are (1) poor definition and control of residual fuel stability and (2) no control of ignition performance. While other workers have in fact defined the former for many years, addressing the latter issue has been hampered by the lack of a suitable, reliable test method. This paper briefly reviews the situation regarding stability control — i.e. do the existing methods function with modern fuels? — and some recent developments in this area. In greater depth it reviews some of the output from work that we have been conducting on a recently released instrument claimed to give information on the ignition and combustion performance of residual fuels.

### A Brief History

Since the early 20th century, residual fuel oil has been used to power ships. It started with early trials in a British Royal Navy vessel in an effort to replace coal to fire the boilers. Some time later, fuel oil was adopted as the fuel of choice in merchant ships powered with steam engines.

The diesel engine soon proved to be much more fuel-efficient and, as its reliability improved, rapidly replaced the steam engine in merchant shipping. Initially, diesel engines were burning distillate fuels, which gave them a commercial disadvantage over the residual oil (boiler fuel) fuelled steam ships. In the late 1940s, John Lamb [1] proved it was possible to use boiler fuels by running tests on Shell tankers. Burning boiler fuel in a diesel engine required several modifications to the fuel system and engine: heating to reduce the viscosity in order to be able to pump and spray the fuel, pre-treatment by using a settling tank and centrifuge to remove water and sediments. What many people do not realise is that even in those days the fuels included thermally cracked residues from the thermal cracker that had been in operation in the then Shell refinery in Curaçao. Even in the 1950s, the problems surrounding residual fuel stability

were being experienced, and this stimulated early work to define the chemistry of the issue.

As the decades passed, diesel engines became more common and a large number of them burned residual fuels. There were engine reliability issues and a few fuel stability problems, but on the whole nothing that was unmanageable. It was not until after the oil crises of the 1970s that a dramatic change in the oil refining and shipping industries occurred. The drivers were reduced availability and increased price of crude oil. This forced the refiners to become much more efficient at producing as much distillate product as possible from a given quantity of crude. This resulted in a rapid increase in the number of thermal and catalytic conversion units used in refineries globally. Shipping was hit by a massive increase in fuel prices from about USD30/mt to a peak of over USD200/mt. This economic change was the death knell of the steam ship, which had been surviving because of the relatively low cost of fuels and its inherently much higher reliability and low maintenance costs. The late 1970s and early 1980s saw queues of steam ships waiting to enter the scrap yards.

As the number of motor ships and the amount of fuels containing thermally cracked residues increased, so did the number of operational problems related to fuels. Density was a major issue, as fuels were being supplied at or over 0.991 kg/litre at 15°C. This was giving serious problems with the centrifugal purifiers. At this time there were no industry standards or specifications for marine fuels. Given the magnitude of the problems being experienced, the marine shipping industry, through the British Standards Institute, published the first marine fuels specification BS MA100 1982 “Specification for petroleum fuels for marine oil engines and boilers”. This Standard was always intended to be a precursor to an international standard. The first International Standard for marine fuels, ISO 8217, was published in 1987.

Residual fuel stability was a major issue during this period, as the thermal cracker operators pushed their units to the limits. On occasions they would push too far, resulting in an unstable fuel. At the same time there was an increasing awareness of compatibility issues where two stable fuels, when mixed, produced an unstable mixture. It was during this period that the chemistry underpinning residual fuel stability became better understood and test methods refined to give good control. ISO 8217 only contained the Sediment by Hot Filtration–Potential as a specification parameter for stability. As we will show, however, this test does not adequately control fuel oil stability.

Also during this period, the marine industry experienced its first serious ignition performance problems. These primarily affected vessels that changed over from distillate fuels to one of the low viscosity residual fuel grades, usually 30, 40 or 60 mm<sup>2</sup>/s at 15°C. At that time, the density limit for all residual fuels was 991.0 kg/m<sup>3</sup> at 15°C. In some locations where advanced refineries were in operation with large catalytic crackers, low viscosity fuels were manufactured at the density limit due to the extensive use of cycle oils. Many of these vessels suffered serious operating problems and in some cases serious engine damage. It was because of this that Shell carried out a major R&D project in order to understand the root causes of the problems and develop remedial solutions. The Calculated Carbon Aromaticity Index – CCAI – was born from this work [2].

During the 1980s, threats of further crude supply disruptions and, far more importantly, environmental legislation affecting retail and commercial transportation fuels along with industrial fuels were driving the refining industry to change the way it operated. This resulted in new processing technologies and upgrading of existing units to meet the new demands. Such upgrades included a series of step changes in thermal cracker design and operation resulting in higher than ever “net distillate yields” (Figure 1). The side effect of this was lower quantities of residues (which were more aromatic and had much lower stability reserves). These are two changes that have had an enormous impact on the marine fuels industry. Stability, as already mentioned, is well understood and can be managed with existing tools if the issues are fully understood. The big change is the increase in aromaticity.

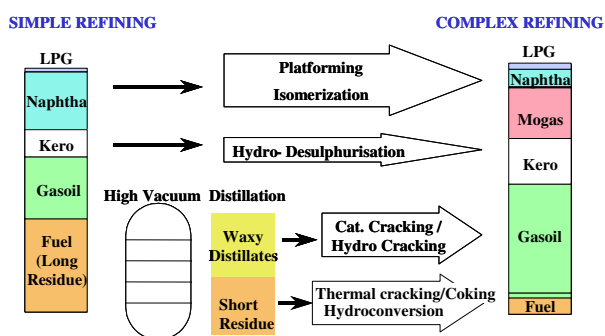


Figure 1 – Change in product split with deeper conversion of residue to increase distillate yield

To put this into context, aromatics have high auto-ignition temperatures, which increase with increasing aromaticity. Compression ignition engines depend on the fuel auto-igniting when it is sprayed into the cylinder. There is therefore a point where, as the auto ignition temperature of the fuel

approaches the temperature of compression, the engine will fail to operate. There isn't a hard cut-off point; rather, the engine will go through a period of increasingly poor performance until a point is reached where operation will be impossible.

Infrastructural changes and developments in the worldwide refining industry may lead to the production of fuels with challenging characteristics with respect to combustion in compression ignition engines.

Towards the end of the 1990s, we noticed a small increase in the number of problems that vessels were experiencing with fuels which, to all intents and purposes, fully met the requirements of ISO 8217:1996. During 2002 and 2003 there were a small number of serious incidents that resulted in us changing the blending controls we used in a number of ports.

### Example 1

Fuel delivered from Port A to vessels P, Q and I

Independent analysis of the delivered fuel to vessel P gave the results shown in Table 1. Vessel machinery consisted of a single low speed engine and four medium speed auxiliary engines for electrical power generation. The vessel was essentially a uni-fuel vessel. One of the auxiliary engines, however, was set up for burning marine diesel fuel only.

Table 1 – Third Party Analysis of Fuel “X” (2002)

Tested Results	Units	RMG35	Specification
Density @15C	kg/m <sup>3</sup>	0.9897	max 0.991
Viscosity @50C	mm <sup>2</sup> /s	250	
Viscosity @100C	mm <sup>2</sup> /s	27.55	max 35
Flash Point	Deg C	70	min 60
Pour Point	Deg C	-3	max 30
Net Caloric Value	MJ/kg	40.26	
Water	% v/v	0.2	max 1.0
Micro Carbon Residue	% m/m	15.03	max 18
Sulphur	% m/m	2.65	max 5
Total Sediment Acc.	% m/m	0.033	max 0.10
Ash	% m/m	0.056	max 0.20
Vanadium	mg/kg	122	max 300
Sodium	mg/kg	20	
Aluminium	mg/kg	22	
Silicon	mg/kg	20	
Iron	mg/kg	33	
Nickel	mg/kg	40	
Calcium	mg/kg	6	
Lead	mg/kg	LT1	
Zinc	mg/kg	14	
Phosphorus	mg/kg	1	

During an ocean crossing two of the auxiliary engines failed completely and one was badly damaged. The only engine burning marine diesel fuel was undamaged. The main engine operated on the same fuel without problems.

