# High Biofuel Blends in Aviation (HBBA)

## ENER/C2/2012/ 420-1
## Final Report

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# Contents

# 1 Introduction and overview

This report presents the results of the research performed in accordance with tender ENER/C2/2012/ 420-1 “High Biofuel Blends in Aviation”. The purpose of this research was to analyse the properties of bio kerosene blends with various samples of conventional kerosene, with a focus on blends with high percentages of bio kerosene.

## 1.1 Economic Background

The issue of using high biofuel content blends in aviation might seem to be of merely academic relevance given that the share of bio kerosene of the overall aviation kerosene market is not expected to be more than a few per cent in the next ten years. However, for the practical introduction of bio kerosene it will be relevant to know about high biofuel blends even at an early stage in order to minimize blending and logistical costs.

The reason here is that for every bio kerosene blend three analyses have to be performed before it may be used in commercial aviation:

- An ASTM D1655 analysis of the conventional kerosene before blending
- An ASTM D7566 analysis of the neat bio kerosene before blending
- An analysis of the blend, which is described in ASTM D7566, but in practice is an analysis of the ASTM D1655 parameters, plus some additional ones.

It takes about 20 man hours to perform a full ASTM D1655 analysis, and requires use of specialized and expensive equipment. The cost of such an analysis is therefore thousands of Euros. In the case of the first two analyses this cost is independent of the blend ratio, and will typically be performed for large batches of thousands of tons, so the cost per ton is only a few Euros, which is a normal cost element of selling and shipping kerosene. In the case of the analysis after blending, however, the cost impact per ton of biofuel is crucially dependent on the blend ratio. If blend ratios of only a few per cent are used, the cost for the analysis will be incurred for selling only a few tons of bio kerosene, leading to very high costs per ton. At high blend ratios, on the other hand, these costs will not be an issue. In addition, use of low blend ratios imply that large volumes of conventional kerosene have to be transported to the blending point, making logistics complex and expensive, as well as potentially creating environmentally undesirable extra transports of the conventional kerosene.

For a producer or blender of biofuels it will therefore be important to know how much bio kerosene can possibly be blended, and how blend percentages can be maximized, even while the bio kerosene market is at an early stage. It will also be relevant for governments and communities involved in the planning of logistics and blending capacities.

## 1.2 Technical Background and Fuels Used

The specification relevant for bio kerosene in Europe is DefStan 91-91, which however for alternative fuels mirrors the US ASTM approval process. Thus, for practical purposes, the specifications of interest for this study are ASTM D1655 and ASTM D7566. Of these, ASTM D1655 covers kerosene in general, whereas ASTM D7566 specifically covers alternative fuels and its blending with conventional kerosene. According to these specifications, the maximum amount of bio-synthetic kerosene that can be mixed with conventional kerosene is currently restricted by two factors:

- The requirement that the content of bio-synthetic kerosene does not exceed the maximum percentage permitted by ASTM D7566.
- The requirement that the blend has to meet the same parameters as conventional ASTM D1655 kerosene, plus some additional ones

The first requirement is an arbitrary one, based solely on caution. It is the explicit intention of ASTM to eventually relax this restriction. The second requirement however is based on technical considerations – every specification parameter of ASTM D1655 is there for a reason, and this reason will not go away with the introduction of biofuels. Even when the formal maximum limit for synthetic kerosene will be removed by ASTM, the maximum bio kerosene content possible will be limited by the ability of the bio kerosene blend to meet the ASTM D1655 parameters.

However, as ASTM D1655 specifies minimum or/and maximum values for fuel parameters rather than defined values, conventional kerosene properties cover a rather broad range. The maximum possible blend ratio for bio kerosene therefore does not only depend on the bio kerosene, but also on the conventional kerosene. This is because conventional kerosene that is comfortably within specification limits can be used to compensate unfavourable properties of neat bio kerosene, and still produce an on-spec blend.

For this study, therefore, a total of five different conventional kerosene samples, covering a broad range of properties, were used for blending with bio kerosene. The range and distribution of properties observable for conventional kerosene, and details of the conventional kerosene used in this study are described in chapter 2 and annex 9.1.

For the biofuels to be analysed in this study, the original intention had been to primarily use three different samples of HEFA bio kerosene, and in addition investigate only a limited number of other kinds of bio kerosene blends, as it was assumed that only HEFA would be available in sufficient volume to permit an extensive blending programme. However, as the project progressed it became evident that development of alternative fuels was progressing faster than originally assumed, and samples for most of the relevant production processes were actually available. At the same time evidence showed that different HEFA samples would be very similar to each other, such that analysing three different samples would merely produce three sets of basically the same results. It was therefore agreed with DG Energy to modify the scope of the study such that only one HEFA sample was used, and instead samples of bio kerosene from a variety of pathways were included. A description of the bio kerosene used in this study, including their production pathways, is given in chapter 3 and annex 9.2.

As one of the tasks of the study also was to give an overview of biofuels in aviation, chapter 3 in addition gives a technical description of the production pathways and the certification status for all bio kerosene production pathways either already certified or undergoing ASTM certification, including these pathways for which no samples could be obtained for inclusion in the analytical part of the study.

The latest information on production pathways reflected in the interim report published in February 2015 was that provided at the San Diego ASTM meeting in early December 2014. For the final report, new information was added where appropriate, but no systematic update was undertaken. Except for FT- and HEFA-kerosene the description of the production pathways is based on the information provided by the manufacturer, either for certification purposes or in personal communication, as no other sources were available.

## 1.3 Blend Analyses

The results of the blend analyses are presented in chapter 4 and annex 9.3. The topic of interest here was the relationship between parameters of the blend and the blend ratio. For some parameters this relationship is linear, such that e.g. blending neat bio kerosene with a parameter value of 80 and neat conventional kerosene with a parameter value of 70, using a blend ration of 50%/50%, results in a blend with a parameter value of 75. Such relationships, which in particular were typically observed for volume or mass related parameters (like density or sulphur content), are straightforward and pose no particular challenges regarding blends. However, for other parameters the relationship is non-linear and more complex. It is with respect to these parameters that we consider this study to be of particular use for practical blenders and users of bio kerosene. For two parameters, lubricity and freezing point, we even found cases where the parameter value of the blend actually went beyond the range defined by the parameters of the two original fuels.

One major factor currently limiting maximum biofuel blend ratios is aromatics content. This is because ASTM D7566 requires minimum aromatics content for the blend of 8%, but several of the bio kerosene production pathways yield a fuel with virtually zero aromatics content. For these fuels, all aromatics must come from the conventional kerosene. However, aromatics content of conventional kerosene is limited by ASTM D1655 to a maximum value of 25%, so any blend with more than 68% of bio kerosene must have an aromatics content of below 8%, and hence be off-spec.[1] Moreover, as is shown in chapter 2, the typical aromatics content of conventional kerosene is well below the maximum figure, hence the practical limit for blend ratios is well below 68%.

There is potentially a simple way around this obstacle, by adding aromatics. It is to be assumed that this route will be pursued in the future, and indeed one of the fuels currently up for ASTM approval consists almost solely of aromatics and is explicitly designed as such a blend component (see section 3.9). However, the addition of aromatics to the fuel will in itself alter the properties of the blend; hence it was considered relevant for future blending applications to assess what these effects are likely to be. Accordingly, for each of the three bio kerosenes concerned (FT-kerosene, HEFA, ATJ) two high-level blends were produced, and then aromatics were added to increase their content to the minimum value required by ASTM D 7566. The results of this research are described in chapter 5 and annex 9.4.

It had originally also been planned to analyse the effects of blending in STADIS 450, which is an anti-static additive that all kerosene transported in Europe must contain. However, initial research found the influence of this component on fuel properties to be virtually nil, hence this approach was dropped.

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[1] To be precise, there are two alternative ways of measuring aromatics content, ASTM D1319 and ASTM D6379. If the first is used, minimum aromatics content of the blend is 8% and maximum aromatics content is 25%. If the second is used, the respective figures are 8.4% and 26.5%.

## 1.4 Materials Compatibility Tests

In addition to analysing the properties of the various bio kerosene blends, the study also investigated the influence of the different synthetic fuels on the elastomers of which the seals in fuels systems typically are composed. This analysis of materials compatibility was conducted on seals from Nitrile-Butadiene Rubber, Fluorosilicone Rubber and Fluorocarbon Rubber. For these tests no blends were used; instead, the elastomer material was exposed to the neat bio kerosene, as well as for reference to the various conventional fuels used in this study.

The effect of fuel on seal tightness is generally attributed to the aromatics content. To verify the effect of aromatics on elastomers, and to investigate the role of different kinds of bio kerosene, aromatics were systematically added to the aromatics-free bio kerosene, and the tests repeated.

In a final step, the elastomer materials were first exposed to the conventional fuel with the highest aromatics content, and subsequently exposed to the neat aromatics-free bio kerosene, simulating a situation where an aircraft has been operated on conventional kerosene and is then exposed to bio kerosene.

The results of the materials compatibility tests are described in chapter 6 and annex 9.5.

## 1.5 Aircraft Engine Emissions Tests

In addition to the safety aspects of bio kerosene, which are extensively investigated during the ASTM approval process, another technical aspect of bio kerosene is their emissions behaviour. Consideration of emissions is not part of the ASTM fuel certification process, and indeed it would be very difficult for ASTM to include emissions in a fuel specification, since emissions are primarily dependent on the engine the fuel is burned in. Emission measurements therefore are not a required part of the ASTM process, and little emissions data is typically presented in the research reports submitted to ASTM. All the same, some fuels will burn cleaner in a given engine than others. It is therefore of interest to see whether biofuels will lead to an improvement of the emissions of a given engine. For that reason, emissions tests were included in the program of this study.

The initial planning for the emissions tests was based on the same assumptions as the lab tests, i.e. that only HEFA would be available in relevant quantities. The original intention therefore was to perform one set of emissions tests for each of the three HEFA biofuels which initially were planned to be included. However, as with the lab tests, this plan was changed when it became evident that tests of several HEFA batches would produce very little variation in results, and on the other hand availability of fuel from other production pathways progressed better than assumed, whereas HEFA availability was worse than expected. It was therefore agreed with DG Energy to conduct the emissions tests with other kinds of bio kerosene, and a first set of tests was conducted in November 2013, using farnesane. However, it was only in early 2016 that sufficient volumes of a second bio kerosene could be procured, with test rig and test engine availability only permitting the actual tests to be conducted in November 2016. The results of the emissions tests are presented in chapter 7.

## 1.6 Conclusions

The conclusions of this study are presented in chapter 8. Section 8.1 explores the results of the study by fuel properties, discussing which properties are expected to be critical for future blend ratios of bio kerosene, but also discussing properties which are not likely to be critical for blending but where the relationship between the blend ratio and the property was considered worth pointing out. The latter are not relevant for blending bio kerosene, but are potentially of interest for others. Section 8.2 explores the same results by fuel type, discussing which role the individual kinds of bio kerosene are likely to play in future blending activities.

One particularly critical property is aromatics content. It is critical not only because several bio kerosene production pathways result in fuel that is virtually aromatics-free, but also because the role of aromatics is a two-faced one, with aromatics being currently necessary to preserve the tightness of fuel systems but on the other hand being undesirable from a fuel burn and emissions point of view. This specific role of aromatics is discussed in section 8.3.

# 2 Conventional Kerosene

The primary task of the HBBA Study is to analyse how various samples of conventional kerosene, covering the range of kerosene properties, blend with different bio kerosene. The first task of the HBBA Study therefore was to establish the relevant range of properties of conventional kerosene, and to identify sources for supply of suitable samples.

## 2.1 Published Data on Conventional Fuel Properties

For all Jet A-1 kerosene produced worldwide, data on its key properties is in principle readily available, as these parameters must be determined at point of manufacture, and a certificate stating their numerical values issued for every batch (Refinery Certificate of Quality, RCQ), with a new analysis and certificate (Certificate of Analysis, CoA) necessary if different batches of fuel are commingled and rebatched.[2] The respective certificates are the basis for aviation fuel quality assurance, and are handed over whenever there is a change of custody. It is therefore easy to identify the properties for any individual batch of aviation kerosene.

However, these certificates are usually only used for quality control along the supply chain. They are typically faxed or distributed as paper, and are not available in an electronically readable form. Once a batch of kerosene has been passed on, or consumed, the respective certificate is filed as documentary proof of conformity with specifications, but other than that the property information is typically not recorded or aggregated. Moreover, where individual users do aggregate some information (e.g. a refinery aggregating and analysing information on all its individual batches), this aggregated information is typically not published or otherwise made available externally. Thus, although information on the properties of individual batches is readily available, there are very few sources available for aggregate information on the spectrum of properties.

### 2.1.1 Petroleum Quality Information System (PQIS)

There is currently only one regularly published source giving data on the actual distribution of aviation kerosene properties. This source is the Petroleum Quality Information System (PQIS) Report, which is published annually by the US Defense Logistics Agency (DLA).

DLA is the only organization known to systematically collect and publish analysis results for the fuel purchased by it. The data sources for each individual fuel batch are the usual lab certificates of fuel properties which must accompany every fuel batch sold. However, DLA centrally collects the information contained in the certificates and evaluates it for distribution of fuel properties. The results are published annually in the PQIS report.

The PQIS report contains information on a variety of fuels purchased by the DLA, the most important ones being JP8, F-76 (a marine diesel), JP5 (a high-flashpoint kerosene for use on aircraft carriers) and Jet A-1.[3] Of these, JP8 and Jet A-1 are of interest for the HBBA Study, JP8 being a US military specification that essentially is identical to the civil Jet A-1

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[2] EI/JIG Standard 1530: Quality assurance requirements for the manufacture, storage and distribution of aviation fuels to airports, 1st edition October 2013, p.16/17

[3] 2013 PQIS Report, p. 10, Table 2-2

specification.[4] Statistics in the PQIS Report give data on minimum, maximum, mean and weighted mean for all properties covered in the report, both for the total of all purchases, and differentiated by region. Even more useful, the PQIS Report contains histograms on the distribution of the individual properties (only for the total of all purchases). For users wishing to make a more detailed analysis, DLA offers to provide the raw data, with refinery identification removed, on a disk.

It needs to be emphasized that the PQIS Report is a report on the fuel purchased by the US government, and is not intended as a representative survey of kerosene properties in the US or worldwide. The bulk of DLA purchases take place in the US, where the kerosene used by civil aviation is Jet A, which has a higher freezing point than JP8 (-40°C vs. -47°C for Jet A-1). If the PQIS Report is used as a proxy for US kerosene properties generally, allowance for sampling bias must be made, as not every refinery producing aviation kerosene also produces JP8. For example, of all JP8 batches for which data is included in the 2013 PQIS Report, only 7 originated from US East Coast refineries, but more than 50 times as much (361) from US Midwest refineries.[5] All the same, 2013 DLA purchases of JP8 and Jet A-1 were some four million tons, consisting of 1,287 batches[6], which by sheer volume make the PQIS Report a very valuable data base.

From a European point of view, the biggest weakness of the PQIS report is that by its nature it focusses on the US. Of the batches covered in the report, only 97 (89 Jet A-1 and 8 JP8) originated from Europe. Moreover, sampling bias must be suspected for these, as DLA purchases are likely to favour those refineries with access to the NATO pipeline network.

### 2.1.2 UK Survey Data

A European source for aviation kerosene property distribution is the UK Survey “The Quality of Aviation Fuel Available in the United Kingdom”. This is a survey based on test certificates for new batches of aviation kerosene (aviation turbine fuel, AVTUR) either produced in, or imported into, the UK.[7] This report was first published by QinetiQ Fuels & Lubricants Centre in 1974, and has been annually published until reporting year 2008.[8] Unlike the PQIS, this report is not limited to government purchases, but aims at national coverage. For all specification properties, data are given for minimum, maximum and weighted mean. Also, histograms showing the distribution of the properties are presented for all properties. Given the large number of batches covered (1.686 batches for 2008),[9] this is a valuable source. However, publication of the Survey was discontinued after the reporting year 2008, thus our work had to be based on data for 2008. A recent decision has been made by the CRC and the Energy Institute to again publish it regularly starting with the reporting year 2014, and in the interim a Survey giving data for the years 2009 to 2013 has been published.[10] However, publication of this Survey was too late for inclusion of the data in this report.

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[4] 2013 PQIS Report, p. 39 and 101. There are small differences, e.g. in maximum permissible sulfur mercaptane content, but these are minor.

[5] 2013 PQIS report, p. 40 / 41

[6] Calculated from 2013 PQIS report, pages 48 and 105

[7] The Quality of Aviation Fuel Available in the United Kingdom, Annual Survey 2008, p. 7

[8] Ibid., p.6

[9] Ibid.

[10] The Quality of Aviation Fuel Available in the United Kingdom, Annual surveys 2009 to 2013

### 2.1.3 World Fuel Sampling Program

A data source frequently cited in connection with approval of new kerosene production pathways is the World Fuel Sampling Program report, published in June 2006 as CRC Report No. 647. This is the report on a worldwide fuel sampling and testing program conducted jointly by Boeing, Goodrich, General Electric, ChevronTexaco and the United States Air Force.[11] In this program, properties were not established on the basis of existing fuel certificates. Rather, a total 57 samples was gathered worldwide, and analysed in detail.[12] This analysis was not limited to the specification properties, but went far beyond, and therefore is valuable for a deeper understanding of fuel properties. However, the study deliberately went for a diversity of samples[13], and thus is not indicative of actual distributions. Moreover, the sample size of 57 fuels is small, and only 12 of these were Jet A-1 samples from Europe.

## 2.2 Lufthansa Study on German Kerosene Properties

Given the limited information on kerosene property distributions in general, and the almost complete absence of such data for Germany, Lufthansa in 2011-2013 conducted its own study on German kerosene properties. The reason for this study was to identify conventional kerosene suitable for blending with HEFA kerosene at high blend ratios, for the purpose of emissions measurements as part of the burnFAIR research project.[14]

The data for the study was collected by approaching the intoplane fuelling companies at the main German airports, asking them to provide fuel certificates for one year of fuel supplies into the airport fuel system. This data was then manually evaluated by Lufthansa. For Frankfurt, certificates for deliveries from November 1, 2010 to October 31, 2011 were used, as analysis was started in November 2011 at that airport. For all other airports data for the calendar year 2011 were used.

Unlike the PQIS and the UK Survey data this analysis was not based on data at point of production or at point of import, but on data at point of consumption, i.e. at the airport. Accordingly not all certificates analysed were RCQs; in particular, CoAs dominated at airports with pipeline access, due to commingling and rebatching.

Data was gathered for Berlin-Tegel, Berlin-Schönefeld, Bremen, Düsseldorf, Dresden, Frankfurt, Hamburg, Hannover, Köln, Leipzig, München, Münster/Osnabrück, Nürnberg and Stuttgart airports. Fuel companies were not yet required to check and archive supply certificates in 2011, as EI/JIG 1530 was not yet in force. However, almost all of them already complied with the requirement, thus Lufthansa was able to get data for almost all deliveries. The sole exception was Stuttgart airport, where no data were available for one fuel source accounting for some 30 % of 2011 Stuttgart fuel deliveries. For Berlin-Tegel production certificate data from Schwedt refinery was used rather than intoplane company data, as virtually all supply to Berlin-Tegel was from Schwedt anyway, and using intoplane company data would have involved analysing documents for thousands of truck deliveries.

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[11] CRC report No. 647, p.6

[12] Ibid., p. 86 - 99

[13] Ibid., p.7

[14] For more detail on the background, see chapter 3.4 of Deutsche Lufthansa AG: Abschlussbericht zu dem Vorhaben Projekt burnFAIR, Arbeitspakete 1.1 bis 1.4, Frankfurt am Main, June 2014

Analysis of the certificates was by manually entering data on sulphur content, aromatics content, smoke point, density, freezing point, viscosity at minus 20°C and specific energy in MJ/kg into an Excel spreadsheet. As a rule, for every certificate a new data set was generated; however, several supplies to one and the same airport from the same kerosene batch (and hence with an identical RCQ or CoA) were only counted once. For supplies of different airports from the same production batch, two data sets were generated for airport specific analysis; however these double entries were removed for the overall analysis. In total, some 2.400 data sets were entered, of which some 400 were double entries.

Density, freezing point, viscosity at minus 20°C and specific energy in MJ/kg were selected because they were assumed to be relevant for blending purposes. Sulphur content, aromatics content and smoke point were selected for analysis due to their importance for emissions, as emissions measurement was the original focus of the Lufthansa analysis, with aromatics being relevant for both blending and emissions.

At a later stage of the study distillation curve data (initial boiling point, 10% recovery, 50% recovery, 90% recovery, and end point) were also evaluated. For reasons of simplicity, separate data sets not linked to the other data were created for the distillation curve information. For the distillation curve data, no removal of double entries was performed.

Due to the labour intensiveness of the manual data entry process the analysis was only finished in January 2013. Key results were published in the June 2014 final burnFAIR report.[15]

## 2.3 Distribution of Kerosene Properties

Note: In this section, figures are given as stated in the study quoted. As different studies have different rounding conventions, and sometimes themselves reflect different rounding on individual certificates, the number of significant digits in this section is variable.

### 2.3.1 Density

According to the 2013 PQIS Report, the minimum observed density for JP8 in 2013 was 783.4 kg/m³, and the maximum was 833.6 kg/m³.[16] This closely agrees with the Lufthansa results for Germany, where the minimum density was 786.9 kg/m³, and the maximum was 834.2 kg/m³. The distribution is also similar (Figure 1).

The density range in the UK Survey was narrower, with a minimum density of 786.7 and a maximum density of 824.2 kg/m³.[17] Density distribution (not shown here) is slightly different, with only 38.3% of all batches having a density of 800 kg/m³ or less.[18]

The World Fuel Sampling program deliberately went for a diversity of samples; hence one could have expected that the density range for the fuels covered in this report would be particularly large. This is true in that the study included some materials that were not jet fuels at all (neat CTL, Stoddard solvent), for which densities were indeed very low. However,

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[15] See Deutsche Lufthansa AG June 2014, chapter 3.5

[16] 2013 PQIS Report, p.39

[17] The Quality of Aviation Fuel Available in the United Kingdom, Annual Survey 2008, p. 16

[18] Ibid, p.29

if only Jet A-1 and JP-8 fuels are considered, the range is smaller than that found in the other studies, with a minimum density of 788.7 kg/m³ for a kerosene sample from China, and a maximum of 820.6 kg/m³ for a sample from Canada.[19]

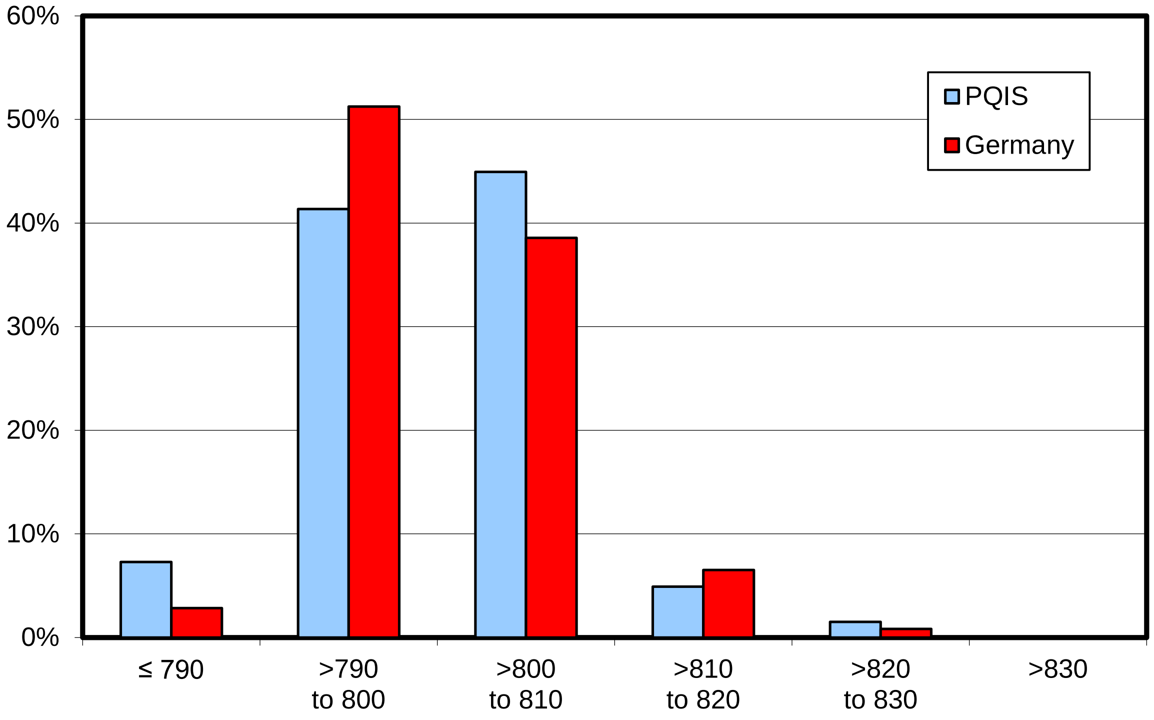

*Figure 1: Distribution of density in kg/m³ in 2013 PQIS Report and in Lufthansa study*

The density range given in the PQIS Report for Jet A-1 purchases is fairly narrow, ranging from a minimum of 784.7 kg/m³ to a maximum 809.4 kg/m³.[20] This narrow range is however not surprising, as it is based on data from only 107 batches[21], and small samples are not a good estimator of extreme values.

### 2.3.2 Freezing Point

The lowest freezing point for JP8 in 2013 was -80°C, whereas the highest was at the specification limit of -47°C.[22] The corresponding figures in the Lufthansa study were -100°C and -47°C. However, it should be noted that for fuels with a very low freezing point laboratories often are not equipped to measure the exact freezing point, but merely give the freezing point as being “lower than …” The difference between “-80” and “-100” may therefore reflect the cut-off limits of the respective fuel labs rather than differences between the fuels themselves. Freezing point distribution (Figure 2) differs significantly between the PQIS report and the Lufthansa study. The mode is the same in both cases, at >-55°C to – 50°C, but in Germany most of the other observations have a freezing point below the mode, whereas in the US most of them have a freezing point above the mode. This can

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[19] CRC report No. 647, p.86
[20] 2013 PQIS Report, p.101
[21] 2013 PQIS Report, p.100
[22] 2013 PQIS Report, p.39

probably be explained by the fact that the US refinery system is primarily geared towards producing Jet A, which has a higher freezing point than Jet A-1.

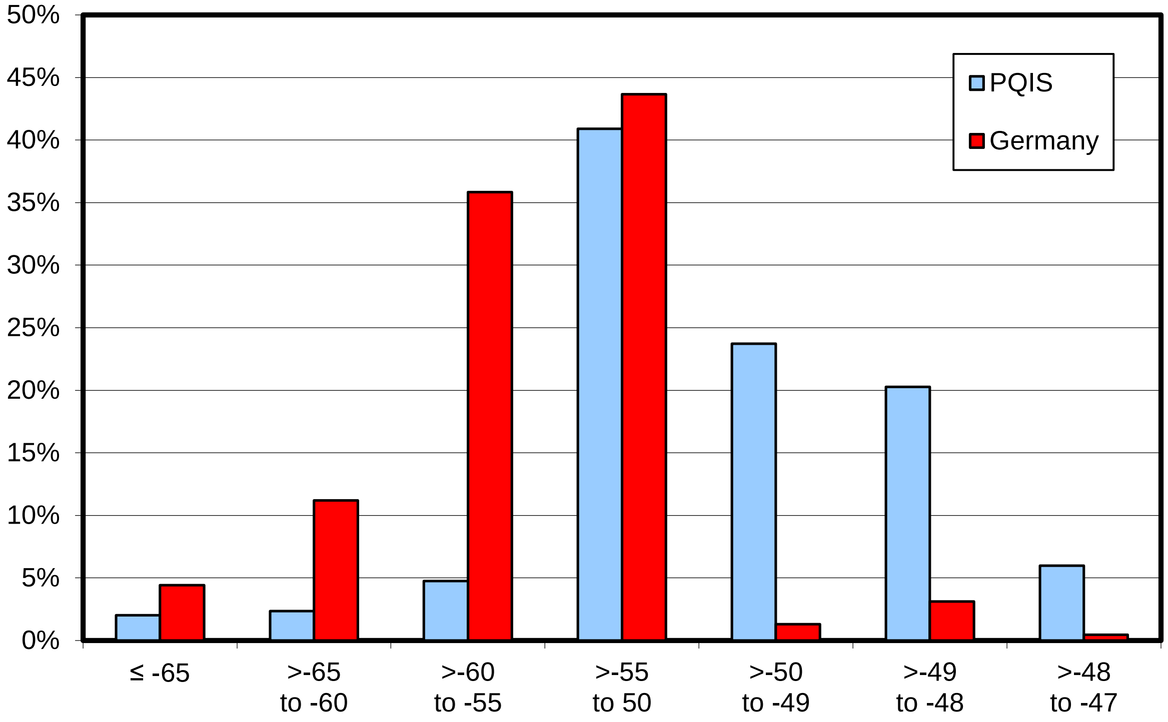

*Figure 2: Distribution of freezing point in °C in 2013 PQIS Report and in Lufthansa study*

The density range in the UK Survey was again smaller, with a lowest freezing point of -60.6°C and a highest freezing point of -45°C.[23] The latter value is actually off-spec, as a maximum value of -47°C is required, but all the same this value was found on one certificate.[24]

Freezing point range in the World Fuel Sampling report, counting only Jet A-1 and JP8 fuels, is from -71°C for a Canadian Jet A-1 to an (off-spec) value of -46.2°C measured for several samples both from the US and from Canada.[25] The range is again smaller than that found in the far larger PQIS and Lufthansa study samples.

The freezing point range given in the PQIS Report for Jet A-1 purchases is similar to that of the World Fuel Sampling report, ranging from a lowest value of -72°C to a highest value of -48°C.[26] Again, small sample size is likely to be the main factor for the narrower range.

### 2.3.3 Viscosity at -20°C

The lowest viscosity at -20°C for JP8 in 2013 was 2.8 cSt, and the highest was 7.728 cSt.[27] The corresponding values in the Lufthansa study were 1.140 cSt and 5.324 cSt. Viscosity distribution (Figure 3) is markedly different in the PQIS report and the Lufthansa study, with German fuels significantly less viscous.

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[23] The Quality of Aviation Fuel Available in the United Kingdom, Annual Survey 2008, p. 16

[24] Ibid, p.10

[25] CRC report No. 647, p.86

[26] 2013 PQIS Report, p.101

[27] 2013 PQIS Report, p.39

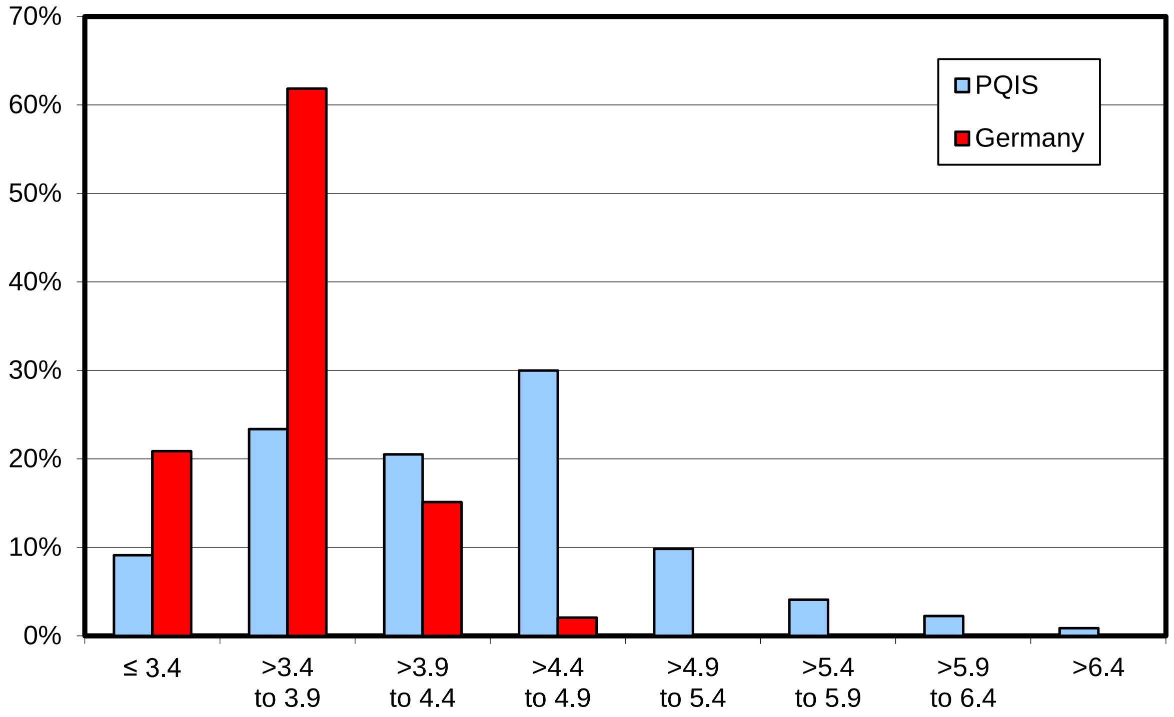

*Figure 3: Distribution of viscosity at -20°C in cSt in 2013 PQIS Report and in Lufthansa study*

Again, the range in the UK Survey was smaller, with a minimum value of 2.719 cSt and a maximum value of 5.65 cSt.[28] Distribution of viscosity at -20°C (not shown) is intermediate between the PQIS and the Lufthansa study data.[29]

The corresponding range in the World Fuel Sampling report, again counting only Jet A-1 and JP8 fuels is from 2.8 cSt for an Australian Jet A-1 to 6.0 cSt for an US JP8.[30] The range is again somewhat smaller than that found in the far larger PQIS and Lufthansa study samples.

The viscosity range given in the PQIS Report for Jet A-1 purchases is fairly narrow, ranging from a lowest value of 2.758 cSt to a highest value of 4.318 cSt.[31] Again, small sample size is likely to be the main reason for the narrowness of the range.

### 2.3.4 Specific Energy (Net Heat of Combustion)

The lowest specific energy for JP8 in 2013 was 42.8 MJ/kg, which is the minimum requirement, and the highest was 45.090 MJ/kg.[32] The corresponding values in the Lufthansa study were 42.85 MJ/kg and 43.505 MJ/kg. In spite of the far higher maximum value for US fuels, however, property distribution (Figure 4) is similar. Almost all US fuel shows energy densities below 43.6 MJ/kg, raising the possibility that the 45.090 MJ/kg value is the result of an erroneous data entry.

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[28] The Quality of Aviation Fuel Available in the United Kingdom, Annual Survey 2008, p. 16

[29] Ibid., p.31

[30] CRC report No. 647, p.90

[31] 2013 PQIS Report, p.101

[32] 2013 PQIS Report, p.39

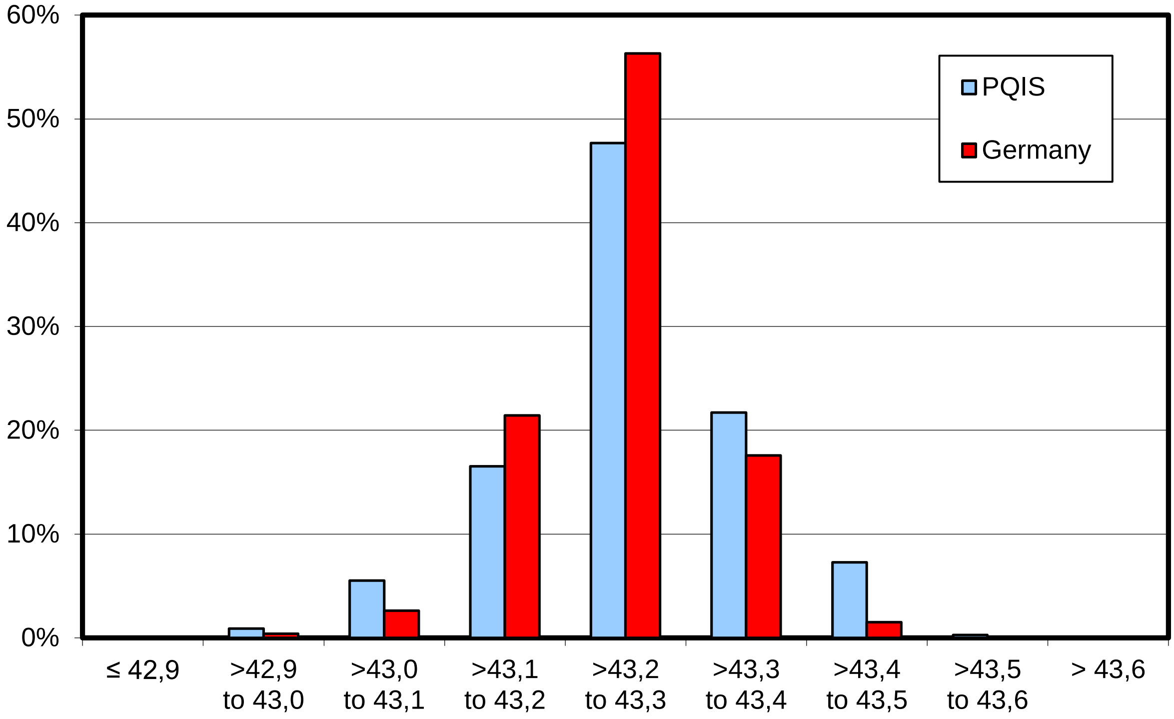

*Figure 4: Distribution of specific energy in MJ/kg in 2013 PQIS Report and in Lufthansa study*

Again, the range in the UK Survey was smaller, with a minimum value of 43.00 MJ/kg and a maximum value of 43.49 MJ/kg.[33] Distribution of specific energy (not shown) is similar to the PQIS and the Lufthansa study data, though the distribution in the UK Survey is somewhat skewed to the left.[34]

In the World Fuel Sampling report specific energy is given in btu/lb. Again counting only Jet A-1 and JP8 fuels, the range is from 18,434 btu/lb for an US JP8 to 18,596 btu/lb for a Chinese Jet A-1.[35] Converted into MJ/kg, this corresponds to a range of 42.85 MJ/kg to 43.22 MJ/kg. This range is again smaller than that found in the far larger PQIS and Lufthansa study samples.

The property range given in the PQIS Report for Jet A-1 purchases is again fairly narrow, ranging from 43.092 MJ/kg to 43.500 MJ/kg.[36] Again, small sample size is likely to be the main reason for the narrowness of the range.

### 2.3.5 Sulphur Content

The lowest sulphur content for JP8 in 2013 was 0 ppm, and the highest was 3,000 ppm, which is the permitted maximum.[37] The corresponding values in the Lufthansa study were 1 ppm and 2,676 ppm. The property distributions (Figure 5) are rather different, with hardly any German kerosene having sulphur content above 1,500 ppm.

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[33] The Quality of Aviation Fuel Available in the United Kingdom, Annual Survey 2008, p. 16

[34] Ibid., p.31

[35] CRC report No. 647, p.91

[36] 2013 PQIS Report, p.101

[37] 2013 PQIS Report, p.39

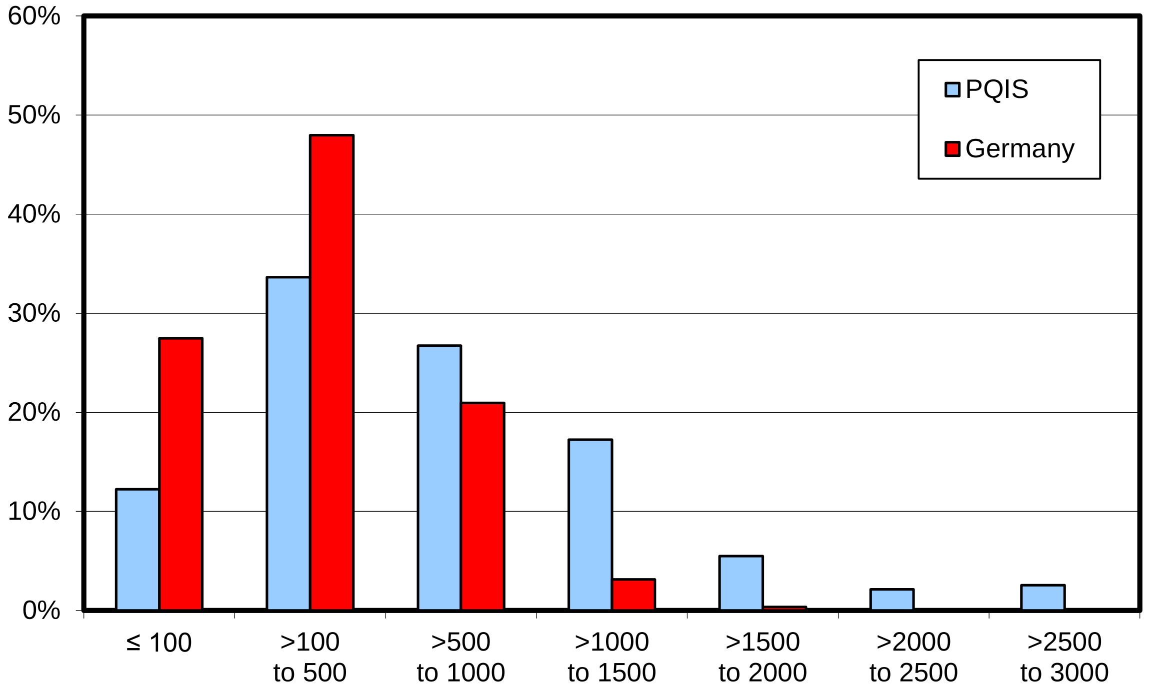

*Figure 5: Distribution of sulphur content in ppm in 2013 PQIS Report and in Lufthansa study*

The range in the UK Survey this time was as large as that in the PQIS report, ranging from the lowest possible value, 0 ppm, to the permitted maximum of 3,000 ppm.[38] Distribution of sulphur content is similar to that in the PQIS report.[39]

The corresponding range in the World Fuel Sampling report, again counting only Jet A-1 and JP8 fuels is from 7 ppm for an Australian Jet A-1 produced from shale oil to 2,453 ppm for a Canadian Jet A-1.[40] The range is yet again somewhat smaller than that found in the far larger PQIS and Lufthansa study samples.

The property range given in the PQIS Report for Jet A-1 purchases is this times almost as broad as for JP8, ranging from 5 ppm to 3,000 ppm.[41]

### 2.3.6 Aromatics Content

The lowest aromatics content for JP8 in 2013 was 8.2%, and the highest was 24.3%.[42] The corresponding figures in the Lufthansa study were 5.9% and 25.5%; however it must be pointed out that in the Lufthansa study in some certificates aromatics content was determined according to ASTM D 1319, while others used ASTM D 6379. While both methods give similar results, they are not identical, ASTM D 6379 results being somewhat higher. The highest observed figures were ones measured by ASTM D 6379.

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[38] The Quality of Aviation Fuel Available in the United Kingdom, Annual Survey 2008, p. 16

[39] Ibid., p.21

[40] CRC report No. 647, p.89

[41] 2013 PQIS Report, p.101

[42] 2013 PQIS Report, p.39

The property distributions (Figure 6) are essentially similar. The predominance of the modal values “>16 to 18” and “>18 to 20” in Germany is probably due to the fact that many of the certificates evaluated in Germany were CoAs originating in the pipeline or tank system. As such certificates reflect rebatching, and hence combinations of different batches, this creates an averaging tendency, and hence a stronger concentration at modal values.

In view of the current requirement of a minimum aromatics content of 8% for bio kerosene blends it is of interest that to note that 15 of the German batches had an aromatics content of below 8%, conventional kerosene not being required to meet the 8% minimum. These were all produced by one refinery over a course of two months, and were delivered directly from the refinery to two airports, where this refinery was in one case the only and in the other case the major supplier. No adverse issues relating to the low aromatics content were observed at these airports over the course of the two months delivery of low aromatics fuel.

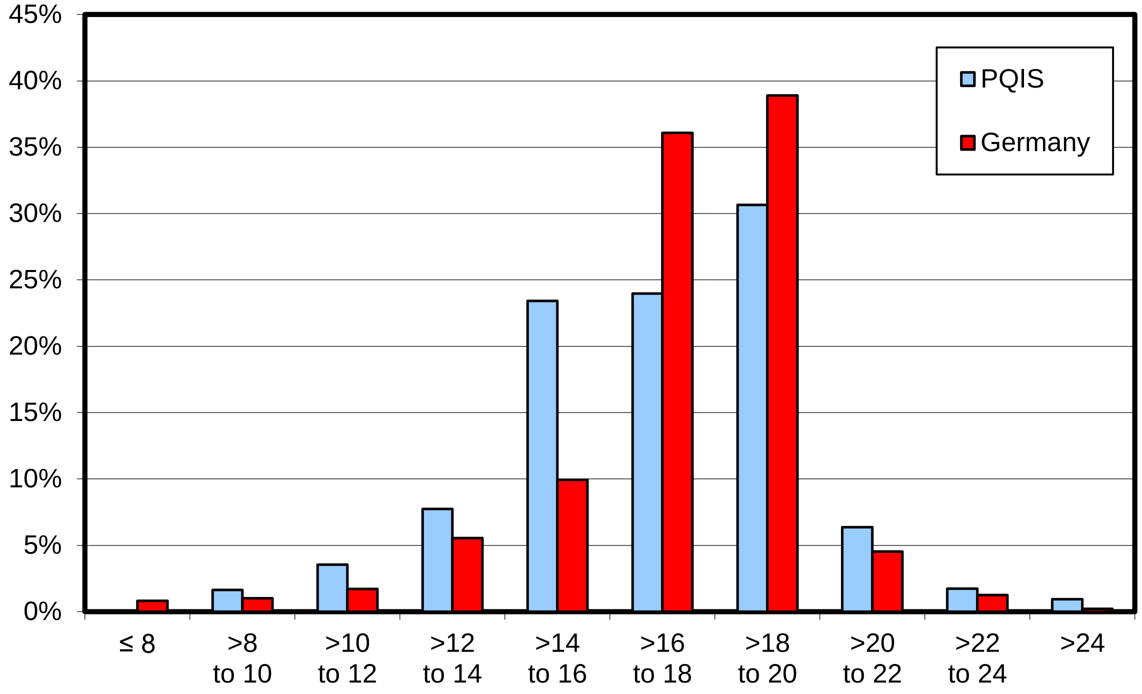

*Figure 6: Distribution of aromatics content in vol% in 2013 PQIS Report and in Lufthansa study*

Again, the range in the UK Survey was smaller, with a minimum aromatics content of 10.3% and a maximum of 24.8%.[43] Distribution of aromatics content (not shown) is similar to the Lufthansa study data.[44]

In the World Fuel Sampling report figures are given both for aromatics content according to ASTM D 1319 and according to ASTM D 6379. On the basis of ASTM D 1319, and again counting only Jet A-1 and JP8 fuels, the range in the World Fuel Sampling report is from 11.8% for a Peruvian Jet A-1 to 21.8% for a Canadian Jet A-1.[45] The corresponding range on the basis of ASTM D 6379 is from 13.00% to 24.37%, with the same fuels again representing

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[43] The Quality of Aviation Fuel Available in the United Kingdom, Annual Survey 2008, p. 16

[44] Ibid., p.20

[45] CRC report No. 647, p.89

the extreme values. In either case, the range is yet again somewhat smaller than that found in the far larger PQIS and Lufthansa study samples.

The property range given in the PQIS Report for Jet A-1 purchases is fairly narrow, ranging from 15.0% to 24.4%.[46] Again, small sample size is likely to be the main reason for the narrowness of the range.

### 2.3.7 Smoke Point

The lowest smoke point for JP8 in 2013 was 19 mm, and the highest was 30 mm,[47] where the higher number indicates the cleaner burning fuel. The corresponding figures in the Lufthansa study were 18 mm and 30 mm. The property distributions (Figure 7) are similar, with a slight tendency for German kerosene to have a higher smoke point.

Again, the range in the UK Survey was smaller, with a minimum smoke point of 19.5 mm and a maximum smoke point of 27 mm.[48] Distribution of smoke point (not shown) is similar to the PQIS report and Lufthansa study data, but with a stronger concentration at the mean.[49]

Smoke point was not among the parameters analysed in the World Fuel Sampling Program, hence no such data are included in the report. [50]

The property range given in the PQIS Report for Jet A-1 purchases is similar to that in the UK Survey, ranging from 19 mm to 27 mm.[51]

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[46] 2013 PQIS Report, p.101

[47] 2013 PQIS Report, p.39

[48] The Quality of Aviation Fuel Available in the United Kingdom, Annual Survey 2008, p. 16

[49] Ibid., p.33

[50] CRC report No. 647, p.6

[51] 2013 PQIS Report, p.101

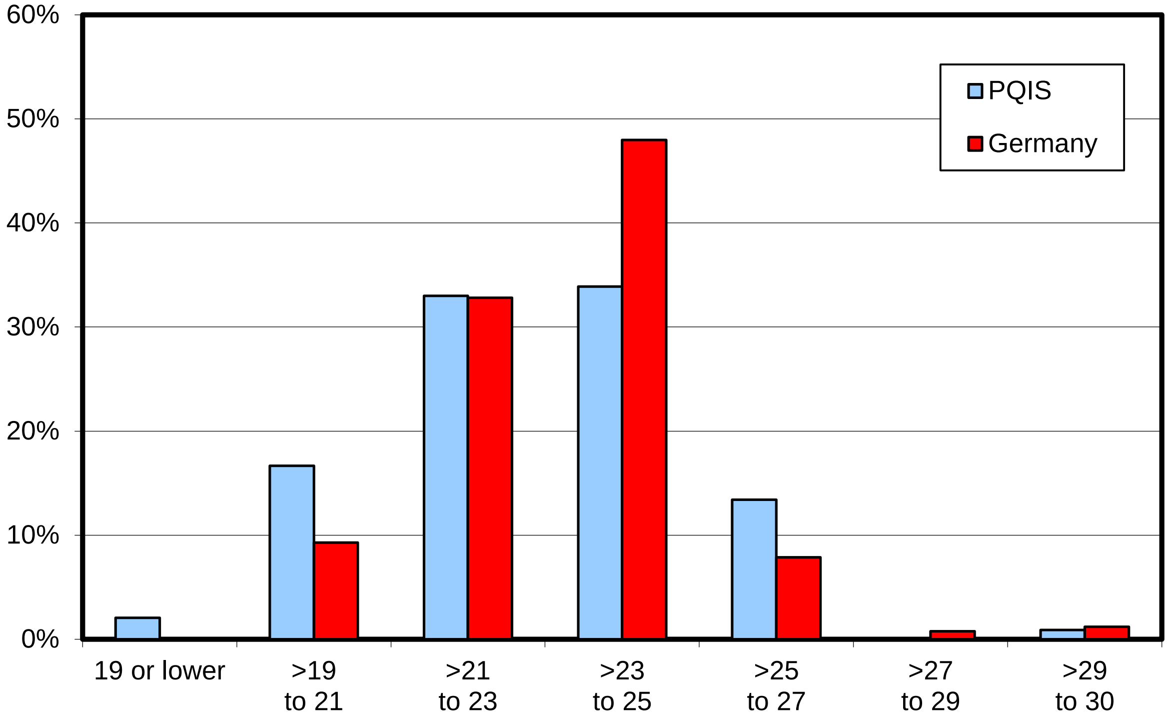

*Figure 7: Distribution of smoke point in mm in 2013 PQIS Report and in Lufthansa study*

## 2.4 Kerosene Samples Selected for HBBA Study

The purpose of the HBBA Study was to assess the properties of blends of synthetic fuels and conventional fuels for a wide range of different kerosene. At the same time, for reasons of cost and efficiency, the number of samples of conventional kerosene had to be limited, as for each of these samples numerous blends with bio kerosene were analysed. The task therefore was to identify refineries whose products, taken together, would represent the bulk of property variation with a limited number of samples.

Of the studies discussed in section 2.1, only the World Fuel Sampling report identifies refineries and that only by city. Moreover, the World Fuel Sampling report was written in 2006, and it was very unlikely that the production program of the participating refineries still would have been the same in early 2013, when selection of fuels for the HBBA Study was begun.

However, one of us [AZ] had been the person conducting the Lufthansa study; hence access to the refinery information for that study was not a problem. In addition, the Lufthansa study was still recent, and the refineries were situated in Germany, facilitating sourcing and logistics. Accordingly, six refineries were identified on the basis of the Lufthansa study information, and approached for samples. The fuels from five of these refineries were used in the study to represent the spectrum of existing fuel properties. These fuels were given the internal numbers 085, 112, 114, 117 and 123. The sixth fuel, number 100, had average properties, and only was used as part of the analysis of farnesane blends, with a view to using fuel from this refinery for the emissions tests described in section 7.

The complete properties of the conventional kerosene samples are given in annex 9.1. Table 1 (below) compares, for the properties discussed in section 2.3, the minimum and maximum values for the five samples analysed, with the corresponding minima and maxima of the World Fuel Sampling report. As can be seen, for most parameters the five samples analysed in the HBBA Study cover a similar property range as the 39 JP8 and Jet A-1 fuels in the World Fuel Sampling report, which themselves had been deliberately selected to cover a wide range of properties. The five samples of the HBBA Study also cover the main different production processes, with one sample being Merox-treated, two samples consisting solely of lightly hydroprocessed components, one sample containing primarily lightly hydroprocessed components combined with both severely hydroprocessed and non-hydroprocessed components, and one example containing primarily severely hydroprocessed components.

| | World Fuel Sampling Program | | HBBA Study sample | |
|---|---|---|---|---|
| | Minimum | Maximum | Minimum | Maximum |
| Density [kg/m³] | 788.7 | 820.6 | 789.0 | 818.6 |
| Freezing Point [°C] | -71 | -46.2 | -89.4 | -49 |
| Viscosity at -20°C [mm²/s] | 2.8 | 6.0 | 3.008 | 4.357 |
| Specific Energy [MJ/kg] | 42.85 | 43.22 | 43.073 | 43.391 |
| Sulphur Content [ppm] | 7 | 2,453 | 10 or less | 1,000 |
| Aromatics [vol%] | 11.8 | 21.8 | 13.7 | 21.6 |

*Table 1: World Fuel Sampling Program and HBBA Study sample minima and maxima*

The main areas where World Fuel Sampling report property extremes were not covered by the HBBA Study fuels are sulphur content and viscosity at -20°C. In the case of sulphur, the Lufthansa study found no RFC from a German refinery for kerosene with sulphur content above 1,100 ppm. All certificates showing higher sulphur content were CoAs, and probably included fuel from imported batches. Identification of the producing refineries was not possible on the basis of the available documentation.

However, sulphur content of the conventional kerosene is not likely to be a limiting factor for blending bio kerosene. If the sulphur content of the conventional kerosene is very high, blending with bio kerosene will merely reduce this content to the levels more usually observed. If on the other hand the sulphur content is very low, blending with bio kerosene will reduce this content even further, but one observation from the Lufthansa study is that several German airports are already now exclusively supplied with kerosene with very low sulphur content, without this having any known adverse effects whatsoever. Not including conventional kerosene with very high sulphur content is therefore not likely to have a material effect on results.

In the case of viscosity at -20°C, the HBBA Study samples clearly do not cover the whole range of observable parameter variation. Also, unlike sulphur content, viscosity is potentially a limiting factor for blending, since some bio kerosene has poor viscosity as a neat fuel. This is even truer now that issue ASTM D7566 since 2014 requires the blend not only to meet the ASTM D1655 minimum of 8 cSt at -20°C, but also to additionally have a maximum 12 cSt at -40°C.[52] However, as both Figure 3 and the World Fuel Sampling report[53] show, high viscosity at -20°C is basically a US phenomenon, probably as a result of typically producing Jet A rather than Jet A-1. In the US, therefore, viscosity can be expected to be a major constraint. Indeed, several of the US fuels analysed in the World Fuel Sampling Program, plus one Canadian, already had viscosity above 12 cSt at -40°C even as neat fuels, which would have completely ruled out their use for blending bio kerosene. No values above 12 cSt at 0°C were found in the World Fuel Sampling Program for any location outside North America.[54]

With regard to blending in North America, the results of the HBBA Study must therefore be considered not to completely cover the constraints resulting from viscosity. This, however, was accepted for the HBBA Study as its focus is on Europe. Judging by Figure 4, typical European viscosity ranges are well covered by the fuels analysed in the HBBA Study.

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[52] ASTM D7566, issue 14a, table 1, part 2

[53] CRC report No. 647, p.90

[54] Ibid.

# 3 Bio Kerosene Production Pathways

## 3.1 Fischer-Tropsch-Kerosene

### 3.1.1 Pathway Description

The Fischer-Tropsch (FT) process is the first approved production pathway for synthetic kerosene.

The pathway consists of four main steps. In the first step, the feedstock is converted into syngas (a mixture of CO and $H_2$). This syngas then enters the Fischer-Tropsch step proper, where it is converted into long chain alkanes / paraffinic waxes or olefins[55], which in the subsequent step are hydrocracked and isomerized. In the final step, the raw product is distilled and separated into individual products, of which kerosene is one.[56]

If the feedstock is natural gas, the syngas is produced via steam reforming (reaction with water) or via partial oxidation of the feedstock (reaction with oxygen)[57], followed by conditioning[58]. If the feedstock is a solid (e.g. coal or woodchips), syngas production involves partial oxidation and steam gasification[59], again followed by conditioning. In addition, if the feedstock is a biomass, pre-treatment of the feedstock will typically be necessary. Figure 8 shows the schematics of the production of Fischer-Tropsch fuel from wood.

Possible feedstocks for the FT process are manifold. Large-scale production facilities exist for the conversion of coal to liquid fuels (Sasol in South Africa) and for the conversion of natural gas (Shell in Qatar).[60] At both of these facilities, FT blendstock for jet kerosene is routinely produced. Conversion of bio material to fuel has been demonstrated at pilot scale, but not beyond. An attempt by the German company Choren to build a demo scale plant for the FT conversion of woodchips was abandoned when Choren went bankrupt.[61] There are currently no FT facilities producing kerosene blendstocks from bio materials worldwide.

A novel approach to feedstocks was planned by British Airways and Solena, involving a facility for the conversion of urban waste into fuel.[62] To handle the extreme heterogeneity of this feedstock the planned facility was supposed to produce the syngas at temperatures up to 5,000 °C in an $O_2$ deprived environment[63], followed by a FT conversion as described

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[55] Low temperature FT using a cobalt catalyst produces paraffinic waxes, high temperature FT using iron catalyst produces olefins.

[56] For details see chapter 7.3 of Deutsche Lufthansa AG: Abschlussbericht zu dem Vorhaben Projekt burnFAIR, Arbeitspakete 1.1 bis 1.4, Frankfurt am Main, June 2014

[57] Weissermel, K., Arpe H.-J., Industrielle Organische Chemie, fünfte Auflage, Wiley-VCH, Weinheim 1998, p.16 onw.

[58] “Conditioning“ of the gas means removal of particulates, adjustment of the relationship between $H_2$ and CO and removal of water and $CO_2$, see Deutsche Lufthansa June 2014, p. 149

[59] Weissermel/Arpe, ibid.

[60] Zennaro, Roberto: Fischer-Tropsch Process Economics, p.155; in: Peter M. Maitlis and Arno de Klerk (eds.): Greener Fischer-Tropsch Processes for Fuels and Feedstocks, Weinheim 2013

[61] Wikipedia entry “Choren industries”, http://de.wikipedia.org/wiki/Choren_Industries, researched 16.9.2014

[62] “GreenSky project prepares to land in Thurrock”; British airways press release, 16. April 2014

[63] Solena Group, Inc: “BioEnergy platforms: A vision for the future”, p.6

above.[64] This project has been terminated[65] due to the October 2015 bankruptcy of Solena[66], but a similar approach is now planned by Fulcrum Inc. with various airlines[67].

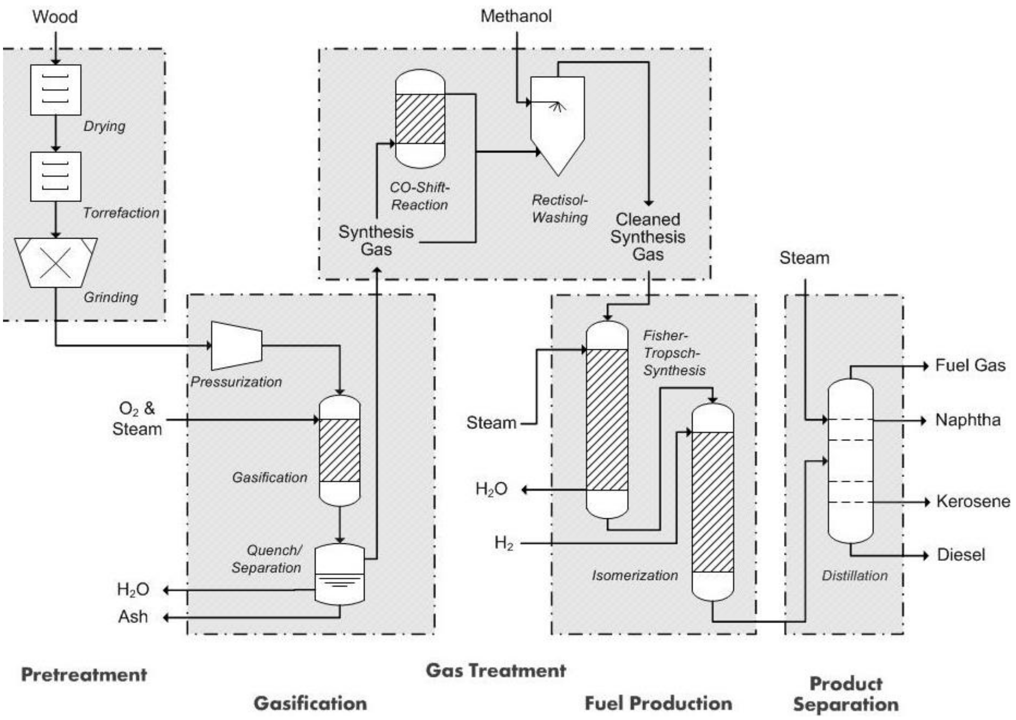

*Figure 8: Schematics of the production of Fischer-Tropsch fuel from wood*[68]

### 3.1.2 Approval Status

The approval process for FT kerosene was started by Sasol in 1999. In this year Sasol was granted approval by DEF STAN 91-91/Issue 3 to blend synthetic, iso-paraffinic kerosene with a Merox-treated jet fuel from petroleum to make semi-synthetic Jet A-1 aviation kerosene. This approval was for a maximum blend ratio of 50% and was specific to Sasol and to one product stream produced by one refinery. This was extended to additional refining streams from the same refinery under DEF STAN 91-91/Issue 4. [69]

A generic approval for FT kerosene as a blendstock with a maximum blend ratio of 50% was given by ASTM in 2009. For this purpose, a new specification ASTM D7566 was created, which is a specification for blends with synthetic kerosene. This specification is referred to in the jet fuel specification, ASTM D1655, to the effect that these blends are jet fuel; hence a blend meeting ASTM D7566 is an ASTM D1655 jet fuel. Although the approval was largely based on Sasol research using coal as a feedstock, the generic approval covers product from FT processes in general, regardless of feedstock.

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[64] "GreenSky project …", op. cit.

