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Study to evaluate test methods to assess the stability and compatibility of marine fuels in view of the IMO MARPOL Annex VI Regulation 14.1.3 for 2020 Sulphur requirements

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Study to evaluate test methods to assess the stability and compatibility of marine fuels in view of the IMO MARPOL Annex VI Regulation 14.1.3 for 2020 Sulphur requirements

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ABSTRACT

This report describes work sponsored and coordinated by Concawe and conducted by ISO/ TC28/ SC4/ WG6 in view of the variety of fuel blend formulations expected to enter into the market as a result of tightening sulphur limits for marine fuels as of 1 January 2020. The objective was to explore whether the test methodologies of ASTM D7157, D7112 and D7060 can be applied to residual marine fuels to obtain additional insight into their stability with respect to precipitation of asphaltenes and whether these methods can be used to predict the compatibility between fuels, without blending the fuels together. The study was conducted on a limited number of fuel samples as 0.50% max. sulphur fuels were not widely available at that time. The study shows that ASTM D7157, D7112 and D7060 can be used to obtain information on the degree of compatibility, though in some cases inconsistencies have been observed. Where possible, testing for compatibility of fuels to be comingled is recommended. Good practices to minimise the risk of incompatibility of fuels should be maintained and more data collected on commercially available samples.

KEYWORDS

Stability, compatibility, total sediment aged

INTERNET

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1. SUMMARY

With the introduction of the 0.50% max. sulphur limit as of 1 January 2020 for marine fuels, it is expected that due to the current limited availability of these fuels, a wide variety of new blend formulations will enter into the market. All residual type (RM) fuels supplied have to be stable at the point of delivery which is controlled by the total sediment aged limit of 0.10 mass % max., as specified in the ISO 8217 Standard that sets specifications for marine fuels. While it is recommended to segregate different loadings of residual fuels on board the ship to avoid precipitation of asphaltenic sludge, this is not always possible in practice and some commingling cannot be excluded. In those instances, it is of interest to know the degree of compatibility of the fuels being comingled. Suppliers cannot guarantee the compatibility between different fuels and with the anticipated variability in 0.50% S max. fuel blend formulations, more questions on the compatibility of fuels and how to determine it have been raised.

Therefore, an industry study has been performed to investigate whether test methods ASTM D7157, D7112 and D7060, currently not yet widely used for marine fuel stability testing, can provide additional and consistent information on the stability and potential instability of marine fuels or mixtures of fuels. The fuel set used included ultra low sulfur fuel oil (ULSFO), very low sulfur fuel oil (VLSFO), low sulfur fuel oil (LSFO) and high sulfur fuel oil (HSFO) samples. VLSFO samples might be prototype fuels provided by fuel suppliers and traders and not necessarily identical to what will be available as of 1 January 2020 whereas ULSFO, LSFO and HSFO samples have been provided by either fuel suppliers, traders or shipping companies.

The study showed that it is recommended to use the potential total sediment test to guarantee the sediment aged limit of 0.10 mass % and that D7157, D7112 and D7060, which are laboratory tests but not yet widely available, can be used for the determination of parameters to assess the stability of residual marine fuels. These tests can be used to obtain an indication of the degree of compatibility of residual fuels at a certain ratio when the fuels have been tested with the same test method.

Although the study is based on a limited number of samples as 0.50% max. sulphur fuels were not widely available at that time. ASTM D7157, D7112 and D7060 predict a similar percentage (respectively 69% and 65%) of all possible fuel combinations to give stable blends whatever the mixing ratio is. The study shows that ASTM D7157, D7112 and D7060 can be used to obtain information on the degree of compatibility, though in some cases inconsistencies have been observed. Where possible testing for compatibility of fuels to be comingled is recommended. Good practices to minimise the risk of incompatibility of fuels should be maintained and more data collected on commercially available samples.

2. DEFINITIONS

The definitions are as included in ISO/PAS 23263 [1].

2.1. STABILITY OF A RESIDUAL FUEL

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

2.2. COMPATIBILITY

The ability of two or more fuels to be commingled at a defined ratio without evidence of material separation, which could result in the formation of multiple phases e.g. flocculation, where dispersed particles of asphaltenes form bigger clusters which might lead to sludge formation.

2.3. STABILITY RESERVE

The ability of an oil to maintain asphaltenes in a peptized (colloidally dispersed) state and prevent flocculation of the asphaltenes.

2.4. EXISTENT TOTAL SEDIMENT (TSE)

Total sediment determined by ISO 10307-2, i.e. on the sample itself.

2.5. TOTAL SEDIMENT AGED

2.5.1. Potential total sediment (TSP)

Total sediment, determined by ISO 10307-2, after ageing a sample of residual fuel for 24 h at 100 °C under prescribed conditions. [source: ISO 10307-2 procedure A]

2.5.2. Accelerated total sediment (TSA)

Total sediment, determined by ISO 10307-1, after dilution of a sample of residual fuel with hexadecane in the ratio of 1 ml per 10 g of sample under carefully controlled conditions, followed by storage for 1h at 100 °C. [source: ISO 10307-2 Procedure B]

3. INTRODUCTION

3.1. MARINE FUELS

Marine fuels as we know them today, are either distillate (DM) or residual (RM) type products predominantly consisting of hydrocarbons primarily derived from petroleum sources but may also contain hydrocarbons from renewable or synthetic sources or from co-processing of a renewable feedstock with a petroleum feedstock.

RM type fuels can have a viscosity up to 700 cSt at 50 °C or higher and are generally blends of refinery high viscosity residual components and lower viscosity materials such as kerosene, gasoil, diesel, light cycle oil or heavy cycle oil, in order to achieve the desired viscosity and to meet ISO 8217 specifications [2]. The higher viscosity residual components typically contain asphaltenes, high molecular weight polar molecules having a predominantly aromatic structure, which are kept in colloidal suspension[1]. RM fuels are manufactured with a certain degree of aromaticity reserve to avoid precipitation of the asphaltenes and with the stability guarantee of maximum total sediment aged (ISO 10307-2) of 0.10 mass %.

While two RM type fuels can meet the stability requirement, it does not necessarily mean that commingling of two stable fuels will lead to a stable final fuel blend.

3.2. 0.50 % MAX SULPHUR FUEL OILS

On 1st of January 2020, MARPOL Annex VI Regulation 14.1.3 enters into force in order to reduce exhaust SOx emissions from shipping and reduces the sulphur content in marine fuels from 3.50 to 0.50 mass % max. when operating outside emission control areas (ECAs). Marpol Annex VI allows the use of equivalent methods such as exhaust gas cleaning systems to achieve the same level of emission reduction, which then allows ships to continue to burn higher sulphur fuel oils. This regulation will result in a major change to the range of fuel formulations being offered on the marine fuel market. The International Maritime Organization asked ISO/TC 28/SC 4/WG 6 to consider the framework of ISO 8217 (Specifications of marine fuels) with a view to ensuring consistency between the relevant ISO standards on marine fuels and the implementation of the new sulphur limit in 2020. ISO/PAS 23263 “Considerations for fuel suppliers and users regarding marine fuel quality in view of the implementation of maximum 0.50% S in 2020” has therefore been developed.

To address the potential risk of incompatibility when commingling fuels having varying blend formulation, ISO/TC 28/SC 4/WG 6 initiated a test program to investigate whether test methods currently not yet widely used for marine fuel stability testing, can provide further and consistent information on the stability and potential instability of fuels or mixtures of fuels. The fuels studied are anticipated to be likely representative for what will be encountered in the market from late 2019 onwards, including VLSFO, ULSFO, LSFO and HSFO.

The study was sponsored and coordinated by Concawe and the testing awarded to an independent lab, SGS Nederland B.V. testing was either performed by SGS or the test equipment manufacturer. ISO TC28/ SC4/ WG6 thanks SGS Nederland B.V., Rofa France, Finnish Measurement Systems Ltd (FMS) and Zematra for their support.

[1] Colloidal suspension: in which one substance of microscopically dispersed insoluble particles is suspended throughout another substance

4. STUDY OUTLINE

4.1. PART 1

4.1.1. Fuel samples

Fifty two fuel samples, including 0.10% max. sulphur fuels (ULSFO), 0.50% max. sulphur fuels (VLSFO), 1.00% max. sulphur fuels (LSFO) and 3.50% max. sulphur fuels (HSFO) have been sourced from fuel suppliers, traders and shipping companies. It should be noted that the VLSFO samples might be prototype fuels and not necessarily identical to what will be available as of 1 January 2020.

The fuel samples were distributed as follows:

- 9 ULSFO (DM and RM)
- 27 VLSFO (DM and RM)
- 5 LSFO (3 of them having a S content between 1.08 and 1.15% mass)
- 11 HSFO

Table 1 provides more details on the distribution of the sample matrix

Table 1 Sample matrix

Number of samples	9 ULSFO	27 VLSFO	5 LSFO	11 HSFO
Samples from traders and shipping companies	5	0	3	10
Samples from fuel suppliers	4	27	2	1
Number of suppliers	unknown	9	1	unknown
Off-specification samples	0	3 TSP	2 - TSP - TSP, CCAI density, Al+Si	0
ISO 8217 fuel category	7 DMA 1 RMA10 1 RMG180	1 DMA 1 RMA10 3 RMB30 7 RMD80 7 RMG180 5 RMG380 2 RMG500 1 RMK380	1 RMD80 2 RMG380 1 RMK380 1 RMK700	1 RMG180 5 RMG380 1 RMG500 4 RMK500

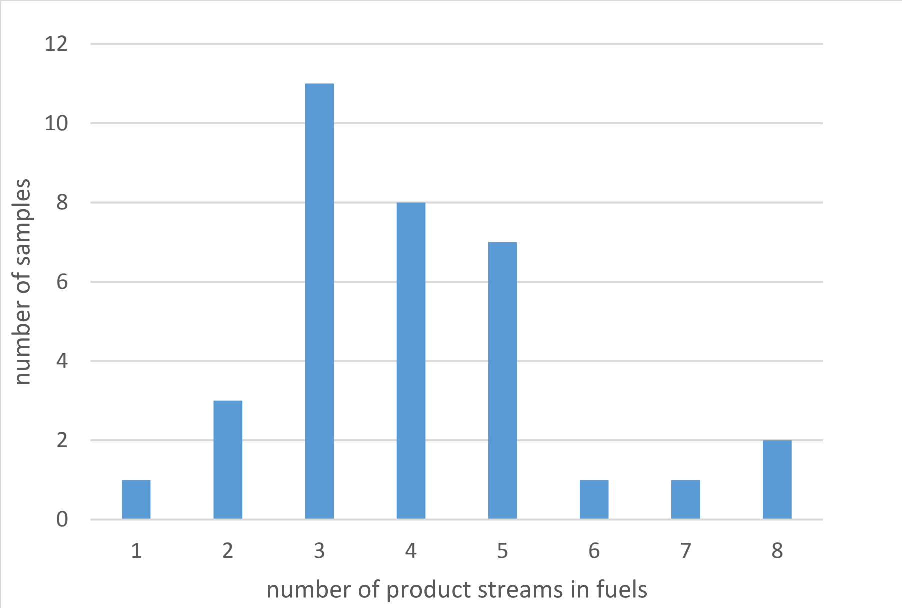
For the VLSFO samples, the supplier/trader indicated which refinery product streams, according to a pre-set list of potential streams, were used for the blending of the VLSFOs.

Thirty four samples (VLSFO, ULSFO and LSFO) were provided with a detailed description (see Table 2) and contain 1 to 8 streams. Most of these samples are composed of 3 to 5 streams (see Figure 1) but the details are not included here in order to preserve the anonymity of the samples.

Table 2 Description of product streams entering in the fuel samples recipes

Refinery unit	Stream	Description	Times used
Atmospheric Distillation Column	Straight run atmospheric distillates	Distillate fractions from crude atmospheric distillation (e.g. straight run gasoil)	9
	Straight run atmospheric residue (HS or LS)	Residues from crude atmospheric distillation with no further processing	9
Vacuum Distillation Column	Straight run vacuum distillates	Vacuum Gasoil from crude vacuum distillation (VGO) - also after mild hydrotreatment	10
	Straight run vacuum residue (HS or LS)	Residues from crude vacuum distillation with no further processing	14
Residue hydrotreater	Hydroprocessed residues	Residues subject to sulphur reduction via hydrogenation	9
Distillate hydrotreaters	Hydrotreated distillates	Main product from hydrotreating unit	18
Fluid Catalytic Cracker	Catalytically cracked distillates	Distillate fractions from Fluid Catalytic Cracker (e.g. LCO)	14
	Catalytically cracked residues (HS or LS)	Residues from Fluid Catalytic Cracker (e.g. slurry oil)	14
Thermal Cracker	Thermally cracked distillates	Distillate fractions from thermal cracking units (e.g. VBU, TGU)	4
	Thermally cracked residues (HS or LS)	Residues from thermal cracking units (e.g. VBU, TGU)	6
Hydrocracker	Hydrocracked distillates	Distillate fractions from hydrocracker unit (no residues as feed)	9
	Hydrocracker bottoms	Waxy residual stream from hydrocracker unit, coming from distillate feeds (e.g. VGO)	8
Ethylene cracker	Pyrolysis Gasoil	Gasoil fraction from ethylene cracker	2
	Pyrolysis Fuel Oil	Residue from ethylene cracker	2
	Biocomponents	components coming from biomass processing (e.g. FAMEs, HVO, pyrolysed bio-oil)	0
	Other	Streams that do not fit the descriptions above	8

Figure 1 Distribution of product streams in the fuel samples recipes



4.1.2. Fuel samples testing

4.1.2.1. General testing

The supplier/trader/shipping company provided the ISO 8217:2017 analysis test data and data for the additional tests:

- asphaltenes content - IP143
- spot test - ASTM D4740 [3]
- sediment content, existent (TSE) and accelerated (TSA) - ISO 10307-1 and ISO 10307-2 (chemical ageing).

Characteristics for which no analysis data were provided, have been tested by SGS Nederland B.V. and in addition, to ensure that the received samples were matching with the description/data supplied by the fuel supplier/trader/shipping company, the following tests were performed for verification:

- density@15°C – ISO 12185
- viscosity@40/50°C – ISO 3104
- sulphur content – ISO 8754
- existent total sediment (TSE) – ISO 10307-1

4.1.2.2. Additional stability testing

ASTM D7157 [4], ASTM D7112 [5] and ASTM D7060 [6] cover procedures involving addition of an aromatic solvent to the fuel (e.g. toluene/xylene/methylnaphthalene), titration with a non-aromatic solvent (e.g. n-heptane, n-hexadecane) and optical detection of the flocculation/precipitation of the asphaltenes.

These test methods are laboratory tests typically being used at refineries and instruments used in these methods are currently not widely available at marine fuel testing services.

For ASTM D7157, Rofa France kindly agreed to loan an instrument for the duration of the project to SGS Nederland B.V. and has provided the necessary training to a lab technician. The Zematra analyser, used for ASTM D7060, was available already at SGS Nederland B.V. and testing according to ASTM D7112 using the Porla analyser was performed by FMS in their laboratory in Finland.

Details on each test method are summarized in Table 4.

Table 3 Test method details

	ASTM D 7157 (S-value/Rofa analyser)	ASTM D7112 (P-value/Porla analyser)	ASTM D7060 (P-ratio/Zematra analyser)
Principle	Determination of stability parameters by the detection of asphaltenes flocculation with an optical probe		
Scope	HFO, residues and crude oils Asphaltenes > 0,5 mass %	HFO, residues and crude oils Asphaltenes > 0,05 mass %	HFO and residues Asphaltenes > 1 mass %
Range	S > 1 Sa < 1	P > 1 Pa < 1	FR_{max}: 32 - 76 Po: 36 - 95
Sample quantity	1 to 9g (function of sample viscosity)	20g	5 to 9g
Number of dilutions	3	3	2 coarses, 4 fines
Solvent	toluene	xylene	1-methylnaphtalene
Dilution ratio (sample/solvent)	0,2 to 4,5g/mL	0,25 to 2 g/g	1 to 6 g/mL
Titration agent	n-heptane	n-heptane	n-hexadecane
Detection	Optical probe		

Parameters referenced in ASTM D7157, D7112, D7060 related to stability are:

- S-value /P-value/ P-ratio are an indication of the stability or available solvency power of an oil with respect to precipitation of asphaltenes. An S or P value/ratio of 1 or below indicates that the fuel has no stability reserve or is unstable and asphaltenes can precipitate from the fuel without addition of any paraffinic material/solvent. A higher value/ratio indicates the fuel has a higher stability with respect to flocculation of asphaltenes.

