European Aviation Safety Agency

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SIoBiA - Safety Implication of Biofuels in Aviation

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SAFETY IMPLICATION OF BIOFUELS IN AVIATION

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1 Introduction and Outline of Work

Biofuels potentially interesting also for aviation purposes are predominantly liquid fuels produced from biomass. The most common biofuels today are biodiesel and bioethanol. Since diesel engines are rather rare in aviation this survey is focusing on ethanol admixed to gasoline products.

The Directive 2003/30/EC of the European Parliament and the Council of May 8th 2003 on the promotion of the use of biofuels or other renewable fuels for transport encourage a growing admixture of biogenic fuel components to fossil automotive gasoline. Some aircraft models equipped with spark ignited piston engines are approved for operation with automotive gasoline, frequently called "MOGAS" (motor gasoline). The majority of those approvals is limited to MOGAS compositions that do not contain methanol or ethanol beyond negligible amounts. In the past years (bio-)MTBE or (bio-)ETBE have been widely used as blending component of automotive gasoline whilst the usage of low-molecular alcohols like methanol or ethanol has been avoided due to the handling problems especially with regard to the strong affinity for water. With rising mandatory bio-admixtures the conversion of the basic biogenic ethanol to ETBE, causing a reduction of energetic payoff, becomes more and more unattractive. Therefore the direct ethanol admixture is accordingly favoured.

Due to the national enforcements of the directive 2003/30/EC more oxygenates produced from organic materials like bioethanol have started to appear in automotive gasolines already. The current fuel specification EN 228 already allows up to 3 % volume per volume (v/v) (bio-)methanol or up to 5 % v/v (bio-)ethanol as fuel components. This is also roughly the amount of biogenic components to comply with the legal requirements to avoid monetary penalties for producers and distributors of fuels.

Since automotive fuel is cheaper than the common aviation gasoline (AVGAS), creates less problems with lead deposits in the engine, and in general produces less pollutants it is strongly favoured by pilots. But being designed for a different set of usage scenarios the use of automotive fuel with low molecular alcohols for aircraft operation may have adverse effects in aviation operation. Increasing amounts of ethanol admixtures impose various changes in the gasoline's chemical and physical properties, some of them rather unexpected and not within the range of flight experiences even of long-term pilots.

After a frame-setting failure mode and effects analysis (FMEA) that highlighted the predominant threats of ethanol present in future MOGAS sorts the most problematic objectives have been investigated in further detail, both by theoretical investigations and practical exemplary flight and test rig experiments. Even if the general level of pollutant emissions is usually reduced by utilization of biogenic components in the fuel it cannot be excluded straight away that also undesired side-effects, both on a local and global scale, may be incurred, e.g. by super- or sub-stoichiometric combustion typical in aviation operation. Accordingly, another aspect under investigation is the life cycle analysis of the usage of ethanol admixed gasoline for aviation purposes.

Lastly, prior reports identified water as one of the most problematic substances for fuel handling and utilization in the area of aviation. There is no simple, practical measurement tool for the assessment of solved water content in gasoline so far, however. Accordingly it is one of the aims of this report to identify potential respective measurement procedures that deem promising for a development of such instrumentation.

The EASA call for tenders, based on previous information gathering, already collected most of these issues and formulated several basic objectives. The results of this report necessitated a slightly different internal logical structure to adequately organize the acquired knowledge, though. Therefore the referencing of the tender's topics is included in the individual section headings:

T 1: Literature scan and statistical data gathering
T 2a: Phase separation
T 2b: Icing
T 2c: Long term storaging of gasoline
T 3: Vapour locking
T 4: Compatibility of materials
T 5: Life cycle analysis of ethanol admixed gasolines
T 6: Potential methods of water in gasoline detection
T 7: FMEA on functions and parts

The sections have been assembled in a different order that is more oriented towards easier reading and logical interconnection of topics. The main part of the report is followed by a series of annexes documenting the immediate work of cooperation partners, and additional tabulated results referenced in the main part.

2 Summary and Recommendations

In its effort to introduce regenerating and hence sustainable energy resources into the existing combustibles mix, recent European legislation enforces the admixture of biogenic fuels into conventional fossil gasoline. For economic reasons this is, as of today, mainly ethanol. Compared to the fossil gasoline ingredients ethanol has a different chemical structure, leading to a potentially dangerous physico-chemical behaviour, especially in the presence of water. As there is a stronger economically driven tendency to use vehicle gasolines as aviation fuel this may lead to potentially dangerous scenarios especially in the operation of the smaller General Aviation aircraft.

The SIoBIA study addresses these scenarios by an in-depth study on the various potential threats imposed by ethanol admixtures up to 15 % v/v.

First, a failure mode and effects analysis has been performed. For the current fleet of General Aviation aircraft the associated individual threats (phase separation, vapour locking, icing, material compatibility) were confirmed on the parts and functional levels by an expert group. The span of risks covers the range of “just a nuisance” to “deadly dangerous if not adequately and pro-actively handled”. For the major threats a clustering of recommendations for a further treatment of the identified issues has been given.

A statistical analysis of European aircraft numbers and types, reconciling several base data sets on European General Aviation, lead to an assessment of the number of potentially affected aircraft. About 20,000 aircraft ($\approx 10\,\%$) throughout Europe are either directly or potentially endangered by the various negative effects of an ethanol admixture in the nearer future.

The consecuting theoretical and practical work highlighted the most prominent threats in parallel tasks, namely water-induced phase separation, carburettor icing, vapour locking by gasoline brand mixing, construction material compatibility, and proactive water detection in the fuel system. These threat investigations were flanked by a life cycle analysis on the environmental impacts of ethanol addition to aircraft fuels.

Especially for the vast majority of existing carburettor engines there are various general threats stemming from ethanol-admixed gasolines, potentially leading to disrupted engine operation. Some of them are readily encountered by sensitive operation and increased maintenance efforts, while others may occur rather unexpectedly during a flight mission, even to the point that the engine(s) will stall and not start again, so an unmotored emergency landing has to be performed.

Main issues are

- the material compatibility of hitherto only gasoline-exposed fuel system parts, especially elastomers and sealants,
- the danger of phase separation in water containing gasoline if the fuel is stored for prolonged periods in vented aircraft tanks, and if it is inevitably cooled down during a flight,
- the increased likelihood of a vapour lock due to increased vapour pressure of gasolines mixtures of different ethanol abundancies if the first fuel pressure raising pump is not in a cold section of the fuel system, and the
- carburettor icing due to raised enthalpy of evaporation for ethanol-admixed gasolines if there is no additional heat input into the intake air,

The experiences from vehicle technology may, to a rather great extent, be transferred to the operating conditions of ultralights. Here rather modern engine technology prevails, and the usually low service ceiling keeps temperature change effects below an acceptable bound. Other types of General Aviation aircraft are more prone to run into difficulties due to their markedly higher service ceiling and the resulting major differences in temperature and ambient pressure, as well as their longer conceptual histories, leading predominantly to material compatibility problems. For those major threats intensive studies and results, as well as respective guidelines, are given in this report. Further recommended activities are listed below.

Material incompabilities should be explicitly addressed in airworthiness qualification and certification processes, even for replacement parts. A comprehensive study of all materials used in the past 50 years for certified aircraft construction is not feasible. Only general guidelines for future material selection or replacement can be given in this report.

A crucial point in phase separation avoidance is a strict proactive control on the occurrence of *solved* water in the gasoline. Unluckily there is no practical and affordable test procedure at hand as of today even though some measurement principles indicate the potential of creating a respective tool.

Life cycle analysis showed that substantial green-house gas (GHG) savings are possible if ethanol is admixed to conventional gasoline in the amounts discussed in this report. This effect is mostly related to the old, but reliable technology and the non-existence of exhaust gas catalyzers in aviation: While the savings through replacing fossil fuel by biogenically produced ethanol are at least detectable the major effect stems from the combustion process itself, as it is cleaner and produces less GHG emissions in the presence of ethanol.

Most of the endangering issues would presumably vanish if butanol would be deployed as biogenic supplement of the fossil fuels as its longer hydrocarbon tail provides much more affinity to the non-polar gasoline majority ingredients. Butanol would exhibit other advantages as well: Compared to ethanol its energy content is larger, and it would presumably have less effect on the vapour pressure if gasolines of different admixture levels are mixed. Presently there is no commercially viable biogenic supply path, even though some promising exploratory efforts exist [16]. Should this alternative of biogenic admixing be pursued in future its effects should be studied in detail in a follow-up project as there is no practical experience on butanol-admixed gasolines deployment in aviation as of today.

The SIOBIA study sheds light on the present status of the most problematic issues with respect to ethanol admixtures in aviation gasoline, but partially only up to the point that further investigations and research should be undertaken to get in-depth and directly practical information. The following topics are suggested for further activities:

- **Investigations on the bubble creation behaviour (threat of vapour locking) of a larger number of commercially sold gasolines and their potential mixtures.** Different compositions of gasolines are likely to affect the vapour bubble creation, especially so if encountering unforeseen amounts of ethanol due to a mixing of residues in the aircraft's tank. As a result a matrix of potential mixing scenarios should be collected and progressively filled over time as new brands with differing ethanol content appear on the market. The tests should be performed especially with raised temperatures in an dynamic manner, simulating those of common aircraft fuel systems. If possible, a maximum operation temperature and/or maximum service ceiling should be identified and published on a work-in-progress basis on a freely accessible web site.
- **Determination of the temperature-depending maximum solved water abundancies for a larger number of commercially sold gasolines, potentially in combination with random**

sampling results on water content. The outcome of these investigation could yield a definition of a conservative envelope of tolerable water in gasoline contents. This value is becoming more and more of interest as the bearing capability increases with increasing amount of ethanol there is no normative numerical upper limit of water content in gasolines as of today.

- **Quantitative determination of water absorbed out of the tank venting air.** Temperature inversion in the tank of a descending aircraft may lead to a significant absorption of humidity due to the rather large air volume throughput rates of venting. Here experiments for temperature and humidity niveau determination, in combination with a theoretical study taking into account knowledge of the atmospheric states and compositions, should be performed to determine quantitative water balances.
- **Research and/or development of a practical sensor for water solved in gasoline.** The water content of present gasolines is reportedly well above zero and a potential object of future economical optimization with respect to gasoline price fixations as there is no normative quantified upper limit in the gasoline composition definitions. Reported field tests with hydrous E-15 [21], saving the expenses of providing super-azeotropic ethanol provision for gasoline admixing, already point in this direction. As this will foreseeably not create a problem for ground based locomotion, contrary to aviative purposes with its strong temperature decrease in the gasoline tanks, the pilot should be equipped with a practical method of solved water determination.

3 Operating Existing Engines with Ethanol-Admixed Fuels

3.1 Definition of an “Old” Engine

Compared to the vehicle fleet the various types of operated aircraft are typically much older. While in Western Europe the average age of passenger cars is about 7 – 8 years [3] small aircraft are usually much older: Wastinage [33] reports an average age of 31 years for the USA, and the European fleet is not much younger.

Even many younger aircraft do not profit from recent development of vehicle engine technology, as even for rather recently sold gasoline operated models old designs are still maintained [33]. The market volume is quite small so expensive investments into research and development of modernized designs are economically usually not perceived as appropriate.

Accordingly, the design of currently running engines and fuel systems lags substantially behind those of vehicles. The vast majority is not equipped with modern control systems like a FADEC, let alone any observation or concern of fuel quality like adaptive knock sensors.

Nevertheless some engines are able to run at least on vehicle gasoline (“motor gasoline”, or MOGAS) after some more or less heavy modifications on the fuel system and potentially the engine. Apart from rather recent engine designs that are by definition capable of operating on DIN EN 228 compliant gasoline with up to 5 % ethanol, most supplementary type certificates (STC) that grant MOGAS operation limit the ethanol content to 1 %. Experiences from the last years show that this setting did not cause any perceivable additional numbers of accidents or casualties.

Nevertheless it is to be feared that an unreflecting extension of the allowed limit to the 5 % value — or even beyond that, keeping the recent policies for road transport in view — may create problems hitherto not encountered. There are several issues founded in the system concept and parts design of older engines in combination with their fuel systems that can be expected to cause potentially severe dangers. The consecutive sections of this report will scrutinize these in detail.

3.2 Survey of Aircraft Frames and Engines Authorized for MOGAS Operation

The usage of MOGAS (gasoline fuel for vehicles, complying with the aviation guidelines for MOGAS, though) requires a certification for both aircraft cell and engine. As of today EASA provided supplementary type certificates for the consecuting types of engines and cells. The European STCs are in many cases derived from respectively given FAA STCs. By far the mosts STCs are issued by DAeC (see e.g. their web page http://www.daec.de/te/erteillte_emz.php), but some other institutions contributed others, too. A full list of FAA-STCs is reported in Appendix A.

The subsequent list does not raise the claim to be complete. It rather helps with identifying a certain aircraft as worthwile for interrogating the manufacturer on this behalf.

EMZ no.	Applicant	German LBA no.	Type	Based on	Date
Engines:					
EN 0014	DAeC	4519	C90-()	alternative fuel, FAA-STC SE 2031 CE	19.12.00
EN 0015	DAeC	4525	O-470	alternative fuel, FAA-STC SE 1997 CE	20.12.00
EN 0016	DAeC	4519a	RR O-200-()	alternative fuel, FAA-STC 00137 WI	21.12.00
EN 0017	DAeC	4524a	RR O-300-()	alternative fuel, FAA-STC SE 00135 WI	22.12.00
EN 0018	DAeC	4579	O-235-()	alternative fuel, FAA-STC SE 2606 CE	22.12.00
EN 0019	DAeC	4578	O-320-() nicht -H	alternative fuel, FAA-STC SE 1931 CE	27.12.00
EN 0020	DAeC	4578	O-320-() nicht -H	alternative fuel, FAA-STC SE 2587 CE	10.11.00
EN 0032	DAeC	4563	O-360 B, D	alternative fuel, FAA-STC SE 2574 CE	06.08.01
EN 0033	DAeC	4563	O-360A, C, F, HO 360 C	alternative fuel, FAA-STC SE 2563 CE	06.08.01
EN 0038	DAeC	4561	O-540-B()	alternative fuel, FAA-STC SE 1909 CE	30.05.02
EN 0039	DAeC	4561	O-540-A(), -D(), -E(), -G(), -H()	alternative fuel, FAA-STC SE 2653 CE	30.05.02
EN 0037	Aerotec GmbH & Co. KG	4602	Porsche PFM 3200N01	—	28.03.02

EMZ no.	Applicant	German LBA no.	Type	Based on	Date
Cells:					
SA 1214	DAeC	539a	Cessna F 172 P	FAA-STC SA 00330 WI	18.06.01
SA 1224	DAeC	539a	Cessna F 172 D, E, F, G, H, K, L, M	FAA-STC SA 00215 WI 6	02.08.01
SA 1225	DAeC	539	Cessna 172 A, B, C, D, E, F, K, L, M	FAA-STC SA 1948 CE	13.08.01
SA 1229	DAeC	539	Cessna 172 P	FAA STC SA 2601 CE	31.08.01
SA 1232	DAeC	518, 518a	PA-28-140, PA-28-151	FAA STC SA 1963 CE	29.11.01
SA 1242	DAeC	722	PA-18, PA-18 “105” Special, PA-18A, PA-18 “125”, PA-18 “135”, PA-18A “135”, PA-18 “150”, PA-18A “150”, PA-19	FAA STC SA 1961 CE	22.01.02, 28.05.02
SA 1249	DAeC	610 610b	Cessna 150, 150A, -B, -C, -D, -E, -F, -G, H, -J Cessna 150K, -L, -M, A 150K, A 150L, 152, A 152	FAA STC SA 2048 CE	29.01.02
SA 1250	DAeC	610a, 610b	Cessna F 150G, -H, -J, -K, -L, -M, FA 150K, -L	FAA STC SA 00216WI	29.01.02
SA 1259	DAeC	549 549a	C 182, 182A, B, C, D, E, F, G, H, J, K, L, M 182N, P only with "gravity fuel systems"	FAA STC SA2000CE	04.03.02
SA 1260	DAeC	1088	A-1 (Husky)	FAA STC SA2670CE	04.03.02
EASA IM.A.S.02586	Petersen	518, 518a	PA-28-160, Pa-28-180, PA-28-161, PA-28-181 for consecuting no.	FAA STC SA2660CE	10.09.07
SA 1243	DAeC	511	C 170A, 170B only with "gravity fuel systems"	FAA STC SA2019CE	18.06.02
SA 1271	DAeC	610b	C152, C A152	FAA STC SA2613CE	01.07.02
SA 1272	DAeC	610b	C F 152, C FA 152, C A 152 only with "gravity fuel systems"	FAA STC SA00329WI	01.07.02
SA 1275	DAeC	712	PA-22, PA-22 "135", PA-22S "135", PA-22 "150", PA-22S "150", PA-22 "160", PA-22 108 only with "gravity fuel system"	FAA STC SA1949CE and FAA STC SA2599CE	28.08.02
SA 1274	DAeC	1020	Grumman AA-5, AA-5A only with O-320-E2G	FAA STC SA1965CE 6 25.09.02	

SA 1339	DAeC	529	Bellanca 11AC, 11BC	FAA ST SA2079CE	24.02.04
SA 1340	DAeC	627	Beech 35-33, 35-B33, 35-C33, E33	FAA STC SA2049CE	24.02.04
SA 1341	DAeC	719	Cessna 120, 140	FAA STC SA2100CE	24.02.04
SA 1342	DAeC	719	Cessna 140A	FAA STC SA2096CE	24.02.04
SA 1343	DAeC	713	Piper J3C, PA-11	FAA STC SA2080CE	24.02.04
SA 1344	DAeC	548	Piper PA-12	FAA STC SA2075CE	24.02.04
SA 1345	DAeC	518	Piper PA 28-235	FAA STC SA1964CE	24.02.04
SA 1370	DAeC	545	Cessna 195, 195A, 195B	FAA STC SA2421CE	24.02.04
SA 1337	DAeC	688	Aero Commander 100	FAA STC SA2103CE	16.02.04
SA 1338	DAeC	525	Bellanca (Champion), (Aeronca) 7AC, 7CCM, 7EC, 7ECA, 7FC, 7GCB, 7GCBC	FAA STC SA1970CE	16.02.04
EASA A.S.01546	Gomolzig	1001	DR 300/108 -/125 -/180R, DR 315, DR 400/120(d) -/125 -/2+2 -/140 -/140B -/180R	—	14.09.05
PS 0005	Gomolzig	820	HL 36 R, HK 36 TS, HK 36 TC „Super Dimona“	—	26.09.03
PS 0009	FEA Frisch Engineering + Aerotech	820	H 36 Dimona	—	17.09.03
SA 1178	Aero-Club Gelnhausen e.V.	745	PLZ-104 Wilga 35A	—	05.07.00
SA 1259	DaeC	549, 549a	Cessna 182, 182A, 182B, 182C, 182D, 182E, 182F, 182G, 182H, 182J, 182K, 182L, 182M, 182N, 182P	—	04.03.02

3.3 Legislative and Practical Boundary Conditions for Biogenic Components Admixing

The European Union officially adopted a 20-20-20 Renewable Energy Directive on Dec. 17th 2008 to redefine its climate change reduction goals for the next decade. The catchphrase "20-20-20" is an abbreviation for a triple goal definition:

- 20 % reduction in greenhouse gas (GHG) emissions by 2020 compared with 1990 levels,
- 20 % cut in energy consumption through improved energy efficiency by 2020,
- and a 20 % increase in the use of renewable energy by 2020.

In 2005 renewable energies from hydro power, solar, wind, biomass, or geothermal sources accounted for less than seven percent of the EU's total energy consumption. To achieve the 20 percent target, the new directive defines mandatory national targets for its member states by promotion of the use of renewable energy for electricity generation, transport, and heating / air conditioning. Targets for GHG emission reductions include all locomotion fuels — fossil fuels as well as biofuels, blends, electricity and hydrogen. The directive requires fuel suppliers to reduce GHG emission caused by any action taken in the whole processing chain, including land use changes, transportation and distribution, processing and combustion of locomotion fuels. Reductions in GHG emissions could be achieved by using more biofuels, alternative fuels, or by reducing gas wasting at oil wells or refineries.