[65] Meghan Sapp: British Airways drops Solena project after failure to raise funds to build plant, 27.11.2015

[66] Center for Biological Diversity: United Nations Urged to wirhdraw Misleading Biofuels Report, 7.4.2016

[67] Jim Lane: United Airlines invests $30M in Fulcrum BioEnergy; inks $1.5B+ in aviation biofuels contracts; in: Biofuels Digest 30.6.2015

[68] Source: Deutsche Lufthansa June 2014, p. 147; translation into English by DBFZ

[69] C.A. Moses, G. Wilson, Piet Roeds: Evaluation of Sasol synthetic kerosene for suitability as jet fuel; San Antonio / Sasolburg, December 2003, p. 7

The FT fuels described above do not contain aromatic compounds. However, a certain percentage of aromatics is required in jet fuel to ensure seal swell and tightness of valves. This is one of the reasons why the fuel may only be used as a blend with conventional kerosene, with a maximum blend ratio of 50%. The specification also states that the blend must have a minimum aromatics content of 8%.[70]

In 2003, Sasol submitted to DEF STAN research on a fully synthetic kerosene produced from the streams of its Secunda refinery, using a blend of several refinery streams, including some containing aromatics.[71] Approval for this fuel was given under DEF STAN 91-91 Issue 6[72], and extended in DEF STAN 91-91 Issue 7 to permit the inclusion of a further refinery stream.[73] This approval is specific to Sasol and to product from the Secunda refinery.[74] The original reason for Sasol's approval request was to have a second refinery option in case of product shortages.[75] However, although some fuel was produced according to the specification, and supplied to flights from Johannesburg[76], a change in refinery economics resulted in this production process no longer being economically viable, and Sasol is no longer actively pursuing further certification work of this pathway.

Instead, Sasol pursued approval of a semi-synthetic fuel called IPK/A which is partly synthesised via the Fischer-Tropsch process and partly from the naphtha cut produced from the coal-tar-product of coal gasification.[77] Although this product would in principle constitute a fully synthetic kerosene, approval was for the moment only sought for its use as a 50% blend, as ASTM is currently reluctant to approve fully synthetic fuels. This approval has been granted by ASTM in November 2015.[78]

### 3.1.3 Representation in HBBA Study

The FT approach is a pathway for the production of FT kerosene from bio materials that is widely discussed in literature;[79] hence the inclusion of FT kerosene blendstock in the HBBA Study was clearly desirable. Unfortunately there are currently no facilities producing FT kerosene blendstock from bio materials, but the FT process proper, and hence the resulting product, is largely independent of the feedstock. It was therefore decided to use FT kerosene blendstock from fossil material for the purposes of this study. The fuel actually used was kindly provided by Sasol, and consisted of 141 kilogram of IPK. The material was received in December 2013.

No attempt was made to secure IPK/A material as the aromatics in this pathway by specification come from coal gasification, not from bio material. A pathway producing FT kerosene with aromatics from renewable resources was temporarily pursued by the US

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[70] ASTM 7566, issue 14a, Table 1 Part 2. This requirement already existed in the 1999 approval, see Moses, Wilson, Roeds, p.7.

[71] Moses, Wilson, Roeds, entire report

[72] Clifford A. Moses: Evaluation of FT Kerosenes Containing Synthesized Aromatics as Blending Streams to make Semi-Synthetic Jet Fuel, New Braunfels March 2013, p. 1

[73] Ibid, p.49; DEF STAN 91-91 issue 7, section D.4.3

[74] DEF STAN 91-91 issue 7, D.4.3.4

[75] Moses, Wilson, Roeds, p.10

[76] Moses March 2013, p.2

[77] Clifford A. Moses: Evaluation of Synthesized Aromatics Co-Produced with Iso-Paraffinic Kerosene for the Production of Semi-Synthetic Jet Fuel, New Braunfels July 2013

[78] ASTM D7566 15c

[79] See section 5.2 of Deutsche Lufthansa June 2014

company Rentech[80], but this was dropped in 2013 when Rentech changed its focus away from biofuels[81], so no product is available for this pathway.

## 3.2 HEFA-Kerosene

### 3.2.1 Pathway Description

HEFA stands for Hydrotreated Esters and Fatty Acids. Until ASTM certification in 2011 this pathway was usually referred to as HVO, for Hydrotreated Vegetable Oils, but as ASTM aims for a generic specification and some feedstocks are solid fats rather than oils a new acronym was introduced, and the production pathway approved as HEFA.

The production pathway (Figure 9) is similar to conventional refining of fossil crude oils. As a first step, the bio-material is pre-treated and prepared for the actual production. The prepared material is then reacted with hydrogen (hydrotreatment). This production step removes the oxygen and converts the material into hydrocarbons. These are subsequently cracked and isomerized to yield a mixture of n-alkanes and iso-alkanes which provide the desired good cold flow properties. Subsequent to that, the raw product is distilled and separated into individual products.[82]

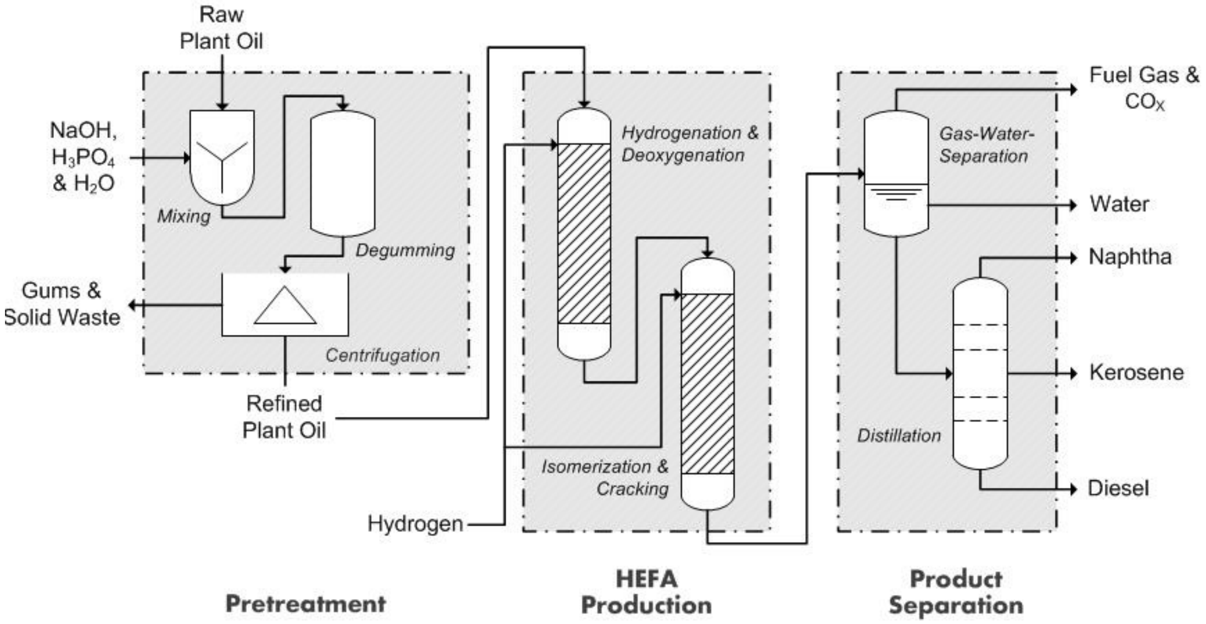

*Figure 9: Schematics of the production of HEFA fuel from vegetable oil*[83]

Possible feedstocks for the HEFA process are more limited than for the FT process. The feedstock is a triglyceride, typically a solid fat or oil. This can be edible oils like palm oil or rapeseed oil, which are commercially available in large quantities, but can also be oily or fatty wastes, like palm oil press residues or slaughterhouse waste. As the use of edible materials for fuel production purposes is politically contentious there is a tendency for

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[80] Clifford A. Moses March 2013, p. 3 and 44

[81] “Rentech to close product demonstration unit”, Biomass Magazine, 1. March 2013

[82] For details see chapter 7.2 of Deutsche Lufthansa AG June 2014

[83] Source: Ibid., p. 142; translation into English by DBFZ

refiners to increasingly source waste materials. In 2013, waste and residues already accounted for some 52% of the feedstock used by HEFA market leader Neste Oil,[84] and the corresponding figure for the third quarter of 2016 was 79%.[85] The production process itself is the same for all feedstock, although pre-treatment has to be different.

### 3.2.2 Approval Status

HEFA has been approved by ASTM in July 2011, and is now covered by Annex 9.2 of ASTM D7566. Like normal FT kerosene, it does not contain aromatic compounds, and is only certified for use as a blend with a 50% maximum blend ratio.[86] Approval is currently pursued for a process exclusively yielding aromatics, and such aromatics could be used in conjunction with HEFA kerosene. However, use of these aromatics is not specific to HEFA, so this process is discussed separately in this report in section 3.9. In a similar vein, the US company Swift Fuels has proposed producing a blend of HEFA kerosene and aromatics that requires no further blending with conventional kerosene, but little information is available on that approach.[87]

A process using essentially the same feedstock as HEFA is currently pursued by the US company Applied Research Associates. For this process, the terminology "HEFA-SKA" is sometimes used, although the technical process is different from that for HEFA. This process is discussed in section 3.6.

Approval is currently pursued by Boeing for broadening the specification for neat HEFA fuel used in blends, such that part of the diesel fraction would be included in the specification.[88] This approach would for example see the freezing point for the neat HEFA considerably reduced, or even completely remove the freezing point requirement from the specification for neat HEFA, while the requirements to be met by the blend would be fully maintained. The ratio behind this approach is that with such a fuel it will not be necessary to build refining capacity specifically capable of producing HEFA kerosene, but instead will be possible to utilize the existing capacity for road bio fuels.[89] Although Boeing has already conducted one flight using such a fuel blend in 2014,[90] the approval process is still ongoing, with the proposal first being formally presented to ASTM at the December 2014 meeting in San Diego.[91]

### 3.2.3 Representation in HBBA Study

There are currently several HEFA refineries worldwide, which typically produce road fuels. The largest operator of HEFA refineries is Neste Oil, with a total annual production capacity

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[84] "Neste Oil produced enough renewable fuel from waste and residues last year to power over 1 million cars" , Neste press release 4.2.2014

[85] Neste Corporation Interim Report January – September 2016, p.10

[86] ASTM D7566, issue 14a, paragraph 6.1.2

[87] http://swiftfuels.com/fuel/renewable-jet-fuel, researched 18. September 2014; personal communication

[88] "Boeing Sees Opportunity to Use "Green Diesel" as Significant New Source of Sustainable Jet Fuel", Boeing press release, 14. January 2014

[89] Boeing presentation at 5. March 2014 SAFUG meeting, p. 10/11

[90] "Boeing Conducts World's First Flight with 'Green Diesel' as Aviation Biofuel", Boeing press release, 3. December 2014

[91] James D. Kinder: High Freeze Point HEFA Approval, presentation at ASTM D02 Committee week – San Diego, 9th December 2014

of two million tons.[92] Certification of HEFA as a production pathway for aviation kerosene was primarily supported by UOP, using rented production capacity at Pasadena, Texas for the production of small batches. The largest HEFA kerosene batch so far have been the 800 tons produced by Neste in 2011 for the Lufthansa burnFAIR in service evaluation, using the Neste facilities at Porvoo[93] , and the similarly sized batch produced by Neste in 2015 for into-hydrant deliveries at Oslo airport. Some smaller facilities have also been or are producing limited quantities of HEFA kerosene for aviation purposes, particularly the Dynamic Fuels refinery at Geismar, Louisiana, used by SkyNRG to procure fuel for KLM.[94] However, no facilities routinely producing HEFA bio kerosene at large scale currently exist.

A recent development has been the start of deliveries of HEFA kerosene to United Airlines at Los Angeles airport. These deliveries are by AltAir Paramount, from a refinery converted to the production of HEFA products, and take place on the basis of a multi-year supply contract between United Airlines and AltAir.[95] No data on actual volumes have yet been released, but this operation may be the closest to a routine production of HEFA bio kerosene at large scale currently existing.

It had originally been intended to analyse and compare several batches of HEFA kerosene, using fuel produced from different feedstock and by two different producers (UOP and Neste). However, Neste did not produce any HEFA kerosene during the time the lab analyses were conducted, and UOP ended its kerosene production in Pasadena when the HBBA Study was at an early stage. The AltAir operation, on the other hand, only started regular production in 2016, by which time the research was already finished. Therefore only a single batch of 320 gallons of HEFA kerosene produced by UOP could be sourced for the purposes of the HBBA Study. The later comparison of the analysis results of the UOP fuel with analysis results from the Neste HEFA blend used in the Lufthansa burnFAIR study however indicated that both HEFA fuels are very similar. It is therefore likely that the inclusion of several different HEFA fuels would not have gained much additional insight.

The fuel purchased from UOP had been produced from a blend of inedible corn oil and used cooking oil, and was part of the final batch produced by UOP at the Pasadena facility. It was delivered via container to a site in Utzedel, Germany, in August 2013. In Utzedel, about 150 litres of the HEFA kerosene were filled into a separate barrel and sent to the WIWeB lab in Erding, where the fuel was analysed. During this analysis it was discovered that the fuel had been contaminated by pollen, dirt and water, which also was found in the original container in Utzedel. However, this contamination could be removed and did not adversely affect the lab analysis.

No attempt has been made to reflect the Boeing approach, and include blends of HEFA road bio diesel and aviation kerosene. This is due to the proposal first being made when the HBBA Study already was well advanced, and the suggested changes to the specification only being clarified when work on the study was essentially finished. However, possible blend ratios

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[92] http://2013.nesteoil.com/business/renewable-fuels/

[93] For details see chapter 2 of Deutsche Lufthansa AG June 2014

[94] "KLM plans drive-down of jet biofuel price premium as it starts regular series of biofuel transatlantic flights", GreenAir online 18. March 2013

[95] United Airlines Makes History with Launch of Regularly Scheduled Flights Using Sustainable Biofuel; United Airlines press release 11. March 2016

with this approach are anyway expected to be fairly low, and thus outside the focus of this study. The test flight conducted by Boeing used a 15% bio blend ratio.[96]

## 3.3 SIP Kerosene

### 3.3.1 Pathway Description

SIP stands for Synthesized Iso-Paraffins produced from Hydroprocessed Fermented Sugars. SIP is the acronym under which this fuel has been certified by ASTM. Prior to ASTM certification the pathway used to produce SIP has been referred to as DSHC (Direct Sugar to Hydrocarbons).

The production of SIP fuel consists of two major steps. In the first step, microorganisms are used to ferment sucrose and produce farnesene, which is a branched C15 alkene with four double bonds. In the next step, farnesene is converted into the respective alkane, a molecule with no double bonds, by reacting hydrogen with farnesene through a catalytic bed. The resulting product is a saturated alkane, farnesane, which in the next step is then purified by distillation to produce an aviation grade. The final resulting SIP fuel ideally consists purely of farnesane, although in practice traces of remaining farnesene and olefins (partially hydrogenated farnesene) may be present in the final product as well as some other trace by-products.[97]

Although SIP fuel is currently produced using sugar from sugarcane as a feedstock, it can potentially be produced from all kinds of plant sugars, including cellulosic sugars.[98] It is therefore conceptually possible to eventually produce SIP fuel from woody biomass and avoid conflict with food use.

### 3.3.2 Approval Status

SIP fuels were approved as a kerosene blendstock in June 2014, and are now covered by Annex 3 of ASTM D7566. Unlike FT- and HEFA fuels, SIP fuels are only approved to a maximum blend ratio of 10%.[99] The lower maximum blend ratio is due to the SIP fuel solely consisting of one single compound, namely farnesane, although all the tests were also performed at 20% incorporation and show no deviation as compared to conventional jet fuel.

### 3.3.3 Representation in HBBA Study

There is currently only one producer of SIP kerosene blendstock, which is Total / Amyris, who agreed to provide a fuel sample for the HBBA Study. The sample was received at the Erding WIWeB lab in August 2013, and was analysed August to November 2013. The results

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[96] “Boeing Conducts World's First Flight with 'Green Diesel' as Aviation Biofuel”, op. cit.

[97] Total, Amyris, USAFRL: Evaluation of Synthesized Iso-Paraffins produced from Hydroprocessed Fermented Sugars (SIP Fuels), February 2014, p. 15 – 21; personal communication

[98] http://www.amyris.com/Company/151/BusinessStrategy,, called up 15.8.2014

[99] ASTM D7566 14a, paragraph 6.1.3

of the analysis were shared with Total / Amyris, and were included in the research report that was the basis for ASTM approval.

## 3.4 ATJ-SPK

### 3.4.1 Pathway Description

ATJ-SPK stands for Alcohol To Jet Synthesized Paraffinic Kerosene. This acronym specifically refers to Alcohol to Jet fuel not containing aromatics. There is also a production pathway for Alcohol to Jet fuel that does contain aromatics. This pathway is called ATJ-SKA, and is described in section 3.5.

The ATJ process starts with an alcohol with the general formula ROH, where R represents a saturated alkyl group with the chain length of 2 - 5 carbon atoms and –OH is a hydroxyl group.[100] There are several sub-pathways expected to be eventually approved by ASTM as ATJ-SPK production pathways, covering conversion of alcohols either as single alcohol or as mixture. Such alcohols may be linear or branched.[101]

The production of ATJ fuel consists of two separate steps: The production of the alcohol, and the conversion of the alcohol to a fuel. These steps are in principle independent of each other, and can take place at different locations. Although the source of the alcohol can be of decisive importance from a sustainability point of view, it is only the conversion process of the alcohol to a fuel that is of relevance for technical certification.

To convert the alcohol to a fuel, it is first dehydrated into the respective alkene product containing the same number of carbon atoms. The product is then separated from liquid water and impurities by fractionation, and enters the next process step as a gas. In the next step the gaseous material is oligomerised into higher molecular weight unsaturated compounds. Unsaturated oligomers that have molecular weight approximately consistent with jet fuel are separated and further processed in the third major step, hydrogenation over a solid-phase catalyst with hydrogen gas. In the final step the hydrogenated product is distilled to yield the final products of which kerosene is one.[102]

The feedstock for the ATJ is the respective alcohol. The feedstock for the alcohol, in turn, is highly variable. A currently popular approach is fermentation of lignocellulosic residues, but in principle the feedstock can be all kinds of biomass, or even be inorganic substances – the New Zealand company LanzaTech company has developed a gas fermentation process by which ethanol can be produced from steel work flue gases as the sole source of carbon and energy.[103]

A schematic diagram of the ATJ process is shown in Figure 10.

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[100] Subcommittee J on Aviation Fuels: Evaluation of Bio-Derived Alcohol to Jet Synthetic Paraffinic Kerosenes, Version 4, 12. March 2014, P.21

[101] Swedish Biofuels communication

[102] Subcommittee J on Aviation Fuels 12. March 2012, p. 20/21

[103] “LanzaTech and Baosteel’s 100,000 gallon/year waste-gas-to-ethanol pre-commercial facility exceeds productivity expectations and hits major milestones in advance of commercialization”, LanzaTech press release 3. December 2012

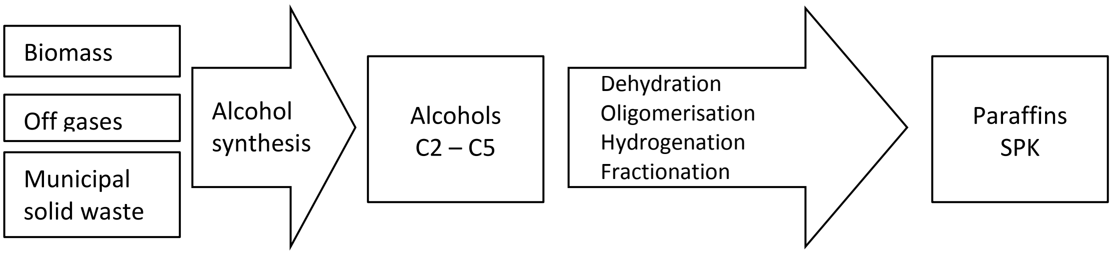

*Figure 10: Simplified overview diagram of the ATJ-SPK process*[104]

### 3.4.2 Approval Status

ATJ-SPK is not yet approved by ASTM. In 2011 the companies Cobalt, Gevo, Swedish Biofuels and UOP joined together to create a suitable data set through AFRL and other independent sources and to provide the necessary scientific reports to initiate ASTM certification of ATJ.[105] Certification work has been performed by Gevo on ATJ-SPK from iso-butanol, by Cobalt on ATJ-SPK from butanol, by Swedish Biofuels on ATJ-SPK from ethanol and by UOP on ATJ-SPK from both iso-butanol and various alcohols.[106] Work on the Gevo sub-pathway is the most advanced, with all lab tests (specification testing, fit-for-purpose testing and materials compatibility testing) passed and several rig tests as well as flights on military aircraft performed. For the Cobalt sub-pathway most lab tests have been performed and passed, but some materials compatibility work is still over-due, and no rig or flight tests have yet been done.[107]

The Swedish Biofuels sub-pathway is slightly different from the others in that it is not limited to the conversion of a single alcohol, but can convert all types of alcohols, as single alcohol and or as mixture of alcohols, including all types of alcohol isomers, both linear (n-) and branched (iso-). Conversions have been demonstrated both from ethanol and from 2,3-butanediol. The aromatics content resulting from this process can be adjusted as required, ranging from next to zero to the maximum permitted. Thus, this process can be used to produce either ATJ-SPK or ATJ-SKA, and 99% of all tests performed so far have been on ATJ-SKA, which is the current focus of Swedish Biofuels. Only a limited amount of testing on ATJ-SPK has therefore been submitted by Swedish Biofuels.[108]

A research report on ATJ-SPK was approved by ASTM in November 2014, with some minor corrections to be included as an annex.[109] Use of ATJ-SPK blends as aviation kerosene was approved in April 2016[110], but was limited to ATJ from iso-butanol (the Gevo pathway). This limitation to only one sub pathway was contested[111], but was based on the assessment that the other sub-pathways have not yet submitted sufficient documentation for inclusion in the approval.

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[104] Source: Swedish Biofuels
[105] Swedish Biofuels communication
[106] Subcommittee J on Aviation Fuels 12. March 2012, p. 23
[107] Ibid, whole report
[108] Swedish Biofuels communication
[109] “Alcohol To Jet Synthesized Paraffinic Kerosene (AT-SPK) Task Force Report – D02.J6”, presentation at ASTM D02 Committee week – San Diego, 9th December 2014, slides 8/9; oral presentations at meeting
[110] ASTM D7566 -16
[111] Wright. Michael: ATJ-SPK Annex Options, presentation at ASTM D02 Committee week – San Diego, 9th December 2014

### 3.4.3 Representation in HBBA Study

As the main producer of ATJ-SPK Gevo was contacted, and agreed to provide a sample. The shipment, consisting of one drum containing 55 USG of neat ATJ-SPK, arrived at the Erding lab on 31. March 2014.

## 3.5 ATJ-SKA

### 3.5.1 Pathway Description

ATJ-SKA stands for Alcohol To Jet - Synthesized Kerosene with Aromatics. This acronym refers to Alcohol to Jet fuel containing aromatics. ATJ-SKA produced by Swedish Biofuels is also known by its trade name SB-JP-8.[112]

The principle pathway for ATJ-SKA is the same as the ATJ-SPK pathway described in 3.4, except for an additional aromatization step. Depending on the technological capability of the technology provider, production of aromatics can be performed as an integrated stream in the overall production process. As with ATJ-SPK, fractionation is the final step. Feedstocks are the same as described in section 3.4.

A schematic diagram of the ATJ-SKA process is shown in Figure 11.

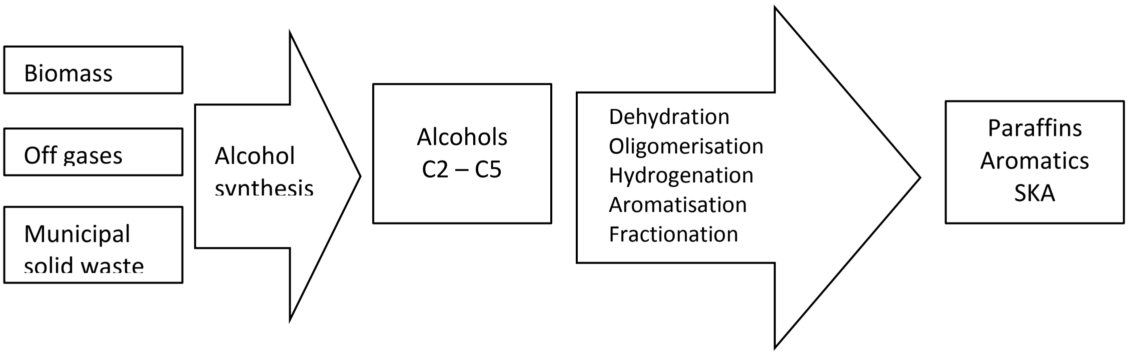

*Figure 11: Simplified overview diagram of the ATJ-SKA process*[113]

This schematic refers to the Swedish Biofuels production process. Information on the Byogy production process is available on their website, but is extremely limited.[114] However, their process follows the same structure as described above.[115]

A competing approach was proposed by the US company Terrabon/Logos. However, available information on that companies' production process is largely limited to the conversion of biomass to alcohols, whereas the conversion step to Jet Fuel is vaguely

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[112] Swedish Biofuels communication

[113] Source: Swedish Biofuels

[114] http://www.byogy.com/technology/index.html, researched 18.9.2014

[115] Byogy communication

described as “oligomerization”.[116] Work on this approach was terminated when Terrabon/Logos went bankrupt in 2012.[117]

### 3.5.2 Approval Status

ATJ-SKA is not yet approved by ASTM. Certification work has been mainly performed by Swedish Biofuels and Byogy.

Swedish Biofuels technology was demonstrated using funding from US DARPA. The goal of the funding was testing and demonstration of a jet fuel meeting both military and civil standard specifications for aviation fuel, not specifically to demonstrate meeting ASTM D7566. The US Air Force has conducted extensive lab tests on Swedish Biofuels SKA fuel including specification tests (MIL-DTL-83133), Fit-for-Purpose tests, toxicology assessments, and material compatibility tests. All these tests have been successfully passed, as have a fuel atomizer spray test, APU combustor test and nozzle flow test. A draft Research Report is being finalised, and is planned to be submitted to ASTM in early 2017.

No work by Terrabon/Logos on ASTM certification is known to have taken place.

### 3.5.3 Representation in HBBA Study

As the properties of ATJ-SKA are such that in principle it could be used as a neat fuel without blending with conventional kerosene, practical blending is not expected to be an issue for future use of ATJ-SKA. The purpose of the HBBA Study is therefore not of major relevance for ATJ-SKA. All the same it was considered to be of interest to include a small sample of ATJ-SKA in the HBBA Study. As the main producer of ATJ-SKA Swedish Biofuels was contacted, and agreed to provide such a sample. The shipment, consisting of 20 litres of neat ATJ-SPK, arrived at the Erding lab in July 2014.

## 3.6 CH kerosene

### 3.6.1 Pathway Description

The terminology for this process is somewhat confusing. In this report it is referred to as CH process, after the core element of the production pathway. It has also been variously referred to as HEFA-SKA, BIC process or “Biofuels ISOCONVERSION”, which is the long name of BIC. CH stands for Catalytic Hydrothermolysis, which is the term used by the US company Applied Research Associates (ARA) to refer to its proprietary element of the production pathway. The subsequent hydrotreatment step uses technology owned by Chevron Lummus Global. The product from the process is also known under the trademarked name “ReadiJet”. [118] As part of the ASTM certification project, the production pathway has since publication of the HBBA Interim Report been renamed CHJ (for Catalytic Hydrothermolysis

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[116] Hartmut Pflaum: Qualitätssicherung und Nachhaltigkeit bei der Bereitstellung von Biokraftstoffen für die Luftfahrt – Schlussbericht Fraunhofer UMSICHT, Juni 2014, p.17

[117] Ibid., p.18

[118] Edward N. Coppola: Evaluation of Hydroprocessed Esters and Fatty Acids (HEFA) Synthetic Kerosene containing Aromatics (SKA) Readijet Renewable Jet Fuel, June 2014, p.1

Jet), and it is assumed that this appellation will prevail. However, it would have involved considerable work to replace “CH” with “CHJ” throughout the Final Report, hence the old nomenclature has been retained.

Despite the use of the HEFA-SKA appellation, the process is technically different from the HEFA process described in 3.2.

The production pathway of CH fuel consists of three major steps. It starts with Catalytic Hydrothermolysis, where triglyceride oils, other esters or fatty acids are converted into n- and iso-alkanes, cycloalkanes and aromatic compounds.[119] In the next step, the material is mildly hydrotreated to saturate residual olefins and remove residual oxygenates, preserving aromatics and cycloparaffins[120]. In the final step the output stream is distilled and fractionated into the final products of which kerosene is one.[121]

Feedstock for the CH process is similar to that for HEFA, i.e. oils and fats. A variety of edible and non-edible materials have been successfully tested by ARA, with the current focus on oil from Brassica Carinata, a non-edible oil.[122]

CH kerosene is a fully synthetic kerosene, including synthetic aromatics. According to ARA, aromatic content can be controlled to between 10% and 20% by controlling processing severity.[123]

### 3.6.2 Approval Status

CH kerosene is not yet approved by ASTM. Certification work is being performed by ARA, based on fuel produced from its 4 barrel per day pilot and 100 barrel per day demonstration plants.[124]

Neat CH kerosene is very similar in composition and properties to fossil kerosene, including in aromatic content.[125] No information has yet been released on blend ratios targeted for certification. From its composition it could in principle be used as a neat fuel without blending, but current tendency at ASTM is for the moment only to approve blends with a maximum 50% blend ratio.

Extensive tests have been conducted, including a test flight in 2012.[126] A research report has been finished and submitted for OEM review.[127] Personal communication from ARA indicates that a formal ASTM ballot is aimed for soon.

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[119] Ibid., p.4

[120] Ibid, p.6; Red, Chuck: ReadiDiesel ReadiJet next Generation alternative Fuels, presentation, June 2012, p.3

[121] Red, Chuck, ibid.

[122] http://www.ara.com/fuels/Feedstocks-evaluated-CH-process.html, , researched 28. August 2014

[123] Personal communication

[124] http://www.ara.com/fuels/CH-Technology-Status.html, researched 28. August 2014; personal communication

[125] http://www.ara.com/fuels/Readi-Jet-Diesel-Specs.html, researched 28. August 2014

[126] http://www.ara.com/fuels/CH-Technology-Status.html, researched 28. August 2014

[127] Edward N. Coppola: Evaluation of Hydroprocessed Esters and Fatty Acids (HEFA) Synthetic Kerosene containing Aromatics (SKA) Readijet Renewable Jet Fuel, December 2014

### 3.6.3 Representation in HBBA Study

The only provider of CH kerosene is currently ARA. This company was contacted and agreed to provide a sample. The shipment consisted of 5 USG of neat CH kerosene designed to meet Jet A specification as a neat fuel.

## 3.7 HDCJ kerosene

### 3.7.1 Pathway Description

HDCJ stands for Hydroprocessed Depolymerized Cellulosic Jet. This term encompasses the production pathway better known under the term “pyrolysis”, but also includes similar pathways where alternative processes are used for depolymerisation.

The production pathway of HDCJ fuel consists of three major steps. It begins with a feedstock of lignocellulosic biomass, which is essentially a combination of lignin, cellulose and hemicellulose, each of which are complex polymers comprised of carbon, hydrogen and oxygen. In the first step, the feedstock is depolymerised, i.e. the polymers are broken down into smaller fragments. In the case of pyrolysis, depolymerisation is conducted by heating the material in an oxygen-free atmosphere. Other possible ways of depolymerisation are hydrothermal or catalytic approaches or combination with pyrolysis. The depolymerised material is then hydroprocessed to remove oxygen, converting the oxygenates to hydrocarbons and to some extent saturating aromatic compounds. In the final step the hydrocarbon product is distilled to produce the final products of which kerosene is one.[128]

Feedstock for the HDCJ process can be a broad variety of lignocellulosic material, like wood, straw, miscanthus, switchgrass or bagasse.[129] The US company KiOR, which has so far produced most of the HDCJ fuel, has used woody biomass as a feedstock.[130]

### 3.7.2 Approval Status

HDCJ is not yet approved by ASTM. Most of the certification work has so far been performed by KiOR, based on their production pathway where depolymerisation is performed by a combined thermo catalytic process. Some work has also been done by UOP using pyrolysis for depolymerisation, but this process is still being developed.[131]

Neat HDCJ has an aromatic content of some 50%[132], which is above the permissible maximum for jet fuel of 25%. It is therefore inevitable that HDCJ will have to be blended with conventional jet kerosene for the aromatic content to be diluted to specification levels. Approval is currently pursued for a maximum blend ratio of 30%.[133]

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[128] Edwards, Tim/ Trewella, Jeff/Sanchez, Vicente/Leisenring, Roger jr.: Evaluation of Hydroprocessed Depolymerized Cellulosic Jet (HDCJ) Fuels and Blends; April 2014, p.8-10

[129] Ibid, p. 8

[130] Ibid, p. 10/11

[131] Ibid, p. 9-13

[132] Ibid, p. 15

[133] Ibid, p. 6/7

Almost all fuel so far used for ASTM certification has been produced by KiOR in their 10 bbl/day demo facility in Pasedena, Texas.[134] Lab tests have been performed on a blend of 70% conventional kerosene and 30% HDCJ, with specification testing, fit-for-purpose testing and materials compatibility testing all passed.[135] In addition, engine and APU rig tests have been successfully performed on various blends of KiOR HDCJ, conventional jet kerosene and FT kerosene.[136] No further tests are currently planned.

A research report on the testing performed on HDCJ fuels has been drawn up and distributed to the OEMs in July 2014.[137] Incorporation of OEM feedback into the report was begun,[138] but the process was then slowed down by the financial problems of KiOR, which in November 2014 filed for bankruptcy.[139]

### 3.7.3 Representation in HBBA Study

The chief purpose of the HBBA Study is to investigate high level blends, in particular blend ratios above the ASTM limits. In the case of HDCJ such an analysis would be moot, as the high aromatics levels of HDCJ mean that blend ratios above 30% soon become off-spec. Even at a 30% blend ratio, the aromatics content of the conventional kerosene needs to be below 14.3% for the blend to be within specification. In the German conventional kerosene analysis discussed in section 2.2, only some 9.5% of the batches met this requirement. Of the conventional kerosene used in the HBBA Study, only one (No. 114) meets this requirement. For the kerosene with the highest content of aromatic compounds (No. 85) the maximum HDCJ blend ratio would have been a mere 12%.

HDCJ is therefore not particularly well suited for the main task of the HBBA Study. All the same it would have been interesting to include it for selected analyses. As discussed the only possible provider of HDCJ kerosene is currently KiOR. This company was contacted for possible inclusion of their product in the HBBA Study, however the KiOR plant has been idle since March 2014[140], and no fuel was available. Accordingly no data on HDCJ blends is provided in this report.

## 3.8 HDO-SK

### 3.8.1 Pathway Description

HDO-SK stands for Hydrodeoxygenated Synthesized Kerosene. This is the term used by the US company Virent to refer to a product from its “BioForming” process. Whereas “BioForming” is registered as a Trademark and describes a process resulting in various product streams, HDO-SK is specific to one product stream and is intended as a generic term for purposes of ASTM certification.

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[134] Ibid, p. 71
[135] Ibid, chapter 2
[136] Ibid., chapter 3 and appendices 6 and 7
[137] Ibid, whole report
[138] Personal communication
[139] Biofuelsdigest.com: KiOR seeks Chapter 11 reorganisation after asset bid received, Meldung vom 11.11.2014
[140] E4tech (UK) Ltd.: Sustainable Aviation Fuels - Potential for the UK industry, July 2014, p.8

The production pathway of HDO-SK fuel consists of four major steps. In the first step, plant-derived oxygenated compounds are hydrodeoxygenated, resulting in intermediate products like alcohols, ketones and other oxygenates with limited reactivity. This is a thermochemical process using metal catalyst. In the next step the resulting intermediate products are dehydrated, oligomerised and hydrogenated to produce a mixture of normal paraffins, iso-paraffins, cycloparaffins and aromatics. This is a single catalytic step during which several types of reactions occur. The resulting components are all hydrocarbon types also found in fuel derived from fossil sources. The final two steps are essentially the same as in conventional refining, with the material being first hydrotreated, and then distilled into the final products of which HDO-SK is one.[141]

Feedstock for the production of HDO-SK fuel can be a broad variety of both cellulosic material (like wood or straw) and commercial sugars.[142] Actual production so far has essentially been from corn syrup.[143]

### 3.8.2 Approval Status

HDO-SK is not yet approved by ASTM. Certification work is being performed by Virent in cooperation with Shell.

Neat HDO-SK has a cycloparaffin content of 80% and only minor aromatics content.[144] It is therefore inevitable that HDO-SK will have to be blended with conventional jet kerosene, to achieve the required minimum aromatics content and dilute the cycloparaffins. No blend ratios have as yet been formally proposed but testing of blends has so far concentrated on a 50% blend.[145]

Certification testing of HDO-SK has so far been limited to lab tests. Specification testing and fit-for-purpose testing are essentially finished, with no issues identified, but only preliminary materials compatibility tests have been performed. Work on rig and engine tests is still pending. HDO-SK therefore is still some time away from ASTM certification.[146]

### 3.8.3 Representation in HBBA Study

The only producer of HDO-SK kerosene is currently Virent. Virent was contacted in 2014 about the availability of a sample for the HBBA Study. However, so far only a total of 114 gallons of HDO-SK had been produced, all of which was required for the lab certification tests.[147] Accordingly, no fuel could be provided for the purposes of the HBBA Study, thus no data on HDO-SK blends is included in this report.

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[141] Dally, Brice / Ginestra, Cynthia / Edwards, Tim / Heminghaus, Gregory: Evaluation of Hydrodexygenated Synthesized Kerosene (HDO-SK) and Blends, March 2014, p. 11-14; Pflaum, p. 18/19

[142] Dally/Ginestra/Edwards/Heminghaus, p.11

[143] Ibid, p. 15

[144] Ibid, p. 16-20

[145] Ibid, p. 32

[146] Ibid, p.65

[147] Ibid, p. 15

## 3.9 HDO-SKA

### 3.9.1 Pathway Description

HDO-SKA stands for Hydrodeoxygenated Synthesized Aromatic Kerosene. Like HDO-SK described in section 3.8, this term is used by the US company Virent to refer to one of the products from its “BioForming” process. In the case of HDO-SKA this is a product stream consisting almost solely of aromatics.

The production pathway of HDO-SKA fuel consists of three major steps. As with HDO-SK in the first step plant-derived oxygenated compounds are catalytically hydrodeoxygenated, resulting in intermediate products like alcohols, ketones and other oxygenates with limited reactivity. The resulting intermediate products are then condensated as a second step to form longer carbon chains through C-C bond forming reactions. This is a single catalytic step during which several types of reactions occur. In this step, the oxygenates are converted to olefin intermediates, which react to produce aromatics resembling those typically found in jet fuel, together with low levels of n-paraffins, iso-paraffins, and cycloparaffins. In the final step, the material is distilled into the final products of which HDO-SKA is one.[148]

As is the case for HDO-SK, feedstock for the production of HDO-SKA fuel can be a broad variety of both cellulosic material (like wood or straw) and commercial sugars.[149]

### 3.9.2 Approval Status

HDO-SKA is not yet approved by ASTM. Certification work is being performed by Virent in cooperation with Shell.

Neat HDO-SKA consists solely of aromatics, the other components having been removed by distillation.[150] This composition gives the neat fuel poor thermostability and an off-spec smoke point[151] and anyway is way above the maximum permissible aromatics content of 25%. It is therefore unsuitable for use as a neat fuel, and is not intended to be used as such. Rather, approval is pursued for use as a blend component where appropriate and advantageous.[152] A prospective use could be for blending with synthetic fuels not containing aromatics, like FT or HEFA, as a balancing blend component in a 50/50 blend with conventional jet fuel.[153] No maximum blend ratios for HDO-SKA have been proposed but the maximum aromatics content of 25% constitutes a natural upper limit.

Certification testing of HDO-SKA has so far been limited to lab tests. Specification testing, fit-for-purpose testing and toxicity testing are essentially finished, with no issues identified, but only preliminary materials compatibility tests have been performed. Work on rig and engine tests, including emissions performance, is planned but is still pending. HDO-SKA therefore is still some time away from ASTM certification.[154]

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[148] Dally, Brice / Ginestra, Cynthia / Heminghaus, Gregory: Evaluation of Hydrodexygenated Synthesized Aromatic Kerosene (HDO-SKA) and Blends, May 2014, p. 11-14

[149] Ibid, p.11

[150] Ibid, p. 17-19

[151] Ibid, p. 24

[152] Ibid, p.15

[153] Ibid

[154] Ibid, p.66

### 3.9.3 Representation in HBBA Study

The chief purpose of the HBBA Study is to investigate high level blends, in particular blend ratios above the ASTM limits. In the case of HDO-SKA such an analysis would be moot, as HDO-SKA consists solely of aromatics and is intended as blendstock at fairly low blend levels. All the same it would have been interesting to include HDO-SKA for limited analysis.

The only producer of HDO-SKA kerosene is currently Virent. Virent was contacted about the availability of a sample for the HBBA Study. However, so far only some 450 litres of HDO-SKA had been produced, all of which was required for the lab certification tests.[155] Accordingly, no fuel could be provided for the purposes of the HBBA Study, thus no data on HDO-SKA blends is provided in this report.

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[155] Ibid, p. 17

# 4 Properties of Blends of Alternative Fuels with Jet A-1

The properties studied for blends of fossil fuel with high ratios of synthetic fuel (up to 90 vol%) were those specified in ASTM D1655 and ASTM D7566.

Tests according to ASTM D1655 and ASTM D7566 include the determination of several contents, like aromatics, sulphur etc. These can readily be calculated once the respective concentrations in the individual neat blend components have been determined, provided that the volume of the mixture is the sum of volumes of the components and anomalies like e.g. volume contraction can be excluded. As soon as density vs. blend ratio of the mixture displays a linear behaviour, it is safe to calculate contents and gratuitous to measure these parameters. Anyhow, to confirm this, sporadic measurements have been performed.

In the following, only selected results are discussed. A detailed compilation of all data can be found in annex 9.3.

Error bars in the charts correspond to the repeatability of the respective method.

## 4.1 Experimental Procedures

Test methods employed for this study are those specified in ASTM D1655 and ASTM D7566 with the following exceptions:

### Total Sulphur

For jet fuels and blends DIN EN ISO 14596 (for contents > 10 ppm) and for neat synthetic fuels DIN EN 20884 (for contents < 10 ppm) were applied. However, these methods are technically equivalent to those specified in ASTM D1655 and D7566.

### Flash Point

For flash points up to 75 °C IP 170 was used instead of ASTM D56. Values obtained from IP 170 correspond well to those from ASTM D56. However, because of the exceptionally high flash point of neat Farnesane, ASTM D93 has been employed for this fuel, since this method is suitable for samples with flash points > 75 °C.

### Microseparometer (MSEP)

This test is typically only performed at place of manufacture and has therefore not been included in the study.

Yet, to assess the fuel blend´s behaviour towards water, water reaction according to ASTM D1094 has been determined instead, which can be used as an alternative test for MSEP.

### Electrical Conductivity

According to ASTM D1655 and D7566 electrical conductivity only needs to be determined at points of use. Values for electrical conductivity strongly depend on handling of the fuel. Therefore, measurements performed in the laboratory have no validity with regard to the actual electrical conductivity in practice (e.g. in storage tanks or fuel distribution systems at point of use). Therefore, determination of electrical conductivity has not been performed in this study.

#### Additive Content

Information on additive content of the Jet A-1 fuels has been provided by the manufacturers in the respective certificates. Synthetic fuels are free of additives; additive contents of blends could therefore be calculated rather than measured in this study.

#### Hydrocarbon Composition

Determination of hydrocarbon composition according to ASTM D2425 or ASTM D5291 has not been conducted. However, the samples were analysed by gas chromatography and mass spectrometry to be able to correlate certain properties with composition. The respective results are discussed in the appropriate sections.

#### Nitrogen, Metals and Halogens

Tests according to ASTM D4629 (Nitrogen), UOP 389 (Metals) and ASTM D7359 (Halogens) have not been performed. These tests are intended to monitor the production processes at the point of manufacture[156], and are not suitable further downstream, since even trace contaminations inevitable during fuel handling will lead to exceedance of the respective limits.

#### Viscosity at -40°C

This requirement was only added in version 14a of ASTM D7566, which was published in June 2014, when the bulk of the analytical work had already been performed. It could therefore not be included in this study.

## 4.2 Results

This chapter will summarize the findings to point out trends and critical changes in properties that result upon incorporation of high amounts of synthetic into fossil fuels.

### 4.2.1 Blends of SIP Fuel with Jet A-1

The SIP fuel Farnesane consists, except for traces of some alkyl cycloalkanes, almost exclusively of a single compound, namely 2,6,10-trimethyl dodecane. In this respect Farnesane differs fundamentally from most of the other synthetic fuels used for this study, which are complex mixtures of isomeric alkanes and in part also contain aromatics. A gas-chromatogram of Farnesane is shown in Figure 12.

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[156] ASTM D7566 – 11a, sections A 1.6.1 and A2.6.1

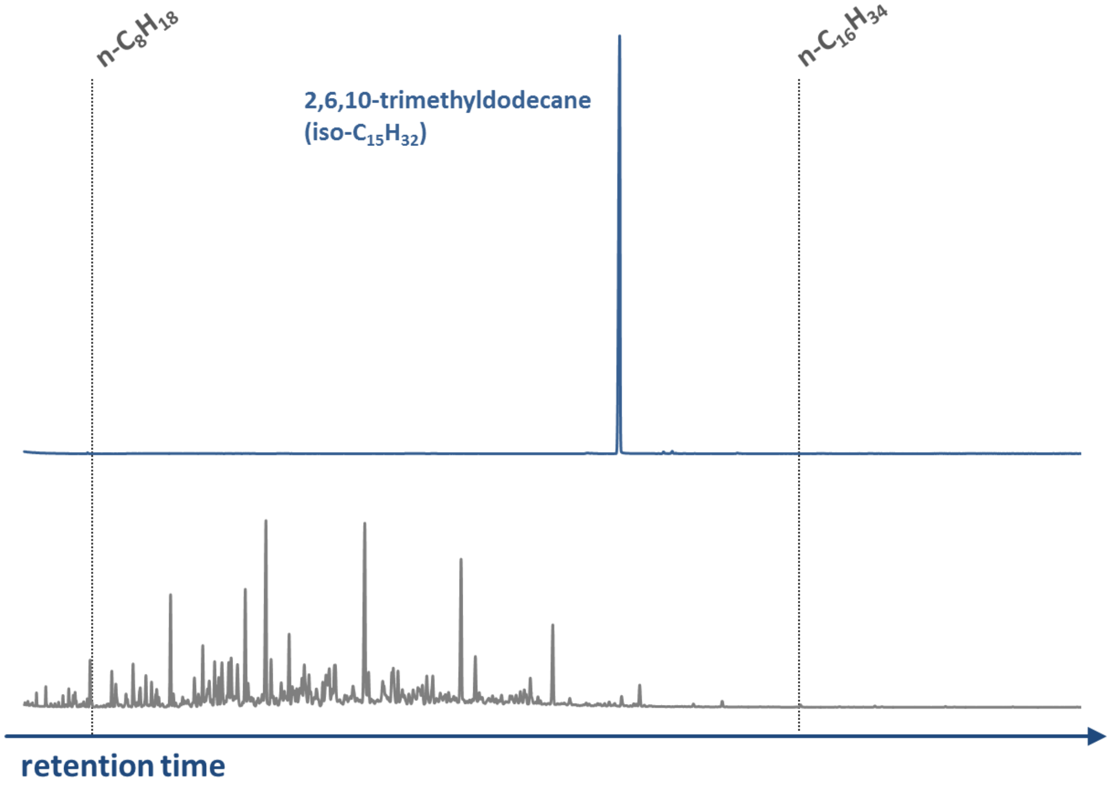


*Figure 12: Gas-chromatograms of Farnesane (top) and a typical Jet A-1 fuel (bottom)*

**Density**

Measurements show that there exists a precise linear relationship between density and Farnesane content of the blend (Figure 13). The density of Farnesane blends can therefore readily be calculated from the values of the neat blend components and the blend ratio.

Unlike neat Fischer-Tropsch or HEFA kerosene, whose specified density range is 730 – 770 kg/m³, neat farnesane has a density of 773.1 kg/m³ and therewith slightly below the lower limit for blends (775 kg/m³). Except in the case of an extremely low density fossil jet fuel, density is no constraint for the maximum blend ratio. For the investigated fuels, blends with Farnesane content up to ca. 90 vol% meet the specification requirement for density.

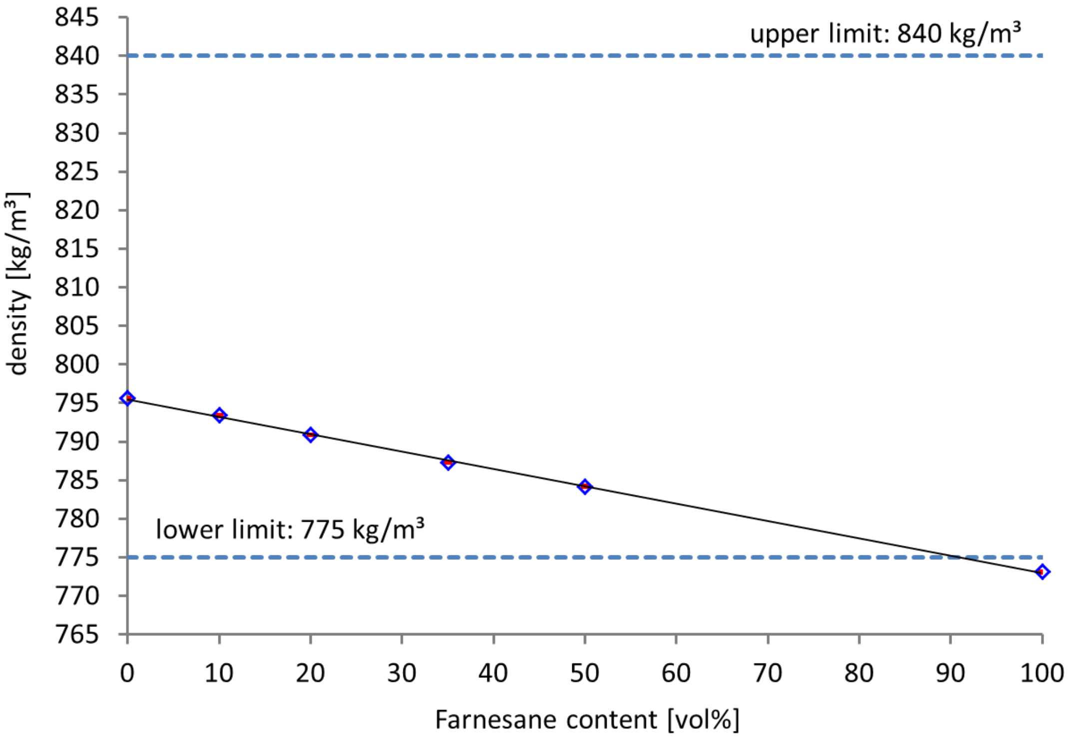
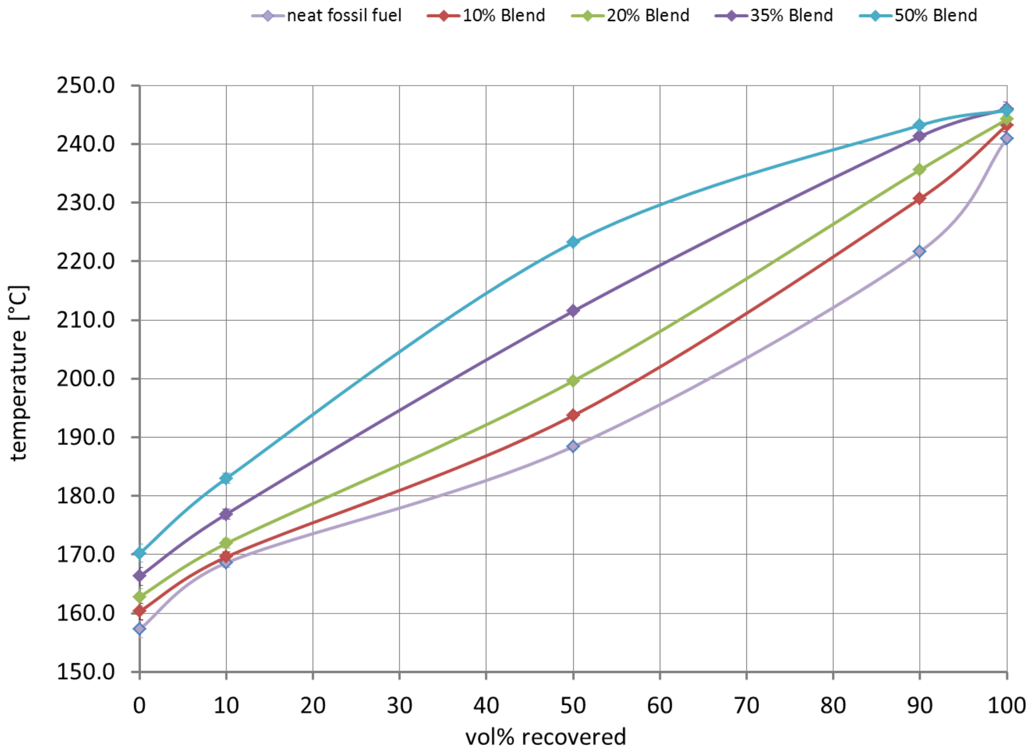


*Figure 13: Density of fuel 100, Farnesane and blends with 10, 20, 35 and 50 vol% Farnesane*

**Distillation**

The distillation curves of the Farnesane blends with fuels 100 and 117 are shown in Figure 14.



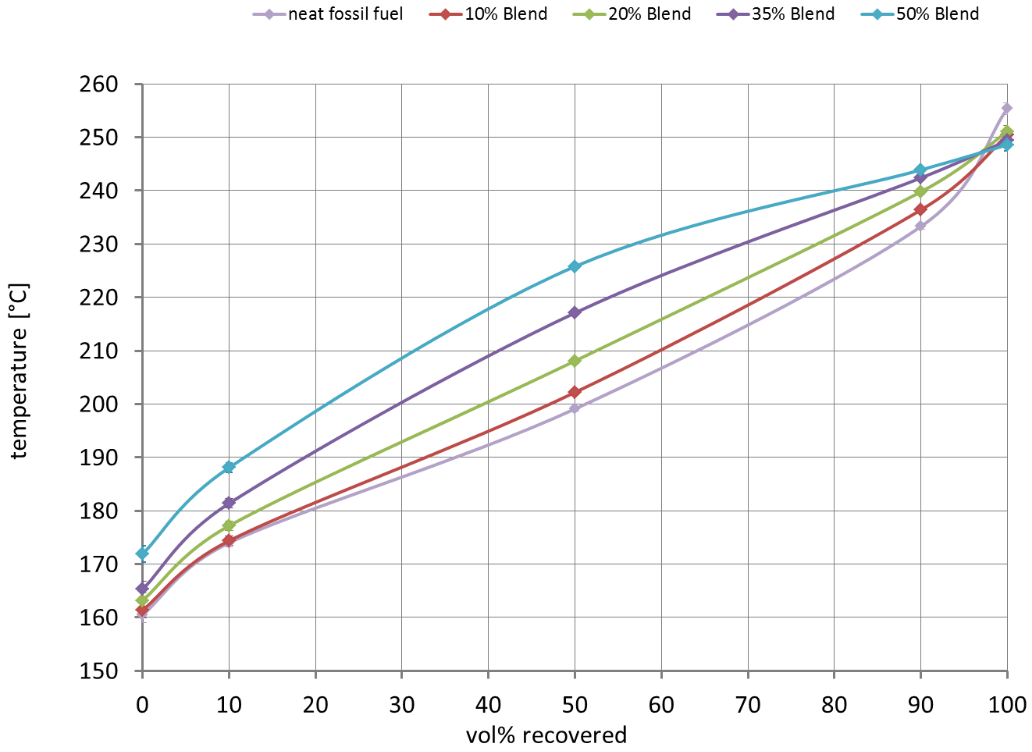


*Figure 14: Distillation curves of Jet A-1 and blends with 10, 20, 35 and 50 vol% Farnesane. Top: blend with fuel 100, bottom: blend with fuel 117*

The distillation curves of fuel 100 as well as those of fuel 117 blends are shifted to higher temperatures upon increasing the amount of Farnesane in the blend. Neat Farnesane has a boiling point of 247 °C[157] which lies close to the final boiling point of the Jet A-1 fuels. Thus,

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[157] Determined according to ASTM D1120

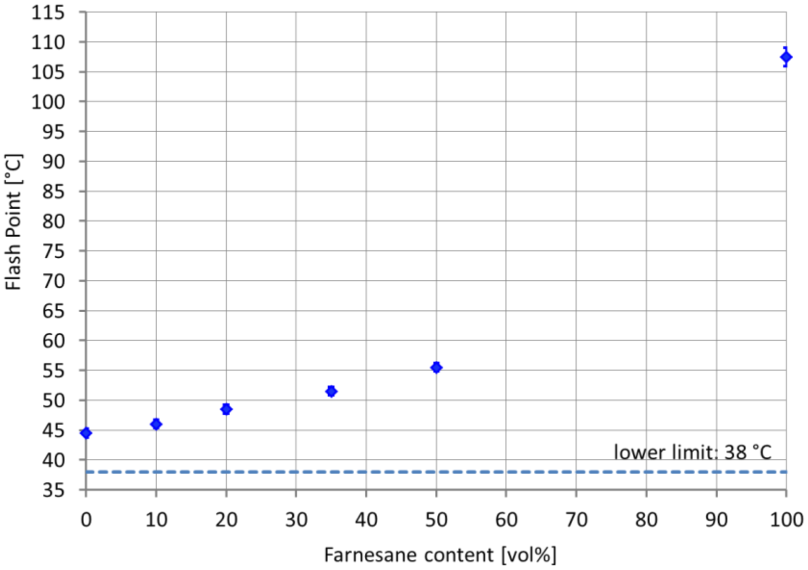
its incorporation into the fuel lowers the vapour pressure of the blend which is reflected by the increase in boiling temperature. This effect is most pronounced in the 50 vol% recovered region but has also a considerable influence on the beginning (cf. initial boiling point and 10 vol% recovered) and the end of the distillation (cf. 90 vol% recovered).

However, the criteria for distillation as defined in ASTM D1655 and ASTM D7566 are met for all blend ratios.

### Flash Point

Due to the high boiling point of Farnesane, its blends with Jet A-1 exhibit higher flash points compared to neat Jet A-1 because the vapour pressure of the mixture decreases. This observation agrees nicely with the shift of the entire boiling curves to higher temperatures. Figure 15 shows the respective graphs for fuel 100 and fuel 117 which qualitatively show good resemblance.

It is noteworthy that incorporation of 10 to 50 vol% Farnesane into Jet A-1 only marginally increases the flash point, although Farnesane itself exhibits a comparatively high flash point of 107 °C. This is because the flash point of the mixture primarily depends on the presence of volatile compounds in the jet fuel which – even though diluted – still are present in the blends. The slight increase in flash point upon adding high boiling Farnesane is due to the overall lowering of the mixture’s vapour pressure.



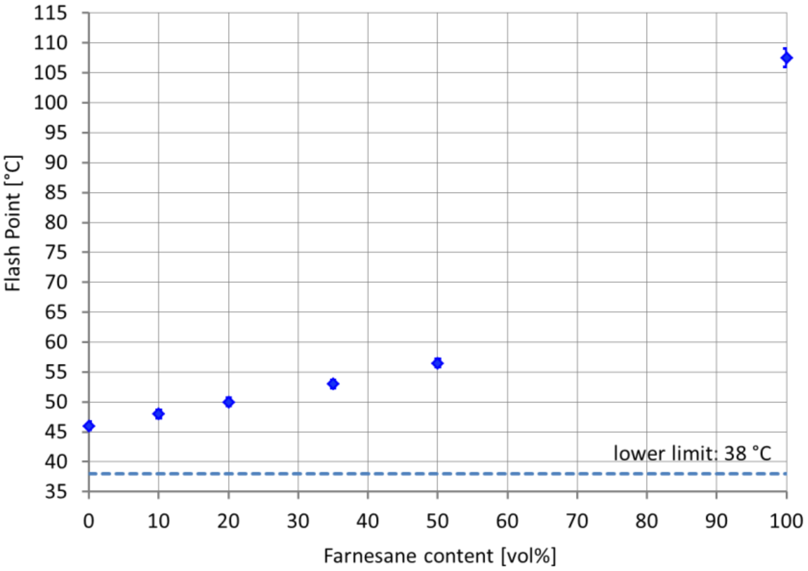


*Figure 15: Flash Points of Farnesane and blends with fuel 100 (top) and fuel 117 (bottom)*

### Freezing Point

The freezing point of Farnesane (< -100 °C) is far below the upper limit for both jet fuel and blends (-47 °C). Therefore, any specification compliant fossil kerosene blended with farnesane will meet the requirements of ASTM 7566 regardless of blend ratio. Nevertheless, the respective measurements have been conducted and reveal a widely linear relationship between freezing point and blend ratio.

### Existent Gum

The existent gum value for the neat Farnesane sample was repeatedly determined as ca. 10 mg/100 ml and exceeds the limit for blends and neat synthetic fuel (7 mg/100 ml).

FTIR-spectroscopic analysis of the residue obtained from neat Farnesane reveals that it mainly consists of aliphatic hydrocarbons along with silicone compounds. The latter finding has been confirmed by energy dispersive X-ray spectroscopy (EDX), where significant amounts of the element silicon have been detected. It needs to be mentioned that combustion of silicones leads to the formation of silicon dioxide, which is undesirable. However, the source of this contamination is unknown, and may have been accidentally introduced during transport.

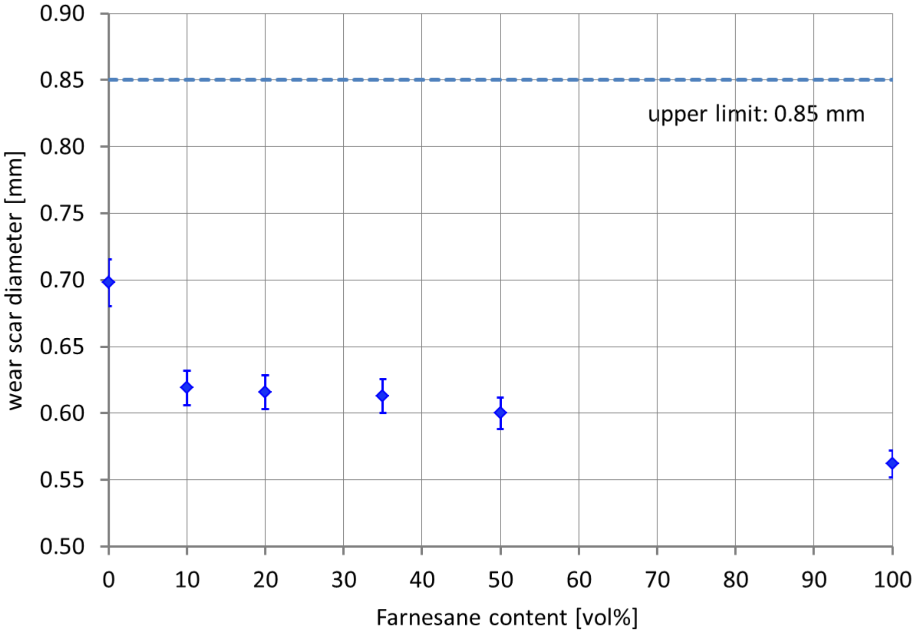
The respective values for fuel 100 and fuel 117 are below the detection limit of the method (1 mg/100 ml). The dependency of gum content and blend ratio is – as expected – linear. All measured values of the blends up to 50 vol% lie considerably below the upper limit of 7 mg/100 ml.