Figure 2 is a photograph of a piston from one of the damaged auxiliary engines – many of the other pistons had a similar appearance.



Figure 2 – One of a number of pistons from an engine using fuel with poor ignition characteristics

Figure 3 shows the Fuel Ignition Analyser (FIA) Rate Of Heat Release (ROHR) graph for the supplied fuel - Fuel X.

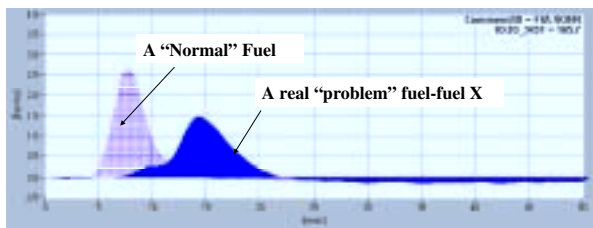


Figure 3 – Ignition and combustion performance of a problem fuel, as measured by FIA (2002)

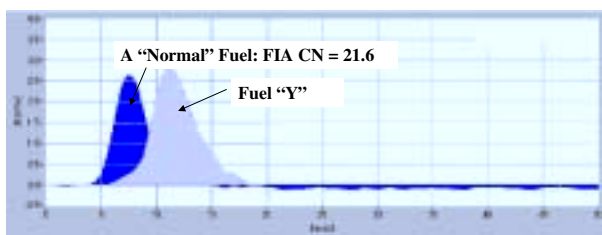


Figure 4 – FIA ROHR Graph for Fuel “Y” that resulted in erratic engine speed at low load (2003)

The FIA was a relatively untested instrument at the time with no standardised test methodology. Was the engine damage caused by the apparent poor ignition quality of the fuel? There was strong evidence that there was a link. Investigations with vessels P & I revealed that due to significant ROBs they had only just started using the fuel. Their

auxiliary engines were also performing poorly. We stopped them from using the fuel and exchanged it at the nearest practical port.

### Example 2

Fuel delivered at port B to vessels R and S

Both vessels complained of erratic running of the small bore low speed main engines. In addition starting was not reliable: not a very comfortable situation for a vessel that reverses by reversing the rotation of the engine itself. While nothing could be found wrong with the basic properties of the fuel (Table 2), the ignition performance as measured by FIA was shown to be relatively poor (Figure 4).

Table 2 – Third Party Analysis of Fuel “Y” (2003)

Tested Results	Units	RMH35	Specification
Density @15C	kg/m3	963	max 991
Viscosity @50C	mm2/s	5.2	
Viscosity @100C	mm2/s	16.9	
Flash Point	Deg C	80	
Water	% v/v	0.3	max 1.0
Micro Carbon Residue	% m/m	12	max 22
Sulphur	% m/m	2.4	max 5
Total Sediment Potential	% m/m	0.03	max 0.10
Ash	% m/m	0.06	max 0.20
Vanadium	mg/kg	81	max 600
Sodium	mg/kg	22	
Aluminium	mg/kg	18	
Silicon	mg/kg	24	
Iron	mg/kg	29	
Nickel	mg/kg	25	
Calcium	mg/kg	12	
Magnesium	mg/kg	2	
Lead	mg/kg	LT 1	
Zinc	mg/kg	5	
Phosphorus	mg/kg	2	
FTIR		- NORMAL -	
Acid number	mg KOH/g	2.1	

This experience indicated a need to understand in a more scientific way the relationship between the data produced by the FIA instrument and actual performance in diesel engines.

It was on the basis of this that we funded R&D to try to establish possible linkages between the data generated in the FIA and actual performance in real engines.

## FUEL OIL IGNITION

To date, marine fuel oil specifications (ISO 8217) still do not contain a limit on ignition quality, which is in some way remarkable since the primary role of a fuel is to burn and deliver energy in a compression ignition engine.

With increasing complexity of fuel oil production and the general perception that ignition quality of fuel oils is continuously deteriorating, there is a need for a relevant test that can distinguish fuels,

which ignite and burn in a satisfactory manner, so that end-users have confidence that the fuel delivered is indeed fit-for-purpose.

However, when new techniques are accepted for specification purposes it is important that these tests measure fundamental properties and have been validated, so that scientific evidence is available that demonstrates the relationship to fuel performance.

In general terms, one can define ignition as the onset of a very fast oxidation of a fuel-air mixture. Fuel is injected into the engine cylinder under high pressure through a single or multiple nozzles to form a spray of very fine fuel droplets in a pressurised and preheated chamber. Light components evaporate rapidly and mix with air to form an ignitable mixture. After a certain delay, the oxidation rate sharply increases with formation of heat. The heat developed helps to evaporate the liquid part of the fuel. Combustion of fuel oil is very different from distillate fuels in the sense that heavy fuel oil contains a large fraction of components with a high molecular weight that will not evaporate, which means that part of the fuel is burned in liquid form.

The combustion behaviour of fuels strongly depends on fuel composition. In a diesel engine the air/fuel mixture ignites without flame or spark (self-ignites). Aromatic compounds have a high resistance to auto-ignition. Paraffinic compounds normally ignite more easily. Hence, a measure of resistance to ignition or ignition delay is the aromaticity of the fuel.

Due to the robustness of marine diesel engines and the limited variation in fuel quality, for a long time it was not considered necessary to specify the ignition quality of heavy fuel oil. As mentioned earlier in this paper, ignition problems were experienced with some low viscosity high-density (991.0 kg/m<sup>3</sup> at 15°C) fuels. As a result of this, Shell commissioned a project to try to devise a simple method of predicting the ignition performance of residual fuels. In 1983 Zeelenberg [2] introduced the concept of CCAI as a measure of fuel aromaticity. The Calculated Carbon Aromaticity Index (CCAI) is calculated from the density and viscosity of the fuel. Studies on test engines (2- and 4-stroke) demonstrated the correlation of the CCAI with ignition delay in the engine (Figure 5).

In practice, the CCAI proved to be a very useful tool to rank fuels by ignition quality. However, because of the large differences between engine types it was not promoted for specifications, although it was the basis of the reduced density limits for the

low viscosity fuel grades contained in the ISO 8217 Standard.

Schenk et al [1998: ref 3] made an attempt to improve the correlation of the CCAI with engine performance by using the aromaticity of the vapour: the so-called CVAI. The CVAI is calculated from the CCAI and microcarbon residue (MCR). This was a creative concept, but it did not improve the correlation with ignition.