The Directive 2009/28/EC of the European Parliament and of the Council [26], repealing the former valid Directives 2001/77/EC and 2003/30/EC, concretized these goals by also defining a mandatory share of 10 % energy input for the locomotion oriented fuel consumption as a subdivision of the general energy consumption.

As the starting points, the renewable energy potentials and the energy mix of the EU member states differ quite strongly the Community's 20 % target will be translated into individual targets for each member state, taking into account the existing level of energy from renewable sources and the energy mix, as well as its particular amount of contribution to the European energy consumption as a whole. By contrast, it is regarded as appropriate for the 10 % target for energy from renewable sources in transport to be set at the same level for each member state in order to ensure consistency in transport fuel specifications and availability. Respective national targets are given in Table 1.

Some member states have a large share of aviation in their gross final consumption of energy due to their insular and peripheral character. In view of the current technological and regulatory constraints that prevent the commercial use of biofuels in aviation, a partial exemption is deemed appropriate for them. For aviation consumption purposes they may exclude an amount of 1.5 times the average amount of aviation fuel consumption in the EU, as calculated by Eurostat.

Cyprus and Malta e.g. have a gross final consumption of energy in national air transport which is disproportionally high, i.e. more than three times the Community's average in 2005. They would thus be disproportionately affected by the current technological and regulatory constraints. For those member states, that do contribute to the European General Aviation fleet only marginally, though, other target limits apply.

Since the underlying European Directive is very recent, dating from April 2009, there has not yet been the transformation into national law. This is to be expected rather soon, though. As of today the older limits given in Table 2 origninating in the EU's Directive of 2003 still apply.

	Share of energy from renewable sources in gross final consumption of energy, 2005	Target for share of energy from renewable sources in gross final consumption ofenergy, 2020
Belgium	2.2 %	13 %
Bulgaria	9.4 %	16 %
Czech Republic	6.1 %	13 %
Denmark	17.0 %	30 %
Germany	5.8 %	18 %
Estonia	18.0 %	25 %
Ireland	3.1 %	16 %
Greece	6.9 %	18 %
Spain	8.7 %	20 %
France	10.3 %	23 %
Italy	5.2 %	17 %
Cyprus	2.9 %	13 %
Latvia	32.6 %	40 %
Lithuania	15.0 %	23 %
Luxembourg	0.9 %	11 %
Hungary	4.3 %	13 %
Malta	0.0 %	10 %
Netherlands	2.4 %	14 %
Austria	23.3 %	34 %
Poland	7.2 %	15 %
Portugal	20.5 %	31 %
Romania	17.8 %	24 %
Slovenia	16.0 %	25 %
Slovak Republic	6.7 %	14 %
Finland	28.5 %	38 %
Sweden	39.8 %	49 %
United Kingdom	1.3 %	15 %

Table 1: *National overall targets for the share of energy from renewable sources in gross final consumption of energy in 2020 [26].*

quota [in % e/e]	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
biodiesel in diesel	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40
bioethanol in gasoline	1.20	2.00	2.80	3.60	3.60	3.60	3.60	3.60	3.60
total quote (gasoline and diesel)			6.25	6.75	7.00	7.25	7.50	7.75	8.00

Table 2: *German quotas for biogenic fuel admixtures for the years 2007 — 2015. The given quotas are minimal values for the respective subgroups of fuel types. Starting 2009 a total quota is defined in addition, to be fulfilled for the sum of all distributed fuels.*

Again it should be minded that similar exemption rules for aviation fuels have been defined for the legislation currently in action.

As 2009 is the first year that will impose admixture quota missing penalties to fuel vendors the preceding years should not be referenced in comparisons of “habitual fuel compositions”. Fig. 1 shows both a strong overall increase of biogenic admixtures and a gradual replacement of ETBE by crude ethanol admixing in the years 2007 to 2009. The looming penalties for underfulfillment of legally requested biogenic shares, to be imposed to the manufacturers and vendors of fuels first time 2009, make the overall biogenic gasoline admixtures grow to about 4.6 %.

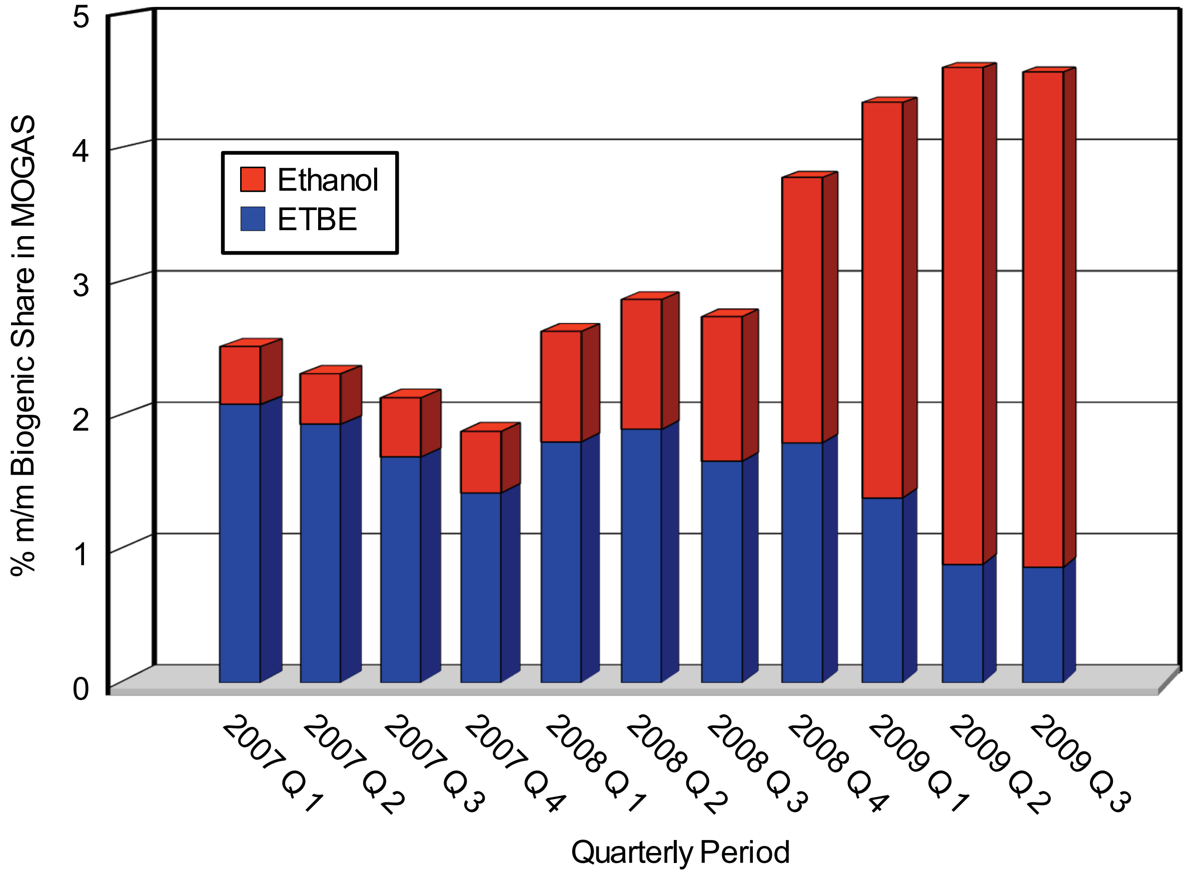

Figure 1: *Development of biogenic fuel shares from 2007 to 2009 in Germany. For ETBE only the part of its complete amount is shown that originates in biogenic sources. Source: Mineralölwirtschaftsverband Deutschland*

Since the biogenic share seems not to be accomplishable by ETBE alone, as only 47 % of its amount may be calculated as of biogenic origin, ethanol admixture is mandatory to fulfill the quota. But after necessarily introducing the latter as a fuel component it seems even more practical to even replace ETBE by ethanol.

As of the time this report was written (Dec. 2009) the majority of Super Plus quality fuels seems to usually incorporate only minor amounts of ethanol (see Fig. 2 for statistical probes taken in June 2009, and Fig. 88, p. 198, for such taken in Jan. 2009).

3.3.1 Usage Statistics of Various Fuel Types

The relative share of gasoline/petrol type and/or aviation-oriented fuels sold in Europe is depicted in Fig. 3. The comparison shows impressively how small the share of AVGAS is compared to its larger rivals Jet Fuel and vehicle gasoline. MOGAS, being thought of as the share of vehicle gasoline deployed for aviation usage, is included in the large vehicle gasoline share in this graphic. Since the amount of MOGAS flown in General Aviation is even much smaller than that of AVGAS it is immediately clear that there is no market pressure at all to maintain a distinct supply of aviation dedicated, less ethanol admixed gasoline brands, at least in the long run.

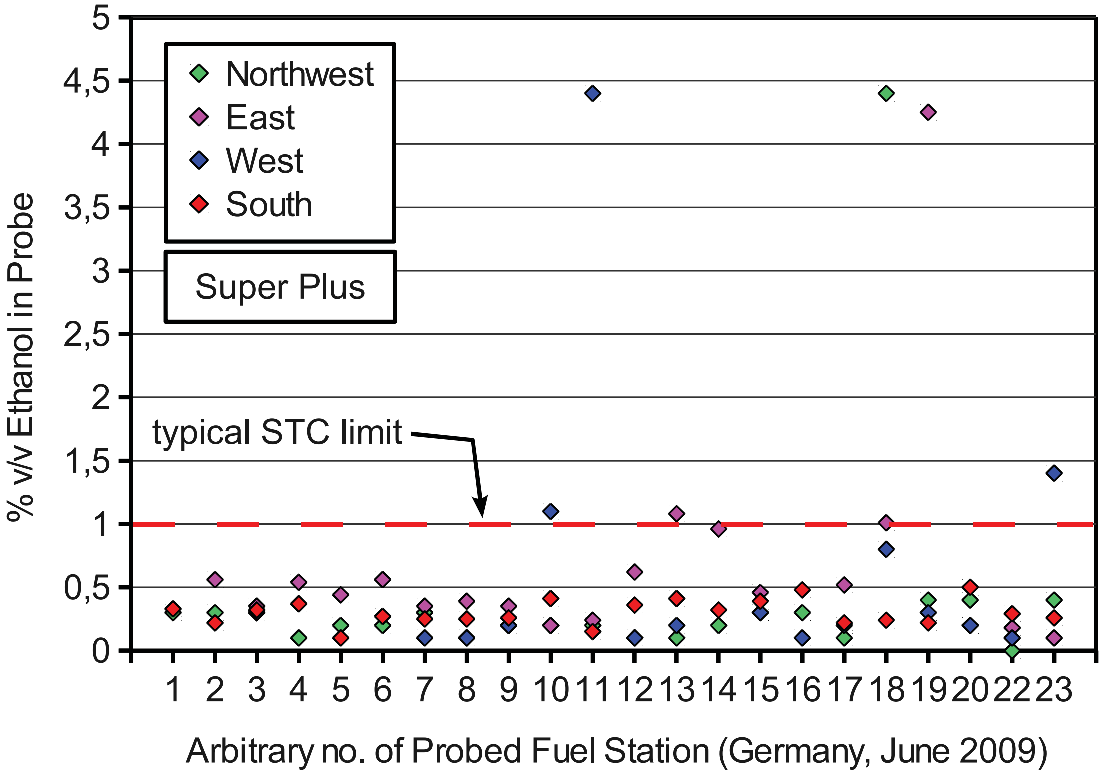

Figure 2: *Ethanol content in random German Super Plus gasoline probes taken in June 2009. Source: Total Deutschland GmbH*

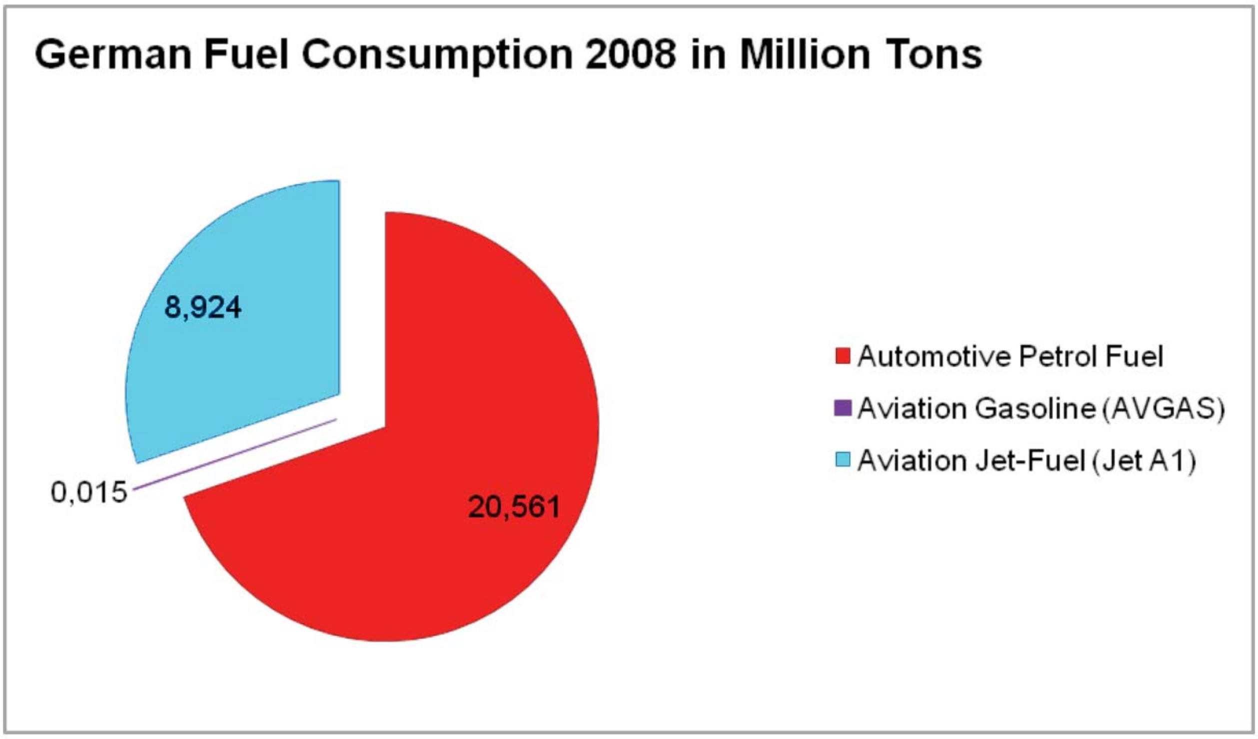

Figure 3: *Shares of different fuel types (Diesel fuel excluded) for 2008 in Germany. The share titled "Automotive Petrol Fuel" also contains the amount of gasoline taken for aviation purposes, which is smaller than the* AVGAS *share (see Sect. B). Source: Mineralölwirtschaftsverband Deutschland*

Presently some companies provide the General Aviation community with “dedicated MOGAS”, certifying a less than 1 % v/v share of ethanol. This is, even in the light of a gross admixture legal minimum share, not surprising as these brands are taken from the vehicle “Super Plus” gasoline production. This in turn shows a declining consumption in Europe being already on a very low level in total market share (only some percent, Fig. 4).

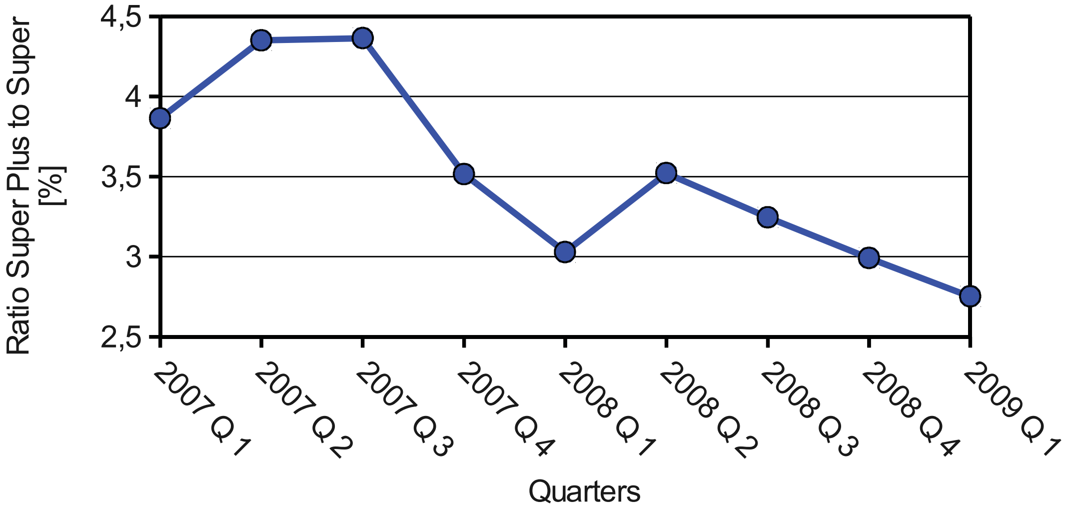

Figure 4: *Ratio of consumed Super Plus RON 100 to Super RON 98 gasoline amounts for Germany for the years 2007 to 2009. Source: Mineralölwirtschaftsverband Deutschland*

As long as this high octane number gasoline is provided to the vehicle market and the market share remains as low as of today the availability of classical MOGAS with less than 1 % ethanol content may be expected to be kept up. Should the market share of these brands rise significantly a necessity may arise to introduce additional ethanol as well. Presently the “Super Plus” brands are produced with ETBE as octane booster that serves at the same time as a (partial) biogenic input path, cushioning the impact of its non-ethanol specification on the suppliers biogenic balance. Since practically all vehicles comply to the DIN EN 228 and are thus able to operate on up to 5 % v/v of ethanol there is ample room to increase its biogenic share without breaking normative specifications.

3.4 Aircraft Fitness for Ethanol Admixtures

Similar to vehicle technology there is an issue of compatibility of old gasoline-only combustion system designs with chemically different constituents in the fuel. The complete design of the combustion system, including the fuel provision starting in the tank, is gasoline-oriented. A rather large portion of the equipment still stems from decades ago, with the choice of the materials for the relevant parts not oriented to fuel diversity.

While the smaller parts of the fuel systems like hoses, fittings, seals, or even fuel pumps, may sensibly be replaced by such made from more recent materials there are original parts that will oppose simple replacements. Here custom made parts like closely fitted tanks, carburettors, custom engine-integrated fuel pumps or aluminium cylinder head parts exposed to hot liquid or evaporated fuel must be kept in mind.

As ethanol admixtures considerably change the physico-chemical behaviour of the gasoline in various aspects each of them must be scrutinized individually to ascertain a secure operation of the whole aircraft.

Modern flex-fuel engines and fuel systems of recent vehicles are able to operate on a wide range of combustibles since they incorporate a quite complex adaptive fuel conditioning. Would aircraft engines be supplied with a similar conditioning system they should, in case of a phase separation (see section 5.1) taking place in the fuel, at least be able to operate on the low-octane gasoline portion. Without an adaptive conditioning this is at least very questionable.

Even though modern engines, like those presently built into the majority of ultra-light aircraft, are certified for vehicle gasoline usage and therefore principally compatible with respective ethanol admixtures they are not equipped with flex-fuel instrumentation. As long as the gasoline does not exhibit a phase separation those engines will behave as they should, with all other vehicle gasoline technical shortcomings relative to AVGAS properties being taken care of. Should a phase separation occur even these most recent engines are not to be expected to cope with that.

Since ethanol admixed fuels feature a larger enthalpy of evaporation the temperature drop of the ingested air together with the evaporating gasoline in the carburettor is some degrees centigrade larger, leading faster to ice deposits. Accordingly a stronger pre-heat of the air is required. If an aircraft is already known to be prone to carburettor icing the utilization of ethanol admixed fuels will presumably add to the threat.

