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WHITEPAPER

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With the prevalent operational issues associated with VLSFO, understanding the causes for truly effective and timely mitigation is crucial for ship operators and crew to avoid costly operational disruptions and permanent machinery damage.

CTI-Maritec shares key insights with in-house data evidence and recommendations to shed light on optimal testing and management of VLSFO.

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1. Introduction

Since 01 January 2020, the International Maritime Organization (IMO) enforced a 0.50% global sulphur cap in marine fuels for the shipping industry to reduce sulphur oxide (SOx) emissions, which is a significant reduction from the previous limit of sulphur at 3.5%. Therefore, greater use of Very Low Sulphur Fuel Oil (VLSFO) came into play post 2020. However, a comparison between fuel properties of High Sulphur Fuel Oil (HSFO) and VLSFO reveals that VLSFO exhibits greater instability, waxiness, lower density, and viscosity, lower calculated Carbon Aromaticity Index (CCAI), lower vanadium content, higher net specific energy, higher pour point, and higher acid number.

The decreased stability reserve (detected by higher paraffinic and lower aromatic content) of VLSFO also raises concerns about compatibility issues when different fuels are mixed. Even after four years of using VLSFO, the long-term storage of VLSFO still remains a challenge and pain-point for the marine industry.

All present-day complexities of VLSFO arise due to its formulation and the processes used to achieve 0.50% sulphur content. The composition of VLSFO varies widely because it is a blend of several types of refined petroleum products, including distillate oil, residual fuels and additives, among others. VLSFOs are more paraffinic than HSFOs owing to its composition, which consists predominantly of small and medium chain hydrocarbons, including alkanes (paraffins) and cycloalkanes (naphthene), among others.

Furthermore, due to the widely varied compositions of VLSFOs sold in the bunker fuel oil market, the physical and chemical properties and qualities vary greatly, thus exhibiting significantly different chemical behaviours, which can only be accurately determined through focused monitoring/testing. This variability can affect engine performance. The characteristics of VLSFO also demands more attention towards storage and handling practices to prevent issues like stratification or sludge formation, especially during the fuel change over process. VLSFO reduces SOx emissions, however, the emission of other pollutants, such as black carbon remain a concern. Therefore, a careful fuel management process is required to optimally manage VLSFO.

Additionally, the issue of chemical contamination has plagued the bunkering industry for years, and the risk of receiving contaminated bunker fuels is likely to persist due to the complexity of the fuel supply chain.

2. CTI-Maritec data evidence on main challenges observed with VLSFO

Basis data of 2022 till date from CTI-Maritec's Marine Fuel Testing Programme (MFTP), 50-55% of samples tested are for VLSFO. Currently, there is no specific grade basis a standard available for VLSFO. Out of all VLSFO tested by CTI-Maritec, 55-60% are of RMG380 grade, 25-30% are of RME180 grade and the rest are of other grades.

Important points to note to understand characteristics of today's VLSFO:

- The average viscosity, density, and MCR of VLSFOs are lower than HSFOs indicating that they are more paraffinic compared to HSFOs.
- CCAI is lower for VLSFO compared to HSFO, which means VLSFO Ignition quality is better than HSFO.
- The calculated calorific value of VLSFO is higher than HSFO.
- The average acid number of VLSFOs is higher than HSFOs.

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2.1 Comparison of off-spec parameters (Chart-1) and machinery & operational issues for HSFO vs VLSFO (Chart-2) from 2022 till date

CTI-Maritec has found 4-5% of all VLSFOs tested between 2022 till date, as part of our MFTP, have reported at least one specification parameter as off-spec.

The data indicates that Sulphur, Water, Viscosity and Pour Point are the top-most in the off-spec list of overall off-spec parameters. Based on reported machinery problems CTI-Maritec also observed a paradigm shift in the nature of machinery issues after transitioning from HSFO to VLSFO.