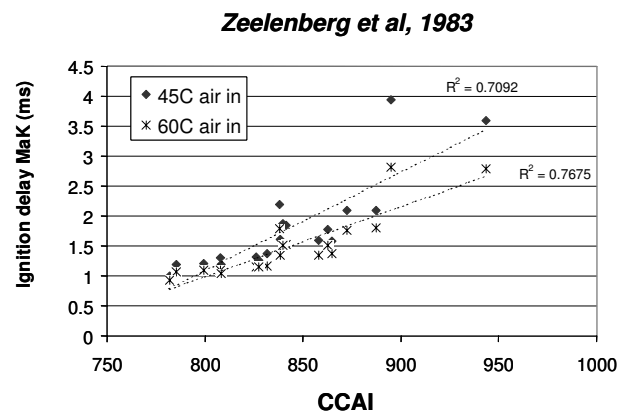


Figure 5 - Correlation CCAI and ignition delay in MaK test engine

In their study, Schenk et al. used not only engine tests to measure ignition properties, but also a fuel ignition test rig, the so-called “Shell bomb”. This was an electrically heated, cylindrical combustion chamber (4 litre), which could be heated to max 600°C and a pressure of 50 bars. The combustion process was followed by measuring the pressure as a function of time. The advantages of such a test rig are obvious, as it allows a more rapid screening of fuels but also allows us to gain a deeper understanding of fuel combustion under more controlled conditions than in a diesel engine.

The design of this “bomb” was based on a similar rig developed earlier by Baert at Delft University using early 1990s technology [4]. Baert studied the ignition and combustion of fuel oils and concluded that the ignition delay of heavy fuel oil related to pressure and temperature, but also that the ranking of fuels by ignition delay changes with changing temperature and pressure.

Deeper analysis of the results reported by Schenk [3] reveals that the correlation is influenced by the fuel composition. The fuels used in that study were combinations of straight run and or cracked components. To illustrate the effect of fuel composition on the correlation between CCAI and ignition delay, only the fully straight run fuels and fully cracked fuels are considered. The correlation

of CCAI with ignition delay of these two families of fuels is shown in Figure 6.

This clearly shows two different correlations between CCAI and ignition delay, but also suggests that the CCAI of cracked fuels underestimates its ignition quality. More importantly, this emphasizes the need to improve our understanding of fuel combustion and develop better techniques for measuring ignition and combustion quality of fuel oil, especially since fuel oil composition is liable to further change as a result of changing refinery processes and fuel oil blending, as a result of changing requirements driven mainly by legislation.

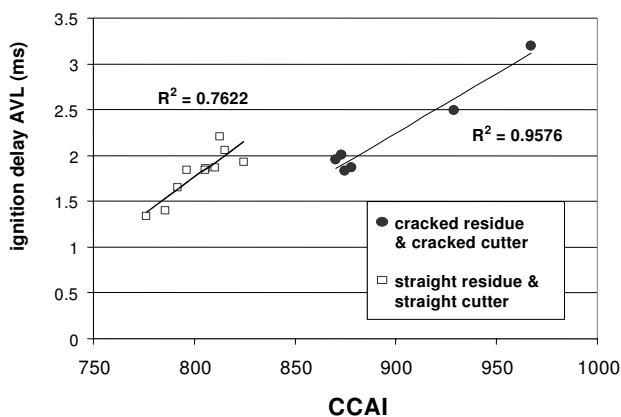


Figure 6 - Influence fuel composition of correlation CCAI and ignition delay in AVL (1998)

## CORRELATION BETWEEN FIA AND COMBUSTION BEHAVIOUR IN THE ENGINE

In 2002 the Shell Research laboratory in Amsterdam purchased FIA100/X from Fueltech. Considerable effort has been invested in helping to improve the robustness and reliability of the test rig, for example by participating in the IP task force. More recently, with the improved version (FIA/100 FCA) available, ignition and combustion characteristics have been studied more fundamentally.<sup>1</sup>

Having accumulated a considerable amount of data from the FIA, it was recognised that there was a need to compare values obtained from the instrument with actual performance in engines, which could be extensively instrumented to monitor the ignition and combustion behaviour of the fuel.

<sup>1</sup> In this paper we mainly address ignition delay. However, other parameters from the combustion curve may be as important or perhaps even more important for certain engine types. This is part of our ongoing research programme which, at the time of writing, is not ready for publication

## Engine Tests

A series of fuels was prepared for testing. The fuels consisted of commercially available fuels and research fuels made from the normal components used to manufacture marine fuels, from a range of refinery locations.

These fuels were tested in the FIA instrument located in our Amsterdam laboratory and in two of our test engines located in our Marine and Power Innovation Centre in Hamburg. For the purposes of this work we chose to use the AVL-Caterpillar 1Y540 and Bolnes 1DNL190 engines.

## Engine test conditions



Figure 7 – AVL Caterpillar 1Y540 test engine

The AVL-Caterpillar 1Y540 is a single-cylinder 4-stroke high-speed diesel engine (Figure 7). The start of injection was set to occur at 31 °CA BTDC (static). The injector opening was derived from both the needle lift signal and the fuel line pressure reaching 260 bars, as every day the spring tension of the cleaned injector was adjusted to open at this pressure. This injector opening generally occurred at approximately 19 °CA BTDC (dynamic). The engine was fully instrumented for ignition parameter measurements, i.e. with pressure transducers in both the combustion chamber and the high-pressure fuel line approximately 10cm in front of the injector housing, injector needle lift sensor and shaft encoder for main axis angular position (degrees crank angle, °CA) 2.

The fuel was supplied from a heated 60-litre container placed on a balance, allowing continuous monitoring of fuel consumption at the desired fuel temperature for a 13 mm<sup>2</sup>/s injection viscosity. The operating conditions were varied during a single

run by using a sequence of 6 modes in which the engine load and pressure were reduced stepwise (360 to 90 Nm; inlet air pressure: 3.1 to 1.2 bar), with an engine speed of 1400 and 1000 rpm, and constant inlet air temperature (50 °C), cooling water (80 °C) and lubricating oil temperatures (80 °C).

The start of injection was defined as the point where the needle from the injector is lifted from its seat. In practice, this is when the needle lift signal exceeds 10% of the maximum signal. The engine was started on Marine gas oil, but as soon as possible the fuel was switched to the test fuel. Prior to the measurements, the engine was allowed to stabilise at all modes until the exhaust gas temperature was constant; normally this took ~30 minutes. Measurement of the ignition and combustion and the fuel consumption took another 15 minutes. The total time required per mode was 45 minutes.

The start of ignition/combustion was derived from the combustion pressure trace, obtained from the cylinder pressure by mathematical correction for the compression pressure. The compression curve is calculated using polytropic compression with  $k=1.39$  on the basis of the actual volumes and the air inlet pressure. The start of ignition is taken as the angle (moment) where the pressure rise between 2 adjacent measuring points exceeds 0.1 bar and the pressure rise between the averages of 5 data points immediately before and after the 'moment of ignition' exceeds 0.3 bar. Ignition delay is the difference between the crank angle at which injection takes place and the crank angle at which ignition takes place. The difference in angle can be converted into a delay time assuming the speed of rotation to be constant.

A similar program was conducted on a 2 stroke crosshead engine: Bolnes 1DNL190 (Figure 8). All settings were taken as the standard settings for this engine. The speed and torque applied (4 test conditions) were derived as for ISO 8178 part 4 test cycle type E3.



Figure 8 - Bolnes 1 DNL190 test engine

#### FIA and engine conditions

The FIA is a constant volume combustion chamber based instrument designed to resemble engine conditions. However, there are of course differences, as is illustrated in Table 3.