Mixing unintentionally ethanol containing gasolines may lead to elevated vapour pressures. This reduces the margin of acceptable heat-up of fuel system parts relative to the conventional non-admixed MOGAS before an engine stifling vapour lock may take place. Again, if an aircraft is known to be susceptible to vapour locking with former MOGAS qualities already a vapour pressure exceeding this typical level could be detrimental.

4 Determination of the Status Quo in General Aviation

4.1 Gasoline Types

Carburettor fuels (gasoline, petrol, MOGAS) are multi-component mineral oil based products with a boiling range between 30 °C and 210 °C. They consist of various hydrocarbons that are predominantly distilled from fossil oil. A base gasoline is mixed from crack benzines, olefins, pyrolysis gasolines, iso-parafins, butane alcylates and replacement components like alcohols and ethers. Various admixtures improve certain properties relevant for the distribution, the intermediate storage and the subsequent combustion process.

One of the most relevant properties of an internal combustion engine fuel is the knocking behaviour, characterized by its octane number (see section 4.1.3). Without additives the octane number is rather poor for pure gasolines. Historically it was boosted by introducing organic lead compounds for a long time until their toxicity and the availability of less or non toxic alternatives became available. Being forbidden in vehicle gasolines, lead compounds are still prevalent in aviation gasolines and a matter of increasing concern.

4.1.1 Historic Development of Gasolines and their Alcohol Admixtures

1861 Invention of the Lenoir engine, being the first stationary operated engine following an Otto-like combustion management. The typical fuel was coal gas.

1862 Nikolaus Otto develops a spiritus carburettor for his engine, so it could be used for vehicles. An excerpt from the patent text: *"The engine is of utmost ease and simplicity! It may be put to* *operation or standstill at liberty. A quart of spiritus suffices to keep it running for three hours at an output of one horsepower. The material is easily acquired and does not require mentionable space."*

1900 Broad availability of vehicle oriented light gasoline with ethanol admixture. The latter presumably led to its german name "Sprit", derived from the everyday language "spiritus" for concentrated ethanol.

1908 Henry Ford develops his "Modell T" and the assembly belt. He prognosticated great returns for the american agronomy as cars were constructed for bio-ethanol usage: *"The fuel of the future is going to come from fruit like that sumach out by the road, or from apples, weeds, sawdust — almost anything."* (Henry Ford).

1924 Engine knock is explored and leads to the development of high octane numbered fuels consisting of a mixture of aromats and aliphats (*"Aral"*). In the USA, TEL admixing is started.

1925 In Germany the "Reichskraftsprit" is founded to improve the fuel supply situation by ethanol admixtures distilled from potato schnaps.

195x Ethanol admixing is stopped in Germany and most European and northern American countries since the cheap fossil oil rendered the production and conditioning of ethanol as uneconomic.

1970 Additives are entered into gasoline to prevent carburettor icing. For healthcare reasons a reduction of the lead content is requested and a maximum value is defined.

1980 Introduction of the catalyzer to reduce pollutant emissions into the atmosphere. In conjunction with the catalyzer lead-free gasoline is provided and legaly requested. Volatility is enhanced by adding certain additives.

198x Due to a broad availability of cane based production methods ethanol becomes the default fuel for Otto engines in brasil. More than 90 % of the local vehicle production is built to run on ethanol. In the mid-eighties a complete turnover happens, though, as the food product market promises more returns. Nevertheless the fuel contains 25 % v/v ethanol in Brasil by default [19].

1985 Wide-spread market introduction of lead-free high octane gasoline (Superbenzin, RON 95) in Europe, facilitating higher compression ratios and hence higher engine powers and efficiency levels.

1990 Gasoline quality "Super Plus" (RON 98) is introduced, yielding again a rise in specific power, efficiency and enabling smaller engines.

2000 Regulations of the European Council and the European Parliament define boundary conditions for pollutant emissions into air. In subsequent national regulations these are transferred into national legislation, defining among others the pollutant emission of vehicles.

2006 The German "Biokraftstoffquotengesetz" rules the minimal admixture of biogenic components and their continuous increase into standard fuels. In conjunction penalties are defined for lower amounts.

Properties	Units	min	max	Test Method
Resarch octane number RON		$95^{(1)}$ $98^{(2)}$	-	prEN ISO5164
Motor octane number MON		$85^{(1)}$ $88^{(2)}$	-	prEN ISO5163
Lead content	mg/l	-	5	prEN 237
Density at 15 °C	kg/m^3	720	775	EN ISO 3675, EN ISO 12185
Sulphur content	mg/kg		10	EN ISO 20846, EN ISO 20884
Oxidation stability	Min	360	-	EN ISO 7536
Involatile residues (mass)	mg/100ml	-	5	EN ISO 6246
Corrosion effect on copper	corr. grade	cl. 1	cl. 1	EN ISO 2160
Appearing	clear and free of haze			visual
Content of olefines	% (v/v)	-	18	ASTMD1319, prEN 14517
Content of aromates	% (v/v)	-	35	ASTMD1319, prEN 14517
Content of benzol	% (v/v)	-	1	EN 12177,EN 238, prEN 14517
Oxygen content	% (m/m)	-	2,7	EN 1601, EN 13132
Methanol content	% (v/v)	-	3	EN 1601, EN 13132
Ethanol content	% (v/v)	-	5	EN 1601, EN 13132
Isopropyle alcohol content	% (v/v)	-	10	EN 1601, EN 13132
Isobutyle alcohol content	% (v/v)	-	10	EN 1601, EN 13132
Tert-butyle alcohol content	% (v/v)	-	7	EN 1601, EN 13132
Ether content (<5 C atoms)	% (v/v)	-	15	EN 1601, EN 13132
Content of other oxygenates	% (v/v)	-	10	EN 1601, EN 13132

Table 3: *Properties of DIN EN 228 “Super lead-free” (1) and “Super Plus lead-free” (2) gasolines.*

4.1.2 Prevailing Legal Boundary Conditions and Norms for Vehicle Gasolines

The European norm EN 228 fixates numerous minimal and maximal values for gasolines. For the ubiquitous quality “Super lead-free” the conditions summarized in Table 3 are defined.

Due to its inherently high octane number benzol is a technically sensible means to boost the knock resistance of gasolines. Benzol is, with respect to human health, as a carcinogene a very dangerous substance, though. Accordingly the EU EN 228 limits its abundance in gasolines to a maximum of 5 % v/v. In recent years its usage strongly dropped, and market levels of 2 % were hardly reached. As of today the benzol content is limited to max. 1 % v/v.

For some years, another octane number defined gasoline quality, the “Super Plus”, is widely offered besides the ordinary “Super” quality. Its octane values are ≥ 98 octane (RON) and ≥ 88 octane (RON), respectively.

Sulphur Content

In crude oil sulphur is found bound as di-sulfide and mercaptane sulphur, in quantities in the range of 0.01 ...7 % m/m. If the sulphur remains in the distilled products its oxidation compounds

Parameter	Unit	Methanol	Ethanol	TBA	MTBE	ETBE	Super RON 95	Av-Gas 100LL	Av-Gas 80
RON	-	112	106	-	116	118	95		81
MON	-	91	89	-	98	102	85	100	80
RVP	Psi	4.6	2.5	3.4	7.8	4.4			
PVP	kPa	0.32	0.17	0.23	0.54	0.3	0.45... 0.90	0.38... 0.49	0.38... 0,49
Boiling pt.	°C	64.7	78.3	82	55	70	(210)	(170)	(170)
Freezing pt.	°C	-98	-117	27	-108	-		-58	-58
Density	kg/m^3	0.79	0.789	-	0.745	0.751	0.75	0.718	
Calorific value	kJ/kg	22676	29710	35560	36010	36810	43500[1]	47000	43500
Enthalpy	kJ/kg	1100	910	544	322	-	335		
Flash pt.	°C	11	13	11	-26	-			
Lead content	g/l	-	-	-	-	-	0.005	0.56	0.13

Table 4: *Physical and chemical properties of usual gasolines and frequent additives (Data compiled from various sources).*

are formed in the combustion process, leading to undesired by-effects: Besides SO_2 emissions, malodorous H_2S is formed in unregulated catalyzers and the catalyzer efficiency decreases. In the EN 228 the maximum sulphur concentration was limited to 150 mg/kg. Since 2005 it was further reduced voluntarily to less than 10 mg/kg.

The process of desulphurization extracts further surface active substances from the fuel needed for lubrication in the fuel pumps. Accordingly increased wear may be encountered.

Additives

Additives and further organic compounds are admixed to fuels to ameliorate certain properties. Their exact mixture varies from brand to brand and is mostly unknown as this cocktail is subject to corporate secrecy. Gasoline producers watch out for interchangeability of different brands, though, and accordingly guarantee arbitrary mixability. Phosphorous compounds depositing as films on the carburettor inner surfaces help to repell water attaching. They are not allowed in unleaded gasolines, though. The acid content in ethanol admixed fuels must not exceed 0.007 %.

Table 4 shows a comparison of physical and chemical properties of typical Otto gasolines and auxiliary additives. (For explanation of abbreviations see glossary, Appendix F, p. 277)

For the different classes of ethanol admixture a general nomenclature is frequently used: A denomination of the kind of E*xx* points to the volumetric ethanol content. Usual admixture classes are E-5 (i.e. 5 % v/v ethanol in gasoline) and E-85. For quite a period the wide-spread introduction of E-10 has been discussed but was dropped in spring 2008, for the time being, due to apprehended

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[1] There is no fixed/mandatory calorific value for vehicle gasoline. The given value, to be interpreted as a typical one, will presumably decrease in the forthcoming years due to the increasing admixture of ethanol with its smaller calorific value both per volume and per mass.

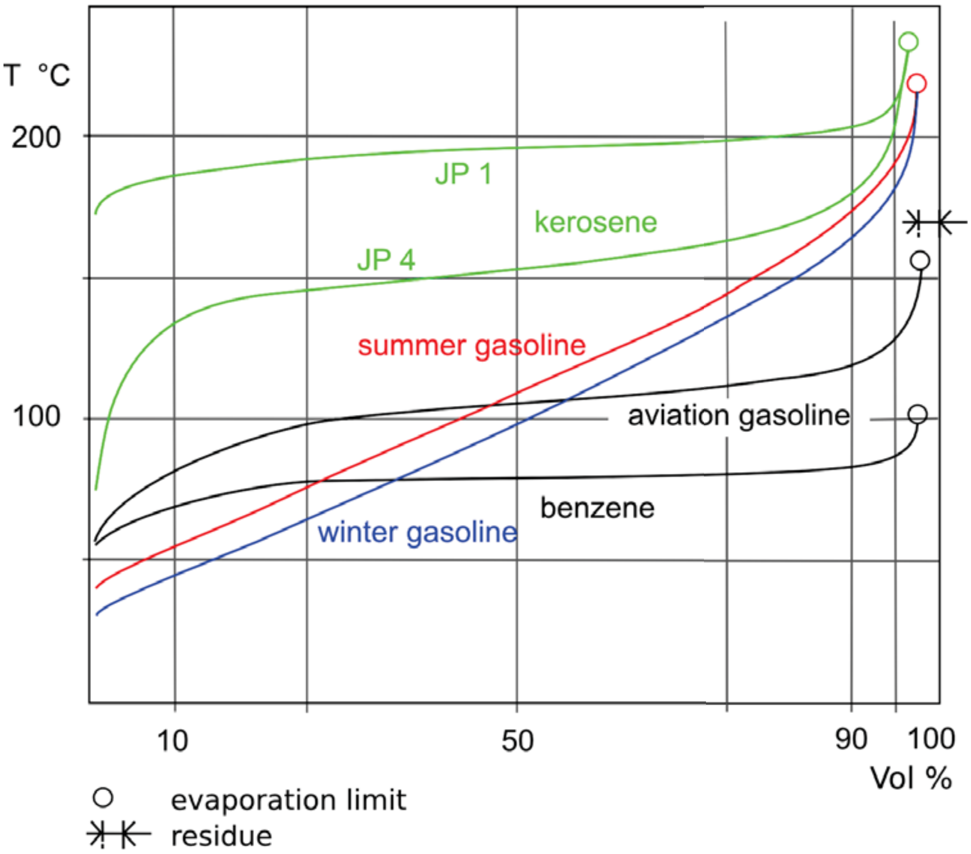

Figure 5: *Qualitative evaporation curves for various gasoline types and two jet fuels. Adapted from [35]*

incompatibilities of the fuel systems of older cars. Frequently intermediate values like E-20, E-50 or even E-100 (pure ethanol) are found in literature which are to be interpreted accordingly.

Boiling behaviour

Coarsly the boiling behaviour can be described by a single, global value for a given fuel: the vapour pressure that builds up in a closed vessel over a respective liquid. For any given substance it is a function of temperature. For gasoline its value is mainly dependent on the light-off components. The vapour pressure of gasoline products is usually determined and specified as RVP (Reid Vapour Pressure) according to the Norm EN 12. In 2000 this norm has been replaced by the so called *Dry Vapour Pressure Equivalent* (DVPE) as defined by the norm *pr EN 13016-1*, mostly to take into account methanol–hydrocarbon azeotropes. Both values differ from the so-called “true vapour pressure” (physical vapour pressure), but its measurement procedure is schematized world-wide and therefore comparable.

A more detailed judgement of the boiling properties resp. the volatility of a fuel is possible on the base of the boiling curve. For the determination of the boiling curve according to DIN EN ISO 3405 a fuel sample is heated with a fixed heating rate of 1 °C/min and hereby evaporated. The temperature at which a certain part of the liquid volume has been boiled away is plotted, see Fig. 5 for a qualitative comparison of different fuel types.

In general it may be noticed that too low a vapour pressure leads to cold start problems while to high a vapour pressure results in poor hot start and hot operation qualities, and in problems in transport and storaging. The low-boiling fractions are important for an easy cold start but may lead to the creation of vapour bubbles and hence vapour locking in hot conditions, as well as to carburettor icing in high humidity conditions.

A too large a fraction of high-boiling substances in the fuel may induce a fuel condensation at the cylinder walls in cold running conditions and thereby an oil dilution. A too low share of medium-boiling components is known to cause a lumpy running of the engine and acceleration cogging.

Fugacity Classes Conforming to EN 228

In the norm EN 228 10 fugacity classes (Table 5) are defined. Each country must declare in a national annex to EN 228 which of these classes A to F1 is valid for which period of the year in which regions.

properties	**unit**	**cl. A**	**cl. B**	**cl. C/C1**	**cl. D/D1**	**cl. E/E1**	**cl. F/F1**	**test method**
vapour pressure	kPa_{min} kPa_{max}	45 60	45 70	50 80	60 90	65 95	70 100	EN13016
% evaporates at 70 °C (v/v)	$\%_{min}$ $\%_{max}$	20 48	20 48	22 50	22 50	22 50	22 50	EN ISO 3405
% evaporates at 100 °C (v/v)	$\%_{min}$ $\%_{max}$	46 71	46 71	46 71	46 71	46 71	46 71	EN ISO 3405
% evaporates at 150 °C (v/v)	$\%_{min}$	75	75	75	75	75	75	EN ISO 3405
boiling end point FBP	$°C_{max}$	210	210	210	210	210	210	EN ISO 3405
distillate residue	$\%_{max}$ (v/v)	2	2	2	2	2	2	EN ISO 3405
VLI (10VP+7E70)	index, max	-	-	C	D	E	F	
VLI (10VP+7E70)	index, max	-	-	C1 1050	D1 1150	E1 1200	F1 1250	

Table 5: *Volatility classes according to DIN EN 228*

from 01. 05.	to 30. 09.	„summer quality“	class A
from 01. 10.	to 15. 11.	„mixed quality“	class D1
from 16. 11.	to 15. 03.	„winter quality“	class D1
from 16. 03.	to 30. 04.	„mixed quality“	class D

Table 6: *Fugacity classes effective in the course of the year in Germany*

As an example, Table 6 lists the fugacity classes being in effect in Germany over the course of the year. Across the various fugacity classes ethanol admixtures in the order of magnitude discussed in this report (up to 15 % v/v) do not lead to noticeable changes in boiling points, upper and lower explosion points etc. as far as obligatory handling procedures are concerned [6].

Fig. 6 shows the result of DVPE testing of a set of gasoline Super and Super Plus samples taken in the north-western and eastern part of Germany in June 2009. While most of the samples comply

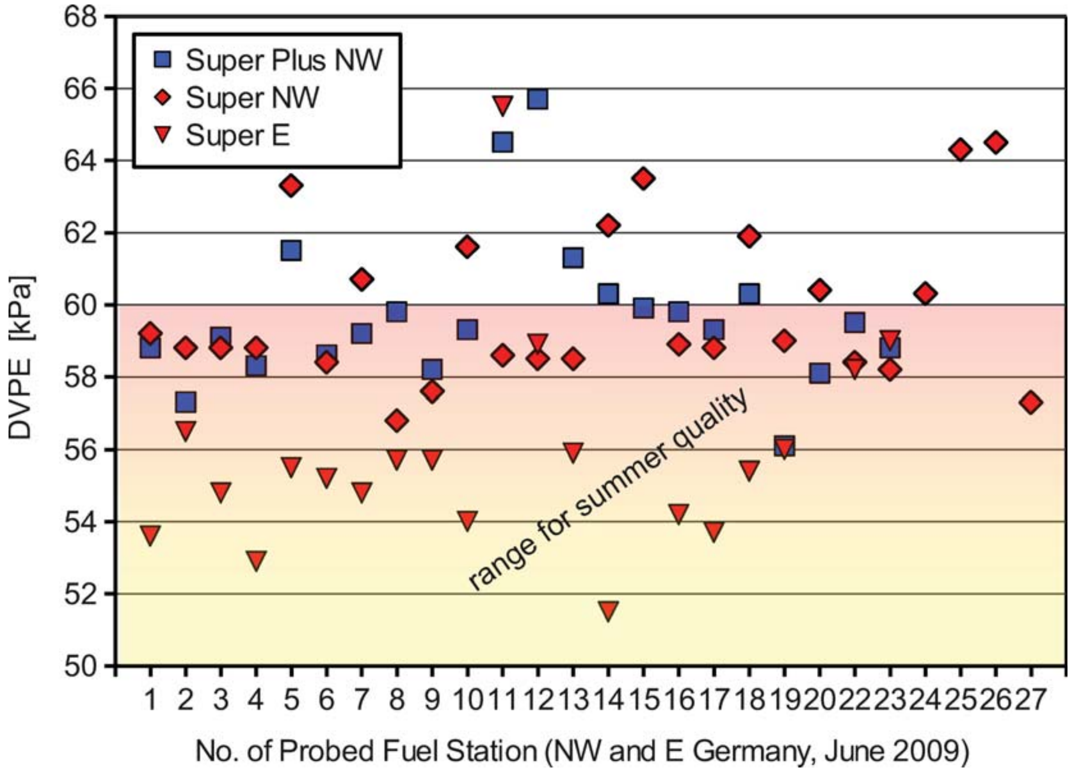

Figure 6: *DVPE values of random test samples taken at different gasoline stations in north-western (NW) and eastern (E) Germany during June 2009. The shaded area represents the range conforming to DIN EN 228 summer quality (curtesy Total Deutschland GmbH)*

with the vapour pressure limits there are some samples definitely exceeding them. For pilots this may result in hot running vapour lock conditions (cf. Sect. 6.5.1).

density [kg / m^3]	**Super Plus**	**Super**	**Normal**
average summer gasoline	753	751	745
average winter gasoline	745	743	735

Table 7: *Typical densities of vehicle gasolines*

As a general information typical densities of vehicle gasolines are given. They usually lie in the range between 720 and 775 kg/m^3. The differences originate from varying ratios of heavier to lighter hydrocarbons (Table 7).