**Lubricity**

Blending Jet A-1 fuels 100 and 117 with Farnesane improves lubricity. For both fuels a significant effect can already be observed by incorporation of 10 vol% Farnesane (Figure 16). Further increase of Farnesane content additionally improves lubricity, yet this effect is less pronounced.

Given the high gum value of neat Farnesane and the contamination by silicone compounds (see above), the question is whether the improvement of lubricity is due to the presence of these compounds. Therefore, the residue from existent gum determination has been dissolved in jet fuel 100 and 117, respectively and lubricity has been determined again. The concentration of the residue in the fuel was the same as in the 50 vol% Farnesane blends. It turns out, that these mixtures exhibit lubricity values comparable to those of the 50 vol% blends. Thus it cannot be ruled out that the effect is at least partly due to presence of the contaminants.

On the other hand, to test the influence of pure long-chain hydrocarbons such as Farnesane on lubricity, n-hexadecane (p.a. quality) has been chosen as a model compound. The lubricity of a 50 vol% blend of n-hexadecane with jet fuel 117 has been determined and in this case, a significant improvement was observed as well. From these results it can be inferred, that pure Farnesane can very well improve lubricity. It is therefore not possible to conclusively attribute the improvement of lubricity to either contaminant or 2,6,10-trimethyldodecane. However, the potential effect of minor impurities must not be underestimated, since lubricity is surface related and substances present in small amounts might exert substantial influence.



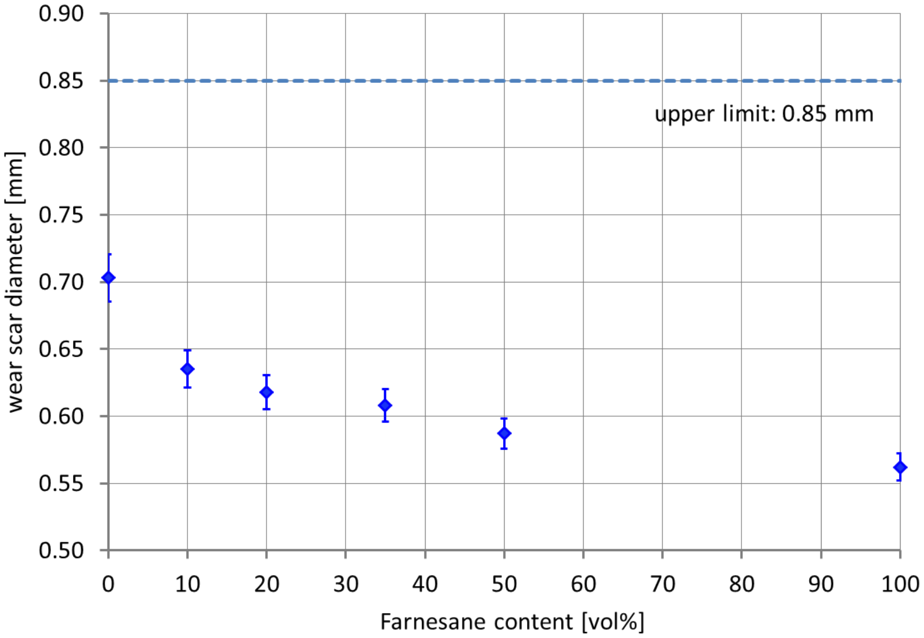


*Figure 16: Lubricity expressed as wear scar diameter for fuel 100 (top) and fuel 117 (bottom), neat Farnesane and respective blends.*

## Viscosity

The kinematic viscosity[158] of neat Farnesane is about 14 mm²/s which is high compared to the limit for fuel blends (8 mm²/s). The maximum amount of Farnesane in the blend is therefore limited. The respective measurements (Figure 17) show, according to the Grunberg-Nissan equation, a logarithmic correlation between viscosity and blend ratio. Thus,

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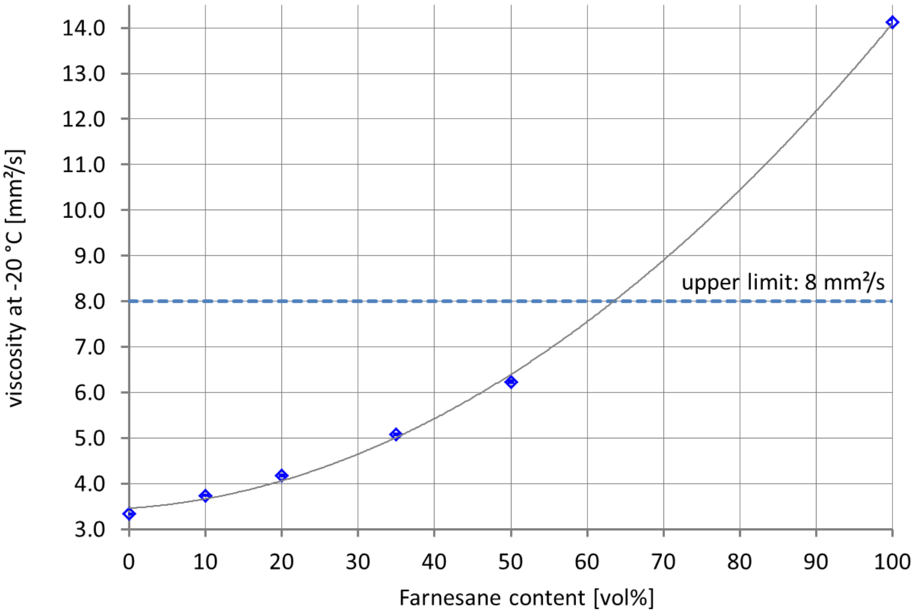
[158] Measurement has been performed according to ASTM D445, although for such high viscosity values, the method does not provide precise results.

at high blend ratios regarding Farnesane, increase in viscosity is more pronounced than at low ratios. Nevertheless, 50 vol% blends of both fuels 100 and 117 meet the requirements according to ASTM D7566.



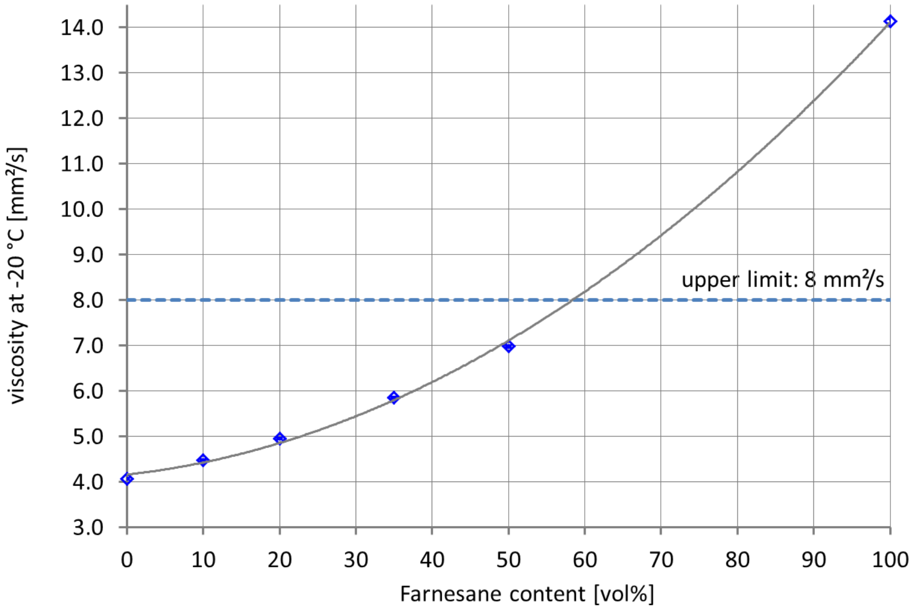


*Figure 17: Viscosity of fuel blends containing Farnesane and fuel 100 (top) and Farnesane and fuel 117 (bottom) as well as for the neat blend components.*

## Thermal Stability and Corrosion

All neat fuels as well as all blends exhibit the same values, which are <1 for deposit rating, 0 mmHg for pressure drop and No. 1a for copper strip corrosion. Requirements of ASTM D7566 are therefore met .

### Smoke Point

The smoke point of neat Farnesane is too high to be accurately measured according to ASTM D1322. In case of blends with either fuel 100 and 117 an increase and therefore an improvement of smoke point upon increasing the amount of Farnesane in the blend is observed (Figure 18).

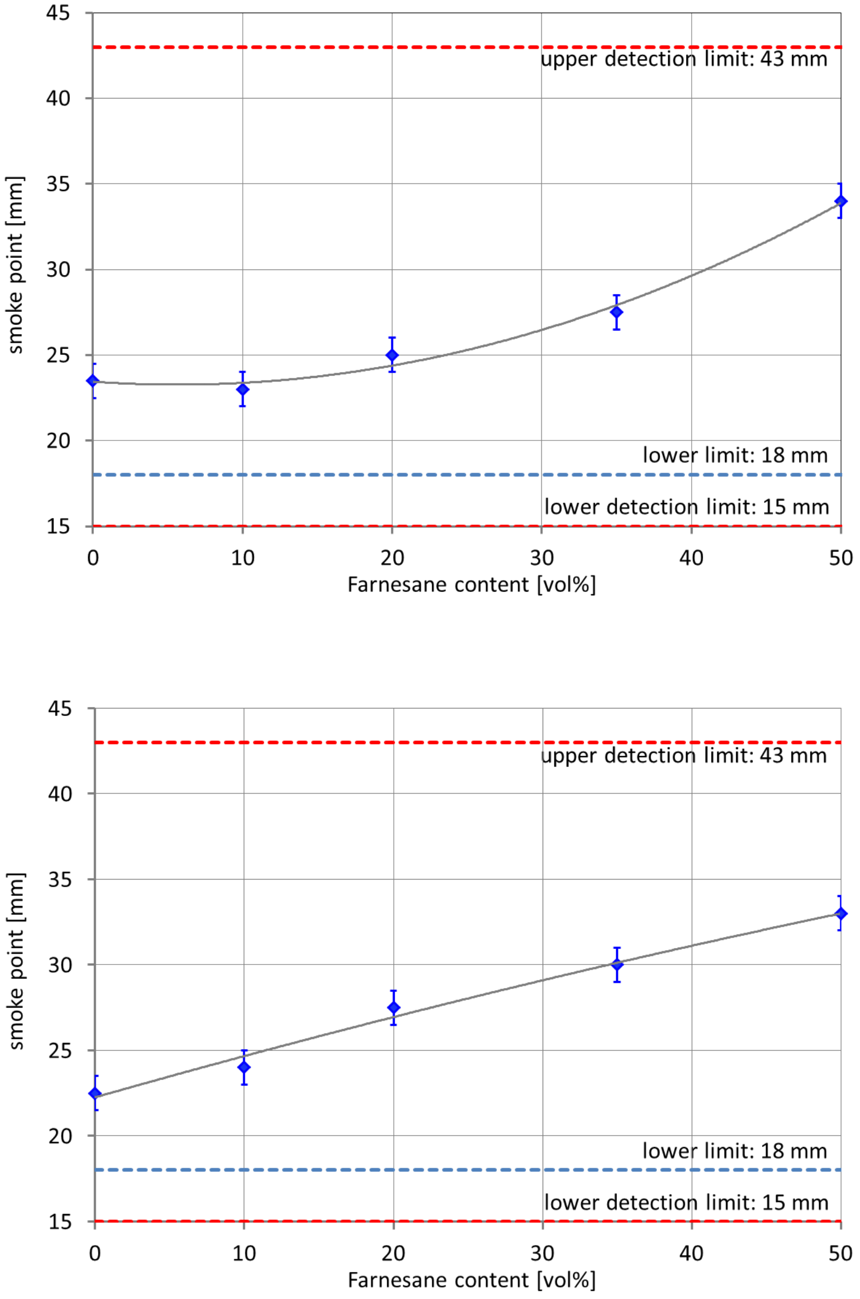
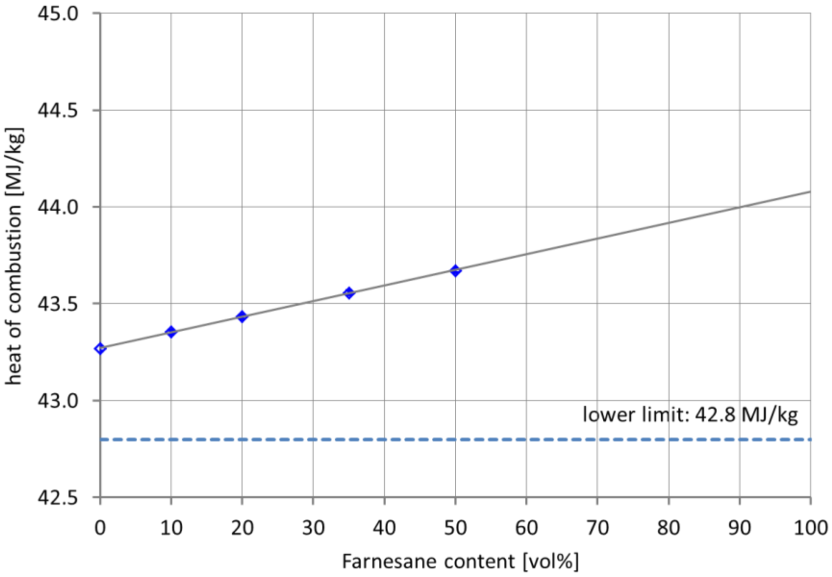


*Figure 18: Smoke point of Farnesane blends with fuel 100 (top) and fuel 117 (bottom). The smoke point of neat Farnesane is too high to be determined according to ASTM D1322*

This finding is plausible if one assumes that aromatic compounds are primarily responsible for soot formation and addition of Farnesane lowers the amount of aromatics in the blend. In fact, the shapes of the respective smoke point curves of the blends with fuel 100 and 117 differ; however, detailed investigations of the underlying effects exceed the scope of this study. The emissions behaviour of farnesane blends is further explored in chapter 7.

### Heat of Combustion

Heat of combustion is calculated from the content of aromatic compounds, the density and the distillation curve, where the latter is being represented by the mean value of T10, T50 and T90. According to the underlying formula, a decrease in the amount of aromatic compounds as well as decreasing density tends to raise the heat of combustion. If the distillation curves are shifted to higher temperatures, heat of combustion raises, too. Since in case of the blends all these variables change linearly, calculating the heat of combustion according to ASTM D3338 results in a linear relationship between Farnesane content and heat of combustion (Figure 19).



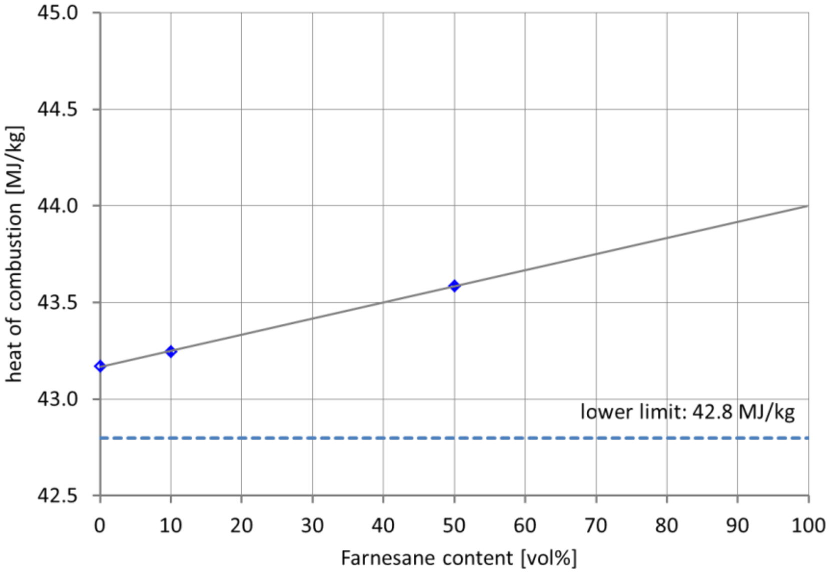


*Figure 19: Heat of Combustion of Farnesane blends with fuel 100 (top) and fuel 117 (bottom)*

### 4.2.2 Blends of HEFA with Jet A-1

HEFA consists of n-alkanes and iso-alkanes and lacks aromatic compounds. In this study the HEFA product was a hydrotreated vegetable oil (HVO). Comparison of the HVO with a typical Jet A-1 sample using gas-chromatography reveals that HVO features compounds in the same retention time interval as Jet A-1. However, at high retention times, the chromatogram of HVO displays a set of additional and poorly resolved peaks with considerable intensity (Figure 20). The concentration of such high boiling compounds in the Jet A-1 sample is negligible.

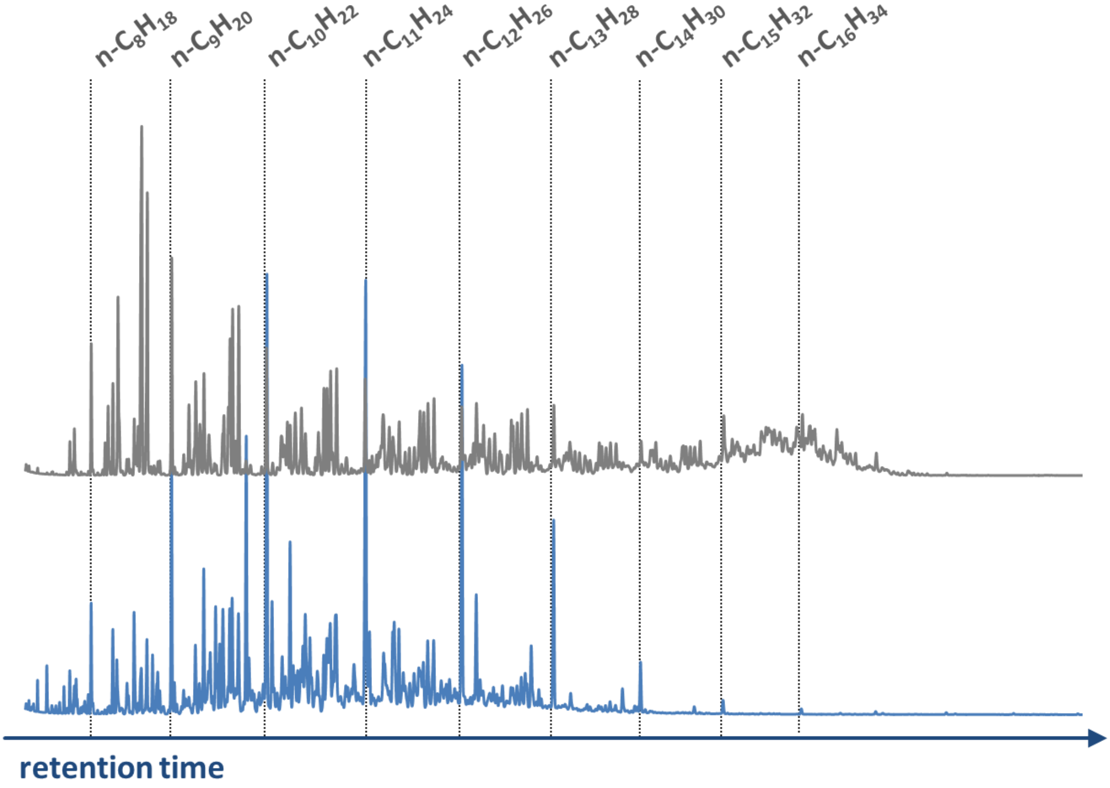


*Figure 20: Gas-chromatograms of HVO (top) and a typical fossil Jet A-1 fuel (bottom)*

**Density**

As for the Farnesane blends, measurements show that densities (ρ) of the HVO blends depend linearly on blend ratio. Since ρ of neat HVO (756.7 kg/m³; required: 730 – 770 kg/m³) lies below the lower limit for jet fuels and blends (775 kg/m³), the maximum blend ratio regarding HVO content is limited. The HVO contents for which the respective jet fuel mixtures reach the 775 kg/m³ limit have been calculated and are given in Table 2.

| Jet A-1 fuel | density ($\rho$) of neat Jet A-1 [kg/m³] | HVO content for which $\rho$ = 775 kg/m³ |
|---|---|---|
| 085 | 797.5 | 55 vol% |
| 112 | 818.6 | 71 vol% |
| 114 | 795.0 | 52 vol% |
| 117 | 811.7 | 67 vol% |
| 123 | 789.0 | 43 vol% |

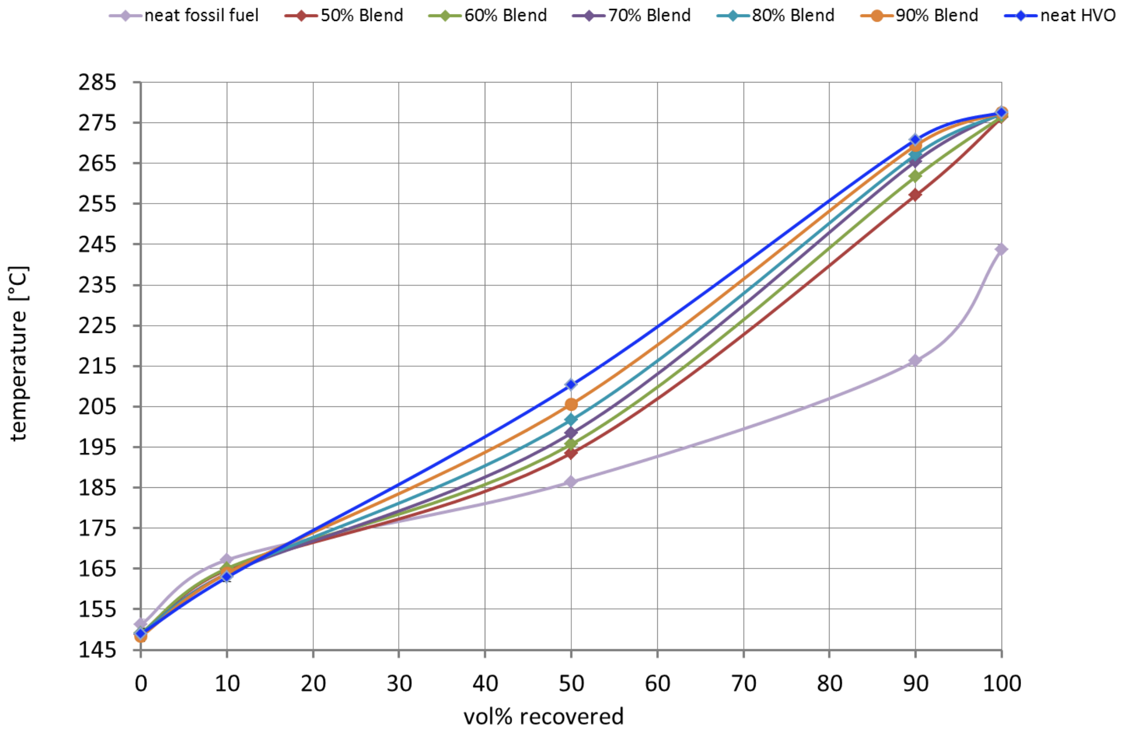
*Table 2: Calculated HVO content for which density of the respective blends with Jet A-1 reach the lower limit of 775 kg/m³*

**Distillation**

Since the distillation curves of fuel 085 and fuel 112 show the most pronounced deviation from that of neat HVO, the curves of their respective blends have been chosen for discussion (Figure 21).

In contrast to the distillation curves of the neat fossil fuels, that of HVO exhibits a relatively constant slope over the entire vol% recovered range and the end point of distillation is shifted to higher temperatures. This agrees with the results from gas-chromatographic analysis which show that HVO contains more high boiling compounds than a typical Jet A-1 sample.

With increasing HVO content, the curve of the respective blend more and more resembles that of neat HVO. Since the measurements show that the curves of the blends lie between those of the neat blend components, one can assume that as long as the blend components themselves fulfil the requirements according to ASTM D1655 and ASTM D7566, the blends do as well regardless of the blend ratio.



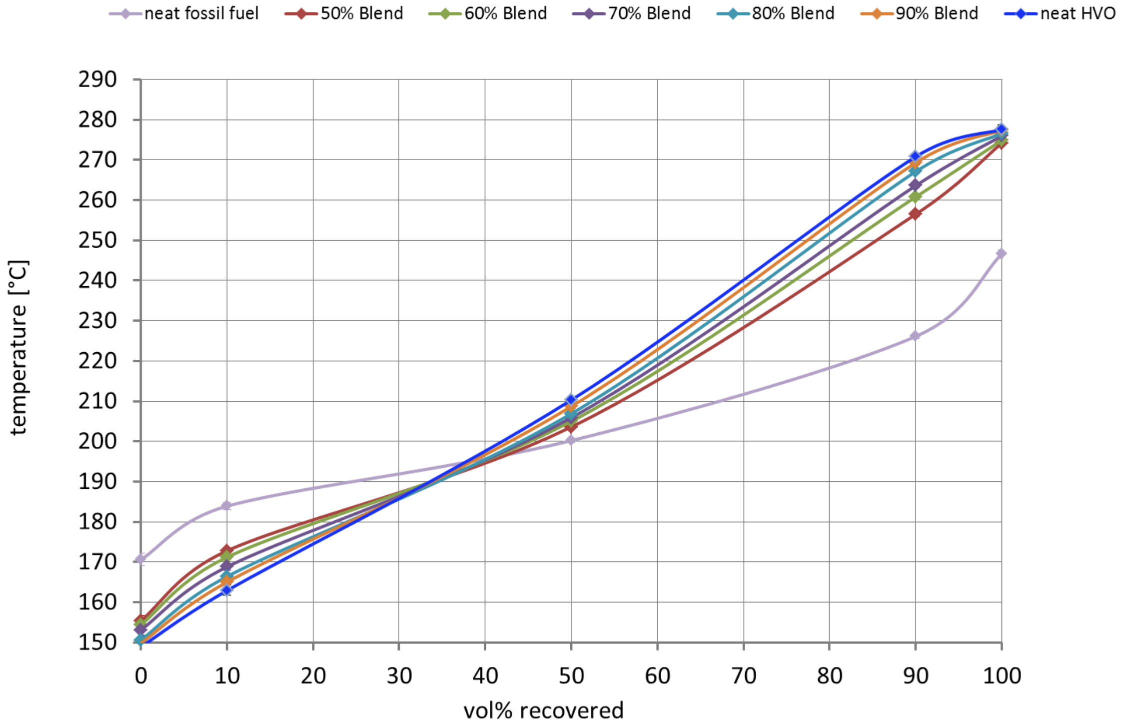


*Figure 21: Distillation curves of neat HVO, fuel 085 and respective blends with 50 – 90 vol% HVO (top) and neat HVO, fuel 112 and respective blends with 50 – 90 vol% HVO (bottom)*

## Flash Point

For discussion of flash point, HVO blends of fuels 085 and 112 have been chosen. HVO exhibits a flash point of 42.0 °C which lies close to that of fuel 085 (40.5 °C). Fuel 112 has the highest flash point among the fossil fuels chosen for this study (53.0 °C). The flash points of the respective HVO-blends lie within the interval between the flash points of the neat blend components and can therefore be estimated from these latter values (Figure 22).

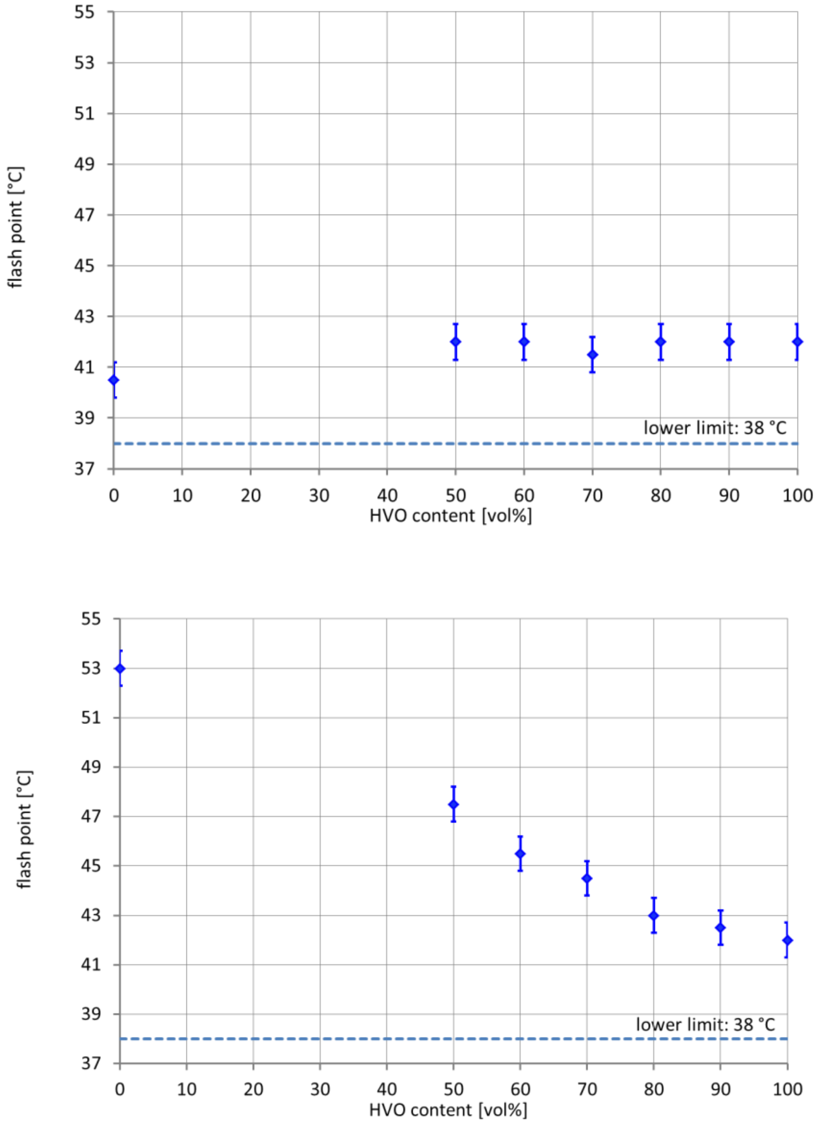
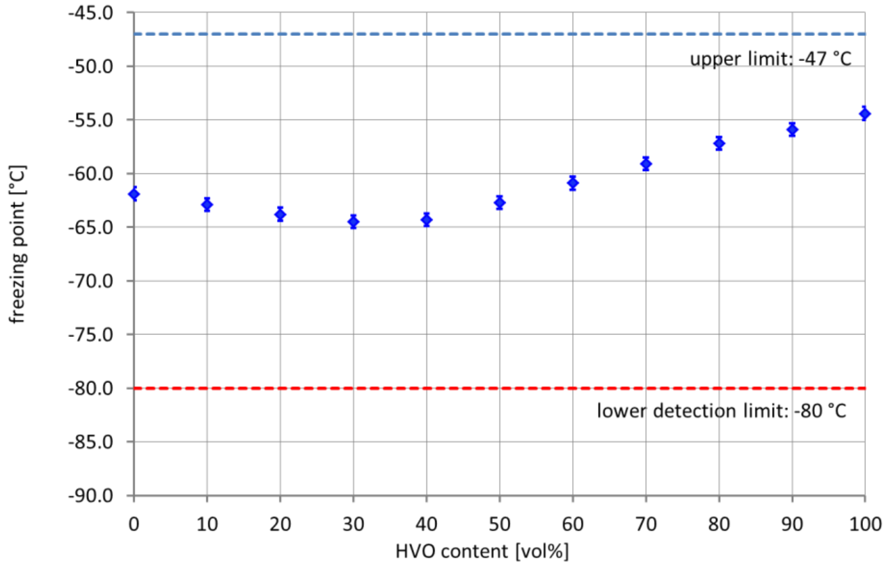


*Figure 22: Flash points of neat HVO, fuel 085 and respective blends with 50 – 90 vol% HVO (top) and neat HVO, fuel 112 and respective blends with 50 – 90 vol% HVO (bottom)*

## Freezing Point

The dependency of freezing point on blend ratio will be discussed using two examples where (i) freezing points of the jet fuel and HVO only slightly differ and (ii) freezing points of the jet fuel and HVO differ significantly (Figure 23).



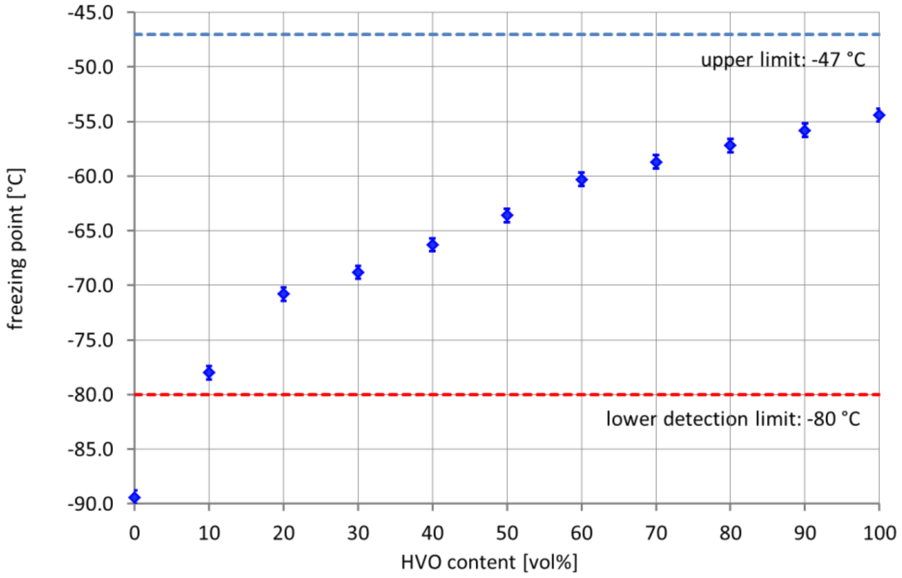


*Figure 23: Freezing points of neat HVO, fuel 123 and respective blends with 10 – 90 vol% HVO (top) and neat HVO, fuel 112 and respective blends with 10 – 90 vol% HVO (bottom)*

Upon blending fuel 123 (freezing point: -61.9 °C) with HVO (freezing point: -54.4 °C), an initial lowering of the freezing point to a minimum of -64.5 °C (HVO content: 30 vol%) was observed, although HVO exhibits a higher freezing point than the jet fuel. The resulting curve remotely resembles the phase diagram of an eutectic mixture. Nevertheless, comparing the observed behaviour to that of an eutectic mixture is doubtful because the investigated blends are complex multicomponent systems and, furthermore, because of the definition of the freezing point for aviation fuels. It is determined by cooling the fuel until the appearance of hydrocarbon crystals followed by heating the sample. The temperature at which the last crystal disappears is defined as the freezing point of the aviation fuel. This differs from the physical definition of the freezing point which is the temperature of phase transition between liquid and solid.

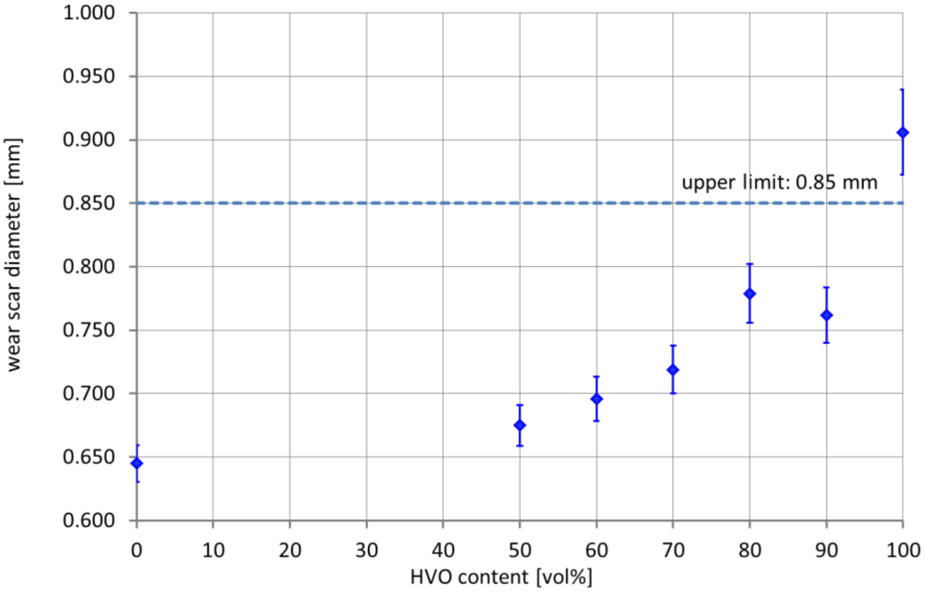
The freezing point of fuel 112 (-89.4 °C) is far below that of HVO. Because of this pronounced difference, the initially observed effect of depression of the freezing point for the blends cannot be observed. Yet, the slope of the resulting freezing point vs. blend ratio curve shows a deviance in the 20 - 50 vol% HVO interval.

In case of the blends with the other fossil fuels (085, 114, 117), depression of the freezing point at a certain blend ratio can be observed as well. As the examples in Figure 23 show, the effect is all the more pronounced, the more similar the freezing points of fossil fuel and HVO are.

**Lubricity**

With a wear scar diameter (wsd) of 0.906 mm neat HVO exceeds the upper limit of 0.85 mm for Jet A-1 and blends. To discuss the influence of HVO on lubricity, blends with Jet A-1 samples 112 and 123 have been chosen. Fuel 112 offers the best lubricity among the fuels used in this study (wsd = 0.645 mm), fuel 123 the worst (wsd = 0.751 mm). Figure 24 shows the dependence of lubricity on blend ratio. In the case of fuel 112 an expected worsening in lubricity by increasing the amount of HVO is observable. Yet, from the data no exact correlation between HVO content and lubricity can be drawn. For HVO-blends with fuel 123 lubricity vs. blend ratio shows no clear trend as well. Yet, the possible worsening of lubricity upon increasing the amount of HVO seems to be compensated by the fossil fuel, even for high HVO contents. As already mentioned, this observation could be explained by lubricity being a surface related effect, which is strongly influenced by the presence of minor compounds.

Lubricity curves of HVO-blends with the other fossil fuels qualitatively resemble those shown in Figure 24.



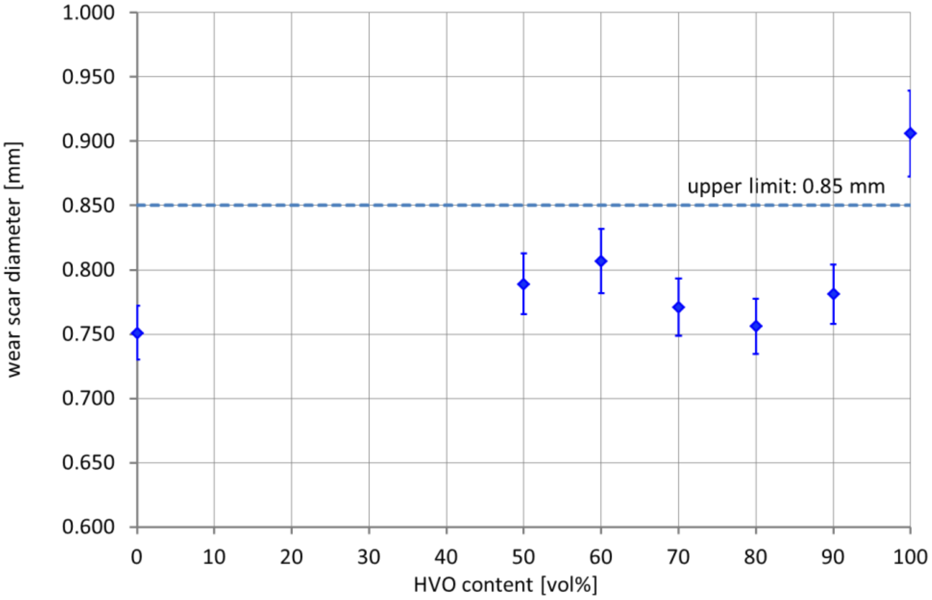


*Figure 24: Lubricity expressed as wear scar diameter for neat HVO, fuel 112 and respective blends with 50 – 90 vol% HVO (top) and neat HVO, fuel 123 and respective blends with 50 – 90 vol% HVO (bottom)*

**Smoke Point**

The smoke point of neat HVO exceeds the upper detection limit of the method. This is not surprising, since HVO lacks aromatic compounds which significantly contribute to soot formation. Therefore, incorporation of HVO into Jet A-1 in general leads to a non-linear improvement of the smoke point as exemplified in Figure 25.

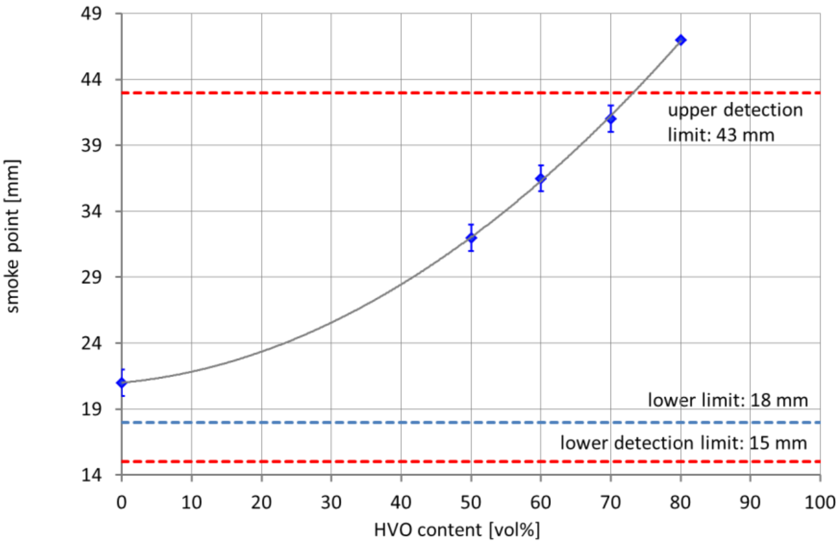


*Figure 25: Smoke points for neat fuel 112 and respective blends with HVO. The value for the 80 vol% blend exceeds the upper detection limit of the method and therefore lacks accuracy. Hence, values for 90 vol% blend and neat HVO have not been determined.*

### 4.2.3 Blends of CTL with Jet A-1

Like HVO, CTL is free of aromatic compounds and solely consists of n-alkanes and iso-alkanes. According to gas-chromatography, the content of n-alkanes is lower than in HVO. Furthermore, the CTL investigated here has a narrower boiling range than fossil Jet A-1. The gas-chromatograms of CTL and a typical fossil Jet A-1 are superimposed in Figure 26.

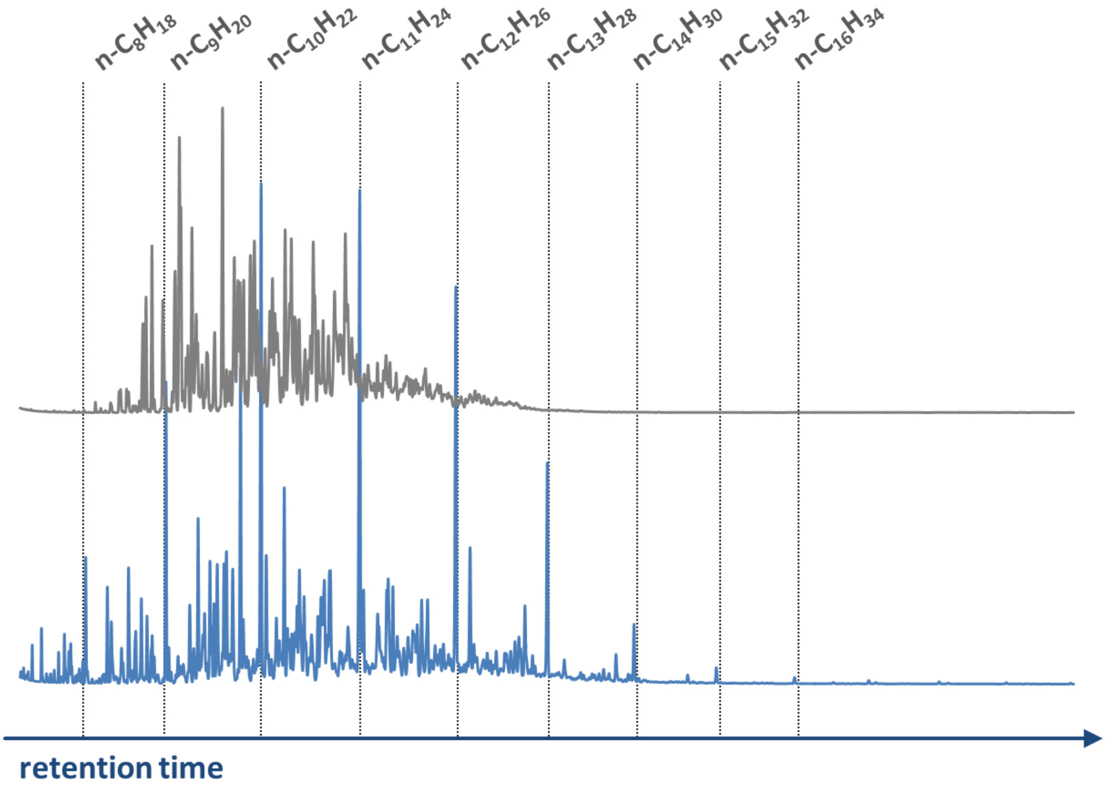


*Figure 26: Gas-chromatograms of CTL (top) and a typical fossil Jet A-1 fuel (bottom)*

**Density**

Like Farnesane- and HVO-blends, those with CTL display a linear relationship between blend ratio and density. Hence, parameters which describe concentrations, e.g. aromatic and sulphur content, are expected to show linear dependence on blend ratio as well which has been verified by sporadic measurements.

Since the density of neat CTL (761.2 kg/m³) falls below the lower limit for blends (775 kg/m³), the maximum content of CTL in the mixtures is limited and depends on the initial density of the fossil fuel. For the Jet A-1 fuels employed in this study the limit varies between ca. 50 and ca. 75 vol% CTL. Table 3 shows the maximum content of CTL, for which the respective blends reach the lower limit for density of 775 kg/m³.

| Jet A-1 fuel | density ($\rho$) of neat Jet A-1 [kg/m³] | CTL content for which $\rho$ = 775 kg/m³ |
|---|---|---|
| 085 | 797.5 | 62 vol% |
| 112 | 818.6 | 76 vol% |
| 114 | 795.0 | 59 vol% |
| 117 | 811.7 | 73 vol% |
| 123 | 789.0 | 50 vol% |

*Table 3: Calculated CTL content for which density of the respective blends with Jet A-1 reach the lower limit of 775 kg/m³*

### Lubricity

In line with the previous results on lubricity of fossil / synthetic fuel blends, no unitary trend with respect to blend ratio can be observed. Yet, all blends meet the requirement for lubricity. Two examples of CTL blends were chosen to visualize this finding (Figure 27).

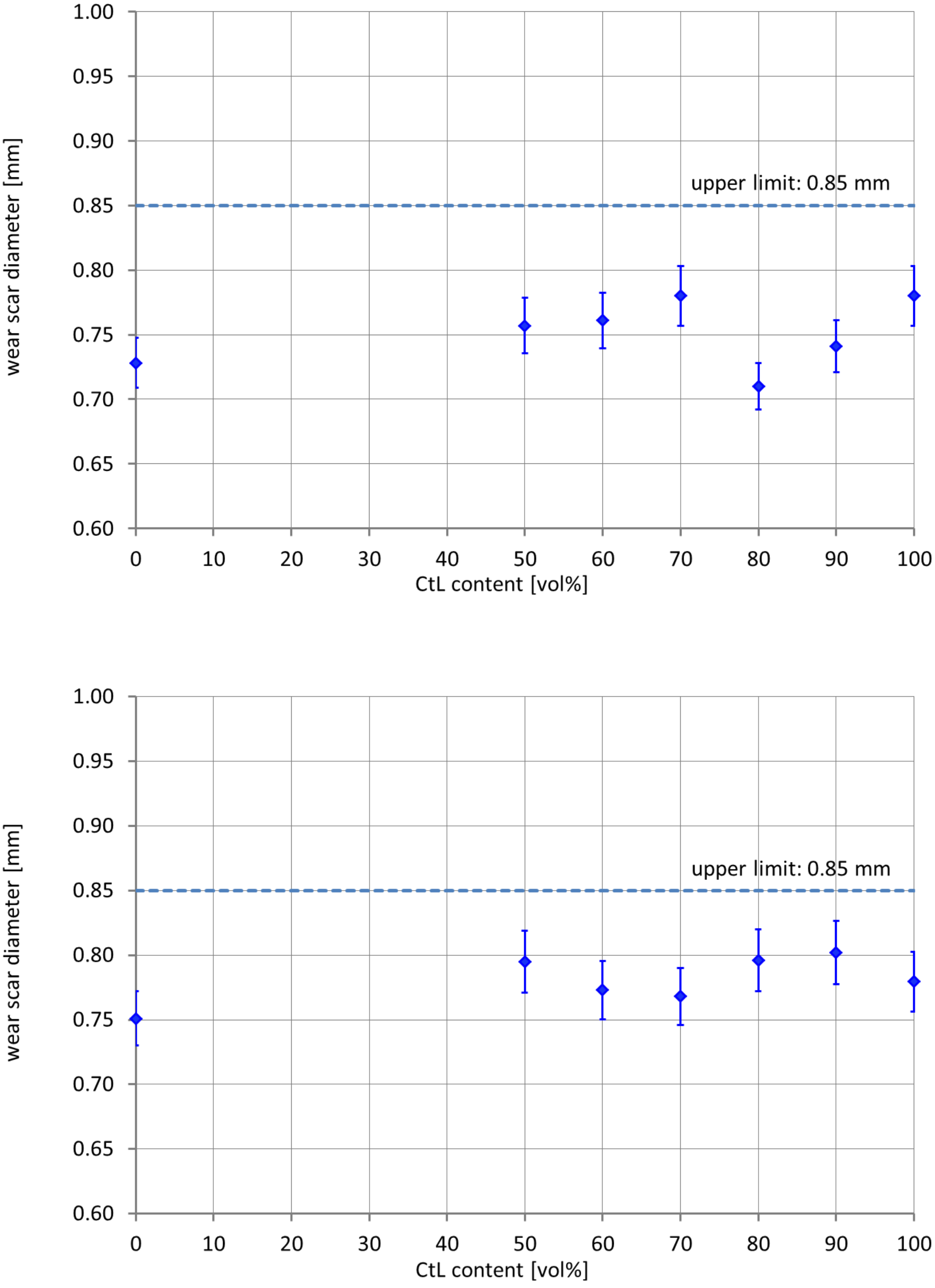


*Figure 27: Lubricity expressed as wear scar diameter for neat CTL, fuel 114 and respective blends with 50 – 90 vol% CTL (top) and neat CTL, fuel 123 and respective blends with 50 – 90 vol% HVO (bottom)*

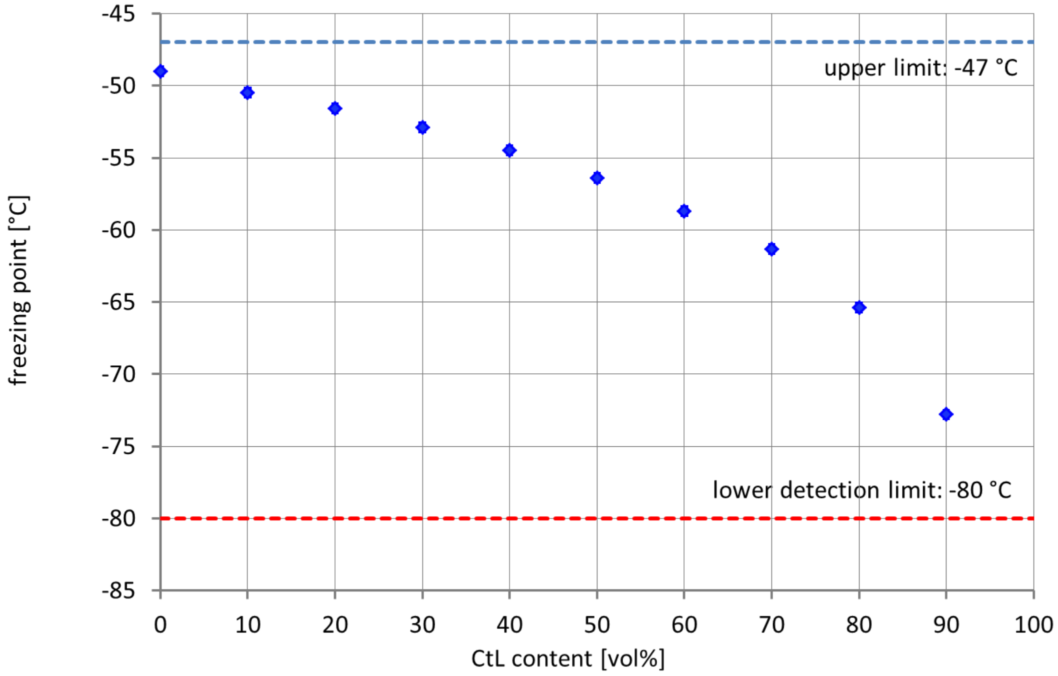
### Freezing Point

The freezing point curves of CTL blends with fossil fuels 114 and 117 are shown in Figure 28. Given that the chemical composition of CTL is quite similar to that of HVO, the question arises, whether a comparable depression of freezing point at a certain blend ratio occurs here as well.

Unlike HVO, the freezing point of CTL lies significantly below that of the fossil fuel. Therefore, due to the steep progression of the freezing point curves and the relatively rough 10 vol% increment, minor deviations in freezing point are hard to observe. At most, in the case of fuel 117 a slight irregularity in curve progression (10 – 40 vol% interval) can be spotted. However, these observations surely have no meaning for practical applications. Given that the freezing point of the neat CTL lies well below the upper limit for jet fuel, it can be assumed that any blends of specification compliant fossil kerosene with CTL will meet the requirements of ASTM 7566 regardless of the blend ratio.

### Thermal Stability

It turns out that neat CTL does not meet the specification limits regarding thermal stability with a pressure drop of 280.0 mm Hg (max. 25 mm Hg acc. to ASTM D7566). As requested by ASTM D7566 thermal stability for neat CTL was determined at 325 °C. However, all blends with CTL comfortably meet the specified requirements regarding thermal stability which might be due to the fact that thermal stability for blends is determined at 260 °C, in accordance with ASTM D7566.



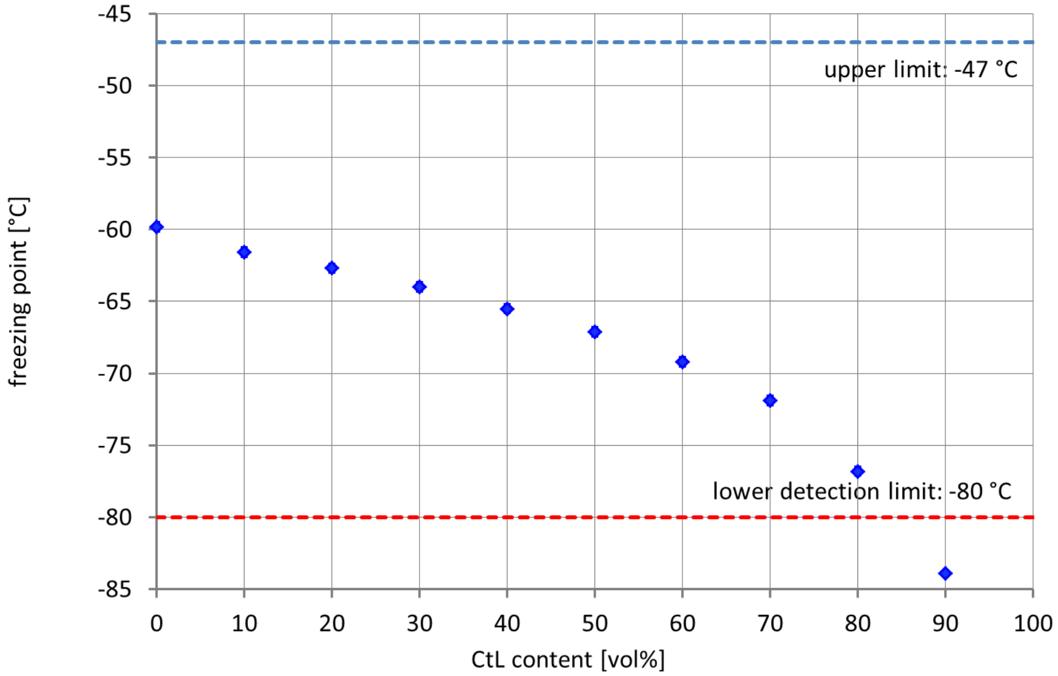


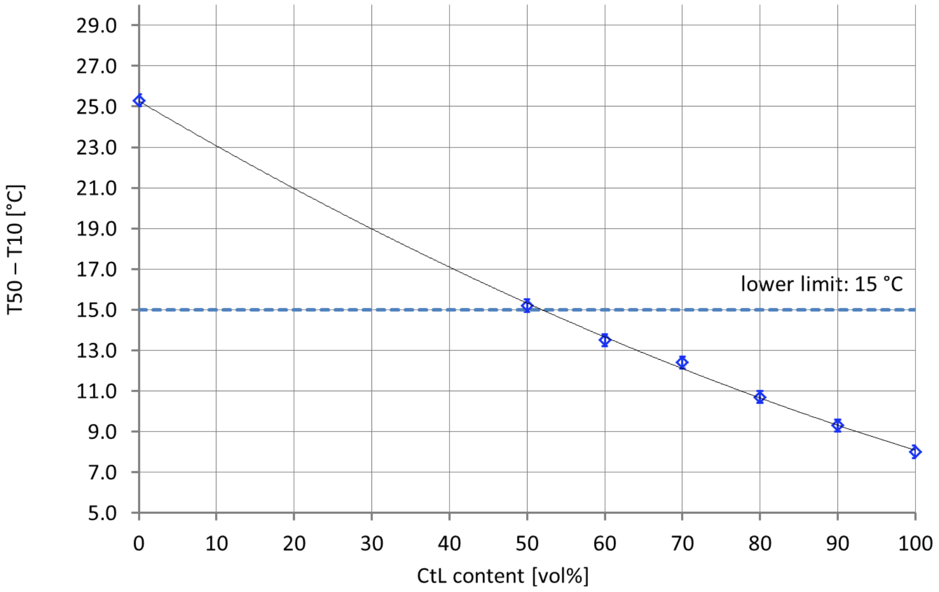
*Figure 28: Freezing points of neat CTL, fuel 114 and respective blends with 10 – 90 vol% CTL (top) and neat CTL, fuel 117 and respective blends with 10 – 90 vol% HVO (bottom)*

### Smoke Point

Since CTL lacks aromatic compounds it has a high smoke point and therefore incorporation of CTL into fossil fuel leads to improvement of smoke point.

**Distillation**

The parameter T50-T10 describes the slope of the distillation curve in the low temperature region and is limited to a minimum of 15 °C. Since T50–T10 of the neat CTL (8.0 °C) is far below the lower limit (15 °C) this parameter becomes critical if the synthetic fuel exhibits a flat distillation curve itself. Figure 29 shows the T50-T10 values as a function of the blend ratio.



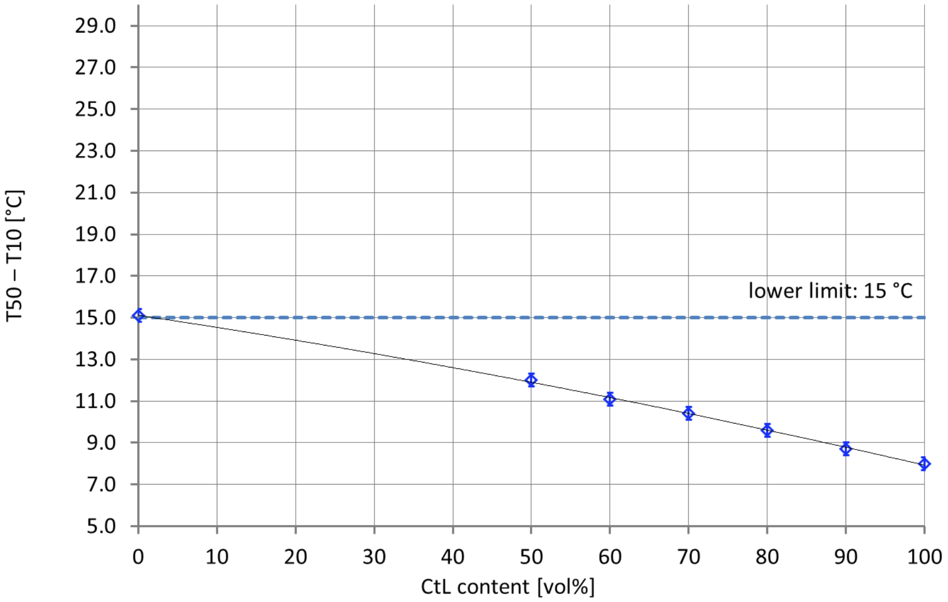


*Figure 29: T50–T10 of neat CTL, fuel 114 and respective blends with 10 – 90 vol% CTL (top) and neat CTL, fuel 123 and respective blends with 10 – 90 vol% CTL (bottom)*

In the case of fuel 114 (Figure 29, top) the limit is reached at approximately 50 vol% synthetic fuel, whereas fuel 123 hardly allows incorporation of CTL at all. The maximum blend ratio can roughly be estimated from T50-T10 values of the neat blend components assuming linear dependency of T50-T10 on blend ratio, although in reality the dependency is not strictly linear.

### 4.2.4 Blends of CH kerosene with Jet A-1

CH kerosene is designed as a fully synthetic fuel, which as a neat fuel meets all the specification requirements for conventional kerosene. It was therefore expected that all blends with conventional kerosene would also meet the specification requirements, hence only a limited set of analyses was conducted using single conventional kerosene. The purpose was to explore the dependence of selected parameters on blend ratio. Fuel 112 was chosen as the conventional fuel to blend with as it has a particularly low freezing point, and therefore differs from the CH kerosene sample. Unlike the other neat bio kerosene, which typically showed freezing points similar to or lower than those of the conventional kerosene, the CH kerosene sample has been manufactured to fulfil Jet A standards and therefore does not meet the Jet A-1 specification requirement of a maximum freezing point of -47 °C.

The CH kerosene sample ReadiJet is a synthetic jet fuel consisting of n- and iso-paraffins, cycloparaffins as well as aromatic compounds (19.7 vol%). Among the latter, alkyl benzenes, indanes, tetrahydronaphthalenes and naphthalines were found. However, the content of naphthalenes is low (0.35 vol%). With this composition, the fuel closely resembles the chemical composition of fossil fuels. Gas chromatograms of the CH kerosene sample, and of a conventional Jet A-1 fuel are superimposed in Figure 30.