- So/Po represent the solvency/peptization power of the fuel oil carrier medium i.e. the ability of the fuel to keep the asphaltenes in colloidal suspension. A higher So/Po value indicates the fuel oil medium has a higher capability to keep the asphaltenes dispersed.

- Sa/Pa/FR_{max} represent the capacity of the asphaltenes to remain in a colloidal dispersion/dispersed. A higher Sa/Pa value or a lower FR_{max} value means that the asphaltenes exhibit a higher capacity to remain in colloidal suspension.

In theory, a fuel is stable when

S-value= So/Fr_{max} > 1 (ASTM D7157)
P-value= Po/Fr_{max} > 1 (ASTM D7112)
P-ratio = Po/Fr_{max} > 1 (ASTM D7060)

In practice, a safeguard is introduced to account for the uncertainty of the method and whose magnitude depends on the method itself.

For marine fuels, typical S/P-values > 1.5 with Sa/Pa > 0.45 and So/Po > 0.8 are reported for stable fuels. Similar values are observed for both methods as they use the same titration agent and the solvents (respectively toluene and xylene) have more or less the same solvency power. However, the S/P-value parameters are not interchangeable for compatibility prediction.

In the case of P-ratio, it is commonly considered that fuels are stable for P-ratios > 1.1, while P-ratios between 1.0 and 1.1 are considered as borderline stable.

4.1.2.3. Test results

Distribution of test results for key ISO characteristics and the asphaltenes content of the VLSFO samples can be found in Appendix 1 and parameters obtained from ASTM D7157 (Rofa), D7112 (Porla) and D7060 (Zematra) are summarized in Appendix 2, 3 and 4.

5 samples had a TSP test result above the limit of 0.10 mass % (see Table 5) and are therefore considered to be unstable.

Table 4 Fuel samples with TSP > 0.10 mass %

Final sample numbers			**2018009**	**2018015**	**2018016**	**2018017**	**2018027**
			VLSFO	**LSFO**	**LSFO**	**VLSFO**	**VLSFO**
Residues from crude atmospheric distillation				**X**			
Residues from thermal cracking units							**X**
Residues from Fluid Catalytic Cracker				**X**	**X**		**X**
Residues subject to sulphur reduction via hydrogenation			**X**			**X**	
Waxy residual stream from hydrocracker unit				**X**	**X**	**X**	
Distillate fractions from crude atmospheric distillation							**X**
Distillate fractions from Fluid Catalytic Cracker							**X**
Distillate fractions from hydrocracker unit				**X**			
Distillate fractions from hydrotreating unit						**X**	**X**
Kinematic Viscosity@50°C	ISO3104	mm^2/s	102.9	65.15	92,36	337,9	40,63
Density@15°C	ISO3675/12185	kg/m^3	921,1	957,6	1018,7	935,1	956,0
Sulphur	ISO8754/14596	mass %	0,29	0,60	0,80	0,49	0,52
Existent Total Sediment	ISO10307-1	mass %	0,02	0,03	0,02	0,33	0,14
Potential Total Sediment	ISO10307-2A	mass %	0,12	0,17	0,67	0,40	0,16
Accelerated Total Sediment	ISO10307-2B	mass %	0,06	0,08	0,53	0,34	0,28
Asphaltenes	IP 143	mass %	0,57	0,81	1,70	1,90	3,96
spot test	ASTM D4740	-	2	3	2	4	1
S-Value parameters Rofa Analyzer	ASTM D7157	S	no flocculation in test range	3,03	1,53	2,07	1,25
		So		0,79	0,76	0,71	0,70
		Sa		0,74	0,50	0,65	0,44
P-value parameters Porla Analyzer	ASTM D7112	P	2,34	unstable	unstable	2,12	1,06
		Po	0,66			0,82	0,65
		Pa	0,72			0,61	0,39
P-ratio parameters Zematra Analyzer	ASTM D7060	Po	asphaltenes <1%	93	direct flocculation	25	74
		Fr_{max}		89		42	71
		P-ratio		1,04		0,60	1,04

VLSFO sample 2018009 contains only one product stream originating from a sulphur reduction by hydrogenation process of a residue (from the atmospheric or vacuum distillation unit). The instability of this fuel is indicated by high TSP only. The P-ratio according to ASTM D7060 cannot be measured as the asphaltene content is below 1 mass % and although asphaltene content is above 0.50 mass % it is also not possible to measure the S-value according to ASTM 7157. ASTM D7112 - P-value of 2.34 and Pa-value of 0.72 – do not indicate any stability issue for this sample.This product stream appears also in other VLSFO samples (e.g. 2018007 and 2018008). Their P-value (ASTM D7112) is lower but the TSP is within the specification of 0.10 mass % max. The S-value (ASTM D7157) and P-ratio (ASTM D7060) could not be measured on these samples.

LSFO samples 2018015 and 2018016 and VLSFO sample 2018017 contain a waxy residual stream (to be considered highly paraffinic) from a hydrocracker unit in combination with a residue containing asphaltenes. This however does not explain the instability observed (TSP > 0.10 mass %) as other fuel blends containing a waxy residual stream from a hydrocracker unit in combination with a residue containing asphaltenes don't show any stability issue (samples 2018011 and 2018014 for instance). S-value of all three samples and measured P-value of sample 2018017 do not indicate these fuels to be unstable. P-ratio of 2018015 indicates borderline stability and P-ratio of 2018017 confirms the fuel to be unstable.

VLSFO 2018027 contains a residue from a thermal cracking unit. All sediment tests exceed 0.10 mass% and all three optical methods for stability measurement conclude this VLSFO to be unstable. The asphaltenes stability is quite low (Sa = 0.44 / Pa = 0.39) and the aromaticity of the fuel matrix is not sufficient to keep the asphaltenes well dispersed.

VLSFOs 2018012, 2018013, 2018025, 2018026 and 2018014 also contain a residue from a thermal cracking unit but exhibit a higher Sa / Pa or lower FR_{max}. The asphaltenes in these fuel oils do not show the same instability as in VLSFO 2018027 (only VLSFO 201814 has higher asphaltenes content than 2018027). This may depend on the severity of the thermal cracking unit, which has a big influence on the ability of the asphaltenes to remain dispersed in the fuel oil medium.

The above indicates that the stability of a marine fuel recipe cannot be based on the identity of the streams used to manufacture the fuel, but rather depends on a set of measurements that quantify the equilibrium between the asphaltenes stability and the aromaticity of the oil matrix (which is provided by the stability tests described above). Therefore, the compatibility between marine fuels cannot be related to the streams constituting each single fuel recipe but on parameters that characterize the asphaltene stability and the aromaticity of the oil matrix of each fuel. The methodology is described in Part 2 of this report.

4.2. PART 2

4.2.1. Compatibility testing

ASTM D7112 uses the oil compatibility model as developed by I. Wiehe [7], based on the calculation of the SBN (solubility blending number) and IN (insolubility number) to assess compatibility. SBN and IN are an output from ASTM D7112 whereas these parameters can also be calculated from S-value (ASTM D7157) parameters according to the following formula:

$$IN = 100 \times (1 - Sa)$$
$$SBN = IN \times (1 + (S\text{-value} - 1) \times d_{15}/1000)$$

d_{15} is the density @15°C in kg/m^3

SBN measures the ability of the oil to keep asphaltenes in solution.
IN measures the degree of asphaltenes insolubility and a higher IN indicates a higher risk for asphaltenes precipitation.

The oil compatibility model is based on two approximations:

- SBN of a mixture of fuels, SBN_{mix}, is the volumetric average of the SBN of the individual fuels
- IN of a mixture of fuels, IN_{max}, equals the highest IN of the fuels in the mixture

When $SBN_{mix} > IN_{max}$ a blend of fuels should be stable, but a precautionary approach is generally taken by considering a margin for error.

In this study, the approach was taken to evaluate the compatibility between marine residual fuels using 1.4 as the margin for error in comparison with TSP and spot test results (1.4 is commonly applied as margin for error when using the methodology for crude oil compatibility evaluations).

Based on the above, different areas can be defined:

Stable area: $SBN_{mix} > 1.4 * IN_{max}$ (fuel 1, fuel 2)
Critical area: $IN_{max} < SBN_{mix} < 1.4 * IN_{max}$
Unstable area: $SBN_{mix} < IN_{max}$

ASTM D7060 Appendix X1 describes how to use FR_{max} and Po parameters of the individual fuel samples to assess the compatibility of two fuels.
The same principle as for the oil compatibility model is applied:

- Po_{mix} = sum ($\nu i \times Poi$) where νi is the volume fraction of fuel i
- FR_{max} of a mixture of fuels is the highest FR_{max} of any fuel in the mixture

A mixture of fuels is considered stable when Po is higher than FR_{max}, that is $Po/FR_{max} > 1$. The Po and FR_{max} ratio is termed the P-ratio. For compatibility prediction, ASTM D7060 does not consider a margin for error. The use of different solvent and titration agent results in more stringent parameters.

4.2.2. Examples of compatibility diagrams using ASTM D7157, D7112 and D7060 (where possible)

<u>Example 1: fully compatible fuels</u>

Figure 2 Compatibility diagrams for fully compatible fuel blends

ASTM D7157 (Rofa)	2018012	2018020
IN	37	39
SBN	55	72
IN_{max}	39	
$1{,}4IN_{max}$	55	

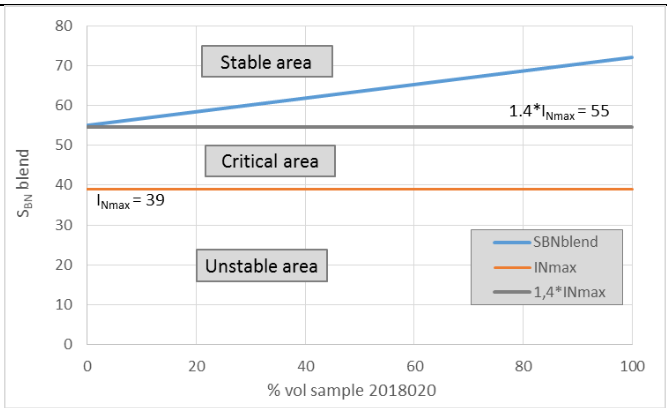


Figure 2a

ASTM D7112 (Porla)	2018012	2018020
IN	21	53
SBN	96	95
IN_{max}	53	
$1{,}4*IN_{max}$	74	

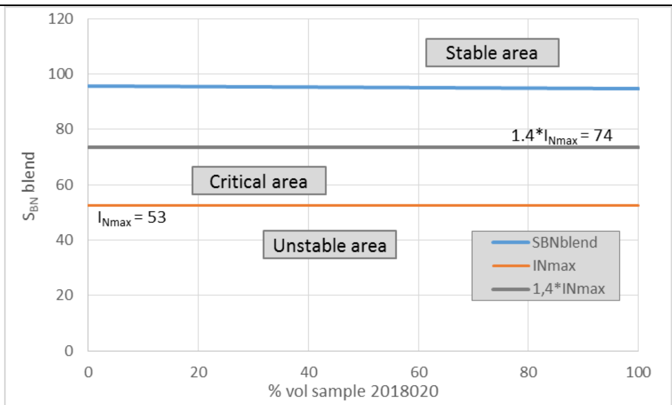


Figure 2b

ASTM D7060 (Zematra)	2018012	2018020
FR_{max}	50	86
Po	93	107
$(FR_{max})_{max}$	86	

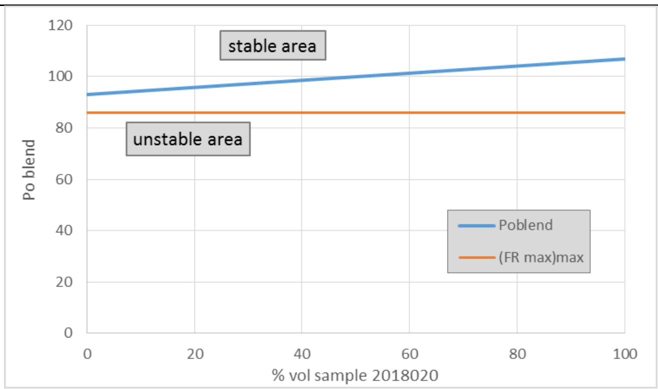


Figure 2c

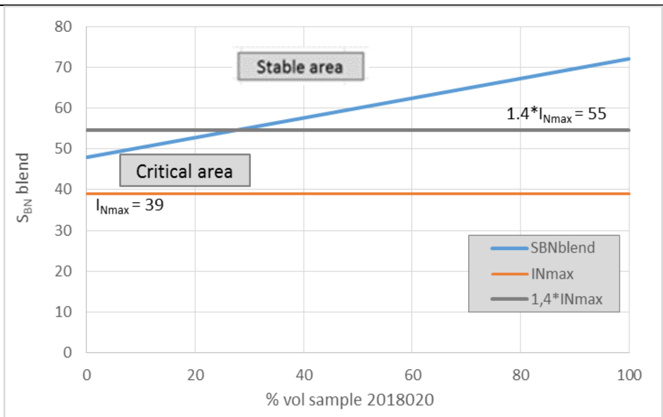
As figure 2 shows a mixture of sample 2018012 and 2018020 is predicted to be always in the stable area, hence 2018012 and 2018020 are compatible at any mixing ratio.

Example 2: Blends with critical area

Figure 3 Compatibility diagrams for blends overlapping with the critical area

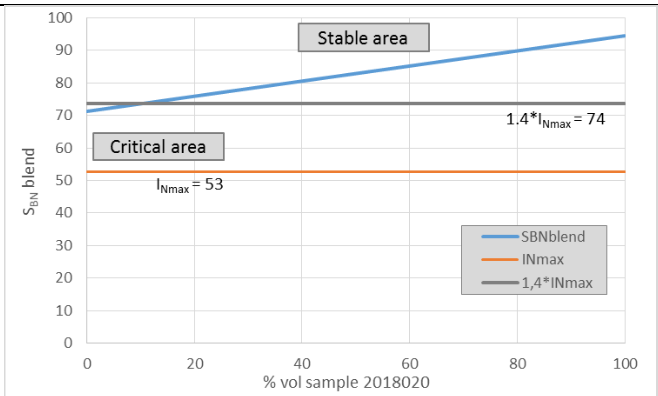
ASTM D7157 (Rofa)	2018025	2018020
IN	21	39
SBN	48	72
IN_{max}	39	
$1.4*IN_{max}$	55	

Figure 3a



ASTM D7112 (Porla)	2018025	2018020
IN	29	53
SBN	71	95
IN_{max}	53	
$1.4*IN_{max}$	74	

Figure 3b



ASTM D7060 (Zematra)	2018025	2018020
FRmax	50	86
Po	65	107
$(FRmax)_{max}$	86	

Figure 3c

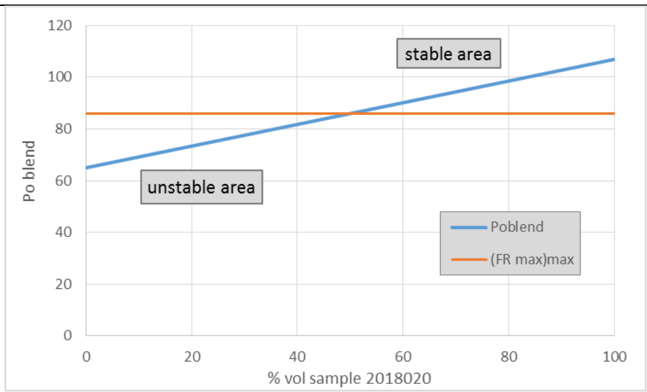


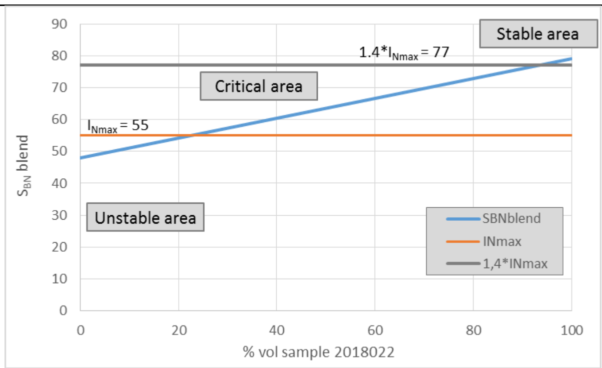
Figure 3 shows that a mixture of 2018025 and 2018020 is predicted to be stable when 2018020 is above 28% with ASTM D7157, 10% with ASTM D7112 and 50% with ASTM D7060.