Since for vehicles the fuel is priced on a volumetric basis and the consumption is calculated on the basis of liters per distance generally the fuel with higher density offers advantages with respect to consumption. Fuel distributors have to ensure that no water detachment by phase separation takes place for any climatic condition typical for the respective country. If there is a risk of water detachment anti-corrosion additives have to be put to use.

4.1.3 Assessment of Knocking Properties for Gasolines by Octane Numbers

The knock resistance is an important parameter of gasolines. It limits the possibility to compress and heat up the fuel air mixture inside the combustion chamber of an engine without a self-ignition and detonation of the mixture taking place. If the limit is transgressed detonation waves are prone to damage cylinder head gaskets, valves and spark plugs rendering a dysfunct engine in the midst of operation.

On the other side the highest possible compression ratio is desired as this determines major quality parameters of the engine like a high power to weight ratio, a high efficiency and a low fuel consumption.

Modern gasoline operated vehicle engines are equipped with knock sensor systems to automatically adapt the operating conditions (mainly the ignition timing, the manifold pressure and the throttle flap setting) to a rather wide range of fuel qualities in the range of ROZ 91 to 98. This facilitates the gentle engine operation even with low-quality fuels, even though with reduced power output, while at the same time exploiting the most efficient and economical combustion for high-quality gasoline brands. Due to some engine specific conditions (compression ratio, piston geometry, valve position) a lower quality limit must be obeyed.

The predominant parameter determining the combustive fuel quality is the octane number. It describes the (lack of) tendency to spontaneous inflamation and hence limitation of the fuel air mixture compression. Depending on the operational state of an engine different octane numbers have been defined and are taken for assessment purposes.

For vehicle operation the following octane number definitions are frequently found:

Research Octane Number (RON) characterizes the knock resistance at low engine load and rotational speed. Too low a RON leads to a tinkling knock of the engine.

Motor Octane Number (MON) describes the knock resistance at high (thermic) load conditions and high rotational speeds. Too low a MON leads to heavy load knocking which is quite destructive for the engine and frequently is not perceived due to elevated other engine noises. The MON nowadays is the most important octane number.

The octane number scale is defined by combustion of well-defined reference fuels: A value of 0 is defined for the knock-prone pure heptane, while a value of 100 is set for the knock-resistant iso-octane. Mixture ratios of these substances define intermediate values. Practial octane numbers for arbitrary fuels are determined in a well-defined CFR test engine in comparison to respective heptane/octane ratios by means of a compression ratio variation. Octane numbers surpassing the value of 100 are assessed according to the guidelines of the ASTM specifications (e.g. D910 for AVGAS).

For aviation gasolines octane number ratings deviate from the vehicle definitions in order to better approximate the specific operating conditions. The following should be mentioned:

- AVGAS octane number according to ASTM D909, “supercharge method”
- Lean run assessment according to ASTM D2700, IP 236 “engine method”

As this report addresses the potential use of vehicle gasolines for aviation purposes, an aviation related assessment of the vehicle gasolines would be most desirable. No sources of such assessments could be found, though.

Table 8 summarizes octane numbers and densities of typical gasoline brands and related pure substances, determined by the vehicle-centered methods.

Component	MON	RON	Density [kg/m^3]
distillate gasoline	62	64	680
light crack gasoline	69	81	670
catalytic crack gasoline, heavy	77	86	800
butane	87	92	595
hydrocrack, light	64	90	670
catalytically cracked gasoline, light	80	92	685
alcylate	90	92	700
isomerisate	87	92	625
pyrolysis gasoline	82	97	800
polymer gasoline	80	100	740
MTBE	98	116	745
methanol / TBA 1:1	91	112	790
ethanol (at 15 °C)	89	106	789
ETBE (at 15 °C)	102	118	751

Table 8: *Octane numbers and densities (at 20 °C) of typical gasoline brands and related pure substances*

A realistic impression of the variation span of recent gasoline octane number variations may be derived from actual sample data provided by Total Deutschland GmbH for January 2009 (Fig. 7). Most samples are slightly above the norm's minimal values, but a few ones not quite fulfilling it.

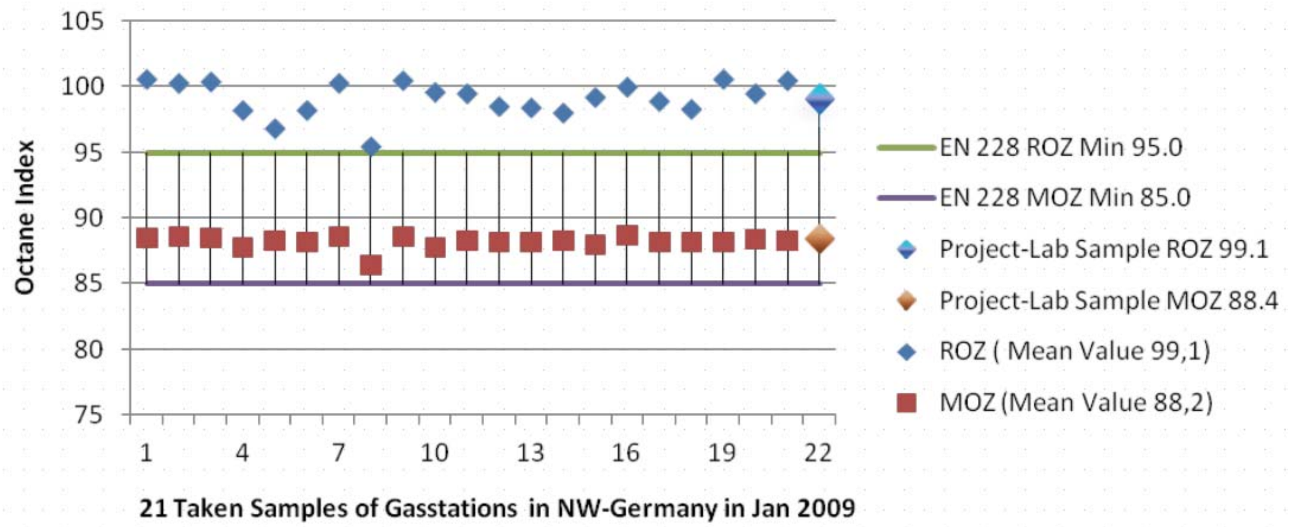

Figure 7: *Octane numbers of 21 test samples taken at different gasoline stations in north-western Germany during January 2009. The 22nd entry shows the RON and MON values for the standard gasoline taken for all experiments conducted in the* SIOBIA *project (curtesy Total Deutschland GmbH)*

Despite of their health-adverse, mostly cancerogenic properties aromates have been put to work as an octane boosters for quite a long time. Table 9 lists their values. Ether substances presented an earlier, widely spread used alternative. One of the most interesting issues in this report, alcohols can as well be used as octane boosters as the numbers in Table 9 show as well. Besides the vapour

Substance (aromate in gasoline)	Mixture MON	Mixture RON	Evaporation range or boiling point [°C]
toluol	112	124	110
ethylene benzol	107	124	136
xylol	103…127	120…146	138…144
C9 aromates	105…138	118…171	152…176
C10 Aromates	117…144	114…155	169…210
Ethers:			
methyle-tertiary-butyle-ether (MTBE)	98	116	55
ethyle-tertiary-butyle-ether (ETBE)	102	118	70
di-iso-propyle-ether (DIPE)	100	110	68
tertiary-amyle-methyle-ether (TAME)	98	111	85
Alcohols:			
methanol	91	112	64.7
ethanol	89	106	78.3
iso-propanol	101	118	82.3
iso-butyle alcohol	90	110	107.7

Table 9: *Octane number of various pure substances or mixtures relevant to gasolines*

pressure rise this fact has a major importance for the potential dangers of using alcohol-admixed gasolines in aviation as is detailed in Sect. 5.1.

4.2 Synoptical Statistical Data on General Aviation (T 1)

A statistical evaluation of available cell, engine and flight data was performed to assess the potential danger of incorrect ethanol admixed MOGAS usage. As discussed with EASA available statistical base data are rather distributed for the different countries and, due to slightly differing boundary settings of individual aircraft classes, not well adapted to comparison purposes. Cell and engine resolved lists of operated aircraft and/or flying hours could only be obtained for Germany and the United Kingdom. Accordingly, an extrapolation for the whole European Union can be given only on some assumptions of an approximate equi-popularity of the different aircraft types throughout.

The full resulting workflow of statistical evaluation and the sources used for the derivation of the comprehensive results is detailed out in Appendix B. Here, only some synoptical results are presented in short.

Main source of quantitative data were United Kingdom and German Aerospace Authorities. Their evaluation lead to the categorization results shown in Fig. 8. Even though the shares of the various classes differ strongly there are comparable amounts of potentially affected aircraft.

Combined with additional information this leads to an estimate of the total count of potentially affected aircraft for the whole of Europe, as shown in Fig. 9. The derived complete European statistics on small aircraft distribution is shown in a map in Fig. 10. Local habits differing from those in the United Kingdom and Germany, e.g. caused by deviating pricing policies for the different types of gasoline, can not be taken into account, though. Since the UK and Germany together already form about 60 % of the total European small aircraft count the effect to be expected by respective deviations should be rather minor.

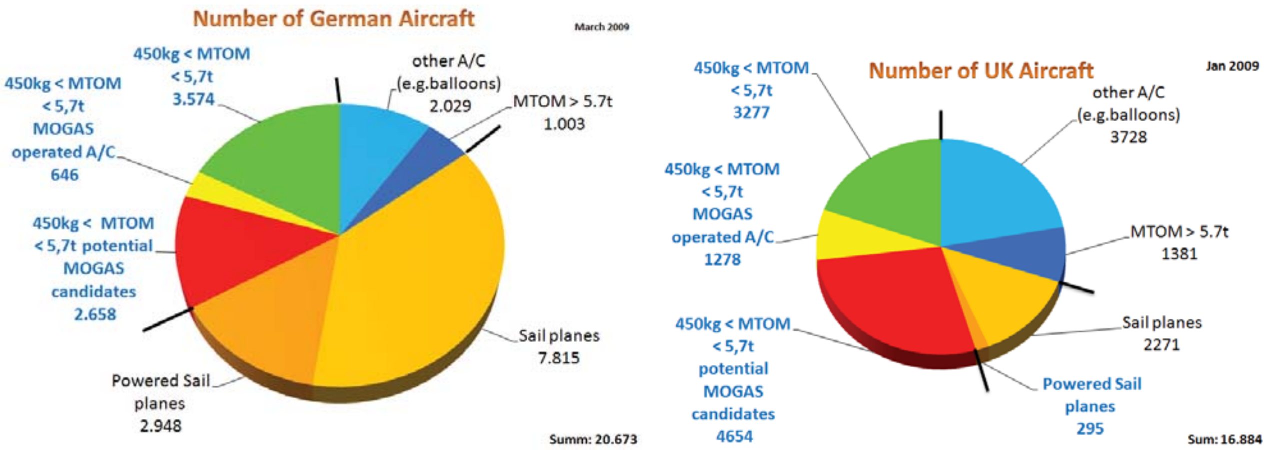

Figure 8: *German and United Kingdom numbers for the aircraft categories of interest. No distinction is made with respect to used fuel type.*

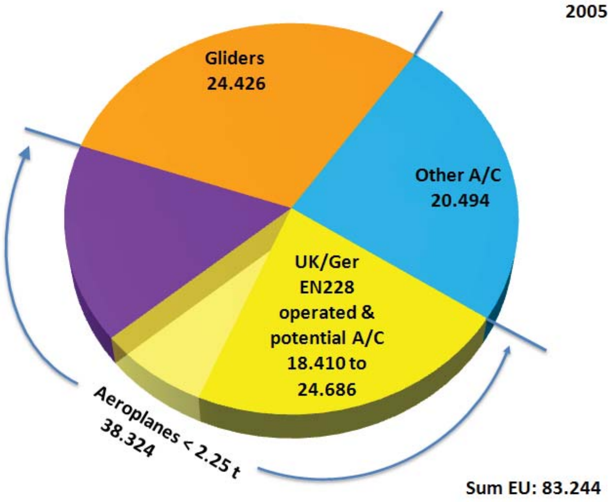

Figure 9: *Estimated European total numbers for the aircraft categories of interest*

Additionally, the German statistics on operating hours [11] allow a rough estimate on the popularity of MOGAS operation. While only 48 % of all General Aviation aircraft fall into the category of being principally MOGAS capable, 57 % of flight hours are delivered by the respective types if the comparison is performed on the basis of German data for flown hours since last check.

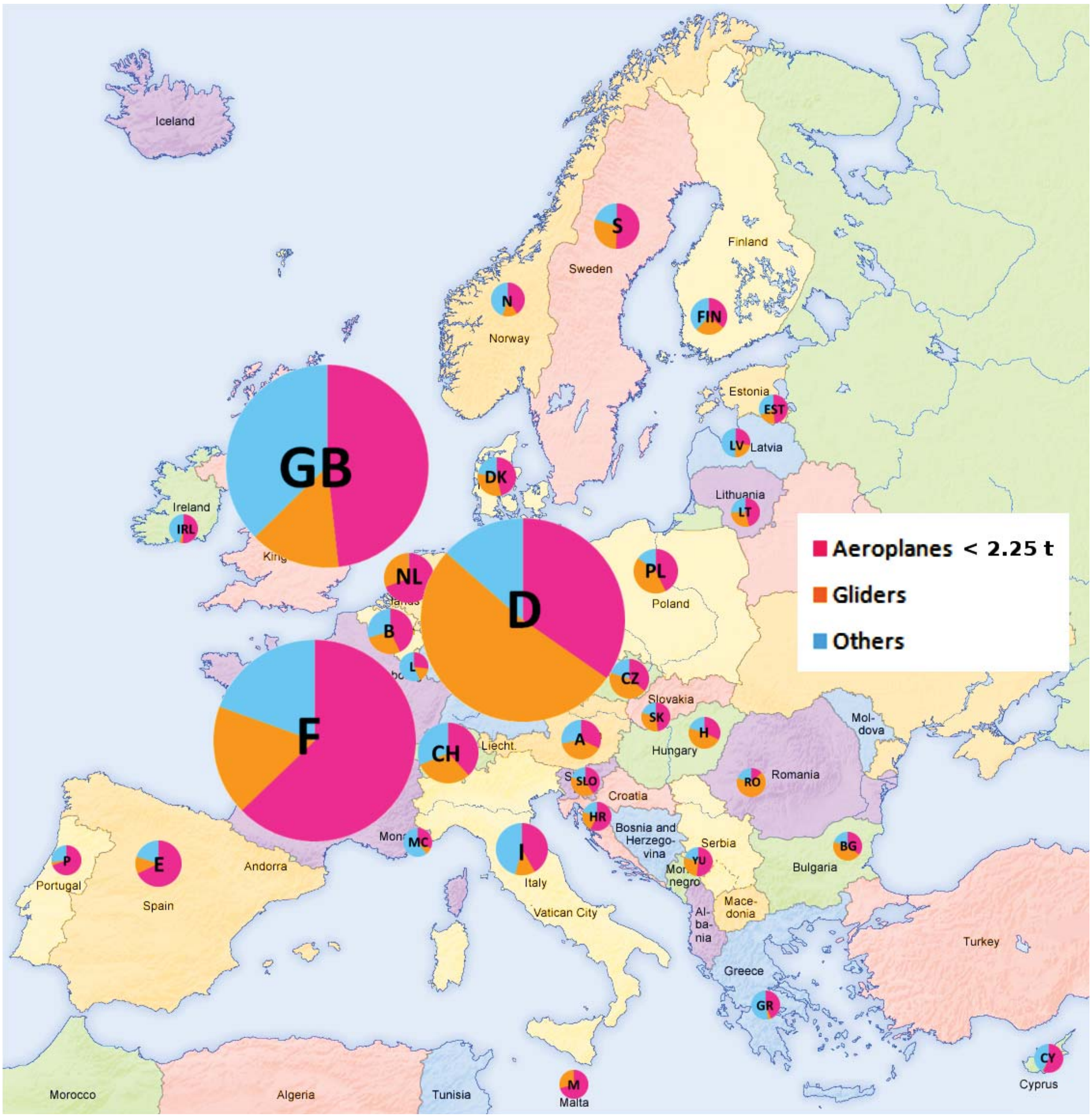

Figure 10: *Graphical display of the distribution of small aircraft (less than 2.25 t) in Europe. The three largest cakes (UK, D, F) are reduced to 70 % of their correct size whereas very small contributions (Malta, Estonia, ...) are disproportionally large to be able to display them at all. For comparative numerical data see Table 27, page 156.*

5 Scientific and Technical Boundary Conditions for Ethanol-Admixed Gasoline Usage in Aviation (T 1)

5.1 Water-Induced Phase Separation in Gasoline-Ethanol Mixtures

Many liquid substances are miscible only within certain relative concentration ranges. If other concentrations prevail the liquid as a whole unmixes and thereby creates at least two physically and chemically discernible phases. Due to their typically different densities gravity separates them vertically. The concentration ranges that exhibit this behaviour are called a miscibility gap. It is dependent, apart from the chemical structure of the involved substances, also from temperature and potential further (minority) admixtures that may interfere with the basic molecular interactions of the main substances involved.

For mixtures of two well-known pure substances (binary mixtures) their miscibility gaps are usually well known or relatively simple to investigate. As soon as three substances (or even more) are involved things usually change: The amount of required measurement data to characterize such ternary (quaternary, quinternary ...) mixtures dramatically increases with rising number of the substances involved.

For typical gasolines things are even worse: As they consist of quite different molecularly structured substances (aliphates, aromates, and various not so rare additives that do not fit into this simple categorization, even solid, non-evaporative residues) they would have to be described as kind of multi-nary mixtures for which no stringent description is usually at hand.

As long as the mixed substances stem from chemically similar structure classes (like homeopolar substances, e.g. aliphates and aromates) only few surprises may be expected. A different thing is a mixture of stronger bipolar and homeopolar substances, like water and "gasoline". In this case very large miscibility gaps prevail usually. In combination with water and gasoline, ethanol presents a special case: Ethanol is, as a single substance miscible with both water and gasoline in arbitrary concentrations. In the presence of a bit water ethanol acts like a detergent: On a molecular view water molecules get surrounded by ethanol ones and their polar behaviour is catched by the polar heads of the ethanol, at the same time pointing the homeopolar tails towards the gasoline environment.

If (base) gasoline is regarded as a homogeneous molecular substance a ternary diagram can be taken to describe the miscibility behaviour of the three substances "gasoline", ethanol and water (Fig. 11). Since in the presence of just three components in a mixture there are only two degrees of freedom a planar drawing is suitable to describe all possible concentration possibilities. Usually the typical ternary diagram is chosen, displaying an equilateral triangle with respective concentration axes at every side. In Fig. 11 the vertical axis, and in accordance with that the horizontal level lines inside the diagram, describe the percentage of ethanol present in the mixture. The gasoline axis is pointing downwards to the right, in accordance with the respective level lines perpendicular to it.

The left side of the triangle describes the possible mixtures of water (lower left corner point) and ethanol (top corner). The right side of the triangle shows the more interesting mixtures of gasoline (lower right corner) and ethanol, also possible on the whole range of the scale. The greyed area below the red border line is the miscibility gap, i.e. the range of concentrations that will eventually produce at least two distinct liquid phases.