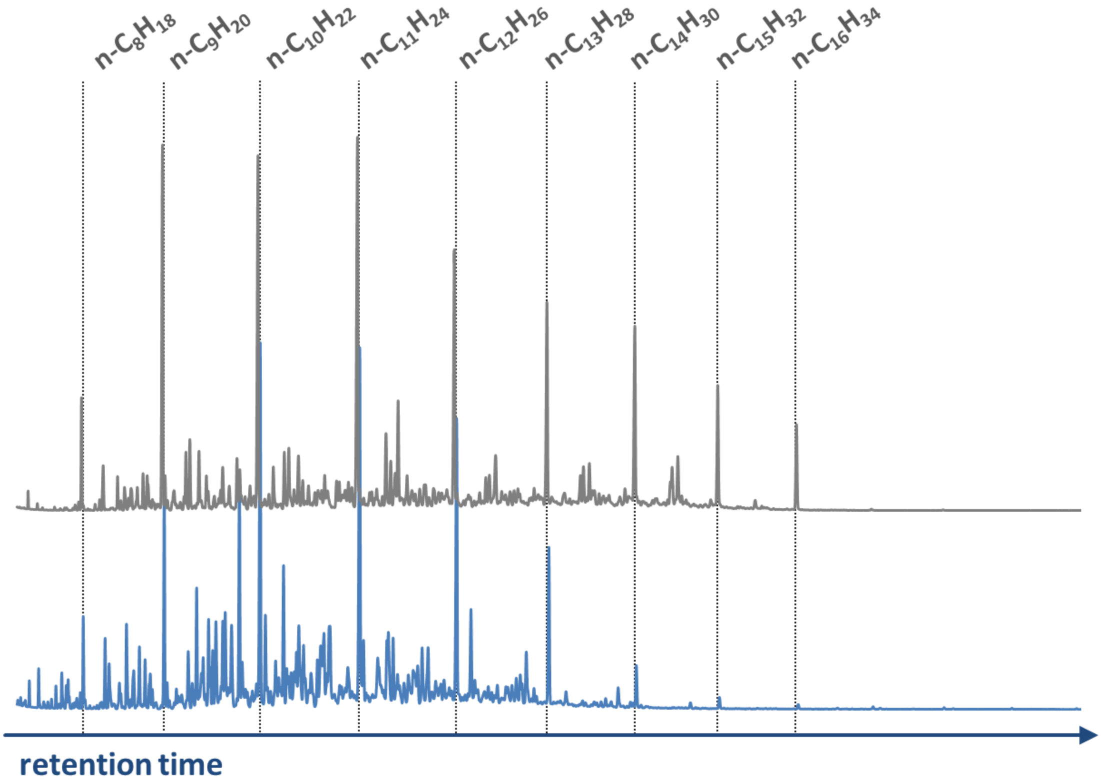


*Figure 30: Gas-chromatograms of CH kerosene (top) and a typical fossil Jet A-1 fuel (bottom)*

### Density

The density of ReadiJet (805.2 kg/m³) is close to that of the fossil fuel (818.6 kg/m³) and the dependence of density on blend ratio is - as expected - strictly linear. Parameters describing contents can therefore be calculated which has been verified in respective measurements.

### Distillation

The 50 vol% recovery points of the CH kerosene (200.2°C) and of the conventional kerosene 112 (200.1°C) are nearly identical, so that the 50 vol% recovery points for all blends are as well (Figure 31). For initial boiling point, 10 vol% and 90 vol% recovery points and final boiling point, values for the blends depend linearly on blend ratio. As the CH kerosene's distillation curve has a sufficient slope, the T50-T10 and T90-T10 limits are never an issue, and T50-T10 and T90-T10 of the fossil fuel are actually improved upon blending with CH kerosene.

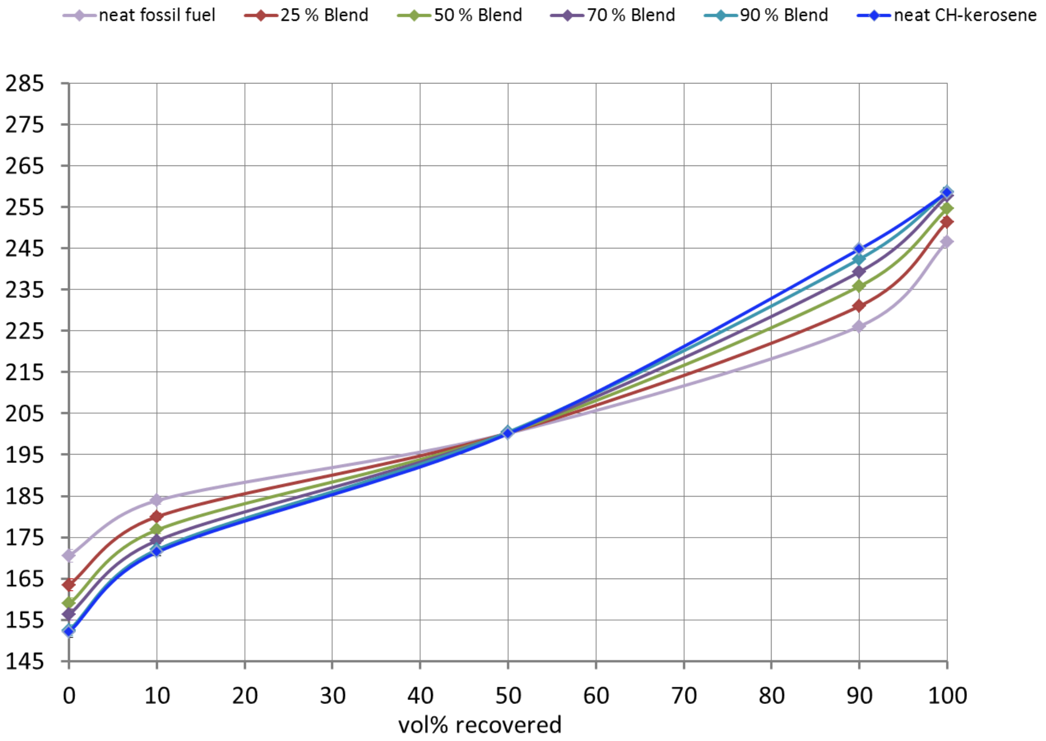


*Figure 31: Distillation curves of neat CH kerosene, fuel 112 and respective blends with 25, 50, 70 and 90 vol% CH kerosene*

### Freezing Point

As discussed, the freezing point of pure ReadiJet (-41.3 °C) exceeds the upper limit for Jet A-1 (-47 °C). It needs to be emphasized that this batch of CH kerosene has been produced to meet the Jet A standard. However, the process is also capable of producing fuel that meets the freezing point requirement for Jet A-1, and such fuel was sourced later for the emissions tests described in section 7.2.

The freezing point curve - here for blends with a Jet A-1 featuring a very low freezing point - (Figure 32) shows an irregularity in the 50 vol%-region, where the freezing point is close to the value of the 35 vol% blend. This finding agrees with similar observations for other synthetic fuel blends. However, depression of freezing point is favourable, since it is only limited to an upper value.

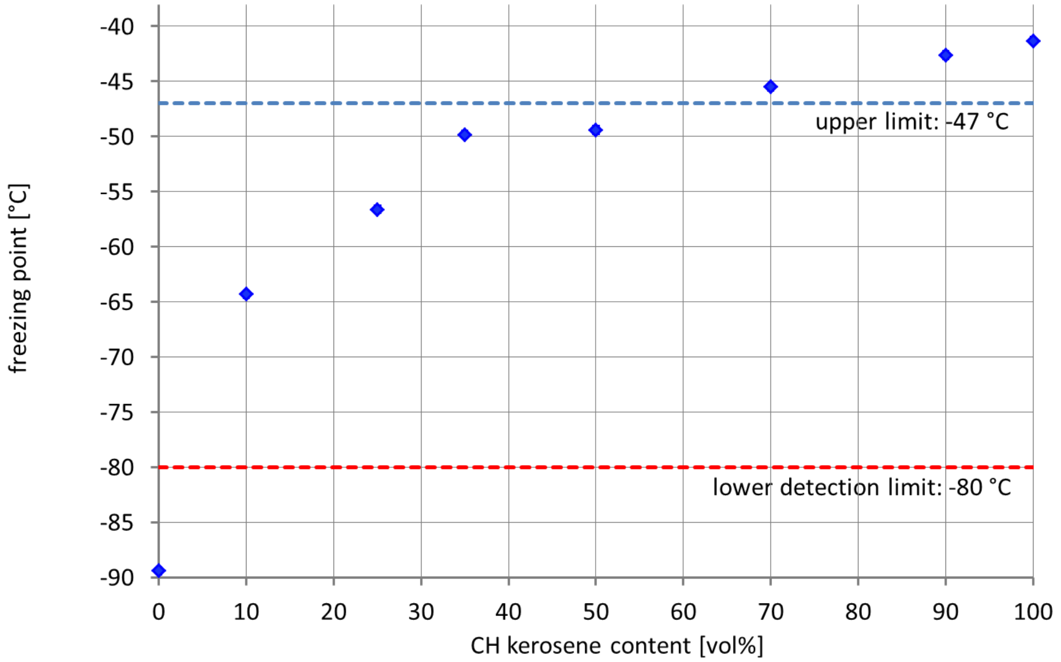


*Figure 32: Freezing points of neat CH kerosene, fuel 112 and respective blends with 10 – 90 vol% CH kerosene*

**Lubricity**

For all examined blends, lubricity values are better than the lubricity values of either the neat CH kerosene or the neat fossil kerosene (Figure 33). This is a favourable outcome, but confirms previous observations for other blends that lubricity is hard to predict from the values of the neat blend components and needs to be determined experimentally.

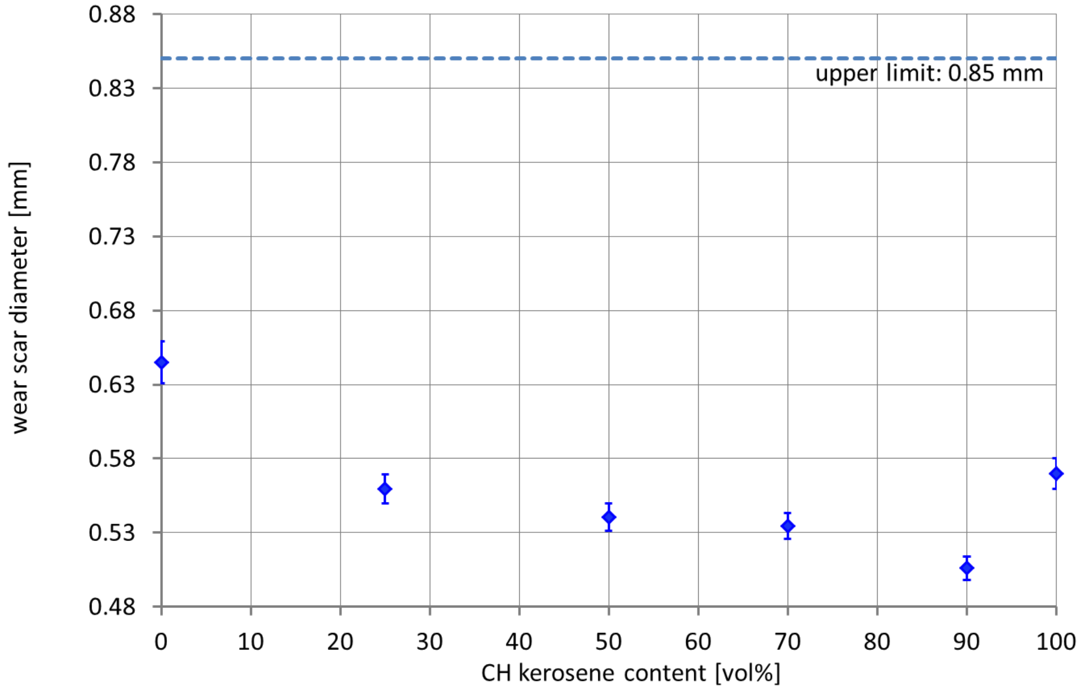


*Figure 33: Lubricity expressed as wear scar diameter for neat CH kerosene, fuel 112 and respective blends*

### 4.2.5 Blends of ATJ-SPK with Jet A-1

Alcohol-to-Jet fuels are produced from $C_2$ to $C_6$ alcohols that are accessible biotechnologically, e.g. by fermentation. After dehydration of the alcohols, the resulting alkenes are oligomerised. These higher olefins are then hydrogenated to produce iso-alkanes. It is in principle also possible to produce aromatic compounds from the alkene intermediates, but ATJ-SPK is by specification essentially free of aromatic compounds. In the case of the Gevo fuel produced from isobutanol, ATJ-SPK consists essentially of two iso-alkanes, namely 2,2,4,6,6-pentamethylheptane and 2,2,4,4,6,8,8-heptamethylnonane, where the former is the major compound. Gas-chromatograms of ATJ-SPK and a typical fossil fuel are shown in Figure 34.

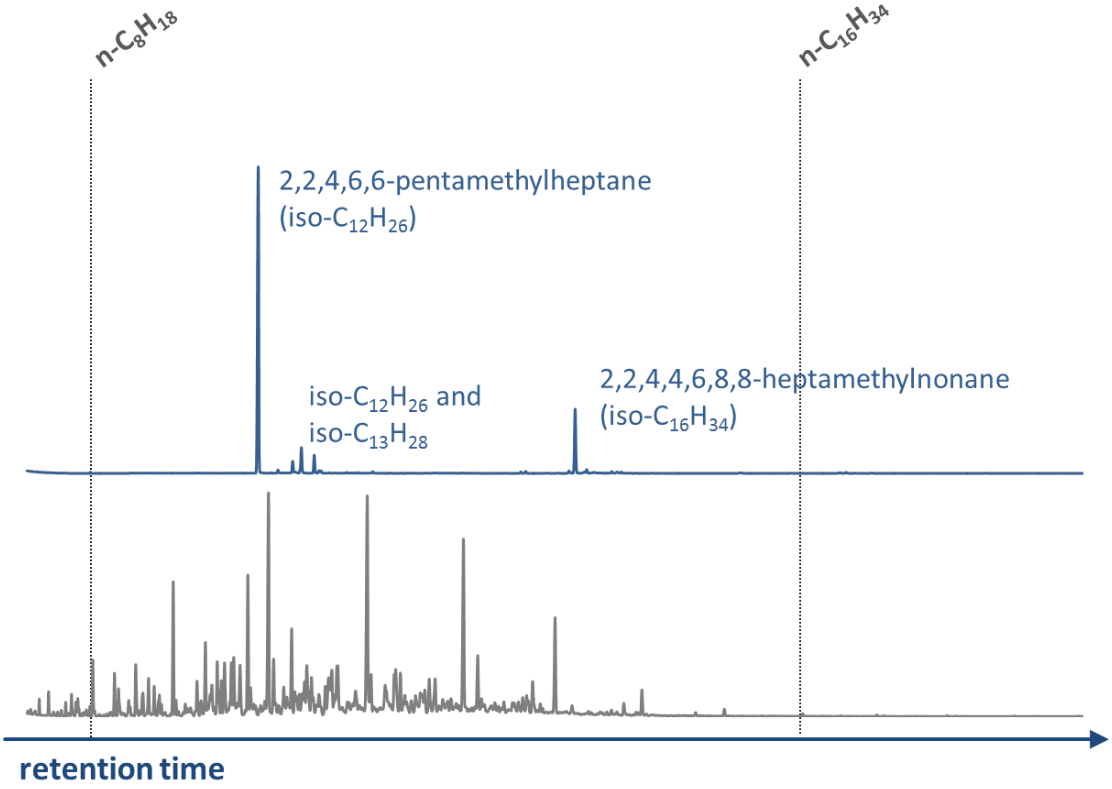


*Figure 34: Gas-chromatograms of ATJ-SPK (top) and a typical fossil Jet A-1 fuel (bottom)*

**Density**

For fossil fuel blends with ATJ-SPK, dependency of density on blend ratio is again strictly linear and therefore other parameters describing contents can readily be calculated from initial values of the blend components. Since density of ATJ-SPK (757.1 kg/m³) falls below the lower limit (775 kg/m³), the maximum blend ratio regarding ATJ-SPK is limited; for the fuels included in the study, the limits range from ca. 40 vol% to ca. 70 vol%.

**Distillation**

The ATJ-SPK fuel has a remarkably flat distillation curve (T50-T10 = 2.9 °C) as compared to that of a fossil fuel, which is far below the lower limit for blends (15 °C). Upon increasing the amount of ATJ-SPK in the blend, the shapes of the respective blends´ distillation curves converge to that of neat ATJ-SPK (Figure 35). Therefore the maximum ATJ-SPK content is limited and can be very low, if the fossil fuel features a flat distillation curve as well. For four of the fossil fuels included in the study, the maximum blend ratio ranges between 10 – 40 vol% ATJ-SPK. Yet, in the case of fuel 123, blending with ATJ-SPK is not allowed at all, since T50-T10 of this fossil fuel (15.1 °C) is already very close to the limit for blends. However, it should be noted that for neat fossil fuels T50-T10 is not specified.

As will be discussed in the conclusions (chapter 8), the question can be raised how useful the T50-T10 and T90-T10 limits actually are. However, as long as the requirement exists it will be a major limiting factor for blending ATJ-SPK.

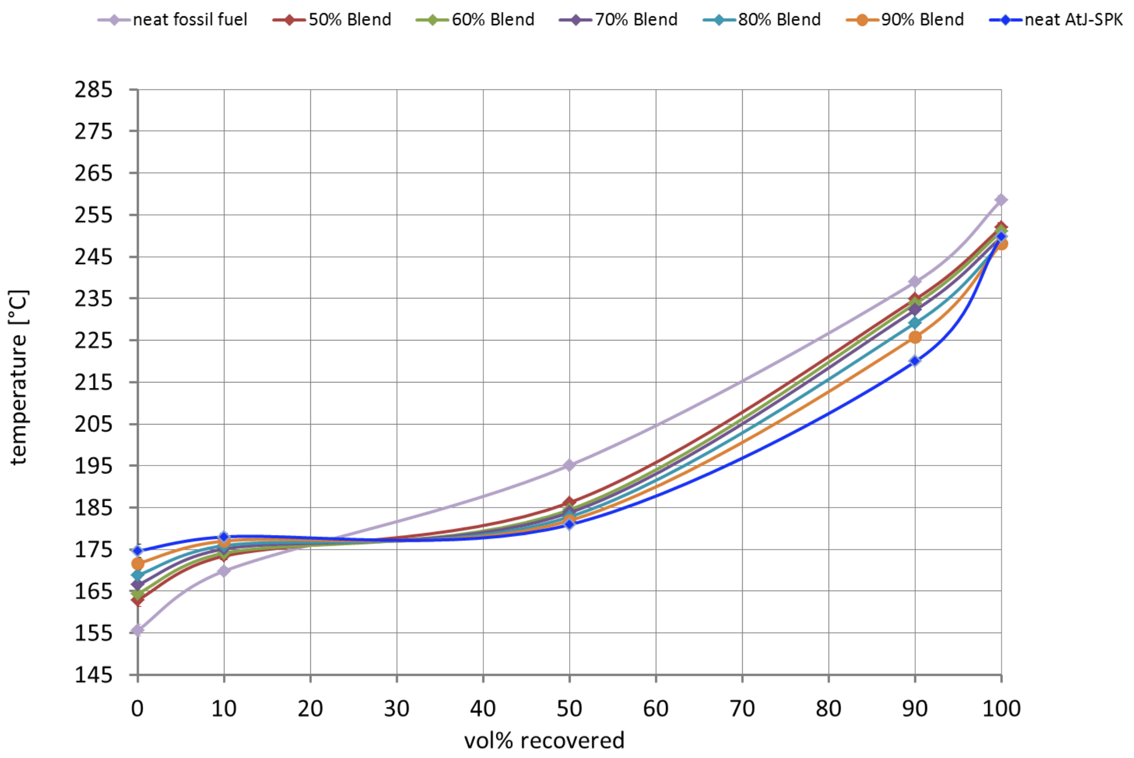
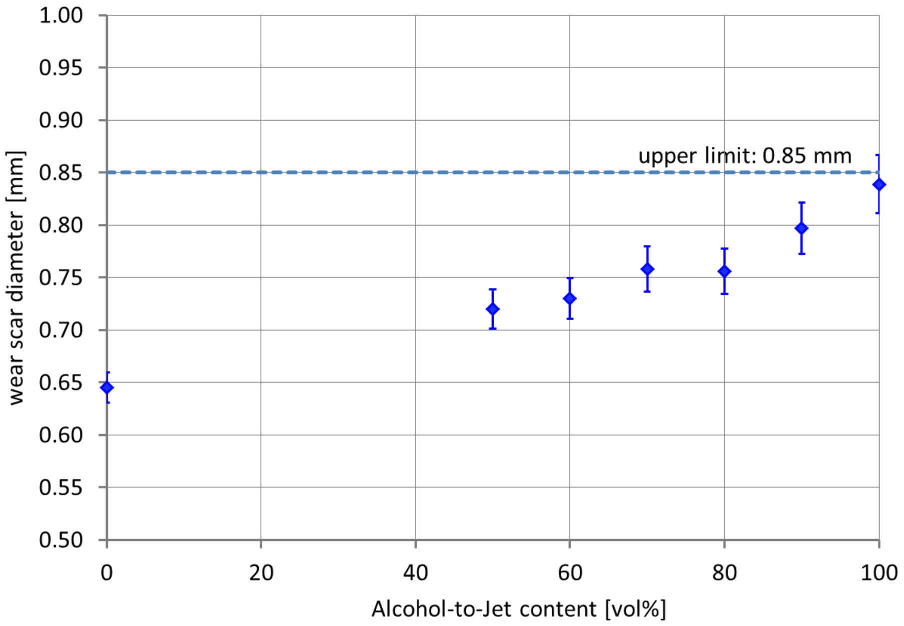


*Figure 35: Distillation curves of ATJ-SPK, fossil fuel 114 and their blends with 50 – 90 vol% ATJ-SPK*

## Lubricity

The dependence of lubricity on ATJ-SPK content will be discussed using two examples (Figure 36) which illustrate the different characteristics found for lubricity curves. On the one hand, a roughly linear dependency of lubricity on ATJ-SPK content can be found (Figure 36, top), on the other hand, lubricity behaves completely unpredictable (Figure 36, bottom). This again confirms previous observations which point out that special attention on this parameter has to be paid in practice. Yet, for ATJ-SPK blends of all fossil fuels included in the study, values for lubricity lie within the interval defined by the neat blend components.



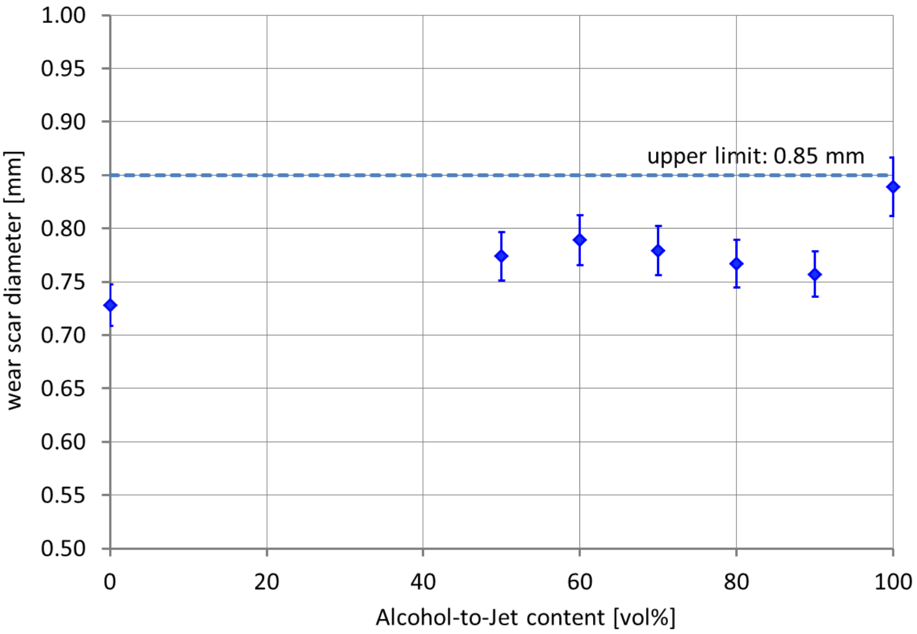


*Figure 36: Lubricity expressed as wear scar diameter for neat ATJ-SPK, fuel 112 and respective blends with 50 – 90 vol% ATJ-SPK (top) and neat ATJ-SPK, fuel 114 and respective blends with 50 – 90 vol% ATJ-SPK (bottom)*

### 4.2.6 Blends of ATJ-SKA with Jet A-1

ATJ-SKA is designed as a fully synthetic fuel, which as a neat fuel meets all the specification requirements for conventional kerosene. It was therefore expected that all blends with conventional kerosene would also meet the specification requirements. Hence, only a limited set of analyses was conducted. Because the neat ATJ-SKA sample did not meet the T50-T10 and T90-T10 requirements of ASTM D7566, for blending the fossil fuels 085 and 114 were selected. Fuel 114 is the fuel with the highest gradient of the distillation curve, and fuel 085 is the one with the lowest. For fuel 085 only a single blend at 50 vol% was analysed to investigate the shape of the resulting distillation curve, whereas the main analysis focused on blends with fuel 114.

Gas chromatograms of ATJ-SKA and a typical fossil Jet A-1 fuel are superimposed in Figure 37. ATJ-SKA contains n-alkanes and iso-alkanes, in which those with boiling points close to that of n-undecane ($C_{11}H_{24}$) occur in comparatively high amounts; minor amounts of cycloalkanes can be found as well. The sample has an aromatic content of 15.8 vol%, while the spectrum of aromatic compounds is more limited than in the CH kerosene sample (4.2.4). The aromatics consist mainly of alkyl benzenes, indanes and tetrahydronaphthalenes. The content of naphthalenes (0.080 vol%) is low.

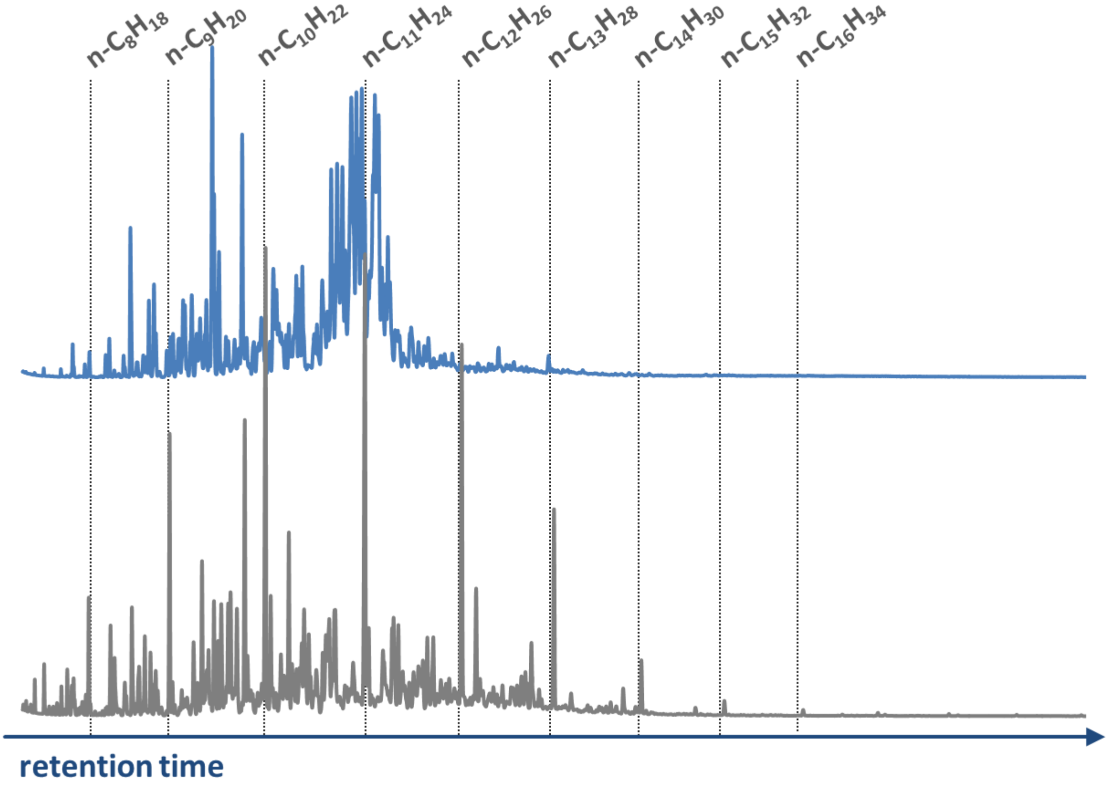


*Figure 37: Gas-chromatograms of ATJ-SKA kerosene (top) and a typical fossil Jet A-1 fuel (bottom)*

**Distillation**

Distillation curves of ATJ-SKA blends with fossil fuel 114 are shown in Figure 38.

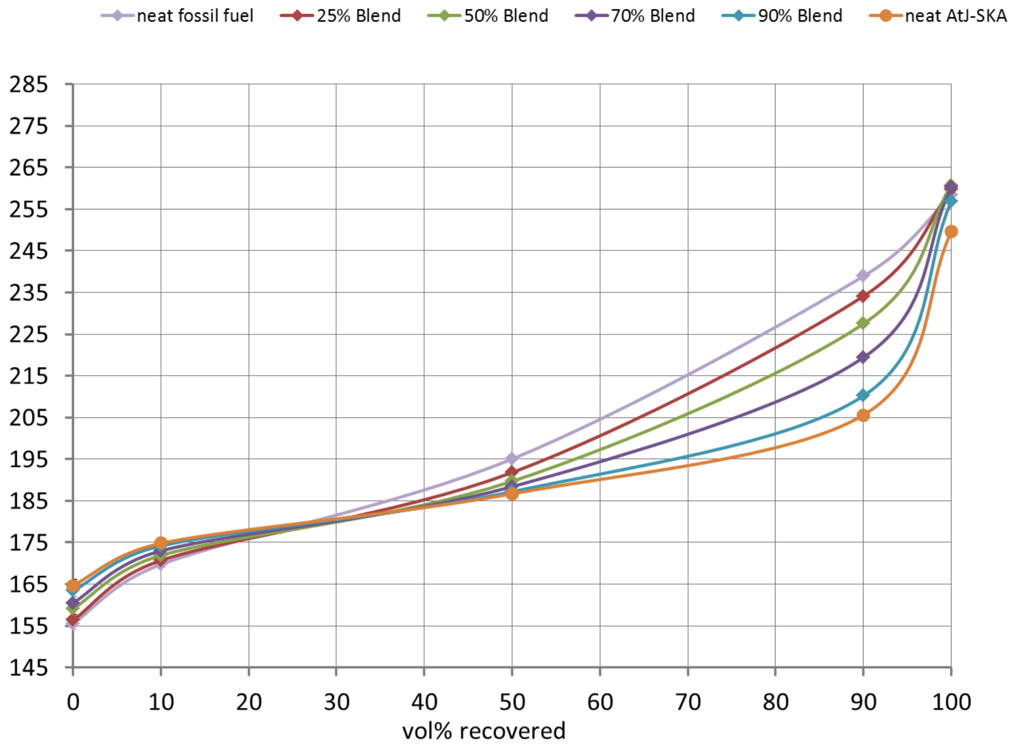


*Figure 38: Distillation curves of ATJ-SKA, fossil fuel 114 and their blends with 25, 50, 70, 90 vol% ATJ-SKA*

Distillation start and end points of ATJ-SKA lie close to those of the fossil fuel. However, in the 10 to 90 vol% interval, the gradient of the ATJ's curve is low, followed by a late steep increase in the 90 to 100 vol% interval. Regarding the T50-T10 values, maximum blend ratio is therefore limited to approximately 70 vol%. T90-T10 is an issue as well, although here, the limit for blend ratio lies between 80 and 90 vol% synthetic fuel so that T50-T10 is the more critical parameter.

The distillations curves of neat ATJ SPK (Figure 35) as well as neat ATJ-SKA are both rather flat at the start of the distillation, so that T50-T10 constitutes a limiting factor in either case. Yet, T90-T10 is only limiting for ATJ-SKA because of the late rise of the curve's gradient.

For blends with fuel 085, which has a flat distillation curve itself, distillation curve gradients are more of a constraint. Here, both the T50-T10 and the T90-T10 for the 50 vol% blend are barely above the specification minimum, hence blend ratios above 50 vol% can be expected to be largely off-spec.

For ATJ-SKA with distillation curves similar to the sample provided, T50-T10 and T90-T10 will severely limit maximum blend ratios. However, the manufacturer has since provided documentation showing that it is also possible to produce this fuel with a steeper distillation curve gradient.

## Lubricity

Lubricity of the neat ATJ-SKA (wsd = 0.606 mm) is already quite good (Figure 39) and in fact better than that of the fossil fuel 114 (0.728 mm). In this case, lubricity of all blends lies within the interval of values for the neat blend components. However, improvement of lubricity upon incorporation of ATJ-SKA becomes evident only at high blend ratios regarding ATJ-SKA. At low blend ratios, the positive influence on lubricity is weak.

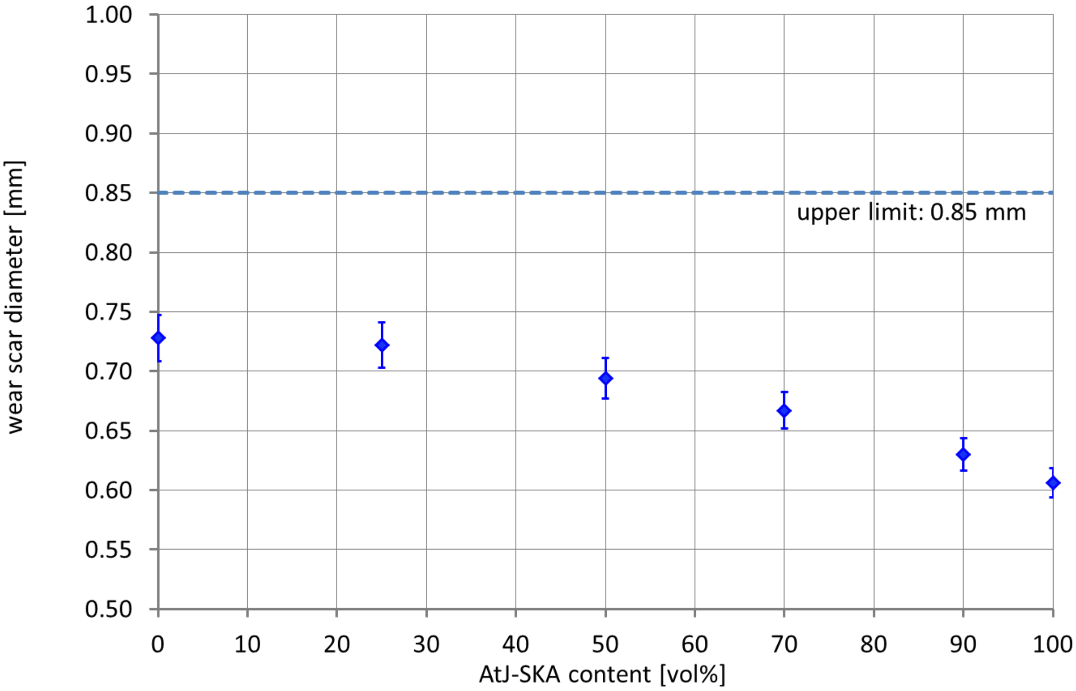


*Figure 39: Lubricity expressed as wear scar diameter for neat ATJ-SKA, fuel 114 and respective blends*

## 4.3 Summary

The summary concentrates on parameters which have proven to be of special interest with respect to the evaluation of alternative fuel blends.

### Density

For all blends density linearly depends on blend ratio and no anomalies for instance due to volume contraction are observed. Thus, fuel properties describing contents can be calculated from the respective values of the neat blend components.

Upon comparing the major groups of chemical components found in conventional fuels, density increases in the order alkanes < cycloalkanes < aromatics. Therefore, fuels consisting only of n- and iso- alkanes have low densities. For example HEFA ($\rho_{HEFA}$ = 756.7 kg/m³) blends become off-spec at blend ratios between 43 vol% and 71 vol% HEFA. CTL has a slightly higher density of 761.2 kg/m³ and here maximum CTL contents between 62 and 76 vol% are possible. In the case of SIP fuel (Farnesane), which consists only of a single iso-alkane compound, namely 2,6,10-trimethyl dodecane, density is however quite high ($\rho_{Farnesane}$ = 773.1 kg/m³) and only slightly below the lower limit for synthetic fuel blends (775 kg/m³). Hence, regarding the density restriction, blends with maximum SIP contents of > 80 vol% are possible. Densities of CH kerosene and ATJ-SKA are 805.2 kg/m³ and 785.9 kg/m³, respectively, and above the lower limit for blends. Here, the density constraint is not an issue.

### Aromatic content

This value can be calculated from the value of the neat blend components and the blend ratio. For synthetic fuels, which contain no aromatics, their maximum content in blends range from 42 vol% for the conventional fuel with the lowest aromatic content (fuel 114) to 63 vol% for the one with the highest (fuel 085). CH kerosene and ATJ-SKA have aromatic contents of 19.7 and 15.8 vol%, respectively which means that the 8 vol% aromatics restriction does not limit maximum blend ratios.

### Distillation curve gradients

Distillation curve gradients are specified in ASTM D7566 by the values T50-T10 (min. 15 °C) and T90-T10 (min. 40 °C). They become restricting if the synthetic kerosene features a relatively flat distillation curve. This parameter turned out to be critical for CTL (T50-T10 = 8.0 °C; T90-T10 = 27.2 °C) and ATJ-SPK (T50-T10 = 2.9 °C; T90-T10 = 42.1 °C) in a way that for one conventional fuel (fuel 123), practically no incorporation of CTL and ATJ-SPK was allowed at all. However, in contrast to CTL, T90-T10 for ATJ-SPK meets the specification, since the distillation curve of that fuel has a steep increase at higher temperatures. For neat ATJ-SKA both gradient values (T50-T10 = 11.9 °C; T90-T10 = 30.8 °C) are below the specified minimum values, which was surprising. However, the manufacturer has since documented that this is specific to the individual batch investigated, and is not a generic property of ATJ-SAK.

### Lubricity

Lubricity of a blend in general is hard to predict from the values of the neat blend components since there is no correlation with blend ratio. However, in blends the component with the better lubricity usually positively influences this parameter. SIP fuel, for example, has a very good lubricity (wsd = 0.562 mm) and its incorporation into fossil fuel leads to a significant improvement.

For lubricity it is also possible that the respective values for blends lie outside the interval defined by the neat blend components but in such a way that lubricity improves; a significant worsening has not been observed. In the case of CH-kerosene (wsd = 0.570 mm) and fuel 112 (wsd = 0.645 mm), this was most evident: Blends throughout exhibited a better lubricity (wsd values ranging from 0.560 mm to 0.506 mm) than either of the neat fuels.

### Freezing Point

Freezing point was shown to be never an issue, if the values for the neat blend components meet the specification. Yet, an anomaly was evident, namely a depression of the freezing point for most of the synthetic fuel blends at certain blend ratios. This effect is the more pronounced, the more similar freezing points of the blend components are. In the case of fuel 123 (-61.9 °C) and HEFA (-54.4 °C) freezing point drops to approximately -65 °C. Only in the case of blends with SIP fuel (Farnesane), this effect was not detectable. However, since freezing point improves, the observed anomaly is not valued as critical.

### Smoke point

The smoke point primarily depends on the presence of aromatic compounds in the fuels. Therefore, blends with aromatic free synthetic fuels show an improved smoke point. For the synthetic fuels which contain aromatics, CH kerosene and ATJ-SKA, smoke points are 22.5 and 23.0 mm and thereby above the minimum value according to ASTM D7566 (18 mm). If this is the case for the neat blend components, smoke point is not a limiting parameter for blends.

### Flash point

Flash point is dominated by the presence of volatile fuel components. In blends this property strongly depends on the blend component with the lower flash point. Only at high contents of the blend component with the higher flash point, that of the blend significantly rises. For all blends investigated here, flash point was not an issue.

# 5 Properties of Alternative Fuel Blends after Addition of Aromatic Compounds

Of the various kinds of synthetic kerosene investigated (chapter 4), only CH kerosene and ATJ-SKA contain aromatic compounds. However, as will be dealt with in detail in chapter 6, aromatics are currently still required in fuels to ensure the tightness of seals, hence for synthetic kerosene for aviation use, ASTM D7566 requires a minimum aromatic content of 8 vol%. As was shown in chapter 4, this is a major limiting factor for high level blends, and in many cases even prevents reaching the currently permitted maximum 50 vol% blend ratio.

One possible way of avoiding this issue, and permitting higher blend ratios, is the addition of aromatics to the fuel blend, as for example Shell / Virent plan to do (see section 3.9). However, adding aromatics will not only affect aromatic content, but also other parameters, potentially in an undesirable manner. This study therefore investigated which effect the addition of aromatics has on other parameters of the blend.

For this purpose, two conventional fuels (085 and 114) were blended with ATJ, HVO and CTL at a ratio of 30 vol% conventional and 70 vol% synthetic fuel. 085 and 114 were selected because they feature the highest resp. lowest percentage of aromatics among the conventional fuels. Blends with farnesane were not evaluated because farnesane is not designed for blending at high ratios.

To these blends aromatics were added in order to raise aromatic content to 8 vol%, and full analysis according to ASTM D7566 was performed. The aromatics added were a mixture of the commercial Exxon products Solvesso 100, Solvesso 150 and Solvesso 200 (purchased from BestChem, Linsengericht, Germany) in a 25/53/22 ratio (by volume) according to DeWitt et al.[159] For discussion of the results, those parameters of the original blends which did not meet the respective requirements have been selected. Beyond that, lubricity and smoke point have been included in the following discussion, because the former is hard to predict and the latter strongly depends on aromatic content (Table 4 - Table 9).

| Property | Limits | | Jet A-1 085 with 70 vol% ATJ-SPK | after addition of aromatics to 8 vol% |
|---|---|---|---|---|
| | lower | upper | | |
| Aromatics [vol%] | 8 | 25 | 6.5* | 8.0* |
| Density [kg/m³] | 775 | 840 | 769.3 | 771.7 |
| Distillation T50 - T10 [°C] | 15 | - | 8.2 | 8.3 |
| Lubricity [mm] | - | 0,85 | 0.788 | 0.727 |
| Smoke Point [mm] | 18 | - | 26.5 | 25.5 |

*Table 4: Selected properties for the 70 vol% ATJ-SPK blend with Jet A-1 085 and for the blend after addition of aromatic compounds to 8 vol%. (red numbers indicate deviations from specified values, green numbers indicate values that meet the respective requirement; * calculated from values of the neat blend components)*

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[159] M.J. DeWitt, E. Corporan, J. Graham, D. Minus, *Energy & Fuels* **2008**, *22*, pp. 2411

| Property | Limits | | Jet A-1 114 with 70 vol% ATJ-SPK | after addition of aromatics to 8 vol% |
|---|---|---|---|---|
| | lower | upper | | |
| Aromatics [vol%] | 8 | 25 | 4.1* | 8.0* |
| Density [kg/m³] | 775 | 840 | 768.6 | 774.5 |
| Distillation T50 - T10 [°C] | 15 | - | 8.7 | 8.8 |
| Lubricity [mm] | - | 0,85 | 0.784 | 0.765 |
| Smoke Point [mm] | 18 | - | 27.0 | 26.0 |

*Table 5: Selected properties for the 70 vol% ATJ-SPK blend with Jet A-1 114 and for the blend after addition of aromatic compounds to 8 vol%. (red numbers indicate deviations from specified values, green numbers indicate values that meet the respective requirement; * calculated from values of the neat blend components)*

| Property | Limits | | Jet A-1 085 with 70 vol% HVO | after addition of aromatics to 8 vol% |
|---|---|---|---|---|
| | lower | upper | | |
| Aromatics [vol%] | 8 | 25 | 6.5* | 8.0* |
| Density [kg/m³] | 775 | 840 | 769.0 | 771.4 |
| Lubricity [mm] | - | 0,85 | 0.730 | 0.737 |
| Smoke Point [mm] | 18 | - | 42.0 | 26.0 |

*Table 6: Selected properties for the 70 vol% HVO blend with Jet A-1 085 and for the blend after addition of aromatic compounds to 8 vol%. (red numbers indicate deviations from specified values, green numbers indicate values that meet the respective requirement; * calculated from values of the neat blend components)*

| Property | Limits | | Jet A-1 114 with 70 vol% HVO | after addition of aromatics to 8 vol% |
|---|---|---|---|---|
| | lower | upper | | |
| Aromatics [vol%] | 8 | 25 | 4.1* | 8.0* |
| Density [kg/m³] | 775 | 840 | 768.3 | 774.2 |
| Lubricity [mm] | - | 0,85 | 0.725 | 0.745 |
| Smoke Point [mm] | 18 | - | > 42 | 26.5 |

*Table 7: Selected properties for the 70 vol% HVO blend with Jet A-1 114 and for the blend after addition of aromatic compounds to 8 vol%. (red numbers indicate deviations from specified values, green numbers indicate values that meet the respective requirement; * calculated from values of the neat blend components)*

| **Property** | **Limits** | | **Jet A-1 085 with 70 vol% CTL** | **after addition of aromatics to 8 vol%** |
|---|---|---|---|---|
| | **lower** | **upper** | | |
| Aromatics [vol%] | 8 | 25 | 6.5* | 8.0* |
| Density [kg/m³] | 775 | 840 | 772.2 | 774.3 |
| Distillation T50 – T10 [°C] | 15 | - | 11.4 | 11.3 |
| Distillation T90 – T10 [°C] | 40 | - | 35.5 | 35.6 |
| Lubricity [mm] | - | 0.85 | 0.759 | 0.728 |
| Smoke Point [mm] | 18 | - | 34.0 | 24.5 |

*Table 8: Selected properties for the 70 vol% CTL blend with Jet A-1 085 and for the blend after addition of aromatic compounds to 8 vol%. (red numbers indicate deviations from specified values, green numbers indicate values that meet the respective requirement; * calculated from values of the neat blend components)*

| **Property** | **Limits** | | **Jet A-1 114 with 70 vol% CTL** | **after addition of aromatics to 8 vol%** |
|---|---|---|---|---|
| | **lower** | **upper** | | |
| Aromatics [vol%] | 8 | 25 | 4.1* | 8.0* |
| Density [kg/m³] | 775 | 840 | 771.3 | 777.5 |
| Distillation T50 – T10 [°C] | 15 | - | 12.4 | 12.1 |
| Lubricity [mm] | - | 0.85 | 0.780 | 0.760 |
| Smoke Point [mm] | 18 | - | 37.5 | 25.0 |

*Table 9: Selected properties for the 70 vol% CTL blend with Jet A-1 114 and for the blend after addition of aromatic compounds to 8 vol%. (red numbers indicate deviations from specified values, green numbers indicate values that meet the respective requirement; * calculated from values of the neat blend components)*

Since the mixture of aromatic compounds has a relatively high density of approximately 910 kg/m³, addition of aromatics to a fuel blend increases density. This is beneficial since the density of the original blends is low, and actually is below the specification minimum. However, the amount of aromatics added to the blends is small, therefore density undergoes only relatively minor changes and solely in the case of CTL/Jet A-1 114 (Table 9) addition of aromatics increases density to a value above the lower limit.

Distillation, expressed by T50-T10 and T90-T10, is a critical parameter for many blends, especially at high percentages of synthetic fuel. However, the impact of addition of aromatics on distillation is negligible.

In most of the tests lubricity was improved upon addition of aromatics, only for the HVO-blends, worsening of lubricity was observed.

Aromatic content is considered in literature to be a major factor influencing smoke point. In the case of the blends discussed in this chapter, smoke points before addition of aromatics are very good, particularly for HVO and CTL blends. Adding aromatic compounds considerably lowers these smoke points. As the original values were that good, the blends easily stay within specification, but all the same the lower smoke point is undesirable as smoke point can be considered as a proxy for emissions behaviour. This issue is explored further in chapter 7 of this study and in the conclusions (chapter 8).

# 6 Influence of Alternative Fuels on Physical Properties of Elastomers

## 6.1 Experimental Procedures

Preparation and storage of elastomer samples in fuels was conducted based on DIN ISO 23529. Mass and volume change were determined according to DIN ISO 1817, tensile strength and elongation at break according to DIN 53504. Measurement of hardness is based on DIN ISO 7619.

The blend of aromatics for the addition to aromatic-free synthetic fuels was prepared by mixing in the commercial Exxon products Solvesso 100, Solvesso 150 and Solvesso 200 (purchased from BestChem, Linsengericht, Germany) in a 25/53/22 ratio (by volume) according to DeWitt et al.[160]

## 6.2 Results

### 6.2.1 Nitrile-Butadiene-Rubber (NBR)

**Storage of NBR in Fossil and Synthetic Fuels**

In the following, the influence of conventional and synthetic fuels on physical properties of Nitrile-Butadiene-Rubber (NBR) is described. Figure 40 shows the percentaged mass and volume change of the elastomer samples after storage in fossil Jet A-1 fuels as well as in neat synthetic fuels. Since aromatic compounds can have a pronounced influence on elastomer properties, values for aromatic contents are included as orange dots in the respective charts.

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[160] M.J. DeWitt, E. Corporan, J. Graham, D. Minus, *Energy & Fuels* **2008**, *22*, pp. 2411

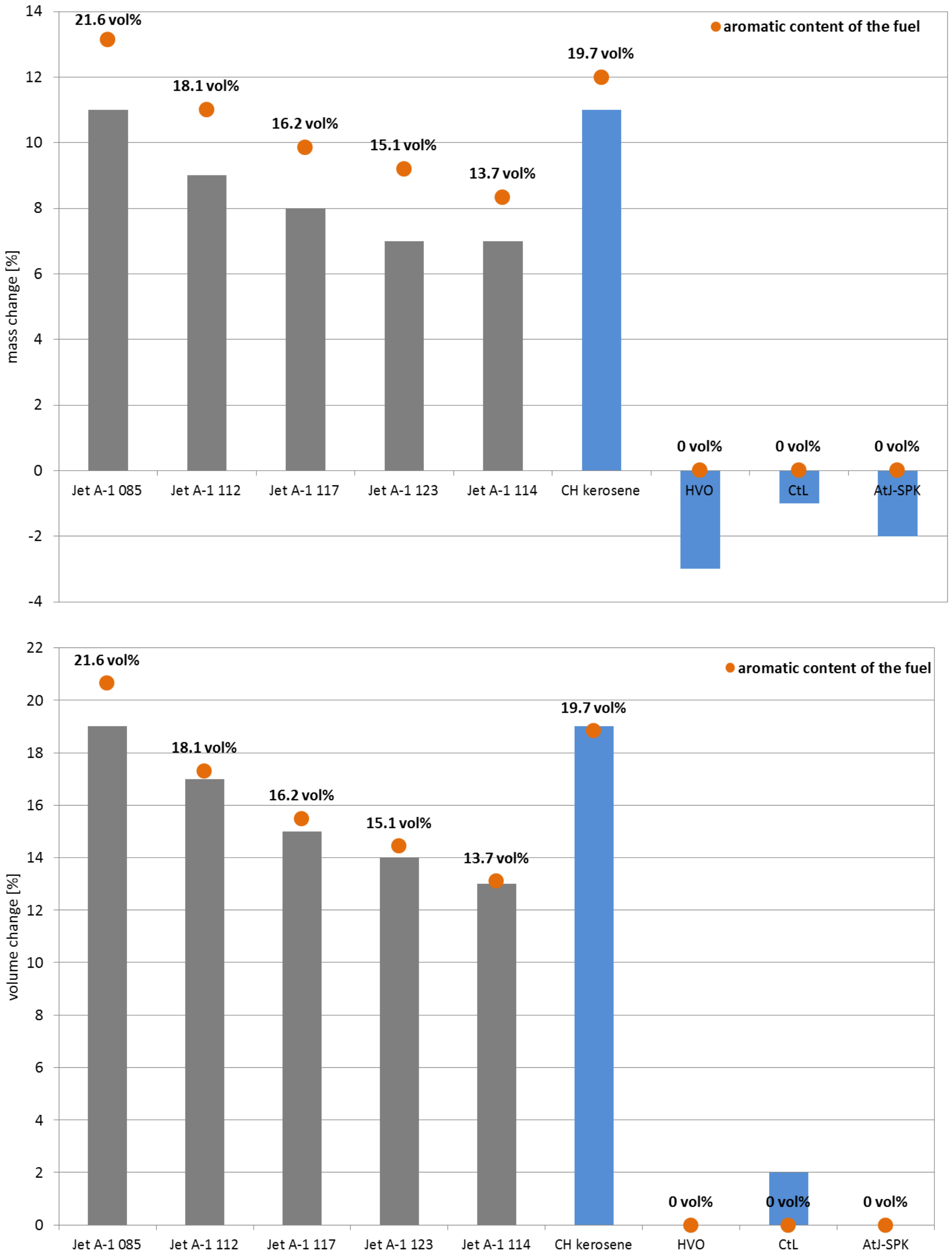


*Figure 40: Percentaged mass (top) and volume change (bottom) of NBR samples after storage in fossil and synthetic fuels (orange dots visualize the fuels' aromatic contents)*

Regarding mass change, a generally known dependency on aromatic content exists in which an increasing amount of aromatic compounds leads to an increase in mass of NBR after storage. On the other hand, absence of aromatic compounds in the fuels results in a negative mass change, due to extraction of additives (e.g. plasticizer and antioxidants). Minor differences in mass change upon storage in HVO, CTL and ATJ-SPK can be neglected in this context. In the case of fuels with aromatic compounds, additives are extracted of course as well. Yet, the impact of extraction on mass is overcompensated by incorporation of aromatics into the elastomer. Regarding aromatic-free synthetic fuels, which - in our case - consist of n-alkanes and iso-alkanes, additives are replaced to a much lower extend by these compounds as the aromatics would be able to. The reason for this can be found in the comparatively high polarity of NBR, which causes the more polar fuel compounds (here: aromatics) to be incorporated in higher amounts than unpolar compounds (here: n-alkanes and iso-alkanes).

Although measurement of mass change might mislead to the conclusion, that alkanes are not incorporated into the elastomer at all, gas-chromatographic investigations on extracts of stored elastomers show that n-alkanes and iso-alkanes are incorporated into the elastomer as well. This topic has since been researched in more detail by Scheuermann, Förster et al., but the results have not yet been published.

Concerning volume change of NBR after storage in fuels, it turns out, that volume increases with increasing amount of aromatic compounds which correlates with the observed mass change. As for the aromatic free fuels (HVO, CTL, ATJ-SPK), no change in volume is observed; the minor change of 2 % in the case of CTL can be neglected in this context. Regarding practical applications it can be stated, that neat synthetic fuels which lack aromatic compounds do not promote the swelling of NBR seals.

It should be noted that the aromatic content of fossil fuels may range between 8 vol% and 25 vol% according to ASTM D1655. As shown in Figure 40, such fuels cause a significant volume change. As far as fossil/synthetic fuel blends are concerned the lower limit of 8 vol% aromatics (ASTM D7566) guarantees swelling of NBR.

The hardness of original NBR samples and after storage in fossil and synthetic fuels is illustrated in Figure 41. It becomes obvious that - depending on the fuel - hardness can be significantly reduced.

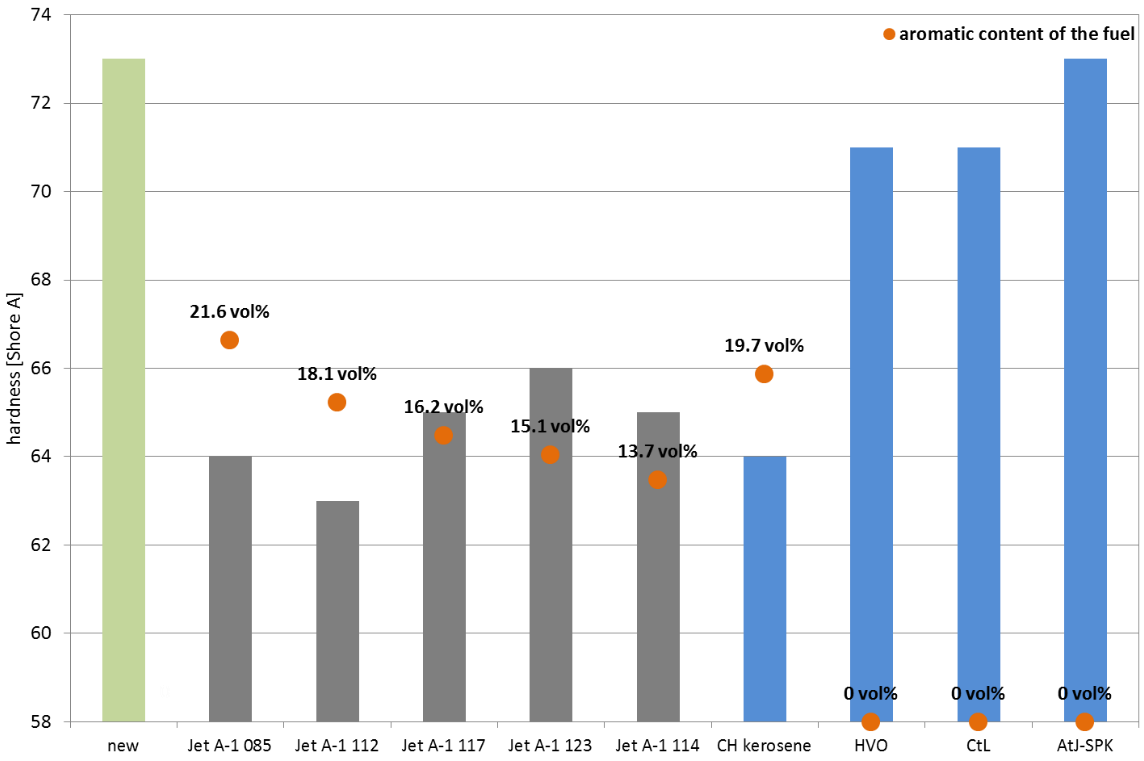


*Figure 41: Hardness of an original NBR sample (green) and after storage in fossil and synthetic fuels (orange dots visualize the fuels' aromatic contents)*

There exists a rough dependency of decrease in hardness and aromatic content, with decrease being more pronounced, the higher the aromatic content is. Hardness decreases, because fuel compounds, preferentially aromatics, diffuse into the material and for their part adopt the role of plasticisers.

Synthetic fuels devoid of aromatic compounds hardly affect hardness, presumably because n-alkanes and iso-alkanes have a much lower tendency to diffuse into the NBR (cf. mass and volume change). Remarkably, storage of NBR in ATJ-SPK has no effect on hardness at all, although the two iso-alkanes ATJ-SPK consists primarily of diffuse into the material (as proven by gas-chromatography of extracts after storage).

Depending on the fuel the NBR elastomer has been stored in, elongation at break (Figure 42) can be significantly reduced. In general, fuels containing aromatics cause a more pronounced reduction of this value than those without aromatics. The latter might even have no effect at all (cf. ATJ). Yet, a clear trend regarding content of aromatic compounds and reduction of elongation at break is not obvious.

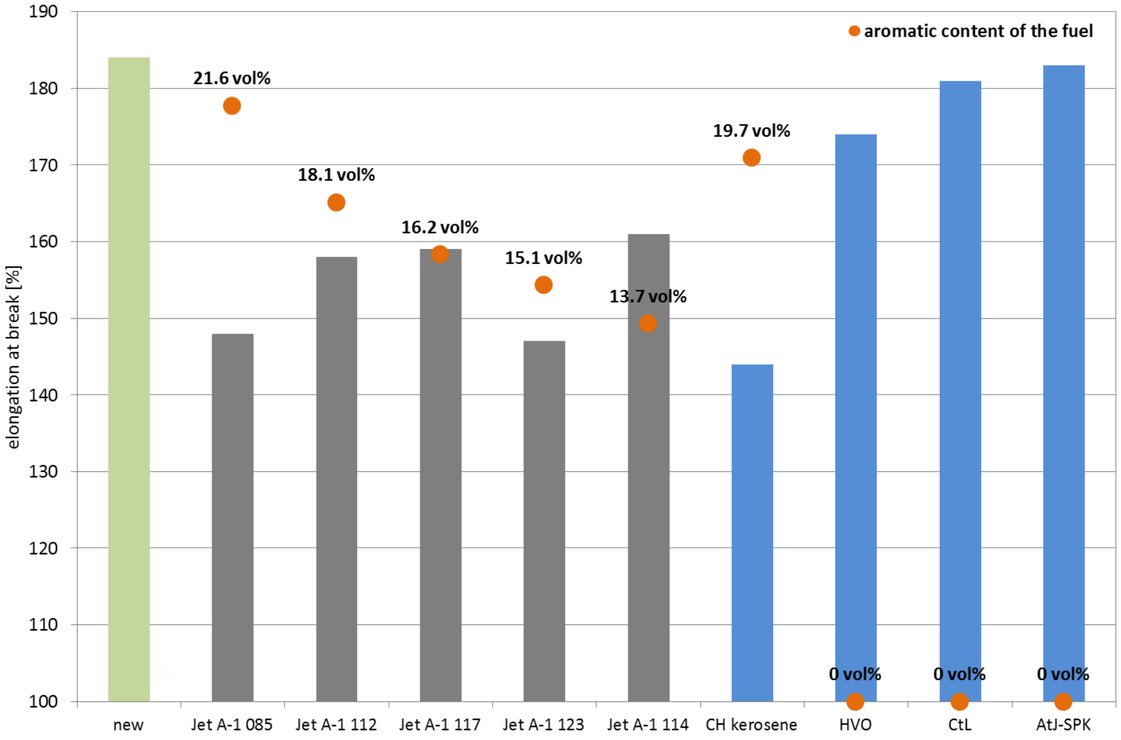


*Figure 42: Elongation at break of an original NBR sample (green) and after storage in fossil and synthetic fuels (orange dots visualize the fuels' aromatic contents).*

Tensile strength is the maximum tensile force a material can withstand, before it finally breaks. For NBR stored in the fuels used in this study, results for tensile strength are depicted in Figure 43.