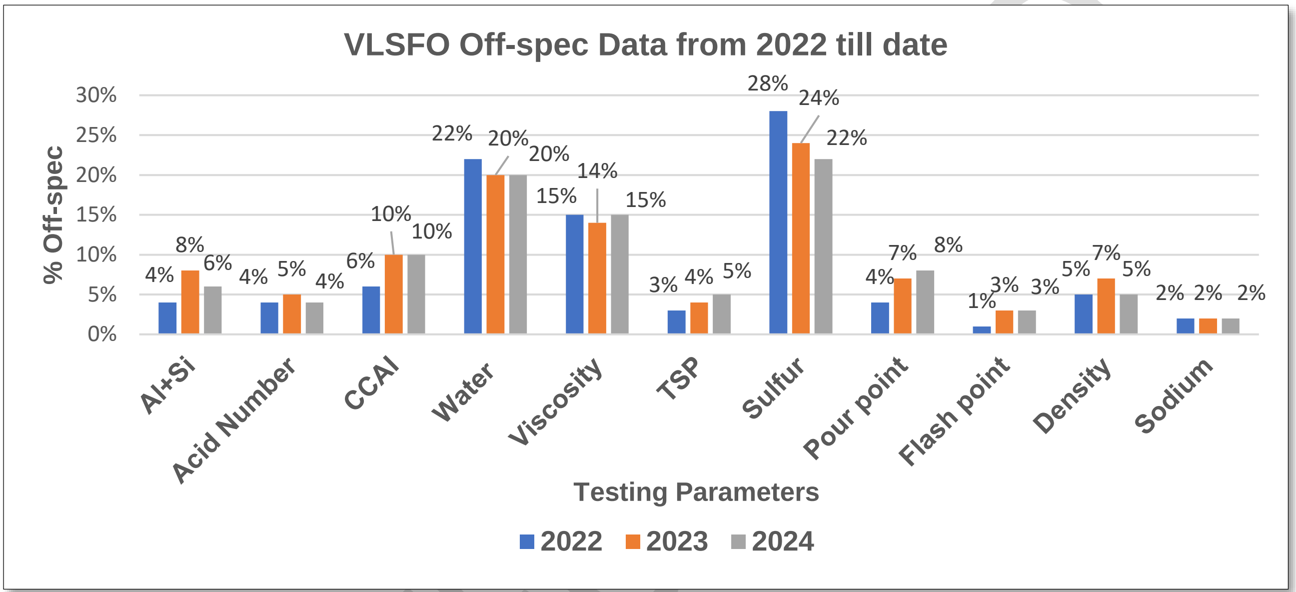

Chart 1: Off-spec data evidence in parameters tested for VLSFO samples from 2022 till date