<u>Example 3: blends with incompatible, critical and stable areas</u>

Figure 4 Compatibility diagrams for blends overlapping with incompatible, critical and stable area

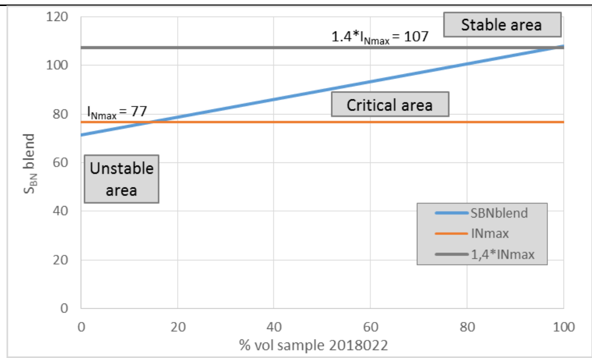
ASTM D7157 (Rofa)	2018025	2018022
IN	21	55
SBN	48	79
IN_{max}	55	
$1.4*IN_{max}$	77	

Figure 4a



ASTM D7112 (Porla)	2018025	2018022
IN	29	77
SBN	71	108
IN_{max}	77	
$1.4*IN_{max}$	107	

Figure 4b



As figure 4 shows a blend of 2018025 and 2018022 is predicted to be unstable when 2018022 is below 23% with ASTM D7157 and 15% according to ASTM D7112.

Note: compatibility prediction according to ASTM D7060 is not possible because direct flocculation was observed when testing fuel 2018022 according to ASTM D7060. TSP of fuel 2018022 is however well within the specification limit.

4.2.3. ASTM D7157 and D7112 compatibility matrix

SBN and IN values of the individual fuel samples obtained using ASTM D7157 (Rofa) and D7112 (Porla) data are included in Appendix 2 and 3. The compatibility matrix for ASTM D 7157 and D7112 is based on the methodology as explained in 4.2.1, using SBN and IN of the individual fuel samples and a margin for error of 1.4 to predict the ratio at which the fuels are compatible when being mixed.

Only samples for which SBN and IN are available and TSP ≤ 0.10 mass % are considered for the development of the compatibility matrix. ULSFOs are excluded from the compatibility matrix since the asphaltenes content of these fuels is outside the scope of the test methods.

The compatibility matrix (Appendix 5 and 6) considers:

- 3 LSFO samples
- 16 VLSFO samples
- 9 HSFO samples

In the matrix fuels that are predicted to be compatible whatever the mixing ratio is, are shaded green.

Cells shaded grey represent fuels that when mixed in a certain ratio have SBN < 1.4 IN_{max} and fall within either the critical or unstable area.

Appendix 5 and 6 show that approximately 69% of all possible fuel combinations are predicted to give stable blends whatever the mixing ratio is.

4.2.4. ASTM D7060 compatibility matrix

Po and Fr_{max} values of the individual fuel samples are included in Appendix 4. The compatibility matrix for ASTM D7060 (Appendix 7) is based on the methodology as explained in 4.2.1.

The compatibility matrix considers:

- 3 LSFO samples
- 13 VLSFO samples
- 9 HSFO samples

In the matrix fuels that are predicted to be compatible whatever the mixing ratio is, are represented by cells shaded green.

Cells shaded grey represent fuels that when mixed in a certain ratio are predicted to have Po < FR_{max} and to fall within the unstable area.

Appendix 7 shows that approximately 65% of all possible fuel combinations are predicted to give stable blends whatever the mixing ratio is.

4.2.5. Verification of the compatibility

Thirty five blends (see Appendix 8) falling within the different areas (stable, critical and unstable) of the prediction models have been selected and tested using ASTM D7157, D7112 and D7060 in comparison with ASTM D4740, TSE, TSA and TSP results. The difference in CCAI value of the individual fuels was one of the criteria to select the blends. CCAI is a calculated property of fuels based on the density and viscosity of the fuels and gives an indication of the ignition quality of the fuels.

Three levels of CCAI have been defined:

- CCAI < 820 (CCAI1)
- 820 < CCAI < 850 (CCAI2)
- CCAI >850 (CCAI3)

While it is not possible to predict the compatibility with ULSFO DM type fuels, 5 additional blends containing ULSFO DM have also been tested with the same methods.

4.2.5.1 Compatibility of stable blends

Table 6 summarizes the blends that are predicted to be always stable (with a margin for error of 1.4) at any mixing ratio according to at least one of the test methods ASTM D7157/D7112/D7060). Testing of the blends revealed TSE, TSP, TSA always to be far below 0.10 mass %.

Table 5 Summary of compatibility of stable blends

Blend N°	Fuel 1	Fuel 2	Predicted Compatibility	Comment	Ratio A Fuel1/Fuel 2	Ratio B Fuel1/Fuel2	Ratio C Fuel1/Fuel 2
1	2018011	2018019	Rofa, Porla: always stable Zematra: stable when fuel 2 > 50%	CCAI1 with CCAI3	50/50		
3	2018013	2018029	Rofa, Porla: always stable Zematra : stable when fuel 2 < 80%	CCAI2 with CCAI1; both relatively high viscosity but difference in density and pour point	50/50		
4	2018037	2018047	Rofa, Porla, Zematra: always stable	CCAI3 with CCAI2 HSFO vs LSFO	50/50		
7	2018025	411-277	Rofa, Porla, Zematra: always stable	same CCAI3 VLSFO vs HSFO	50/50		
8	2018004	2018015	Rofa, Porla: always stable Zematra: stable when fuel 2> 94%	CCAI1 with CCAI2; sample 2018015 higher TSP than TSA	50/50		
9	2018012	2018020	Rofa, Porla, Zematra: always stable	CCAI2 with CCAI3	50/50		
10	2018019	2018029	Rofa, Porla: always stable Zematra : stable when fuel 2 < 41%	CCAI3 with CCAI1	95/5	80/20	10/90
14	2018004	2018025	Rofa, Porla: always stable Zematra: stable when fuel 2 > 61%	CCAI1 with CCAI3	50/50		
16	2018015	2018034	Rofa: always stable Porla: stable when fuel 2 < 39%, unstable when fuel 2 > 61% Zematra: stable when fuel 2 < 9%	CCAI2 with CCAI3	20/80	40/60	
24	2018008	2018030	Porla: always stable (no Rofa, Zematra data for 2018008)	CCAI1 with CCAI2	90/10		

In appendix 9 are some examples of corresponding calculations ASTM D7157/D7112/D7060 of selected blends – blend 3 (example 1) and blend 8 (example 2).

4.2.5.2 Blends with TSA/TSP values of max 0.10 mass%

Table 7 summarizes the blends that are predicted to be in the stable, critical or unstable area according to ASTM D7157/D7112 but with a TSA/TSP value of max. 0.10 mass %. For blends 19 to 23, it was not possible to predict the compatibility as the asphaltenes content of at least one of the fuels was too low to measure the S/P-value. Blends for which D7060 test data are available are predicted to be stable.

Table 6 Compatibility of blends with TSA/TSP value of max. 0.10 mass%

Blend N°	Fuel 1	Fuel 2	Compatibility	Comment	Ratio A	Ratio B	Ratio C
6	2018019	2018022	Rofa: critical when 2018022 < 72% Porla: critical when 2018022 < 97%	same CCAI3; different PP	25/75	75/25	
12	2018043	2018031	Rofa, Porla: always in critical area Zematra : always stable	CCAI2 with CCAI3, sample 31 high density, similar asphaltenes content; HSFO with VLSFO	50/50	90/10	10/90
15	2018012	2018031	Rofa: critical area when 2018031 <31% Unstable area when 2018031 <31% Porla: always critical Zematra: always stable	CCAI2 with CCAI3	40/60	90/10	
19	2018025	2018001		VLSFO vs ULSFO	50/50		
20	2018025	2018042		VLSFO vs ULSFO	50/50		
21	2018004	2018044		VLSFO vs ULSFO	50/50		
22	2018011	2018044		VLSFO vs ULSFO	50/50		
23	2018012	2018044		VLSFO vs ULSFO	50/50		

Examples of calculations are given in Appendix 9 for blends 12, 15, 19, 20, 21 and 23 (Examples 3-8).

4.2.5.3 Blends with total sediment (aged) exceeding 0.10 mass%

Table 14 summarizes the blends that are predicted to be in the stable, critical or unstable area according to ASTM D7157/D7112/D7060 but with total sediment aged test result(s) exceeding 0.10 mass %. While most of the blends have been prepared at the beginning of Part 2 of the study, additional blends of interest were identified 3 months later. In order to ensure that the fuels involved in these additional blends didn't evolve during the storage, potential total sediment, TSP, of each fuel was retested (indicated by * in the tables). An increase of TSP of sample 2018034 from 0.05 to 0.14 mass % was observed, which relates with a borderline S-value and unstable P-value and P-ratio.

Table 7 Summary of compatibility of blends with TSA/TSP in excess of 0.10 mass%

Blend N°	Fuel 1	Fuel 2	Compatibility	Comment	Ratio A	Ratio B
2	2018045	2018004	Rofa: compatible when 2018004 < 54% Porla: compatible when 2018004 < 86% Zematra: compatible when 2018004 < 39%	CCAI2 with CCAI3; high asphaltenes content vs very low asphaltenes content	30/70	70/30
5	2018027	2018014	Rofa, Porla: always in critical area Zematra: compatible when 2018014 < 30%	same CCAI2 always below the critical zone	50/50	
11	411-280	2018034	Compatible when Rofa: 2018034 < 74% Porla: 2018034 < 37% Zematra : 2018034 < 75%	Same CCAI2, HSFO with VLSFO	90/10	80/20
13	2018047	2018031	Rofa: incompatible when 2018031 < 7%, critical when > 7% Porla: incompatible when 2018031 < 55%, critical when > 55% Zematra: Always stable	CCAI2 with CCAI3, LSFO with ULSFO	95/5	80/20
17	2018028	2018022	Rofa: incompatible when 2018022 < 20%, compatible when > 93% Porla: compatible when 2018022 > 96%, critical when < 96%	CCAI2 with CCAI3	60/40	20/80
18	2018030	2018034	Rofa: compatible when 2018034 < 96% Porla: incompatible when 2018034 > 83%, stable when < 68% Zematra: compatible when 2018034 < 44%	Same CCAI2	20/80	

Examples of calculations of some of the above blends are given in Appendix 9 for blends 2, 13, 11 (Examples 9 – 11)

5. STATISTICAL EVALUATION

5.1. CLASSIFICATION METHODOLOGY

The statistical analysis focused on evaluation of the performance of the existing prediction methodology of ASTM D7157, D7112 and D7060 in comparison with the total sediment aged specification.

Any statistical methodology for such exploratory analysis works best with “large” datasets. In statistical terms, “large” would be a minimum of hundreds of samples with a sizeable proportion of samples in each of the categories (stable, borderline and unstable). In this study we have just 35 usable blends, the vast majority of which are in the stable category. This is a “small” dataset for this type of methodology and is a serious limitation.

For the purposes of the analysis, the actual stability of the comingled fuels has been defined as shown in table 9 using the measured values of TSP and TSA:

Table 8 Defined stability of comingled fuel

TSP ≤ 0.10 mass %	TSA ≤ 0.10 mass %	Stable
0.08 ≤ TSP ≤ 0.10 mass %	TSA > 0.10 mass %	Borderline. Just on spec according to TSP but TSA is high
TSP > 0.10 mass %		Unstable

The number of fuel blends[2] in each category based on these definitions is shown in table 10.

Table 9 Number of fuels

	Stable	Borderline	Unstable
D7157/D7112	28	2	5
D7060	24	2	4

The performance of the prediction methodology is tabulated (table 11):

[2] Only blends for which individual fuel test data are available are considered

Table 10 Performance of prediction methodology

ASTM D7157 (Rofa) prediction		Actual blend stability based on TSP and TSA		
		Stable	Borderline	Unstable
Predicted classification	Stable	16	2	1
	Borderline	10	0	3
	Unstable	2	0	1
ASTM D7112 (Porla) Prediction		**Actual blend stability based on TSP and TSA**		
		Stable	Borderline	Unstable
Predicted classification	Stable	13	1	1
	Borderline	14	1	2
	Unstable	1	0	2
ASTM D7060 (Zematra) prediction		**Actual blend stability based on TSP and TSA**		
		Stable	Borderline	Unstable
Predicted classification	Stable	18	2	0
	Unstable	6	0	4

For the purpose of this analysis, the quality of the predictions is defined as follows:

- **"Good" predictions** are shaded green in the above tables. If blends are predicted to be borderline or unstable then this is deemed to be satisfactory if the actual blend is also borderline or unstable. Likewise, a stable prediction of a stable blend is a good prediction.
- **"Poor" predictions** are shaded orange in the above table. These are blends that are predicted borderline or unstable but are, in practice, stable (TSP and TSA ≤ 0.10 mass %) or are predicted stable but are in fact borderline (0.08 ≤ TSP ≤ 0.10 mass % but TSA >0.10 mass %)
- **"Bad" predictions** are shaded red in the above table. This is when a blend is predicted to be stable but in practice is unstable i.e. off spec with TSP > 0.10 mass %.

Table 12 lists the number of "good", "poor" and "bad" predictions for ASTM D7157, D7112 and D7060.

Table 11 Predictions for ASTM tests

	ASTM D7157		ASTM D7112		ASTM D7060	
	# blends	% of blends	# blends	% of blends	# blends	% of blends
Good	20	57	18	51	22	73
Poor	14	40	16	46	8	27
Bad	1	3	1	3	0	0

5.2. ATTEMPT TO IMPROVE CLASSIFICATION METHODOLOGY FOR ASTM D7157 AND D7112

The margin for error for a "stable" prediction considered in this study is 1.4. The balance between "good", "poor" and "bad" is shown in Figures 12 and 13 for a range of values of the margin for error factor for the ASTM D7157 (Rofa) and ASTM D7112 (Porla) respectively. Figures 12 and 13 show that:

- Reducing the factor to 1.3 increases the number of "good" predictions for both ASTM D7157 and D7112 without having any adverse effect on the number of "bad" predictions. Decreasing the factor below 1.3, the number of "bad" predictions is increased.

- Increasing the factor for both ASTM D7157 and D7112 reduces the number of “bad” predictions without noticeable improvement of the “good” predictions for ASTM D7157 but with a clear decrease of the “good” predictions for ASTM D7112.

At this stage, it is, not recommended to make any changes to the margin for error factor used in the study. Further testing after the introduction of the 0.50 mass % sulphur fuels in the market, is required to support modification of the margin for error factor that might improve the compatibility prediction.