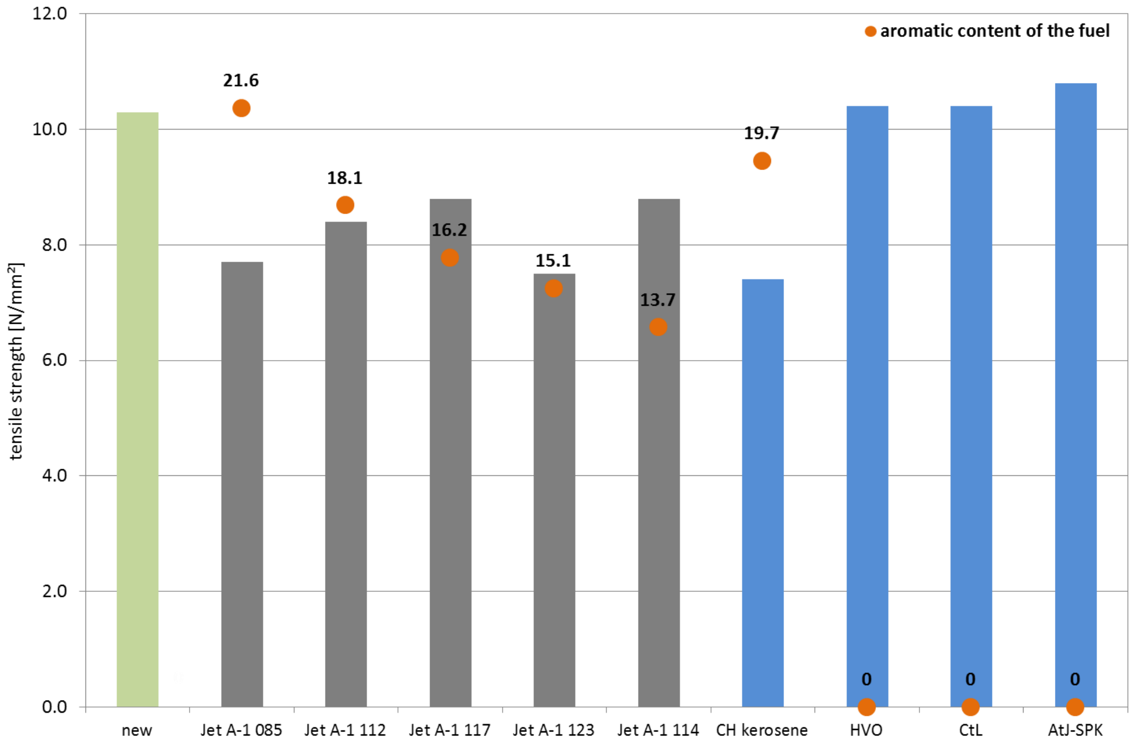
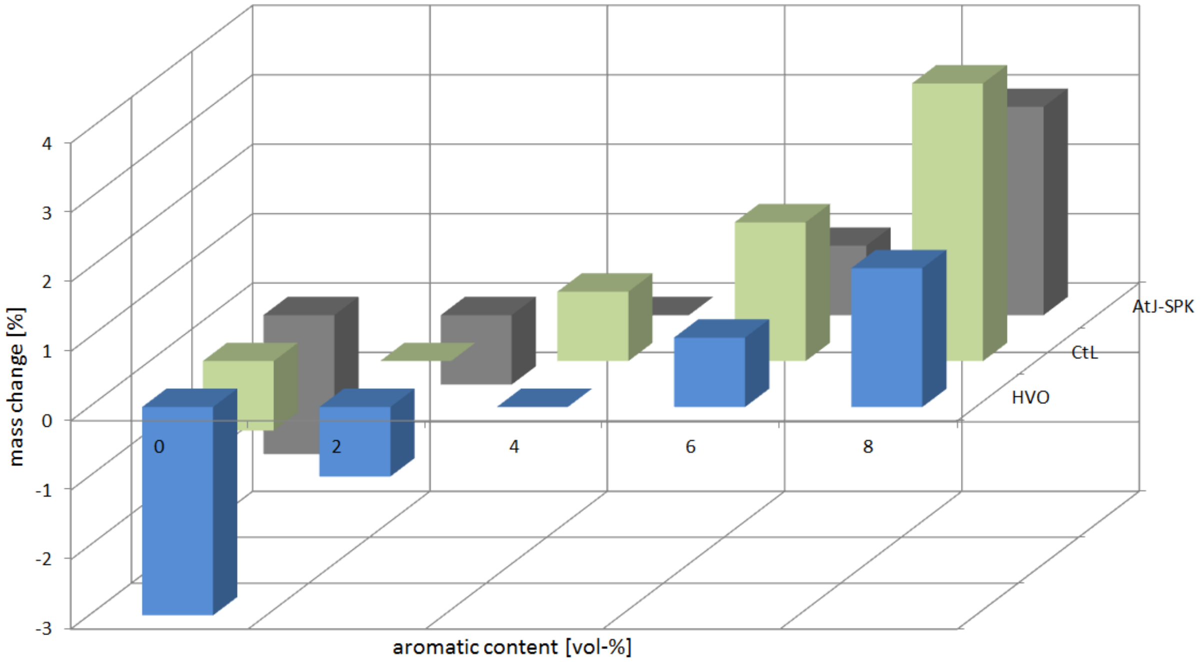


*Figure 43: Tensile strength of an original NBR sample (green) and after storage in fossil and synthetic fuels (orange dots visualize the fuels' aromatic contents)*

Just as for elongation at break, storage of NBR in a fuel can reduce tensile strength while it seems that fuels free of aromatics exert no influence on this parameter. However, correlating aromatic content with reduction of tensile strength shows no trend. The small increase in tensile strength after storage of NBR in ATJ-SPK lies within the error of the method and is therefore negligible.

### Storage of NBR in Synthetic Fuels Enriched With Aromatic Compounds

The aromatic free synthetic fuels CTL, HVO and ATJ-SPK were enriched with 2, 4, 6 and 8 vol% aromatic compounds, NBR samples were stored in these mixtures and properties of the elastomers determined after storage. Figure 44 shows volume and mass change in dependence of aromatic content of the synthetic fuels.



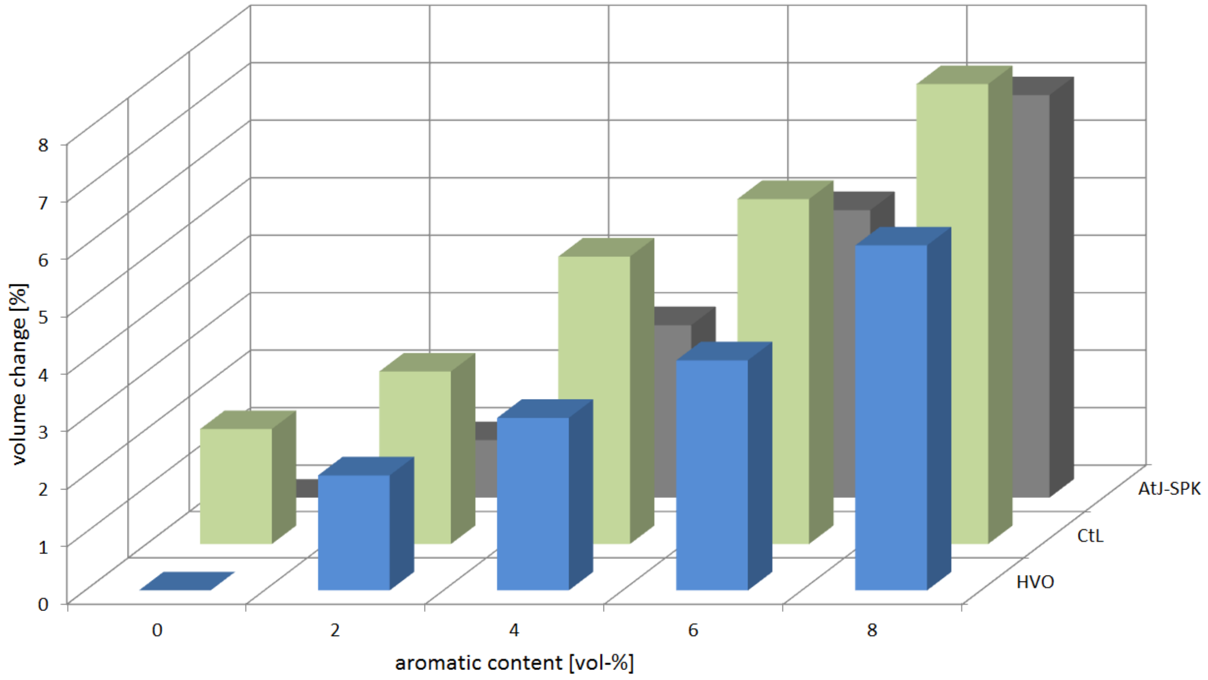


*Figure 44: Mass (top) and volume change (bottom) of NBR samples after storage in synthetic fuels enriched with aromatic compounds*

As expected, volume and mass change depend almost linearly on content of aromatic compounds of the synthetic fuels. For the fossil fuels, this has already been shown in Figure 40. At an aromatic content of 4 vol%, extraction of additives from the elastomer is compensated by incorporation of fuel components to an extend that no negative mass change can be observed any more.

Regarding hardness (Figure 45), neat ATJ-SPK has no influence on NBR (before and after storage: 73 Shore A; cf. Figure 41). Enrichment of ATJ with aromatic compounds, however, leads to a small decrease in hardness to 69 Shore A at 8 vol%. For HVO and CTL, storage in the neat synthetic fuels already decreases hardness slightly by two units. Yet, in the case of HVO, no significant effect due to addition of aromatics can be observed and for CTL decrease in hardness is negligible. It has to be pointed out, that in the 0 – 8 vol% interval, changes in hardness due to aromatic content are generally small. However, the initial influence of neat HVO and CTL on hardness is distinct as compared to the value of new NBR.

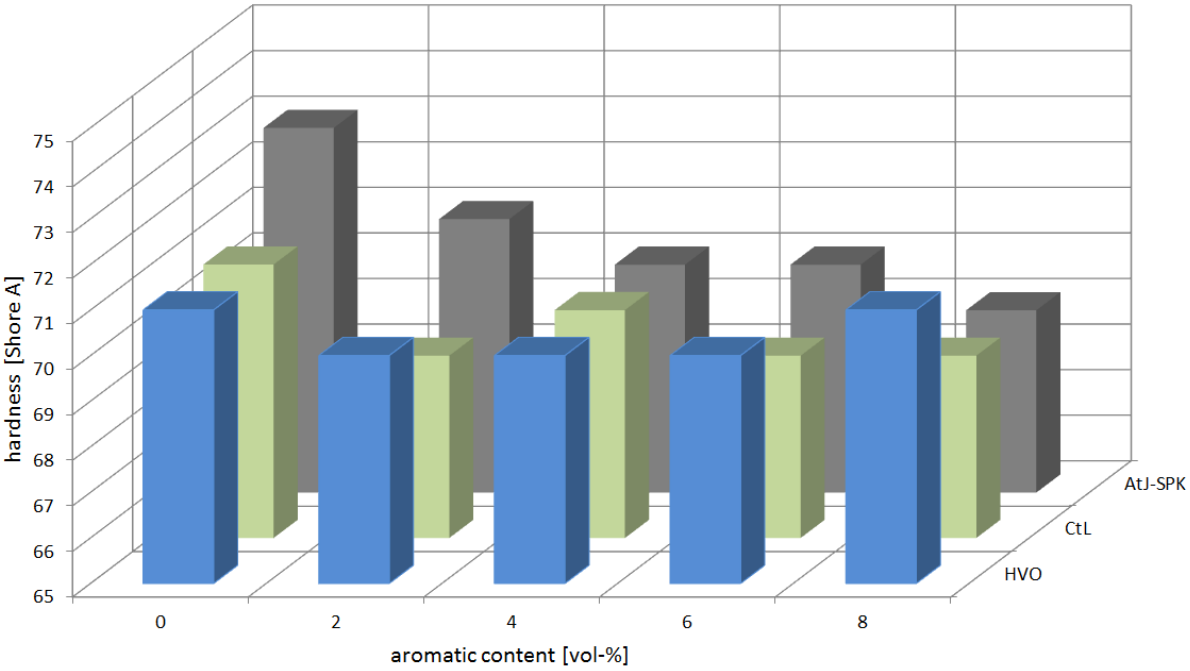


*Figure 45: Hardness of NBR samples after storage in synthetic fuels enriched with aromatic compounds*

## 6.2.2 Fluorocarbon Rubber

### Storage of Fluorocarbon Rubber in Fossil and Synthetic Fuels

It can be stated that regardless of the fuel fluorocarbon has been stored in - fossil or synthetic, with or without aromatics - mass and volume of the elastomer do not change. The same is true for hardness. A slight decrease from 74 to 73 Shore A can be regarded as irrelevant, especially for application of the elastomer.

For elongation at break one generally observes a small increase from 185 % (before storage) to max. 209 %, irrespective of aromatic content. Only for Jet A-1 117 elongation at break decreases by 12 % but these changes are small compared to the measurement accuracy.

Tensile strength increases for almost all fuels by max. 2.6 N/mm², except for Jet A-1 117, where the value decreases by 1.0 N/mm². However, compared to the measurement accuracy, these changes are negligible as well.

### Storage of Fluorocarbon in Synthetic Fuels Enriched With Aromatic Compounds

The results from storage of fluorocarbon in synthetic fuels enriched with aromatic compound closely resemble those obtained after storage in neat fossil and synthetic fuels:

Mass and volume do not change; hardness undergoes minor changes by ±1 Shore A, compared to the new elastomer and variation of aromatic content is not reflected in the results.

Elongation at break (new elastomer: 185 %) increases by max. 24 % and decreases by max. 12 %. Regarding tensile strength, variations from max. -1.0 N/mm² to max +2.6 N/mm² can be observed. These results are essentially the same as for storage in neat fossil and synthetic fuels. Aromatic content does not correlate with the change of properties and overall, changes lie within the errors of the respective methods.

### 6.2.3 Fluorosilicone Rubber

**Storage of Fluorosilicone Rubber in Fossil and Synthetic Fuels**

Mass change for fluorosilicone after storage in neat fossil or neat synthetic fuels is in the range of 2 - 4 % and therefore low compared to that of NBR (7 - 11 %). Furthermore, since fluorosilicone hardly contains extractable substances, no negative mass change for neat aromatic-free fuels was observed.

Volume increases by 4 - 7 % for all fuels the elastomer has been stored in. In comparison, for NBR a higher volume change is observable (13 - 19 %), but only for fuels with aromatics. If these compounds are absent, NBR exhibits almost no volume change after storage. For storage in HVO, the lowest volume change was observed.

Regarding hardness, storage in the respective neat fossil and synthetic fuels leads to a decrease up to ten units, while decrease is more pronounced for fuels containing aromatics (Figure 46). The impact of storage of fluorosilcone rubber on hardness is comparable to that for NBR stored in fuels containing aromatics.

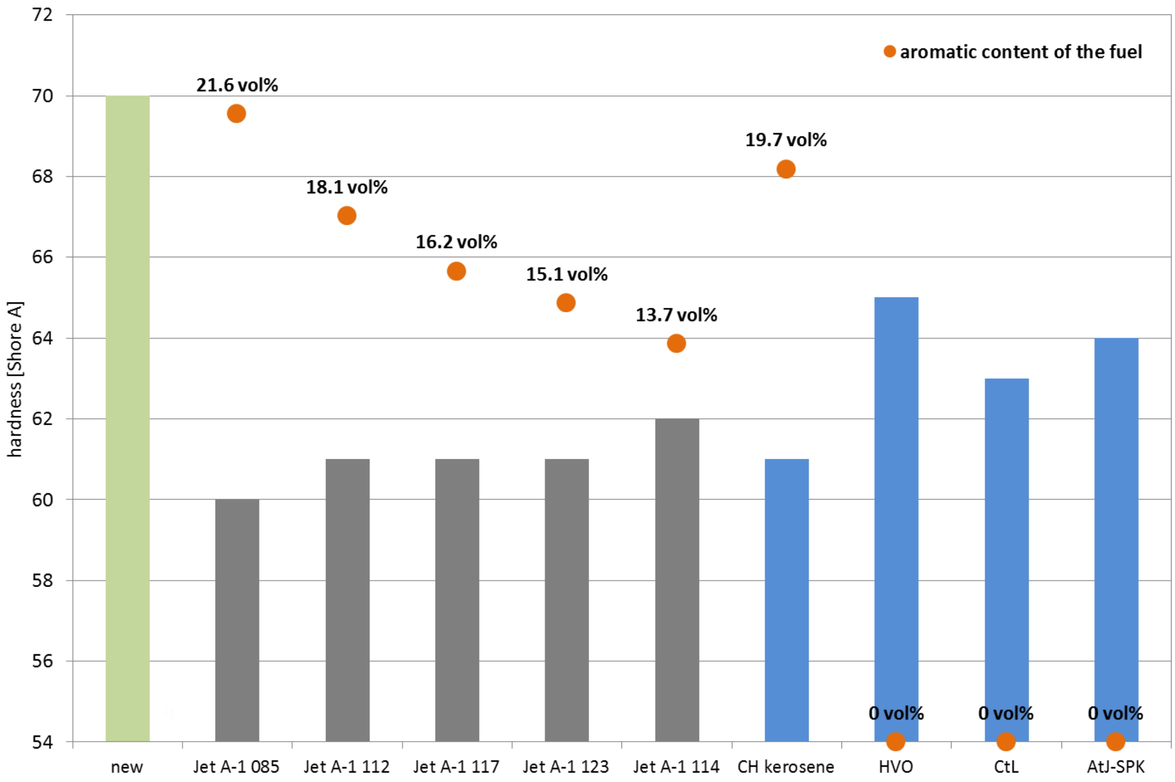


*Figure 46: Hardness of an original fluorosilicone sample (green) and after storage in fossil and synthetic fuels (orange dots visualize the fuels' aromatic contents)*

Elongation at break can be slightly affected upon storage of the elastomer in the fuels (new: ca. 240 %; after storage: ca. 240 – 200 %). Yet, the observed variations of the respective median values are close to the range of the individual values.

For tensile strength a slight reduction by max. 1.3 N/mm² compared to the original sample is observed while fuels with aromatics do not differ from fuels without.

### Storage of Fluorosilicone in Synthetic Fuels Enriched With Aromatic Compounds

Mass change of the elastomer after storage is in the interval from 2 – 4 % and therefore similar to that observed for storage in fossil fuels. Variations of aromatic content is not reflected in mass change. Volume change ranges – as for the neat fossil and synthetic fuels – from 4 – 8 % and shows no correlation with aromatic content. Similar to the neat fuels, HVO and its blends, cause the lowest volume change overall (Figure 47).

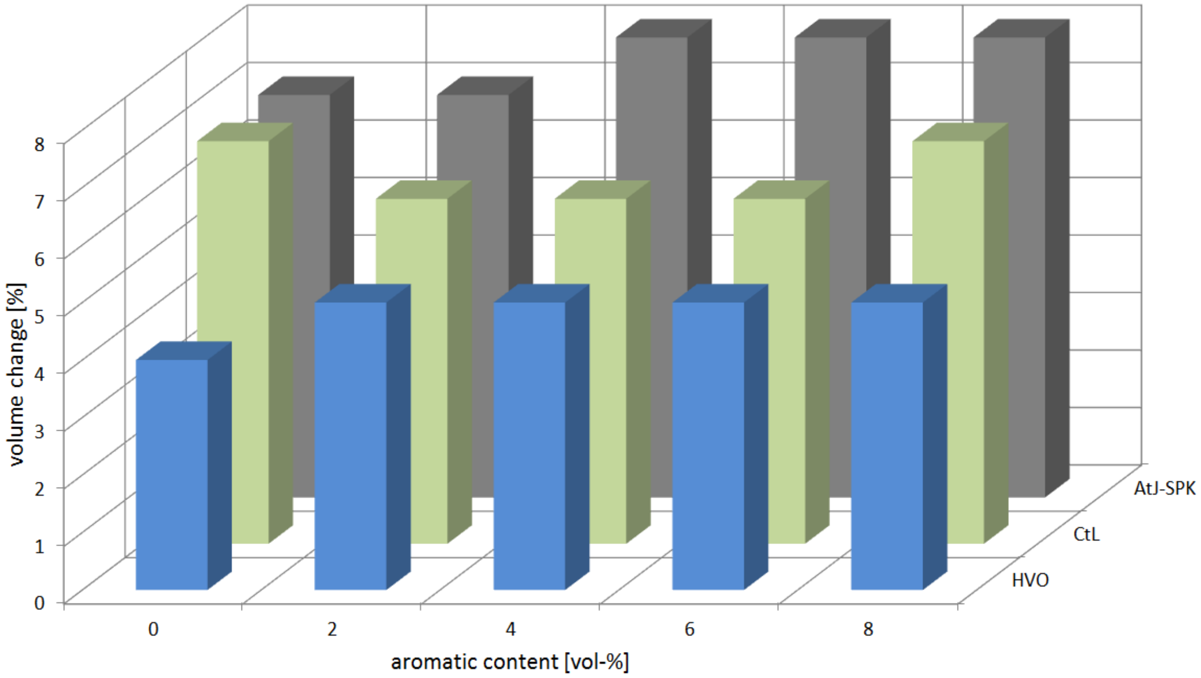


*Figure 47: Volume change of fluorosilicone samples after storage in synthetic fuels enriched with aromatic compounds*

Elongation at break and tensile strength decrease slightly upon storage and the level of decrease is similar to that observed for storage in neat fossil and synthetic fuels. However, these changes are low and close to the measurement accuracy.

## 6.3 Elastomer Properties after Subsequent Storage in Fossil and Synthetic Fuel

To test the impact of synthetic fuels on elastomers that have previously been in contact with fossil fuels, the following test procedure was employed:

Elastomers were stored first in the fossil fuel with the highest content of aromatic compounds (fuel 085) and then in neat HVO (which contains no aromatics at all), to simulate an extreme scenario of change in fuel composition.

All determined properties of all elastomers (NBR, fluorocarbon and fluorosilicone) after this twofold storage did not significantly differ from those after single storage in HVO.

However, it needs to be emphasized, that especially in the case of NBR, storage in fossil fuel causes increase and subsequent storage in HVO decrease in volume and mass. That means that the elastomers significantly shrink upon changing the medium from fossil to aromatic free synthetic fuel, which may impact tightness of seals.

## 6.4 Summary

Three different types of elastomers (fluorocarbon rubber, fluorosilicone rubber and nitrile-butadiene rubber) were stored in conventional fuels and neat synthetic fuels as well as in synthetic fuels enriched with aromatics (2, 4, 6, 8 vol%). The properties determined were mass and volume change, hardness, tensile strength and elongation at break.

Among the different types of elastomers, fluorocarbon rubber turned out to be widely inert towards fuels, either conventional or synthetic, with or without aromatics. The observed changes in properties are weakly pronounced and discussing these minor variations is gratuitous.

Fluorosilicone rubber shows minor increase in mass and volume upon storage irrelevant of the type of fuel (with or without aromatics). Hardness decreases upon storage while decrease is more pronounced if the fuel contains aromatics. Tensile strength is slightly reduced, irrespective of the fuel type, and changes in elongation at break are weakly pronounced.

The properties of nitrile-butadiene-rubber (NBR) on the other hand are significantly influenced by the fuel the elastomer has been stored in. For synthetic fuels free of aromatic compounds one observes a decrease in mass of NBR samples compared to new elastomers due to extraction of additives; a change in volume, however, was not observed. The effect on NBR seals was essentially the same for all aromatic-free fuels, with neglectable differences between the different fuel types.

One the other hand mass and volume of NBR samples after storage increase if aromatic compounds are present in the fuel. This increase is more pronounced, the higher the aromatic content of the fuel is. Hardness of NBR decreases upon storage in fuels containing aromatics, but no correlation with aromatic content can be drawn. Synthetic fuels devoid of aromatics hardly affect hardness.

Elongation at break and tensile strength of NBR decrease upon storage in fuels with aromatics, while fuels without these compounds exert almost no influence regarding these parameters.

To simulate an extreme scenario of change in fuel composition, elastomers were first stored in the conventional fuel with the highest aromatic content and then in an aromatic free synthetic fuel (HEFA). For NBR it was found that after this twofold storage, the properties of the elastomer were almost the same as after single storage in the aromatic free synthetic fuel, i.e. a small decrease in mass and, in this case , also in volume. Yet, compared to the properties of NBR after storage in conventional fuel, the change in mass and volume is pronounced.

For fluorocarbon and fluorosilicone there is no difference between the effects of single and twofold storage on mass and volume change.

# 7 Emissions Measurements

In addition to $CO_2$, aircraft also emit a number of other substances in flight and taxi. The quantities involved are far smaller than those of $CO_2$ emissions, but all the same the environmental effects of some of these emissions are considered relevant. In particular the effect of these emissions on climate due to the formation of more and denser contrails is by some scientists regarded as considerable[161], although there is still a scientific debate on this aspect.

The extent of non-$CO_2$ emissions is largely dependent on the engine[162], and great progress has been achieved in recent decades.[163] Given this dependence on the engine the fuel is burned in, it would be very difficult for ASTM to include emissions in a fuel specification. Accordingly, emissions are not considered part of the ASTM fuel certification process, and little emissions data is typically presented in the research reports submitted to ASTM.

All the same, some research has been performed, particularly on the effect of fuel on soot formation[164], and of sulphur content on contrail formation[165], and it is clear that some fuels will burn cleaner in a given engine than others. It is therefore of interest to see whether biofuels will lead to an improvement of the emissions of a given engine. Research on this subject is however at an early stage[166], and for that reason, emissions tests were included in this study.

The initial planning for the emissions tests was based on the same assumptions as the lab tests, i.e. that only HEFA would be available in relevant quantities. The original intention therefore was to perform one set of emissions tests for each of the three HEFA biofuels which initially were planned to be included. However, as with the lab tests, this plan was changed when it became evident that tests of several HEFA batches would produce very little variation in results, and on the other hand availability of fuel from other production

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[161] Simon Blakey, Lucas Rye, Christopher William Wilson: Aviation gas turbine alternative fuels: A review, in: Proceedings of the Combustion Institute 33 (2011). P.2866; Ulrike Burkhardt / Bernd Kärcher: Global radiative forcing from contrail-induced cloudiness, SPIE Newsroom 10.1117/2.1201110.003764, 2011; B. Kärcher / F.Yu: Role of aircraft soot emissions in contrail formation, in: Geophysical Research Letters vol. 36 (2009). A recent paper by Bernd Kärcher (The importance of contrail ice formation for mitigating the climate impact of aviation, Journal of Geophysical Research, doi: 10.1002/2015JD024696) estimates that radiative forcing due to aviation contrails is almost double that due to all aviation CO2 emissions since the first powered airplane flight.

[162] See e.g. A. Petzold, M. Gysel, X. Vancassel, H. Puxbaum, S. Vrochticky, E. Weingartner, U. Baltensperger, P. Mirabel: On the effects of organic matter and sulphur-containing compounds on the CCN activation of combustion particles, in: Atmospheric Chemistry and Physics 5, 3187-3203, 2005, p. 3188

[163] Intergovernmental Panel on Climate Change: IPCC Special Report on Aviation and the Global Atmosphere, Cambridge 1999, section 7.5.4.1; for expected future developments see von der Bank, Ralf, Donnerhack, Stefan, Rae, Anthony, Cazalens, Michel, Lundblath, Anders, Dietz, Martin: LEMCOTEC – Improving the core-engine thermal efficiency, ASME TURBO EXPO 2014, June 16-20, Düsseldorf

[164] Chevron Aviation Fuels Technical Review, 2006, p.11-13

[165] U. Schumann/F.Arnold/R. Busen/J. Curtius/B.Kärcher/A.Kiendler/A.Petzold/H.Schlager/Fr. Schröder/K.-H.Wohlfrom: Influence of fuel sulfur on the composition of aircraft exhaust plumes: The experiments SULFUR 1-7, in: Journal of Geophysical Research, Vol. 107

[166] For an overview, see these papers presented at the FORUM-AE Workshop in Madrid, Spain, 21.October 2014: LeClerq, Patrick: Impact of Alternative Aviation Fuels on Combustor Performance and Emissions; Lobo, Prem: PM Emission Reductions with Alternative Fuels; Penenhoat, O., Burguburu, j:, figure, A., Jagueneau, A., Harivel, N.. Vancassel, Xavier, Delhaye, David, Demoment, Pascale, Starck, Laurie: Emission measurements and combustion modelling in CEAR project; Zarzalis, Nikolas: Comparison of the Emissions of Jet A-1 and Synthetic Jet Fuels

pathways progressed better than assumed, whereas HEFA availability was worse than expected. It was therefore agreed with DG Energy to conduct the emissions tests with other kinds of bio kerosene, and a first set of tests was conducted in November 2013, using SIP kerosene. The results of that test are presented in section 7.1.

However, availability of other bio kerosene in volumes sufficient for engine tests was not achievable in 2014, hence it became necessary to reschedule this part of the study. As a result, the interim report only contained information on the emissions tests performed on SIP kerosene. It was only in early 2016 that sufficient volumes of a second bio kerosene could be procured, with test rig and testbed engine availability only permitting the actual tests to be conducted in November 2016. The results from this test are presented in section 7.2.

## 7.1 Effect of SIP Kerosene on Emissions

### 7.1.1 Test Setup

The purpose of the testing performed by Lufthansa was to evaluate the impact of the SIP fuel on engine performance and emissions at up to 20% SIP kerosene content. The test was performed at the Lufthansa engine test rig in Hamburg on 15th November 2013.

The engine used was a single annular combustor CFM56-5C4 engine (serial number 741931). This type of engine is power rated to 151.3 kN and is used to power the Airbus A340. The individual engine used for the test entered Lufthansa service 15. May 2000 and at the time of the test had 60,890 flight hours / 8,856 cycles since new and 16,595 flight hours / 2,440 cycles since last overhaul, and was scheduled to undergo routine heavy maintenance / overhaul after the SIP kerosene blend tests.

The test was run by first performing an acceptance test of the engine, using the regular fuel feed of the Lufthansa test facility. This was the test Lufthansa routinely performs on an engine, and served to ensure that there were no issues with the engine which could have distorted the results for the SIP kerosene blend. After successful completion of this test, fuel supply of the test cell was switched to a bowser truck, which during the subsequent tests was used to feed the test cell. The physical arrangement of the fuel supply (see Figure 48) mirrored that used during tests at Snecma in June 2013.[167]

The fossil Jet A-1 fuel used for the test was sourced from the Leuna refinery in Saxony, Germany. Fuel from this refinery was selected because its properties (see annex 6) put it into the middle of the range of German kerosene. A different batch from the same refinery had been one of the fuels (No. 100) previously analysed as part of the lab tests of the impact of the incorporation of SIP kerosene into different Jet A-1 fuels (see sections 2.3 and 4.1).

The Leuna fuel was transported to the test site by a tanker truck, which was then positioned next to the bowser truck and used to refuel the bowser truck between test runs (see Figure 49). SIP kerosene was then added as required from drums, using a small pump, with the SIP

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[167] Total, Amyris, USAFRL: Evaluation of Synthesized Iso-Paraffins produced from Hydroprocessed Fermented Sugars (SIP Fuels), February 2014, p. 95 - 98

kerosene and the fossil kerosene subsequently blended in the bowser truck. The properties of the resulting blends are given in annex 9.7 and 9.8.

*Figure 48: Fuel Truck piping arrangement*

*Figure 49: Overall fuel supply arrangement*

A total of three runs were performed, first with the neat fossil fuel to generate reference data, then with 10% SIP kerosene added, and finally with 20% SIP kerosene added. At the beginning of each of the runs, the engine was first run at cruise power to burn the fuels still present in the piping from the prior run. After that the actual test was performed by running the engine

- 10 minutes at Minimum Idle
- 5 minutes at Flight Idle
- 5 minutes at Cruise Power

- 3 minutes at Climb Power
- 1 minute at Take Off Power
- followed by another couple of minutes at Minimum Idle for engine cool-down.

Fuel consumption for each of the runs was some 2,000 litres, including fuel left in the piping and then burned during the next run.

### 7.1.2 Emissions Measurements

Emissions were measured via a probe inserted into the exhaust tunnel of the test rig. Insertion was through a hole drilled in the after part of the tunnel wall. This arrangement gave a high naturally occurring dilution of particles, minimizing subsequent particle agglomeration in the lines leading to the measuring equipment, and thus permitting determination of particle sizes. Figure 50 shows the positions of the probe (red arrow) and of the engine (at the tunnel entrance, green arrow).

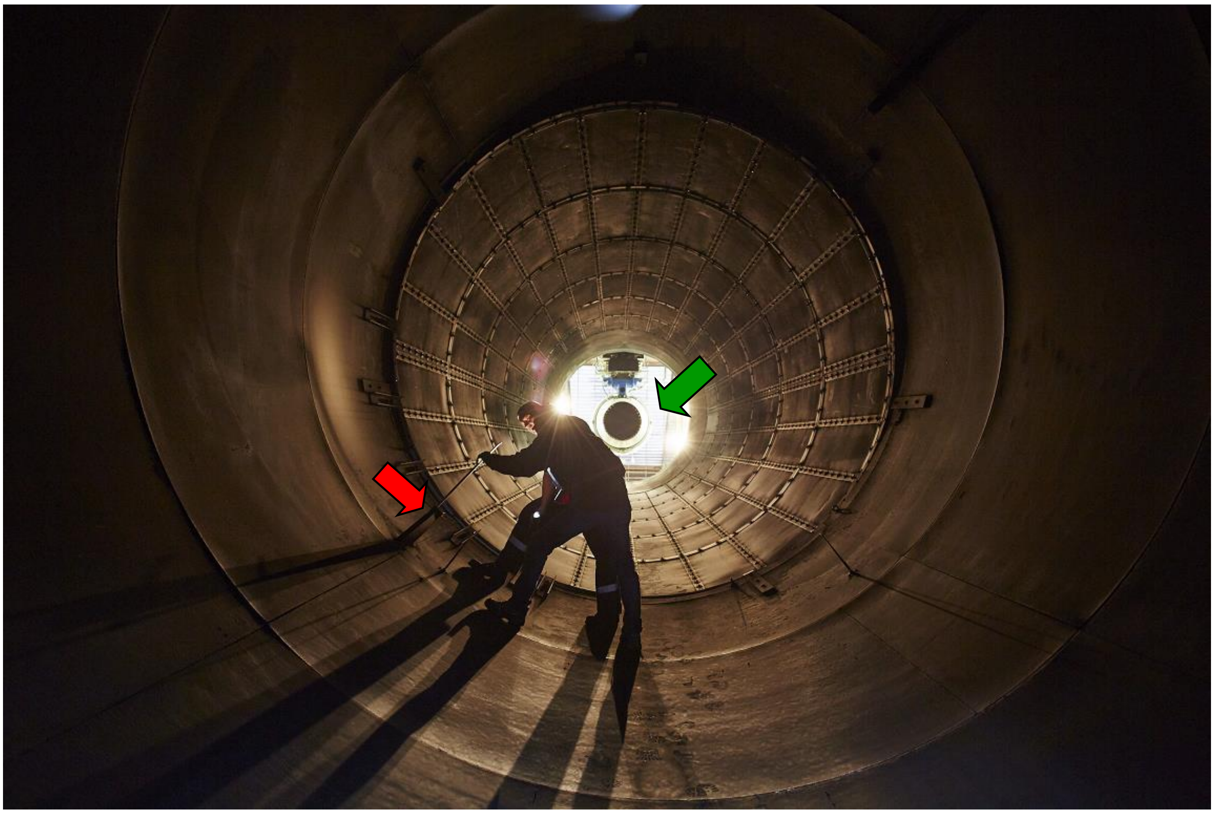

*Figure 50: Arrangement of emissions measurement probe*

The Hamburg test rig is a standard engine test arrangement operating at ambient conditions. Test results are therefore influenced by weather conditions. However, during the relevant time window from 12:00 to 19:20 hours weather conditions were nearly constant (temperature range 6 to 7 °C, dew point range 4.3 to 5 °C, pressure range 1028 to 1030.9 hPa). A detailed list of Hamburg weather data for November 15, 2013 is given in Table 60 in annex 9.9. This list is based on data from the weather monitoring equipment at Hamburg Fuhlsbüttel airport, where the test rig is located.

Measurement of the emissions and evaluation were performed by an expert team from DLR (German Aerospace Center). Control of the engine parameters was performed by the Lufthansa team operating the test rig, using the normal control equipment. Changes from one power setting to the next had to be performed gradually, as the fuel flow from the bowser truck had to be manually adjusted for these changes. These periods of power changes were eliminated from analysis by the DLR team, including only periods of established power settings. The timing of the individual segments included in the analysis is given in Table 61 in annex 9.10.

Emissions measured were:

- CO
- NOx
- Particles

The obtained data were converted into emission indices per kilogram of fuel burned, to compensate for dilution. Conversion was performed on the basis of corrected $CO_2$ emissions and known fuel properties.

### 7.1.3 Results

A graphical comparison of CO emissions for the reference kerosene, the 10% SIP kerosene blend and the 20% SIP kerosene blend is shown in Figure 51. Table 62 in annex 9.11 gives the numerical values. CO emissions are basically identical for the two SIP kerosene blends and the reference kerosene. In this graph, SIP kerosene is referred to as farnesane, its original name.

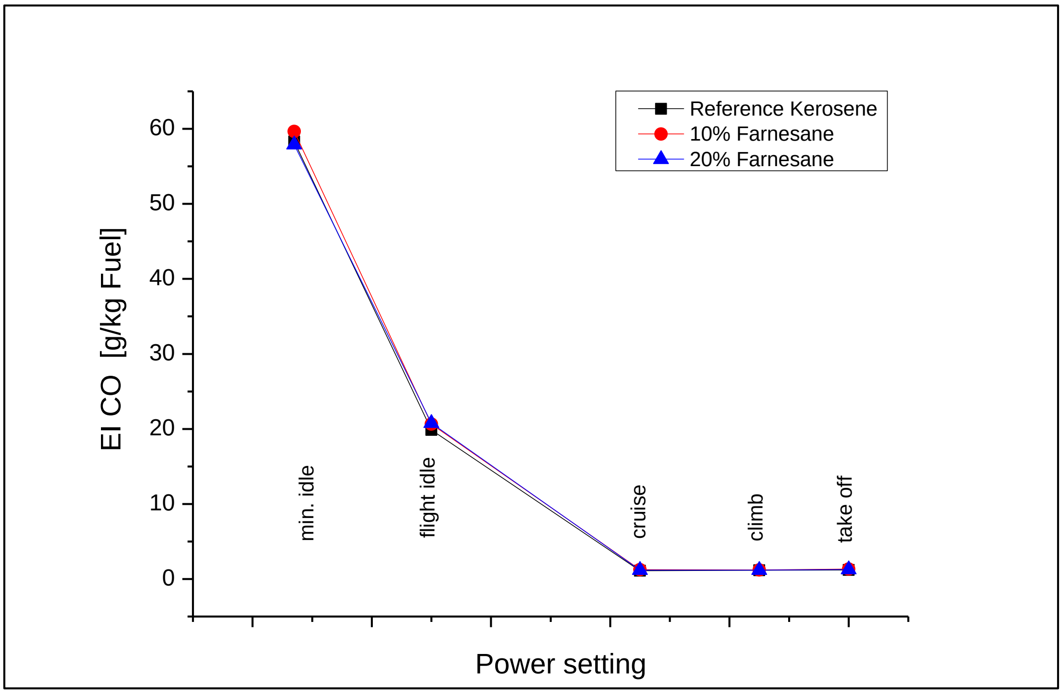

*Figure 51: CO emissions*

For NOx (Figure 52), some difference among the three fuels is discernible. For most power settings, emissions from the SIP kerosene blends are somewhat below the emissions from the reference fuel, whereas for cruise they are somewhat above. However, the figures are similar for all three fuels used. The numerical values contained in the graph are given in Table 63 in annex 9.11.

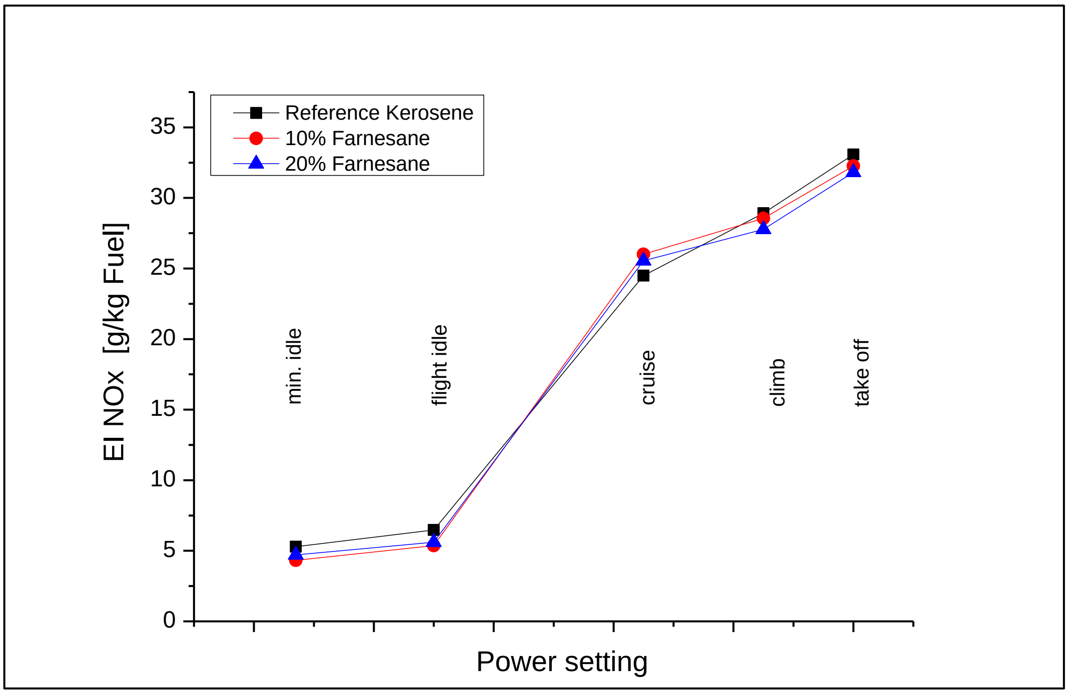

*Figure 52: NOx emissions*

In the case of particle emissions, an improvement at a 20% blend ratio had been expected on the basis of the preceding lab tests, where the ASTM D1322 smoke point for the 20% blend had been significantly higher than that of the reference kerosene (see Table 57 in annex 9.6). For the 10% blend the results from the lab tests had been inconclusive, so it was more doubtful whether an improvement would be seen at that ratio. However, as it turned out the improvement was consistent both for soot mass (Figure 53) and for total surface (Figure 54), occurring both at the 10% and the 20% blend level, and proportional to the blend ratio.

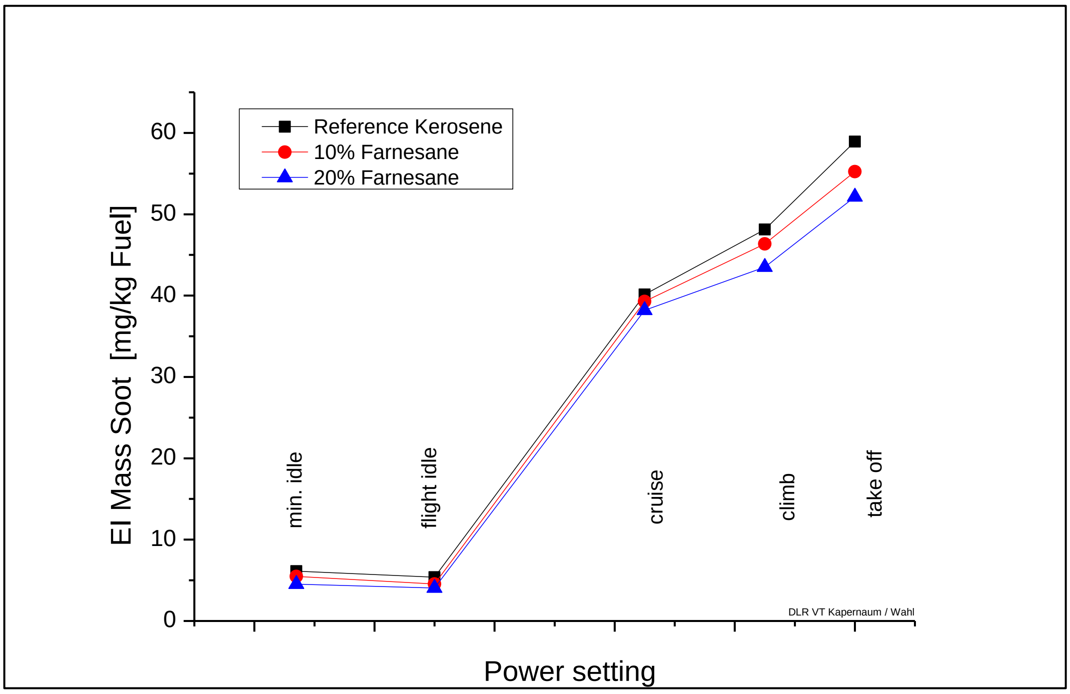

*Figure 53: Particle emissions, total mass*

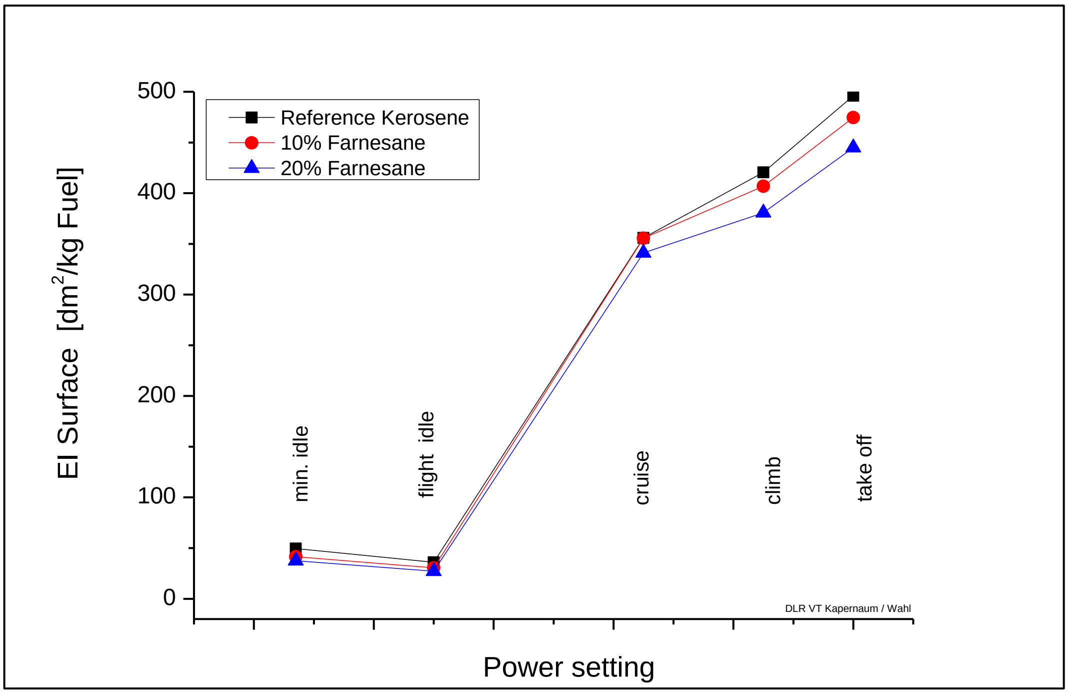

*Figure 54: Particle emissions, total surface*

The calculation of the total surface was performed on the assumption of perfectly spherical particles, which is the standard practice.

The picture is less clear-cut for number of particles (Figure 55) and for average (geometrical mean) particle diameter (Figure 56). The number of particles is lower for the SIP kerosene blends than for the reference kerosene, but there is little difference between the 10% blend and the 20% blend. For average particle diameter, there is no clear pattern.

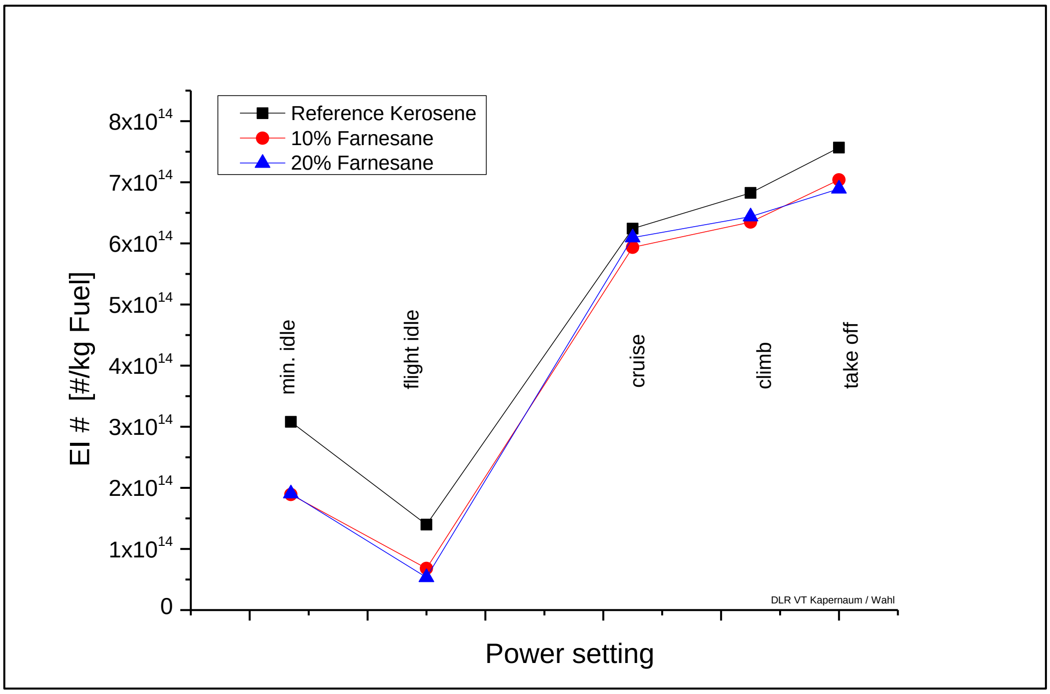

*Figure 55: Particle emissions, number of particles*

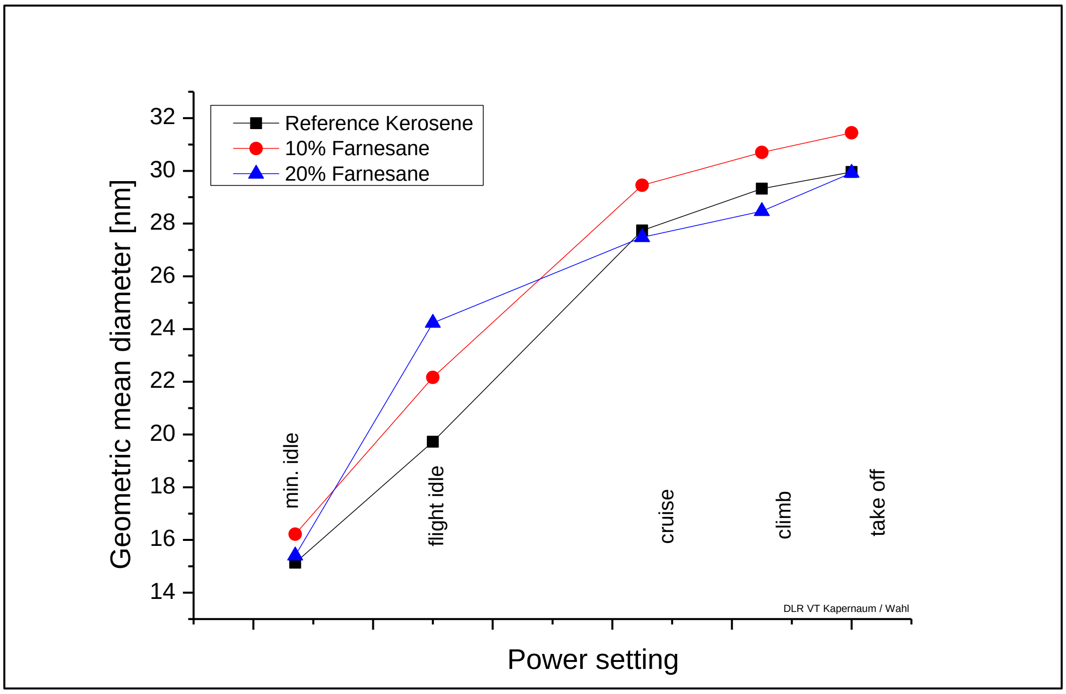

*Figure 56: Particle emissions, average particle diameter (geometric mean)*

The numerical values contained in Figure 53 to Figure 56 are given in Table 64 to Table 67 in annex 9.11.

## 7.2 Effect of CH kerosene on emissions

As the second kerosene to be investigated, ARA CH kerosene was selected. As shown in section 4, this fuel meets all the requirements of fossil kerosene even as neat fuel, without need for blending. It was therefore felt possible to burn the CH kerosene as a neat fuel in an engine without encountering any adverse effects. Using a neat fuel for emissions measurements has the advantage that the results are not impacted by the properties of the fossil kerosene the fuel is blended with. It also is best in keeping with the task of our research which was to analyse bio kerosene at as high percentages as possible. It therefore was decided to use CH kerosene neat without prior blending.

Emissions of ARA CH kerosene had already been determined as part of the Rolls Royce CLEEN program testing.[168] No conclusions were drawn from these tests concerning the ARA fuel, but the published data show virtually no difference to conventional kerosene, including for particle emissions.[169] However, the tests had been conducted using an Auxiliary Power Unit, not a full engine,[170] and the focus of the research clearly was on technical compatibility, making sure that emissions are not worsened by alternative fuels, not on analysing possible improvements.

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[168] Rolls-Royce Alternative Fuels program – Rig Test of Candidate Fuels: Emissions Testing; FAA Report number DOT/FAA/AEE/2015-06; May 2015

[169] Ibid., p. 10/11

[170] Ibid., p. 5

### 7.2.1 Test Setup

The CH fuel was purchased directly from the manufacturer, and imported by Lufthansa from the US. As the fuel was part of a larger batch produced mainly for the US Navy, it already came with an antioxidant (BHT) and a corrosion inhibitor (CI/LI- GE Spec-Aid 8Q22) added, in both cases at a dosage of 24 mg/L. This is however unlikely to have had an effect on emissions, and even if it had it is to be assumed that the reference kerosene contained similar additives. The actual additive content of the reference kerosene is not known, due to the commingling of fuel batches occurring in jet fuel storage, but as a rule jet fuel does contain such additives.[171]

The properties of the CH fuel, as documented by the manufacturer's release certificate, are shown in annex 9.12. It should be noted that the aromatics content of this batch was rather high, at 20.9%, and the smoke point is low at 20.2 mm. In a fossil fuel, such parameters would indicate a fuel tending to produce a fairly high number of particulate emissions. However, for the CH kerosene previously supplied for the lab analysis part of this study, the corresponding parameters were very similar, at 19.7% and 22.5 mm. These parameters therefore seem to be not unusual for CH kerosene.

CH kerosene is as yet not approved by ASTM, and it was felt that it would be problematic to run an in-service engine on 100% of non-approved fuel. Accordingly, the test was conducted using not an in-service engine, but the Lufthansa Technik (LHT) EVE test bed. EVE is a CFM 56-5C4 engine, which is the same type of engine that had been used for the SIP tests. However, the EVE engine has been withdrawn from commercial service, and equipped with extra instrumentation for research purposes. Its prime purpose is to support better modelling of the thermodynamic process within the engine, but it is also available for related research. As it is not an in-service engine, Lufthansa may use non-certified fuels on this engine. All the same, this is a normal engine except for some additional instrumentation, hence results obtained with this engine can be considered representative for operational engines.

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[171] See Lori M. Balster / Steven Zabarnick / Richard C. Striebich / Linda M. Shafer / Zachary J. West: Analysis of Polar Species in Jet Fuel and Determination of their Role in Autoxidative Deposit Formation; in: Energy & fuel 2006, 20, 2564-2571, p. 2566. The experience available in-house at Lufthansa also confirmed that such additives are typically present in jet fuel.

*Figure 57: EVE engine in test rig chamber*

The test was conducted on 3 November 2016. The test arrangement was largely identical to the one described in section 7.1.1, except that this time no blending was necessary, and a larger bowser truck was used, maintaining fuel pressure at the inlet at a fairly constant 40 to 42 PSI, thus permitting automatic adjustment of the fuel flow from the bowser truck to the test cell.

In the case of the previous SIP emissions measurements, engine power points had been determined on the basis of ICAO numbers. However, these are generic values, and typically do not correspond to the appropriate settings for a specific engine type. In consultation with the technical experts of LHT, it was decided to conduct the engine run for the CH kerosene emission measurements at typical power settings for the CFM 56-5C4. This resulted in the engine being run at the following N1 settings, in this order:

- 3 minutes at 4684 RPM (C4 Take-Off)
- 3 minutes at 4398 RPM (C4 Maximum Continuous Thrust)
- 3 minutes at 4292 RPM (C2 Maximum Continuous Thrust)
- 3 minutes at 3800 RPM
- 3 minutes at 3000 RPM
- 5 minutes at 1325 RPM (Flight Idle)
- 5 minutes at 940 RPM (Ground Idle).

As emissions are influenced by the technical state of a given engine, a first run was conducted using the normal fuel feed of the Lufthansa test facility, and the conventional fossil fuel in use at that time. This run established a reference baseline with which to compare the emissions related to the CH kerosene. After the completion of this run the fuel connection of the test cell was switched to the bowser truck, and CH kerosene was fed to the test cell. After completion of this run, a test run with another bio kerosene in connection with another project was conducted. The normal fuel feed of the Lufthansa test facility was then restored, and a second reference run was performed. Performing a second test run permitted estimating the normal variability of the process, so as to better assess the relevance of differences between the emissions from the CH kerosene and the reference kerosene. Each of the four runs was preceded by an engine warm up run at cruise speed setting, which also served to consume the fuel remaining in the pipes from the previous runs.

### 7.2.2 Emissions Measurements

Except that adjustment of the fuel flow from the bowser truck to the test cell was automatic, arrangements for the measuring of emissions were unchanged from those described in section 7.1.2. Weather parameters this time were determined directly at the test cell, using the equipment of the cell. Weather conditions were someone more variable than during the SIP tests, (temperature range 3 to 9 °C, dew point range -0.2 to 3.8 °C, pressure range 14.747 to 14.777 PSI)[172], but still within a fairly narrow range.

All runs were recorded using the instrumentation of the test rig. This instrumentation records more than 200 parameters, and is normally used for the acceptance of engines that have been maintained, and are about to re-enter flight service. By the judgement of the experienced operators of the test rig, the behaviour of the engine during operation on CH kerosene was within what is normally observed, and none of the parameter values recorded for the run on CH kerosene would in any way have prevented acceptance of the engine for operational service if this had been a normal test. Differences between the parameters recorded for the two reference runs and those for the run on CH kerosene were minor.

Figures 58 to 63 compare the emissions measured from the two reference runs to those of the run using CH kerosene. Results are shown for CO emissions, NOx emissions, total mass of particle emissions, total surface of particle emissions, number of particles and average particle diameter. The numerical values contained in the graphs are given in Table 68 to 73 in Annex 13.

In all cases the result is essentially the same: There is no significant difference between the CH kerosene and the two reference runs. Emissions from the CH kerosene actually are worse than emissions from the reference kerosene, particularly for total mass of particle emissions. However, the difference is smaller that the difference between the two reference runs, and hence must be considered as being within the variability of the process.

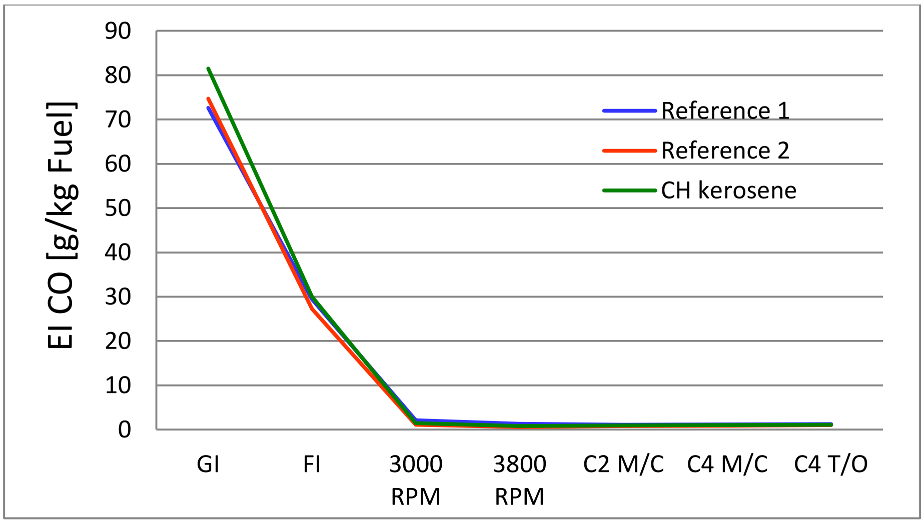

*Figure 58: CO emissions*

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[172] Values prior to the start of the individual test runs.