Table 3 – Comparison test engine conditions and FIA

		FIA	AVL (25-100% load)	Bolnes (100% load)
<b>Temperatures</b>				
at fuel injection (theoretical)	C	500	533	503
<b>Pressures</b>				
at fuel injection	bar	45	27 - 63	87
at TDC (top-dead-centre)	bar	na	66 - 137	116
max compression pressure	bar	45	49 - 108	106
maximum pressure	bar	53-55	72 - 150	130
<b>Time</b>				
start injection (from TDC)	ms / °CA	0	-19 to -22	-10.5
end injection (from TDC)	ms/°CA	3	-5 to 28	15.5
injection duration	°CA		18 - 49	26
start ignition	°CA	na	7.8 - 17.4	1.8 - 2.8
end main combustion	°CA	na	37.6 - 64.2	36.5 - 37.1
start scavenging	°CA	na	120	108
start ignition	ms	5 - 8.3	0.95 - 2.08	0.4 - 0.8
end main combustion	ms	10 - 25	5.4-7.6	12.2 - 12.4
Compression ratio		na	13.8	14.3
Air-fuel ratio			26 - 37	35
Nozzle		1 hole	1 * 6 hole	2 * 1 hole

In the FIA there are no moving parts, and starting conditions are controlled more precisely. Fuel is injected in a fixed injection period (2-3 ms) through a single nozzle injection system (Bosch) and into a chamber with fixed dimensions (1 litre). Heating of the air is achieved by heating the chamber wall, which means that the actual air temperature is a little lower than the temperature setting.

The injected fuel mixes with air, and when a combustible fuel/air mixture is formed ignition takes place with release of heat and combustion gases which give a pressure increase. The pressure

curve (Figure 9a/b) can be transformed into a curve showing the rate of heat release ( $dp/dt$ ).

The full combustion starts a little later than the moment of ignition (FIA ID) [see the Nomenclature for a list of FIA terminology and abbreviations]. This is called the main combustion delay (FIA MCD). From the combustion curve, various parameters can be extracted. Important is the maximum rate of heat release (maxROHR), referred to as combustion hardness; high combustion hardness may lead to engine damage as result of strong pressure peaks.

Time to complete combustion (EC) may give information on the formation of combustion products and unburned or burned fuel components which affect emission, and may also relate to formation of engine deposits and wear.

Actual engine conditions are, however, different from those of the FIA. In the compression stroke, air is heated to 500-550°C (theoretical) just before the point of ignition. The pressure in our 4-stroke test engine easily reaches 70-130 bars, and for the 2-stroke test engine pressure can reach 170 bars, much higher than the 45 bars used in the FIA.

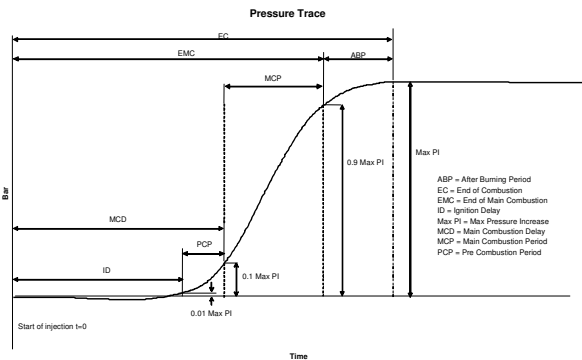


Figure 9a – Combustion pressure curve in the FIA

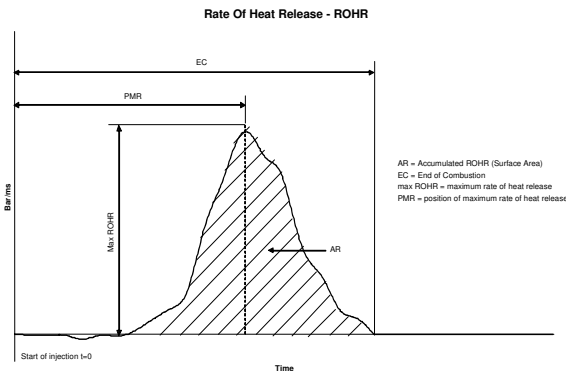


Figure 9b – Rate of heat release curve in the FIA

Apart from differences in thermodynamics, there is another difference that relates to fuel injection. In the FIA all fuel is injected in a fixed period between 2-3 ms. This means that all fuel is injected well before ignition, because most fuel oils have an ignition delay of more than 4 ms.

In the engine, especially at high loads, the fuel injection overlaps ignition and combustion, as can be seen in Figure 10. This means that a large part of the fuel (max 80%) is injected into a space with a flame.

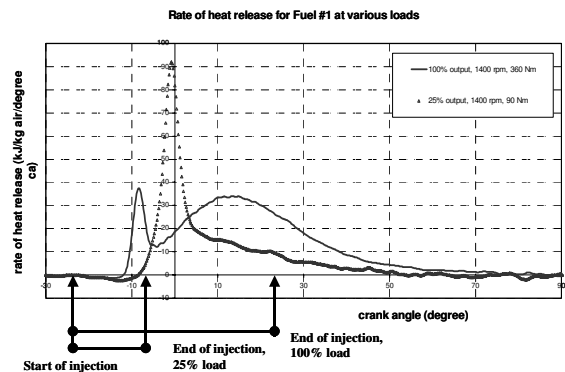


Figure 10 - Influence injection period on combustion in AVL test engine at 25% and 100% load

Figure 10 also shows that at higher angle loads, the heat release curve in the engine shows two peaks. The first peak immediately following ignition is the so-called pre-mixed combustion. Here the fuel/air mixture ignites and combusts with rapid increase of pressure and heat release. This maximum of the first peak is the 'combustion hardness'.

The combustion hardness is related to the amount of fuel injected and, consequently, the ignition delay; a longer ignition delay allows more fuel to be injected, which once ignited gives a stronger pressure peak. High combustion hardness may lead not only to engine damage but also to increased NOx emissions.

The second peak shows a more gradual combustion, the so-called diffusive combustion, where reaction rates are determined by diffusion of fuel and oxygen molecules.

### Analyses of FIA parameters

In the FIA, work to date shows that fuels with a short ignition delay also produce a high maxROHR, a high combustion rate (low MCP) and short EC. This is illustrated in Figure 11, showing the results of ~100 commercial fuel oils (180-500 cSt). However there are some exceptions, in particular at the lower and higher end of the ignition delay.

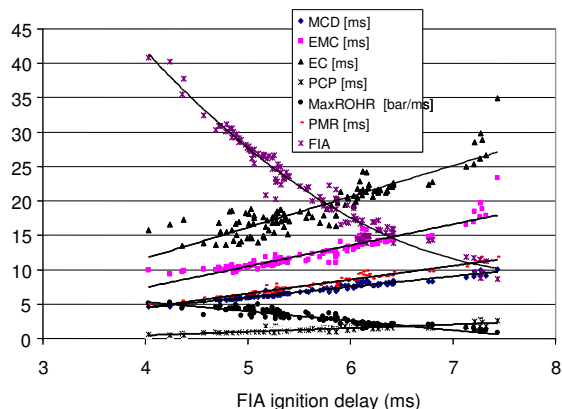


Figure 11 – Correlation ignition delay with other FIA parameters

Some of the properties are clearly linked; the best correlation is obtained between ID, MCD and PMR. A poorer correlation is observed between ID and EC. No correlation is observed between ID, ABP and maximum pressure increase.

Interestingly, the FIA maxROHR increases with reducing FIA ID, whereas previously it was observed in the engine that the maxROHR in the pre-mixed combustion decreases with reducing ignition delay. This difference is explained by the fact that in the engine, effects of fuel injection are also observed, as explained in the previous section. The maxROHR in the engine is mainly controlled by the amount of fuel injected prior to ignition. Consequently, there is no fundamental relationship between FIA maxROHR and combustion hardness in the engine.