Deliberate mixing processes can be displayed in the diagram as well: If we e.g. take an initially "dry" mixture of 90 % gasoline and 10 % ethanol (E-10, Point A in Fig. 11) and add water we

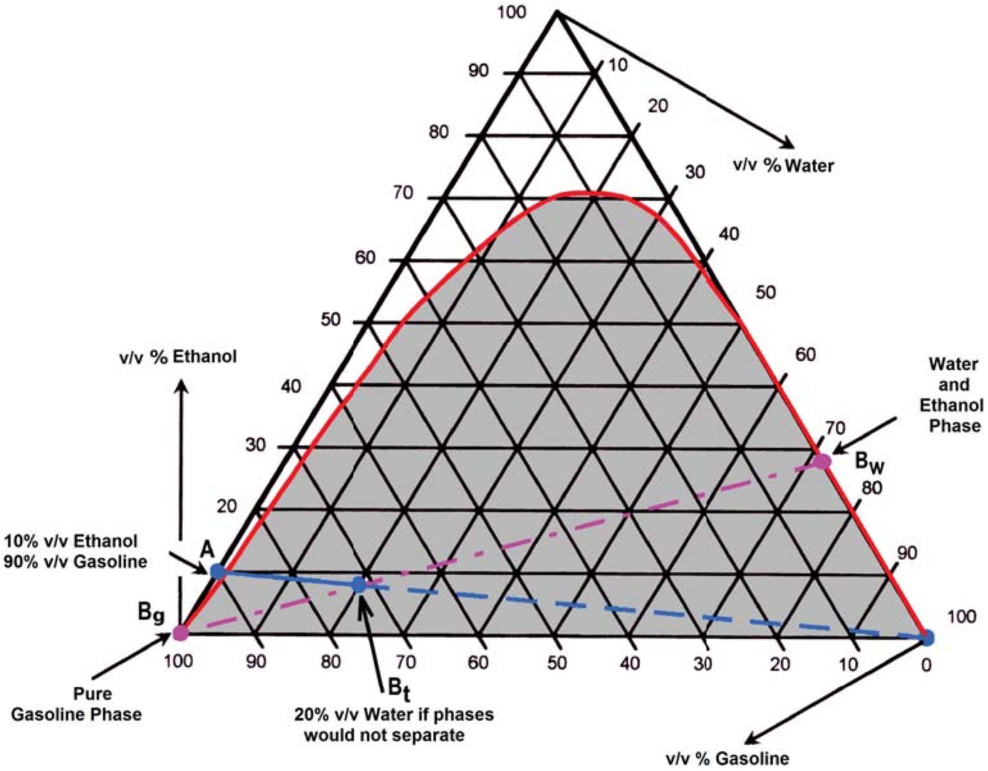

Figure 11: *Ternary diagram for the substances gasoline, water and ethanol at 21 °C, after [31]. Percentages are given as m/m values. Explanation see text.*

create a new concentration ratio somewhere on the blue line. If we enter such an amount that the abundance of water is 20 % in the final mixture the concentrations of gasoline and ethanol will accordingly drop to about 72 % and 8 % respectively. This new theoretical mixture point Bt would be situated well inside the miscibility gap, rendering an unstable mixture that will immediately decompose into two stable phases Bw and Bg. We obtain an almost gasoline-only phase (Bg) and a water-alcohol mixture (Bw).

The water-alcohol mixture is heavier than the gasoline phase and therefore settles at the bottom of the tank. It is not ignitable and would lead to an instant starvation of the engine should it be sucked in.

The pure gasoline phase on top is not so much better, though: The ethanol it former contained was boosting the octane number, so running the engine on the remaining gasoline phase is prone for knocking combustion and potentially leading to severe damages.

In practice the potential amount of water added to a gasoline-ethanol fuel must be scrutinized, however. Conventional gasoline is able to actively dissolve about 150 ppm water at 20 °C, which is in the order of cm^3 for typical tank sizes of some hundred liters. This is not much. As soon as partially polar oxygenates, especially higher alcohols, are entered as additives the water acceptance increases rather soon to tenfold values, see Fig. 12[2].

Although gasoline should be sold „free of water“ the ubiquity of humidity poses a logistical problem of delivering the fuel without water contact to the customer. Regular quality controls of actually offered gasolines at diverse gasoline stations throughout the country show that the issue

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[2] Please note that the procedure leading to the results of Fig. 12 is determined by cooling down a sample with a given amount of solved water. This leads to different limiting values (i.e. slightly higher water acceptance values) than active water dissolution.

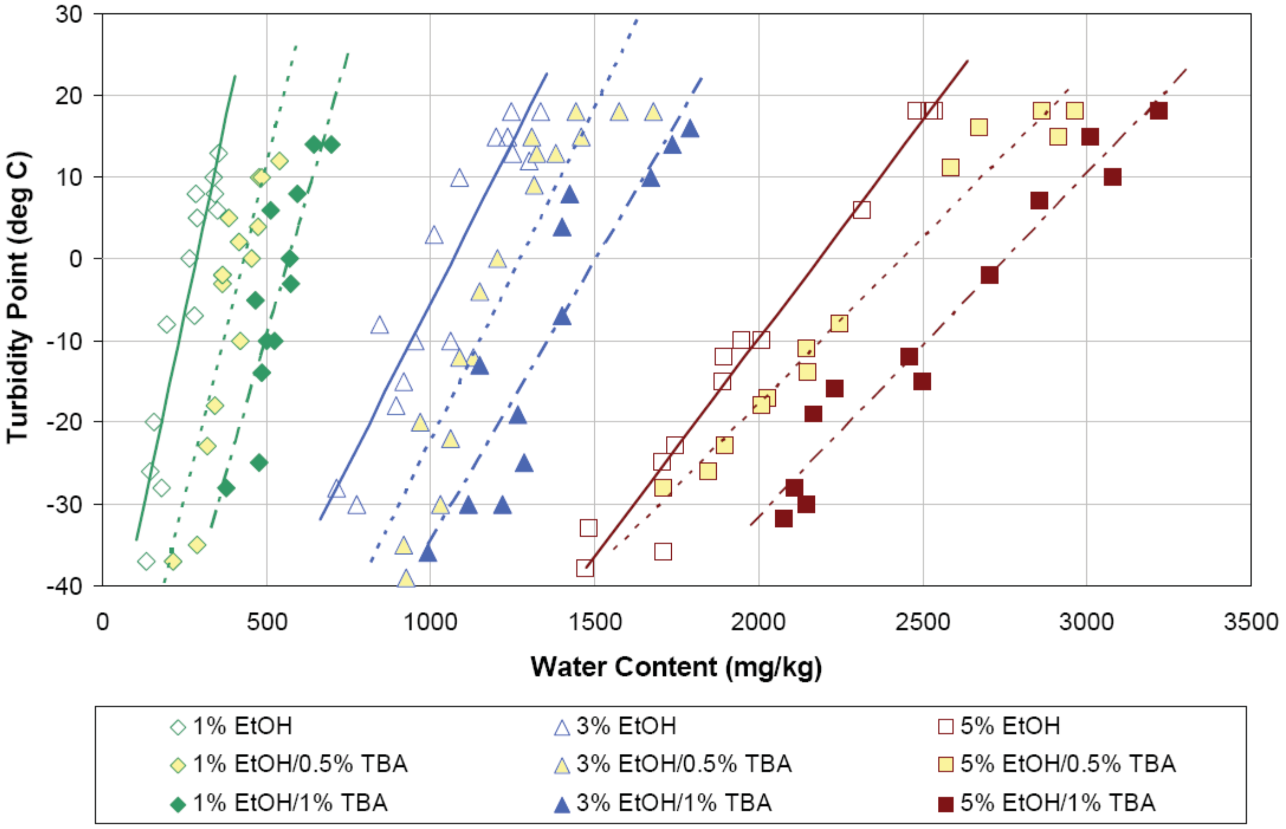

Figure 12: *Maximum water concentrations in different gasoline/ethanol mixtures as a function of temperature, after [28]. By cool-down experiments the onset of turbidity was measured as a function of fuel composition, denominating the limit of water acceptance. Percentages are given as m/m values. Explanation see text.*

remains: Fig: 13 displays the result of such quality controls for summer 2009 in Germany.

The generally accepted quality value of 200 mg water/kg fuel, mandatorily defined for Diesel fuels but not for gasolines so far, is transgressed quite often. There are several Super Plus samples that may be regarded as mostly saturated with water. The water abundancies found in the With the Super samples the situation is not as serious even though there are even more ones with rather high absolute water content values: Most of the Super samples contain near to 5 % of ethanol, so the water bearing ability is comparatively high.

Accordingly it may be feared that the compiled humidity by delivery borne water content and partially long-term condensation may affect the operational properties, especially if the gasoline is cooled as during a high altitude flight. Some measurement device developers like [32] point into that direction and towards a rising danger if the respective fuel is not treated properly. The main issue of envisioned danger is the fact that none of the separated phases is able to support a sound engine operation any more. Accordingly, any separation must be suppressed by all means. This contrasts sharply the generally comparable problem of a separation of a small amount of (mostly condensation originating) water from gasoline without ethanol contents in it: First, the water phase contribution is very small and may be well drained just before any flight. Second, the remaining gasoline phase does not change its combustion behaviour, so no further danger is to be expected. Third, any additional water fallout due to a temperature and hence water acceptance decrease during the flight will set free only very small amounts of water, as may be understood by following the rather steep curves of 1 % EtOH admixed gasoline. Those will either not be ingested by the fuel system or will be so small that a changed engine reaction will not be noticed.

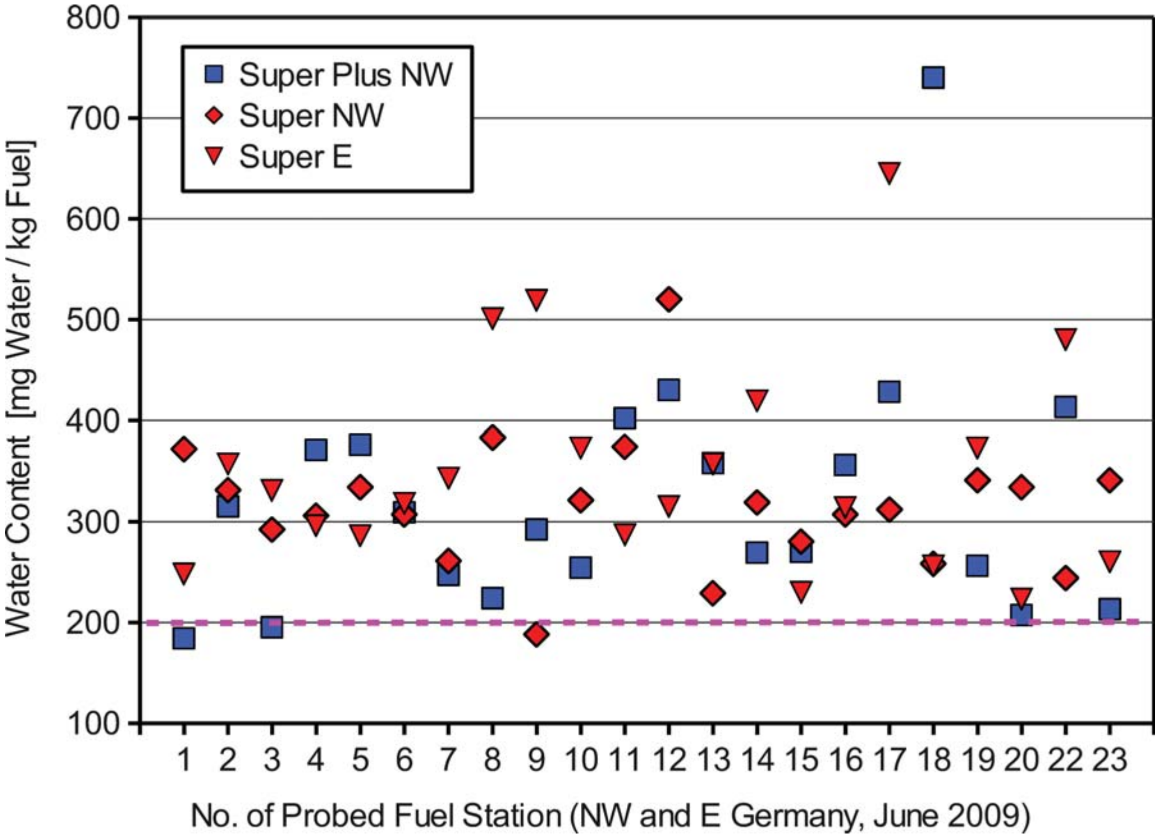

Figure 13: *Measured water concentrations in different commercially offered gasolines. Shown are random Super Plus and Super samples taken from gasoline stations in the north-western (NW) and eastern (E) part of Germany, June 2009. As of today there is no obligatory limit defined in DIN EN 228. The dashed line indicates the limit value valid for* Diesel *fuels. (No water content results have been reported for the Super Plus samples taken in the eastern part.)*

The envisioned danger with its detrimental effects on the aircraft engine output is in sharp contrast with reported accidents that might have been caused by a phase separation, though. For the USA, the NTSB database contains information from 1962 and later about civil aviation accidents and selected incidents within the United States, its territories and possessions, and in international waters. Just one accident entry ([25]) can be found in it via the online search facility (*http://www.ntsb.gov/ntsb/query.asp#query_start/*) if the search keywords "ethanol and gasoline" are used. Even for this entry a striking cause-effect relationship to the ethanol-admixed gasoline found in the tank is not ascertained[3].

A clue to this discrepancy is revealed if both practical experiences of vehicle operation are taken into account and a closer look is taken to the thermodynamics of mixture formation and stability.

First, it is a well known procedure to "dry out" water biased vehicle gasoline tanks by adding some amount of ordinary spiritus to the fuel. Although this commercial spiritus is not dried and hence imports about 5 % water (relative to the volume of the added alcohol) into the tank, a phase separation is *not* observed.

Second, the pure equilibrium consideration of free enthalpy calculations, leading to the so-called binodal limit lines in the ternary diagrams for a given constant temperature (see Fig. 14), are

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[3] If only "ethanol" is inquired, 478 accidents are reported by the NTSB database. The vast majority of them indicates problems with a pilot's ingestion of ethanol.

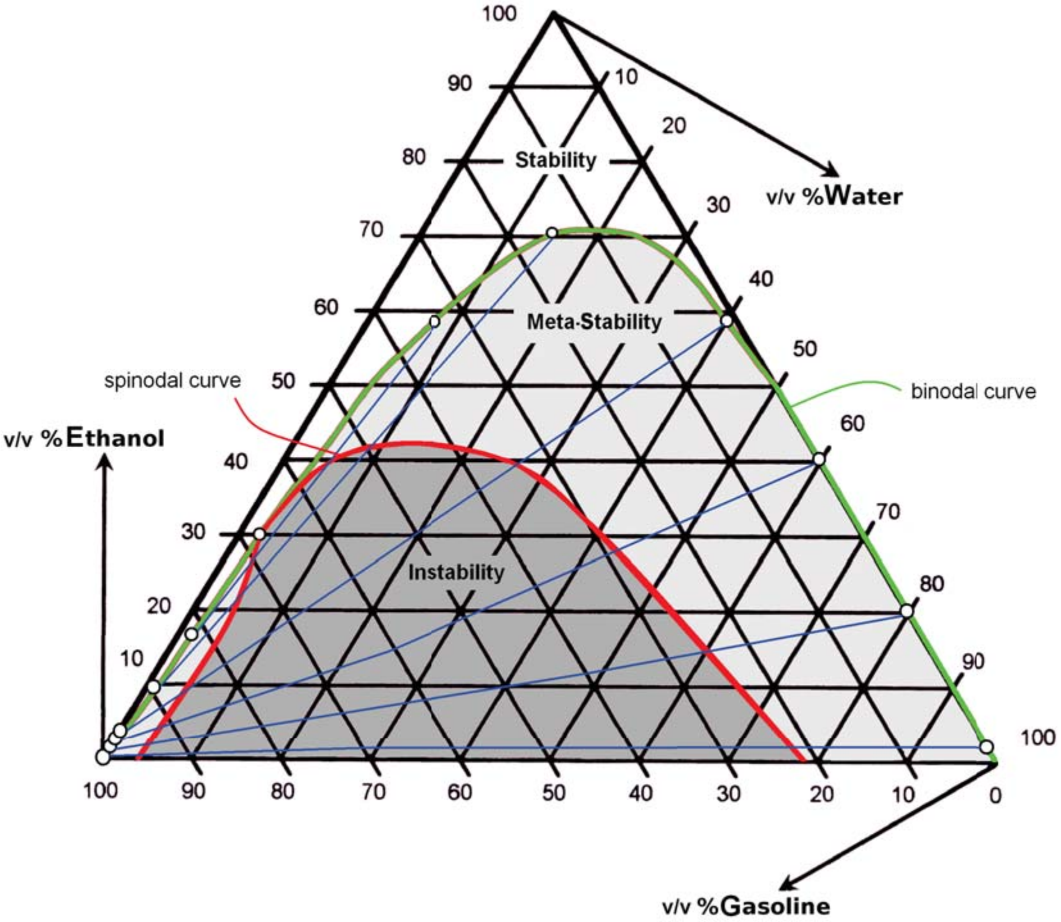

Figure 14: Position of the binodal and spinodal limit curves in a ternary GEW diagram for a certain temperature [21].

misleading: The condition that the free enthalpy of a GEW mixture is larger than that of a split state with separate phases is not sufficient for the generation of such phases. The creation of distinct phases consumes additional energy that must be taken somewhere from. In the immediate neighbourhood of the binodal limit line the gain of free enthalpy is too small to support such a creation of phase interfaces. Accordingly the incident region of the miscibility gap is governed by a meta-stability that reaches non-neglectably into the gap. If gasoline is in this state there is still no danger of a macroscopical distinct phase creation in a relevant time interval.

Since the required surface generation energy is coupled to the surface tension, and the surface tension is a function of material interfaces, e.g. at the tank surface, the region of meta-stability may be dependent on the tank material.

Even though a spontaneous disintegration of a formerly homogeneous phase into two distinct ones will usually occur in the form of cloudiness of the fuel, i.e. the small alcohol/water droplets will mostly remain wavering in the gasoline without aggregating to a macroscopically distinctive phase, such a condition should be avoided by all means as there is no guarantee how long this physically meta-stable suspension will remain in existence. In addition, this suspension does not exhibit the same physical properties as the homogeneous combined phase as the microscopically distinct phases may behave differently at surfaces of small bores and in filters and thus create new problems.

With increasing ethanol admixture to the base gasoline the emergent alcohol/water phase will occupy a respective share in the tank if a phase separation has taken place and the heavier hydrous phase is settling: For an E-5 gasoline this would yield already about 5 % of volumetric occupancy, so any low-positioned tank outlet would fall into this range, delivering predominantly the alcohol phase to the engine which will choke on it.

This situation is even aggravated by the fact that the miscibility gap is rather strongly temperature dependent. Fig. 12 illustrates the dependency of water tolerance as a function of temperature for various mixtures of gasoline with ethanol and an additional alcoholic solubilizer. The large temperature differences between ground and cruise height, frequently some ten degrees Centigrade, will lead to a cool-out of the fuel tank. This in turn may lead to the situation that a homogeneous fuel at pre-flight conditions may not show any peculiarities when being drained in the usual manner but may separate during the flight.

Unfortunately there is no simple means to extract *solved* water from the fuel. A micro-filter that may well separate even emulgated water will not do. Accordingly the companies manufacturing and trading ethanol-admixed gasoline fuels are well aware of the necessity to keep any kind of water (liquid and gaseous) from entering the fuel storage vessels. Respective venting systems with water traps are applied throughout. Ethanol or ethanol admixed fuel must not be transported by ship or through pipelines.

While this care to prevent water intrusion may well be positively assumed for the production and distribution phases it cannot be ruled out with the same stringency afterwards. FMEA results (see section 6.1) pointed to potentially dangerous settings both for the end consumer supply step in European regions with less stringent control structures and for the partially casual pilot's handling of fuel in the individual aircraft. Especially the latter case should be scrutinized thoroughly as it is frequent use to leave smaller aircraft with filled tanks in the hangars and not fly them for prolonged periods of time (see section 6.3.4). Here gaseous water may enter the tank unnoticed via the breathers or by porous tank fill cap sealings and the like.