Figure 5 Predictions for different margin for error factors (Rofa)

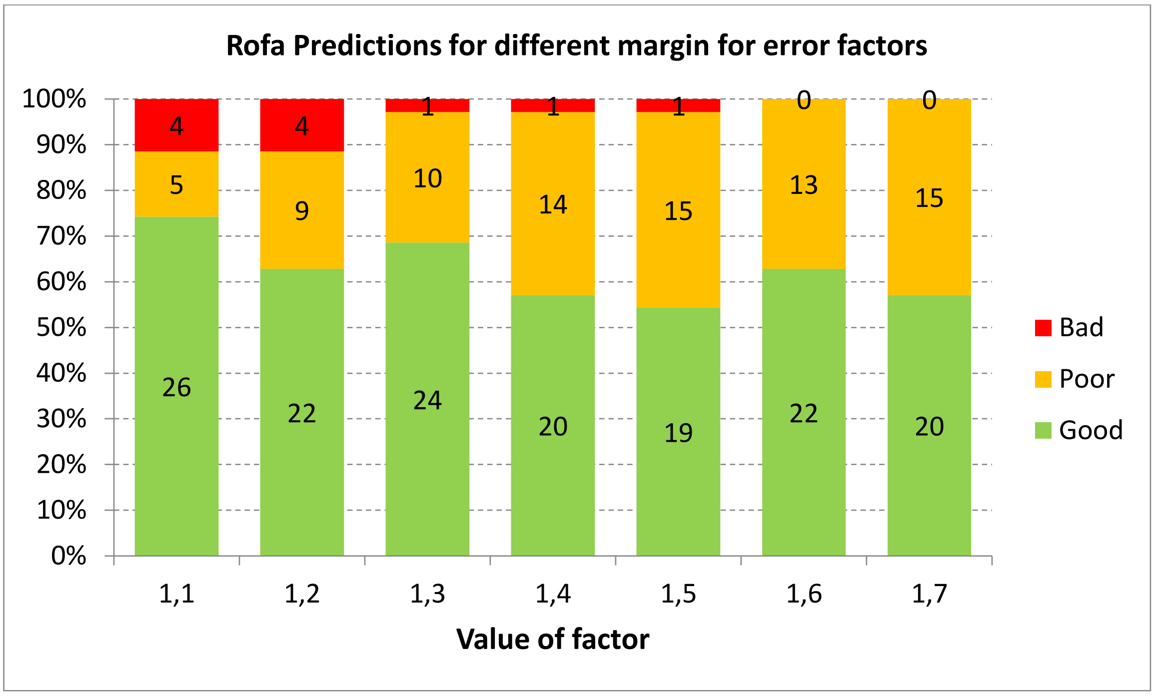
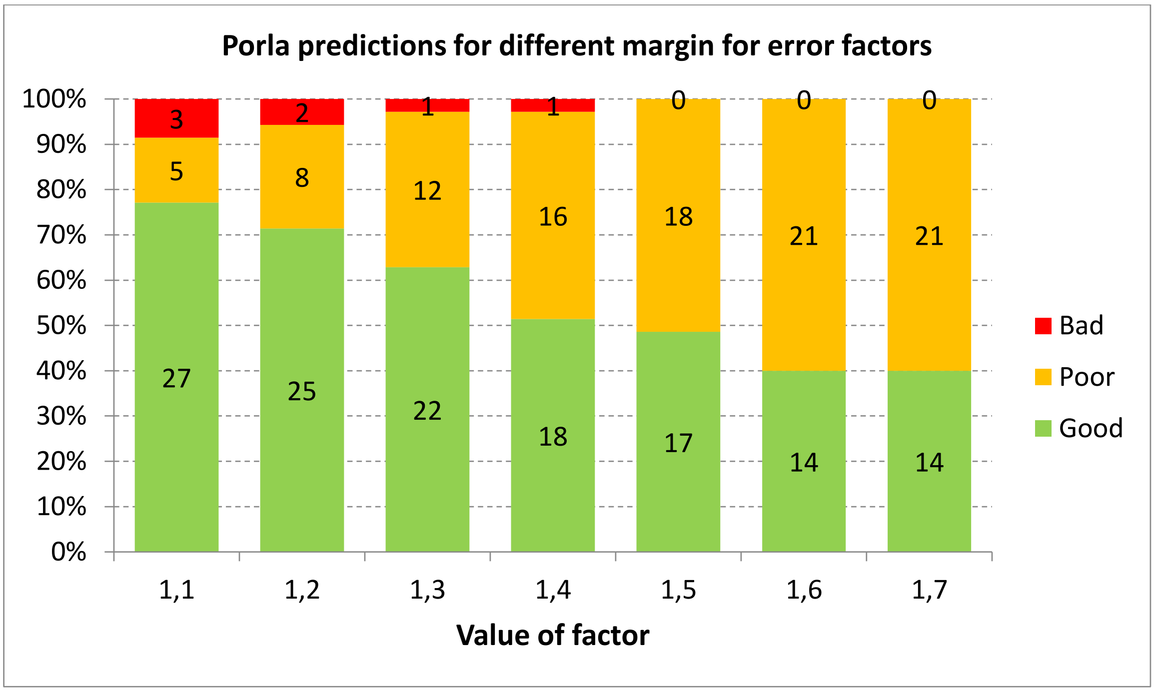


Figure 6 Predictions for different margin for error factors (Porla)



6. CONCLUSION

Based on the testing conducted in Part 2, it can be concluded that fuels, tested according to D7157/D7112 can be predicted to be fully compatible with TSP within the specification limit of 0.10 mass % max. when SBN_{mix} is above 1.4*IN_{max}, whatever the mixing ratio. When SBN_{mix} is in the critical area or unstable area, additional testing of the mixture of fuels for TSP is recommended.

Fuels tested according to D7060 can be predicted to be fully compatible with TSP within the specification limit of 0.10 mass % max. when Po_{mix} is above the maximum FR_{max}. When the fuels are deemed to be not fully compatible, testing of the mixture of fuels for TSP is recommended.

The compatibility prediction methodology can only be applied when the fuels have been tested with the same test method.

While the compatibility matrixes are based on a limited number of samples, it indicates that ASTM D7157/D7112 and D7060 predict a similar percentage (respectively 69% and 65%) of all possible fuel combinations to give stable blends whatever the mixing ratio is. The compatibility matrix for ASTM D7157 and D7112 have 60% of the possible fuel combinations that are always stable whatever the mixing ratio is, in common (i.e. 60% of the green cells).

When considering all three test methods, approximately 50% of the possible fuel combinations that are predicted to be always stable whatever the mixing ratio is, are common. It should be noted that D7060 uses different solvent and titration agent which is considered to have a different impact on the chemistry of asphaltenes precipitation.

Eliminating fuels from the matrix that have individual S or P value < 1.5 or P-ratio < 1 predicts respectively 86% of the fuels to be compatible whatever the mixing ratio is when tested according to D7157, 95% according to D7112 and 70% according to D7060. However, this would restrict availability of marine fuels which nevertheless meet TSP of 0.10 mass % max.

The study has been conducted on a limited number of fuel samples as 0.50% max. sulphur fuels were not widely available at that time. The study shows that ASTM D7157, D7112 and D7060 can be used to obtain information on the degree of compatibility, though in some cases inconsistencies have been observed. Where possible testing for compatibility of fuels to be comingled is recommended. Good practices to minimise the risk of incompatibility of fuels should be maintained and more data collected on commercially available samples.

7. GLOSSARY

CCAI	Calculated carbon aromaticity index
S	Sulphur
PP	Pour point
TSE	Existent total sediment
TSA	Accelerated total sediment
TSP	Potential total sediment
ULSFO DM	Ultra low sulphur fuel oil, distillate properties, Sulphur max 0.10 mass %
ULSFO RM	Ultra low sulphur fuel oil, residual properties, Sulphur max 0.10 mass %
VLSFO DM	Very low sulphur fuel oil, distillate properties, Sulphur max 0.50 mass %
VLSFO RM	Very low sulphur fuel oil, residual properties, Sulphur max 0.50 mass %
LSFO	Low sulphur fuel oil, Sulphur max. 1.00 mass %
HSFO	High sulphur fuel oil, Sulphur above 1.00 mass %
HFO	Heavy fuel oil
HS	High sulphur
LS	Low sulphur
VGO	Vacuum gasoil
LCO	Light cycle oil
VBU	Visbreaker unit
TGU	Thermal gasoil unit
SBN	Solubility blending number
IN	Insolubility number
FAME	Fatty Acid Methyl Ester(s)
HVO	Hydrotreated vegetable oil

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- Pauline Ziman for the statistical evaluation

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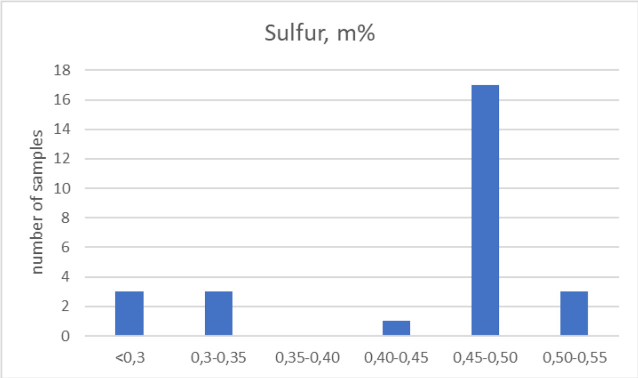
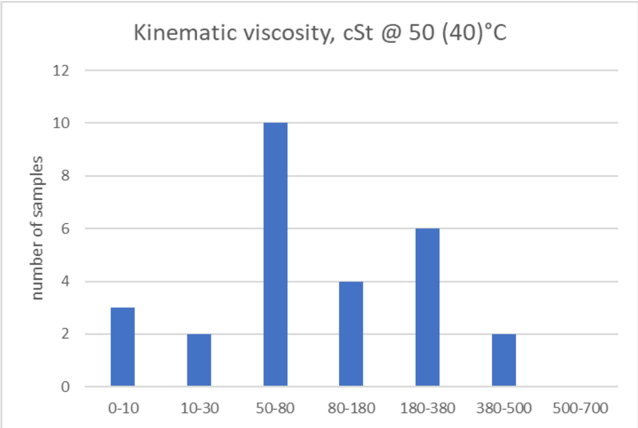
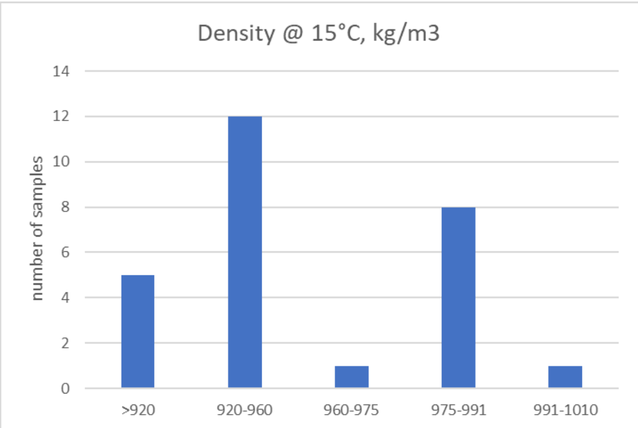
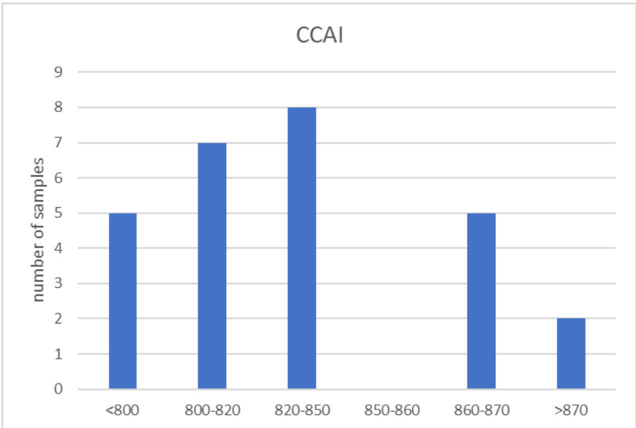
7. US58771634A-Process for blending potentially incompatible petroleum oils, I Wiehe, R Kennedy, 1999

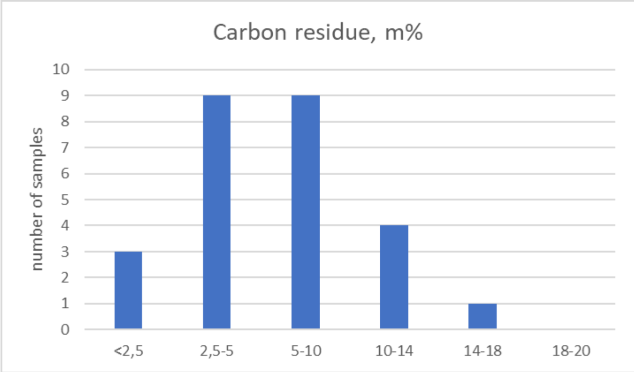
APPENDIX 1 - VLSFO fuel test data distribution










Carbon residue, m%
number of samples
0
1
2
3
4
5
6
7
8
9
10
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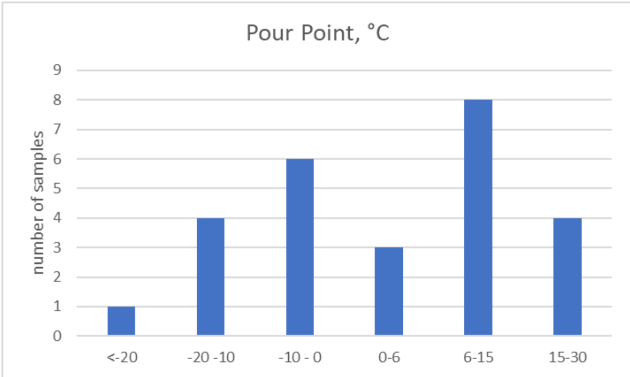
2,5-5
5-10
10-14
14-18
18-20


Pour Point, °C
number of samples
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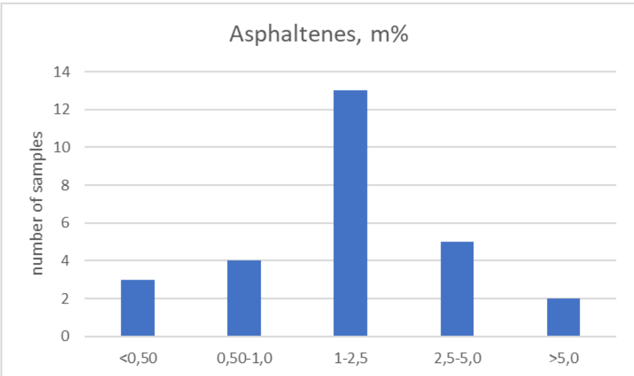
1
2
3
4
5
6
7
8
9
<-20
-20 -10
-10 - 0
0-6
6-15
15-30


Asphaltenes, m%
number of samples
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2
4
6
8
10
12
14
<0,50
0,50-1,0
1-2,5
2,5-5,0
>5,0