#### Correlation between FIA and 2-stroke Bolnes engine

The Bolnes engine was run (300 rpm) at variable loads. The engine was started on gasoil and then switched to fuel oil, running from full load to respectively 75%, 50%, 25% and idling conditions. When the engine was running idle, it was observed that both injectors were fully in operation only part of the time, because of the low fuel demand. This of course normally does not happen in modern engines, particularly those fitted with high-pressure electronic injection systems.

The correlation between the ignition delay in the Bolnes and the ignition delay determined by the FIA is shown in Figure 12. Even at low loads, the correlation is still very acceptable, and further improves with increasing loads. The main combustion delay (FIA MCD) gives an even better correlation with ignition delay from the engine, which supports the choice of FIA MCD as a basis

to calculate the FIA estimated Cetane Number (ECN).

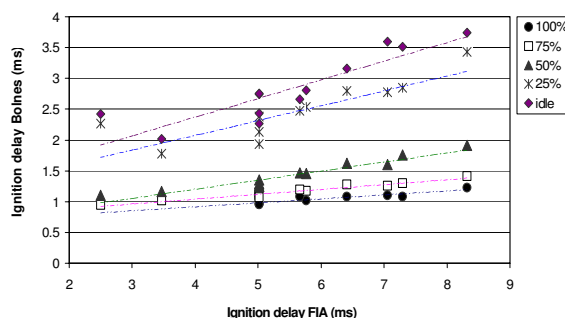


Figure 12 – Correlation ignition delay in FIA with ignition delay in 2-stroke low speed Bolnes test engine

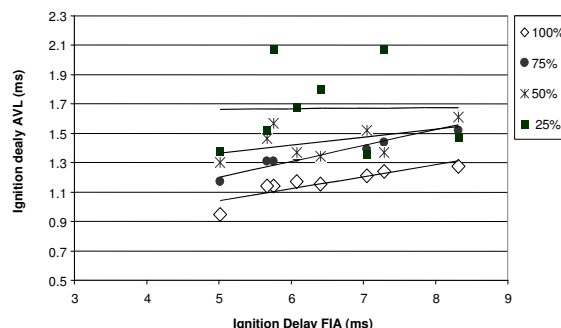


Figure 13 – Correlation ignition delay in FIA with ignition delay in 4-stroke medium speed AVL test engine

#### Correlation between FIA and 4-stroke AVL engine

The same fuels were tested in the 4-stroke medium speed (1400 rpm) AVL-Caterpillar test engine. Typically, two fuels were tested on a single day with the engine running from low to high loads (25-100%). Figure 13 shows that the correlation between FIA and test engine is acceptable to good at 75% and 100% load. However, at low loads the correlation is very poor.

Normally, conditions in the 4-stroke engine are least favourable at low load conditions, with lowest temperatures and pressures. This explains the longer ignition delays; however it may also have affected the ranking of fuels. This was also observed by Baert et al [4b] and later by Stassen [5] in the fuel ignition test rig built at the Shell research centre in Amsterdam. In that study, a large number of fuels were tested at different temperatures and pressures. The effect of temperature on ignition delay is shown in Figure 14.

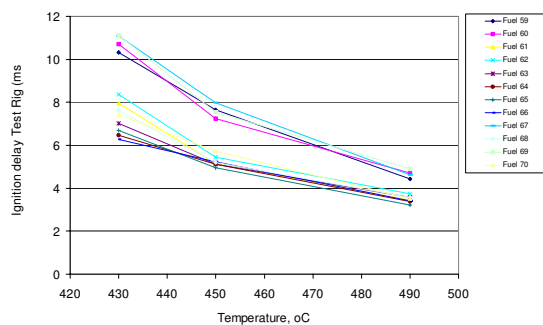


Figure 14 – Temperature effect on ignition delay of fuels in SRTCA fuel ignition test rig (1993)

This confirms that by changing the temperature the ranking of fuels by ignition delay may also change, which may also explain the poor correlation found in the AVL at low loads.

Attempts to correlate combustion parameters from the FIA (e.g. EC, EMC, ABP) with corresponding engine parameters failed, both with the AVL and Bolnes test engines. This may be partly due to differences in test conditions between FIA and engine, affecting reaction kinetics. However, apart from other differences between FIA and engine, fuel injection in the engine is also very different and strongly affects the combustion process, as was demonstrated in previous sections. This area is subject to further work.

### CCAI versus FIA

One of the objectives of this study was to verify the relationship between ignition in the FIA and diesel engines, in order to assess if FIA is indeed a better technique for determining ignition quality of fuel oils.

For that reason, the correlation between FIA and engine was compared with the CCAI on the basis of the regression coefficients, assuming a linear relationship (Table 4). Overall, the FIA ECN does indeed give an improved correlation with engine performance. At low load in the medium speed AVL engine, both FIA MCD and CCAI give a poor correlation.

Table 4 – Comparison regression coefficients from correlation of FIA and CCAI with ignition delay in test engines

#### Bolnes engine

load (%)	Ignition delay	Main combustion delay	CCAI
1.00	0.829	0.831	0.745
0.75	0.952	0.957	0.695
0.50	0.915	0.928	0.734
0.25	0.696	0.732	0.766
idle	0.790	0.814	0.514

#### AVL Caterpillar engine

load (%)	Ignition delay	Main combustion on delay	CCAI
100%	0.775	0.768	0.583
75%	0.925	0.914	0.801
50%	0.256	0.205	0.656
25%	0.000	0.000	0.020

## INFLUENCE OF FUEL COMPOSITION

As indicated earlier in this paper, there is evidence that the composition of a fuel has a major influence on ignition and combustion characteristics, i.e. fuels with the same or very similar physical properties can have completely different ignition performance.

To improve our understanding of the relationship between ignition quality of components and those of blends, a series of blends was prepared on the basis of a visbroken residue (VBR) which was diluted with distillate components having different ignition qualities, respectively heavy cycle oil (HCO), light cycle oils (LCO-1 and LCO-2) and vacuum gas oil (VGO). The effect of diluent concentration is shown in Figure 15.

As an aside, extrapolation of the blending curves gave a point of intersection at an FIA ECN of ~14, which suggests that the visbroken residue has a *pseudo* cetane number of 14. Most visbroken residues cannot be determined directly in the FIA because of their high viscosity. A procedure is now available to determine the ignition quality of residue, which allows ranking and selecting residues by ignition quality.

The blending curves clearly do not follow simple linear rules, which means that FIA ECN of a blend cannot be calculated from the properties of the individual components. When producing fuel oil, the situation is often even more complex, as most contain three or more components, instead of two. Further work is needed to improve our

understanding of the relationship between fuel composition and FIA.

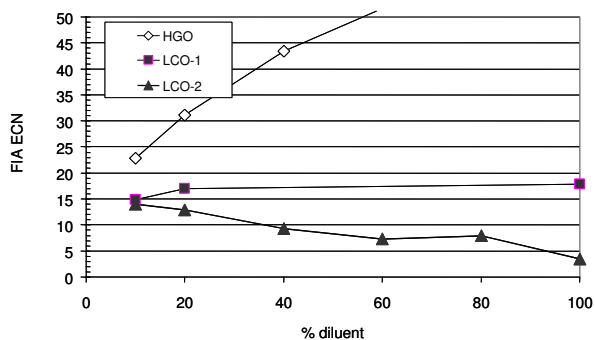


Figure 15 – Effect diluent concentration on FIA ECN of blends with Visbroken residue

This brings us back to the tests carried out in the AVL Caterpillar engine, which further illustrate the complexity of this issue.