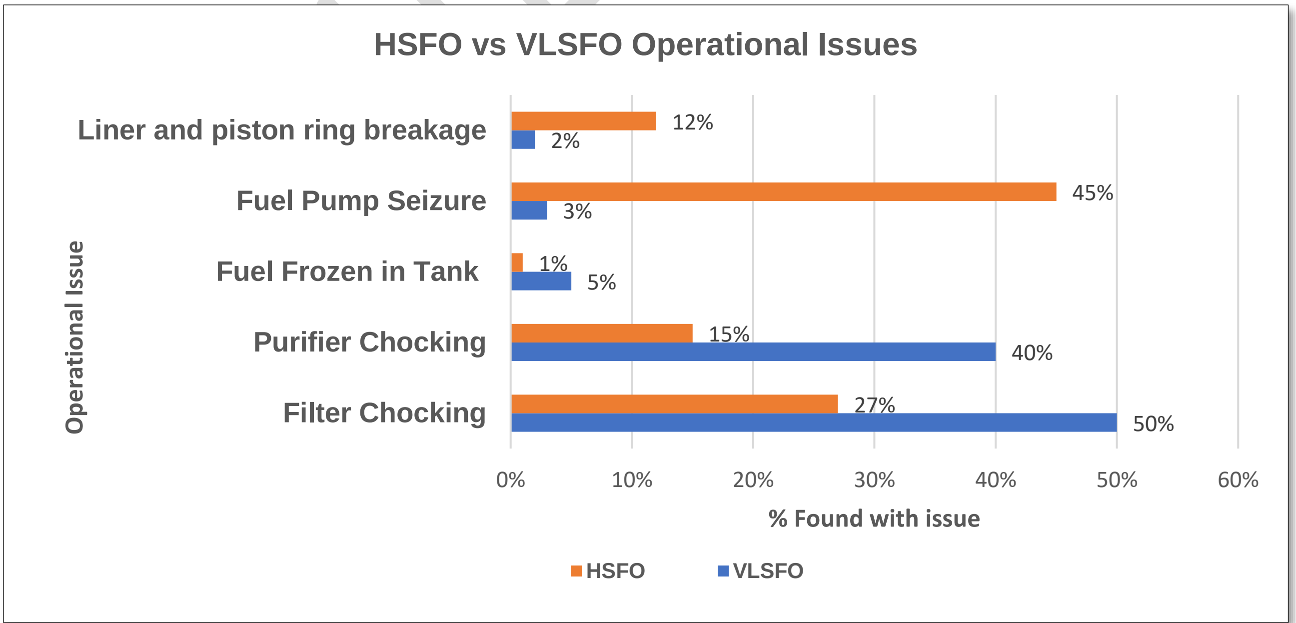

Chart 2: Comparison of reported machinery issues for HSFO vs VLSFO

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2.2 Cold Flow Properties Issues, Testing Recommendations & Pour Point vs WAT & WDT

CTI-Maritec has observed that there is a rise in cold flow property issues within paraffinic-grade VLSFOs, characterized by higher Pour Points, which can potentially introduce concerns regarding cold flow problems, particularly wax formation. Basis on our database this trend was also observed in Bio-VLSFOs like B24 and B30.

The wax formation in VLSFO during storage is one of the most frequently reported operational issues to CTI-Maritec. Specifically, the issue can grow to be of serious concern when VLSFOs have viscosity below 100cst and Pour Points above 21 Degrees Celsius (°C).

CTI-Maritec recommends testing for Wax Appearance Temperature (WAT) and Wax Disappearance Temperatures (WDT) when fuel is found to have Pour Point at 21 °C and above.