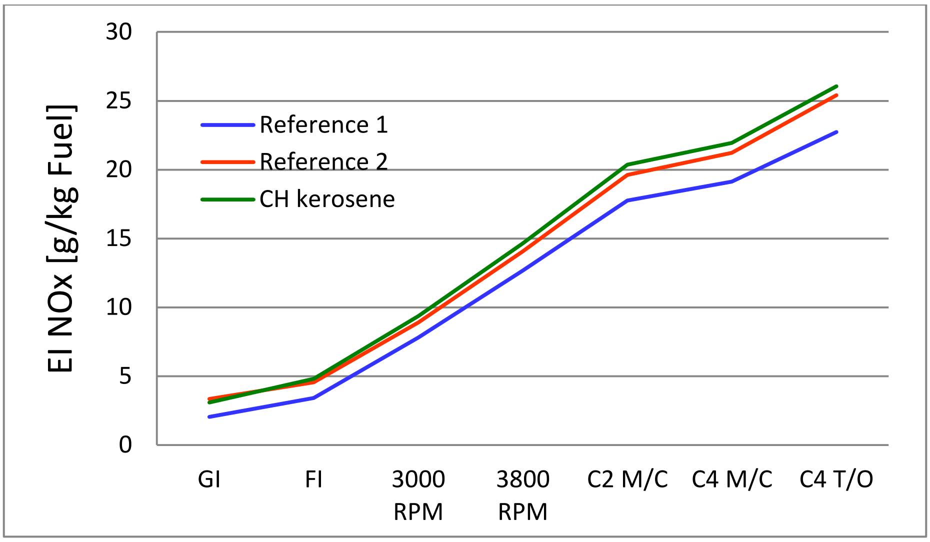

*Figure 59: NOx emissions*

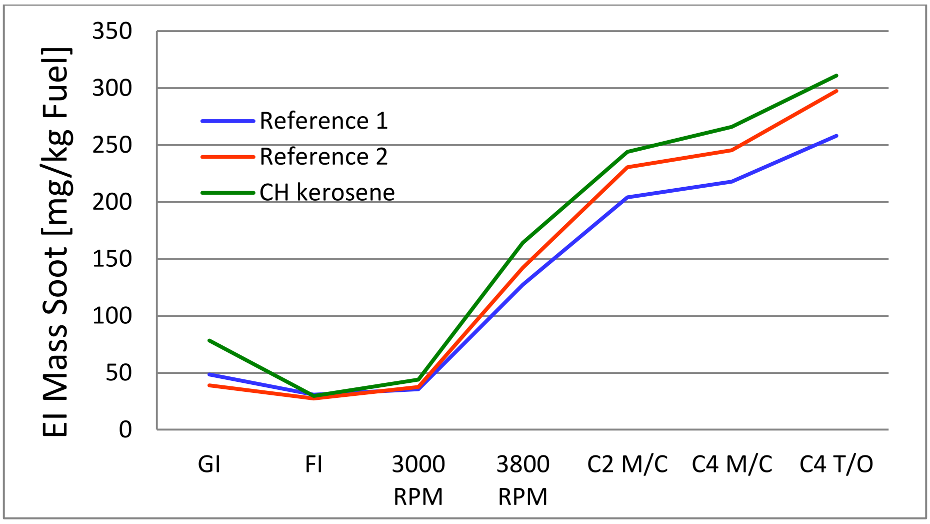

*Figure 60: Particle emissions, total mass*

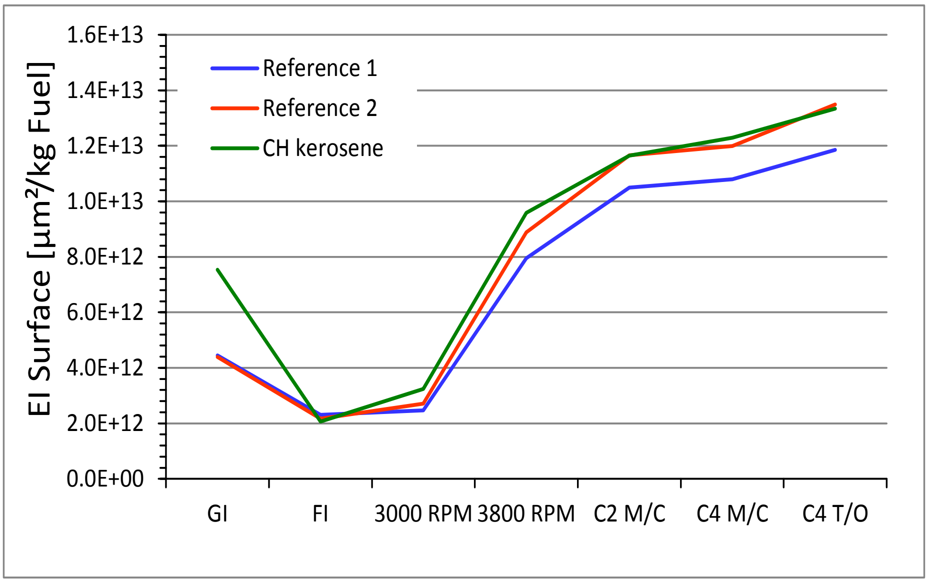

*Figure 61: Particle emissions, total surface*

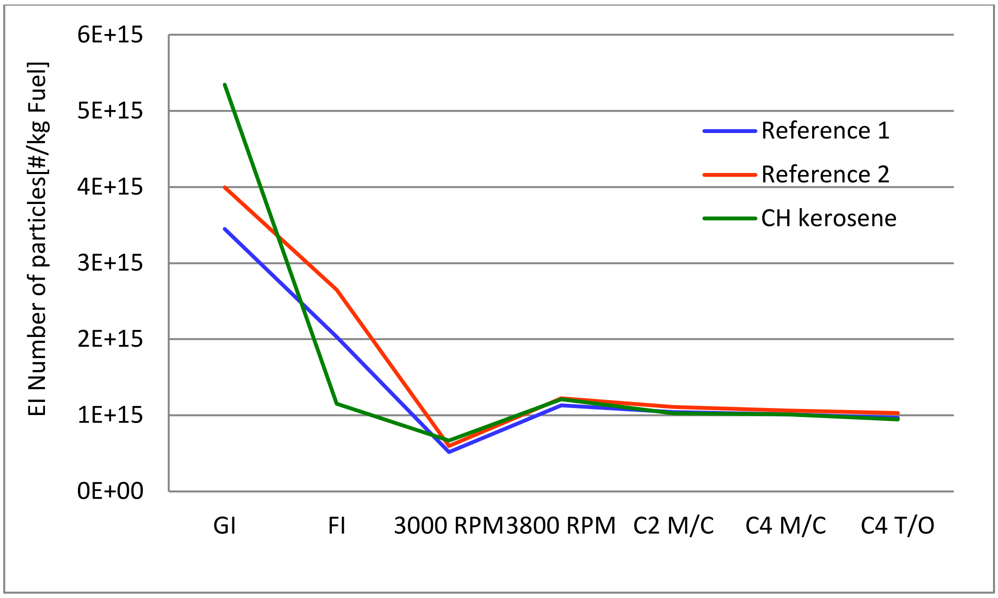

*Figure 62: Particle emissions, number of particles*

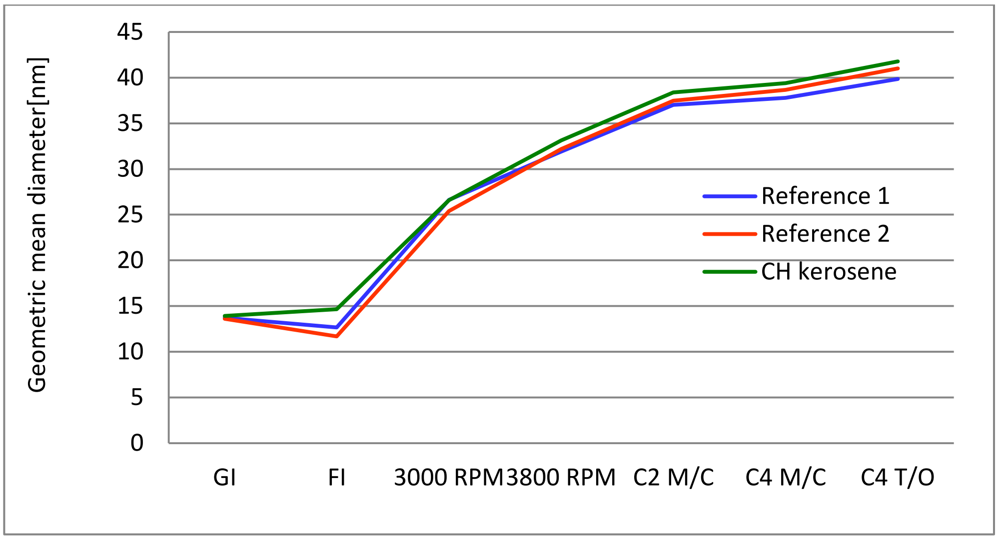

*Figure 63: Particle emissions, average particle diameter (geometric mean)*

This result was expected for CO and for NOx, as the composition of the CH kerosene essentially corresponds to that of a fossil fuel, and little impact had been observed even for SIP (see section 7.1.3). However, given that CH kerosene contains virtually no di-aromatics, it was felt that a positive impact on particle emissions would be perceptible, as di-aromatics are considered to be more conducive to soot formation than mono-aromatics[173]. The fossil reference kerosene, by comparison, had a di-aromatic content of 1.9%, so this expectation was not unreasonable However, this clearly did not happen, at least not in the sense of reducing overall emissions. There may possibly have been a beneficial impact from the absence of di-aromatics, but the kerosene used in Hamburg only had an overall aromatics content of 15.6% and a smoke point of 23.1[174], thus if there was an effect from the absence of di-aromatics in the CH kerosene, it has been overcompensated by the higher overall aromatics content of the CH kerosene. As a matter of fact, such a positive effect from the absence of di-aromatics is likely given that the aromatics content of the CH kerosene of

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[173] ASTM D7566 - 15c, section X1.4

[174] Analysis results provided by DLR

20.9% is some 34% higher than that of the reference kerosene, yet emissions are only worsened to an extent that is not significant. All the same, the effect of the aromatics content clearly dominates.

This result accords well with the results of emission measurements using CH kerosene which have been published in a recent updated version of the ASTM Research Report for CH kerosene[175], citing tests using an Honeywell 131-9 APU[176], a PW615 aero engine[177] and a CF-700-2D-2 static engine[178]. In all these cases, aromatic content of the CH fuel had been slightly less than that of the fossil fuel, and emissions from the CH fuel correspondingly also were slightly lower.

## 7.3 Summary of Emission Measurements

The results of the two sets of measurements conducted are quite different in the individual outcomes, but support the same conclusions.

Blending in SIP fuel, which is essentially the addition of iso-paraffinic material, does not seem to have any effect on CO emissions. There may be an effect on NOx, but the data is not entirely consistent, and the reduction is small. If there is a beneficial effect it is too small to be considered significant, at least for the fairly low percentages of SIP kerosene that were added. What can be said, however, is that at least it can be ruled out that SIP kerosene has an adverse effect on NOx. This was also the result of the burnFAIR emission measurements.[179]

The situation is different for particles, where an improvement of emissions had been expected, as SIP fuel contains no aromatics. This expectation was confirmed: Total mass of particle emissions, total surface of particle emissions and number of particles all went down. This agrees with the results obtained by DLR when analysing the effects of GTL kerosene.[180]

Particle emissions are important as they are considered the major cause for contrails, which in turn are considered a factor contributing to global warming. The size of this contribution is very much under debate: Burkhardt and Kärchner estimate that this effect may be as large as that from aviation's $CO_2$ emissions,[181] but that is not a generally accepted position. However, in spite of the uncertainty about the magnitude of the effect, there is a general consensus that reduction of particle emissions is beneficial; hence the observed outcome is a favourable one for aromatics-free fuel.

The data show no tendency for reduction of particle emissions to be achieved at the expense of producing a large number of extremely small particles, which are considered a potential health issue on the ground. The effect on average particle diameter is not clear, but there is no tendency for average particle diameter to decrease.

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[175] Edward N. Coppola: Renewable Jet Fuel Produced by Catalytic Hydrothermolysis (CH) Readijet, Prepared for ASTM Subcommittee J, August 2016

[176] Ibid, p. 59 - 62

[177] Ibid, p. 65 - 68

[178] Ibid, p. 68 - 75

[179] Deutsche Lufthansa AG: Abschlussbericht ..., op. cit., p. 45-47

[180] Claus Wahl / Manfred Kapernaum / Joris Melkert / Tim Snijders / Joanna Bauldreay / Paul Bogers: Nanoparticle emissions of a flight Gas Turbine running Jet A-1 and GTL Mixtures, 2013

[181] Ulrike Burkhardt / Bernd Kärcher: Global radiative forcing..., op. cit.

Running the engine on neat CH kerosene, which is a fully synthetic bio kerosene and contained some 20% of aromatics, produced no significantly different emissions than the reference runs on fossil kerosene. This held true not only for CO and NOx, but also for particle emissions. CH kerosene emissions were actually higher than for fossil kerosene, although within the process variability.

These results show that it is indeed the absence of aromatics that is the cause for the improvement in particle emissions seen for FT, HEFA, SIP and ATJ-SPK kerosene. Conversely, it also shows that these benefits will be lost if a synthetic kerosene is produced with a high percentage of aromatics. Given the importance of particle emissions discussed above, production and blending strategies should be developed so as to keep the aromatics content at minimum rather than at maximum limits. For fuels like CH kerosene, where aromatics content is a flexible function in the production process, this will not constrain blending, but merely determine which percentage to select when producing the fuel. For other fuels, like HDCJ, this will be a further constraint on blending ratios.

# 8 Conclusions

## 8.1 Conclusions Regarding Physical Properties

### 8.1.1 Properties Critical for Blends

From the investigations conducted in this study, and described in detail in chapter 4, it is clear that some properties will be particularly critical when aiming to blend alternative kerosene at high percentages with conventional fuels. These are summarized and discussed in this section.

**Aromatics**

ASTM D7566 specifies a minimum aromatic content of 8 vol% for bio kerosene blends, yet four out of the six synthetic kerosene investigated in this study contain virtually no aromatic compounds. Therefore aromatic content is of particular importance when blending these fuels.

If the conventional kerosene has a low aromatic content itself, maximum blend ratio regarding aromatic free synthetic fuel may be low. For the set of fuels investigated here, maximum synthetic fuel content ranged from about 42 vol% to 63 vol%.

Aromatic content must therefore be considered a major constraint if blend ratios for synthetic fuel are to be increased beyond the 50 vol% limit. However, conventional fuels with low aromatic content do not even allow blending of 50 vol% synthetic fuel. Since aromatic content depends linearly on blend ratio, it can readily be calculated if the values for the respective blend components are known.

One possible way around this constraint is to increase the blend’s amount of aromatic compounds above the 8 vol% level by adding them as a third component. This approach has been explored in chapter 4.3. However, a high aromatic content of a fuel adversely effects emissions as discussed in detail in chapter 7.

**Density at 15 °C**

Density at 15 °C is again a constraining factor especially for aromatic-free fuels, i.e. FT-, HEFA-, SIP- and ATJ-SPK kerosene. This is partly because aromatic compounds have a fairly high density, and their absence can result in a decreased density of the respective fuel. Moreover, the aromatic-free fuels consist almost exclusively of n-alkanes and iso-alkanes and lack cycloparaffins, which also have a higher density than the n- and iso-paraffins.

The extent to which density at 15 °C is a constraint depends on the properties of both the conventional kerosene and the bio kerosene. For HEFA, investigated blends become off-spec at blend ratios between about 40 vol% and 70 vol% HEFA. The maximum blend ratio resulting from the density constraint is therefore of the same magnitude as that from aromatics content, and in some cases is the more binding one for HVO blends.

For blends with CTL and ATJ-SPK the situation is similar. SIP fuel, on the other hand, has a density of 773.1 kg/m³ which is only slightly below the lower limit of conventional kerosene

(775 kg/m³), hence density is not a constraint until contents of well above 80 vol% SIP fuel have been reached, which is way beyond the targeted blend ratio for SIP fuel.

A possible way of solving the density issue is the addition of both cycloparaffins and aromatics, which is the idea behind the synthetic fuels currently being developed by Shell/ Virent (see sections 3.8 and 3.9). Once such blend stocks have been approved, they should help to raise the density of the blends to the required values.

**Distillation Curve Gradients (T50-T10 and T90-T10)**

A major result of this study is the importance of distillation curves gradients. They are not an issue for HEFA, which has a steep gradient, such that its incorporation actually improves T50-T10 and T90-T10 for all conventional kerosene used in this study. It also is not an issue for CH kerosene, which also has a steep distillation curve. However, it is extremely critical for ATJ-SPK, where T50-T10 is very low and therefore severely curtails achievable blend ratios. For four of the conventional fuels used in this study maximum possible blend ratios are between 10 and 40 vol% ATJ-SPK, and in one case blending with ATJ-SPK resulted in fuels being off-spec at all blend ratios.

The situation is similar for neat CTL where T50-T10 and T90-T10 are below the minimum values required for the blend. From the distillation curves for FT published in literature it appears that this is typical for FT kerosene, although it is also possible to produce FT kerosene with a steep distillation curve gradient.[182] Surprisingly enough also for neat ATJ-SKA both T50-T10 and T90-T10 were below the specification minima for the blend, although this fuel has been designed as a fully synthetic fuel and otherwise meets ASTM D7566 requirements in all respects. Again, however, is also possible to produce this fuel with a steeper distillation curve gradient.

SIP fuel consists almost exclusively of a single compound, and hence by itself has a very narrow distillation range. However, its boiling point is high, hence blending conventional keronese with SIP fuel actually improves T50-T10 and T90-T10 for the investigated blends up to 50 vol% SIP for all conventional kerosene used in this study.

It needs to be pointed out that the distillation curve gradient requirement is only specified for blends with synthetic fuels, but not for conventional kerosene. This requirement was introduced when ASTM certified CTL blends as a jet fuel, and was based on the recognition that the CTL samples on which ASTM certification was based had a fairly broad distribution of alkanes of different carbon chain lengths, but that it was also possible to produce CTL with a far narrower distribution and otherwise still remain on-spec. As such fuels had not been investigated during the certification process, there was concern that this might possibly cause problems, hence the distillation curve gradient requirements were explicitly introduced to ensure that the CTL fuels feature a distillation range which covers at least the distillation range of three consecutive n-alkanes.

It has been argued by Gevo that in the case of ATJ-SPK a very narrow distillation range was given throughout the entire ASTM process. These fuels were extensively researched and found not to pose a problem. Hence, no requirements to safeguard against a fuel with such composition should be necessary. On the basis of this logic it can be challenged whether the

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[182] See e.g. Edwin Corporan / Tim Edwards / Linda Shafer / Matthew J. DeWitt / Christopher Klingshirn / Steven Zabarnick / Zachary West / Richard Striebich / John Graham / Jim Klein: Chemical, Thermal Stability, Seal Swell, and Emissions Studies of Alternative Jet Fuels, in: Energy Fuels 2011, 25, 955-966: page 958, table 2

T50-T10 and T90-T10 requirements really are necessary, or whether they can be abandoned at least for ATJ-SPK. However, as long as these requirements exist they will be major restricting factors for practical blending for some alternative fuels.

### Cold Flow Viscosity

ASTM D1655 specifies a maximum viscosity of 8 mm²/s at -20°C. This requirement was met by all blends analysed in this study, and with the exception of neat SIP fuel was also met by all neat synthetic kerosene investigated. Even though viscosity at -20°C for neat SIP fuel was far too high, all blends up to 50 vol% of SIP fuel stayed comfortably below 8 mm²/s. Viscosity at -20°C therefore was not found to be a limiting factor for blending.

However, from an aviation safety point of view the relevant parameter is not viscosity at -20°C, but viscosity at -40°C, since this is the parameter relevant for APU relight. APUs are required to start at -40°C provided the viscosity of the fuel at this temperature is 12 mm²/s or less. Version 14a of ASTM D7566 therefore introduced an additional requirement of a maximum viscosity at -40°C of 12 mm²/s for blends, and it is under discussion to turn this into a general requirement for all aviation kerosene.

ASTM D7566 version 14a was only published in June 2014, by which time the analyses conducted for this study were already largely completed. It therefore was not possible to include viscosity at -40°C in the study. However, it is possible to approximate results for viscosity at -40°C by looking at values for viscosity at -20°C. Although the exact relationship between viscosity at -20°C and viscosity at -40°C varies from fuel to fuel, as a rule of thumb it can be said that a fuel has a high probability of not meeting the 12 mm²/s at -40°C requirement if its viscosity at -20°C is 5.5 mm²/s or higher.[183] For all blends analysed in this study which showed a viscosity at -20°C of 5.5 mm²/s or higher it is therefore quite likely that they would have failed the test at -40°C, although it is not possible to say so with certainty.

However, using the lower threshold value of 5.5 mm²/s does not change the picture very much, as all of the fossil fuels and all of the bio kerosene except SIP fuel have viscosities at -20°C of well below 5.5 mm²/s. The only blends with values above 5.5 mm²/s were blends with SIP fuel at 35 and 50%. The additional requirement of having a maximum viscosity of 12 mm²/s at -40°C therefore is not likely to affect achievable blend ratios of bio kerosene other than SIP fuel, for which it is the most binding constraint.

It needs to be pointed out, however, that this statement is strictly true only where the cold flow viscosity of the conventional fuel can be relied to be 12 mm²/s or less at -40°C. If this is not the case there will be an impact, albeit an unusual one in that e.g. HEFA kerosene will improve this property in the blend, hence low blend ratios with synthetic fuel may be off-spec while high blend ratios are not. As was shown in chapter 2 outside North America viscosity at -40°C can be expected to be below 12 mm²/s, hence outside North America this is more of a theoretical issue. It can be practical issue for blends with Jet A-1 produced in North America, where viscosities are markedly higher than elsewhere, and probably even more so for blends with Jet A.

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[183] Honeywell communication at San Diego ASTM conference, December 2014

### 8.1.2 Other Properties of Interest

Two properties analysed in this study, lubricity and freezing point, were not found to be constraining factors for blend ratios, but are worth mentioning because their dependency on blend ratio qualitatively differs from that of most of the other parameters.

#### Lubricity

In the case of most parameters assessed in this study, their dependence on blend ratio was found to be linear. Some parameters exhibited non-linear behaviour which nevertheless could be described using more complex mathematical terms (cf. viscosity). However, in the case of lubricity, this is not the case and no correlation with blend ratio was found.

The effect that minor concentrations of compounds with high lubricity significantly improve the lubricity of the whole mixture is well known and is used for example in form of lubricity improvers in fuels. Lubricity is a surface related effect that only weakly depends on the concentration of the respective compound in the fuel.

One observation is that if there is a marked difference between the lubricity of the conventional and the synthetic fuel, the better lubricity usually prevails. In the case of SIP fuel, which has a markedly good lubricity, blends with 10 vol% SIP fuel already show significantly improved lubricity. On the other hand neat HEFA fuel has a far too poor lubricity to meet the specification for aviation kerosene, but even at 90 vol% HEFA the blend is still comfortably within the specification limits.

A further observation is that in several cases lubricity for a certain blend was determined to be outside the interval defined by the values of the respective neat conventional and synthetic fuel. This was most evident in the case of blends of CH kerosene with fuel 112, where lubricity of the various blends was consistently better than lubricity of either neat component.

From the point of view of maximizing bio kerosene blend ratios lubricity needs not be considered a critical factor, particularly given the tendency of the better lubricity to dominate in the blend. However, the behaviour of this property is difficult to predict.

#### Freezing Point

Freezing point is the second property where in one case the observed values for a blend lay outside the interval defined by the neat fuels. This was observed in the case of a HEFA blend (10 – 50 vol%) with a conventional fuel that featured a freezing point close to that of HEFA.

The depression of freezing point in blends of synthetic and conventional fuels was also found for most of the other synthetic fuels used in the study, although less pronounced. This effect is the more obvious, the more similar the freezing points of the neat blend components are. The same phenomenon has already been observed for CTL blends, and filed as a patent, by Shell.[184]

Interestingly enough, the depression was also found in the case of CH fuel, although the composition of this fuel is close to that of conventional fuels.

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[184] Joanna Margaret Bauldreay, Richard John Heins, Johanne Smith: Depressed Freeze Point Kerosene Fuel Compositions and Methods of Making and Using same, Patent No. US 7,666,294 B2, 23. February 2010

## 8.2 Conclusions Regarding Fuel Type

The fuels analysed in this study can be sorted into five different groups

1. **Fuels largely consisting of n- and iso-paraffins**. To this group belong FT-, HEFA- and ATJ-SPK fuels.
2. **Fully synthetic fuels that have a composition similar to conventional fuels**. To this group belong ATJ-SKA and CH fuel.
3. **Fuels that are designed as blend components**. These are HDO-SK (primarily cycloparaffins) and HDO-SKA (exclusively aromatics).
4. **HDCJ fuel with an aromatic content of some 50 vol%**.
5. **SIP which consists virtually of one single compound**.

For all fuels in the first group, lack of aromatics is a major constraint, as ASTM D7566 requires a minimum aromatics content of 8 vol%. Depending on the conventional fuel, this parameter limits achievable blend ratios to typically 40-70 vol%, independent of the maximum blend ratio set by ASTM (currently at 50 vol% for FT- and HEFA fuels, but expected to be released eventually).

The second limiting factor for these fuels is density, which typically is almost as constraining as aromatics content, and in some cases even more so.

For ATJ-SPK, distillation curve gradients (particularly T50-T10) are the key constraining factor, which in the study in all cases was found to be more restrictive for ATJ-SPK blend ratios than either aromatics content or density.

For the second group of fuels, because of their intended use as full-fledged substitutes for conventional fuels there should be no constraints for maximum blend ratios. This was confirmed for CH fuels, but surprisingly for ATJ-SKA distillation curve gradients were an issue, and constrained achievable blend ratios to 50-70 vol%. None of the other parameters were a constraint for ATJ-SKA, and as was discussed before the manufacturer of the fuel has since documented that the low gradients were specific to the individual batch investigated, and it is also possible to produce fuel with steeper distillation curves with this pathway.

For the third group, no fuel was available for analysis in this study. However, from the material provided to ASTM, and from the statements of the manufacturer, it is clear that these fuels are not primarily designed for binary blends with conventional fuel, but are intended to be added to blends of fuels from the first group with conventional fuel, to provide the components which the fuels of the first group lack, i.e. aromatics (HDO-SKA) and cycloparaffins (HDO-SK).

The potential benefit from these fuels is evident, and the market logic behind their development is clear. How well these fuels actually perform could not be assessed because they were not available. Nevertheless, the effect of addition of aromatics on blend properties was investigated in the study by using a mixture of aromatics that closely resembles the set of aromatic compounds present in conventional fuels. These were used to raise aromatic content for selected blends to 8 vol%, as required by ASTM D7566. Besides the increase of aromatic content, their addition, as expected, increases density. It has to be noted that the increase in density is weak for small quantities of aromatics. If one intended to use larger quantities of aromatics to increase density, their impact on properties like smoke point must not be underestimated.

To raise density significantly, further addition of cycloparaffins would be necessary. However, addition of cycloparaffins was not investigated. The impact of aromatics on distillation was found to be negligible.

HDCJ was not available for analysis. From the information provided for ASTM certification, HDCJ is intended as a biofuel for blending with conventional kerosene, not as blendstock for the improvement of other blends.[185] However HDCJ has an aromatics content of some 50 vol%, which is way above the permitted maximum for aviation kerosene of 25 vol%, hence any blending with conventional kerosene must serve to dilute aromatic content to specification limits. The blend ratios actually achievable will depend on the aromatic content of the conventional fuel. The maximum blend ratio suggested in the ASTM documents is 30 vol%, but given the aromatic content of conventional kerosene (chapter 2) actual blend ratios will in most cases be considerably lower. It therefore seems that aromatic content will be the major constraint for HDCJ blend ratios, but in the reverse situation from that of group 1 fuels, being too high rather than too low. This holds double when considering that due to emissions considerations an aromatics content of well below the maximum figure should be aimed at in the target blend (see section 7.3).

For SIP fuels, the limiting factor is viscosity at -40°C. We were not able to include measurement of this parameter in the study as the respective requirement was only introduced into ASTM D7566 when most of the lab work was already finished. However, calculation based on viscosity at -20°C indicates that viscosity at -40°C will typically prevent SIP contents beyond 20-30 vol% (see section 8.1). ,

## 8.3 Conclusions on the Role of Aromatics

### 8.3.1 Effects of Synthetic Fuel on Elastomers

The effect of various bio kerosene on elastomers is discussed in chapter 6. For the aromatics-free fuels clearly visible differences to conventional fuels were identified for NBR material, particularly with regard to mass and volume change. The point here was not that NBR material exposed to the aromatics free material shrank - there was only a minor decrease in mass, and no change at all in volume. Rather, the issue was that the material did not increase in either volume or mass, whereas immersion in conventional kerosene resulted in an increase of both volume and mass that was directly proportional to the aromatics content of those fuels.

For the other NBR properties, there was only a weak relationship between aromatics content and the parameter values, and in the case of tensile strength, the aromatics-free fuels actually outperformed. However, according to the feedback we received when discussing our results with experts in the field, the crucial properties are mass and volume, as in practical operations NBR seals are subject to wear and shrinkage that must be compensated by the expansion of the materials due to the aromatics.

This effect is said[186] to be most pronounced if there is a switch from an aromatics-rich to an aromatics-poor environment, as was simulated in the study by immersing NBR material first

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[185] Edwards/Trewella/Sanchez/Leisenring, op. cit, p. 6

[186] information provided by Freudenberg

in the one and then in other type of fuel. The simulation however only weakly confirms this statement. The results for mass and volume change were a little stronger than when the NBR material had been directly immersed in aromatics free fuel, but the differences were minor and not significant. We can however not rule out that the set-up of the experiment was not suitable to capture the effects that occur in practical operation.

The effect on NBR seals was essentially the same for all aromatics-free fuels, with fairly little differences observed among them. On the other hand CH kerosene, which already contains aromatics, performed similar to conventional kerosene. This confirms that the effect is indeed largely the result of the presence or absence of aromatics, as was also confirmed by adding various percentages of aromatics to the aromatics-free fuels, and then measuring the effects on NBR seals.

Effects of the bio kerosene on fluorocarbon and fluorosilicone material were also investigated, but here no relevant effect was observed. Use of aromatics-free fuel therefore does not seem to be an issue for this type of material. To the extent that fluorocarbon and fluorosilicone materials can also be used in the ambient temperature range, where NBR materials are used, it would in principle be possible to use fluorocarbon or fluorosilicone to replace NBR material and hence dispose with the need for aromatics in the fuel. However this would be uneconomic as fluorocarbon and fluorosilicone material is far more expensive than NBR material, and at any rate fluorocarbon material has a glass transition temperature around -20°C[187] and hence may have problems at very cold temperatures. It would also currently be pointless as at the moment almost all kerosene still contains aromatics anyway.

### 8.3.2 Effects of Synthetic Fuel on Emissions

The effects of synthetic kerosene on engine emissions are covered in chapter 7. Two series of emission measurements were made, one on SIP kerosene that contains no aromatics, and one on CH kerosene that contained 20.9% of synthetic aromatics.

Evidence from the measurement on SIP kerosene indicated that its effect on CO2 emissions is virtually nil, the effect on NOx is minor but the effect on particle emissions is very evident. This effect of aromatics-free bio kerosene on emissions has since then been confirmed by further research.[188] The absence of aromatics had generally been considered to be the major factor behind the reduction in particle emissions, but had so far been empirically inseparable from the effects of trace contaminants, which also are essentially absent in bio kerosene but are present in fossil fuel.

The measurements performed on CH kerosene conclusively prove that the effect predominantly results from the absence of aromatic compounds, since the aromatics-containing CH kerosene resulted in emissions indistinguishable from those of the test runs with fossil kerosene. Neither the absence of trace contaminants nor the absence of di-aromatics seems to have had more than a minor impact, at least not when compared to a good quality fossil fuel, as such fuels already are quite clean.

In order to have an effect on non-CO2 emissions, synthetic fuels should have as little aromatic content as is possible. In principle, this is not a problem: Unlike fossil kerosene,

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[187] Rolls-Royce Alternative Fuels Program – Rig Test of Candidate Fuels: Elastomer Testing; FAA Report Number DOT/FAA/AEE/2015-7; May 2015, p. 17

[188] For an overview, see Braun-Unkhoff M., Riedel U., Wahl C., 2016: “About the Emissions of Alternative Jet Fuels”, CEAS Aeronautical Journal, (), 1-14, doi: 10.1007/s13272-016-0230-3

where the aromatic compounds are inevitably introduced by the crude oil, synthetic kerosene is actually easier to produce without than with aromatic compounds. However, as discussed in section 6, aromatic compounds are necessary to preserve the tightness of seals and valves. In the long run it may be possible to move to non-aromatic kerosene by moving away from NBR materials for seals and valves, but that is not a realistic prospect for the near term.

For the foreseeable future, therefore, aviation will have to live with the two-faced nature of aromatic compounds, which are indispensable in the fuel while it is being pumped or stored, but are a disadvantage when it is being burnt. However, the emergence of synthetic fuels at least gives the possibility to make a conscious decision on what had previously been an inevitable effect of the crude oil source, by minimising the aromatics content to what is compatible with aviation safety.

To identify this minimum aromatics content should therefore be one focus of future research. The 8% minimum limit introduced by ASTM on a rule of thumb basis should be empirically verified, and if possible be lowered a result of research. In addition, it seems sensible to continue the approach pursued by Shell with the HDO fuels (see sections 3.8 and 3.9) of identifying specific aromatic compounds which have the required beneficial effect on seals but burn fairly clean. Using these two approaches, it should be possible in the future to come up with a bio kerosene that is fully synthetic, safe to use and contributes to a reduction of aviation emissions below the current levels.

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# 9 Annex

## 9.1 Annex 1: Properties of the Conventional Kerosene

| Property | Method | 085 | 100 | 112 | 114 | 117 | 123 |
|---|---|---|---|---|---|---|---|
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.001 | 0.003 | 0.001 | <0.001 | 0.001 |
| Aromatics [vol%] | D1319 | 21.6 | 18.1 | 18.1 | 13.7 | 16.2 | 15.1 |
| Distillation [°C] | D86 | | | | | | |
| IBP (°C) | | 151.2 | 156.2 | 170.6 | 155.6 | 159.7 | 154.7 |
| 10 vol% recovered at T [°C] | | 167.2 | 168.8 | 183.9 | 169.8 | 175.3 | 165.5 |
| 50 vol% recovered at T [°C] | | 186.4 | 189.0 | 200.2 | 195.1 | 198.4 | 180.6 |
| T50 – T10 [°C] | | 19.2 | 20.2 | 16.3 | 25.3 | 23.1 | 15.1 |
| 90 vol% recovered at T [°C] | | 216.3 | 225.4 | 226.1 | 238.9 | 235.6 | 219.0 |
| T90 – T10 [°C] | | 49.1 | 56.6 | 42.2 | 69.1 | 60.3 | 53.5 |
| FBP [°C] | | 243.7 | 241.7 | 246.6 | 258.5 | 256.1 | 236.7 |
| Residue [vol%] | | 1.1 | 1.1 | 1.1 | 1.2 | 1.2 | 1.1 |
| Loss [vol%] | | 0.9 | 0.9 | 1.1 | 0.9 | 0.9 | 0.8 |
| Flash point [°C] | IP170 | 40.5 | 44.5 | 53.0 | 44.0 | 46.0 | 41.5 |
| Density at 15°C [kg/m³] | D4052 | 797.5 | 795.6 | 818.6 | 795.0 | 811.7 | 789.0 |
| Freezing point [°C] | D7153 | -63.0[a] | -57.6 | < -80.0 | -49.0 | -59.8 | -61.9 |
| Lubricity [mm] | D5001 | 0.739 | 0.698 | 0.645 | 0.728 | 0.703 | 0.751 |
| Viscosity at -20°C [mm²/s] | D445 | 3.113 | 3.335 | 4.357 | 3.778 | 4.059 | 3.008 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.170 | 43.275 | 43.073 | 43.391 | 43.174 | 43.370 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1a | 1b |
| Smoke Point [mm] | D1322 | 21.0 | 23.5 | 21.0 | 26.0 | 22.5 | 25.5 |
| Naphthalene [vol%] | D1840 | 0.69 | 0.13 | 0.30 | 1.17 | 0.41 | 0.16 |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | 0.0014 | 0.0009 | 0.0015 | <0.0003 | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | 0.0145 | 0.0048 | 0.10 | < 0.001 | < 0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 10: Properties of the six conventional Jet A-1 fuels. Methods are according to ASTM unless specified otherwise.*
*[a] The method used for measuring freezing point of lot 085 was ASTM D2368*

## 9.2 Annex 2: Properties of the Alternative Kerosene

| **Property** | **Method** | **SIP** | **HEFA** | **CTL** | **CH-kerosene** | **ATJ-SPK** | **ATJ-SKA** |
|---|---|---|---|---|---|---|---|
| Acidity, total [mg KOH/g] | D3242 | 0.002 | 0.001 | 0.001 | 0.014 | 0.002 | 0.003 |
| Aromatics [vol%] | D1319 | - | - | - | 19.7 | - | 15.8 |
| Distillation [°C] | D86 | | | | | | |
| IBP (°C) / Boiling Point for SIP (°C; acc. to ASTM 1120) | | 247[a] | 148.9 | 166.0 | 152.1 | 174.6 | 164.8 |
| 10 vol% recovered at T [°C] | | | 162.9 | 171.5 | 171.4 | 178.0 | 174.8 |
| 50 vol% recovered at T [°C] | | | 210.3 | 179.5 | 200.1 | 180.9 | 186.7 |
| T50 – T10 [°C] | | | 47.4 | 8.0 | 28.7 | 2.9 | 11.9 |
| 90 vol% recovered at T [°C] | | | 270.8 | 198.7 | 244.8 | 220.1 | 205.6 |
| T90 – T10 [°C] | | | 107.9 | 27.2 | 73.4 | 42.1 | 30.8 |
| FBP [°C] | | | 277.6 | 215.2 | 258.5 | 249.8 | 249.6 |
| Residue [vol%] | | | 1.2 | 1.1 | 1.5 | 1.2 | 1.1 |
| Loss [vol%] | | | 1.1 | 1.1 | 0.9 | 0.9 | 1.1 |
| Flash point [°C] | IP170 / | 107.5[b] | 42.0 | 46.0 | 42.5 | 47.5 | 48.5 |
| Density at 15°C [kg/m$^3$] | D4052 | 773.1 | 756.7 | 761.2 | 805.2 | 757.1 | 785.9 |
| Freezing point [°C] | D7153 | <-80.0 | -54.4 | - | -41.3 | <-80.0 | <-80.0 |
| Lubricity [mm] | D5001 | 0.562 | 0.906 | 0.780 | 0.570 | 0.839 | 0.606 |
| Viscosity at -20°C [mm$^2$/s] | D445 | 14.13 | 4.801 | 3.71 | 3.977 | 4.795 | 3.421 |
| Existent gum [mg/100 mL] | D381 | 10.0 | <1 | <1 | <1 | 2 | 1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | |
| Deposit Rating | | <1 | 1[c] | <1[c] | <1 | <1[c] | <1 |
| Pres. Drop [mm Hg] | | 0.0 | 0.0[c] | 280.0[c] | 0.0 | 0.0[c] | 0.0 |
| Net Heat of Combustion [MJ/kg] | D3338 | - | 44.154 | - | 43.202 | - | 43.396 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1b | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | - | - | >45.0 | 22.5 | 27.0 | 23.0 |
| Naphthalene [vol%] | D1840 | - | - | - | 0.35 | - | 0.08 |
| Mercaptane Sulphur [wt.%] | D3227 | - | <0.0003 | <0.0003 | - | <0.0003 | - |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Water Reaction, Appearance | | - | 1b | 1b | 1b | 1b | 1 |

*Table 11: Properties of the six synthetic fuels*

*[a] Boiling Point of neat SIP fuel was determined according to ASTM 1120*

*[b] Flash Point for neat SIP fuel was determined according to DIN EN ISO 2719*

*[c] Thermal stability was determined at 325 °C*

## 9.3 Annex 3: Properties of the Blends

| | | blends of fossil fuel with 10 vol% SIP fuel | | | | | |
|---|---|---|---|---|---|---|---|
| Property | Method | 085 | 100 | 112 | 114 | 117 | 123 |
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.001 | 0.003 | 0.001 | <0.001 | 0.001 |
| Aromatics [vol%] | D1319 | 19.4 | 16.0 | 16.1 | 12.2 | 14.7 | 13.6 |
| Distillation [°C] | D86 | | | | | | |
| IBP (°C) | | 153.5 | 160.3 | 172.7 | 157.4 | 161.4 | 157.4 |
| 10 vol% recovered at T [°C] | | 166.2 | 169.6 | 182.8 | 171.3 | 174.4 | 166.4 |
| 50 vol% recovered at T [°C] | | 191.0 | 193.7 | 203.5 | 201.2 | 202.2 | 186.3 |
| T50 – T10 [°C] | | 24.8 | 24.1 | 20.7 | 29.9 | 27.8 | 19.9 |
| 90 vol% recovered at T [°C] | | 224.9 | 230.7 | 229.8 | 241.0 | 236.4 | 226.6 |
| T90 – T10 [°C] | | 58.7 | 61.1 | 47.0 | 69.7 | 62.0 | 60.2 |
| FBP [°C] | | 244.8 | 243.2 | 244.7 | 256.6 | 250.4 | 240.9 |
| Residue [vol%] | | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |
| Loss [vol%] | | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| Flash point [°C] | IP170 | 42.5 | 46.0 | 55.5 | 46.0 | 48.0 | 44.0 |
| Density at 15°C [kg/m³] | D4052 | 795.1 | 793.4 | 814.1 | 792.8 | 807.9 | 787.1 |
| Freezing point [°C] | D7153 | -64.0a | -58.7 | < -80.0 | -49.9 | -60.9 | -63.1 |
| Lubricity [mm] | D5001 | 0.606 | 0.619 | 0.614 | 0.647 | 0.635 | 0.643 |
| Viscosity at -20°C [mm²/s] | D445 | 3.491 | 3.739 | 4.790 | 4.227 | 4.477 | 3.381 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.256 | 43.354 | 43.160 | 43.455 | 43.245 | 43.444 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1a | 1b |
| Smoke Point [mm] | D1322 | 22.0 | 23.0 | 21.5 | 25.5 | 24.0 | 25.0 |
| Naphthalene [vol%] | D1840 | 0.63 | 0.13 | 0.26 | 1.04 | 0.37 | 0.13 |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | 0.0013 | 0.0008 | 0.0014 | <0.0003 | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | 0.001 | 0.0136 | 0.0048 | 0.0938 | <0.001 | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 12: Properties of the five conventional Jet A-1 fuels blended with 10 vol% SIP fuel. Methods are according to ASTM unless specified otherwise. [a]The method used for measuring freezing point was ASTM D2368.*

| | | blends of fossil fuel 100 with SIP fuel | | | |
|---|---|---|---|---|---|
| Property | Method | 10 vol% | 20 vol% | 35 vol% | 50 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.002 | 0.002 | 0.002 |
| Aromatics [vol%] | D1319 | 16.0 | 14.3 | 11.5 | 8.5 |
| Distillation [°C] | D86 | | | | |
| IBP (°C) | | 160.3 | 162.8 | 166.3 | 170.2 |
| 10 vol% recovered at T [°C] | | 169.6 | 171.9 | 176.9 | 183.0 |
| 50 vol% recovered at T [°C] | | 193.7 | 199.6 | 211.5 | 223.2 |
| T50 – T10 [°C] | | 24.1 | 27.7 | 34.6 | 40.2 |
| 90 vol% recovered at T [°C] | | 230.7 | 235.6 | 241.3 | 243.2 |
| T90 – T10 [°C] | | 61.1 | 63.7 | 64.4 | 60.2 |
| FBP [°C] | | 243.2 | 244.2 | 246.0 | 245.7 |
| Residue [vol%] | | 1.3 | 1.3 | 1.3 | 1.3 |
| Loss [vol%] | | 0.6 | 0.6 | 0.6 | 0.6 |
| Flash point [°C] | IP170 | 46.0 | 48.5 | 51.5 | 55.5 |
| Density at 15°C [kg/m³] | D4052 | 793.4 | 790.9 | 787.3 | 784.2 |
| Freezing point [°C] | D7153 | -58.7 | -59.6 | -61.6 | -64.6 |
| Lubricity [mm] | D5001 | 0.619 | 0.616 | 0.613 | 0.600 |
| Viscosity at -20°C [mm²/s] | D445 | 3.739 | 4.182 | 5.079 | 6.235 |
| Existent gum [mg/100 mL] | D381 | <1 | 3 | 4 | 4 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.354 | 43.433 | 43.557 | 43.672 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 23.0 | 25.0 | 27.5 | 34.0 |
| Naphthalene [vol%] | D1840 | 0.13 | 0.11 | 0.09 | 0.06 |
| Mercaptane Sulphur [wt.%] | D3227 | 0.0013 | 0.0012 | 0.0009 | 0.0007 |
| Sulphur [wt.%] | DIN EN ISO 14596 | 0.0136 | 0.0118 | 0.0095 | 0.0073 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b |

*Table 13: Properties of Jet A-1 fuel 100 blended with 10, 20, 35 and 50 vol% SIP fuel. Methods are according to ASTM unless specified otherwise.*

| | | blends of fossil fuel 117 with SIP fuel | | | |
|---|---|---|---|---|---|
| Property | Method | 10 vol% | 20 vol% | 35 vol% | 50 vol% |
| Acidity, total [mg KOH/g] | D3242 | <0.001 | <0.001 | <0.001 | <0.001 |
| Aromatics [vol%] | D1319 | 14.7 | - | - | 8.4 |
| Distillation [°C] | D86 | | | | |
| IBP (°C) | | 161.4 | 163.2 | 165.3 | 171.9 |
| 10 vol% recovered at T [°C] | | 174.4 | 177.2 | 181.4 | 188.1 |
| 50 vol% recovered at T [°C] | | 202.2 | 208.1 | 217.1 | 225.8 |
| T50 – T10 [°C] | | 27.8 | 30.9 | 35.7 | 37.7 |
| 90 vol% recovered at T [°C] | | 236.4 | 239.8 | 242.4 | 243.9 |
| T90 – T10 [°C] | | 62.0 | 62.6 | 61.0 | 55.8 |
| FBP [°C] | | 250.4 | 251.1 | 249.4 | 248.6 |
| Residue [vol%] | | 1.3 | 1.3 | 1.3 | 1.3 |
| Loss [vol%] | | 0.6 | 0.6 | 0.6 | 0.6 |
| Flash point [°C] | IP170 | 48.0 | 50.0 | 53.0 | 56.5 |
| Density at 15°C [kg/m³] | D4052 | 807.9 | 804.0 | 798.2 | 792.5 |
| Freezing point [°C] | D7153 | -60.9 | -62.0 | -63.8 | -66.2 |
| Lubricity [mm] | D5001 | 0.635 | 0.618 | 0.608 | 0.587 |
| Viscosity at -20°C [mm²/s] | D445 | 4.477 | 4.953 | 5.845 | 6.978 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | 3 | 4 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.245 | - | - | 43.585 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 24.0 | 27.5 | 30.0 | 33.0 |
| Naphthalene [vol%] | D1840 | 0.37 | 0.33 | 0.27 | 0.22 |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | <0.0003 | <0.0003 | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | <0.001 | <0.001 | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b |

*Table 14: Properties of Jet A-1 fuel 117. blended with 10, 20, 35 and 50 vol% SIP fuel. Methods are according to ASTM unless specified otherwise.*
*[a]The method used for measuring freezing point was ASTM D2368*

| | | blends of fossil fuel 085 with HVO | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | < 0.001 | 0.001 |
| Aromatics [vol%] | D1319 | 21.6 | - | 8.5 | 6.4 | - | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 151.2 | 148.7 | 149.1 | 149.0 | 149.0 | 148.3 | 148.9 |
| 10 vol% recovered at T [°C] | | 167.2 | 164.8 | 165.1 | 163.8 | 163.8 | 163.9 | 162.9 |
| 50 vol% recovered at T [°C] | | 186.4 | 193.5 | 195.7 | 198.4 | 201.7 | 205.6 | 210.3 |
| T50 – T10 [°C] | | 19.2 | 28.7 | 30.6 | 34.6 | 37.9 | 41.7 | 47.4 |
| 90 vol% recovered at T [°C] | | 216.3 | 257.1 | 261.7 | 265.5 | 267.1 | 269.4 | 270.8 |
| T90 – T10 [°C] | | 49.1 | 92.3 | 96.6 | 101.7 | 103.3 | 105.5 | 107.9 |
| FBP [°C] | | 243.7 | 276.3 | 276.5 | 277.5 | 277.2 | 277.5 | 277.6 |
| Residue [vol%] | | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Loss [vol%] | | 0.9 | 1.1 | 1.1 | 1.0 | 1.1 | 1.1 | 1.1 |
| Flash point [°C] | IP170 | 40.5 | 42.0 | 42.0 | 41.5 | 42.0 | 42.0 | 42.0 |
| Density at 15°C [kg/m³] | D4052 | 797.5 | 777.0 | 773.1 | 769.0 | 765.0 | 760.9 | 756.7 |
| Freezing point [°C] | D7153 | -63.0a | -59.6 | -59.0 | -58.5 | -56.9 | -55.7 | -54.4 |
| Lubricity [mm] | D5001 | 0.739 | 0.741 | 0.728 | 0.730 | 0.760 | 0.736 | 0.906 |
| Viscosity at -20°C [mm²/s] | D445 | 3.113 | 3.812 | 3.996 | 4.218 | 4.373 | 4.572 | 4.801 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | 1b |
| Pres. Drop [mm Hg] | | 0.0 | 1.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0b |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.170 | - | 43.768 | 43.863 | - | - | 44.154 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1b | 1b | 1b | 1b | 1b | 1b |
| Smoke Point [mm] | D1322 | 21.0 | 34.5 | 37.5 | 42.0 | 45.0 | - | - |
| Naphthalene [vol%] | D1840 | 0.69 | 0.35 | 0.28 | 0.21 | 0.14 | 0.07 | - |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | <0.0003 | <0.0003 | <0.0003 | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 15: Properties of Jet A-1 fuel 085, neat HVO and blends with 50 - 90 vol% HVO. Methods are according to ASTM unless specified otherwise.*
*[a] The method used for measuring freezing point was ASTM D2368.*
*[b] Thermal stability for neat HVO was determined at 325 °C.*

| | | blends of fossil fuel 112 with HVO | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.003 | 0.002 | 0.002 | 0.001 | 0.001 | 0.001 | 0.001 |
| Aromatics [vol%] | D1319 | 18.1 | 8.9 | - | 5.3 | - | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 170.6 | 155.4 | 154.4 | 153.1 | 150.6 | 149.8 | 148.9 |
| 10 vol% recovered at T [°C] | | 183.9 | 172.8 | 171.2 | 168.8 | 166.4 | 165.0 | 162.9 |
| 50 vol% recovered at T [°C] | | 200.2 | 203.6 | 205.0 | 205.9 | 206.9 | 208.7 | 210.3 |
| T50 – T10 [°C] | | 16.3 | 30.8 | 33.8 | 37.1 | 40.5 | 43.7 | 47.4 |
| 90 vol% recovered at T [°C] | | 226.1 | 256.5 | 260.8 | 263.6 | 267.1 | 269.3 | 270.8 |
| T90 – T10 [°C] | | 42.2 | 83.7 | 89.6 | 94.8 | 100.7 | 104.3 | 107.9 |
| FBP [°C] | | 246.6 | 274.2 | 274.9 | 276.0 | 276.6 | 277.4 | 277.6 |
| Residue [vol%] | | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Loss [vol%] | | 1.1 | 1.0 | 1.1 | 1.0 | 1.0 | 1.0 | 1.1 |
| Flash point [°C] | IP170 | 53.0 | 47.5 | 45.5 | 44.5 | 43.0 | 42.5 | 42.0 |
| Density at 15°C [kg/m³] | D4052 | 818.6 | 787.8 | 781.6 | 775.4 | 769.2 | 763.0 | 756.7 |
| Freezing point [°C] | D7153 | < -80.0 | -63.6 | -60.3 | -58.7 | -57.2 | -55.8 | -54.4 |
| Lubricity [mm] | D5001 | 0.645 | 0.675 | 0.696 | 0.719 | 0.779 | 0.762 | 0.906 |
| Viscosity at -20°C [mm²/s] | D445 | 4.357 | 4.545 | 4.606 | 4.662 | 4.718 | 4.750 | 4.801 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | 1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.073 | 43.597 | - | 43.816 | - | - | 44.154 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1a | 1a | 1b |
| Smoke Point [mm] | D1322 | 21.0 | 32.0 | 36.5 | 41.0 | >45.0 | - | - |
| Naphthalene [vol%] | D1840 | 0.30 | 0.15 | 0.12 | 0.09 | 0.06 | - | - |
| Mercaptane Sulphur [wt.%] | D3227 | 0.0009 | 0.0005 | 0.0004 | - | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | 0.0048 | 0.0024 | 0.0021 | 0.0015 | 0.0011 | <0.001 | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 16: Properties of Jet A-1 fuel 112, neat HVO and blends with 50 - 90 vol% HVO. Methods are according to ASTM unless specified otherwise.*
*[a] Thermal stability for neat HVO was determined at 325 °C.*

| | | blends of fossil fuel 114 with HVO | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.002 | 0.002 | 0.002 | 0.002 | 0.001 | 0.001 |
| Aromatics [vol%] | D1319 | 13.7 | 6.8 | 5.4 | - | - | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 155.6 | 150.9 | 151.9 | 150.5 | 150.2 | 149.4 | 148.9 |
| 10 vol% recovered at T [°C] | | 169.8 | 165.9 | 165.6 | 164.7 | 164.5 | 163.9 | 162.9 |
| 50 vol% recovered at T [°C] | | 195.1 | 199.9 | 202.1 | 203.4 | 205.9 | 207.9 | 210.3 |
| T50 – T10 [°C] | | 25.3 | 34.0 | 36.5 | 38.7 | 41.4 | 44.0 | 47.4 |
| 90 vol% recovered at T [°C] | | 238.9 | 259.3 | 263.1 | 265.3 | 267.6 | 269.1 | 270.8 |
| T90 – T10 [°C] | | 69.1 | 93.4 | 97.5 | 100.6 | 103.1 | 105.2 | 107.9 |
| FBP [°C] | | 258.5 | 273.9 | 275.8 | 276.2 | 277.2 | 277.5 | 277.6 |
| Residue [vol%] | | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Loss [vol%] | | 0.9 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.1 |
| Flash point [°C] | IP170 | 44.0 | 43.5 | 42.5 | 42.5 | 42.5 | 42.5 | 42.0 |
| Density at 15°C [kg/m³] | D4052 | 795.0 | 775.9 | 772.1 | 768.3 | 764.4 | 760.6 | 756.7 |
| Freezing point [°C] | D7153 | -49.0 | -53.1 | -53.7 | -54.2 | -54.7 | -54.8 | -54.4 |
| Lubricity [mm] | D5001 | 0.728 | 0.729 | 0.725 | 0.725 | 0.752 | 0.759 | 0.906 |
| Viscosity at -20°C [mm²/s] | D445 | 3.778 | 4.233 | 4.339 | 4.443 | 4.564 | 4.681 | 4.801 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | 1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.391 | 43.766 | 43.845 | - | - | - | 44.154 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1a | 1a | 1b |
| Smoke Point [mm] | D1322 | 26.0 | 37.5 | 41.5 | - | - | - | - |
| Naphthalene [vol%] | D1840 | 1.17 | - | 0.47 | - | 0.23 | - | - |
| Mercaptane Sulphur [wt.%] | D3227 | 0.0015 | 0.0008 | - | 0.0005 | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | 0.10 | 0.0538 | 0.0428 | 0.0323 | 0.0216 | 0.0113 | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 17: Properties of Jet A-1 fuel 114, neat HVO and blends with 50 - 90 vol% HVO. Methods are according to ASTM unless specified otherwise.*
*[a] Thermal stability for neat HVO was determined at 325 °C.*

| | | blends of fossil fuel 117 with HVO | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | 0.001 |
| Aromatics [vol%] | D1319 | 16.2 | 8.1 | 6.4 | - | - | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 159.7 | 152.0 | 151.7 | 150.8 | 150.0 | 149.5 | 148.9 |
| 10 vol% recovered at T [°C] | | 175.3 | 168.2 | 167.6 | 166.5 | 165.4 | 163.9 | 162.9 |
| 50 vol% recovered at T [°C] | | 198.4 | 202.6 | 203.6 | 205.2 | 206.5 | 208.0 | 210.3 |
| T50 – T10 [°C] | | 23.1 | 34.4 | 36.0 | 38.7 | 41.1 | 44.1 | 47.4 |
| 90 vol% recovered at T [°C] | | 235.6 | 258.0 | 261.7 | 264.8 | 267.4 | 269.0 | 270.8 |
| T90 – T10 [°C] | | 60.3 | 89.8 | 94.1 | 98.3 | 102.0 | 105.1 | 107.9 |
| FBP [°C] | | 256.1 | 274.9 | 275.7 | 276.8 | 277.1 | 277.2 | 277.6 |
| Residue [vol%] | | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Loss [vol%] | | 0.9 | 0.8 | 0.9 | 0.8 | 0.9 | 0.9 | 1.1 |
| Flash point [°C] | IP170 | 46.0 | 44.0 | 44.0 | 43.5 | 43.0 | 42.5 | 42.0 |
| Density at 15°C [kg/m³] | D4052 | 881.7 | 784.3 | 778.9 | 773.3 | 767.9 | 762.3 | 756.7 |
| Freezing point [°C] | D7153 | -59.8 | -59.8 | -58.9 | -57.7 | -56.7 | -55.6 | -54.4 |
| Lubricity [mm] | D5001 | 0.703 | 0.715 | 0.711 | 0.700 | 0.722 | 0.770 | 0.906 |
| Viscosity at -20°C [mm²/s] | D445 | 4.059 | 4.399 | 4.471 | 4.551 | 4.646 | 4.731 | 4.801 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | 1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.174 | 43.647 | 43.746 | - | - | - | 44.154 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1a | 1b | 1b |
| Smoke Point [mm] | D1322 | 22.5 | 35.0 | 38.0 | 42.5 | >45.0 | - | - |
| Naphthalene [vol%] | D1840 | 0.41 | 0.21 | - | 0.12 | - | - | - |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | - | - | - | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | - | - | - | - | - | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 18: Properties of Jet A-1 fuel 117, neat HVO and blends with 50 - 90 vol% HVO. Methods are according to ASTM unless specified otherwise.*
*[a] Thermal stability for neat HVO was determined at 325 °C.*

| | | blends of fossil fuel 123 with HVO | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | < 0.001 | 0.001 |
| Aromatics [vol%] | D1319 | 15.1 | 7.6 | - | 4.6 | - | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 154.7 | 151.2 | 150.5 | 150.1 | 149.6 | 149.0 | 148.9 |
| 10 vol% recovered at T [°C] | | 165.5 | 164.1 | 163.9 | 163.4 | 163.7 | 163.0 | 162.9 |
| 50 vol% recovered at T [°C] | | 180.6 | 190.2 | 193.3 | 196.3 | 200.6 | 204.6 | 210.3 |
| T50 – T10 [°C] | | 15.1 | 26.1 | 29.4 | 32.9 | 36.9 | 41.6 | 47.4 |
| 90 vol% recovered at T [°C] | | 219.0 | 257.2 | 261.9 | 265.2 | 267.9 | 269.5 | 270.8 |
| T90 – T10 [°C] | | 53.5 | 93.1 | 98.0 | 101.8 | 104.2 | 106.5 | 107.9 |
| FBP [°C] | | 236.7 | 273.9 | 275.5 | 276.1 | 277.1 | 277.0 | 277.6 |
| Residue [vol%] | | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Loss [vol%] | | 0.8 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 1.1 |
| Flash point [°C] | IP170 | 41.5 | 42.0 | 42.0 | 41.5 | 42.0 | 42.0 | 42.0 |
| Density at 15°C [kg/m³] | D4052 | 789.0 | 772.8 | 769.6 | 766.4 | 763.2 | 760.0 | 756.7 |
| Freezing point [°C] | D7153 | -61.9 | -62.7 | -60.9 | -59.1 | -57.2 | -55.9 | -54.4 |
| Lubricity [mm] | D5001 | 0.751 | 0.789 | 0.807 | 0.771 | 0.756 | 0.781 | 0.906 |
| Viscosity at -20°C [mm²/s] | D445 | 3.008 | 3.759 | 3.942 | 4.137 | 4.361 | 4.585 | 4.801 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | 1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.370 | 43.770 | - | 43.922 | - | - | 44.154 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1b | 1b | 1b | 1b | 1b | 1b | 1b |
| Smoke Point [mm] | D1322 | 25.5 | 38.5 | 41.5 | > 45 | - | - | - |
| Naphthalene [vol%] | D1840 | 0.16 | 0.07 | - | 0.05 | - | - | - |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | - | - | - | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | - | - | - | - | - | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 19: Properties of Jet A-1 fuel 112, neat HVO and blends with 50 - 90 vol% HVO. Methods are according to ASTM unless specified otherwise.*
*[a] Thermal stability for neat HVO was determined at 325 °C.*

Additional freezing points were measured for 10 vol% (-62.9°C), 20 vol% (-63.8°C), 30 vol% (-64.5 °C) and 40 vol% HVO (-64.3 °C).