Figure 16 shows the ignition delay as a function of load. A high load represents high temperatures and pressures, normally giving short ignition delays. A low load represents low temperatures and pressures, normally leading to slower ignition, i.e. longer ignition delays.

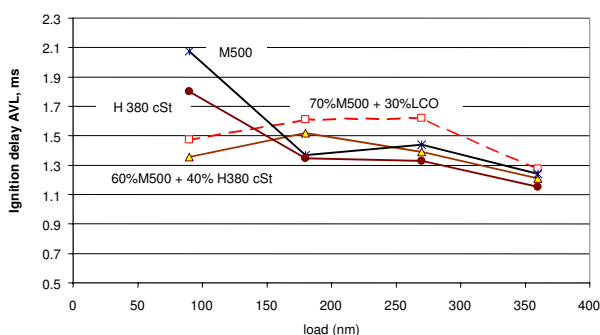


Figure 16 – Effect fuel composition on ignition delay in AVL 1Y450 medium speed test engine

The first observation is that by adding LCO to a 500cSt fuel (M500), the ignition delay increases, as one would expect because of the high aromaticity and poor ignition quality of LCO. However at 25% load (100 Nm), the ignition delay is significantly shorter than that of M500. Secondly, one can observe that a 60/40 blend of M500 and a 380cSt fuel at low load (100 Nm) gives a significantly shorter ignition delay than any of the components.

This further emphasises the complexity of predicting the ignition quality of blends. Indeed it shows that without an extensive knowledge of the ignition performance and composition of components it is difficult to predict reliably the ignition performance of the final blend.

## Gap-fuels

A good fuel oil has the right balance between light and heavy components in order to ensure fast ignition and generation of sufficient heat to evaporate, crack and burn the heavier components. Ideally, a fuel oil has a continuous distribution from light to heavy components.

Occasionally fuels are found which do not have such a distribution, but show a so-called dumb-bell distribution, also referred to as gap-fuels. This is illustrated in Figure 17, which shows the typical boiling point distribution of a “normal” fuel oil and a gap fuel oil. Each bar in this graph represents the mass of a boiling point fraction of 10°C, at the temperature given on the horizontal axis. This distribution is not obtained by distillation, but by using a chromatographic technique, also referred to as simulated distillation (Simdist).

Gap-fuels can seriously hamper smooth engine operation, as they tend to give poor ignition and slow and incomplete combustion. Incomplete combustion affects particulate emission and possibly leads to engine fouling, e.g. on the piston top-lands resulting in liner scuffing, or on the turbo-charger.

In our laboratory, we prepared gap-fuels by blending a heavy residue (propane asphalt) with kerosene to study its behaviour in the FIA. Properties were compared with those of a selection (~100) of commercial fuels; the results are given in Figure 18. The gap-fuels surprisingly show a quite normal ignition (FIA ID), probably because of the considerable amount of very light components. However the period between ignition and main combustion (FIA MCD) is longer than normal, as is indicated by the relatively high MCD. When conditions are worse, the start of the main combustion will be further delayed, resulting in a fuel that may still ignite but only partly combusts.

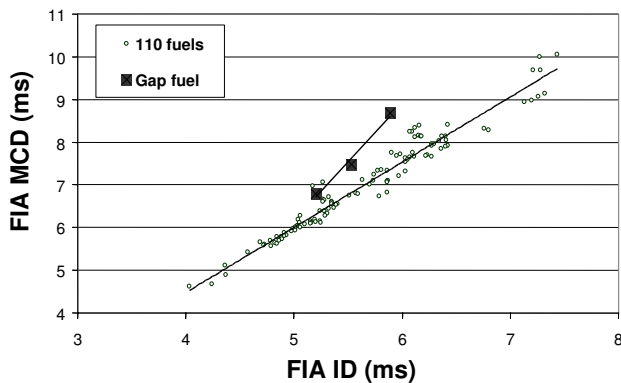


Figure 18 – FIA properties of gap-fuels

Our data show that with SIMDIST, and to a lesser extent FIA, it is possible to identify a gap-fuel, although evidence from FIA is still rather weak.

### IGNITION CONTROL IN FUEL PRODUCTION

In production control, the FIA may not be always be convenient to use or even necessary. As indicated earlier, and illustrated in Figure 19, the CCAI correlates poorly with FIA MCD ( $r^2 = 0.75$ ). However, when the individual blending curves of the blends of VBR and respectively HGO and LCO are considered, the correlation is much better, with regression coefficients of 0.86 up to 0.95. (Figure 20).

This is in line with earlier observations, discussed in previous sections, when separating straight run fuels and cracked fuels from correlations of CCAI and ignition delay (Schenk et al [3]). This illustrates that the CCAI can be a very valuable tool, for example in production control. Additionally, CCAI is a simple tool for providing a rapid estimate of the ignition quality, because information in the field on for instance FIA will in most cases, certainly in the near future, not be available.

### USE OF FIA IN SPECIFICATIONS

The suitability of using ignition and combustion data in residual fuel specification is one of the stated aims of the work that is currently underway. The work carried out so far and the experience we have gained in the field in a number of locations indicate that the data produced by the instrument could be used in the specifications of fuels intended for use in diesel engines. In this respect, it is believed that the FIA Estimated Cetane Number is suitable for this purpose.

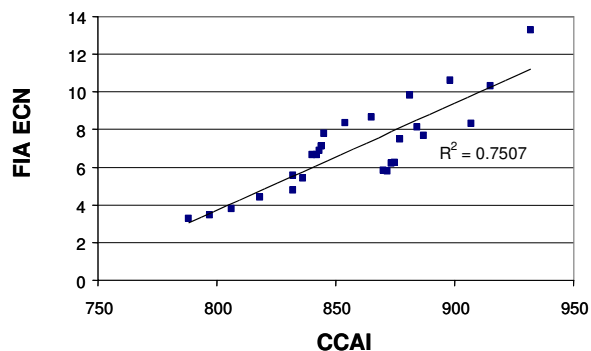


Figure 19 – Correlation CCAI and FIA ECN

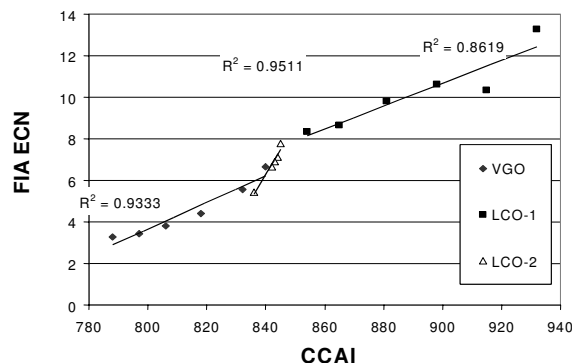


Figure 20 – Correlation CCAI and FIA ECN for separate blending curves

The dilemma is to determine what the limits should be. Unlike the automotive market, where engine builders design their engines in the knowledge that fuels will have a guaranteed minimum Cetane Number in a specific market, marine engine builders have had to decide for themselves on a minimum predicted ignition performance. The additional considerations in the marine market are the two very different engine groups: medium speed trunk piston engines and low speed crosshead engines. The physics of these two engine groups dictates that the ignition performance limits which can be tolerated will be different, with the low speed engine, in theory, being able to tolerate “slower” burning fuels.

What is known from our CCAI work and subsequent field experience is that within the above-mentioned groups the different makes and types of engines can have very different ignition performance requirements.

At this time we do not believe that with the current range of engines in the market a single FIA limit is appropriate. Our work shows that a limit which is ideal for one group of engines may be too low or unnecessarily high for other engines.