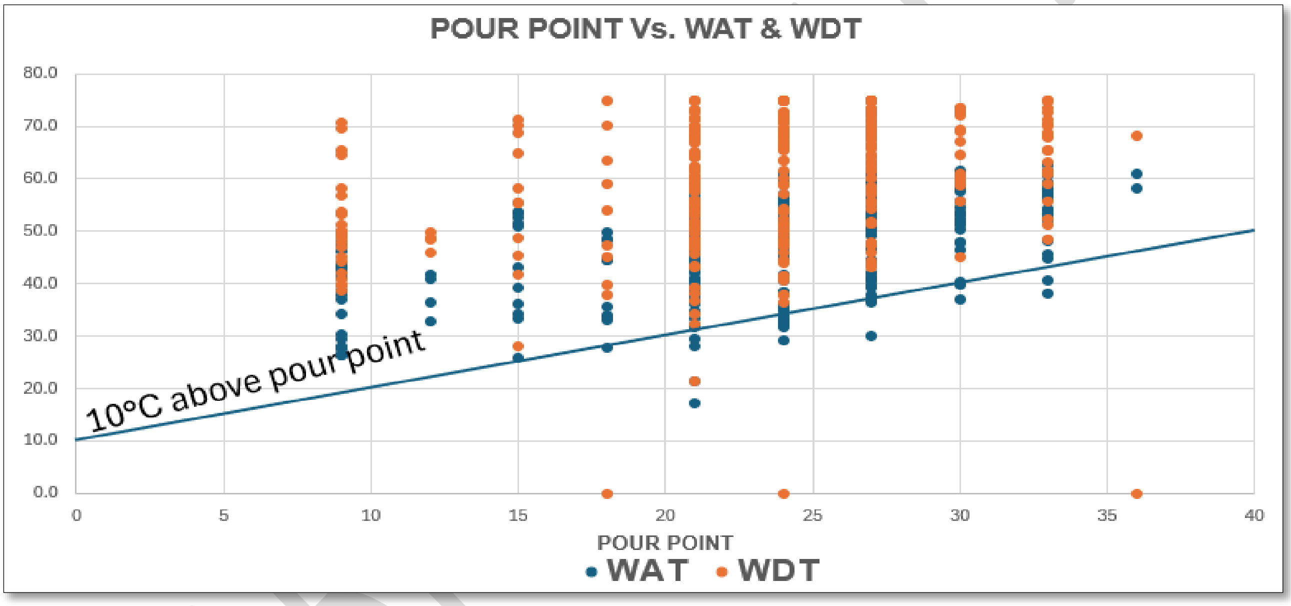

Chart 3: Comparison of WAT & WDT against Pour Point

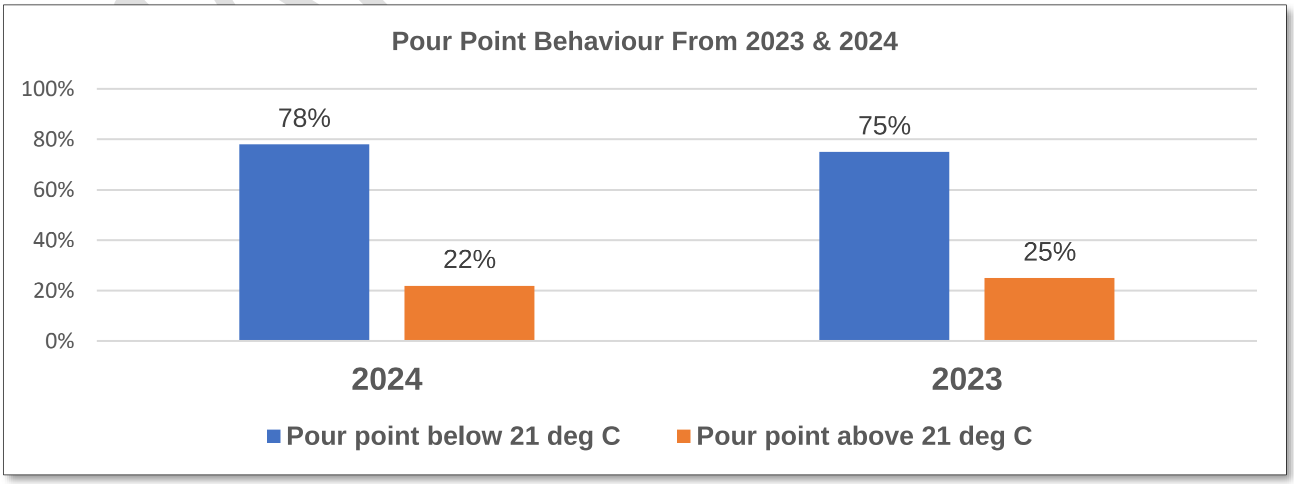

Chart 4: Indication of samples tested in 2023 & 2024 till date with Pour Point above 21°C

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3. Key Insights on handling Issues associated with Onboard System Temperature and Stability with Recommendations for Optimal Management

3.1 Onboard System Temperature

The physical properties of VLSFO like Density, Viscosity and Pour Point affect how fuel is handled and stored. VLSFOs with high Viscosity require heating for efficient pumping and transfer, while very low Viscosity can pose as a potential risk of leakage.

Density of fuel determines how fuels will be stored and segregated; different densities can indicate whether fuels can be mixed or how they should be layered in storage. Again, VLSFOs with low viscosity and high Pour Point is waxier and have high potential to form wax crystals during storage. Therefore, maintaining ideal system temperature onboard is crucial for VLSFO.