| | | blends of fossil fuel 085 with CTL | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| Aromatics [vol%] | D1319 | 21.6 | 11.6 | - | 7.2 | - | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 151.2 | 155.4 | 157.9 | 159.4 | 160.9 | 162.1 | 166.0 |
| 10 vol% recovered at T [°C] | | 167.2 | 168.7 | 169.2 | 169.7 | 170.3 | 170.8 | 171.5 |
| 50 vol% recovered at T [°C] | | 186.4 | 182.3 | 181.8 | 181.1 | 180.5 | 180.0 | 179.5 |
| T50 – T10 [°C] | | 19.2 | 13.6 | 12.6 | 11.4 | 10.2 | 9.2 | 8.0 |
| 90 vol% recovered at T [°C] | | 216.3 | 208.8 | 207.1 | 205.2 | 203.0 | 200.8 | 198.7 |
| T90 – T10 [°C] | | 49.1 | 40.1 | 37.9 | 35.5 | 32.7 | 30.0 | 27.2 |
| FBP [°C] | | 243.7 | 233.5 | 231.3 | 228.2 | 224.7 | 220.3 | 215.2 |
| Residue [vol%] | | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Loss [vol%] | | 0.9 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.1 |
| Flash point [°C] | IP170 | 40.5 | 43.0 | 43.0 | 43.0 | 44.0 | 46.5 | 46.0 |
| Density at 15°C [kg/m³] | D4052 | 797.5 | 779.3 | 775.7 | 772.2 | 768.4 | 764.8 | 761.2 |
| Freezing point [°C] | D7153 | -63.0a | -70.1 | -72.5 | -75.4 | -79.8 | <- 80.0 | - |
| Lubricity [mm] | D5001 | 0.739 | 0.752 | 0.732 | 0.759 | 0.769 | 0.743 | 0.780 |
| Viscosity at -20°C [mm²/s] | D445 | 3.113 | 3.349 | - | - | 3.548 | - | 3.71 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | <1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 280.0b |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.170 | 43.537 | - | 43.700 | - | - | - |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 21.0 | 30.0 | 32.0 | 34.0 | 36.5 | 39.0 | >45.0 |
| Naphthalene [vol%] | D1840 | 0.69 | 0.34 | - | 0.22 | - | - | - |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | - | - | - | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 20: Properties of Jet A-1 fuel 085, neat CTL and blends with 50 - 90 vol% CTL. Methods are according to ASTM unless specified otherwise.*
*[a] Thermal stability for neat CTL was determined at 325 °C*

| | | blends of fossil fuel 112 with CTL | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.003 | 0.002 | 0.002 | 0.001 | 0.001 | 0.001 | 0.001 |
| Aromatics [vol%] | D1319 | 18.1 | 9.5 | - | 5.9 | - | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 170.6 | 165.3 | 165.6 | 165.7 | 165.4 | 165.3 | 166.0 |
| 10 vol% recovered at T [°C] | | 183.9 | 175.8 | 174.9 | 173.6 | 173.0 | 172.2 | 171.5 |
| 50 vol% recovered at T [°C] | | 200.2 | 189.1 | 186.8 | 184.9 | 183.0 | 181.1 | 179.5 |
| T50 – T10 [°C] | | 16.3 | 13.3 | 11.9 | 11.3 | 10.0 | 8.9 | 8.0 |
| 90 vol% recovered at T [°C] | | 226.1 | 217.1 | 214.3 | 210.5 | 207.3 | 202.7 | 198.7 |
| T90 – T10 [°C] | | 42.2 | 41.3 | 39.4 | 36.9 | 34.3 | 30.5 | 27.2 |
| FBP [°C] | | 246.6 | 238.8 | 235.6 | 232.9 | 228.5 | 222.0 | 215.2 |
| Residue [vol%] | | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Loss [vol%] | | 1.1 | 1.0 | 0.9 | 0.8 | 1.0 | 0.9 | 1.1 |
| Flash point [°C] | IP170 | 53.0 | 49.5 | 48.0 | 47.5 | 47.0 | 46.5 | 46.0 |
| Density at 15°C [kg/m³] | D4052 | 818.6 | 789.9 | 784.3 | 778.5 | 772.9 | 767.0 | 761.2 |
| Freezing point [°C] | D7153 | <- 80.0 | <- 80.0 | <- 80.0 | <- 80.0 | <- 80.0 | <- 80.0 | - |
| Lubricity [mm] | D5001 | 0.645 | 0.719 | 0.746 | 0.762 | 0.761 | 0.752 | 0.780 |
| Viscosity at -20°C [mm²/s] | D445 | 4.357 | 4.008 | - | - | 3.837 | - | 3.710 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | <1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 280.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.073 | 43.488 | - | 43.670 | - | - | - |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 21.0 | 27.5 | 29.5 | 33.5 | 36.5 | 39.5 | >45.0 |
| Naphthalene [vol%] | D1840 | 0.30 | 0.14 | 0.11 | - | - | - | - |
| Mercaptane Sulphur [wt.%] | D3227 | 0.0009 | 0.0005 | 0.0004 | - | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | 0.0048 | 0.0025 | 0.0020 | 0.0017 | 0.0011 | <0.001 | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 21: Properties of Jet A-1 fuel 112, neat CTL and blends with 50 - 90 vol% CTL. Methods are according to ASTM unless specified otherwise.*
*[a] Thermal stability for neat CTL was determined at 325 °C*

| | | blends of fossil fuel 114 with CTL | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| Aromatics [vol%] | D1319 | 13.7 | 7.3 | 5.9 | - | - | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 155.6 | 158.9 | 160.6 | 161.5 | 162.3 | 163.9 | 166.0 |
| 10 vol% recovered at T [°C] | | 169.8 | 170.0 | 170.4 | 170.2 | 170.8 | 171.1 | 171.5 |
| 50 vol% recovered at T [°C] | | 195.1 | 185.2 | 183.9 | 182.6 | 181.5 | 180.4 | 179.5 |
| T50 – T10 [°C] | | 25.3 | 15.2 | 13.5 | 12.4 | 10.7 | 9.3 | 8.0 |
| 90 vol% recovered at T [°C] | | 238.9 | 224.5 | 220.3 | 214.9 | 209.4 | 203.9 | 198.7 |
| T90 – T10 [°C] | | 69.1 | 54.5 | 49.9 | 44.7 | 38.6 | 32.8 | 27.2 |
| FBP [°C] | | 258.5 | 250.2 | 247.4 | 243.6 | 237.5 | 227.8 | 215.2 |
| Residue [vol%] | | 1.2 | 1.2 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Loss [vol%] | | 0.9 | 0.9 | 1.1 | 1.0 | 1.1 | 1.0 | 1.1 |
| Flash point [°C] | IP170 | 44.0 | 45.0 | 45.0 | 45.5 | 45.5 | 45.5 | 46.0 |
| Density at 15°C [kg/m$^3$] | D4052 | 795.0 | 778.1 | 774.7 | 771.3 | 767.9 | 764.5 | 761.2 |
| Freezing point [°C] | D7153 | -49.0 | -56.4 | -58.7 | -61.3 | -65.4 | -72.8 | - |
| Lubricity [mm] | D5001 | 0.728 | 0.757 | 0.761 | 0.780 | 0.710 | 0.741 | 0.780 |
| Viscosity at -20°C [mm$^2$/s] | D445 | 3.778 | 3.736 | - | - | 3.710 | - | 3.710 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | <1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.4 | 0.0 | 0.5 | 280.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.391 | 43.664 | 43.730 | - | - | - | - |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 26.0 | 34.5 | 36.0 | 37.5 | 41.5 | >45.0 | >45.0 |
| Naphthalene [vol%] | D1840 | 1.17 | 0.58 | - | 0.36 | - | - | - |
| Mercaptane Sulphur [wt.%] | D3227 | 0.0015 | 0.0008 | - | 0.0005 | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | 0.10 | 0.0531 | 0.0429 | 0.0323 | 0.0218 | 0.0110 | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 22: Properties of Jet A-1 fuel 114, neat CTL and blends with 50 - 90 vol% CTL. Methods are according to ASTM unless specified otherwise.*
*[a] Thermal stability for neat CTL was determined at 325 °C*

| | | blends of fossil fuel 117 with CTL | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | <0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| Aromatics [vol%] | D1319 | 16.2 | 8.4 | - | 5.3 | - | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 159.7 | 160.9 | 161.7 | 162.4 | 163.0 | 163.4 | 166.0 |
| 10 vol% recovered at T [°C] | | 175.3 | 171.9 | 172.0 | 171.9 | 171.5 | 171.5 | 171.5 |
| 50 vol% recovered at T [°C] | | 198.4 | 186.8 | 185.1 | 183.6 | 182.1 | 180.9 | 179.5 |
| T50 – T10 [°C] | | 23.1 | 14.9 | 13.1 | 11.7 | 10.6 | 9.4 | 8.0 |
| 90 vol% recovered at T [°C] | | 235.6 | 223.2 | 219.3 | 214.9 | 209.8 | 204.4 | 198.7 |
| T90 – T10 [°C] | | 60.3 | 51.3 | 47.3 | 43.0 | 38.3 | 32.9 | 27.2 |
| FBP [°C] | | 256.1 | 247.6 | 245.0 | 239.6 | 236.0 | 225.5 | 215.2 |
| Residue [vol%] | | 1.2 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Loss [vol%] | | 0.9 | 1.1 | 1.2 | 1.1 | 1.2 | 1.3 | 1.1 |
| Flash point [°C] | IP170 | 46.0 | 46.0 | 46.0 | 46.0 | 45.5 | 45.5 | 46.0 |
| Density at 15°C [kg/m³] | D4052 | 811.7 | 786.4 | 781.5 | 776.4 | 771.4 | 766.3 | 761.2 |
| Freezing point [°C] | D7153 | -59.8 | -67.1 | -69.2 | -71.9 | -76.8 | <-80.0 | - |
| Lubricity [mm] | D5001 | 0.703 | 0.719 | 0.703 | 0.756 | 0.757 | 0.776 | 0.780 |
| Viscosity at -20°C [mm²/s] | D445 | 4.059 | 3.877 | 3.830 | 3.800 | 3.766 | 3.740 | 3.710 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | <1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.1 | 0.0 | 0.1 | 0.0 | 0.1 | 280.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.174 | 43.548 | - | 43.706 | - | - | - |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 22.5 | 32.0 | 35.0 | 36.5 | 38.5 | 41.5 | >45.0 |
| Naphthalene [vol%] | D1840 | 0.41 | 0.20 | 0.16 | - | - | - | - |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | - | - | - | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | - | - | - | - | - | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 23 Properties of Jet A-1 fuel 117, neat CTL and blends with 50 - 90 vol% CTL. Methods are according to ASTM unless specified otherwise.*

*[a] Thermal stability for neat CTL was determined at 325 °C*

| | | blends of fossil fuel 123 with CTL | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| Aromatics [vol%] | D1319 | 15.1 | 7.9 | - | 4.9 | - | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 154.7 | 157.7 | 159.1 | 160.1 | 162.2 | 162.8 | 166.0 |
| 10 vol% recovered at T [°C] | | 165.5 | 167.8 | 168.6 | 169.3 | 170.0 | 170.8 | 171.5 |
| 50 vol% recovered at T [°C] | | 180.6 | 179.8 | 179.7 | 179.7 | 179.6 | 179.5 | 179.5 |
| T50 – T10 [°C] | | 15.1 | 12.0 | 11.1 | 10.4 | 9.6 | 8.7 | 8.0 |
| 90 vol% recovered at T [°C] | | 219.0 | 209.9 | 207.5 | 205.5 | 203.2 | 200.8 | 198.7 |
| T90 – T10 [°C] | | 53.5 | 42.1 | 38.9 | 36.2 | 33.2 | 30.0 | 27.2 |
| FBP [°C] | | 236.7 | 230.2 | 228.1 | 225.3 | 222.0 | 217.8 | 215.2 |
| Residue [vol%] | | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Loss [vol%] | | 0.8 | 1.1 | 1.0 | 1.2 | 1.2 | 1.1 | 1.1 |
| Flash point [°C] | IP170 | 41.5 | 43.5 | 44.0 | 44.0 | 44.5 | 45.0 | 46.0 |
| Density at 15°C [kg/m³] | D4052 | 789.0 | 775.0 | 772.2 | 769.5 | 766.7 | 763.9 | 761.2 |
| Freezing point [°C] | D7153 | -61.9 | -69.1 | -71.1 | -74.4 | -78.9 | <-80.0 | - |
| Lubricity [mm] | D5001 | 0.751 | 0.795 | 0.773 | 0.768 | 0.796 | 0.802 | 0.780 |
| Viscosity at -20°C [mm²/s] | D445 | 3.008 | 3.301 | 3.414 | 3.444 | 3.531 | 3.614 | 3.710 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | <1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 280.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.370 | 43.646 | - | 43.775 | - | - | - |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1b | 1a | 1a | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 25.5 | 34.5 | 37.5 | 39.5 | 43.0 | >45.0 | >45.0 |
| Naphthalene [vol%] | D1840 | 0.16 | 0.07 | 0.06 | - | - | - | - |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | - | - | - | - | - | 0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | - | - | - | - | - | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 24 Properties of Jet A-1 fuel 123, neat CTL and blends with 50 - 90 vol% CTL. Methods are according to ASTM unless specified otherwise.*

*[a] Thermal stability for neat CTL was determined at 325 °C*

| | | blends of fossil fuel 085 with ATJ-SPK | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 |
| Aromatics [vol%] | D1319 | 21.6 | 11.4 | - | - | 4.7 | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 151.2 | 159.0 | 162.1 | 164.3 | 167.3 | 170.6 | 174.6 |
| 10 vol% recovered at T [°C] | | 167.2 | 171.6 | 172.9 | 174.1 | 175.3 | 176.6 | 178.0 |
| 50 vol% recovered at T [°C] | | 186.4 | 183.2 | 182.7 | 182.3 | 181.7 | 181.3 | 180.9 |
| T50 – T10 [°C] | | 19.2 | 11.6 | 9.8 | 8.2 | 6.4 | 4.7 | 2.9 |
| 90 vol% recovered at T [°C] | | 216.3 | 219.5 | 219.0 | 219.1 | 219.7 | 219.6 | 220.1 |
| T90 – T10 [°C] | | 49.1 | 47.9 | 46.1 | 45.0 | 44.4 | 43.0 | 42.1 |
| FBP [°C] | | 243.7 | 245.7 | 244.3 | 245.4 | 246.5 | 247.4 | 249.8 |
| Residue [vol%] | | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Loss [vol%] | | 0.9 | 1.2 | 1.2 | 1.2 | 1.1 | 1.0 | 0.9 |
| Flash point [°C] | IP170 | 40.5 | 43.5 | 44.5 | 45.0 | 46.5 | 47.0 | 47.5 |
| Density at 15°C [$kg/m^3$] | D4052 | 797.5 | 777.6 | 773.4 | 769.3 | 765.3 | 761.2 | 757.1 |
| Freezing point [°C] | D7153 | -63.0a | -69.1 | -71.4 | -74.2 | -78.2 | <-80.0 | <-80.0 |
| Lubricity [mm] | D5001 | 0.739 | 0.735 | 0.763 | 0.788 | 0.772 | 0.793 | 0.839 |
| Viscosity at -20°C [$mm^2/s$] | D445 | 3.113 | 3.677 | 3.848 | 4.045 | 4.246 | 4.497 | 4.795 |
| Existent gum [mg/100 mL] | D381 | <1 | 1 | 1 | 2 | 2 | 3 | 2 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | <1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.170 | 43.586 | - | - | 43.864 | - | - |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 21.0 | 26.5 | 26.5 | 26.5 | 27.0 | 27.0 | 27.0 |
| Naphthalene [vol%] | D1840 | 0.69 | 0.35 | - | 0.21 | - | - | - |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | - | - | - | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | - | - | - | - | - | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 25: Properties of Jet A-1 fuel 085, neat ATJ-SPK and blends with 50 - 90 vol% ATJ-SPK. Methods are according to ASTM unless specified otherwise.*
*[a] Thermal stability for neat ATJ-SPK was determined at 325 °C*

| | | blends of fossil fuel 112 with ATJ-SPK | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.003 | 0.002 | 0.002 | 0.002 | 0.002 | 0.001 | 0.002 |
| Aromatics [vol%] | D1319 | 18.1 | 9.4 | - | 6.2 | - | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 170.6 | 171.3 | 171.6 | 172.2 | 173.1 | 173.5 | 174.6 |
| 10 vol% recovered at T [°C] | | 183.9 | 179.7 | 179.7 | 179.1 | 178.6 | 178.2 | 178.0 |
| 50 vol% recovered at T [°C] | | 200.2 | 189.5 | 187.8 | 185.8 | 184.3 | 182.7 | 180.9 |
| T50 – T10 [°C] | | 16.3 | 9.8 | 8.1 | 6.7 | 5.7 | 4.5 | 2.9 |
| 90 vol% recovered at T [°C] | | 226.1 | 226.6 | 226.4 | 226.3 | 225.8 | 223.9 | 220.1 |
| T90 – T10 [°C] | | 42.2 | 46.9 | 46.7 | 47.2 | 47.2 | 45.7 | 42.1 |
| FBP [°C] | | 246.6 | 244.6 | 244.6 | 245.4 | 245.5 | 246.2 | 249.8 |
| Residue [vol%] | | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Loss [vol%] | | 1.1 | 1.2 | 1.3 | 1.3 | 1.2 | 1.2 | 0.9 |
| Flash point [°C] | IP170 | 53.0 | 51.0 | 50.0 | 49.5 | 48.5 | 48.0 | 47.5 |
| Density at 15°C [kg/m³] | D4052 | 818.6 | 788.2 | 782.1 | 775.9 | 769.7 | 763.4 | 757.1 |
| Freezing point [°C] | D7153 | <-80.0 | <-80.0 | <-80.0 | <-80.0 | <-80.0 | <-80.0 | <-80.0 |
| Lubricity [mm] | D5001 | 0.645 | 0.720 | 0.730 | 0.758 | 0.756 | 0.797 | 0.839 |
| Viscosity at -20°C [mm²/s] | D445 | 4.357 | 4.460 | - | 4.554 | - | - | 4.795 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | <1 | 2 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | <1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.073 | 43.672 | - | 43.727 | - | - | - |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 21.0 | 25.5 | 26.5 | 26.5 | 27.0 | 27.0 | 27.0 |
| Naphthalene [vol%] | D1840 | 0.30 | 0.14 | - | 0.09 | - | - | - |
| Mercaptane Sulphur [wt.%] | D3227 | 0.0009 | 0.0005 | 0.0004 | - | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | 0.0048 | 0.0022 | 0.0019 | 0.0017 | <0.001 | <0.001 | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 26: Properties of Jet A-1 fuel 112, neat ATJ-SPK and blends with 50 - 90 vol% ATJ-SPK. Methods are according to ASTM unless specified otherwise.*
*[a] Thermal stability for neat ATJ-SPK was determined at 325 °C*

| | | blends of fossil fuel 114 with ATJ-SPK | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.003 | 0.003 | 0.002 | 0.001 | 0.001 | 0.002 |
| Aromatics [vol%] | D1319 | 13.7 | 7.4 | 5.9 | - | - | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 155.6 | 162.9 | 164.4 | 166.5 | 168.8 | 171.6 | 174.6 |
| 10 vol% recovered at T [°C] | | 169.8 | 173.4 | 174.1 | 175.1 | 175.9 | 177.0 | 178.0 |
| 50 vol% recovered at T [°C] | | 195.1 | 186.2 | 184.5 | 183.8 | 182.8 | 181.9 | 180.9 |
| T50 – T10 [°C] | | 25.3 | 12.8 | 10.4 | 8.7 | 6.9 | 4.9 | 2.9 |
| 90 vol% recovered at T [°C] | | 238.9 | 234.8 | 233.7 | 232.2 | 229.1 | 225.8 | 220.1 |
| T90 – T10 [°C] | | 69.1 | 61.4 | 59.6 | 57.1 | 53.2 | 48.8 | 42.1 |
| FBP [°C] | | 258.5 | 252.0 | 251.1 | 249.7 | 248.2 | 248.1 | 249.8 |
| Residue [vol%] | | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Loss [vol%] | | 0.9 | 1.3 | 1.3 | 1.3 | 1.2 | 1.1 | 0.9 |
| Flash point [°C] | IP170 | 44.0 | 45.0 | 45.5 | 46.5 | 47.0 | 47.0 | 47.5 |
| Density at 15°C [kg/m$^3$] | D4052 | 795.0 | 776.2 | 772.4 | 768.6 | 764.8 | 760.9 | 757.1 |
| Freezing point [°C] | D7153 | -49.0 | -55.1 | -57.3 | -60.2 | - | - | <-80.0 |
| Lubricity [mm] | D5001 | 0.728 | 0.774 | 0.789 | 0.784 | 0.767 | 0.757 | 0.839 |
| Viscosity at -20°C [mm$^2$/s] | D445 | 3.778 | 4.115 | - | 4.327 | - | - | 4.795 |
| Existent gum [mg/100 mL] | D381 | <1 | 2 | 1 | 2 | 2 | 2 | 2 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | <1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.391 | 43.706 | 43.777 | - | - | - | - |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 26.0 | 27.0 | 27.0 | 27.0 | 27.0 | 26.5 | 27.0 |
| Naphthalene [vol%] | D1840 | 1.17 | 0.58 | - | 0.38 | - | - | - |
| Mercaptane Sulphur [wt.%] | D3227 | 0.0015 | 0.0009 | - | 0.0005 | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | 0.10 | 0.0541 | 0.0435 | 0.0334 | 0.0220 | 0.0110 | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 27: Properties of Jet A-1 fuel 114, neat ATJ-SPK and blends with 50 - 90 vol% ATJ-SPK. Methods are according to ASTM unless specified otherwise.*
*[a] Thermal stability for neat ATJ-SPK was determined at 325 °C*

| | | blends of fossil fuel 117 with ATJ-SPK | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | <0.001 | 0.001 | 0.001 | 0.002 | 0.001 | 0.001 | 0.002 |
| Aromatics [vol%] | D1319 | 16.2 | 8.8 | - | 5.9 | - | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 159.7 | 164.9 | 166.4 | 168.1 | 170.3 | 172.1 | 174.6 |
| 10 vol% recovered at T [°C] | | 175.3 | 175.2 | 175.9 | 176.3 | 176.8 | 177.5 | 178.0 |
| 50 vol% recovered at T [°C] | | 198.4 | 187.4 | 185.9 | 184.6 | 183.2 | 182.2 | 180.9 |
| T50 – T10 [°C] | | 23.1 | 12.2 | 10.0 | 8.3 | 6.4 | 4.7 | 2.9 |
| 90 vol% recovered at T [°C] | | 235.6 | 232.4 | 231.5 | 230.0 | 228.4 | 224.6 | 220.1 |
| T90 – T10 [°C] | | 60.3 | 57.2 | 55.6 | 53.7 | 51.6 | 47.1 | 42.1 |
| FBP [°C] | | 256.1 | 250.2 | 249.4 | 249.2 | 248.4 | 247.8 | 249.8 |
| Residue [vol%] | | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Loss [vol%] | | 0.9 | 1.1 | 1.2 | 1.1 | 1.2 | 1.1 | 0.9 |
| Flash point [°C] | IP170 | 46.0 | 46.5 | 46.5 | 47.5 | 47.5 | 48.5 | 47.5 |
| Density at 15°C [kg/m$^3$] | D4052 | 811.7 | 784.8 | 779.3 | 773.7 | 768.4 | 762.7 | 757.1 |
| Freezing point [°C] | D7153 | -59.8 | -66.3 | -68.3 | -70.8 | -75.1 | <-80.0 | <-80.0 |
| Lubricity [mm] | D5001 | 0.703 | 0.730 | 0.761 | 0.799 | 0.764 | 0.803 | 0.839 |
| Viscosity at -20°C [mm$^2$/s] | D445 | 4.059 | 4.287 | 4.361 | 4.443 | 4.542 | 4.652 | 4.795 |
| Existent gum [mg/100 mL] | D381 | <1 | 1 | 1 | 2 | 3 | 3 | 2 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | <1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 | 3.2 | 0.0 | 0.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.174 | 43.579 | - | 43.758 | - | - | - |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 22.5 | 25.0 | 26.5 | 27.0 | 27.5 | 27.0 | 27.0 |
| Naphthalene [vol%] | D1840 | 0.41 | 0.21 | - | 0.13 | - | - | - |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | - | - | - | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | - | - | - | - | - | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 28: Properties of Jet A-1 fuel 117, neat ATJ-SPK and blends with 50 - 90 vol% ATJ-SPK. Methods are according to ASTM unless specified otherwise.*
*[a] Thermal stability for neat ATJ-SPK was determined at 325 °C*

| | | blends of fossil fuel 123 with ATJ-SPK | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 60 vol% | 70 vol% | 80 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.002 | 0.001 | 0.001 | 0.001 | 0.001 | 0.002 |
| Aromatics [vol%] | D1319 | 15.1 | 7.9 | - | 4.9 | - | - | - |
| Distillation [°C] | D86 | | | | | | | |
| IBP (°C) | | 154.7 | 161.6 | 163.0 | 165.7 | 168.0 | 170.9 | 174.6 |
| 10 vol% recovered at T [°C] | | 165.5 | 170.5 | 171.9 | 173.3 | 174.7 | 176.4 | 178.0 |
| 50 vol% recovered at T [°C] | | 180.6 | 180.6 | 180.8 | 180.9 | 180.9 | 180.9 | 180.9 |
| T50 – T10 [°C] | | 15.1 | 10.1 | 8.9 | 7.6 | 6.2 | 4.5 | 2.9 |
| 90 vol% recovered at T [°C] | | 219.0 | 220.3 | 220.2 | 220.2 | 219.6 | 219.7 | 220.1 |
| T90 – T10 [°C] | | 53.5 | 49.8 | 48.3 | 46.9 | 44.9 | 43.3 | 42.1 |
| FBP [°C] | | 236.7 | 242.5 | 243.1 | 245.3 | 246.0 | 247.0 | 249.8 |
| Residue [vol%] | | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Loss [vol%] | | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 | 0.9 |
| Flash point [°C] | IP170 | 41.5 | 44.5 | 45.0 | 46.0 | 46.0 | 47.0 | 47.5 |
| Density at 15°C [kg/m³] | D4052 | 789.0 | 773.1 | 769.9 | 766.8 | 763.6 | 760.3 | 757.1 |
| Freezing point [°C] | D7153 | -61.9 | -68.2 | -70.1 | -72.5 | -76.2 | <-80.0 | <-80.0 |
| Lubricity [mm] | D5001 | 0.751 | 0.805 | 0.774 | 0.781 | 0.787 | 0.805 | 0.839 |
| Viscosity at -20°C [mm²/s] | D445 | 3.008 | 3.626 | 3.799 | 3.995 | 4.219 | 4.496 | 4.795 |
| Existent gum [mg/100 mL] | D381 | <1 | 2 | 2 | 2 | 3 | 3 | 2 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 | <1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.370 | 43.699 | - | 43.839 | - | - | - |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1b | 1a | 1a | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 25.5 | 26.0 | 26.0 | 26.5 | 27.0 | 27.0 | 27.0 |
| Naphthalene [vol%] | D1840 | 0.16 | 0.07 | - | 0.05 | - | - | - |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | - | - | - | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | - | - | - | - | - | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 29: Properties of Jet A-1 fuel 085, neat ATJ-SPK and blends with 50 - 90 vol% ATJ-SPK. Methods are according to ASTM unless specified otherwise.*
*[a] Thermal stability for neat ATJ-SPK was determined at 325 °C.*

| | | blends of fossil fuel 112 with CH kerosene | | | | | |
|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 25 vol% | 50 vol% | 70 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.003 | 0.005 | 0.008 | 0.011 | 0.013 | 0.014 |
| Aromatics [vol%] | D1319 | 18.1 | 18.1 | - | 19.0 | - | 19.7 |
| Distillation [°C] | D86 | | | | | | |
| IBP (°C) | | 170.6 | 163.5 | 158.9 | 156.3 | 152.5 | 152.1 |
| 10 vol% recovered at T [°C] | | 183.9 | 180.0 | 176.8 | 174.2 | 172.0 | 171.4 |
| 50 vol% recovered at T [°C] | | 200.2 | 200.3 | 200.3 | 200.4 | 200.5 | 200.1 |
| T50 – T10 [°C] | | 16.3 | 20.3 | 23.5 | 26.2 | 28.5 | 28.7 |
| 90 vol% recovered at T [°C] | | 226.1 | 231.0 | 235.8 | 239.3 | 242.4 | 244.8 |
| T90 – T10 [°C] | | 42.2 | 51.0 | 59.0 | 65.1 | 70.4 | 73.4 |
| FBP [°C] | | 246.6 | 251.4 | 254.6 | 257.7 | 258.7 | 258.5 |
| Residue [vol%] | | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.5 |
| Loss [vol%] | | 1.1 | 1.1 | 1.0 | 1.0 | 1.0 | 0.9 |
| Flash point [°C] | IP170 | 53.0 | 50.0 | 46.5 | 44.5 | 43.0 | 42.5 |
| Density at 15°C [kg/m³] | D4052 | 818.6 | 815.1 | 811.9 | 809.2 | 806.6 | 805.2 |
| Freezing point [°C] | D7153 | <-80.0 | -56.6 | -49.4 | -45.5 | -42.6 | -41.3 |
| Lubricity [mm] | D5001 | 0.645 | 0.560 | 0.541 | 0.535 | 0.506 | 0.570 |
| Viscosity at -20°C [mm²/s] | D445 | 4.357 | 4.238 | 4.139 | 4.070 | 3.999 | 3.977 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1 | <1 | <1 |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.073 | 43.111 | - | 43.166 | - | 43.202 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 21.0 | 21.5 | 22.5 | 23.0 | 23.5 | 22.5 |
| Naphthalene [vol%] | D1840 | 0.30 | - | 0.32 | - | - | 0.35 |
| Mercaptane Sulphur [wt.%] | D3227 | 0.0009 | 0.0007 | 0.0005 | - | - | - |
| Sulphur [wt.%] | DIN EN ISO 14596 | 0.0048 | 0.0033 | 0.0022 | 0.0012 | <0.001 | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1b |

*Table 30: Properties of Jet A-1 fuel 112, neat CH kerosene and blends with 25 - 90 vol% CH kerosene. Methods are according to ASTM unless specified otherwise.*

| | | blends of fossil fuel 085 with ATJ-SKA | | |
|---|---|---|---|---|
| Property | Method | 0 vol% | 50 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.002 | 0.003 |
| Aromatics [vol%] | D1319 | 21.6 | 18.4 | 15.8 |
| Distillation [°C] | D86 | | | |
| IBP (°C) | | 151.2 | 155.7 | 164.8 |
| 10 vol% recovered at T [°C] | | 167.2 | 170.3 | 174.8 |
| 50 vol% recovered at T [°C] | | 186.4 | 186.3 | 186.7 |
| T50 – T10 [°C] | | 19.2 | 16.0 | 11.9 |
| 90 vol% recovered at T [°C] | | 216.3 | 211.8 | 205.6 |
| T90 – T10 [°C] | | 49.1 | 41.5 | 30.8 |
| FBP [°C] | | 243.7 | 248.4 | 249.6 |
| Residue [vol%] | | 1.1 | 1.1 | 1.1 |
| Loss [vol%] | | 0.9 | 1.1 | 1.1 |
| Flash point [°C] | IP170 | 40.5 | 44.5 | 48.5 |
| Density at 15°C [kg/m³] | D4052 | 797.5 | 791.7 | 785.9 |
| Freezing point [°C] | D7153 | -63.0a | -70.6 | <-80.0 |
| Lubricity [mm] | D5001 | 0.739 | 0.640 | 0.606 |
| Viscosity at -20°C [mm²/s] | D445 | 3.113 | 3.252 | 3.421 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | 1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | |
| Deposit Rating | | <1 | <1 | <1 |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.170 | 43.287 | 43.396 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 21.0 | 22.5 | 23.0 |
| Naphthalene [vol%] | D1840 | 0.69 | 0.39 | 0.08 |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | - | - |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | - | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1 |

*Table 31: Properties of Jet A-1 fuel 085, neat ATJ-SKA and a blend 50 vol% ATJ-SKA. Methods are according to ASTM unless specified otherwise.*

| | | blends of fossil fuel 114 with ATJ-SKA | | | | | |
|---|---|---|---|---|---|---|---|
| Property | Method | 0 vol% | 25 vol% | 50vol% | 70 vol% | 90 vol% | 100 vol% |
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.002 | 0.002 | 0.002 | 0.002 | 0.003 |
| Aromatics [vol%] | D1319 | 13.7 | 14.1 | - | 14.6 | - | 15.8 |
| Distillation [°C] | D86 | | | | | | |
| IBP (°C) | | 155.6 | 156.4 | 159.1 | 160.5 | 163.4 | 164.8 |
| 10 vol% recovered at T [°C] | | 169.8 | 170.7 | 171.9 | 173.0 | 174.2 | 174.8 |
| 50 vol% recovered at T [°C] | | 195.1 | 191.8 | 189.7 | 188.4 | 187.2 | 186.7 |
| T50 – T10 [°C] | | 25.3 | 21.1 | 17.8 | 15.4 | 13.0 | 11.9 |
| 90 vol% recovered at T [°C] | | 238.9 | 234.1 | 227.5 | 219.4 | 210.2 | 205.6 |
| T90 – T10 [°C] | | 69.1 | 63.4 | 55.6 | 46.4 | 36.0 | 30.8 |
| FBP [°C] | | 258.5 | 259.7 | 260.7 | 260.2 | 256.9 | 249.6 |
| Residue [vol%] | | 1.2 | 1.2 | 1.2 | 1.1 | 1.1 | 1.1 |
| Loss [vol%] | | 0.9 | 1.0 | 1.0 | 1.0 | 1.1 | 1.1 |
| Flash point [°C] | IP170 | 44.0 | 45.5 | 46.0 | 47.0 | 48.0 | 48.5 |
| Density at 15°C [$kg/m^3$] | D4052 | 795.0 | 792.8 | 790.5 | 788.7 | 786.8 | 785.9 |
| Freezing point [°C] | D7153 | -49.0 | -52.2 | -56.8 | -62.5 | -74.4 | <-80.0 |
| Lubricity [mm] | D5001 | 0.728 | 0.722 | 0.694 | 0.667 | 0.630 | 0.606 |
| Viscosity at -20°C [$mm^2/s$] | D445 | 3.778 | 3.686 | 3.600 | 3.525 | 3.449 | 3.421 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 | <1 | 1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | | | |
| Deposit Rating | | <1 | <1 | <1 | 1 | 1 | <1 |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 3.6 | 280 | 280 | 0.0 |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.391 | 43.397 | - | 43.410 | - | 43.396 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a | 1b | 1a |
| Smoke Point [mm] | D1322 | 26.0 | 23.5 | 22.0 | 23.0 | 23.0 | 23.0 |
| Naphthalene [vol%] | D1840 | 1.17 | - | 0.62 | - | 0.19 | 0.08 |
| Mercaptane Sulphur [wt.%] | D3227 | 0.0015 | 0.0012 | 0.0008 | - | - | - |
| Sulphur [wt.%] | DIN EN ISO 14596 | 0.10 | 0.0795 | 0.0539 | 0.0318 | 0.0105 | <0.001 |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b | 1b | 1 |

*Table 32: Properties of Jet A-1 fuel 114, neat ATJ-SKA and blends with 25 - 90 vol% ATJ-SKA. Methods are according to ASTM unless specified otherwise.*

## 9.4 Annex 4: Properties of Blends after Addition of Aromatics

| Property | Method | neat fossil fuel 085 | fossil fuel 085 with 70 vol% ATJ-SPK | after addition of aromatics to 8 vol% | neat ATJ-SPK |
|---|---|---|---|---|---|
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.002 | 0.002 | 0.002 |
| Aromatics [vol%] | D1319 | 21.6 | - | - | - |
| Distillation [°C] | D86 | | | | |
| IBP (°C) | | 151.2 | 164.3 | 164.9 | 174.6 |
| 10 vol% recovered at T [°C] | | 167.2 | 174.1 | 174.5 | 178.0 |
| 50 vol% recovered at T [°C] | | 186.4 | 182.3 | 182.8 | 180.9 |
| T50 – T10 [°C] | | 19.2 | 8.2 | 8.3 | 2.9 |
| 90 vol% recovered at T [°C] | | 216.3 | 219.1 | 220.5 | 220.1 |
| T90 – T10 [°C] | | 49.1 | 45.0 | 46.0 | 42.1 |
| FBP [°C] | | 243.7 | 245.4 | 246.6 | 249.8 |
| Residue [vol%] | | 1.1 | 1.2 | 1.2 | 1.2 |
| Loss [vol%] | | 0.9 | 1.2 | 1.1 | 0.9 |
| Flash point [°C] | IP170 | 40.5 | 45.0 | 45.5 | 47.5 |
| Density at 15°C [kg/m$^3$] | D4052 | 797.5 | 769.3 | 771.7 | 757.1 |
| Freezing point [°C] | D7153 | -63.0a | -74.2 | -74.5 | - |
| Lubricity [mm] | D5001 | 0.739 | 0.788 | 0.727 | 0.839 |
| Viscosity at -20°C [mm$^2$/s] | D445 | 3.113 | 4.045 | 3.987 | 4.795 |
| Existent gum [mg/100 mL] | D381 | <1 | 2 | 2 | 2 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.170 | - | 43.710 | - |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1b | 1a |
| Smoke Point [mm] | D1322 | 21.0 | 26.5 | 25.5 | 27.0 |
| Naphthalene [vol%] | D1840 | 0.69 | 0.21 | 0.47 | - |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | - | - | - |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | - | - | - |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b |

*Table 33: Properties of Jet A-1 fuel 085, its blend with 70 vol% ATJ-SPK and after addition of aromatics to the blend to reach the 8 vol% margin. Methods are according to ASTM unless specified otherwise.*
[a] *Thermal stability for neat ATJ-SPK was determined at 325 °C.*

| Property | Method | neat fossil fuel 114 | fossil fuel 114 with 70 vol% ATJ-SPK | after addition of aromatics to 8 vol% | neat ATJ-SPK |
|---|---|---|---|---|---|
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.002 | 0.002 | 0.002 |
| Aromatics [vol%] | D1319 | 13.7 | - | - | - |
| Distillation [°C] | D86 | | | | |
| IBP (°C) | | 155.6 | 166.5 | 167.5 | 174.6 |
| 10 vol% recovered at T [°C] | | 169.8 | 175.1 | 175.5 | 178.0 |
| 50 vol% recovered at T [°C] | | 195.1 | 183.8 | 184.3 | 180.9 |
| T50 – T10 [°C] | | 25.3 | 8.7 | 8.8 | 2.9 |
| 90 vol% recovered at T [°C] | | 238.9 | 232.2 | 231.9 | 220.1 |
| T90 – T10 [°C] | | 69.1 | 57.1 | 56.4 | 42.1 |
| FBP [°C] | | 258.5 | 249.7 | 251.5 | 249.8 |
| Residue [vol%] | | 1.2 | 1.2 | 1.2 | 1.2 |
| Loss [vol%] | | 0.9 | 1.3 | 1.1 | 0.9 |
| Flash point [°C] | IP170 | 44.0 | 46.5 | 47.0 | 47.5 |
| Density at 15°C [kg/m$^3$] | D4052 | 795.0 | 768.6 | 774.5 | 757.1 |
| Freezing point [°C] | D7153 | -49.0 | -60.2 | -61.1 | - |
| Lubricity [mm] | D5001 | 0.728 | 0.784 | 0.765 | 0.839 |
| Viscosity at -20°C [mm$^2$/s] | D445 | 3.778 | 4.327 | 4.196 | 4.795 |
| Existent gum [mg/100 mL] | D381 | <1 | 2 | 2 | 2 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | |
| Deposit Rating | | <1 | <1 | 1 | <1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.391 | - | - | - |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 26.0 | 27.0 | 26.0 | 27.0 |
| Naphthalene [vol%] | D1840 | 1.17 | 0.38 | 0.97 | - |
| Mercaptane Sulphur [wt.%] | D3227 | 0.0015 | 0.0005 | 0.0005 | - |
| Sulphur [wt.%] | DIN EN ISO 14596 | 0.10 | 0.0334 | 0.0318 | - |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b |

*Table 34: Properties of Jet A-1 fuel 114, its blend with 70 vol% ATJ-SPK and after addition of aromatics to the blend to reach the 8 vol% margin. Methods are according to ASTM unless specified otherwise.*

*[a] Thermal stability for neat ATJ-SPK was determined at 325 °C.*

| Property | Method | neat fossil fuel 085 | fossil fuel 085 with 70 vol% HVO | after addition of aromatics to 8 vol% | neat HVO |
|---|---|---|---|---|---|
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.001 | 0.002 | 0.001 |
| Aromatics [vol%] | D1319 | 21.6 | 6.4 | - | - |
| Distillation [°C] | D86 | | | | |
| IBP (°C) | | 151.2 | 149.0 | 148.2 | 148.9 |
| 10 vol% recovered at T [°C] | | 167.2 | 163.8 | 164.8 | 162.9 |
| 50 vol% recovered at T [°C] | | 186.4 | 198.4 | 198.8 | 210.3 |
| T50 – T10 [°C] | | 19.2 | 34.6 | 34.0 | 47.4 |
| 90 vol% recovered at T [°C] | | 216.3 | 265.5 | 265.9 | 270.8 |
| T90 – T10 [°C] | | 49.1 | 101.7 | 101.1 | 107.9 |
| FBP [°C] | | 243.7 | 277.5 | 277.4 | 277.6 |
| Residue [vol%] | | 1.1 | 1.2 | 1.2 | 1.2 |
| Loss [vol%] | | 0.9 | 1.0 | 1.2 | 1.1 |
| Flash point [°C] | IP170 | 40.5 | 41.5 | 41.5 | 42.0 |
| Density at 15°C [kg/m³] | D4052 | 797.5 | 769.0 | 771.4 | 756.7 |
| Freezing point [°C] | D7153 | -63.0a | -58.5 | -59.6 | -54.4 |
| Lubricity [mm] | D5001 | 0.739 | 0.730 | 0.737 | 0.906 |
| Viscosity at -20°C [mm²/s] | D445 | 3.113 | 4.218 | 4.155 | 4.801 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | |
| Deposit Rating | | <1 | <1 | <1 | 1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.170 | 43.863 | - | 44.154 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1b | 1a | 1b |
| Smoke Point [mm] | D1322 | 21.0 | 42.0 | 26.0 | - |
| Naphthalene [vol%] | D1840 | 0.69 | 0.21 | 0.47 | - |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | - | - | - |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | - | - | - |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b |

*Table 35: Properties of Jet A-1 fuel 085, its blend with 70 vol% HVO and after addition of aromatics to the blend to reach the 8 vol% margin. Methods are according to ASTM unless specified otherwise.*

*[a] Thermal stability for neat HVO was determined at 325 °C.*

| Property | Method | neat fossil fuel 114 | fossil fuel 114 with 70 vol% HVO | after addition of aromatics to 8 vol% | neat HVO |
|---|---|---|---|---|---|
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.002 | 0.002 | 0.001 |
| Aromatics [vol%] | D1319 | 13.7 | - | - | - |
| Distillation [°C] | D86 | | | | |
| IBP (°C) | | 155.6 | 150.5 | 149.2 | 148.9 |
| 10 vol% recovered at T [°C] | | 169.8 | 164.7 | 165.7 | 162.9 |
| 50 vol% recovered at T [°C] | | 195.1 | 203.4 | 202.8 | 210.3 |
| T50 – T10 [°C] | | 25.3 | 38.7 | 37.1 | 47.4 |
| 90 vol% recovered at T [°C] | | 238.9 | 265.3 | 265.1 | 270.8 |
| T90 – T10 [°C] | | 69.1 | 100.6 | 99.4 | 107.9 |
| FBP [°C] | | 258.5 | 276.2 | 275.8 | 277.6 |
| Residue [vol%] | | 1.2 | 1.2 | 1.2 | 1.2 |
| Loss [vol%] | | 0.9 | 1.0 | 1.2 | 1.1 |
| Flash point [°C] | IP170 | 44.0 | 42.5 | 42.5 | 42.0 |
| Density at 15°C [kg/m³] | D4052 | 795.0 | 768.3 | 774.2 | 756.7 |
| Freezing point [°C] | D7153 | -49.0 | -54.2 | -55.1 | -54.4 |
| Lubricity [mm] | D5001 | 0.728 | 0.725 | 0.745 | 0.906 |
| Viscosity at -20°C [mm²/s] | D445 | 3.778 | 4.443 | 4.345 | 4.801 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | |
| Deposit Rating | | <1 | <1 | <1 | 1 |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 0.0 |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.391 | - | - | 44.154 |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1b |
| Smoke Point [mm] | D1322 | 26.0 | - | 26.5 | - |
| Naphthalene [vol%] | D1840 | 1.17 | - | 0.97 | - |
| Mercaptane Sulphur [wt.%] | D3227 | 0.0015 | 0.0005 | 0.0005 | - |
| Sulphur [wt.%] | DIN EN ISO 14596 | 0.10 | 0.0323 | 0.0318 | - |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b |

*Table 36: Properties of Jet A-1 fuel 114, its blend with 70 vol% HVO and after addition of aromatics to the blend to reach the 8 vol% margin. Methods are according to ASTM unless specified otherwise.*

*[a] Thermal stability for neat HVO was determined at 325 °C.*

| Property | Method | neat fossil fuel 085 | fossil fuel 085 with 70 vol% CTL | after addition of aromatics to 8 vol% | neat CTL |
|---|---|---|---|---|---|
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.001 | 0.002 | 0.001 |
| Aromatics [vol%] | D1319 | 21.6 | 7.2 | - | - |
| Distillation [°C] | D86 | | | | |
| IBP (°C) | | 151.2 | 159.4 | 160.3 | 166.0 |
| 10 vol% recovered at T [°C] | | 167.2 | 169.7 | 170.5 | 171.5 |
| 50 vol% recovered at T [°C] | | 186.4 | 181.1 | 181.8 | 179.5 |
| T50 – T10 [°C] | | 19.2 | 11.4 | 11.3 | 8.0 |
| 90 vol% recovered at T [°C] | | 216.3 | 205.2 | 206.1 | 198.7 |
| T90 – T10 [°C] | | 49.1 | 35.5 | 35.6 | 27.2 |
| FBP [°C] | | 243.7 | 228.2 | 230.0 | 215.2 |
| Residue [vol%] | | 1.1 | 1.1 | 1.1 | 1.1 |
| Loss [vol%] | | 0.9 | 1.0 | 1.1 | 1.1 |
| Flash point [°C] | IP170 | 40.5 | 43.0 | 43.5 | 46.0 |
| Density at 15°C [kg/m$^3$] | D4052 | 797.5 | 772.2 | 774.3 | 761.2 |
| Freezing point [°C] | D7153 | -63.0a | -75.4 | -75.9 | - |
| Lubricity [mm] | D5001 | 0.739 | 0.759 | 0.728 | 0.780 |
| Viscosity at -20°C [mm$^2$/s] | D445 | 3.113 | - | 3.458 | 3.71 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1a |
| Pres. Drop [mm Hg] | | 0.0 | 0.0 | 0.0 | 280.0a |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.170 | 43.700 | - | - |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 21.0 | 34.0 | 24.5 | >45.0 |
| Naphthalene [vol%] | D1840 | 0.69 | 0.22 | 0.46 | - |
| Mercaptane Sulphur [wt.%] | D3227 | <0.0003 | - | - | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | <0.001 | - | - | - |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b |

*Table 37: Properties of Jet A-1 fuel 085, its blend with 70 vol% CTL and after addition of aromatics to the blend to reach the 8 vol% margin. Methods are according to ASTM unless specified otherwise.*
*[a] Thermal stability for neat CTL was determined at 325 °C.*

| Property | Method | neat fossil fuel 114 | fossil fuel 114 with 70 vol% CTL | after addition of aromatics to 8 vol% | neat CTL |
|---|---|---|---|---|---|
| Acidity, total [mg KOH/g] | D3242 | 0.001 | 0.001 | 0.003 | 0.001 |
| Aromatics [vol%] | D1319 | 13.7 | - | - | - |
| Distillation [°C] | D86 | | | | |
| IBP (°C) | | 155.6 | 161.5 | 161.6 | 166.0 |
| 10 vol% recovered at T [°C] | | 169.8 | 170.2 | 171.3 | 171.5 |
| 50 vol% recovered at T [°C] | | 195.1 | 182.6 | 183.4 | 179.5 |
| T50 – T10 [°C] | | 25.3 | 12.4 | 12.1 | 8.0 |
| 90 vol% recovered at T [°C] | | 238.9 | 214.9 | 216.9 | 198.7 |
| T90 – T10 [°C] | | 69.1 | 44.7 | 45.6 | 27.2 |
| FBP [°C] | | 258.5 | 243.6 | 246.4 | 215.2 |
| Residue [vol%] | | 1.2 | 1.1 | 1.1 | 1.1 |
| Loss [vol%] | | 0.9 | 1.0 | 1.2 | 1.1 |
| Flash point [°C] | IP170 | 44.0 | 45.5 | 45.0 | 46.0 |
| Density at 15°C [kg/m$^3$] | D4052 | 795.0 | 771.3 | 777.5 | 761.2 |
| Freezing point [°C] | D7153 | -49.0 | -61.3 | -61.8 | - |
| Lubricity [mm] | D5001 | 0.728 | 0.780 | 0.760 | 0.780 |
| Viscosity at -20°C [mm$^2$/s] | D445 | 3.778 | - | 3.649 | 3.710 |
| Existent gum [mg/100 mL] | D381 | <1 | <1 | <1 | <1 |
| Thermal Stability - 2.5 h at 260°C | D3241 | | | | |
| Deposit Rating | | <1 | <1 | <1 | <1[a] |
| Pres. Drop [mm Hg] | | 0.0 | 0.4 | 0.0 | 280.0[a] |
| Net Heat of Combustion [MJ/kg] | D3338 | 43.391 | - | 43.630 | - |
| Corrosion Copper Strip. 2 h/100°C | D130 | 1a | 1a | 1a | 1a |
| Smoke Point [mm] | D1322 | 26.0 | 37.5 | 25.0 | >45.0 |
| Naphthalene [vol%] | D1840 | 1.17 | 0.36 | 1.01 | - |
| Mercaptane Sulphur [wt.%] | D3227 | 0.0015 | 0.0005 | 0.0005 | <0.0003 |
| Sulphur [wt.%] | DIN EN ISO 14596 | 0.10 | 0.0323 | 0.0328 | - |
| Water Reaction, Appearance | | 1b | 1b | 1b | 1b |

*Table 38: Properties of Jet A-1 fuel 114, its blend with 70 vol% CTL and after addition of aromatics to the blend to reach the 8 vol% margin. Methods are according to ASTM unless specified otherwise.*

*[a] Thermal stability for neat CTL was determined at 325 °C.*

## 9.5 Annex 5: Results of Materials Compatibility Tests

| NBR in neat Jet A-1 | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Property | new | range | 085 | range | 112 | range | 114 | range | 117 | range | 123 | range |
| mass change [%] | - | - | 11 | 0 | 9 | 0 | 7 | 0 | 8 | 0 | 7 | 0 |
| volume change [%] | - | - | 19 | 0 | 17 | 1 | 13 | 0 | 15 | 0 | 14 | 0 |
| hardness [Shore A] | 73 | 1 | 64 | 2 | 63 | 1 | 65 | 1 | 65 | 1 | 66 | 1 |
| tensile strength [N/mm²] | 10.3 | 2.7 | 7.7 | 1.3 | 8.4 | 0.8 | 8.8 | 1.3 | 8.8 | 1.3 | 7.5 | 1.2 |
| elongation at break [%] | 184 | 32 | 148 | 22 | 158 | 17 | 161 | 11 | 159 | 19 | 147 | 17 |

*Table 39: Properties of new NBR samples and after storage in the neat Jet A-1 fuels*

| NBR in neat synthetic fuels | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Property | new | range | 255 | range | 375 | range | 109 | range | 066 | range |
| mass change [%] | - | - | -2.5 | 0 | -1 | 0 | -2 | 0 | 11 | 0 |
| volume change [%] | - | - | 0 | 0 | 2 | 0 | 0 | 0 | 19 | 0 |
| hardness [Shore A] | 73 | 1 | 71 | 1 | 71 | 0 | 73 | 1 | 64 | 1 |
| tensile strength [N/mm²] | 10.3 | 2.7 | 10.4 | 1.9 | 10.4 | 1.0 | 10.8 | 1.0 | 7.4 | 0.8 |
| elongation at break [%] | 184 | 32 | 174 | 31 | 181 | 15 | 183 | 19 | 144 | 9 |

*Table 40: Properties of new NBR samples and after storage in the neat synthetic fuels*

| NBR in HVO | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Property | 0 vol% | range | 2 vol% | range | 4vol% | range | 6 vol% | range | 8 vol% | range |
| mass change [%] | -2.5 | 0 | -1 | 0 | 0 | 0 | 1 | 0 | 2 | 0 |
| volume change [%] | 0 | 0 | 2 | 0 | 3 | 0 | 4 | 0 | 6 | 1 |
| hardness [Shore A] | 71 | 1 | 70 | 2 | 70 | 1 | 70 | 0 | 71 | 1 |
| tensile strength [N/mm²] | 10.4 | 1.9 | 10.3 | 2.0 | 10.0 | 1.1 | 8.4 | 3.6 | 9.7 | 0.3 |
| elongation at break [%] | 174 | 31 | 181 | 30 | 181 | 17 | 156 | 54 | 171 | 7 |

*Table 41: Properties of NBR samples after storage in HVO and HVO with added aromatics*

| NBR in CTL | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Property | 0 vol% | range | 2 vol% | range | 4vol% | range | 6 vol% | range | 8 vol% | range |
| mass change [%] | -1 | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 4 | 0 |
| volume change [%] | 2 | 0 | 3 | 1 | 5 | 1 | 6 | 0 | 8 | 1 |
| hardness [Shore A] | 71 | 0 | 69 | 1 | 70 | 1 | 69 | 1 | 69 | 2 |
| tensile strength [N/mm²] | 10.4 | 1.0 | 9.0 | 1.8 | 8.7 | 1.1 | 8.6 | 0.5 | 8.3 | 0.1 |
| elongation at break [%] | 181 | 15 | 155 | 28 | 159 | 14 | 156 | 10 | 160 | 10 |

*Table 42 Properties of NBR samples after storage in CTL and CTL with added aromatics*

| NBR in ATJ-SPK | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Property | 0 vol% | range | 2 vol% | range | 4 vol% | range | 6 vol% | range | 8 vol% | range |
| mass change [%] | -2 | 0 | -1 | 0 | 0 | 0 | 1 | 5 | 3 | 0 |
| volume change [%] | 0 | 0 | 1 | 1 | 3 | 0 | 5 | 6 | 7 | 4 |
| hardness [Shore A] | 73 | 1 | 71 | 1 | 70 | 1 | 70 | 0 | 69 | 1 |
| tensile strength [N/mm²] | 10.8 | 1.0 | 9.6 | 2.1 | 10.5 | 0.6 | 9.4 | 0.6 | 9.1 | 2.2 |
| elongation at break [%] | 183 | 19 | 165 | 22 | 181 | 6 | 167 | 10 | 167 | 39 |

*Table 43: Properties of NBR samples after storage in ATJ-SPK and ATJ-SPK with added aromatics*

| fluorosilicone in neat Jet A-1 | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Property | new | range | 085 | range | 112 | range | 114 | range | 117 | range | 123 | range |
| mass change [%] | - | - | 4 | 0 | 3 | 0 | 3 | 0 | 3 | 0 | 3 | 0 |
| volume change [%] | - | - | 7 | 0 | 6 | 0 | 6 | 0 | 6 | 0 | 6 | 0 |
| hardness [Shore A] | 70 | 0 | 60 | 2 | 61 | 2 | 62 | 1 | 61 | 1 | 61 | 1 |
| tensile strength [N/mm²] | 6.7 | 0.3 | 5.9 | 1.0 | 5.9 | 0.5 | 5.5 | 0.8 | 6.4 | 0.3 | 6.1 | 0.7 |
| elongation at break [%] | 238 | 16 | 232 | 48 | 224 | 5 | 200 | 50 | 234 | 17 | 224 | 39 |

*Table 44: Properties of new fluorosilicone samples and after storage in the neat Jet A-1 fuels*

| fluorosilicone in neat synthetic fuels | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Property | new | range | 255 | range | 375 | range | 109 | range | 066 | range |
| mass change [%] | - | - | 2 | 0 | 3 | 0 | 3 | 0 | 3 | 0 |
| volume change [%] | - | - | 4 | 0 | 7 | 1 | 7 | 1 | 5 | 0 |
| hardness [Shore A] | 70 | 0 | 66 | 1 | 63 | 1 | 62 | 1 | 61 | 2 |
| tensile strength [N/mm²] | 6.7 | 0.3 | 6.3 | 0.7 | 5.9 | 0.2 | 5.8 | 0.0 | 5.9 | 0.4 |
| elongation at break [%] | 238 | 16 | 235 | 24 | 214 | 15 | 223 | 8 | 225 | 20 |

*Table 45: Properties of new fluorosilicone samples and after storage in the neat synthetic fuels*

| fluorosilicone in HVO | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Property | 0 vol% | range | 2 vol% | range | 4 vol% | range | 6 vol% | range | 8 vol% | range |
| mass change [%] | 2 | 0 | 2 | 0 | 2 | 0 | 2 | 0 | 3 | 0 |
| volume change [%] | 4 | 0 | 5 | 0 | 5 | 1 | 5 | 0 | 5 | 0 |
| hardness [Shore A] | 66 | 1 | 65 | 1 | 64 | 2 | 64 | 6 | 65 | 1 |
| tensile strength [N/mm²] | 6.3 | 0.7 | 6.4 | 0.2 | 5.9 | 0.6 | 5.8 | 0.7 | 5.9 | 0.5 |
| elongation at break [%] | 235 | 24 | 233 | 13 | 227 | 42 | 216 | 31 | 217 | 21 |

*Table 46: Properties of fluorosilicone samples after storage in HVO and HVO with added aromatics*

| fluorosilicone in CTL | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Property | 0 vol% | range | 2 vol% | range | 4 vol% | range | 6 vol% | range | 8 vol% | range |
| mass change [%] | 3 | 0 | 3 | 0 | 3 | 0 | 3 | 0 | 4 | 0 |
| volume change [%] | 7 | 1 | 6 | 0 | 6 | 0 | 6 | 0 | 7 | 3 |
| hardness [Shore A] | 63 | 1 | 62 | 1 | 63 | 2 | 61 | 1 | 62 | 2 |
| tensile strength [N/mm²] | 5.9 | 0.2 | 6.1 | 1.2 | 5.8 | 0.3 | 5.6 | 0.4 | 6.0 | 0.4 |
| elongation at break [%] | 214 | 15 | 225 | 22 | 221 | 19 | 221 | 9 | 226 | 22 |

*Table 47: Properties of fluorosilicone samples after storage in CTL and CTL with added aromatics*

| fluorosilicone in ATJ-SPK | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Property | 0 vol% | range | 2 vol% | range | 4 vol% | range | 6 vol% | range | 8 vol% | range |
| mass change [%] | 3 | 0 | 3 | 0 | 4 | 0 | 4 | 0 | 4 | 0 |
| volume change [%] | 7 | 1 | 7 | 0 | 8 | 0 | 8 | 1 | 8 | 0 |
| hardness [Shore A] | 62 | 1 | 64 | 2 | 65 | 2 | 62 | 4 | 63 | 4 |
| tensile strength [N/mm²] | 5.8 | 0.0 | 5.7 | 0.5 | 5.8 | 0.8 | 6.2 | 0.3 | 6.0 | 0.4 |
| elongation at break [%] | 223 | 8 | 193 | 41 | 220 | 42 | 226 | 26 | 225 | 19 |

*Table 48: Properties of fluorosilicone samples after storage in ATJ-SPK and ATJ-SPK with added aromatics*

| fluorocarbon in neat Jet A-1 | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Property | new | range | 085 | range | 112 | range | 114 | range | 117 | range | 123 | range |
| mass change [%] | - | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| volume change [%] | - | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| hardness [Shore A] | 74 | 1 | 73 | 1 | 74 | 1 | 73 | 0 | 74 | 1 | 73 | 1 |
| tensile strength [N/mm²] | 12.8 | 2.2 | 14.4 | 2.3 | 14.2 | 2.9 | 15.0 | 2.1 | 11.8 | 5.5 | 15.2 | 0.6 |
| elongation at break [%] | 185 | 9 | 198 | 20 | 195 | 29 | 200 | 23 | 173 | 58 | 209 | 3 |

*Table 49: Properties of new fluorocarbon samples and after storage in the neat Jet A-1 fuels*

| fluorocarbon in neat synthetic fuels | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Property | new | range | 255 | range | 375 | range | 109 | range | 066 | range |
| mass change [%] | - | - | 0 | 0 | 0 | 0 | 1 | 4 | 0 | 0 |
| volume change [%] | - | - | 0 | 0 | 0 | 0 | 1 | 7 | -1 | 1 |
| hardness [Shore A] | 74 | 1 | 74 | 0 | 74 | 1 | 73 | 2 | 73 | 1 |
| tensile strength [N/mm²] | 12.8 | 2.2 | 14.0 | 2.6 | 15.4 | 1.5 | 13.8 | 0.8 | 13.7 | 1.2 |
| elongation at break [%] | 185 | 9 | 197 | 20 | 203 | 20 | 194 | 8 | 195 | 22 |

*Table 50: Properties of new fluorocarbon samples and after storage in the neat synthetic fuels*

| | fluorocarbon in HVO | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Property | 0 vol% | range | 2 vol% | range | 4 vol% | range | 6 vol% | range | 8 vol% | range |
| mass change [%] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| volume change [%] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| hardness [Shore A] | 74 | 0 | 74 | 0 | 75 | 0 | 74 | 0 | 74 | 1 |
| tensile strength [N/mm²] | 14.0 | 2.6 | 13.8 | 1.0 | 14.5 | 0.2 | 14.4 | 1.4 | 13.8 | 3.1 |
| elongation at break [%] | 197 | 20 | 193 | 10 | 197 | 1 | 208 | 13 | 196 | 31 |

*Table 51: Properties of fluorocarbon samples after storage in HVO and HVO with added aromatics*

| | fluorocarbon in CTL | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Property | 0 vol% | range | 2 vol% | range | 4vol% | range | 6 vol% | range | 8 vol% | range |
| mass change [%] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| volume change [%] | 0 | 0 | 0 | 0 | 0 | 0 | -1 | 0 | 0 | 0 |
| hardness [Shore A] | 74 | 1 | 74 | 1 | 74 | 1 | 73 | 1 | 73 | 1 |
| tensile strength [N/mm²] | 15.4 | 1.5 | 14.9 | 2.0 | 12.8 | 0.9 | 12.2 | 4.3 | 13.8 | 2.3 |
| elongation at break [%] | 203 | 20 | 204 | 20 | 183 | 10 | 178 | 54 | 197 | 25 |

*Table 52: Properties of fluorocarbon samples after storage in CTL and CTL with added aromatics*

| | fluorocarbon in ATJ-SPK | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Property | 0 vol% | range | 2 vol% | range | 4 vol% | range | 6 vol% | range | 8 vol% | range |
| mass change [%] | 1 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| volume change [%] | 1 | 7 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| hardness [Shore A] | 73 | 2 | 73 | 1 | 74 | 0 | 74 | 0 | 73 | 2 |
| tensile strength [N/mm²] | 13.8 | 0.8 | 14.5 | 0.6 | 13.5 | 2.2 | 14.6 | 1.5 | 12.5 | 2.0 |
| elongation at break [%] | 194 | 8 | 197 | 7 | 195 | 28 | 204 | 6 | 182 | 19 |

*Table 53: Properties of fluorocarbon samples after storage in ATJ-SPK and ATJ-SPK with added aromatics*

| twofold storage of NBR in fuel 085 and HVO | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | new | range | after first storage in 085 | range | after second storage in HVO | range | for comparison: after storage in HVO | range |
| mass change [%] | - | - | 11 | 0 | -4 | 0 | -3 | 0 |
| volume change [%] | - | - | 19 | 0 | -2 | 1 | 0 | 0 |
| hardness [Shore A] | 73 | 1 | 64 | 2 | 72 | 0 | 71 | 1 |
| tensile strength [N/mm²] | 10.3 | 2.7 | 7.7 | 1.3 | 11.0 | 1.9 | 10.4 | 1.9 |
| elongation at break [%] | 184 | 32 | 148 | 22 | 190 | 33 | 174 | 31 |

*Table 54: Properties of new NBR samples, after storage in fossil fuel 085 and after subsequent storage in fossil fuel 085 and HVO. Values for the storage of the elastomer in HVO have been added for comparison. Note: Mass and volume change always refer to the original elastomer sample.*

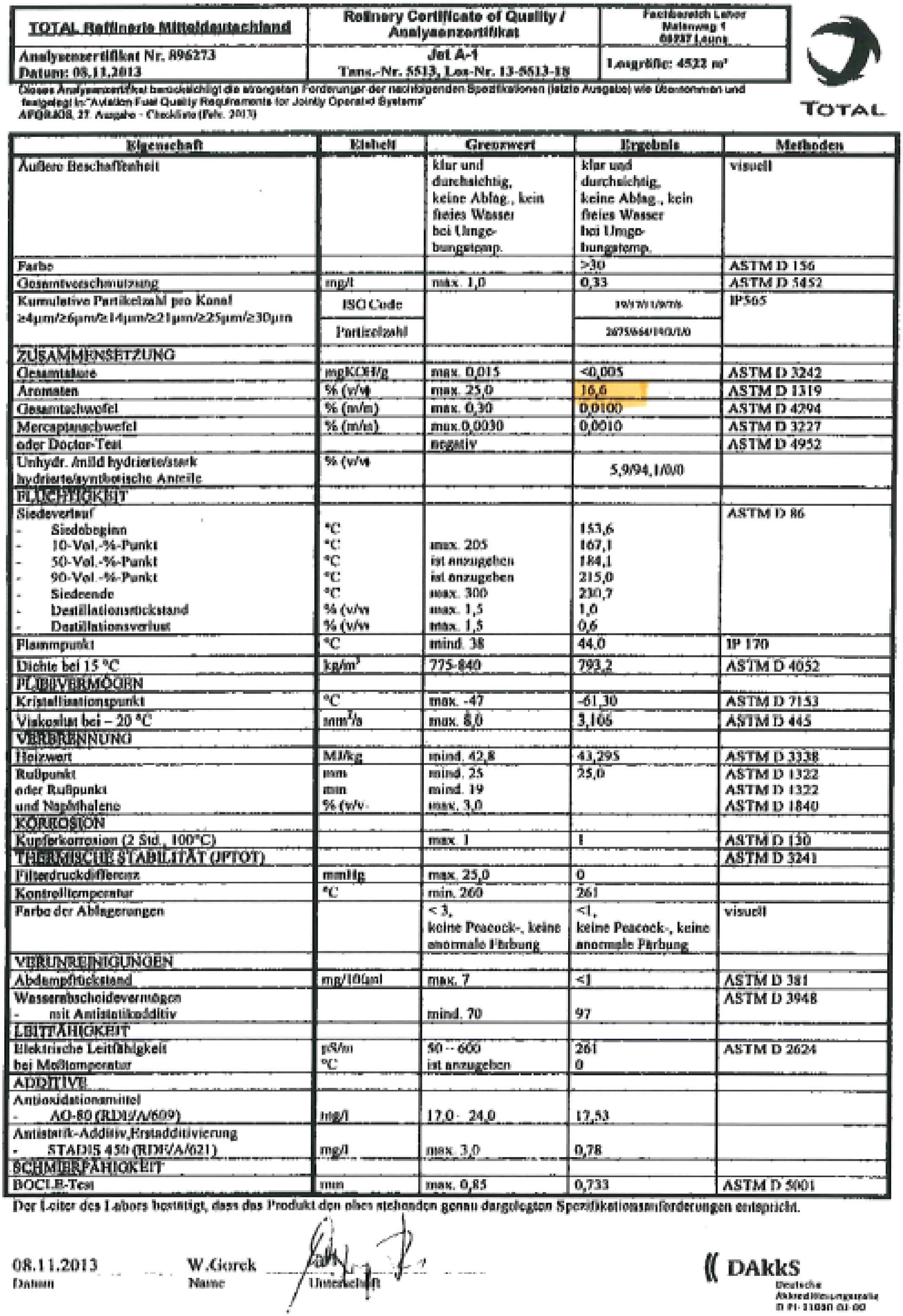
| twofold storage of fluorosilicone in fuel 085 and HVO | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | new | range | after first storage in 085 | range | after second storage in HVO | range | for comparison: after storage in HVO | range |
| mass change [%] | - | - | 4 | 0 | 2 | 0 | 2 | 0 |
| volume change [%] | - | - | 7 | 0 | 4 | 1 | 4 | 0 |
| hardness [Shore A] | 70 | 0 | 60 | 2 | 65 | 1 | 66 | 1 |
| tensile strength [N/mm²] | 6.7 | 0.3 | 5.9 | 1.0 | 6.2 | 0.4 | 6.3 | 0.7 |
| elongation at break [%] | 238 | 16 | 232 | 48 | 222 | 21 | 235 | 24 |