Both general but conflicting recommendations — to keep the aircraft's gasoline tank well filled to prevent larger amount of breathings, and to always freshly fuel the aircraft to be certain about the fuel quality — are valid furtheron. Without custom safeguarding measures the danger of a dangerous deterioration of ethanol containing gasolines appears definitely higher, especially so for E-10 and higher EtOH admixture shares. The breather originating hazard can be countered by installing custom air dryers that take away the largest part of the air humidity before its contact with the gasoline.

Besides constructive materials incompatibilities and accidental vapour locking increases due to gasoline brand mixings the problem of phase separation is supposed to be of major importance to EtOH admixed fuels for aviation purposes, as it is the least known and the most difficult to understand effect for laymen, while at the same time being the most hidden one as there are no practically available measurement procedures for danger assessment — see also Section 7.

5.2 Vapour Locking Potential of Mixtures of Ethanol-Admixed Gasolines

The threat of vapour locking, i.e. the creation of vapour bubbles in the fuel system leading to a stagnation of fuel flow to the engine, is well known within the aviation community, especially so to those pilots operating their aircraft on MOGAS since its comparatively high vapour pressure, compared to AVGAS, is prone to show this effect. Ethanol blended gasolines add a new dimension to this threat as they display a non-linear vapour pressure increment effect in a case of mixing.

As a chemically pure substance ethanol has a temperature-dependent, but clearly defined vapour pressure, contrary to gasoline mixtures that can, as multi-component mixtures, only sensibly be described by boiling curves. During engine operation thermal transients of varying time scales are observed, though. The fuel evaporation in the engine, substantially influencing the ignitability of the fuel air mixture, is a very short-timed process that is mainly governed by the total evaporation enthalpy (see section 5.3). The fuel supply to the carburator or the fuel injectors is, on the other hand, a rather slow process that leads the liquid through various potentially heated aggregates (tubing, pumps, mixers) with extended exposition times. Here the vapour pressure of the light fuel components plays a major role with respect to the danger of spontaneous and fuel flow choking vapour bubble creation.

As a pure substance ethanol shows a rather low vapour pressure unusual for such a small organic molecule. Accordingly, it is a liquid under normal conditions. The low vapour pressure is mainly caused by a rather high polarity, combined with the relatively strong hydrogen bonds of the OH part of the CH_3CH_2OH molecule. In this respect it is somewhat comparable to water. If smaller ethanol amounts are dissolved in less polar media like gasoline this vapour pressure damping effect is strongly reduced as far less partners are available for the retaining hydrogen bonding. Accordingly, a considerably higher vapour pressure is observed in deviation from Raoult's Law for ideal mixing. Interestingly, the maximum vapour pressure is found for a mixture of about 2 % v/v ethanol in a constant gasoline basestock, see Fig. 15.

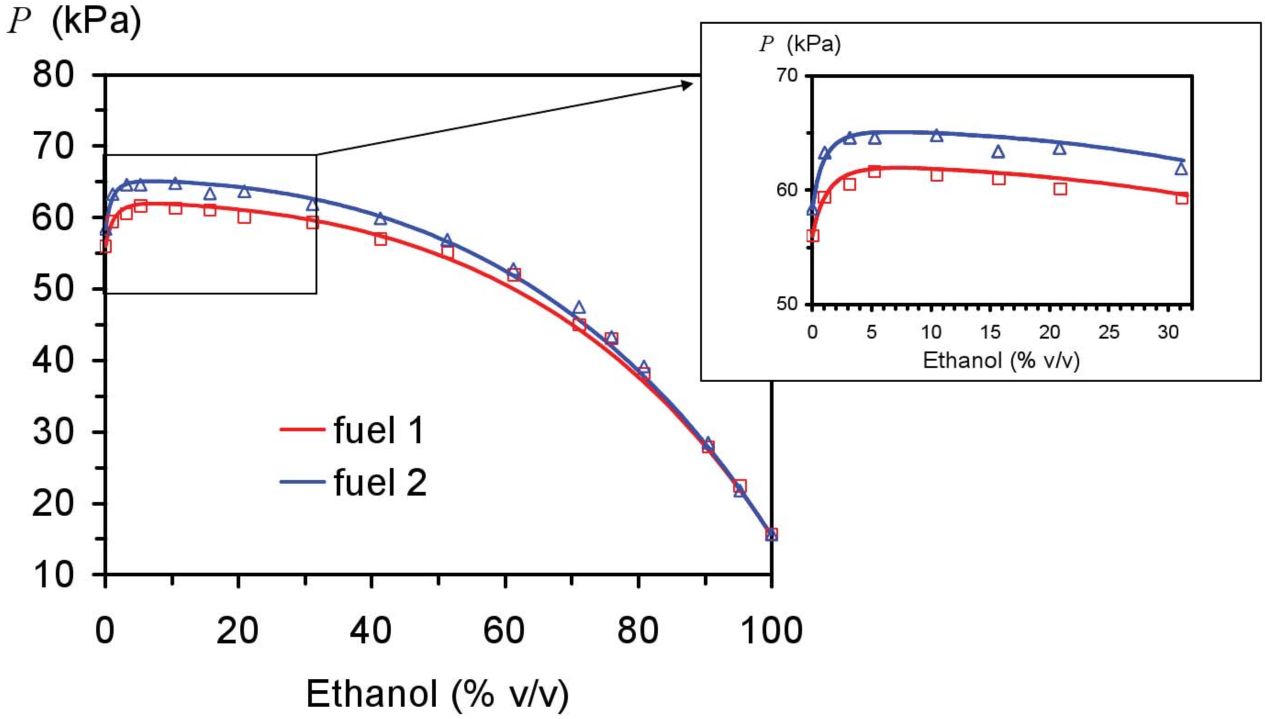

Figure 15: *Dependence of vapour pressure of the same base gasoline on the amount of admixed EtOH, after [28].*

This result represents the behaviour of "cold" gasoline/ethanol mixtures. Another source investigates the vapour pressure at raised temperatures [20]. According to this source, at 60 °C the rise of the vapour pressure with ethanol abundancy proceeds up to an E20 ratio (Fig. 16).

As a consequence for fuel system parts adjacent to the hot engine there is still an increasing effect to be expected with raised ethanol content for the admixture range considered in this report (up to E-15). Fig. 16 shows these dynamically determined vapour pressure results for raised temperatures. (For further discussion with respect to vaporization enthalpy, see also Sect. 5.3).

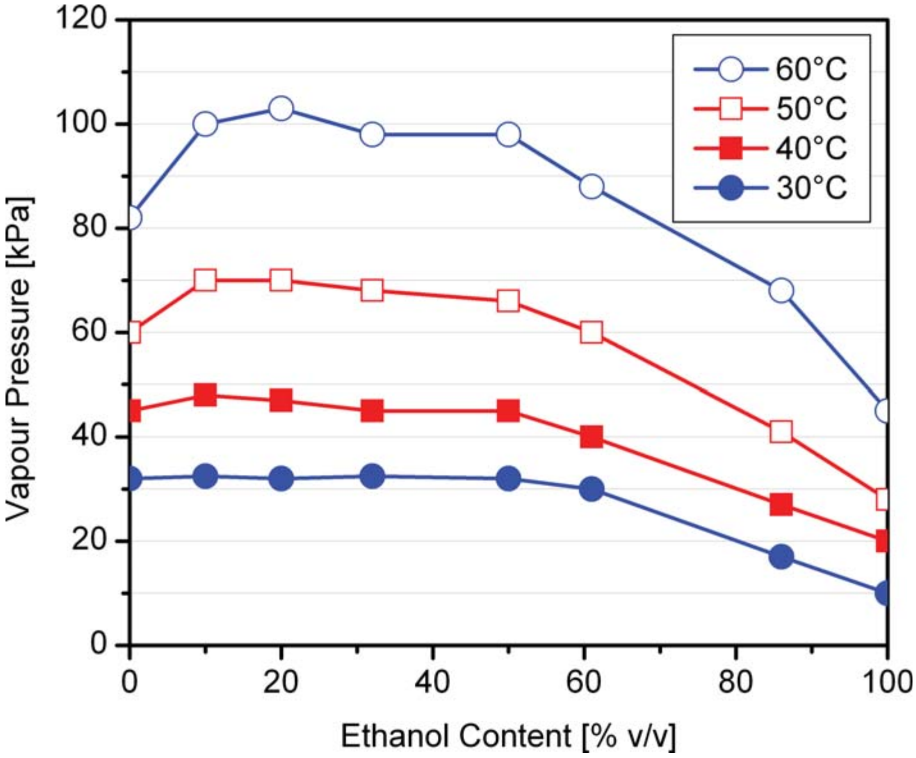

Figure 16: Dependence of vapour pressure of the same base gasoline on the amount of admixed EtOH, measured dynamically [20].

The admixture of ethanol to gasoline therefore much more increases the volatility than the presently mostly used methyle- resp. ethyle-tert-butyle-ethers (MTBE, ETBE). Fig. 15 does not represent actual different vapour pressures of commercial gasoline brands as the vapour pressure of the respective base gasoline is deliberately adjusted to the pressure increase induced by the intended EtOH admixture: When preparing ethanol blended gasolines the formulation of the basic gasoline is suitably chosen so as to comply with the normative evaporation requirements for the final product. Here certain so-called BOBs (basestocks for oxygenated blending) are put to work that take the described vapour pressure increasing effect into consideration by providing a less volatile base gasolines.

Problems may arise if different gasoline blends meet (fig. 17, based on static vapour pressure results): Due to the non-Raoultian mixing properties a mixture may be created that exhibits an up to 8 % increased vapour pressure relative to the individual anteceding qualities. As long as identical ethanol concentrations are mixed it is not likely that the resulting vapour pressure will change significantly at all. It cannot be logistically ruled out, though, that residual amounts of E-5 or E-10 fuel blends are mixed with ethanol-free MOGAS or AVGAS gasoline in winter quality, yielding an unlucky mixture with about 1 … 2 % EtOH content. In that case the raised volatility effect is strongest and may lead to an out-of-bounds REID vapour pressure and hence to the induction of vapour bubbles at fuel system components with elevated temperatures or sharp dynamic pressure drop, especially so if the original gasolines were already top-rated with respect to their vapour pressures. Fig. 18 shows a sample taken from 21 north-western German fuel stations. It should be noticed that some of the probes definitely approach the upper level of normative DVPE values for winter quality gasoline.

Due to the non-trivial dependencies of the vapour pressure on the fuel ingredient abundances it still remains to be investigated in detail which conditions may lead to substantial dangers. Accordingly the scope of the SIOBIA work package is the investigation of partially ethanol-admixed *mixtures*

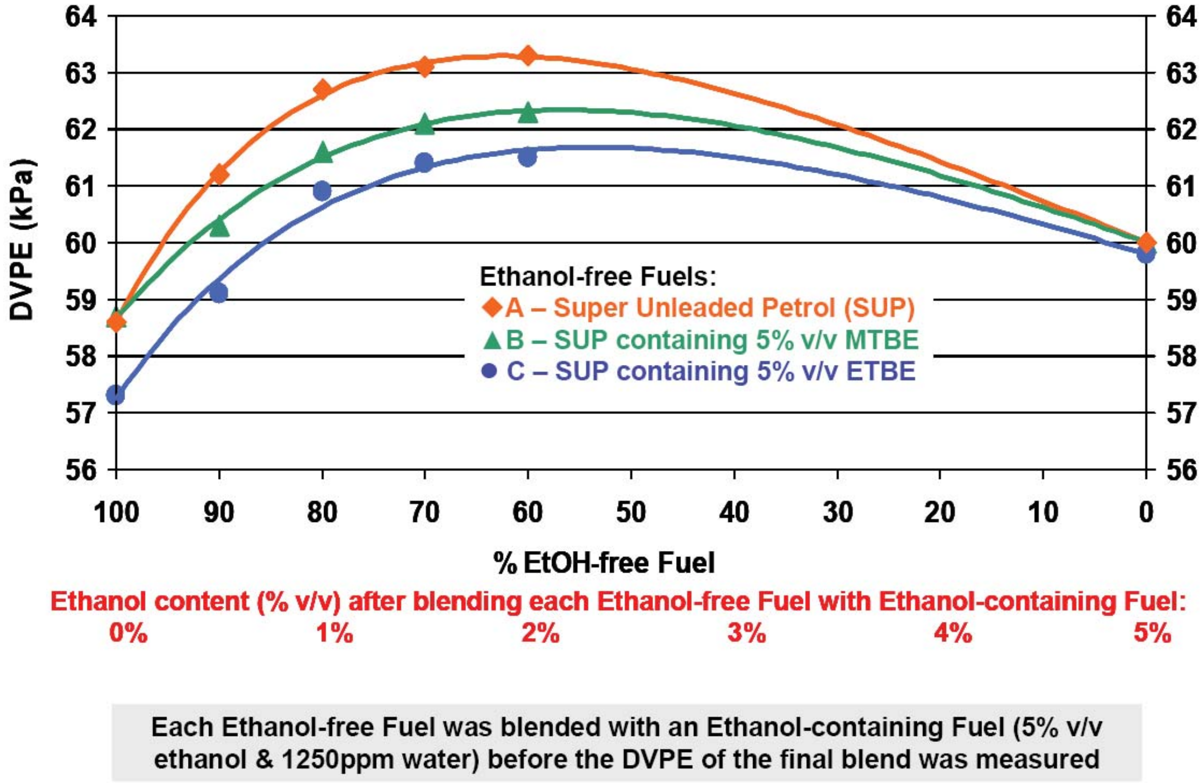

Figure 17: *Dependence of vapour pressure of the same base gasoline on the amount of admixed EtOH, after [28].*

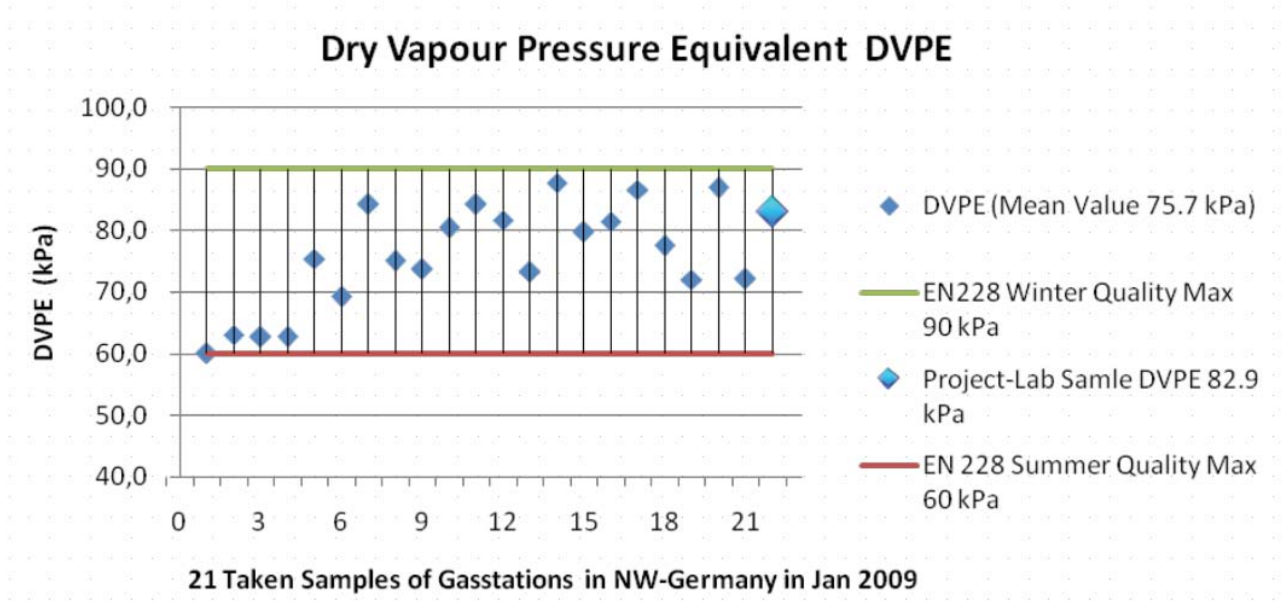

Figure 18: *DVPE values of 21 test samples taken at different gasoline stations in north-western Germany during January 2009, curtesy Total Deutschland GmbH.*

and their volatility behaviour, not a general vapour pressure survey of ethanol admixed fuels by themselves.

As an elevated gasoline vapour pressure is most problematic when coinciding with stronly heated fuel provision system components exemplaric temperature measurements are undertake at ACUAS's flying test lab Morane. A certain flight mission is flown aiming at heating up the engine compartment and the fuel provision system to the extent possible for a safe operating.

Even though not strictly a problem of ethanol-admixed fuels, but aggravated by the fact of a potential vapour pressure rise in case of a casual unlucky mixture, is the potential influence of *vibration induced cavitation and/or boiling* which may as well lead to a vapour lock in the fuel system. The physical effects of cavitation and boiling are usually not treated in combination, although addressing almost the same physical phenomenon of spontaneous creation of a vapour phase out of the liquid one. Brennen [7] discusses them in full detail. With rising temperature of the liquid the tendency of cavitation, induced by dynamic pressure drops, is also rising. Both fast moving parts in pumps or larger vibrations of fuel lines induced by mechanical coupling to the engine may have such an effect. As of today theoretical as well as experimental considerations usually address pure and mostly clean substances to create a basis of scientific reproducibility. Little seems to be known about pressure drop induced evaporation of gasoline-like non-equilibrium mixtures under elevated temperature conditions. It may be stated, however, that the heat input into cavitating liquids is increased, thus contributing to the fact that the fuel lines and with them the fuel may experience additional heating.

In order to adress this issue vibration measurements on tanks and fuel lines are performed to obtain an experimental database for further evaluation (see sect. 6.5.3). A more in-depth theoretical study should be carried out to address this issue in more detail.

5.3 Evaporation Enthalpy Effects

Blending gasoline with ethanol has a profound effect on the evaporation characteristics of the mixture: The thermodynamic properties of the blends can be significantly different from those of the constituents. Literature data on this subject is very limited even though gasoline-ethanol blends are used as biogenically supplemented fuels world-wide.

Many of the reported evaporation properties of respective blends have been investigated in highly controlled quasi-static environments (e.g. [28, 14]. This may not be the appropriate condition to obtain evaporation related results for the highly dynamic process of motoric evaporation processes. A recent publication by Kar [20] investigates these processes with both a ASTM D4953-99a conforming measurement setup and a thermometric in-cylinder cool down measurment in a motored engine. The ASTM procedure (defined for a fixed temperature of 37.8 °C resp. 100 °F) was changed with respect to variegated temperature conditions, being set to 30, 40, 50 and 60 °C and thus being more appropriate for practice-oriented evaporation properties assessment.

From the vaporization pressure data enthalpy of vaporization data have been produced assuming the applicability of the Clausius-Clapeyron equation and by evaluating $(\log(p), 1/T)$ plots. This procedure is valid for narrow temperature-of-evaporation ranges which at first sight do not seem appropriate for the multi-component mixture 'gasoline'. Since in respective experiments only a very minor amount of material is actually evaporated, though, the results may be interpreted as the enthalpy of evaporation for the low-boiling part of the gasoline together with its ethanol share, representing those shares most important for imposed carburettor temperature drops and hence icing.