APPENDIX 2 - ASTM D7157 (Rofa) test results

Sample	S	So	Sa	SBN	IN	TSE	TSP	TSA
2018001	no flocculation available in test range					< 0,01	< 0,01	< 0,01
2018002	no flocculation available in test range					< 0,01	< 0,01	< 0,01
2018003	5,15/4,54	0,98/0,83	0,81/0,79	90	19	0,07	0,09	0,07
2018004	2,9	0,57	0,81	52	19	< 0,01	< 0,01	0,03
2018005	no flocculation available in test range					< 0,01	< 0,01	< 0,01
2018006	no flocculation available in test range					< 0,01	< 0,01	0,03
2018007	no flocculation available in test range					0,01	0,02	0,04
2018008	no flocculation available in test range					< 0,01	0,08	0,04
2018009	no flocculation available in test range					0,02	0,12	0,06
2018010	no flocculation available in test range					0,01	< 0,01	0,02
2018011	4,37	0,84	0,81	78	19	0,03	0,01	< 0,01
2018012	1,52	0,55	0,63	55	37	0,03	< 0,01	0,02
2018013	2,21	0,92	0,59	90	41	0,02	0,02	0,03
2018014	1,64	0,77	0,53	76	47	< 0,01	0,01	0,05
2018015	3,03	0,79	0,74	77	26	0,03	0,17	0,08
2018016	1,53	0,76	0,5	77	50	0,02	0,67	0,53
2018017	2,07	0,71	0,65	70	35	0,33	0,40	0,34
2018018	no flocculation available in test range					0,01	0,01	0,01
2018019	1,91	0,72	0,62	72	38	< 0,01	< 0,01	0,02
2018020	1,85	0,72	0,61	72	39	< 0,01	0,02	0,02
2018022	1,45	0,79	0,45	79	55	0,01	< 0,01	0,02
2018025	2,3	0,49	0,79	48	21	< 0,01	0,01	0,01
2018026	2,79	0,47	0,83	47	17	0,02	0,02	0,01
2018027	1,25	0,7	0,44	69	56	0,14	0,16	0,28
2018028	1,7	0,51	0,7	49	30	0,04	0,07	0,01
2018029	4,24	0,72	0,83	69	17	< 0,01	0,01	0,01
2018030	3,6	1,15	0,68	113	32	0,07	0,08	0,10
2018031	1,41	0,95	0,33	94	67	0,03	0,02	< 0,01
2018032	no flocculation available in test range					0,02	0,02	0,02
2018033	no flocculation available in test range					0,02	0,01	0,01
2018034	1,49	0,43	0,71	42	29	0,05	0,05	0,05
2018035	1,38	0,68	0,51	67	49	0,06	0,03	0,04
2018036	no flocculation available in test range					0,02	0,02	0,02
2018037	2,04	0,77	0,63	75	37	0,05	0,05	0,05
411-278	4,09	0,84	0,8	79	20	< 0,01	0,02	< 0,01
411-277	3,44	0,95	0,72	97	28	< 0,01	< 0,01	0,01
411-279	2,88	0,87	0,7	85	30	< 0,01	0,02	0,01
411-280	1,99	0,71	0,65	69	35	0,04	0,04	0,07
411-291	1,73	0,75	0,57	74	43	0,02	0,02	< 0,01
2018038	2,85	0,93	0,67	95	33	< 0,01	0,04	< 0,01
2018039	Not possible					< 0,01	< 0,01	< 0,01
2018041	1,70	0,84	0,50	85	50	0,03	0,01	0,04
2018042	no flocculation available in test range					< 0,01	< 0,01	< 0,01
2018043	1,81	0,74	0,59	73	41	0,03	0,02	< 0,01
2018044	Not possible					< 0,01	< 0,01	< 0,01
2018045	1,74	0,83	0,53	82	47	0,10	0,02	0,05
2018047	3,35	0,68	0,80	65	20	< 0,01	< 0,01	< 0,01

APPENDIX 3 - ASTM D7112 (Porla) test results

Sample	P	FRS/1	SBN	IN	Pa	Po	TSE	TSP	TSA
2018001	*		65,5				< 0,01	< 0,01	< 0,01
2018002	*		54,5				< 0,01	< 0,01	< 0,01
2018003	1,65	0,45	85,9	52	0,48	0,86	0,07	0,09	0,07
2018004	3,58	0,1	77	21,5	0,79	0,77	< 0,01	< 0,01	0,03
2018005	*		42,2				< 0,01	< 0,01	< 0,01
2018006	*		65,2				< 0,01	< 0,01	0,03
2018007	1,6	0,34	61	38,2	0,62	0,61	0,01	0,02	0,04
2018008	1,52	0,34	57,5	37,9	0,62	0,58	< 0,01	0,08	0,04
2018009	2,34	0,21	66,2	28,3	0,72	0,66	0,02	0,12	0,06
2018010	*		52,9				0,01	< 0,01	0,02
2018011	4,73	0,04	77,2	16,3	0,84	0,77	0,03	0,01	< 0,01
2018012	4,52	0,06	95,6	21,2	0,79	0,96	0,03	< 0,01	0,02
2018013	2,44	0,35	120	49,2	0,51	1,2	0,02	0,02	0,03
2018014	1,65	0,45	85,9	52	0,48	0,36	< 0,01	0,01	0,05
2018015	2,1	0,34	90,6	43,1	0,57	0,91	0,03	0,17	0,08
2018016	***						0,02	0,67	0,53
2018017	2,12	0,3	82	38,7	0,61	0,82	0,33	0,40	0,34
2018018	*		75,6				0,01	0,01	0,01
2018019	1,55	0,44	77	49,6	0,5	0,77	< 0,01	< 0,01	0,02
2018020	1,8	0,44	94,6	52,6	0,47	0,95	< 0,01	0,02	0,02
2018022	1,41	0,7	108,1	76,6	0,23	1,08	0,01	< 0,01	0,02
2018025	2,5	0,2	71,3	28,5	0,72	0,71	< 0,01	0,01	0,01
2018026							0,02	0,02	0,01
2018027	1,06	0,61	65,3	61,3	0,39	0,65	0,14	0,16	0,28
2018028	2,19	0,3	85,7	39,1	0,61	0,86	0,04	0,07	0,01
2018029	4,45	0,05	70,9	15,9	0,84	0,71	< 0,01	0,01	0,01
2018030	4,31	0,07	77,9	18,8	0,81	0,78	0,07	0,08	0,10
2018031	1,21	0,75	93,7	77,7	0,22	0,94	0,03	0,02	< 0,01
2018032	>7 **						0,02	0,02	0,02
2018033	5,34	0,03	127,4	23,8	0,76	1,27	0,02	0,01	0,01
2018034	0,53	0,26	12,7	23,9	0,76	0,13	0,05	0,05	0,05
2018035	1,33	0,51	73,3	55,1	0,45	0,73	0,06	0,03	0,04
2018036	***						0,02	0,02	0,02
2018037	2,36	0,33	108	45,7	0,54	1,08	0,05	0,05	0,05
411-278	3,93	0,09	84,8	21,6	0,78	0,85	< 0,01	0,02	< 0,01
411-277	3,23	0,17	100,1	31	0,69	1	< 0,01	< 0,01	0,01
411-279	2,68	0,22	89,1	33,3	0,67	0,89	< 0,01	0,02	0,01
411-280	2,04	0,3	78,6	38,5	0,61	0,79	0,04	0,04	0,07
411-291	1,7	0,43	85,3	50,2	0,5	0,85	0,02	0,02	< 0,01
2018038	3,09	0,2	108,6	35,1	0,65	1,09	< 0,01	0,04	< 0,01
2018039	*		64,1				< 0,01	< 0,01	< 0,01
2018041	1,45	0,55	87,8	60,4	0,4	0,88	0,03	0,01	0,04
2018042	>7 *		113,9				< 0,01	< 0,01	< 0,01
2018043	1,75	0,42	86,2	49,2	0,51	0,86	0,03	0,02	< 0,01
2018044	*		49,4				< 0,01	< 0,01	< 0,01
2018045	1,85	0,48	106,7	58	0,42	1,07	0,10	0,02	0,05
2018047	4,2	0,09	110,3	26,3	0,74	1,1	< 0,01	< 0,01	< 0,01

* Run with program for asphaltene free samples

** Very stable sample, out of measurement range (max P-value = 7)

*** Test not possible

APPENDIX 4 - ASTM D7060 (Zematra) test results

Sample	Po	Frmax	Po/Frmax	TSE	TSP	TSA
2018001	asphaltenes <1%			< 0,01	< 0,01	< 0,01
2018002	asphaltenes <1%			< 0,01	< 0,01	< 0,01
2018003	34'/18	44'/37	0,8	0,07	0,09	0,07
2018004	27'/27	36'/35	0,8	< 0,01	< 0,01	0,03
2018005	asphaltenes <1%			< 0,01	< 0,01	< 0,01
2018006	asphaltenes <1%			< 0,01	< 0,01	0,03
2018007	asphaltenes <1%			0,01	0,02	0,04
2018008	asphaltenes <1%			< 0,01	0,08	0,04
2018009	asphaltenes <1%			0,02	0,12	0,06
2018010	asphaltenes <1%			0,01	< 0,01	0,02
2018011	60	27	2,2	0,03	0,01	< 0,01
2018012	93	50	1,9	0,03	< 0,01	0,02
2018013	110	63	1,7	0,02	0,02	0,03
2018014	64	51	1,3	< 0,01	0,01	0,05
2018015	93	89	1,0	0,03	0,17	0,08
2018016	Direct flocculation			0,02	0,67	0,53
2018017	25	42	0,6	0,33	0,40	0,34
2018018	asphaltenes <1%			0,01	0,01	0,01
2018019	95	77	1,2	< 0,01	< 0,01	0,02
2018020	107	86	1,2	< 0,01	0,02	0,02
2018022	Direct flocculation			0,01	< 0,01	0,02
2018025	65	50	1,3	< 0,01	0,01	0,01
2018026	112	58	1,9	0,02	0,02	0,01
2018027	74	71	1,0	0,14	0,16	0,28
2018028	67	64	1,0	0,04	0,07	0,01
2018029	51	27	1,9	< 0,01	0,01	0,01
2018030	63	42	1,5	0,07	0,08	0,10
2018031	77	67	1,1	0,03	0,02	< 0,01
2018032	No flocculation			0,02	0,02	0,02
2018033	No flocculation			0,02	0,01	0,01
2018034	47	56	0,8	0,05	0,05	0,05
2018035	72	62	1,2	0,06	0,03	0,04
2018036	No flocculation			0,02	0,02	0,02
2018037	71	41	1,7	0,05	0,05	0,05
411-278	114	52	2,2	< 0,01	0,02	< 0,01
411-277	64	30	2,1	< 0,01	< 0,01	0,01
411-279	109	65	1,7	< 0,01	0,02	0,01
411-280	104	61	1,7	0,04	0,04	0,07
411-291	96	70	1,4	0,02	0,02	< 0,01
2018038	72	38	1,9	< 0,01	0,04	< 0,01
2018039	asphaltenes<1%			< 0,01	< 0,01	< 0,01
2018041	107	82	1,3	0,03	0,01	0,04
2018042	asphaltenes <1%			< 0,01	< 0,01	< 0,01
2018043	86	61	1,4	0,03	0,02	< 0,01
2018044	asphaltenes<1%			< 0,01	< 0,01	< 0,01
2018045	78	58	1,3	0,10	0,02	0,05
2018047	87	53	1,6	< 0,01	< 0,01	< 0,01

APPENDIX 5 - Rofa compatibility matrix

Legend

- VLSFO
- LSFO
- HSFO

Sample	2018 003	2018 004	2018 011	2018 012	2018 013	2018 014	2018 015	2018 019	2018 020	2018 022	2018 025	2018 028	2018 029	2018 030	2018 031	2018 034	2018 035	2018 037	20180 38	411-278	411-277	411-279	411-280	411-291	2018 041	2018 043	2018 045	2018 047
2018003																												
2018004																												
2018011																												
2018012																												
2018013																												
2018014																												
2018015																												
2018019																												
2018020																												
2018022																												
2018025																												
2018028																												
2018029																												
2018030																												
2018031																												
2018034																												
2018035																												
2018037																												
2018038																												
411-278																												
411-277																												
411-279																												
411-280																												
411-291																												
2018041																												
2018043																												
2018045																												
2018047																												

APPENDIX 6 - Porla compatibility matrix

Legend

VLSFO

LSFO

HSFO

Sample	2018 003	2018 004	2018 011	2018 012	2018 013	2018 014	2018 015	2018 019	2018 020	2018 022	2018 025	2018 028	2018 029	2018 030	2018 031	2018 034	2018 035	2018 037	2018 038	411-278	411-277	411-279	411-280	411-291	2018 041	2018 043	2018 045	2018 047
2018003																												
2018004																												
2018011																												
2018012																												
2018013																												
2018014																												
2018015																												
2018019																												
2018020																												
2018022																												
2018025																												
2018028																												
2018029																												
2018030																												
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2018037																												
2018038																												
411-278																												
411-277																												
411-279																												
411-280																												
411-291																												
2018041																												
2018043																												
2018045																												
2018047																												

APPENDIX 7 - Zematra compatibility matrix

Legend

VLSFO
LSFO
HSFO

sample	2018 011	2018 012	2018 013	2018 014	2018 015	2018 019	2018 020	2018 025	2018 028	2018 029	2018 030	2018 031	2018 034	2018 035	2018 037	2018 038	411-278	411-277	411-279	411-280	411-291	2018 041	2018 043	2018 045	2018 047
2018011																									
2018012																									
2018013																									
2018014																									
2018015																									
2018019																									
2018020																									
2018025																									
2018028																									
2018029																									
2018030																									
2018031																									
2018034																									
2018035																									
2018037																									
2018038																									
411-278																									
411-277																									
411-279																									
411-280																									
411-291																									
2018041																									
2018043																									
2018045																									
2018047																									

APPENDIX 8 - Verification blends

									ASTM D7157			ASTM D7112					ASTM D7060		
	fuel #	**%**	**fuel#**	**%**	**TSE**	**TSP**	**TSA**	**SPOT**	**S**	**So**	**Sa**	**P**	**SBN**	**FRS/1**	**Pa**	**Po**	**Po**	**FRmax**	**P**
1A	2018011	50	2018019	50	0,02	<0,01	<0,01	1	1,83	0,59	0,68	2,3	72	0,23	0,69	0,72	67	54	1,24
2A	2018045	30	2018004	70	0,87	0,73	0,90	5	1,11	0,49	0,56	2,9	89	0,19	0,69	0,89	Not possible		
2B	2018045	70	2018004	30	0,06	0,10	0,17	1	1,4	0,67	0,52	2,4	95	0,29	0,6	0,95	50	56	0,89
3A	2018013	50	2018029	50	<0,01	0,01	<0,01	1	2,37	0,70	0,70	2,6	92	0,24	0,65	0,92	77	44	1,75
4A	2018037	50	2018047	50	<0,01	<0,01	0,01	1	2,13	0,76	0,64	3,7	110	0,14	0,7	1,1	57	40	1,43
5A	2018027	50	2018014	50	0,20	0,16	0,28	4	1,38	0,70	0,50	1,4	78	0,51	0,44	0,78	71	63	1,13
6A	2018019	25	2018022	75	0,03	<0,01	0,03	1	1,54	0,80	0,48	1,4	97	0,64	0,31	0,97	66* measured with 2 points instead of 3	66* measured with 2 points instead of 3	
6B	2018019	75	2018022	25	0,03	0,07	0,01	1	1,64	0,81	0,50	1,5	81	0,49	0,46	0,81	80	78	1,03
7A	2018025	50	411-277	50	0,01	<0,01	0,02	1	2,48	0,78	0,68	2,8	84	0,19	0,7	0,84	72	45	1,60
8A	2018004	50	2018015	50	<0,01	0,01	0,01	2	2,08	0,66	0,68	2,8	83	0,19	0,7	0,83	27	47	0,57
9A	2018012	50	2018020	50	0,04	<0,01	<0,01	1	1,71	0,54	0,68	2,2	93	0,32	0,58	0,93	57	53	1,08
10A	2018019	95	2018029	5	0,01	0,01	0,02	1	1,52	0,73	0,52	1,7	75	0,38	0,56	0,75	71	63	1,13
10B	2018019	80	2018029	20	0,01	<0,01	0,03	1	1,69	0,70	0,59	1,8	72	0,34	0,6	0,72	59	58	1,02
10C	2018019	10	2018029	90	<0,01	<0,01	<0,01	1											
11A	411-280	90	2018034	10	0,04	0,06	0,09	1	1,87	0,71	0,62	1,9	74	0,32	0,61	0,74	50	38	1,32
11B	411-280	80	2018034	20	0,04	0,07	0,05	1	1,76	0,67	0,62	1,6	65	0,36	0,59	0,65	55	41	1,34
11C	411-280	10	2018034	90	0,28	0,36	0,40	4											
11D	411-280	50	2018034	50	0,06	0,09	0,17	1											
12A	2018043	50	2018031	50	0,04	0,02	0,05	1	1,48	0,81	0,41	1,4	89	0,58	0,36	0,89	67	61	1,10
12B	2018043	90	2018031	10	0,03	0,03	0,05	1											
12C	2018043	10	2018031	90	0,02	0,03	0,04	1											