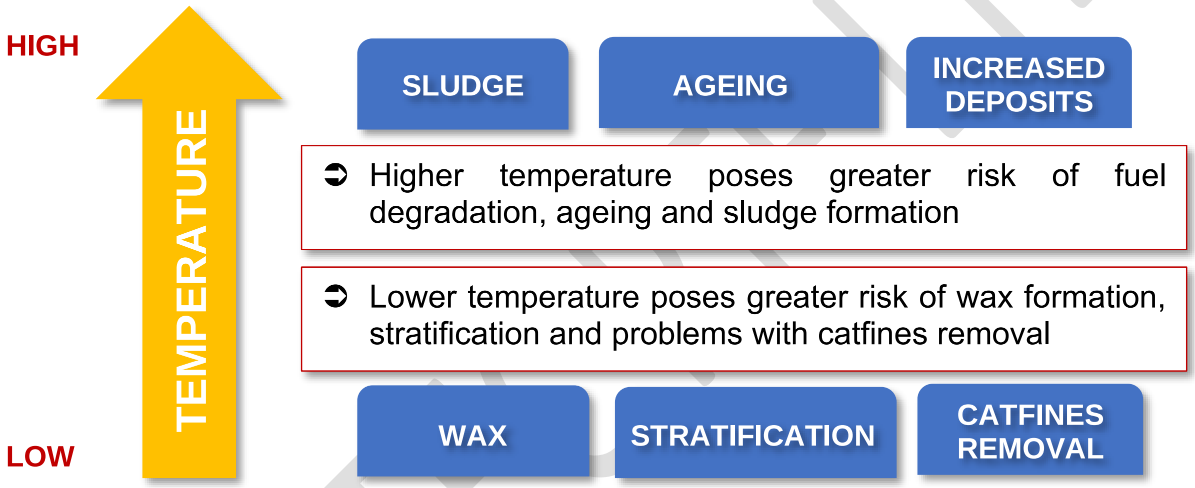

Figure 1: Visual representation of physical property risks associated with Onboard System Temperature when not maintained at optimal levels

3.2 Stability

Stability of a residual fuel is defined by its resistance to the breakdown and precipitation of asphaltene sludge despite being subjected to external forces, such as thermal, mechanical, and ageing (storage duration) stresses, while handled and stored under normal operating conditions.

The factors that influence stability of residual fuels are fuel formulation (an internal factor, fuel blend itself – on whether the fuel has sufficient aromaticity or contains any appreciable amount on non-hydrocarbons) and the external factors such as thermal & mechanical stress and storage duration.

The stability of a residual fuel is important for the safe handling and use on board ships. An increase in fuel stability issues is also observed which arises from two factors. Firstly, the use of hydrotreated blend stocks reduces the stability reserve of the fuel due to lower aromaticity and asphaltene solubility. Secondly, when low sulphur aromatic and paraffinic blend stocks are mixed, fuel instability may occur if the blend lacks adequate aromatic content to dissolve the asphaltenes present. Additionally, an increase in fuel compatibility issues can occur when aromatic and paraffinic-grade VLSFOs are co-mingled, leading to

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incompatibility and potential flocculation of asphaltenes if the blend lacks sufficient aromatics.

The composition of residual fuels is complex to define (depending on crude source and refining processes (as described earlier) but generally residual fuels consist primarily of saturates, aromatics, resins and asphaltenes. In order to keep the asphaltenes in colloidal suspension, the asphaltenes are dispersed by resins and the dispersions are dissolved in aromatics.

A fuel is considered stable if its material properties over time can be retained. Due to various blending composition of VLSFO, asphaltenes and other aromatic, polar, hydrocarbon molecules tend to clump together, forming thick sludges in storage tanks, purifier etc. The sludge formation can lead to clogging of filters, purifier and pipes.

Due to overloaded fuel pumps, there can be problems with ignition and combustion and a risk of permanent damage of piston rings, and cylinder liners. In extreme cases this can even stop the main and auxiliary engines, presenting serious danger to the ship and its crew.

How to determine stability of VLSFO?

There are three sediment tests covered within ISO 8217 for optimal testing to determine stability of VLSFO. They all aim to define the total amount of sediments contained in a fuel sample.

- *Total Sediment Existent (TSE):* ISO 10307-1 is hot filtration method indicating the sludge that is likely to be separated by an on-board centrifuge.
- *Total Sediment Potential (TSP):* ISO 10307-2 is a thermal aging test method to determine the amount of sediment after prolong heating.
- *Total Sediment Accelerated (TSA):* ISO 10307-2 is a chemical aging test method to determine amount of sediment upon acceleration by adding hexadecane, a paraffinic solvent.

The agreed limit for both TSP and TSA is 0.10% m/m – a fuel that falls below this limit should be consider as in-spec fuel.

However, based on CTI-Maritec's data of the past three years, operational issues of unstable VLSFO were reported when Total Sediment Test results were within the specification limit, typically at 0.05% m/m and above.

A logical explanation for this is that at the time of bunkering the fuel may have been stable and therefore Total Sediment Test result indicated 0.05% m/m and above (e.g. 0.10% m/m).

However, based on other contributing factors the fuel was most likely not suitable for long term storage and after a certain period of time the fuel become unstable and total sediment thus increased. It is, therefore, critical to continually test for total sediment to optimally and accurately determine storage behaviours and stability.