Fig. 19 shows the respective results for a volumetric shares evaluation. The main and obvious result is the fact that the enthalpy of vaporization is rising constantly and significantly faster with the ethanol share for the range under investigation in this report than should be expected from the

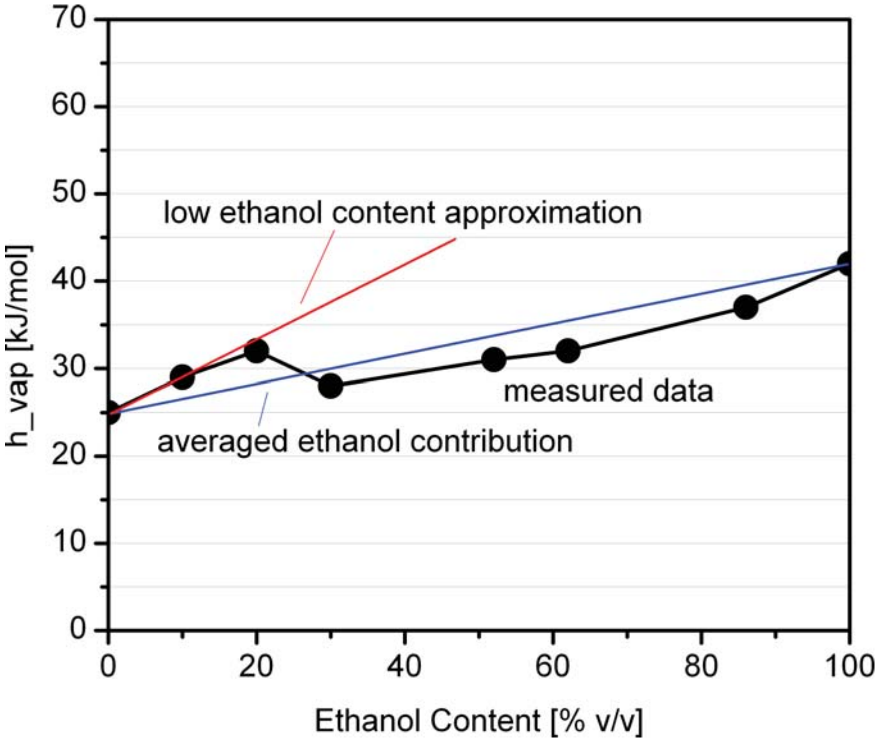

Figure 19: *Enthalpy of vaporization for ethanol admixed gasoline blends, valid for gasoline/ethanol mixtures in the temperature range of 30 – 60 °C, after [20]*

pure substances' data. For E-15 relative to E-0 the value is rising from about 25 kJ/kmol to ca. 32 kJ/kmol, i.e. by about 35 %.

Ambient temperature and humidity in combination with the ethanol fuel blend having a higher enthalpy of vaporization may lead to a pronounced threat of icing. Icing is the condition where water vapour in the air condenses as ice precipitation within the engine inlet system or on carburettor surfaces. This in turn may result in a loss of performance or even engine stalling. Fig. 20 illustrates the combination of ambient temperature and humidity at ground level pressure.

For lower service ceilings these results may be conferred to aircraft carburettor engine operation. Since Fig. 20 relates to ordinary fuel without admixed ethanol and the anticipated additional temperature drop can be proven in air intake manifolds of carburettor aircraft engines (see Sect. 6.4) the icing threat may be regarded as aggravated under these circumstances. The critical icing-prone region depends on two effects: i) the existence of liquid water in the atmosphere, and ii) a temperature drop in the carburettor sufficiently large to cool down the tiny droplets below freezing temperature. Keeping these potential factors in mind it may be expected that the critical region will expand to (slightly) lower humidities and to higher ambient temperatures. The endangering conditions are quite frequent if cloud layers have to be crossed during a flight.

Fuel injection virtually eliminates icing, though, since fuel is delivered into the rather hot inlet port rather than vaporized into the cold intake air at the carburettor.

5.4 Compatibility of Fuel System and Engine Materials with Ethanol Content in Fuel

Quite a lot of different materials are exposed to the fuel of an combustion engine system. Beginning with the tank and its built-in fitments (breathers, tank caps, level indicators, sealers), proceding

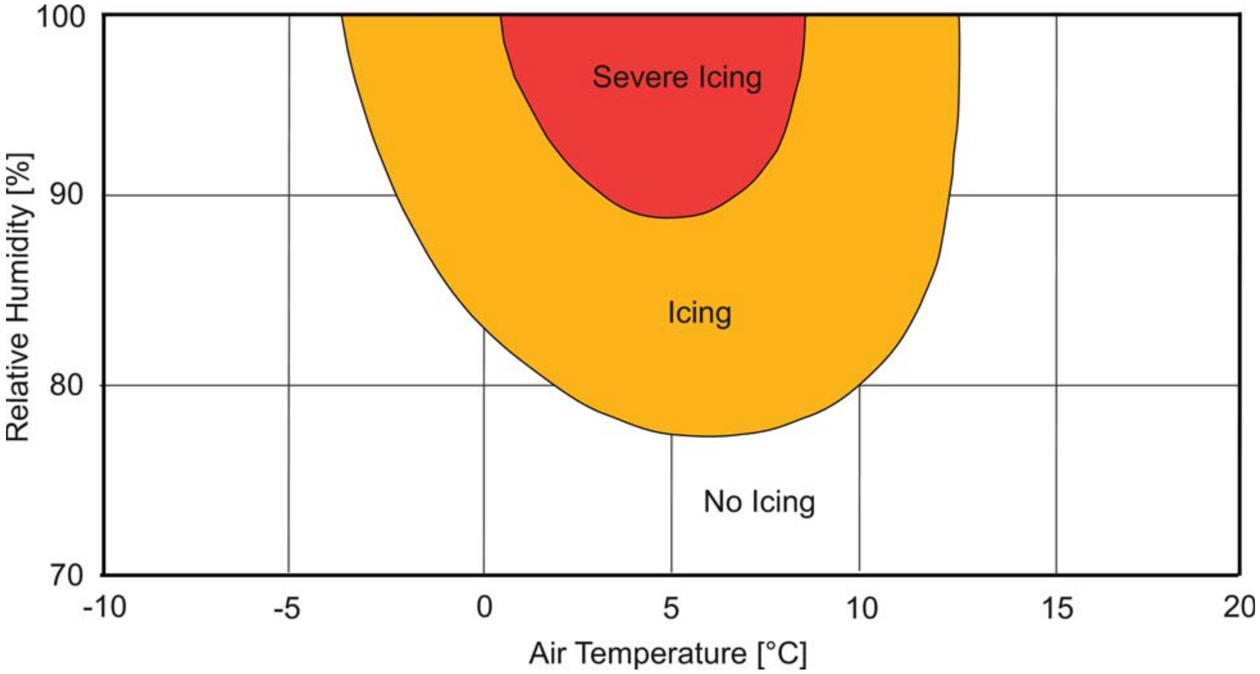

Figure 20: *Temperature / humidity domains for increased danger of carburettor icing at ground atmospheric pressure, after [1]*

fuel hoses, filters, fuel pumps etc., and finally reaching cylinder heads and combustion chamber valves, both individual materials as well as material combinations are subject to fuel interaction. In the past these materials and material combination have been chosen with the best possible resistance and material properties for pure gasoline in mind and hence complying in full with AVGAS. Previous MOGAS gasoline brands, with their EtOH contents limited usually to less than 1 % for aviation purposes, do not deviate substantially from this behaviour. Even though larger amounts of alcohol admixtures to the gasoline (up to 5 % v/v, see section 3.3) are admitted already for a while this upper boundary value has not been touched due to economical reasons. With the onset of compulsory biogenic admixtures this will change, however, and it may well be assumed that at least a larger share of commercial gasolines will contain abundancies up to the legally defined value.

The chemical resistance table from Gates Corp. [10] already points to the fact that materials typically selected for previous non-ethanolic fuels may create problems as the simultaneous coverage of resistance to both gasoline and ethanol is rather small. Accordingly a major inquiry on the compatibility of different material classes with ethanol-admixed fuel is undertaken as a separate task within this report.

5.4.1 Metallic components

Beyond the general problem of increased corrosion induced by a slightly increased electrical conductivity of ethanol-admixed gasolines in combination with a slightly increased water content ([8, 9]) the formation of aluminium alcoholate is a major issue. If *liquid* ethanol is interacting with unprotected aluminium under hot conditions such a specific corrosion is likely to happen. The situation is worsened by the fact that the corrosion can already be induced by just one faulty fueling and will not stop even if the engine is operated on standard non-alcoholic fuel afterwards [2]. The pits eroded by the the ethanol fuel will continue to dig into the affected surface and slowly destroy it.

It should be noted, however, that these corrosion effects are only likely for certain aluminium alloys, and only at temperatures well beyound 100 °C [30]. Accordingly the local pressure must be raised significantly to create respective conditions. As these conditions will only be met in cylinder heads and intake manifolds the potential damage risk related to this cause can be narrowed down to those fuel system / engine zones.

5.4.2 Plastics, Elastomers and Glues

A lot of parts of the fuel system consist of non-metal components. Typical elements are tubings, filters, reservoirs, fittings, tanks, etc.. Depending on the material they consist of they are affected by the fuel constituents in different ways. The utilization and hence the required properties of the respective part determines, to a certain extent, the choice of the available materials. Glues are frequently found in composite expendable items where different material types must be joined. Especially fuel and oil filters are affected as the usual properties of them, like mechanical stability, permeability to a liquid, and retainment of undesired contents, are obtained by different functional constituents.

Accordingly this problem is a subject of recent and ongoing investigations. First results of a work in progress has been reported in [5] where, besides other targets, the stability of typical non-metallic fuel system materials for ethanol admixed fuels is scrutinized for realistic ambient engine conditions like elevated temperatures.

An in-depth analysis of organic materials commonly applied in automotive and aviation oriented applications has been performed by the project's sub-contractor SGS Institut Fresenius, Dortmund, Germany — see Sect. 6.6.2. For a larger number of organic constructive materials (all frequently used ones in automotive and combustion technology applications are covered) their practical properties (temperature range of applicability, compatibility with different solvents, mechanical properties, ...) are detailed. In agreement with recent results from automotive industrial developments and researches appropriate materials *are* available to comply with ethanol admixtures of arbitrary abundancies. The material issue arises from the fact, though, that as of today aviation parts never had to expect to become exposed to larger amounts of (partially hot) ethanol. Accordingly the materials chosen for aviation-certified parts did not take this requirement into account.

Especially for the field of organic materials there is another aspect that strongly influences the applicability of respective products for ethanol admixed gasolines. Production parts are frequently manufactured from material mixes or layered materials, providing them with changed chemical and physical properties. This effect, as desired as it may be, complicates the assessment of ethanol compatibility significantly. A respective compatibility table assemebled by SGS Institute Fresenius, Dortmund, for SIoBIA (Sect. 6.6.2) indicates respective differences even for base materials if it comes to a comparison of properties directly related to certain trade names. While some base materials are not considered as reasonably robust for ethanol/gasoline mixtures some manufacturers claim a compatibility nevertheless. According to material experts this may originate in custom material mixes, surface treatments and the like.

A major issue is the ethanol admixture compatibility of elastomers. Most of the aviation oriented elastic hoses are produced from aviation certified Nitrile Rubbers of the various kinds, usually abbreviated with NBR. For pure gasolines or such with only small amounts of admixed ethanol (less than E-5) they are considered appropriate with respect to their material longevity. Exposed to raised ethanol contents they tend to brittle or swell, depending on the individual kind of elastomer. A solution to this general problem would be the alternative deployment of fluorinated rubbers (FFKM/FFPM et.al., see compatibility table in Sect. 6.6.2, p. 101). Since their price is about ten times that of NBR based materials there has been no commercial interest in them so far. Consequently they were not put to work in certified General Aviation constructive parts.

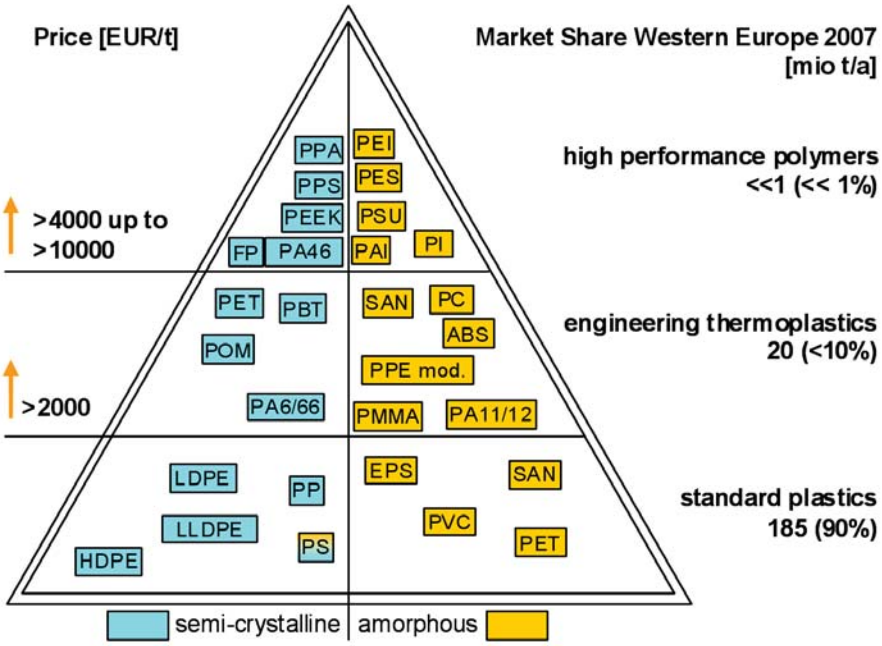

Figure 21: Pyramidal assortment of hard plastics basic materials by price and inversely proportional market shares. For full discussion see Section 6.6.2.

The thermoplastic materials, commonly called "hard plastics" show a similar situation. Fig. 21 depicts an overview over the main basic material categories. A coarse distinction of types is possible on the basis of the molecular structure: The available materials may be separated into semi-crystalline and amorphous types. Especially for amorphous kinds there is a general hydrolysis threat issue, if a larger amount of ethanol is present in the gasoline and the construction part made from the material is operated at elevated temperatures, as frequently encountered in the vicinity of the engine. Accordingly, only semi-crystalline materials should be considered for fuel system component manufacturing.

Even though PA6/PA66, a very common plastic material class for aviation purposes, is situated in the semi-crystalline side of the diagram it is burdened with some less favourite properties in combination with exposition to polar substances like water or ethanol. Instead, PEEK would be a good alternative in general, but is substantially more expensive.

6 Assessment of Danger Potentials Attributed to Gasoline Ethanol Admixtures

6.1 Failure Mode and Effects Analysis (T 7)

6.1.1 Methodology and Approach

A failure mode and effect analysis (FMEA) has been performed to identify potential causes of incidents and accidents both on the overview and on a detailed scale. The FMEA took place during two times two days and included both a functional and a component view.The following aspects were treated in detail (Fig. 22):

- Gasoline provision chain from refinery to aircraft tank
- Impact of ethanol-admixed gasoline on individual parts of the fuel system of small two-stroke and four-stroke gasoline-operated engines
- Potential effects of flight boundary conditions on the behaviour of the fuel in the system

A group of experts was invited to participate in the respective discussions. The organizing company, BRP-Rotax, selected them with the aim of a sincere mix of theoretical and practical application expertise in mind (cf. Appendix C), with some backup experts for remote consultation in case of necessity.

As organizing software tool Plato's SCIO$^{\text{TM}}$ FMEA system, being a specialized spreadsheet application, (http://www.plato-ag.com/platohp/scio-fmea.html) was used. It helps to structure the potential failure scenarios on the basis of a chain consideration:

$$\begin{array}{l} \text{element} \\ \text{function} \end{array} \quad \Rightarrow \quad \text{potential failure mode} \quad \Rightarrow \quad \left\{ \begin{array}{lcl} \text{potential failure effect} & + & \text{severity } (S) \\ \text{potential cause} & + & \text{occurrence probability } (O) \\ \text{prevention measure} & + & \text{detection probability } (D) \end{array} \right.$$

A failure mode is defined as how a system, product, or process may fail. A constructive part or a process can have hundreds of different failure modes based on this definition, most of which are highly correlated to each other because of a common failure mechanism behind them. A failure mechanism is defined as the physical phenomenon behind the failure mode(s) observed, e.g. disintegration of constructive parts, corrosion, degradation of fuel, engine stoppage, etc. .

Severity, occurrence probability and detection probability values are individually assessed by the experts team, whose members assign respective values in the range 1 . . . 10 to each variable. The value to be assigned is determined by the assessment rules as detailed out in Appendix C. If a value cannot be sensibly determined a value of 0 is assigned.

The main goal of the procedure is the quantification of the risk priority number (RPN) for each failure mode considered. It is simply the product of the failure mode severity (S), the failure cause occurrence probability (O), and the detection effectiveness (D) ratings:

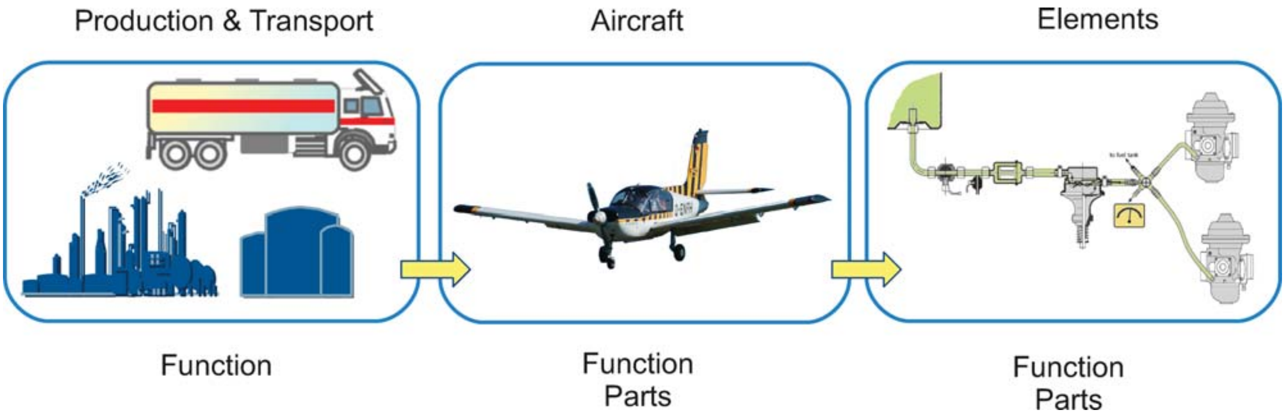

__Figure 22:__ Overview on the objectives treated by the FMEA. Aircraft behaviour and fuel system components issues are both regarded in functional and parts views.

$$RPN = S * O * D$$

The individual attributions of S, O and D were a matter of open discussion within the expert team. In all treated cases an agreement could be reached with respect to the individual valuations. As a general consent in the group the worst possible effect has been assumed.

The focus of the FMEA was on functions & parts, with a rather large number of potential effects having been considered. Even though a very diverse group of experts covering as many fields as possible has been discussing the effects, many of them had to remain untreated at the early stage of the project when the FMEA took place since no scientific expertise was available. The S, O, D values, and hence the resulting RPN value, have been set under these boundary conditions. The FMEA has been taken as an initialization only and has not been persecuted along with the SIOBIA project.

6.1.2 Overall Results of the Failure Mode and Effects Analysis

In the FMEA process a total of about 330 potential failures have been assorted, each of them being attributed with respective S, O, and D values. As was expected and is summarized in Fig. 23 the vast majority of potential issues are of minor importance. Most of them fall into the range of $100 < RPN < 200$ and below.