Certainly from a refiner's point of view, the nature of the components currently available for manufacturing marine fuels means that the higher the FIA CN, the higher the cost.

It is quite feasible to envisage a situation where grades of fuel might appear with different FIA CNs: for instance a fuel that would be guaranteed to work in low speed engines only, which would be cheaper than a fuel with a higher FIA CN and than a fuel that would be fit for use in almost all engines designed to operate on residual fuels.

The FIA already constitutes part of our fuel quality assurance system in a number of specific circumstances.

## RESIDUAL FUEL OIL STABILITY

As indicated earlier in this paper, problems associated with thermally cracked residues were being experienced during the first half of the twentieth century. The effect, in both the refinery systems and in the marine industry, was felt through sludge build up in storage tanks, filter blockage and blockage of heaters.

Work carried out in the early 1950s by van Kerkvoort [6] described the principles of fuel oil stability in terms of flocculation ratio (FR) and peptising power Po(g), later resulting in the Shell Stability concept of the P-value [7], which reflects the stability reserve of a heavy fuel oil. It was during this period that the first version of the Shell Hot Filtration Test [8] was published as an internal test method for assessing the stability of fuel oils. The test became an integral part of Shell's internal specifications for residual fuel oils. It consisted of two parts, the Existent, when the fuel was filtered at an elevated temperature in its original form, and a second test on a sub-sample that had been held at 80C for 24hrs, called the Potential.

As time passed, it was increasingly felt that the quality of residual fuel oil was dropping. Some fuel properties, particularly viscosity, density and carbon residue, were more frequently very close to the specification limits. Also there was a view in the marine industry that traditionally measured properties did not really capture changing quality.

The original Hot Filtration Test was modified and extended [9] by addition of an extra test procedure which involved treating the fuel with 10% hexadecane (cetane; a non-solvent) prior to filtration in order to reduce the aromaticity and stability of the fuel. Marginally stable fuels can be identified in this way. This was called the Accelerated HFT. This test could be completed in three hours, compared to the 25hrs needed for the

normal Potential HFT. These internal test methods were the basis from which the current Sediment by Hot Filtration – ISO 10307-1, ISO 10307-2 (procedures (a) and (b)) or IP375 and IP 390 procedures (a) and (b) were developed.

Heavy fuels oils have a much wider variation in composition than distillate fuels. They contain light liquid and heavy solid components, of which the heaviest fraction is called asphaltenes. Traditionally, asphaltenes are defined as materials that are insoluble in heptane and soluble in toluene. Asphaltenes are large aromatic molecules which require an aromatic medium, often referred to as the maltenes, to keep them in solution. In reality the situation is much more complex; but this simplified description helps to understand and explain a lot of phenomena related to fuel oil stability.

If there is a shortage of solvent, or if the solvent is not aromatic enough, i.e. too paraffinic, asphaltenes may separate from the fuel, flocculate into larger particles (flocs) and eventually form sludge which may block filters, centrifugal separators etc. These asphaltene flocs do not atomise during injection into the combustion chamber, resulting in long burnout times.

When considering test methods to define and measure the stability of residual fuel oils, one method is to use reference materials. In the methods developed by Shell, cetane is used as the low aromaticity reference and is given a Po of 0. For the high aromaticity reference, 1-methylnaphthalene is used, which is given a Po of 100. Table 5 shows the relative ranking of common chemicals used in stability analysis.

Table 5– Solvency power of different chemicals expressed as Po(g)

Solvent	Po(g)
Cetane	0
Heptane	17
Iso-octane	25
Toluene	65
Xylene	65
1-Methylnaphthalene	100

It should be noted that toluene is not used as the high aromaticity reference. This is because our research has shown that the most severe thermal cracking units operating today can produce molecules that are soluble neither in heptane nor toluene but are soluble in 1-methylnaphthalene (1-MN). The presence of these '*super-asphaltenes*' needs to be recognised and their properties understood.

When considering the practical effects of fuel stability, it is not necessary to know the complete chemistry of the fuel. For most applications it is sufficient to know that the fuel is stable and, ideally, has a workable stability reserve.

### P-value

As previously indicated, cetane is a paraffinic anti-solvent that can cause asphaltenes to separate from fuel oil. Test methods have been developed to determine the stability of fuel oil by adding measured amounts of cetane under standard conditions and determining the amount of cetane required to start flocculation of asphaltenes.

Shell developed the concept of the P-value [7], which is a measure of the stability reserve of a fuel oil. For example a P-value of less than 1.0 indicates that the fuel is unstable. A P-value of 1.0 indicates that the fuel oil is borderline stable; whereas P-values of 1.10 and 1.25 mean that 10% and 25% of cetane would need to be added to the fuels respectively to make them unstable. This is illustrated in Figure 21, which shows the relationship between P-value and Hot Filtration Test (TSE: ISO10307): a P-value of less than 1.0 evidently gives high sediments, and indicates that these fuels are unstable.

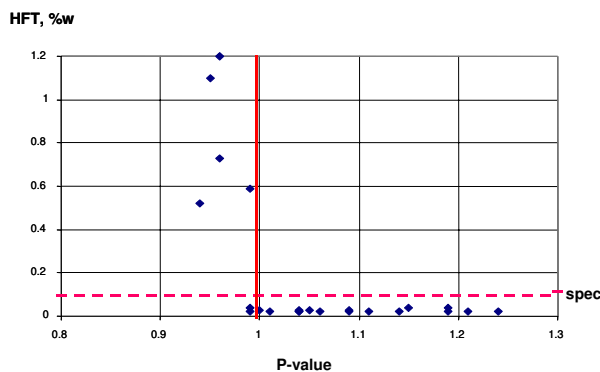


Figure 21 – Comparison P-value and Hot Filtration Test

### Po and FRmax

A more fundamental concept is Po/FRmax: Po is a measure for the peptising (aromaticity) power of the maltenes and FRmax indicates the minimum aromaticity power required to keep the asphaltenes in solution. If  $Po > FRmax$  then the fuel is stable; if  $Po < FRmax$  the fuel is unstable.

Fuel oil blending requires the use of both Po and FRmax, as it is not possible to predict the stability of the blend with P-value only. However, with a suitable database of Po and FRmax values for the different components, it is possible to predict the stability characteristics of blends without having to

carry out HFT analysis on test blends. Having said that, it is still necessary to carry out HFT testing on final blends to be certain the calculations based on Po and FRmax were correct.

### Other methods

While testing for stability is not particularly complex, the existing methods are time consuming, can require expensive laboratory instruments and/or require high calibre laboratory technicians to carry out the tests reliably. There is therefore a considerable incentive to develop a quick and easy test for stability.

In developing such test methods, it is essential that the underlying objective of the test is fully understood, i.e. is the test deriving fundamental chemical properties or is it more empirical and simply measuring a resultant condition? For example, HFT measures sludge in a fuel sample. A single test says nothing about the stability of the sample. Only if the Existent is used in conjunction with a repeat test on the sample after it has been treated either thermally or chemically can stability be determined.

A new technique based on the use of an optical scanning device appeared in the American Society for Testing and Materials (ASTM) Standards books recently, claiming to estimate the stability reserve of residual fuels. To examine the potential of this test method a test instrument, referred to in the test method, was purchased (Turbiscan) [10] in order to compare its output with normal stability tests. A correlation was made with the P-value, a proven technique for determining fuel oil stability reserve.