APPENDIX 9 - Verification blends

									ASTM D7157			ASTM D7112					ASTM D7060		
	fuel #	%	fuel#	%	TSE	TSP	TSA	SPOT	S	So	Sa	P	SBN	FRS/1	Pa	Po	Po	FRmax	P
13A	2018047	95	2018031	5	<0,01	<0,01	<0,01	1	2,91	0,95	0,67	2,4	108	0,32	0,55	1,08	72	55	1,31
13B	2018047	80	2018031	20	0,01	0,02	0,02	1	1,72	0,71	0,59	1,5	99	0,59	0,34	0,99	72	67	1,07
13C	2018047	50	2018031	50	0,02	0,05	0,19	1											
13D	2018047	10	2018031	90	0,06	0,06	0,19	1											
14A	2018004	50	2018025	50	0,03	<0,01	0,01	1	1,79	0,71	0,52						37	45	0,82
15A	2018012	40	2018031	60	0,02	0,03	0,05	1	1,35	0,81	0,40						67	61	1,10
15B	2018012	90	2018031	10	<0,01	<0,01	<0,01	1											
16A	2018015	20	2018034	80	0,03	0,07	0,05	3	1,80	0,81	0,55						46	58	0,79
16B	2018015	40	2018034	60	0,02	0,03	0,04	2	1,95	0,98	0,50						Not possible	Not possible	
17A	2018028	60	2018022	40	0,02	<0,01	<0,01	1	1,42	0,56	0,60						62	71	0,87
17B	2018028	20	2018022	80	0,01	<0,01	0,02	2	1,57	0,79	0,50						96	95	1,01
17C	2018028	90	2018022	10	0,03	0,14	0,13	2											
18A	2018030	20	2018034	80	0,08	0,03	0,07	2	1,78	0,63	0,65						38	45	0,84
18B	2018030	10	2018034	90	0,08	0,15	0,14	2											
19A	2018025	50	2018001	50	0,04	<0,01	0,01	1	1,53	0,70	0,46						54	55	0,98
20A	2018025	50	2018042	50	<0,01	<0,01	0,01	1	No floculation in test range								90	44	2,05
21A	2018004	50	2018044	50	0,05	0,06	0,04	2	2,34	0,56	0,76						30	40	0,75
22A	2018011	50	2018044	50	<0,01	<0,01	<0,01	1	2,61	0,81	0,49						Asphaltenes <1%		
23A	2018012	50	2018044	50	0,18	<0,01	0,07	2	1,37	0,48	0,65						Asphaltenes <1%		
24A	2018008	90	2018030	10	0,02	0,08	0,04	2											

APPENDIX 10 - EXAMPLES OF CALCULATIONS OF COMPATIBILITY

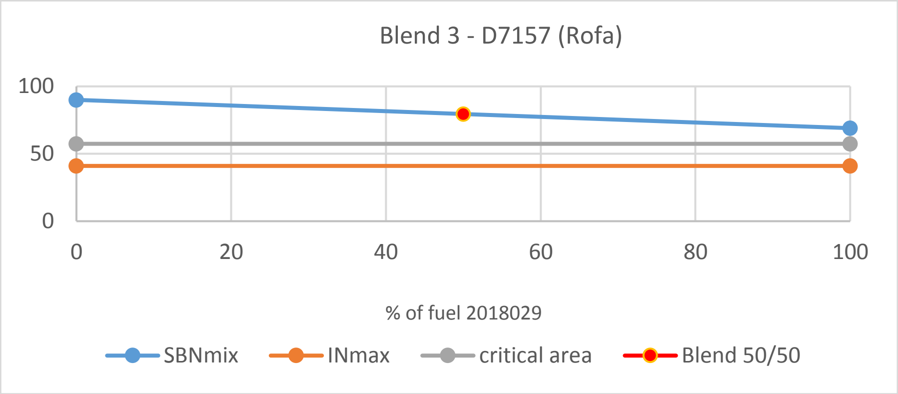
Example 1

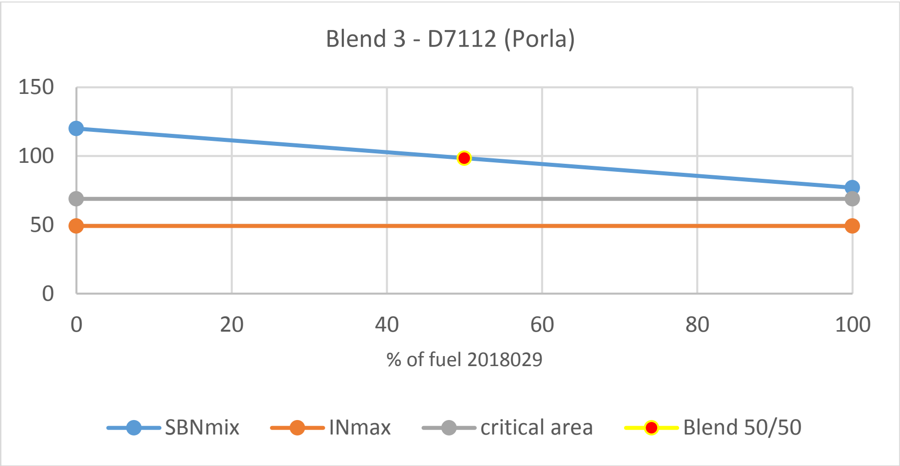
Data for individual fuels and for Blend 3

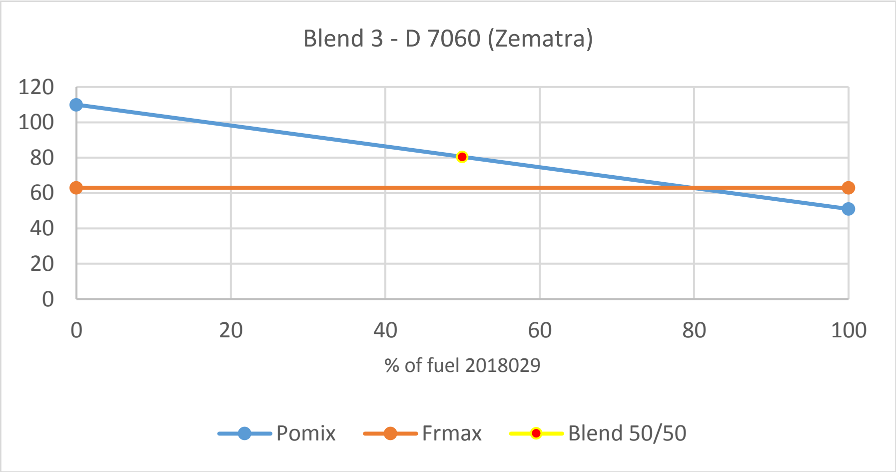
	2018013		**2018029**	
Viscosity, cSt	357,5		495,3	
Density, kg/m3	987,8		944,9	
CCAI	849		803	
$\lvert\Delta CCAI\rvert$	46			
S, mass %	**0,46**		**0,51**	
TSE, mass %	0,02		<0,01	
TSP, mass %	0,02		0,01	
TSA, mass %	0,03		0,01	
Asphaltenes, mass %	2,6		2,4	
Spot test	1		1	
Pour point, °C	0		-15	
Si+Al, mg/kg	<15		2,4	
S/P-value	2,21	2,44	4,24	4,45
So/Po	0,92	1,2	0,72	0,71
Sa/Pa	0,59	0,51	0,83	0,84
SBN	90	120	69	71
IN	41	49	17	16
P-ratio	1,75		1,88	
Po	110		51	
FR_{max}	63		27	

	blend 3	
ratio blend	50/50	
TSE, mass %	< 0,01	
TSP, mass %	0,01	
TSA, mass %	< 0,01	
Spot test	1	
S/P-value	2,37	2,6
So/Po	0,7	0,92
Sa/Pa	0,7	0,65
P ratio	1,75	
Pomix	77	
FR_{max}	44	

Compatibility diagrams for blend 3







Both Rofa and Porla predicts that mixing fuel 2018013 with 2018029 will give a stable blend at any mixing ratio (the lowest SBN of the fuels is above the critical area) whereas Zematra predicts 2018013 to be compatible with 2018029 when 2018013 is more than 20% or 2018029 less than 80%.

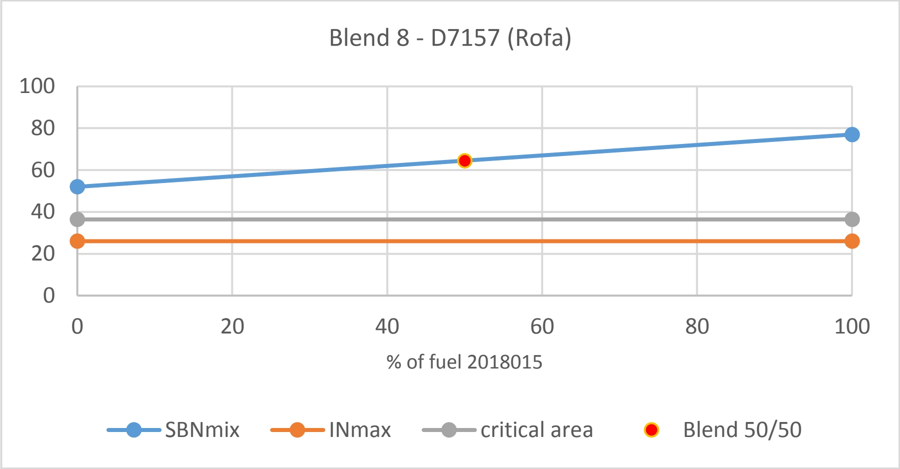
Example 2

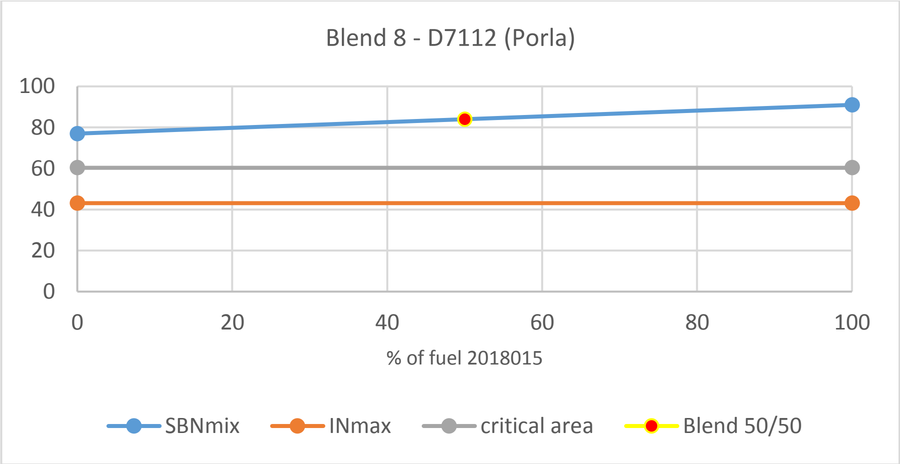
Data for individual fuels and for Blend 8

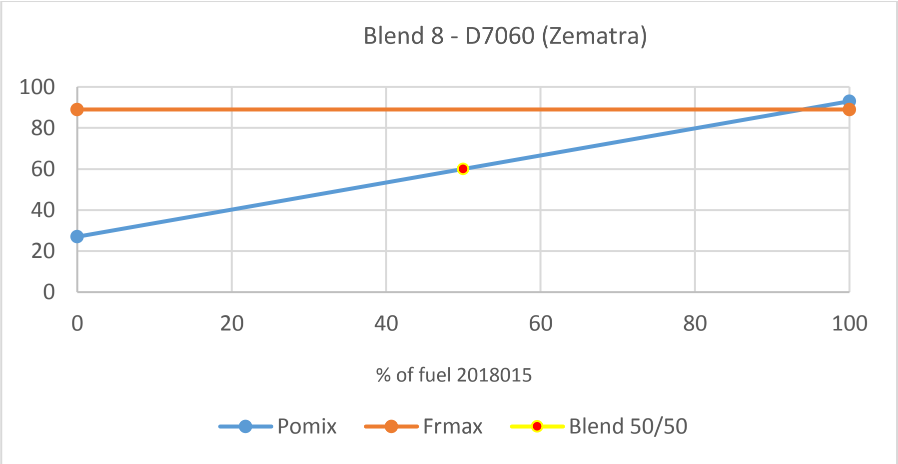
	2018004		2018015	
Viscosity, cSt 50°C	64,93		65,15	
Density, kg/m3	981,4		957,6	
CCAI	864		840	
|ΔCCAI|	24			
S, mass %	**0,51**		**0,6**	
TSE, mass %	0,01		0,03	
TSP, mass %	0,01		0,17	
TSA, mass %	0,01		0,08	
Asphaltenes, mass %	3		0,81	
Spot test	1		3	
Pour point, °C	10		24	
Si+Al, mg/kg	<15		43	
S/P-value	2,3	3,58	3,03	2,1
So/Po	0,49	0,77	0,79	0,91
Sa/Pa	0,79	0,79	0,74	0,57
SBN	48	77	77	91
IN	21	22	26	43
P-ratio	0,77		1,04	
Po	27		93	
FR_{max}	35		89	

	blend 8	
ratio blend	50/50	
TSE, mass %	< 0,01	
TSP, mass %	0,01	
TSA, mass %	< 0,01	
Spot test	1	
S/P-value	2,37	2,8
So/Po	0,7	0,92
Sa/Pa	0,7	0,65
P-ratio	0,57	
Pomix	27	
FR_{max}	47	

Compatibility diagrams for blend 8







Both Rofa and Porla predict that mixing fuel 2018004 with 2018015 will give a stable blend at any mixing ratio (the lowest SBN is above critical area) whereas Zematra predicts the 50/50 blend to be incompatible (P-ratio= 0.57) although it has a TSP of 0.01 mass %.