*Table 55: Properties of new fluorosilicone samples, after storage in fossil fuel 085 and after subsequent storage in fossil fuel 085 and HVO. Values for the storage of the elastomer in HVO have been added for comparison. Note: Mass and volume change always refer to the original elastomer sample.*

| twofold storage of fluorocarbon in fuel 085 and HVO | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Property | new | range | after first storage in 085 | range | after second storage in HVO | range | for comparison: after storage in HVO | range |
| mass change [%] | - | - | 0 | 0 | 0 | 0 | 0 | 0 |
| volume change [%] | - | - | 0 | 0 | 0 | 1 | 0 | 0 |
| hardness [Shore A] | 74 | 1 | 73 | 1 | 73 | 1 | 74 | 0 |
| tensile strength [N/mm²] | 12.8 | 2.2 | 14.4 | 2.3 | 12.6 | 0.2 | 14.0 | 2.6 |
| elongation at break [%] | 185 | 9 | 198 | 20 | 182 | 9 | 197 | 20 |

*Table 56: Properties of new fluorocarbon samples, after storage in fossil fuel 085 and after subsequent storage in fossil fuel 085 and HVO. Values for the storage of the elastomer in HVO have been added for comparison. Note: Mass and volume change always refer to the original elastomer sample.*

## 9.6 Annex 6: Properties of the Conventional Kerosene used for SIP Fuel Emissions Test



| | | |
|---|---|---|
| **TOTAL Raffinerie Mitteldeutschland** | **Refinery Certificate of Quality / Analysenzertifikat** | Fachbereich Labor<br>Maienweg 1<br>06237 Leuna |
| Analysenzertifikat Nr. 896273<br>Datum: 08.11.2013 | Jet A-1<br>Tank-Nr. 5513, Los-Nr. 13-5513-18 | Losgröße: 4523 m³ |

Dieses Analysenzertifikat berücksichtigt die strengsten Forderungen der nachfolgenden Spezifikationen (letzte Ausgabe) wie übernommen und festgelegt in: "Aviation Fuel Quality Requirements for Jointly Operated Systems" AFQRJOS, 27. Ausgabe - Checkliste (Feb. 2013)

TOTAL

| Eigenschaft | Einheit | Grenzwert | Ergebnis | Methoden |
|---|---|---|---|---|
| Äußere Beschaffenheit | | klar und durchsichtig, keine Ablag., kein freies Wasser bei Umgebungstemp. | klar und durchsichtig, keine Ablag., kein freies Wasser bei Umgebungstemp. | visuell |
| Farbe | | | >30 | ASTM D 156 |
| Gesamtverschmutzung | mg/l | max. 1,0 | 0,33 | ASTM D 5452 |
| Kumulative Partikelzahl pro Kanal ≥4µm/≥6µm/≥14µm/≥21µm/≥25µm/≥30µm | ISO Code | | 19/17/11/8/7/6 | IP565 |
| | Partikelzahl | | 2875/664/19/0/1/0 | |
| ZUSAMMENSETZUNG | | | | |
| Gesamtsäure | mgKOH/g | max. 0,015 | <0,005 | ASTM D 3242 |
| Aromaten | % (v/v) | max. 25,0 | 16,6 | ASTM D 1319 |
| Gesamtschwefel | % (m/m) | max. 0,30 | 0,0100 | ASTM D 4294 |
| Mercaptanschwefel | % (m/m) | max. 0,0030 | 0,0010 | ASTM D 3227 |
| oder Doctor-Test | | negativ | | ASTM D 4952 |
| Unhydr. /mild hydrierte/stark hydrierte/synthetische Anteile | % (v/v) | | 5,9/94,1/0/0 | |
| FLÜCHTIGKEIT | | | | |
| Siedeverlauf | | | | ASTM D 86 |
| - Siedebeginn | °C | | 153,6 | |
| - 10-Vol.-%-Punkt | °C | max. 205 | 167,1 | |
| - 50-Vol.-%-Punkt | °C | ist anzugeben | 184,1 | |
| - 90-Vol.-%-Punkt | °C | ist anzugeben | 215,0 | |
| - Siedeende | °C | max. 300 | 230,7 | |
| - Destillationsrückstand | % (v/v) | max. 1,5 | 1,0 | |
| - Destillationsverlust | % (v/v) | max. 1,5 | 0,6 | |
| Flammpunkt | °C | mind. 38 | 44,0 | IP 170 |
| Dichte bei 15 °C | kg/m³ | 775-840 | 793,2 | ASTM D 4052 |
| FLIEßVERMÖGEN | | | | |
| Kristallisationspunkt | °C | max. -47 | -61,30 | ASTM D 7153 |
| Viskosität bei – 20 °C | mm²/s | max. 8,0 | 3,106 | ASTM D 445 |
| VERBRENNUNG | | | | |
| Heizwert | MJ/kg | mind. 42,8 | 43,295 | ASTM D 3338 |
| Rußpunkt<br>oder Rußpunkt<br>und Naphthalene | mm<br>mm<br>% (v/v) | mind. 25<br>mind. 19<br>max. 3,0 | 25,0 | ASTM D 1322<br>ASTM D 1322<br>ASTM D 1840 |
| KORROSION | | | | |
| Kupferkorrosion (2 Std., 100°C) | | max. 1 | 1 | ASTM D 130 |
| THERMISCHE STABILITÄT (JFTOT) | | | | ASTM D 3241 |
| Filterdruckdifferenz | mmHg | max. 25,0 | 0 | |
| Kontrolltemperatur | °C | min. 260 | 261 | |
| Farbe der Ablagerungen | | < 3, keine Peacock-, keine anormale Färbung | <1, keine Peacock-, keine anormale Färbung | visuell |
| VERUNREINIGUNGEN | | | | |
| Abdampfrückstand | mg/100ml | max. 7 | <1 | ASTM D 381 |
| Wasserabscheidevermögen<br>- mit Antistatikadditiv | | mind. 70 | 97 | ASTM D 3948 |
| LEITFÄHIGKEIT | | | | |
| Elektrische Leitfähigkeit<br>bei Meßtemperatur | pS/m<br>°C | 50 – 600<br>ist anzugeben | 261<br>0 | ASTM D 2624 |
| ADDITIVE | | | | |
| Antioxidationsmittel<br>- AO-30 (RDE/A/609) | mg/l | 17,0 - 24,0 | 17,53 | |
| Antistatik-Additiv, Erstadditivierung<br>- STADIS 450 (RDE/A/621) | mg/l | max. 3,0 | 0,78 | |
| SCHMIERFÄHIGKEIT | | | | |
| BOCLE-Test | mm | max. 0,85 | 0,733 | ASTM D 5001 |

Der Leiter des Labors bestätigt, dass das Produkt den oben stehenden genau dargelegten Spezifikationsanforderungen entspricht.

| | | |
|---|---|---|
| 08.11.2013 | W.Gorek | |
| Datum | Name | Unterschrift |

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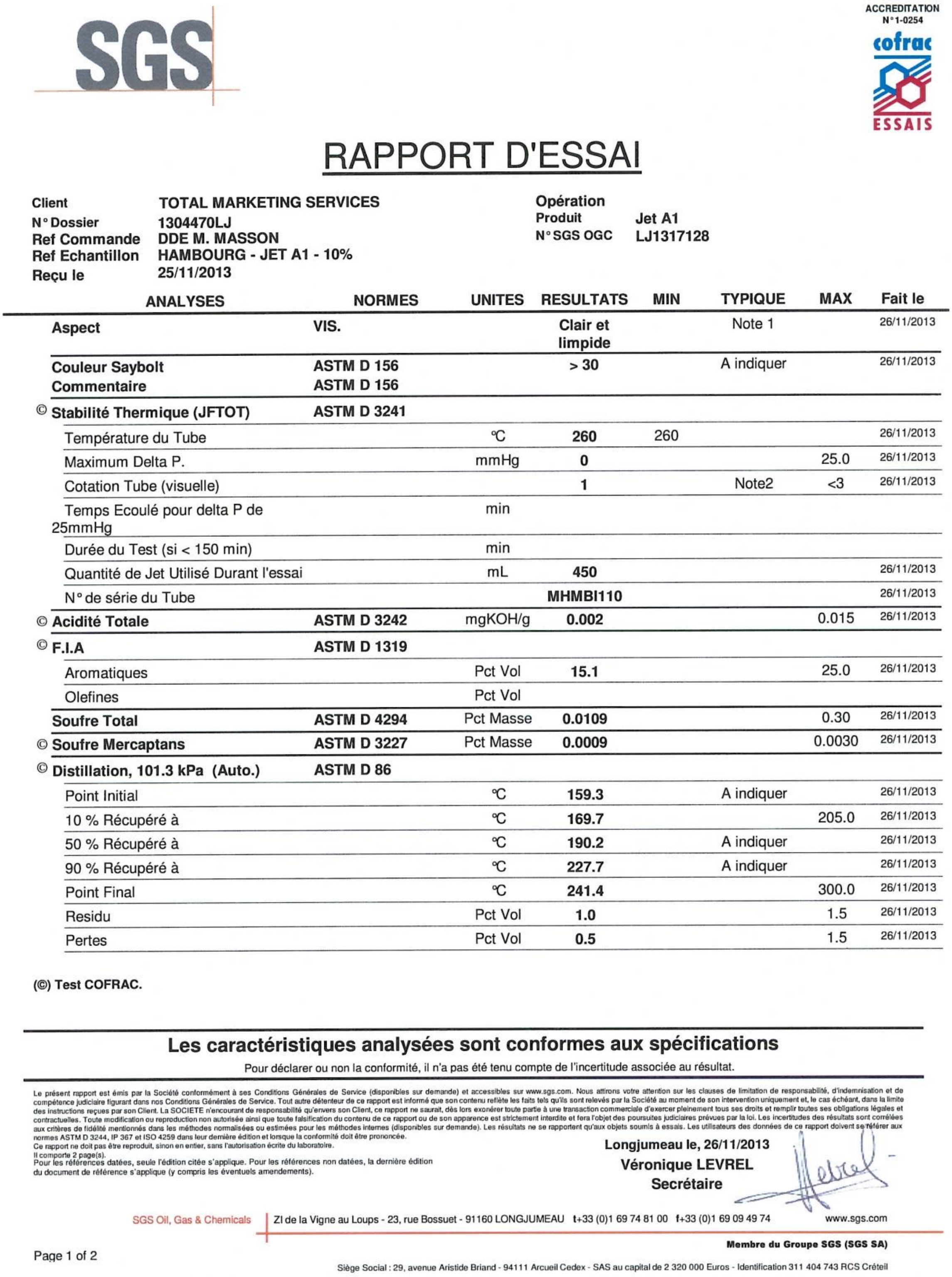
D-PL-11030-01-00

*Table 57: Properties of the conventional kerosene used for SIP fuel emissions test*

## 9.7 Annex 7: Properties of Blend with 10% SIP Fuel Used for Emissions Test



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# RAPPORT D'ESSAI

| | | | |
|---|---|---|---|
| Client | TOTAL MARKETING SERVICES | Opération | |
| N° Dossier | 1304470LJ | Produit | Jet A1 |
| Ref Commande | DDE M. MASSON | N° SGS OGC | LJ1317128 |
| Ref Echantillon | HAMBOURG - JET A1 - 10% | | |
| Reçu le | 25/11/2013 | | |

| ANALYSES | NORMES | UNITES | RESULTATS | MIN | TYPIQUE | MAX | Fait le |
|---|---|---|---|---|---|---|---|
| **Aspect** | VIS. | | **Clair et limpide** | | Note 1 | | 26/11/2013 |
| **Couleur Saybolt** | **ASTM D 156** | | **> 30** | | A indiquer | | 26/11/2013 |
| **Commentaire** | **ASTM D 156** | | | | | | |
| © **Stabilité Thermique (JFTOT)** | **ASTM D 3241** | | | | | | |
| Température du Tube | | °C | **260** | 260 | | | 26/11/2013 |
| Maximum Delta P. | | mmHg | **0** | | | 25.0 | 26/11/2013 |
| Cotation Tube (visuelle) | | | **1** | | Note2 | <3 | 26/11/2013 |
| Temps Ecoulé pour delta P de 25mmHg | | min | | | | | |
| Durée du Test (si < 150 min) | | min | | | | | |
| Quantité de Jet Utilisé Durant l'essai | | mL | **450** | | | | 26/11/2013 |
| N° de série du Tube | | | **MHMBI110** | | | | 26/11/2013 |
| © **Acidité Totale** | **ASTM D 3242** | mgKOH/g | **0.002** | | | 0.015 | 26/11/2013 |
| © **F.I.A** | **ASTM D 1319** | | | | | | |
| Aromatiques | | Pct Vol | **15.1** | | | 25.0 | 26/11/2013 |
| Olefines | | Pct Vol | | | | | |
| **Soufre Total** | **ASTM D 4294** | Pct Masse | **0.0109** | | | 0.30 | 26/11/2013 |
| © **Soufre Mercaptans** | **ASTM D 3227** | Pct Masse | **0.0009** | | | 0.0030 | 26/11/2013 |
| © **Distillation, 101.3 kPa (Auto.)** | **ASTM D 86** | | | | | | |
| Point Initial | | °C | **159.3** | | A indiquer | | 26/11/2013 |
| 10 % Récupéré à | | °C | **169.7** | | | 205.0 | 26/11/2013 |
| 50 % Récupéré à | | °C | **190.2** | | A indiquer | | 26/11/2013 |
| 90 % Récupéré à | | °C | **227.7** | | A indiquer | | 26/11/2013 |
| Point Final | | °C | **241.4** | | | 300.0 | 26/11/2013 |
| Residu | | Pct Vol | **1.0** | | | 1.5 | 26/11/2013 |
| Pertes | | Pct Vol | **0.5** | | | 1.5 | 26/11/2013 |

**(©) Test COFRAC.**

**Les caractéristiques analysées sont conformes aux spécifications**

Pour déclarer ou non la conformité, il n'a pas été tenu compte de l'incertitude associée au résultat.

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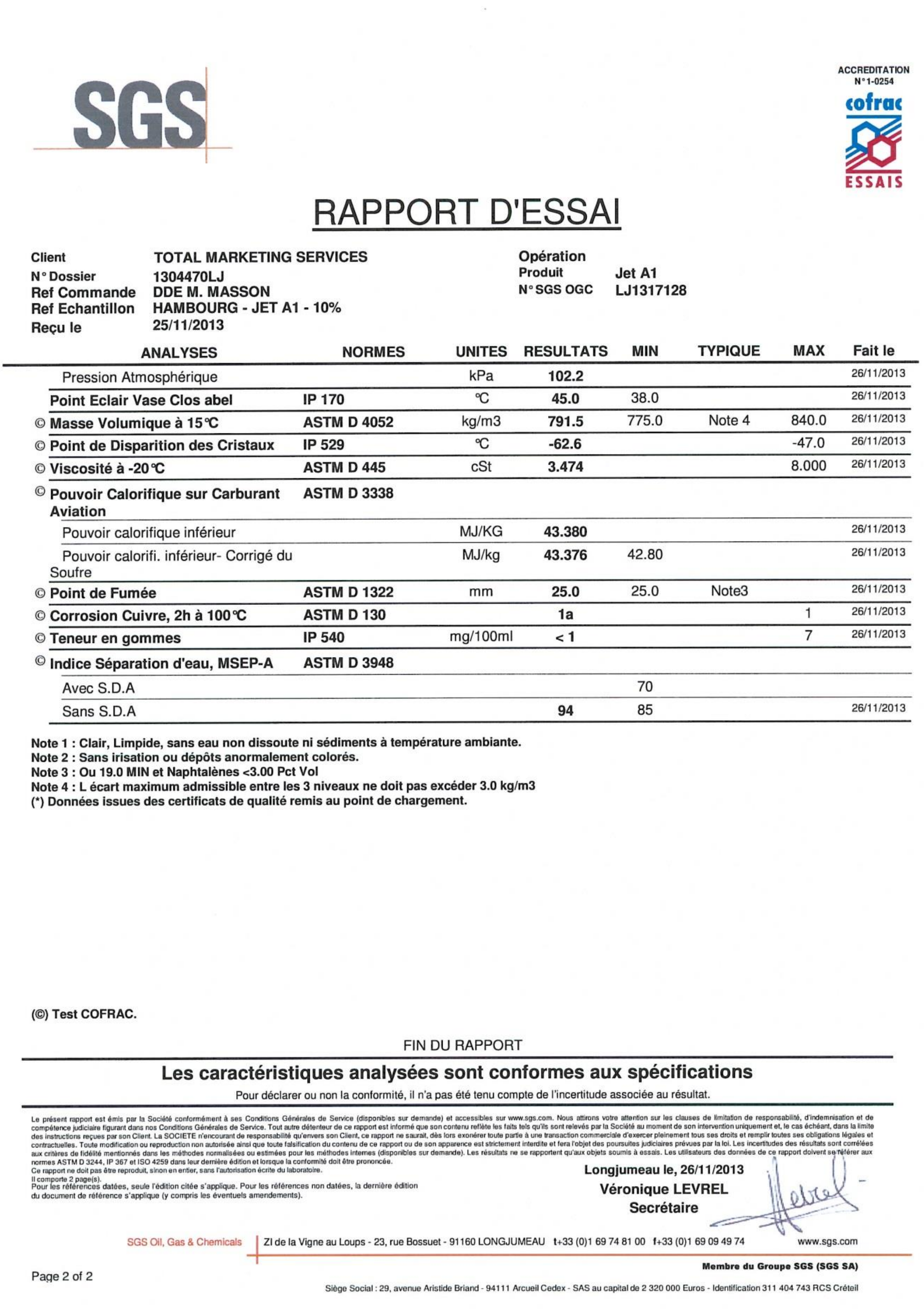

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# RAPPORT D'ESSAI

| | | | |
|---|---|---|---|
| Client | TOTAL MARKETING SERVICES | Opération | |
| N° Dossier | 1304470LJ | Produit | Jet A1 |
| Ref Commande | DDE M. MASSON | N° SGS OGC | LJ1317128 |
| Ref Echantillon | HAMBOURG - JET A1 - 10% | | |
| Reçu le | 25/11/2013 | | |

| ANALYSES | NORMES | UNITES | RESULTATS | MIN | TYPIQUE | MAX | Fait le |
|---|---|---|---|---|---|---|---|
| Pression Atmosphérique | | kPa | **102.2** | | | | 26/11/2013 |
| **Point Eclair Vase Clos abel** | **IP 170** | °C | **45.0** | 38.0 | | | 26/11/2013 |
| © **Masse Volumique à 15°C** | **ASTM D 4052** | kg/m3 | **791.5** | 775.0 | Note 4 | 840.0 | 26/11/2013 |
| © **Point de Disparition des Cristaux** | **IP 529** | °C | **-62.6** | | | -47.0 | 26/11/2013 |
| © **Viscosité à -20°C** | **ASTM D 445** | cSt | **3.474** | | | 8.000 | 26/11/2013 |
| © **Pouvoir Calorifique sur Carburant Aviation** | **ASTM D 3338** | | | | | | |
| Pouvoir calorifique inférieur | | MJ/KG | **43.380** | | | | 26/11/2013 |
| Pouvoir calorifi. inférieur- Corrigé du Soufre | | MJ/kg | **43.376** | 42.80 | | | 26/11/2013 |
| © **Point de Fumée** | **ASTM D 1322** | mm | **25.0** | 25.0 | Note3 | | 26/11/2013 |
| © **Corrosion Cuivre, 2h à 100°C** | **ASTM D 130** | | **1a** | | | 1 | 26/11/2013 |
| © **Teneur en gommes** | **IP 540** | mg/100ml | **< 1** | | | 7 | 26/11/2013 |
| © **Indice Séparation d'eau, MSEP-A** | **ASTM D 3948** | | | | | | |
| Avec S.D.A | | | | 70 | | | |
| Sans S.D.A | | | **94** | 85 | | | 26/11/2013 |

**Note 1 : Clair, Limpide, sans eau non dissoute ni sédiments à température ambiante.**
**Note 2 : Sans irisation ou dépôts anormalement colorés.**
**Note 3 : Ou 19.0 MIN et Naphtalènes <3.00 Pct Vol**
**Note 4 : L écart maximum admissible entre les 3 niveaux ne doit pas excéder 3.0 kg/m3**
**(*) Données issues des certificats de qualité remis au point de chargement.**

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FIN DU RAPPORT

**Les caractéristiques analysées sont conformes aux spécifications**

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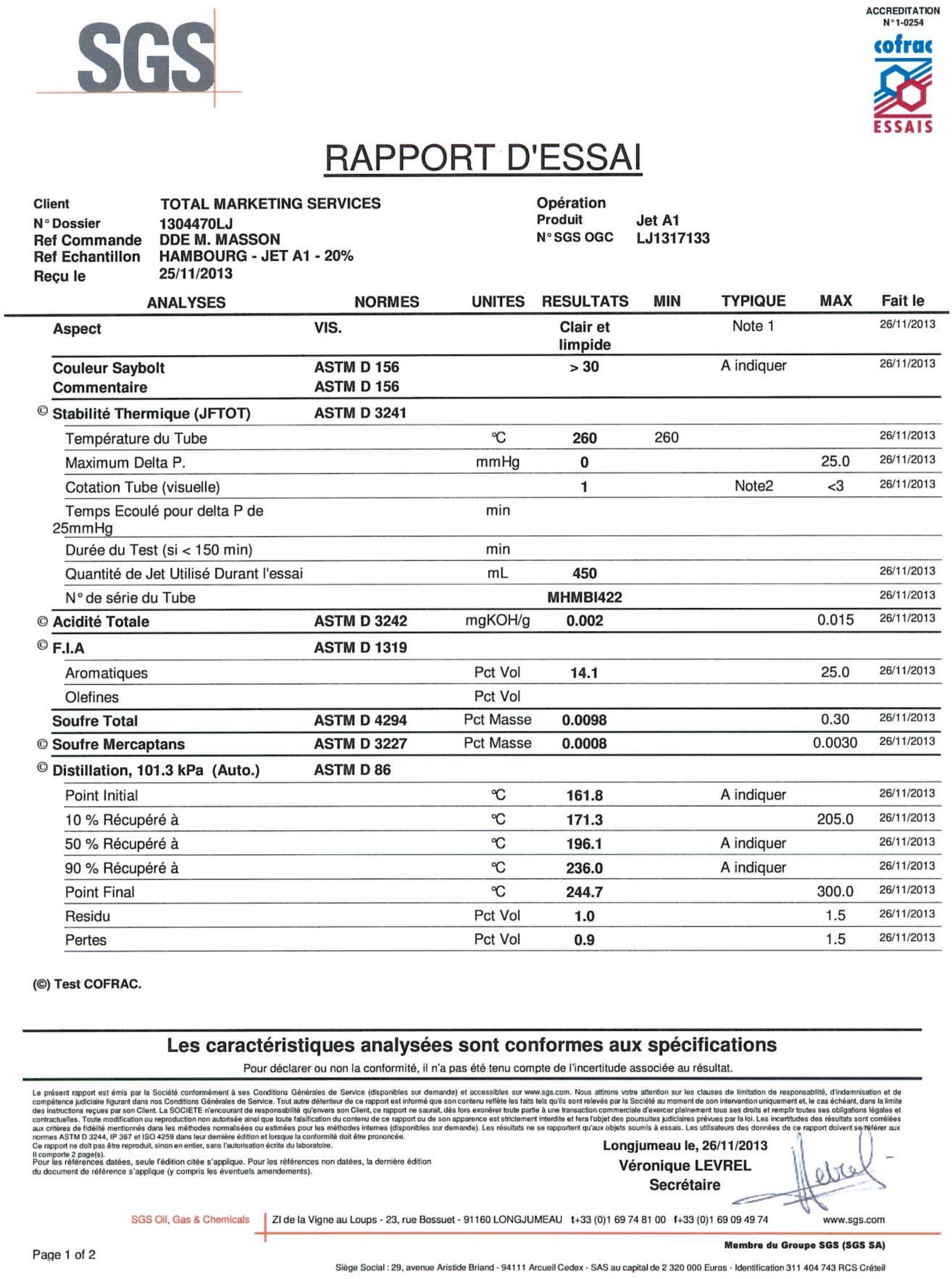
*Table 58: Properties of blend with 10% SIP fuel used for emissions test*

## 9.8 Annex 8: Properties of Blend with 20% SIP Fuel Used for Emissions Test



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# RAPPORT D'ESSAI

| | | | |
|---|---|---|---|
| **Client** | **TOTAL MARKETING SERVICES** | **Opération** | |
| **N° Dossier** | **1304470LJ** | **Produit** | **Jet A1** |
| **Ref Commande** | **DDE M. MASSON** | **N° SGS OGC** | **LJ1317133** |
| **Ref Echantillon** | **HAMBOURG - JET A1 - 20%** | | |
| **Reçu le** | **25/11/2013** | | |

| ANALYSES | NORMES | UNITES | RESULTATS | MIN | TYPIQUE | MAX | Fait le |
|---|---|---|---|---|---|---|---|
| **Aspect** | **VIS.** | | **Clair et limpide** | | Note 1 | | 26/11/2013 |
| **Couleur Saybolt** | **ASTM D 156** | | **> 30** | | A indiquer | | 26/11/2013 |
| **Commentaire** | **ASTM D 156** | | | | | | |
| © **Stabilité Thermique (JFTOT)** | **ASTM D 3241** | | | | | | |
| Température du Tube | | °C | **260** | 260 | | | 26/11/2013 |
| Maximum Delta P. | | mmHg | **0** | | | 25.0 | 26/11/2013 |
| Cotation Tube (visuelle) | | | **1** | | Note2 | <3 | 26/11/2013 |
| Temps Ecoulé pour delta P de 25mmHg | | min | | | | | |
| Durée du Test (si < 150 min) | | min | | | | | |
| Quantité de Jet Utilisé Durant l'essai | | mL | **450** | | | | 26/11/2013 |
| N° de série du Tube | | | **MHMBI422** | | | | 26/11/2013 |
| © **Acidité Totale** | **ASTM D 3242** | mgKOH/g | **0.002** | | | 0.015 | 26/11/2013 |
| © **F.I.A** | **ASTM D 1319** | | | | | | |
| Aromatiques | | Pct Vol | **14.1** | | | 25.0 | 26/11/2013 |
| Olefines | | Pct Vol | | | | | |
| **Soufre Total** | **ASTM D 4294** | Pct Masse | **0.0098** | | | 0.30 | 26/11/2013 |
| © **Soufre Mercaptans** | **ASTM D 3227** | Pct Masse | **0.0008** | | | 0.0030 | 26/11/2013 |
| © **Distillation, 101.3 kPa (Auto.)** | **ASTM D 86** | | | | | | |
| Point Initial | | °C | **161.8** | | A indiquer | | 26/11/2013 |
| 10 % Récupéré à | | °C | **171.3** | | | 205.0 | 26/11/2013 |
| 50 % Récupéré à | | °C | **196.1** | | A indiquer | | 26/11/2013 |
| 90 % Récupéré à | | °C | **236.0** | | A indiquer | | 26/11/2013 |
| Point Final | | °C | **244.7** | | | 300.0 | 26/11/2013 |
| Residu | | Pct Vol | **1.0** | | | 1.5 | 26/11/2013 |
| Pertes | | Pct Vol | **0.9** | | | 1.5 | 26/11/2013 |

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**Les caractéristiques analysées sont conformes aux spécifications**

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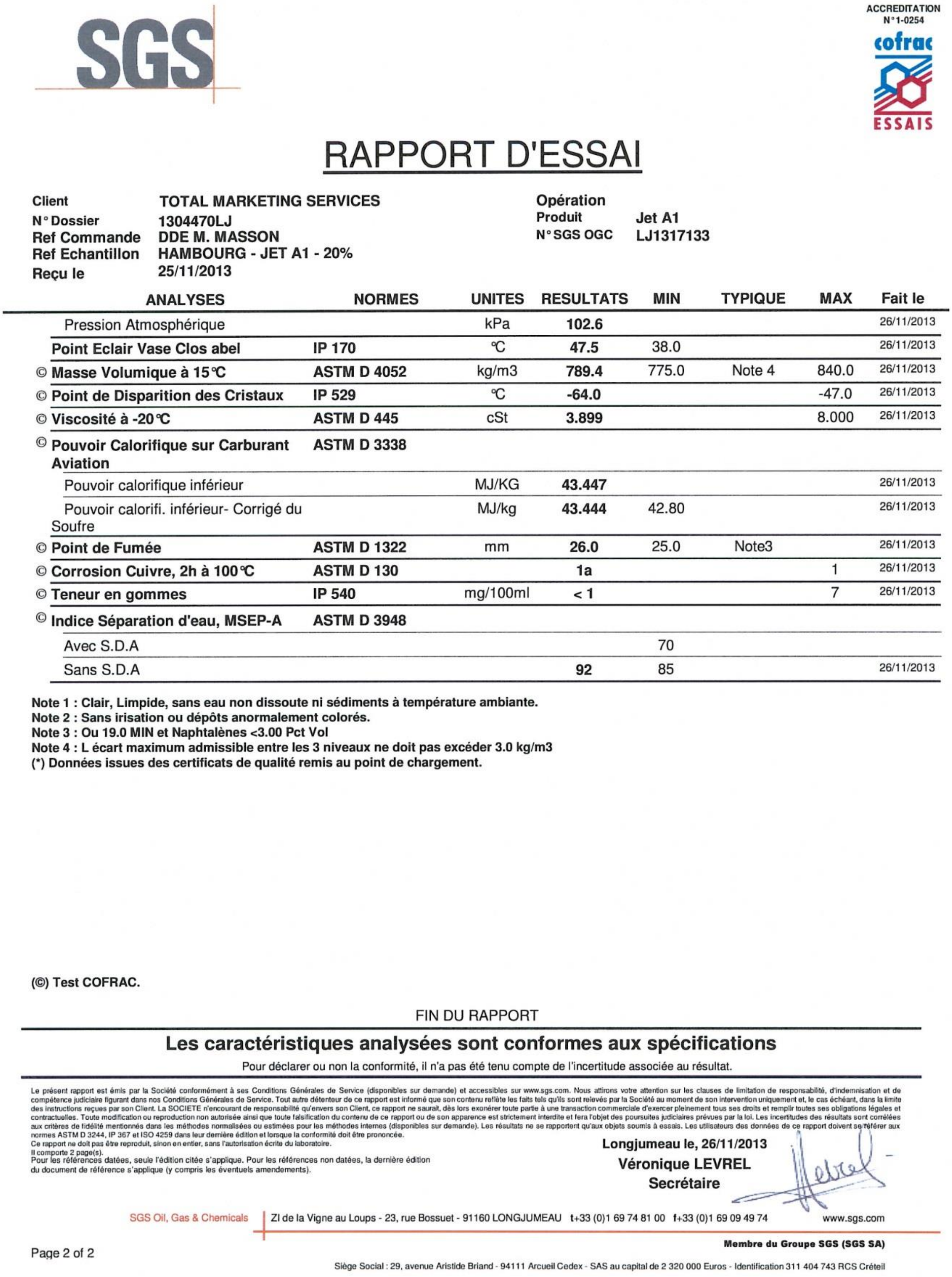

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## RAPPORT D'ESSAI

| | | | |
|---|---|---|---|
| Client | TOTAL MARKETING SERVICES | **Opération** | |
| N° Dossier | 1304470LJ | Produit | Jet A1 |
| Ref Commande | DDE M. MASSON | N° SGS OGC | LJ1317133 |
| Ref Echantillon | HAMBOURG - JET A1 - 20% | | |
| Reçu le | 25/11/2013 | | |

| ANALYSES | NORMES | UNITES | RESULTATS | MIN | TYPIQUE | MAX | Fait le |
|---|---|---|---|---|---|---|---|
| Pression Atmosphérique | | kPa | **102.6** | | | | 26/11/2013 |
| **Point Eclair Vase Clos abel** | **IP 170** | °C | **47.5** | 38.0 | | | 26/11/2013 |
| © **Masse Volumique à 15°C** | **ASTM D 4052** | kg/m3 | **789.4** | 775.0 | Note 4 | 840.0 | 26/11/2013 |
| © **Point de Disparition des Cristaux** | **IP 529** | °C | **-64.0** | | | -47.0 | 26/11/2013 |
| © **Viscosité à -20°C** | **ASTM D 445** | cSt | **3.899** | | | 8.000 | 26/11/2013 |
| © **Pouvoir Calorifique sur Carburant Aviation** | **ASTM D 3338** | | | | | | |
| Pouvoir calorifique inférieur | | MJ/KG | **43.447** | | | | 26/11/2013 |
| Pouvoir calorifi. inférieur- Corrigé du Soufre | | MJ/kg | **43.444** | 42.80 | | | 26/11/2013 |
| © **Point de Fumée** | **ASTM D 1322** | mm | **26.0** | 25.0 | Note3 | | 26/11/2013 |
| © **Corrosion Cuivre, 2h à 100°C** | **ASTM D 130** | | **1a** | | | 1 | 26/11/2013 |
| © **Teneur en gommes** | **IP 540** | mg/100ml | **< 1** | | | 7 | 26/11/2013 |
| © **Indice Séparation d'eau, MSEP-A** | **ASTM D 3948** | | | | | | |
| Avec S.D.A | | | | 70 | | | |
| Sans S.D.A | | | **92** | 85 | | | 26/11/2013 |

**Note 1 : Clair, Limpide, sans eau non dissoute ni sédiments à température ambiante.**
**Note 2 : Sans irisation ou dépôts anormalement colorés.**
**Note 3 : Ou 19.0 MIN et Naphtalènes <3.00 Pct Vol**
**Note 4 : L écart maximum admissible entre les 3 niveaux ne doit pas excéder 3.0 kg/m3**
**(*) Données issues des certificats de qualité remis au point de chargement.**

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**Les caractéristiques analysées sont conformes aux spécifications**

Pour déclarer ou non la conformité, il n'a pas été tenu compte de l'incertitude associée au résultat.

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Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

**Longjumeau le, 26/11/2013**
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*Table 59: Properties of blend with 20% SIP fuel used for emissions test*

## 9.9 Annex 9: Hamburg Weather Data of SIP Fuel Emission Test

Hamburg/Fuhlsbüttel weather station, 15. November 2013

| Time | Temperature | Dew Point | Pressure | weather | Source |
|---|---|---|---|---|---|
| 15.11.2013 23:50 | 6 °C | 5 °C | 1030 hPa | overcast | NWS |
| 15.11.2013 23:20 | 6 °C | 5 °C | 1030 hPa | overcast | NWS |
| 15.11.2013 23:00 | 5.8 °C | 4.7 °C | 1030.7 hPa | hazy | DWD |
| 15.11.2013 22:50 | 6 °C | 5 °C | 1030 hPa | overcast | NWS |
| 15.11.2013 22:20 | 6 °C | 5 °C | 1031 hPa | overcast | NWS |
| 15.11.2013 22:00 | 5.8 °C | 4.6 °C | 1031.3 hPa | hazy | DWD |
| 15.11.2013 21:50 | 6 °C | 5 °C | 1031 hPa | overcast | NWS |
| 15.11.2013 21:20 | 6 °C | 5 °C | 1030 hPa | clouded | NWS |
| 15.11.2013 21:00 | 6.1 °C | 4.8 °C | 1031 hPa | hazy | DWD |
| 15.11.2013 20:50 | 6 °C | 5 °C | 1030 hPa | clouded | NWS |
| 15.11.2013 20:20 | 6 °C | 5 °C | 1030 hPa | overcast | NWS |
| 15.11.2013 20:00 | 6.1 °C | 4.8 °C | 1030.7 hPa | hazy | DWD |
| 15.11.2013 19:50 | 6 °C | 5 °C | 1030 hPa | overcast | NWS |
| 15.11.2013 19:20 | 6 °C | 5 °C | 1030 hPa | overcast | NWS |
| 15.11.2013 19:00 | 6 °C | 4.7 °C | 1030.9 hPa | hazy | DWD |
| 15.11.2013 18:50 | 6 °C | 5 °C | 1030 hPa | overcast | NWS |
| 15.11.2013 18:20 | 6 °C | 5 °C | 1030 hPa | overcast | NWS |
| 15.11.2013 18:00 | 6.1 °C | 4.6 °C | 1030.6 hPa | hazy | DWD |
| 15.11.2013 17:50 | 6 °C | 5 °C | 1030 hPa | overcast | NWS |
| 15.11.2013 17:20 | 6 °C | 5 °C | 1030 hPa | overcast | NWS |
| 15.11.2013 17:00 | 6.2 °C | 4.7 °C | 1030.1 hPa | hazy | DWD |
| 15.11.2013 16:50 | 6 °C | 5 °C | 1029 hPa | overcast | NWS |
| 15.11.2013 16:20 | 6 °C | 5 °C | 1029 hPa | overcast | NWS |
| 15.11.2013 16:00 | 6.5 °C | 4.9 °C | 1030.2 hPa | hazy | DWD |
| 15.11.2013 15:50 | 7 °C | 5 °C | 1030 hPa | overcast | NWS |
| 15.11.2013 15:20 | 7 °C | 5 °C | 1029 hPa | overcast | NWS |
| 15.11.2013 15:00 | 6.4 °C | 4.4 °C | 1030.1 hPa | hazy | DWD |
| 15.11.2013 14:50 | 7 °C | 5 °C | 1029 hPa | overcast | NWS |
| 15.11.2013 14:20 | 7 °C | 5 °C | 1029 hPa | overcast | NWS |
| 15.11.2013 14:00 | 6.5 °C | 4.4 °C | 1029.5 hPa | hazy | DWD |
| 15.11.2013 13:50 | 7 °C | 5 °C | 1029 hPa | overcast | NWS |
| 15.11.2013 13:20 | 7 °C | 5 °C | 1029 hPa | overcast | NWS |
| 15.11.2013 13:00 | 6.5 °C | 4.4 °C | 1029.4 hPa | hazy | DWD |
| 15.11.2013 12:50 | 7 °C | 5 °C | 1029 hPa | overcast | NWS |
| 15.11.2013 12:20 | 7 °C | 5 °C | 1028 hPa | overcast | NWS |
| 15.11.2013 12:00 | 6.9 °C | 4.3 °C | 1029.1 hPa | | DWD |

| Time | Temperature | Dew Point | Pressure | weather | Source |
|---|---|---|---|---|---|
| 15.11.2013 11:50 | 7 °C | 5 °C | 1028 hPa | overcast | NWS |
| 15.11.2013 11:20 | 7 °C | 5 °C | 1028 hPa | clouded | NWS |
| 15.11.2013 11:00 | 6.6 °C | 4.2 °C | 1029 hPa | clouded | DWD |
| 15.11.2013 10:50 | 7 °C | 4 °C | 1028 hPa | clouded | NWS |
| 15.11.2013 10:20 | 6 °C | 4 °C | 1028 hPa | clouded | NWS |
| 15.11.2013 10:00 | 5.9 °C | 3.9 °C | 1028.5 hPa | clouded | DWD |
| 15.11.2013 09:50 | 6 °C | 4 °C | 1028 hPa | clouded | NWS |
| 15.11.2013 09:20 | 6 °C | 4 °C | 1027 hPa | clouded | NWS |
| 15.11.2013 09:00 | 5.4 °C | 4 °C | 1027.2 hPa | clouded | DWD |
| 15.11.2013 08:50 | 6 °C | 4 °C | 1027 hPa | cloudy | NWS |
| 15.11.2013 08:20 | 5 °C | 3 °C | 1026 hPa | clouded | NWS |
| 15.11.2013 08:00 | 4.7 °C | 2.8 °C | 1026.3 hPa | cloudy | DWD |
| 15.11.2013 07:50 | 5 °C | 3 °C | 1026 hPa | few clouds | NWS |
| 15.11.2013 07:20 | 5 °C | 4 °C | 1026 hPa | few clouds | NWS |
| 15.11.2013 07:00 | 5.2 °C | 3.9 °C | 1025.8 hPa | clouded | DWD |
| 15.11.2013 06:50 | 5 °C | 4 °C | 1025 hPa | clouded | NWS |
| 15.11.2013 06:20 | 5 °C | 4 °C | 1025 hPa | clouded | NWS |
| 15.11.2013 06:00 | 5.6 °C | 3.8 °C | 1025 hPa | overcast | DWD |
| 15.11.2013 05:50 | 6 °C | 4 °C | 1024 hPa | clouded | NWS |
| 15.11.2013 05:20 | 6 °C | 4 °C | 1024 hPa | overcast | NWS |
| 15.11.2013 05:00 | 5.7 °C | 3.7 °C | 1024.3 hPa | overcast | DWD |
| 15.11.2013 04:50 | 6 °C | 4 °C | 1024 hPa | clouded | NWS |
| 15.11.2013 04:20 | 6 °C | 4 °C | 1023 hPa | clouded | NWS |
| 15.11.2013 04:00 | 6 °C | 3.8 °C | 1023.7 hPa | overcast | DWD |
| 15.11.2013 03:50 | 6 °C | 4 °C | 1023 hPa | overcast | NWS |
| 15.11.2013 03:20 | 6 °C | 4 °C | 1023 hPa | overcast | NWS |
| 15.11.2013 02:50 | 6 °C | 4 °C | 1023 hPa | overcast | NWS |
| 15.11.2013 02:20 | 6 °C | 4 °C | 1022 hPa | overcast | NWS |
| 15.11.2013 01:50 | 6 °C | 4 °C | 1022 hPa | overcast | NWS |
| 15.11.2013 01:20 | 6 °C | 4 °C | 1022 hPa | overcast | NWS |
| 15.11.2013 01:00 | 5.9 °C | 3.4 °C | 1022.2 hPa | overcast | DWD |
| 15.11.2013 00:50 | 6 °C | 4 °C | 1022 hPa | overcast | NWS |
| 15.11.2013 00:20 | 6 °C | 4 °C | 1021 hPa | overcast | NWS |

*Table 60: Hamburg weather data of SIP fuel emission test*

## 9.10 Annex 10: Timing of Individual Segments of the SIP Fuel Emission Test

| **Reference Jet A1** | |
|---|---|
| 12:20:57 - 12:34:07 | min idle |
| 12:35:07 - 12:40:07 | flight idle |
| 12:43:07 - 12:46:57 | cruise |
| 12:48:37 - 12:50:37 | climb |
| 12:51:47 - 12:52:37 | take off |
| 12:55:07 - 12:59:47 | min idle |

| **10% SIP fuel blend** | |
|---|---|
| 16:08:45 - 16:17:25 | min idle |
| 16:18:25 - 16:23:25 | flight idle |
| 16:27:35 - 16:30:15 | cruise |
| 16:31:15 - 16:33:25 | climb |
| 16:35:05 - 16:35:55 | take off |
| 16:39:05 - 16:43:25 | min idle |

| **20% SIP fuel blend** | |
|---|---|
| 18:26:58 - 18:36:08 | min idle |
| 18:36:58 - 18:42:08 | flight idle |
| 18:44:48 - 18:49:28 | cruise |
| 18:50:38 - 18:53:08 | climb |
| 18:54:08 - 18:55:08 | take off |
| 18:58:28 - 19:02:58 | min idle |

*Table 61: Timing of individual segments of the SIP fuel emission test*

## 9.11Annex 11: Results of SIP Fuel Emission Test

**CO Emissions**

| **CO** | **Jet A-1 Reference** | **10% SIP fuel** | **20% SIP fuel** |
|---|---|---|---|
| min idle 1 | 58.30 | 59.64 | 57.89 |
| flight idle | 19.88 | 20.64 | 20.77 |
| cruise | 1.11 | 1.25 | 1.19 |
| climb | 1.17 | 1.21 | 1.18 |
| take off | 1.20 | 1.34 | 1.26 |
| min idle 2 | 55.48 | 56.15 | 56.96 |

*Table 62: CO emissions at the SIP fuel emission test*

**NOx emissions**

| **NOx** | **Jet A-1 Reference** | **10% SIP fuel** | **20% SIP fuel** |
|---|---|---|---|
| min idle 1 | 5.29 | 4.33 | 4.71 |
| flight idle | 6.47 | 5.37 | 5.61 |
| cruise | 24.49 | 26.01 | 25.55 |
| climb | 28.92 | 28.55 | 27.78 |
| take off | 33.08 | 32.27 | 31.82 |
| min idle 2 | 5.66 | 4.63 | 4.77 |

*Table 63: NOx emissions at the SIP fuel emission test*

**Total Mass of Particle Emissions**

| **Total emitted mass** | **Jet A-1 Reference** | **10% SIP fuel** | **20% SIP fuel** |
|---|---|---|---|
| min idle 1 | 6.13 | 5.49 | 4.52 |
| flight idle | 5.39 | 4.54 | 4.05 |
| cruise | 40.14 | 39.28 | 38.20 |
| climb | 48.12 | 46.36 | 43.51 |
| take off | 58.93 | 55.24 | 52.14 |
| min idle 2 | 6.23 | 5.35 | 4.58 |

*Table 64: Total mass of particles at the SIP fuel emission test*

**Total Surface of Particle Emissions**

| Total particle surface | Jet A-1 Reference | 10% SIP fuel | 20% SIP fuel |
|---|---|---|---|
| min idle 1 | 49.58 | 41.55 | 37.59 |
| flight idle | 36.02 | 30.55 | 27.15 |
| cruise | 355.83 | 355.56 | 341.13 |
| climb | 420.54 | 406.83 | 380.73 |
| take off | 496.11 | 474.55 | 444.99 |
| min idle 2 | 52.67 | 45.06 | 39.06 |

*Table 65: Total surface of particles at the SIP fuel emission test*

**Number of Particles**

| Number of million particles | Jet A-1 Reference | 10% SIP fuel | 20% SIP fuel |
|---|---|---|---|
| min idle 1 | 308 | 189 | 191 |
| flight idle | 140 | 68 | 53 |
| cruise | 624 | 593 | 609 |
| climb | 683 | 635 | 644 |
| take off | 757 | 704 | 689 |
| min idle 2 | 351 | 273 | 215 |

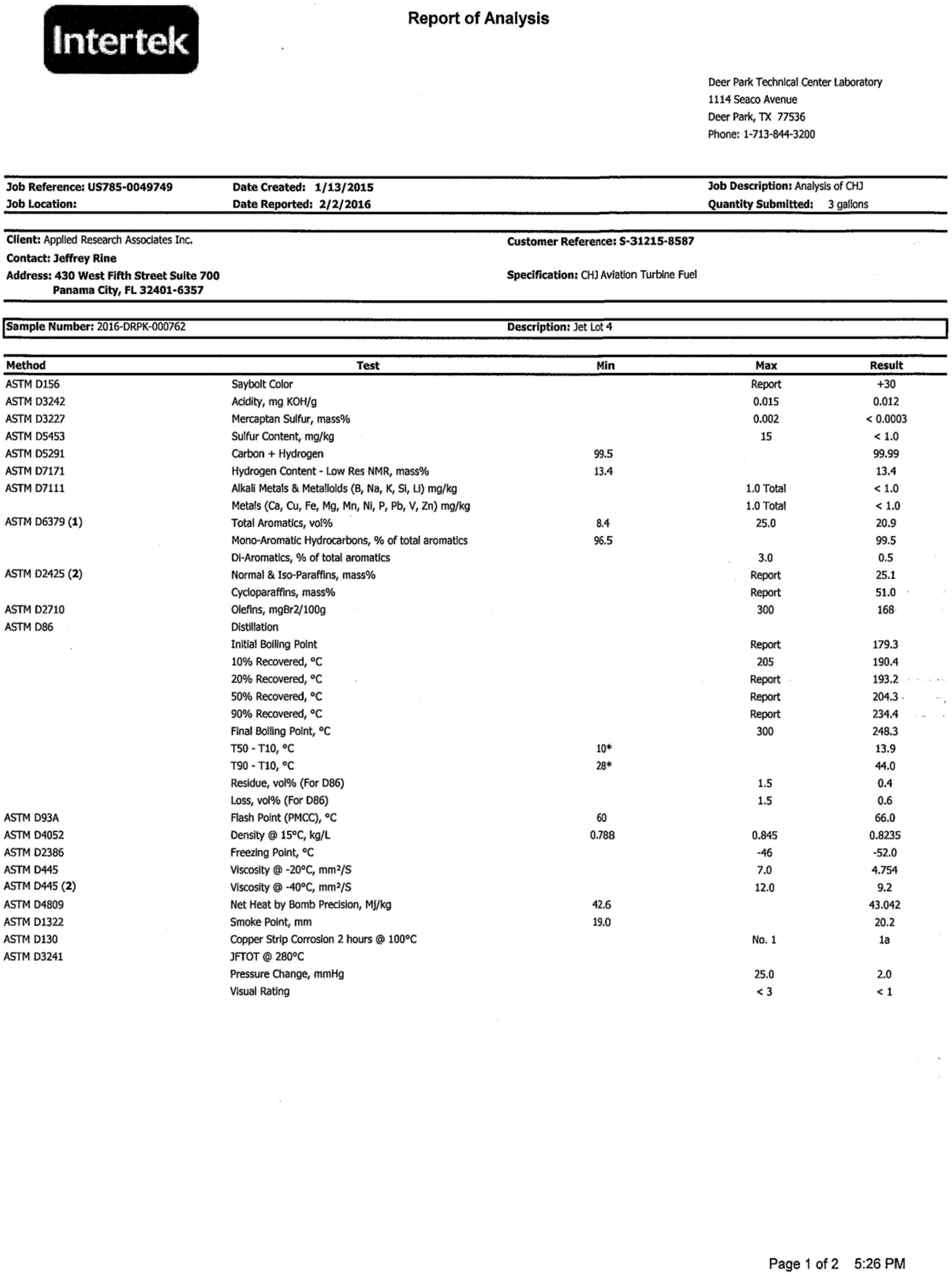
*Table 66: Total number of particles at the SIP fuel emission test*

**Average Particle Diameter**

| Particle diameter | Jet A-1 Reference | 10% SIP fuel | 20% SIP fuel |
|---|---|---|---|
| min idle 1 | 15.13 | 16.22 | 15.41 |
| flight idle | 19.72 | 22.17 | 24.23 |
| cruise | 27.74 | 29.45 | 27.48 |
| climb | 29.33 | 30.70 | 28.47 |
| take off | 29.96 | 31.44 | 29.92 |
| min idle 2 | 14.88 | 15.71 | 15.04 |

*Table 67: Average particle diameters at the SIP fuel emission test*

# 9.12 Annex 12: Properties of the CH kerosene used for emissions measurement



Intertek

## Report of Analysis

Deer Park Technical Center Laboratory
1114 Seaco Avenue
Deer Park, TX 77536
Phone: 1-713-844-3200

**Job Reference:** US785-0049749
**Job Location:**
**Date Created:** 1/13/2015
**Date Reported:** 2/2/2016
**Job Description:** Analysis of CHJ
**Quantity Submitted:** 3 gallons

**Client:** Applied Research Associates Inc.
**Contact:** Jeffrey Rine
**Address:** 430 West Fifth Street Suite 700
Panama City, FL 32401-6357
**Customer Reference:** S-31215-8587
**Specification:** CHJ Aviation Turbine Fuel

**Sample Number:** 2016-DRPK-000762
**Description:** Jet Lot 4

| Method | Test | Min | Max | Result |
|---|---|---|---|---|
| ASTM D156 | Saybolt Color | | Report | +30 |
| ASTM D3242 | Acidity, mg KOH/g | | 0.015 | 0.012 |
| ASTM D3227 | Mercaptan Sulfur, mass% | | 0.002 | < 0.0003 |
| ASTM D5453 | Sulfur Content, mg/kg | | 15 | < 1.0 |
| ASTM D5291 | Carbon + Hydrogen | 99.5 | | 99.99 |
| ASTM D7171 | Hydrogen Content - Low Res NMR, mass% | 13.4 | | 13.4 |
| ASTM D7111 | Alkali Metals & Metalloids (B, Na, K, Si, Li) mg/kg | | 1.0 Total | < 1.0 |
| | Metals (Ca, Cu, Fe, Mg, Mn, Ni, P, Pb, V, Zn) mg/kg | | 1.0 Total | < 1.0 |
| ASTM D6379 **(1)** | Total Aromatics, vol% | 8.4 | 25.0 | 20.9 |
| | Mono-Aromatic Hydrocarbons, % of total aromatics | 96.5 | | 99.5 |
| | Di-Aromatics, % of total aromatics | | 3.0 | 0.5 |
| ASTM D2425 **(2)** | Normal & Iso-Paraffins, mass% | | Report | 25.1 |
| | Cycloparaffins, mass% | | Report | 51.0 |
| ASTM D2710 | Olefins, mgBr2/100g | | 300 | 168 |
| ASTM D86 | Distillation | | | |
| | Initial Boiling Point | | Report | 179.3 |
| | 10% Recovered, °C | | 205 | 190.4 |
| | 20% Recovered, °C | | Report | 193.2 |
| | 50% Recovered, °C | | Report | 204.3 |
| | 90% Recovered, °C | | Report | 234.4 |
| | Final Boiling Point, °C | | 300 | 248.3 |
| | T50 - T10, °C | 10* | | 13.9 |
| | T90 - T10, °C | 28* | | 44.0 |
| | Residue, vol% (For D86) | | 1.5 | 0.4 |
| | Loss, vol% (For D86) | | 1.5 | 0.6 |
| ASTM D93A | Flash Point (PMCC), °C | 60 | | 66.0 |
| ASTM D4052 | Density @ 15°C, kg/L | 0.788 | 0.845 | 0.8235 |
| ASTM D2386 | Freezing Point, °C | | -46 | -52.0 |
| ASTM D445 | Viscosity @ -20°C, mm²/S | | 7.0 | 4.754 |
| ASTM D445 **(2)** | Viscosity @ -40°C, mm²/S | | 12.0 | 9.2 |
| ASTM D4809 | Net Heat by Bomb Precision, MJ/kg | 42.6 | | 43.042 |
| ASTM D1322 | Smoke Point, mm | 19.0 | | 20.2 |
| ASTM D130 | Copper Strip Corrosion 2 hours @ 100°C | | No. 1 | 1a |
| ASTM D3241 | JFTOT @ 280°C | | | |
| | Pressure Change, mmHg | | 25.0 | 2.0 |
| | Visual Rating | | < 3 | < 1 |

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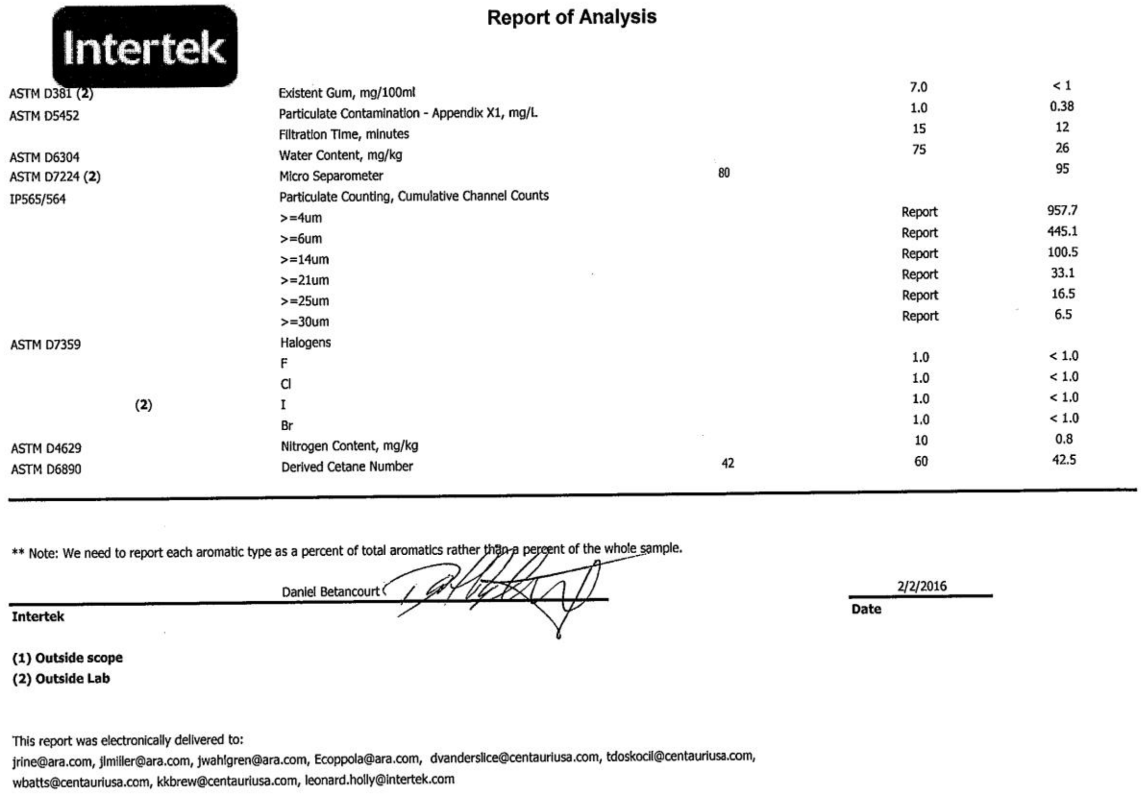

## Report of Analysis

| | | | | |
|---|---|---|---|---|
| ASTM D381 **(2)** | Existent Gum, mg/100ml | | 7.0 | < 1 |
| ASTM D5452 | Particulate Contamination - Appendix X1, mg/L | | 1.0 | 0.38 |
| | Filtration Time, minutes | | 15 | 12 |
| ASTM D6304 | Water Content, mg/kg | | 75 | 26 |
| ASTM D7224 **(2)** | Micro Separometer | 80 | | 95 |
| IP565/564 | Particulate Counting, Cumulative Channel Counts | | | |
| | >=4um | | Report | 957.7 |
| | >=6um | | Report | 445.1 |
| | >=14um | | Report | 100.5 |
| | >=21um | | Report | 33.1 |
| | >=25um | | Report | 16.5 |
| | >=30um | | Report | 6.5 |
| ASTM D7359 | Halogens | | | |
| | F | | 1.0 | < 1.0 |
| | Cl | | 1.0 | < 1.0 |
| **(2)** | I | | 1.0 | < 1.0 |
| | Br | | 1.0 | < 1.0 |
| ASTM D4629 | Nitrogen Content, mg/kg | | 10 | 0.8 |
| ASTM D6890 | Derived Cetane Number | 42 | 60 | 42.5 |

** Note: We need to report each aromatic type as a percent of total aromatics rather than a percent of the whole sample.

Daniel Betancourt

**Intertek**

2/2/2016

**Date**

**(1) Outside scope**
**(2) Outside Lab**

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## 9.13 Annex 13: Results of CH Fuel Emission Test

**CO Emissions**

| | Reference 1 | Reference 2 | CH kerosene |
|---|---:|---:|---:|
| GI | 72.64 | 74.73 | 81.52 |
| FI | 29.45 | 27.22 | 29.96 |
| 3000 RPM | 2.12 | 1.11 | 1.45 |
| 3800 RPM | 1.30 | 0.62 | 0.80 |
| C2 M/C | 1.07 | 0.82 | 0.93 |
| C4 M/C | 1.15 | 0.91 | 0.99 |
| C4 T/O | 1.26 | 1.00 | 1.12 |

*Table 68: CO emissions at the CH fuel emission test*

**NOx emissions**

| | Reference 1 | Reference 2 | CH kerosene |
|---|---:|---:|---:|
| GI | 2.04 | 3.34 | 3.08 |
| FI | 3.41 | 4.55 | 4.81 |
| 3000 RPM | 7.79 | 8.89 | 9.37 |
| 3800 RPM | 12.66 | 14.06 | 14.65 |
| C2 M/C | 17.75 | 19.61 | 20.37 |
| C4 M/C | 19.13 | 21.23 | 21.94 |
| C4 T/O | 22.73 | 25.42 | 26.05 |

*Table 69: NOx emissions at the CH fuel emission test*

**Total Mass of Particle Emissions**

| | Reference 1 | Reference 2 | CH kerosene |
|---|---:|---:|---:|
| GI | 48.46 | 38.92 | 78.42 |
| FI | 30.86 | 27.51 | 29.70 |
| 3000 RPM | 35.54 | 37.50 | 44.09 |
| 3800 RPM | 127.32 | 142.11 | 164.17 |
| C2 M/C | 204.09 | 230.42 | 244.17 |
| C4 M/C | 217.98 | 245.44 | 265.99 |
| C4 T/O | 258.05 | 297.43 | 310.88 |

*Table 70: Total mass of particles at the CH fuel emission test*

**Total Surface of Particle Emissions**

| | Reference 1 | Reference 2 | CH kerosene |
|---|---:|---:|---:|
| GI | 4.45E+12 | 4.39E+12 | 7.54E+12 |
| FI | 2.30E+12 | 2.17E+12 | 2.07E+12 |
| 3000 RPM | 2.46E+12 | 2.71E+12 | 3.24E+12 |
| 3800 RPM | 7.95E+12 | 8.88E+12 | 9.59E+12 |
| C2 M/C | 1.05E+13 | 1.17E+13 | 1.16E+13 |
| C4 M/C | 1.08E+13 | 1.20E+13 | 1.23E+13 |
| C4 T/O | 1.19E+13 | 1.35E+13 | 1.33E+13 |

*Table 71: Total surface of particles at the CH fuel emission test*

**Number of Particles**

| | Reference 1 | Reference 2 | CH kerosene |
|---|---:|---:|---:|
| GI | 3.45E+15 | 4.00E+15 | 5.35E+15 |
| FI | 2.03E+15 | 2.65E+15 | 1.15E+15 |
| 3000 RPM | 5.18E+14 | 5.94E+14 | 6.68E+14 |
| 3800 RPM | 1.13E+15 | 1.22E+15 | 1.21E+15 |
| C2 M/C | 1.04E+15 | 1.11E+15 | 1.02E+15 |
| C4 M/C | 1.01E+15 | 1.06E+15 | 1.01E+15 |
| C4 T/O | 9.64E+14 | 1.03E+15 | 9.46E+14 |

*Table 72: Total number of particles at the CH fuel emission test*

**Average Particle Diameter**

| | Reference 1 | Reference 2 | CH kerosene |
|---|---:|---:|---:|
| GI | 13.70 | 13.61 | 13.90 |
| FI | 12.64 | 11.68 | 14.65 |
| 3000 RPM | 26.63 | 25.42 | 26.60 |
| 3800 RPM | 31.90 | 32.18 | 33.14 |
| C2 M/C | 37.01 | 37.46 | 38.40 |
| C4 M/C | 37.80 | 38.65 | 39.41 |
| C4 T/O | 39.86 | 41.01 | 41.79 |

*Table 73: Average particle diameters at the CH fuel emission test*