For sample preparation in the Turbiscan, it is required to dilute a fuel oil sample diluted with successively toluene and heptane, resulting in at least a 100-fold excess of solvent (85/15 heptane/toluene). This combination of solvents ensures that asphaltenes flocculate even with stable fuels. The Turbiscan then measures the rate in which these asphaltenes settle by means of light scattering, referred to as the separability number (SN). A SN of less than 5 indicates a stable fuel. A SN between 5-10 is indicative for a fuel with minimum stability reserve whereas a SN of more than 10 indicates that the fuel has no stability reserve.

When comparing these data with the P-value, one can observe that even perfectly stable fuels with P-values above 2.0 are classified as unstable according to the Turbiscan method (Figure 22).

This leads to the conclusion that the Turbiscan test method in its current manifestation does not give a

good measure for the fuel oil stability reserve and may erroneously report perfectly stable fuels as unstable or vice-versa.

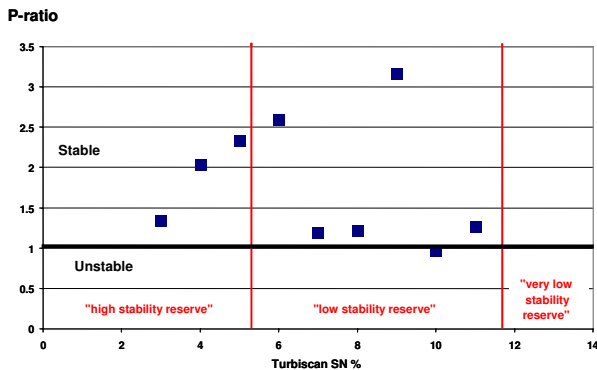


Figure 22 – Comparison P-value and Turbiscan

### Compatibility

This term is used to describe the tendency for two stable fuels and or components to form unstable blends.

Generally ship operators are well aware of the risks of mixing different batches of fuel onboard ship. Wherever possible, fuels are kept segregated in the bunker tanks. Nevertheless there are times when mixing fuels on board is very difficult to avoid. This is particularly the case when a new fuel batch is introduced to the settling and service tank unless the vessel has completely duplicate systems.

Normally the advice is to avoid mixtures that fall around the 50:50 range e.g. avoid 60:40, 40:60 mixing ratios. Normally, mixes outside this range are unlikely to be incompatible.

Work carried out over the last few years has shown that this recommendation does not necessarily hold true when mixing high and low sulphur fuels. This work has shown that mixtures containing as little as 10% low sulphur fuel can become unstable (Figure 23). Clearly ship operators need to take this into account when it is necessary to carry stocks of high and low sulphur fuels onboard, when for instance, the vessel trades in and out of SECA zones.

Unless totally segregated fuel systems are fitted onboard the vessel it would be prudent for the operators to establish whether there are compatibility issues with the fuel stocks onboard before allowing them to mix. Test kits such as the Shell Spot Test Kit can give a good indication as to the risk of compatibility between two given fuels and enable the ship's staff to manage the situation appropriately.

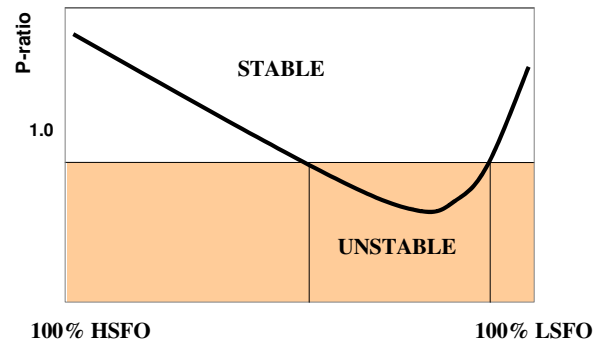


Figure 23 – Example of HSFO-LSFO (in)compatibility

### Conclusion on stability and compatibility

Although there has been a considerable change in the composition of marine fuel oil due to changes in refinery configuration and operation, research has shown that whilst the nature of asphaltenes has changed, the established analysis and testing methods are still appropriate for determining the stability of modern residual fuels.

The compatibility characteristics of high and low sulphur fuels do not follow normal established rules and greater care is necessary where these two types of fuels are mixed.

### SUMMARY

- 1) Ignition delay and main combustion delay determined by the FIA show good correlation with ignition delay in a 2-stroke low speed and 4-stroke medium speed test engine. At low loads in the medium speed test engine, the correlation is poor, which is explained by differences in temperature dependence of the ignition delay.
- 2) MaxROHR from FIA does not correlate with combustion hardness in the engine.
- 3) Temperatures and pressures vary widely in the engine and do not correspond to conditions in the FIA. Additionally, the fuel injection period in the FIA is much shorter than in the engine and does not overlap with the combustion reaction.
- 4) Ignition quality of heavy residual products that cannot be tested in the FIA because of too high viscosity can now be determined by extrapolation from blending curves.
- 5) CCAI is a powerful tool to get a first, quick and rough estimate of fuel oil ignition quality and may be of use in production control, once the relationship with FIA ECN is established.
- 6) Fuel composition has a significant affect on the ignition performance of finished fuels. It cannot be

assumed that generic refinery streams, e.g. cycle oils, will have similar ignition performances. Nor can the ignition performance of blends be predicted, particularly if the streams come from different sources.

7) Gap-fuels can be identified by special chromatography techniques, which nowadays are relatively simple, cheap and fast.

8) The processing units and operating conditions in oil refineries have been changing significantly over the last 10 years in response to crude oil supply issues and increasing emissions regulations being introduced at national and international levels. This has affected the composition and characteristics of residual fuels.

9) The existing Hot Filtration Test methods are still suitable for determining whether a fuel is stable or not. Use of the Accelerated Hot Filtration test imposes a minimum stability reserve. Both the Existing and Potential HFTs are necessary to determine the stability of a fuel.

10) The P-value is a good indicator for fuel oil stability reserve and may be considered for specification purposes.

11) In its current form, Turbiscan is not suitable for determining fuel oil stability reserve and may erroneously classify stable fuels as unstable or vice-versa.

## CONCLUSIONS

Suitable test methods to determine the fuel oil stability reserve and ignition properties are in principle available for performance testing and specification purposes. The robustness of these techniques has been proven, and this paper has presented results which demonstrates their relevance to fuel performance.

Shell Marine Products has introduced the P-value and FIA in their Fuel Oil Quality Assurance System (FOQAS), where it is part of the fuel oil component approval scheme, and is preparing for the introduction of ignition specifications in production control and product specifications.

The primary purpose of this is to ensure that fuels delivered to customers, now and in the future, continue to be fit-for-purpose.

## NOMENCLATURE

P-value - stability reserve of fuel w.r.t. asphaltene flocculation, expressed as ml of cetane that can be added to 1g of fuel oil sample without giving asphaltene flocculation (SMS1600)

Po - peptising power (aromaticity) of the maltenes (ASTM 7060)

FRmax – maximum flocculation ratio or minimum aromaticity require to keep asphaltenes dissolved (ASTM 7060)

SECA – Sulphur Emission Control Area as defined in MARPOL Annex VI

Fuel Ignition Analyser (FIA) terminology:

ABP – After Burning Period

EC – End of Combustion

EMC – End of Main Combustion

ID – Ignition Delay

Max PI – Maximum Pressure Increase

MCD – Main Combustion Delay

MCP – Main Combustion Period

PCP – Pre Combustion Period

ROHR – Rate Of Heat Release

AR – Accumulated ROHR (Surface Area)

EC – End of Combustion

Max ROHR – Maximum Rate of Heat Release

PMR – Position of Maximum Rate of heat release

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