The following (Chart 5) showcases the distribution of TSP (Total Sediment Potential) data for reported operational issues from the past three years, 2022 to 2024 till date.

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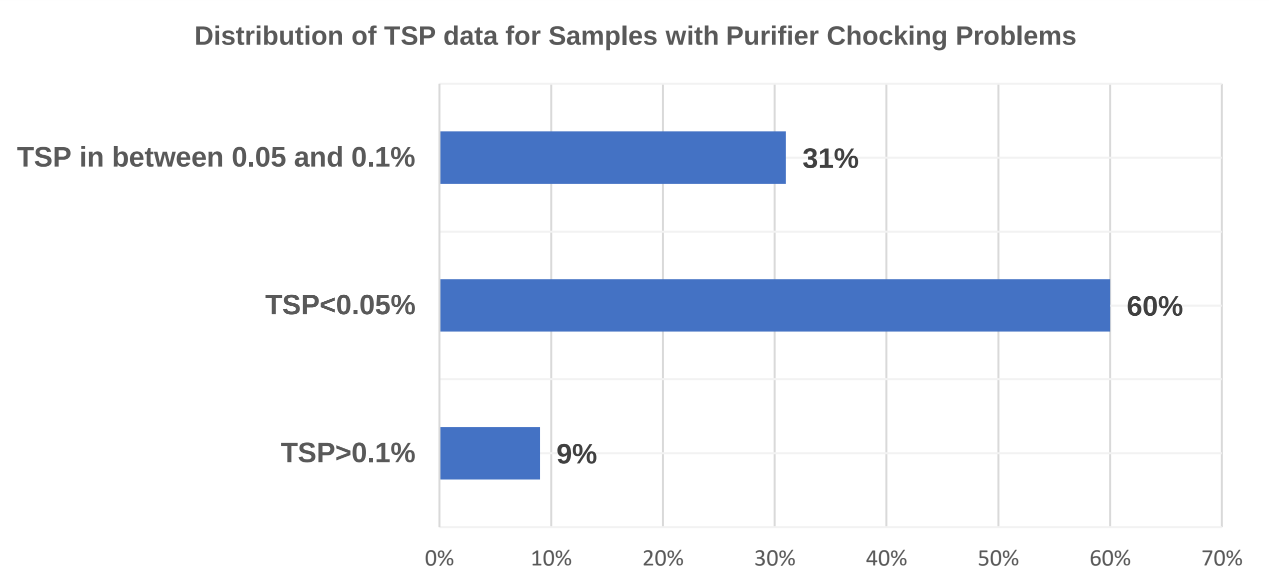

Chart 5: Distribution of TSP data from the past three years

3.3 Stability Reserve & P-value testing by SMS 1600 to measure Long Term Stability

As stability factors of VLSFO cannot be determined solely with Total Sediment data it is important to also determine Stability Reserve to understand long-term stability properties of the fuel.

Stability Reserve is a measure of the ability of an oil to maintain asphaltenes in a dispersed state or to maintain asphaltenes in a peptized (colloidally dispersed) state and prevent flocculation of the asphaltenes.

In another words, stability reserve is a measure of the available solvency power of a fuel with respect to precipitation of asphaltenes. In a layman terms, stability reserve is an indication of the capacity for one fuel to absorb another fuel without asphaltenes dropping out of suspension. ***In this respect, CTI-Maritec recommends routine testing for Stability Reserve to help determine Long Term storage behaviour.***

With VLSFOs, the Stability Reserve test gives an indication of the available solvency power of a fuel with respect to precipitation of asphaltene. The higher the stability reserve the more stable is the particular fuel is with respect to flocculation of asphaltenes.

P-value by SMS 1600 for Measuring Stability Reserve

For P-value by SMS 1600 testing, portions of the test sample are diluted with varying amounts of cetane (10% increment, 10% to 60% or more) and, after a prescribed heating and storage period, the mixtures are examined for the presence of flocculated asphaltenes by means of a microscope.

In this way, the *Critical Cetane Dilution* is determined from which, the P-value of the sample is calculated.

Critical Cetane Dilution (Xmin) is the number of millilitres of cetane with which one gram of the sample can be diluted until it just does not flocculate the asphaltenes.
P-value is equal to 1 plus Xmin (or 1 + Xmin).