Example 3

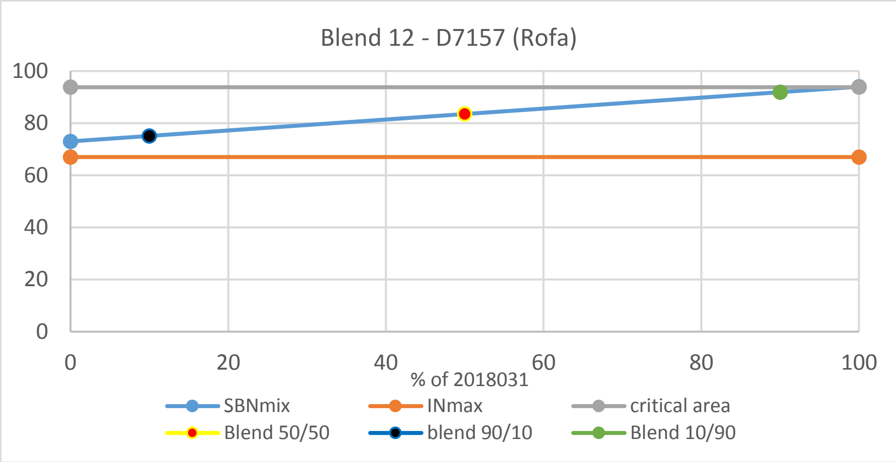
Data for individual fuels and for Blend 12

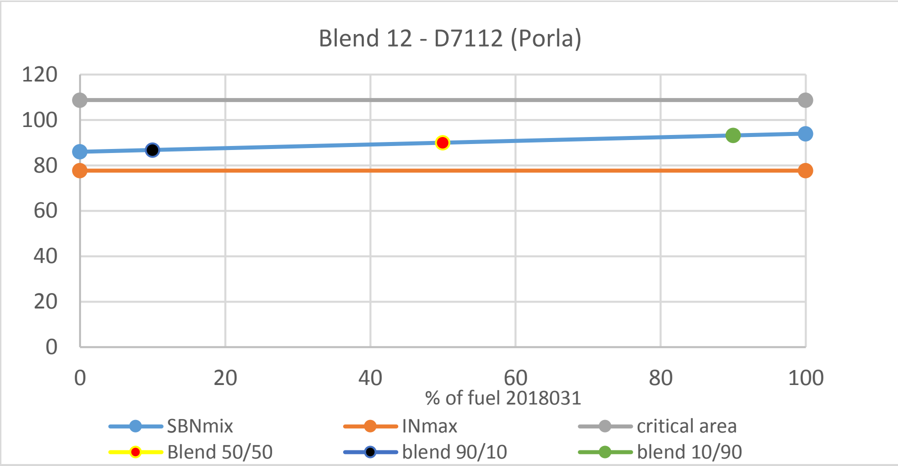
	2018043		2018031	
Viscosity, cSt 50°C	366		188,6	
Density, kg/m3	974,7		1000,7	
CCAI	836		840	
|ΔCCAI|	33			
S, mass %	**2,91**		**0,46**	
TSE, mass %	0,03		0,03	
TSP, mass %	0,02 (0,03)*		0,02	
TSA, mass %	< 0,01		< 0,01	
Asphaltenes, mass %	6,4		5,9	
Spot test	1		1	
Pour point, °C	< 24		-18	
S/P-value	1,81	1,75	1,41	1,21
So/Po	0,74	0,86	0,95	0,94
Sa/Pa	0,59	0,51	0,33	0,22
SBN	73	86	94	94
IN	41	49	67	78
P-ratio	1,41		1,15	
Po	86		77	
FR_{max}	61		67	

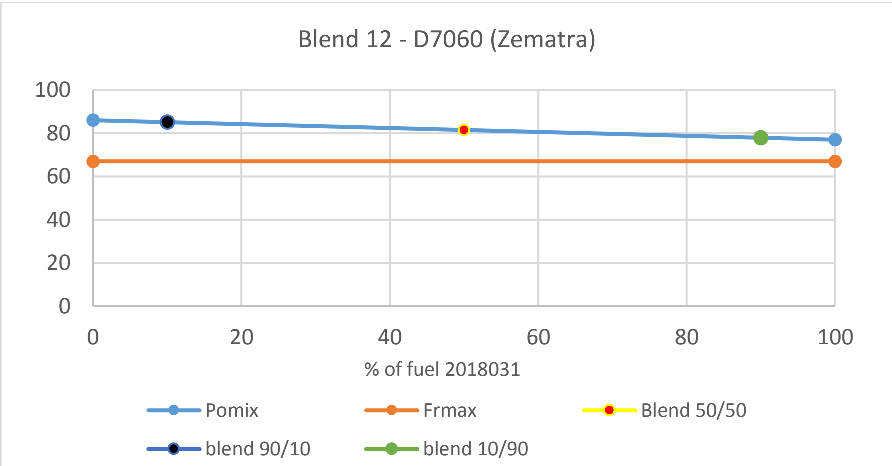
	blend 12			
ratio blend	50/50		90/10	10/90
TSE, mass %	0,04		0,03	0,02
TSP, mass %	0,02		0,03	0,03
TSA, mass %	0,05		0,05	0,04
Spot test	1		1	1
S/P-value	1,48	1,4		
So/Po	0,81	0,89		
Sa/Pa	0,41	0,36		
P-ratio	1,10			
Pomix	67			
FR_{max}	61			

*: re-test after 3 months

Compatibility diagrams for blend 12







Both Rofa and Porla predict that mixing fuel 2018004 with 2018015 will at any mixing ratio give a blend within the critical area but all blends have TSP well within specification and the fuels can be considered to be compatible. Zematra predicts the fuels to be compatible at any mixing ratio.

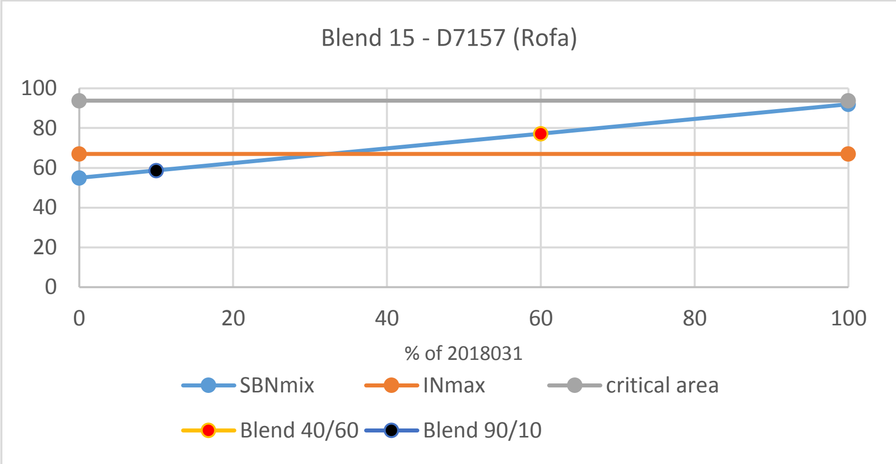
Example 4

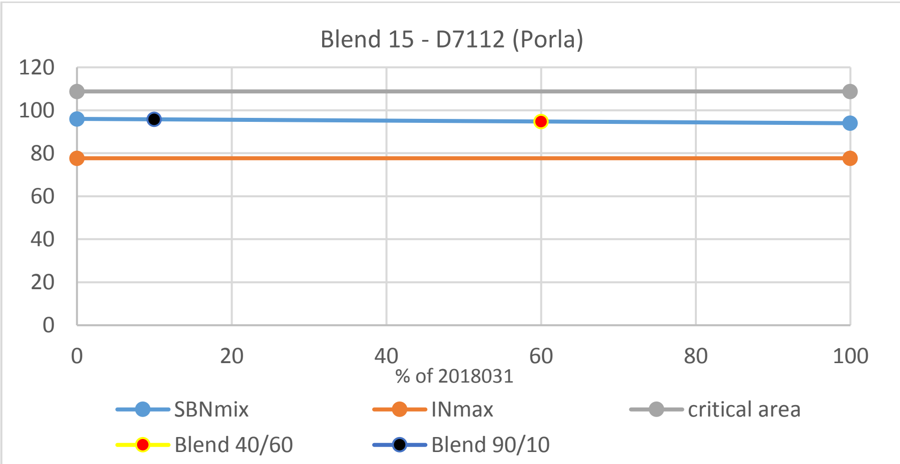
Data for individual fuels and for Blend 15

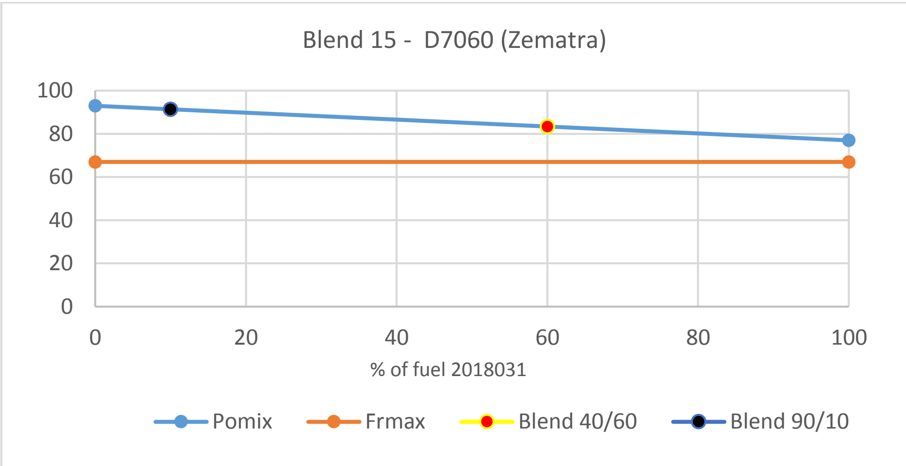
	2018012		**2018031**	
Viscosity, cSt 50°C	63,52		188,6	
Density, kg/m3	955,8		1000,7	
CCAI	839		840	
|ΔCCAI|	30			
S, mass %	**0,46**		**0,46**	
TSE, mass %	0,03		0,03	
TSP, mass %	< 0,01		0,02	
TSA, mass %	0,02		< 0,01	
Asphaltenes, mass %	3,4		5,9	
Spot test	1		1	
Pour point, °C	0		-18	
Si+Al, mg/kg	16		< 15	
S/P-value	1,52	4,52	1,41	1,21
So/Po	0,55	0,96	0,95	0,94
Sa/Pa	0,63	0,79	0,33	0,22
SBN	55	96	94	94
IN	37	21	67	78
P-ratio	1,86		1,15	
Po	93		77	
Fr_{max}	50		67	

	blend 15		
ratio blend	40/60		90/10
TSE, mass %	0,02		< 0,01
TSP, mass %	0,03		< 0,01
TSA, mass %	0,05		< 0,01
Spot test	1		1
S/P-value	1,35	1,9	
So/Po	0,81	0,96	
Sa/Pa	0,40	0,49	
P-ratio	1,10		
Pomix	67		
FR_{max}	61		

Compatibility diagrams for Blend 15







Rofa predicts 2018012 and 2018031 to be incompatible when 2018031 is less than 69%. However, the TSP of a 90/10 blend is well within the limit of 0.10 mass %. Porla predicts that at any mixing ratio the blend is within the critical area and Zematra predicts the fuels to be compatible at any mixing ratio.

Examples 5 & 6

Data for individual fuels and blends 19 and 20

	2018025		2018001	2018042
Viscosity, cSt 50°C	64,93		2,55	108,9
Density, kg/m3	981,4		858,5	909,8
CCAI	864		816	785
S, mass %	**0,51**		**0,09**	**0,10**
TSE, mass %	0,01		< 0,01	< 0,01
TSP, mass %	0,01		< 0,01	< 0,01
TSA, mass %	0,01		< 0,01	< 0,01
Asphaltenes, mass %	3		< 0,50	< 0,50
Spot test	1		2	1
Pour point, °C	< -3		21	27
Si+Al, mg/kg	35		< 15	< 2
S/P-value	2,3	2,5	no flocculation in test range	no flocculation in test range
So/Po	0,49	0,71		
Sa/Pa	0,79	0,72		
SBN	48	71		
IN	21	28		
P-ratio	1,3		asphaltenes < 1%	asphaltenes < 1%
Po	65			
Fr_{max}	50			

	blend 19 2018025/2018001		blend 20 2018025/2018042
ratio blend	50/50		50/50
|ΔCCAI|	48		79
TSE, mass %	0,04		< 0,01
TSP, mass %	< 0,01		< 0,01
TSA, mass %	0,01		0,01
Spot test	1		1
S/P-value	1,53	2,3	no flocculation in test range
So/Po	0,7	0,7	
Sa/Pa	0,46	0,7	
P-ratio	0,98		2,05
Pomix	54		90
FR_{max}	55		44

Blend 19 is a 50/50 blend of a VLSFO with CCAI of 864 with a low viscosity (2.550 St at 50 ˚C) ULSFO with CCAI of 785. While the prediction of compatibility is not possible due to the lack of individual fuel test data, TSP of blend 19 is well within the specification limit of 0.10 mass %. Rofa and Porla test data of the blend indicates the 50/50 blend to be stable and borderline stable according to Zematra.

Blend 20 is a 50/50 blend of the same VLSFO with CCAI 864 with a RM 109 cSt at 50°C ULSFO. TSP of the blend is well within the specification limit of 0.10 mass %. Rofa and Porla report the blend as very stable (no flocculation of asphaltenes in test range) and also Zematra reports the blend as very stable.

Examples 7 & 8

Data for individual fuels and blends 21 and 23

	2018004		**2018012**		**2018044**
Viscosity, cSt 50°C	59,05		63,52		2,889
Density, kg/m3	920,6		955,8		835,1
CCAI	804		839		788
S, mass %	**0,48**		**0,46**		**0,04**
TSE, mass %	< 0,01		0,03		< 0,01
TSP, mass %	< 0,01		< 0,01		?
TSA, mass %	0,03		0,02		< 0,01
Asphaltenes, mass %	0,9		3,4		< 0,50
Spot test	1		1		1
Pour point, °C	10		0		0
Si+Al, mg/kg	< 10		16		< 2
S/P-value	2,9	3,8	1,52	4,52	Tests not possible
So/Po	0,57	0,77	0,55	0,96	
Sa/Pa	0,81	0,79	0,63	0,79	
SBN	52	77	55	96	
IN	19	21	37	21	
P-ratio	0,75		1,86		asphaltenes < 1%
Po	27		93		
Fr_{max}	36		50		

	blend 21 2018004/20180044		**blend 23 2018012/2018044**	
ratio blend	50/50		50/50	
|ΔCCAI|	16		51	
TSE, mass %	0,05		0,18	
TSP, mass %	0,06		< 0,01	
TSA, mass %	0,04		0,07	
Spot test	2		2	
S/P-value	2,34	3,2	1,37	2,8
So/Po	0,56	0,65	0,48	0,75
Sa/Pa	0,76	0,80	0,65	0,69
P-ratio	0,75		Test not possible	
Pomix	30			
FRmax	40			

Blend 21 is a blend of a VLSFO RM type fuel with a low viscosity ULSFO. Prediction of compatibility is not possible due to the lack of individual fuel test data. TSP and TSA of the blend are increased but still within the specification limit of 0.10 mass %. Rofa and Porla test data of the blend indicates the 50/50 blend to be stable but unstable according to Zematra. The 50/50 blend has a spot rating of 2, which is still indicative for the fuels being compatible at that ratio.

Blend 23 is a blend of a VLSFO RM type fuel with a low viscosity ULSFO. Prediction of compatibility is not possible due to the lack of individual fuel test data. The blend has an increased TSA but TSP is within the limit of 0.10 mass % and has a spot rating of 2. Porla test data of the blend indicates the 50/50 blend to be stable and borderline stable according to Rofa. P-ratio measurement was not possible.

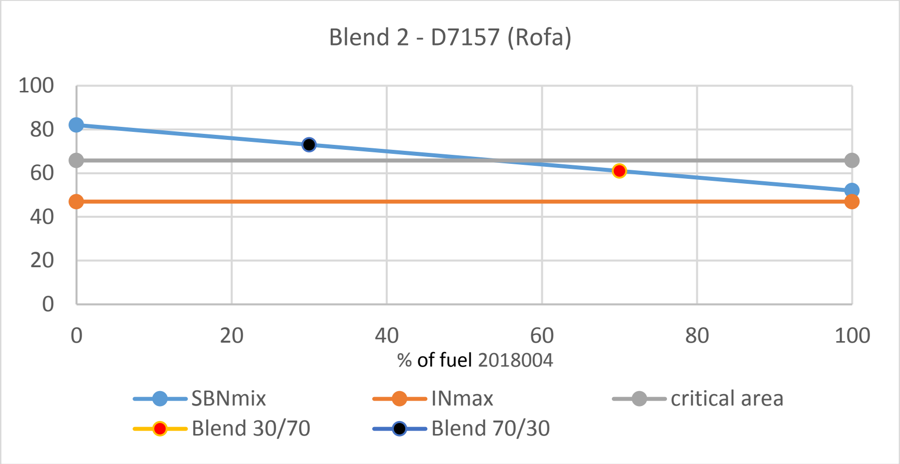
Example 9

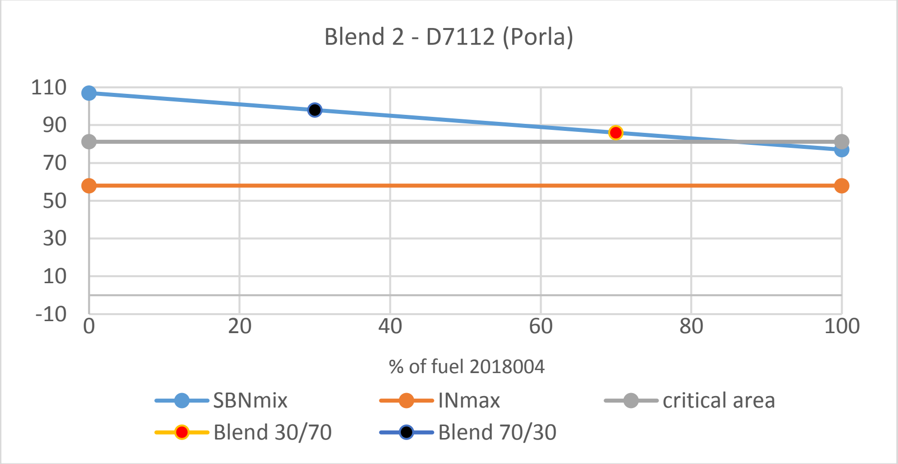
Data for individual fuels and for Blend 2