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The P-value of an oil gives information on stability and stability reserve. A higher P-value indicates that an oil is more stable with respect to flocculation of asphaltenes.

If flocculated asphaltenes are present in the original sample, the P-value is determined as <1.00. Interpretation of P-value by SMS 1600 test results are tabulated as per the table below:

P-Value	**Stability**
P-value <1.00	Fuel is not stable, original sample has flocculated asphaltenes present
1.00 >= P-value < 1.30	Fuel is marginally stable and not suitable for long term storage
1.30 >= P-value =< 1.50	Fuel with acceptable stability and may not be suitable for long term storage
P-value > 1.50	Fuel is stable: For strategic long-term storage, fuels with a higher P value (E.g., > 1.5) are preferred as this provides a wide margin for ageing.

4. Chemical Contamination Issues & CTI-Maritec Investigative Findings

The issue of chemical contamination has plagued the bunkering industry for years, and the risk of receiving contaminated bunker fuels is likely to persist due to the complexity of the fuel supply chain. In recent times, there have been notable machinery issues affecting vessels bunkering from the United States, particularly in the Houston area. These problems include failures in Main Engine startup, loss of power from auxiliary engines resulting in the loss of propulsion, and fuel pump malfunctions, among others. These concerns have been widely reported in the news.

CTI-Maritec, as an independent fuel testing laboratory, undertook an investigation into fuel samples collected from this region. The analysis revealed elevated levels of specific compounds, which have raised concerns about the stability of the fuel being used in these vessels. Our testing identified three vessel fuel samples with significantly high levels of two compounds, being Dihydro-dicyclopentadiene (ranging from 1200 ppm to 6000 ppm) and Tetrahydro-dicyclopentadiene (ranging from 2500 ppm to 5500 ppm).

These samples exhibited a poor reserve stability, measured using manual P-value by SMS1600 test method. This suggests a lack of homogeneity in the fuel sample, which could potentially point to similar conditions in the supplied fuel. Figure 2 shows our findings for one of the samples upon progressive dilution with cetane, a paraffinic solvent prescribed for SMS 1600 test method.

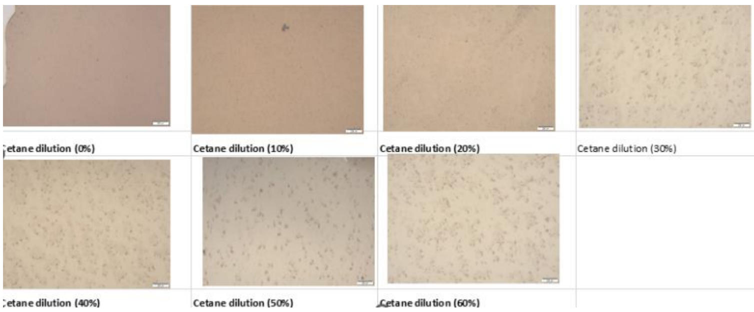

Figure 2: Progressive cetane dilution under microscopic observation

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For acceptable fuel stability asphaltene flocculation generally does not occur upon cetane dilution up to 30%, and fuels that are able to withstand dilution up to 50% are considered as stable fuels for strategic long-term storage.

For the sample tested, asphaltene flocculation was detected prior to cetane dilution and gradual increase of cetane % increased the observed flocculation levels which indicates the fuel has poor stability reserve.

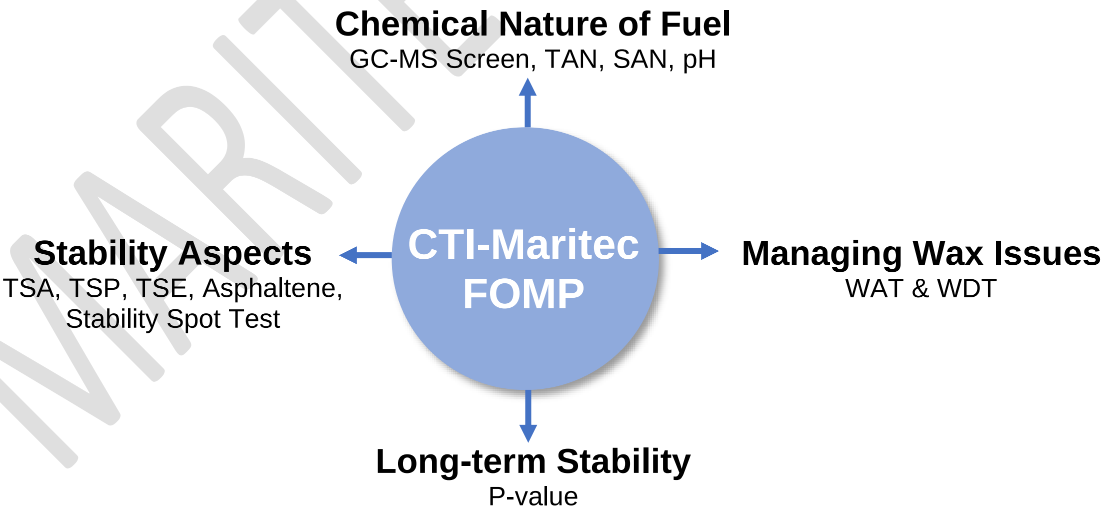
The presence of the compounds detected at elevated levels for the fuels tested increases the risk of unmanageable sludge deposition in the fuel oil system. This, in turn, can result in complications related to fuel treatment processes and engine operation.

It is worth noting that while these compounds are commonly found in marine bunker fuels, their current prevalence in this region is unusually high. This may indicate inadequate quality control measures within the production and supply chain.

Based on the above findings, it can be argued that these fuels represented by the tested samples may not meet the general requirements outlined in Clause 5 of ISO 8217. ***In order to mitigate the risks associated with chemical contamination of VLSFOs, CTI-Maritec recommends pre-emptive Gas Chromatography Mass Spectrometry (GC-MS) Headspace Screening testing for all bunker fuels.***

5. CTI-Maritec 'Fuel Operations Management Package' (FOMP)

CTI-Maritec offers a carefully designed pre-emptive fuel testing package, 'Fuel Operations Management Package' (FOMP), to assist with predicting fuel issues linked to VLSFOs. The testing provided with CTI-Maritec's FOMP supplies extensive guidance to ship operators and crew for optimal operational management of fuel usage.



CTI-Maritec recommends carrying out FOMP testing alongside routine MFTP analysis to augment monitoring and pinpoint issues of VLSFO at the point of bunkering and/or otherwise. The cost effective FOMP services are available 365 days a year with high-speed reporting to ensure guidance is provided efficiently for effective intervention.

For more information on our FOMP services & solutions write to CTI-Maritec at admin.maritec.com.sg.

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6. Summary & Conclusion

As an independent third-party testing laboratory, CTI-Maritec has unbiasedly presented evidence and legitimate observations from data of the last three years (2022 till date), which clearly indicate the prevailing issues with VLSFOs. As given, to summarise, our data indicates that Sulphur, Water, Viscosity and Pour Point are the top-most in the off-spec list of overall off-spec parameters. Furthermore, as an outcome of poor point, wax formation in VLSFO during storage is one of the most frequently reported operational issues to CTI-Maritec.

With reported cases of operational issues of unstable VLSFO (usually in the case of low TSP and TSA), it is also cautious to continually measure Stability Reserve to monitor the long-term storage aspects of VLSFO.

Additionally, CTI-Maritec's findings from a recent study of samples originating from the Houston bunkering area exhibited poor reserve stability due to the presence to two chemical compounds, which further supports the prevailing risks of receiving contaminated bunker fuels and the vital need to conduct routine pre-emptive testing to assist with robust risk mitigation. As a key 'early detection' system, CTI-Maritec strongly recommends routine Gas Chromatography Mass Spectrometry (GC-MS) Screening testing in addition to routine MFTP testing to accurately monitor 16 key compounds under 4 main classes, including Chlorinated Organic Compounds (COCs), for detection of any abnormalities before they escalate into costly operational disruptions.

In today's landscape of marine bunker fuel alongside rising concerns with VLSFO behaviours, owing to their formulation and processes used to achieve the stipulated sulphur cap, taking pre-emptive measures to mitigate risks is no longer a luxury but a necessity in pro-actively protecting vessel health and crew safety.

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