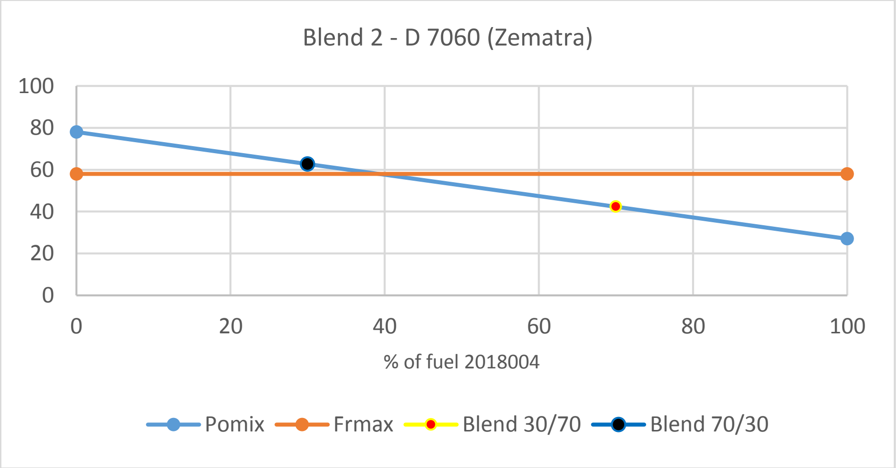
	2018045		**2018004**	
Viscosity, cSt 50°C	429,1		59,05	
Density, kg/m3	996,8		920,6	
CCAI	839		804	
|ΔCCAI|	53			
S, mass %	**2,16**		**0,48**	
TSE, mass %	0,10		< 0,01	
TSP, mass %	0,02		< 0,01	
TSA, mass %	0,05		0,03	
Asphaltenes, mass %	9,3		0,9	
Spot test	1		1	
Pour point, °C	< 9		10	
Si+Al, mg/kg	58		10	
S/P-value	1,74	1,85	2,9	3,58
So/Po	0,83	1,07	0,57	0,77
Sa/Pa	0,53	0,42	0,81	0,79
SBN	82	107	52	77
IN	47	58	19	22
P-ratio	1,34		0,77	
Po	78		27	
FR_{max}	58		35	

	blend 2			
ratio blend	30/70		70/30	
TSE, mass %	0,87		0,06	
TSP, mass %	0,73		0,10	
TSA, mass %	0,9		0,17	
Spot test	5		1	
S/P-value	1,11	2,9	1,4	2,4
So/Po	0,49	0,89	0,67	0,95
Sa/Pa	0,56	0,89	0,52	0,6
P-ratio	Test not possible		0,89	
Pomix			50	
FR_{max}			56	

Data for individual fuels and for Blend 2







Rofa predicts 2018045 and 2018004 to be compatible when 2018004 < 54% and in the critical area when 2018004 is > 54%.
Rofa, Porla and Zematra predict the 70/30 blend to be stable but the blend has TSP at the limit of 0.10 mass %, TSA of 0.17 mass % and a spot rating of 1.
Rofa predicts the 30/70 blend to be in the critical area and Porla predicts this blend to be stable. Zematra predicts the 30/70 blend to be unstable but testing of the blend was not possible. The 30/70 blend has high TSE/TSA and TSP.

Example 10

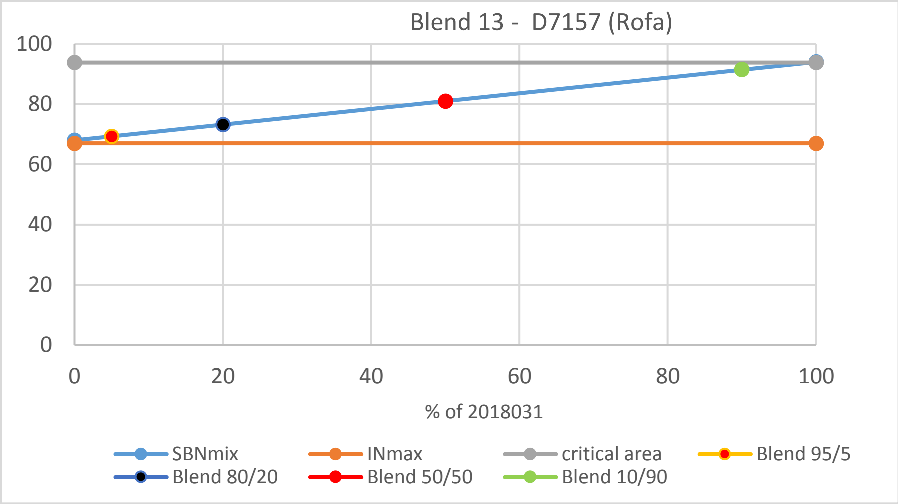
Data for individual fuels and Blend 13

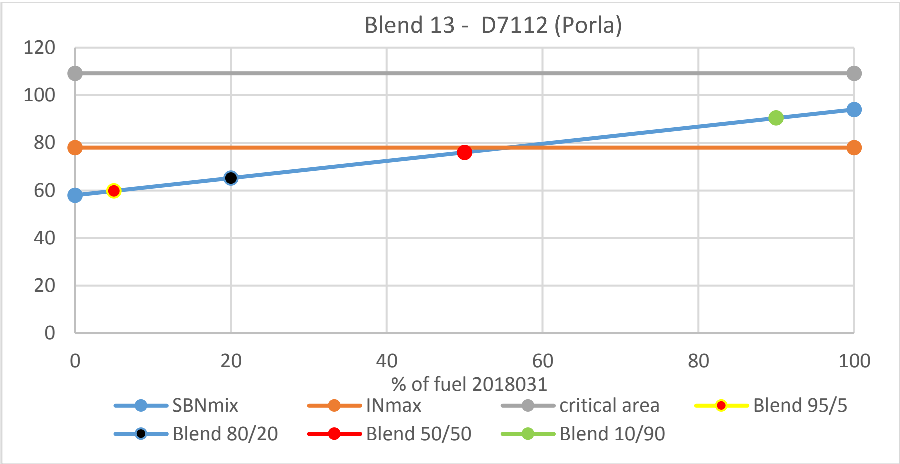
	2018047		2018031	
Viscosity, cSt 50°C	287,3		188,6	
Density, kg/m3	962,6		1000,7	
CCAI	826		869	
|ΔCCAI|	43			
S, mass %	**1,15**		**0,46**	
TSE, mass %	<0,01		0,03	
TSP, mass %	< 0,01 (0,04)*		0,02 **(0,01)***	
TSA, mass %	< 0,01		< 0,01	
Asphaltenes, mass %	1,3		5,9	
Spot test	1		1	
Pour point, °C	< 24		-18	
Si+Al, mg/kg	29		< 15	
S/P-value	3,33	2,85	1,41	1,21
So/Po	0,69	0,58	0,95	0,94
Sa/Pa	0,79	0,80	0,33	0,22
SBN	68	58	94	94
IN	21	20	67	78
P-ratio	1,72		1,15	
Po	74		77	
FR_{max}	43		67	

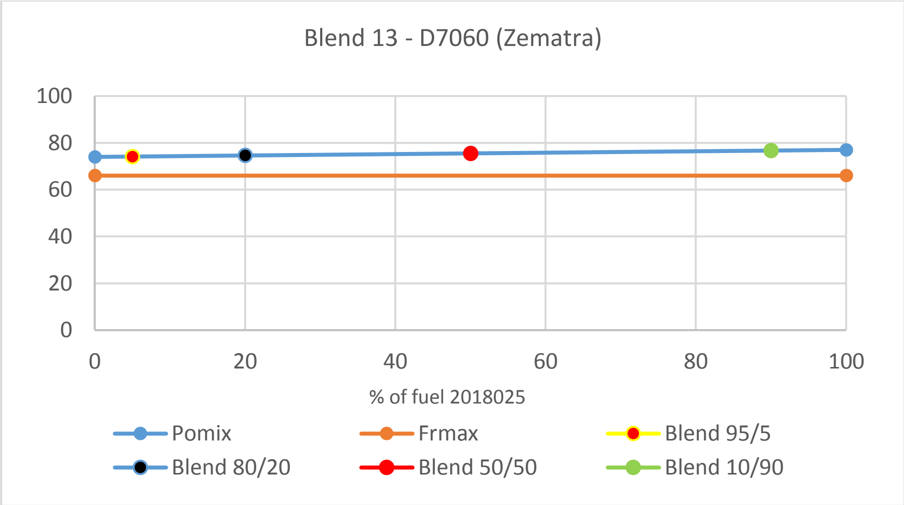
	blend 13					
ratio blend	95/5		80/20		50/50	10/90
TSE, mass %	< 0,01		0,01		0,02	0,06
TSP, mass %	< 0,01		0,02		0,05	0,06
TSA, mass %	< 0,01		0,02		0,19	0,19
Spot test	1		1		1	1
S/P-value	2,91	2,4	1,72	1,5		
So/Po	0,95	1,08	0,71	0,99		
Sa/Pa	0,67	0,55	0,59	0,34		
P-ratio	1,31		1,07			
Pomix	72		72			
FR_{max}	55		67			

*: re-test after 3 months

Compatibility diagrams for Blend 13







All blends considered have TSP < 0.10 mass % and spot rating 1. TSA of blends 50/50 and 10/90 > 0.10 mass % which indicates the blends to have reduced stability reserve. Rofa predicts the 95/5, 80/20, 50/50 and 10/90 blends to be in the critical area. Porla predicts the fuels not to be compatible at the ratios 95/5, 80/20 and 50/50. Zematra predicts the fuels to be compatible at all mixing ratios.

This example illustrates the weakness of the oil compatibility model: when the risk for incompatibility is predicted to increase, TSP decreases. It should be noted that sample 2018031 has S/P-value which deviate from values considered typical for stable marine fuels.

Example 11

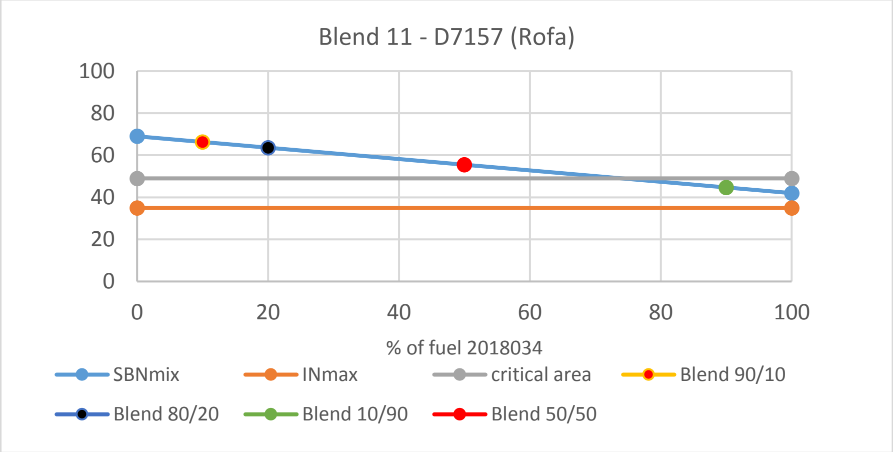
Data for individual fuels and for Blend 11

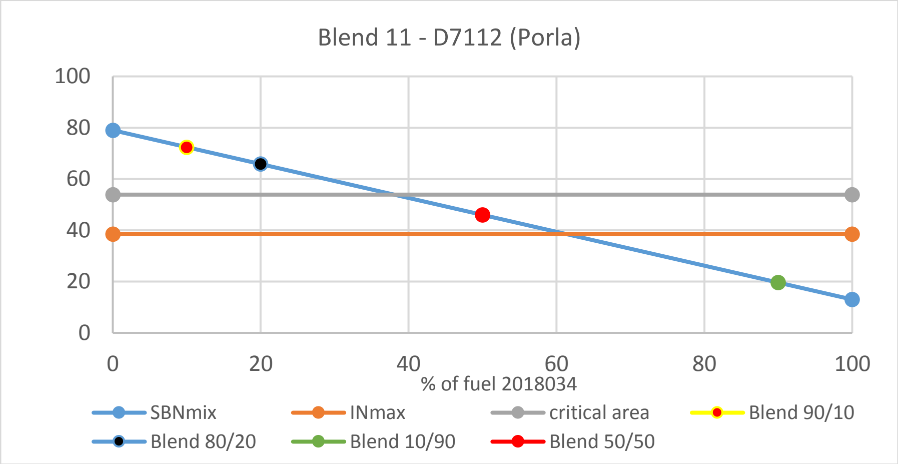
	411-280		**2018034**	
Viscosity, cSt 50°C	381,4		9,8	
Density, kg/m3	981		905,4	
CCAI	842		823	
|ΔCCAI|	19			
S, mass %	**2,76**		**0,48**	
TSE, mass %	0,04		0,05	
TSP, mass %	0,04 **(0,06)***		0,05 **(0,14)***	
TSA, mass %	0,07		0,05	
Asphaltenes, mass %	8,5		0,3	
Spot test	1		1	
Pour point, °C	-12		-7	
Si+Al, mg/kg	33		36	
S/P-value	1,99	2,04	1,49	0,53
So/Po	0,71	0,79	0,43	0,13
Sa/Pa	0,65	0,61	0,71	0,76
SBN	69	79	42	13
IN	35	39	29	24
P-ratio	1,70		0,84	
Po	104		47	
FR_{max}	61		56	

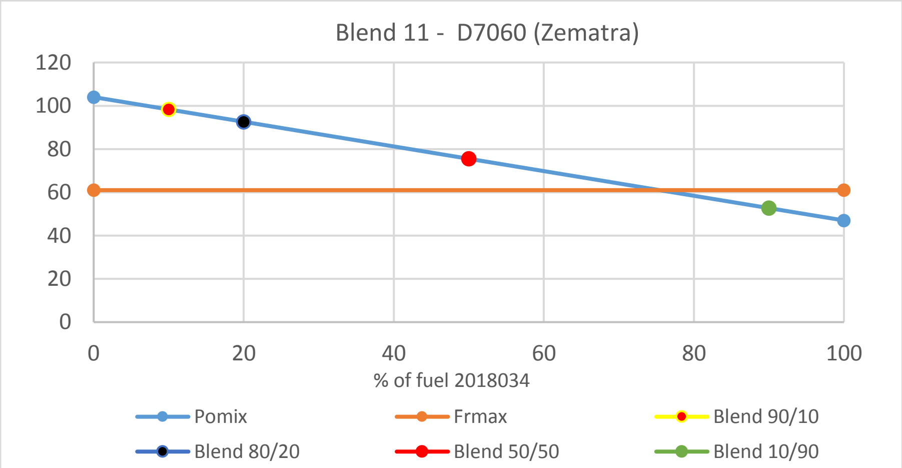
	blend 11					
ratio blend	90/10		80/20		50/50	10/90
TSE, mass %	0,04		0,04		0,06	0,28
TSP, mass %	0,06		0,07		0,09	0,36
TSA, mass %	0,09		0,05		0,17	0,40
Spot test	1		1		1	4
S/P-value	1,87	1,9	1,76	1,6		
So/Po	0,71	0,74	0,67	0,65		
Sa/Pa	0,62	0,61	0,62	0,59		
P-ratio	1,31		1,25			
Pomix	50		55			
FR_{max}	38		41			

*: re-test after 3 months

Compatibility diagrams for Blend 11







Rofa, Porla and Zematra predict the fuels to be compatible when fuel 2018034 is respectively less than 74%, less than 37% and less than 75.5%. Rofa and Zematra predict the fuels to be compatible at 50/50 ratio for a measured TSP of 0.09 mass % and TSA of 0.17 mass %. Rofa predicts the 10/90 blend to be in the critical area but TSA and TSP are exceeding significantly 0.10 mass %, which is aligned with the prediction of Porla and Zematra.

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