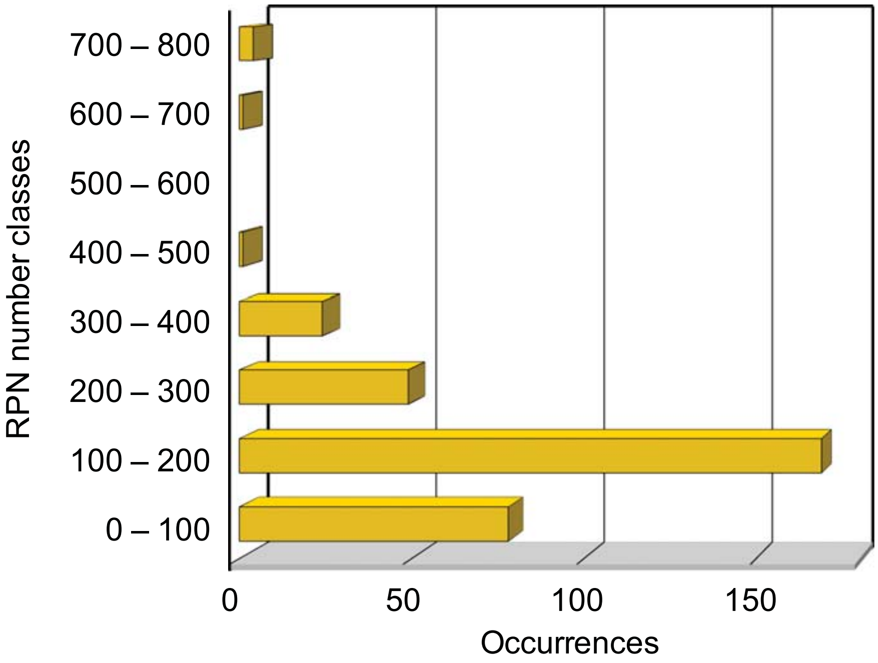

Figure 23: *FMEA risk attribution overview, grouped by classes of severity.*

This led to an identification of 61 issues of major importance, i.e. with RPN values above 200, detailed in Appendix C. They can be assorted to some categories relevant for an internal EASA assessment. As categories the following appear as relevant to distinguish. They do not mutually exclude each other, so some issues may appear in more than one category:

Covered by SIOBIA **activities.** The respective issues are treated by at least one of the practical work actions of the SIOBIA project. This does not mean that a solution or a full understanding will be obtained thereafter but that additional refinements should take into account the results of this project.

Additional research activities required. The SIoBiA work packages performed for this report do not suffice to resolve all issues that surfaced, partially just by the work done. Additional, in-depth investigations on individual issues is necessary.

Resolvable by awareness campaign. Issues listed under this caption may be counteracted by respective targeted information to the community of small aircrafts' pilots and their technical support companies, as maintenance shops and refurbishment companies.

Enforcement of operational / maintenance procedures. Issues are generally already covered by an exact sticking to existing handling and maintenance procedures of technical devices, consumables, or maitenance schemes. Using ethanol admixed fuel may require an even more strict compliance to these procedures than using ordinary fuels.

Recommended regulatory action. EASA or National Aviation Authorities should impose restrictions on usage and/or require new compliance tests even for already tested devices and/or materials.

Fig. 24 displays the numerical assortment of issues on these categories.

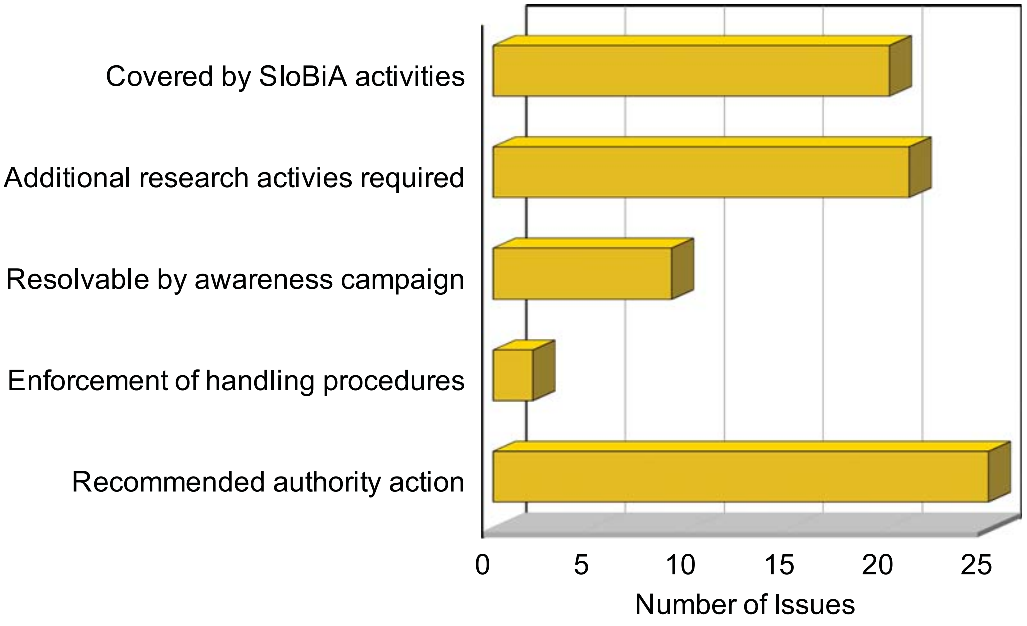

Figure 24: *Overview of the number of issues in the defined categories.*

Besides the the given categorization another aspect is the time horizon of the potential endangerment by a certain risk. Here a rather simple differentiation can be made: Everything concerning phase separation, icing and vapour locking is a very short-term hazard while all material incompatibilities are to be regarded as mostly mid-term (weakening of elastomers, detachment of coatings, etc.) or long-term (mostly corrosion issues).

Some issues have been named in the FMEA that the authors of this report, due to recent developments and investigations performed in the scope of SIoBiA activities, do not consider to be critical. These are issues no. 12, 13, 30, 36[4]. As the FMEA has been executed in an early stage of the project when results had not been aquired yet this should be considered as a normal intelligence acquisition process.

The following collation of important issues is proposed:

- **Covered by** SIOBIA **activities**
  - Issue 11: Engine operation with phase separated E-10 biofuel (RPN 168)
    Risk: By the increased affinity for water, particularly with longer aircraft storage times, a phase separation of the alcohol fuel may occur. This can lead in consequence to an influence of the engine operational behavior up to engine shut down.
  - Issue 15: Insufficient pre-heating of the intake air (RPN 189)
    Risk: Due to the increased evaporation enthalpy of E-10 a too low intake air temperature may be encountered, which could result in carburettor icing and consequentially lead to an engine shut down.
  - Issue 18: Incompatibility of composite material (CFK/GFK) (RPN 168)
    Risk: The solvent characteristics of E-10 in connection with mechanical load or caused by water in connection with high temperature may lead to a decomposition of resins and synthetic material. This on the one hand can result in leakages and on the other hand deposits rinsed out and probably blocking fuel filters.
  - Issue 19: Embrittlement of fuselage tanks made of blown PE-HD or PE-LD (RPN 168)
    Risk: Due to the special characteristics of E-10 a material embrittlement may occur, particular in PE fuselage tanks, which can lead in consequence to leakages. The exact effect currently is unknown.
  - Issue 20: Swelling of NBR rubber material used for tanks (RPN 126)
    Risk: Presumably due to diffusion processes a penetration of E-10 fuel into the rubber material may occur, which can lead in consequence to leakage and/or to the decrease of the mechanical strength of the tank.
  - Issue 21: Difficult draining at NBR tanks (RPN 240)
    Risk: Phase separation of E-10, particularly within NBR tanks, leads to accumulations of the water/ethanol mixture in bulges on the bottom of the tank. On the one hand this bulges filled with water/ethanol mixture could not be drained completely, on the other hand the quantity of the water/ethanol mixture to be drained is much larger than the proportion of water with MOGAS. Further, the remaining fuel after the draining has a very low octane rating and leads in further consequence to a knocking combustion.
  - Issue 23: Decomposition of the tank sealing material (RPN 192)
    Risk: Due to the solvent characteristics of E-10 the tank seal material may be decomposed. According to experts assumptions cork seals are deemed noncritical. Pro-seal, NBR and PRC (e.g. Company Desoto) are classified as critical. Note: Pro-seal consists of components (polysulphide rubber and a further component).

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[4] Most of the issues considered as non-critical within the scope of this report are concerned about a potential freeze-out of water drawn into the gasoline by its raised hygroscopy due to its ethanol content. Freezing of such water must always be accompanied by a prior phase separation. But this phase separation would not produce pure water (as would indeed happen in non-alcohol admixed AVGAS or MOGAS). Instead, the second phase would consist mainly of ethanol containing some water. Such a mixture is well-known as anti-freeze liquid frequently used in cooler devices, though. As the FMEA should highlight *increased* potential hazards caused by ethanol admixtures relative to the contemporary MOGAS definition, the respective issues may be securely downgraded, if not even dropped completely.

- Issue 24: Chemical influence on the tank ventilation (aluminium, plastic or steel pipe placed into the air flow) (RPN 192)
  Risk: Especially larger temperature variations may lead to a leaking of fuel via the tank ventilation. Material incompatibilities could consequently lead to an embrittlement or to pouring. Possibly the tank ventilation may become dysfunct which would have an effect on the engine behavior.
- Issue 25: Chemical influence on filler caps including sealing, e.g. NBR gasket, NBR O-rings, cork gasket, Viton (RPN 120)
  Risk: The chemical influence on filler cap materials can lead to leakage (inward and/or outward) whereby inward is deemed to be more critical to evaluate.
- Issue 26: Chemical influence on fuel filler neck (NBR rubber material) (RPN 126)
  Risk: The chemical influence on fuel filler necks made from NBR material (aluminium is deemed to be noncritical in that context) can lead to leakage of fuel into the airframe.
- Issue 27: Chemical influence on hoses and pipes (PTFE, NBR, Viton, BR, CR-Chloropren rubber) (RPN 378)
  Risk: If there is an undesirable influence on hoses (also vacuum tubings), this possibly leads to pouring, embrittling or shrinking the material (CR and NBR rather most critically). The consequences are, dependent on the material and on the design, leakages, cross-section contractions and/or wall thickness reductions. The effect could be that the hoses detach from the fittings.
  Note: Similar risk potentials also apply to PE and PA fittings and/or to very flexible hoses made of silicone for aerobatics tanks.
- Issue 29: Chemical influence on sealing materials (O-rings, cork, paper, metal, copper, aluminium, ...) (RPN 200)
  Risk: Possible risks are embrittlement, swelling or decomposition of the basic seal material. The consequence of those would be a leakage and/or air ingress.
- Issue 33: Influence on the operational behavior of the engine (RPN 392)
  Risk: By operating the engine with phase separated fuel impairments of the engine operational behavior may occur. This reaches from rough engine operation up to the stop of the engine. By operating the engine with undeteriorated E-10 fuel its smaller energy content possibly leads to impairments of the engine characteristics. Further on, an increased burn temperature of E-10 could result in a knocking combustion.
- Issue 35: Carburettor icing (RPN 216)
  Risk: Particular in case of adverse weather conditions such as very low temperatures and/or high humidity, carburettor icing due to the increased evaporation enthalpy of E-10 may occur.
- Issue 41: Malfunction of the turbo charger (RPN 120)
  Risk: The slightly increased combustion temperature of E-10 could lead to malfunctions of the turbocharger and consequentially to a loss of engine power.
- Issue 42: Chemical influence on sealing materials (e.g. NBR gasket, NBR O-rings, cork gasket, Viton) within oil and fuel system (RPN 225)
  Risk: Due to the characteristics of E-10 seal materials within the oil or fuel system may be disintegrated. After longer periods of time this could lead to leakages and the danger of fire.
- Issue 43: Incompatibility of rubber pipes (RPN 192)
  Risk: If rubber hoses are not E-10 resistant enough, this possibly leads to embrittling, swelling, or to base material decomposition. The consequences depend on the material,

leakages and cross-section contractions. Leakage air may enter a porous fuel system. Cross-section contractions can impair the fuel flow, in the worst case leading to an engine stop.

  - Issue 44: Incompatibility of aluminum, steel, copper pipes (RPN 224)
    Risk: By corrosion (and/or surface corrosion) and rinsed out deposits (due to solvent characteristic of E-10) filters can be jammed. Base material decomposition, pitting corrosion and increased corrosion within the range of welding seams lead to leakages.
  - Issue 51: Incompatibility of (carburettor) rubber flanges (RPN 126)
    Risk: Rubber flanges (at carburettors) can become leaky by corrosion and/or base material decomposition. Leakage in rubber flanges lead to power loss with turbo engines, to undefined idle speeds with suction engines. By swelling the air intake hose could be loosened from the connecting parts.
    Note: Similar risk potentials apply to air intake hoses.
  - Issue 52: Incompatibility of intake manifold (RPN 210)
    Risk: Corrosion can affect the engine operation in two ways. There is a sensitivity to fuel mixture distribution, or detached particles can be carried into the combustion chamber. Also, the intake manifold can become leaky by corrosion/ base material decomposition, or by swelling/embrittlement of gaskets. Leakage in the intake manifold leads to power loss with turbo engines, to undefined idle speeds with suction engines.

- **Additional research activities required**
  - Issue 7: Corrosion of parts or materials during aircraft storage for longer periods (RPN 360)
    Risk: Due to the increased affinity for water, the probability of a phase separation and consequential contact corrosion (local cell), is larger with E-10 than with MOGAS. With leakages of the fuel system additionally the danger of the chemical attack of surfaces exists (e.g. wood, lacquers, Aerodux 185 glues, covering, tire ...)
  - Issue 10: Blocking filters (RPN 144)
    Risk: Due to the solvent characteristics of E-10 a potential danger consists in the separation of material used in tanks or fuel pipes, which contaminate the fuel. In further consequence it can result in blocking fuel filters.
  - Issue 16: Increased risk for corrosion with aluminum and/or steel tanks. (RPN 189)
    Risk: By contact corrosion (local cell) or by electro-chemical corrosion caused by electrical level sensors surface corrosion may be induced, corrosion of the welding seams (if available) up to decomposition of the base material and/or to the pitting corrosion.
  - Issue 28: Chemical influence on electrical fuel pumps and check valves (RPN 160)
    Risk: Due to the undesired chemical influence on different materials (metals and/or synthetics) fuel leakage may occur, leading to functional deficiencies of the electrical fuel pump.
  - Issue 31: Chemical influence on aluminium fuel coolers (required mainly for (RPN 224)
    Risk: Due to the electro-chemical corrosion or oxide film decomposition a base material decomposition could occur at aluminum fuel coolers. Consequentially this could lead to fuel leakage.
  - Issue 37: Reduced lubrication of the fuel pump (RPN 315)
    Risk: The probably worse lubrication characteristics of E-10 (both in the normal

condition and in phase separated condition) may lead to an insufficient lubrication of the fuel pump, potentially causing a loss of its function.

- Issue 38: Insufficient lubrication particularly at 2-Stroke engines (RPN 270)
  Risk: Particularly with 2-stroke engines with oil-in-gasoline lubrication, the more unfavorable lubrication characteristics from E-10 may lead to a lack of lubrication, which can cause an engine shut down and damage.
- Issue 39: Insufficient lubrication of the engine including auxiliary drives (RPN 180)
  Risk: A blow-by of E-10 may reduce the lubrication of the engine and the associated auxiliary drives (e.g. governor, vacuum pump, hydraulic pump, starter, fuel pump, oil pump, alternator, magneto) too strongly.
- Issue 41: Malfunction of the turbo charger (RPN 120, see above)
- Issue 45: Incompatibility of electrical fuel pumps (RPN 210)
  Risk: The higher conductivity of E-10 can lead to an increased wear of the carbon brush conductors. The (partial) degradation of different materials (metals and/or plastics) may lead to fuel leakages. Rinsed out deposits can block moving parts up to the loss of function of the fuel pump.
- Issue 46: Incompatibility of mechanical fuel pumps (RPN 280)
  Risk: Worse lubrication characteristic of E-10, corrosion, base material decomposition, frozen water in “dead end areas”, can result in a pump outage. Deposits rinsed out by E-10 can block moving parts. Different degraded materials may cause leakages. Especially in the case of diaphragm pumps this may lead to the loss of function.
- Issue 50: Material incompatibility of the fuel return pipe check valve (RPN 126)
  Risk: Corrosion leads to a cross section enlargement in the check valve. This may cause a too low fuel pressure.
- Issue 53: Influence of E-10 on combustion chamber parts (RPN 256)
  Risk: E-10 could lead to increased valve seat wear. E-10 could have negative influence on the engine oil. Bad oil can cause deposits in the valve guide. Malfunctioning of the valve guides results in loss of engine power.
- Issue 54: Inappropriate spark plugs (RPN 144)
  Risk: Increased electrode consumption, inapplicable heat rating, leakage on sealing ring, inapplicable isolator.
- Issue 55: Incompatibility of fuel injectors (RPN 280)
  Risk: Corrosion on the injection nozzle causes ill defined injection volumes. Further corrosion, base material decomposition, swelling or embrittlement can block moving parts, which causes a malfunction of the fuel injector.
- Issue 56: Incompatibility of fuel rails (RPN 240)
  Risk: Corrosion on the fuel rail causes cracks or leakage. This can entail fuel loss. Note: Similar risk potentials apply to fuel distributors (in fuel injection systems).
- Issue 57: Incompatibility of fuel pressure regulator (RPN 168)
  Risk: Electro-chemical corrosion can cause base material decomposition. Leakages can result on the one hand from surface corrosion (at aluminum or steel components), on the other hand by swelling or embrittlement of seals.
- Issue 58: Incompatibility of quantity distributor (RPN 144)
  Risk: A malfunctioning of the quantity distributor can be caused by a leaky diaphragm or from base material decomposition/corrosion. Causes for a leaky diaphragm can be embrittlement, swelling or attack on base material.

  - Issue 59: Incompatibility of diaphragm (carburettor, pressure regulator, ...) (RPN 168)
    Risk: Possible risks exist in embrittling, sources or base material decomposition of the diaphragm material, which would entail leakages and/or malfunctioning (e.g. supply pressure of the fuel pump cannot be held anymore, ...).
  - Issue 60: Incompatibility of sensors (RPN 140)
    Risk: Probably sensor lines and/or sensors are not compatible with E-10. Additionally there is a potential risk in “dead end lines” where the fuel always remains the same. If there is an accumulation of water (due to the affinity of E-10 for water) inside those "dead end hoses" the danger of freezing or even corrosion exists which consequentially could lead to wrong set values for the engine management system. Note: Similar risk potentials apply to fuel totalizers
  - Issue 61: Influence of E-10 on engine oil (RPN 160)
    Risk: An ethanol share in the engine oil could probably extract certain components out of it. Also, due to the affinity of E-10 for water, water can intrude. Thus the engine oil lubrication characteristics could deteriorate up to the point of malfunction. Reduced cooling characteristics or corrosion prevention properties (for combustion chamber parts, crankshaft drive, valve train) are possible. Note: Particularly at 2-stroke engines with oil-in-gas lubrication the influence of E-10 is deemed to be most critical.

- **Resolvable by awareness campaign**
  - Issue 3: Aircraft fuelling by using fuel from cans refilled at petrol stations (RPN 720)
    Risk: The risk is to use fuel that is either contaminated by the can itself or has a poor quality because of mixed or long stored fuel. Longer stored E-10 bio fuel can be phase separated and influence the operation of the aircraft.
  - Issue 4: Mixing fuel products during fuelling of the aircraft (RPN 729)
    Risk: Potential risk is to have a remaining quantity of fuel within the aircraft tank and to refill with another product (e.g. mix AVGAS or E-0 with E-10) that could lead to operational problems of the engine. Effects of ethanol admixtures (especially boiling properties) do not behave linearly and thus unexpectedly.
  - Issue 5: Insertion of water during fuelling of the aircraft (RPN 729)
    Risk: The potential risk is to insert water before or during the fuelling process by e.g. counter-sunk filler caps or damaged gaskets. Due to the water affinity of E-10 a phase separated fuel influencing the operation of the engine is likely.
  - Issue 6 : Sparking at refuelling (RPN 180)
    Risk: The potential risk consists of the fact that due to the assumed smaller danger of the sparking with E-10 the pilots probably abstain from electrical grounding during refuelling despite existing regulations. In consequence the danger of sparking is higher than by fuelling MOGAS.
  - Issue 14: Higher vapour pressure due to mixing of different fuels (Avgas and Exx) (RPN 378)
    Risk: Due to non-linear mixing effects the vapour pressure of a mixture of E-10 and a non-alcohol-admixed gasoline may surpass that of any single mixture component, leading to a reduced boiling point of the fuel. This can induce an unexpected vapour lock at usual operational temperatures.
  - Issue 17: Deposits at the tank bottom may get rinsed out (RPN 168)
    Risk: Due to the increased solvent characteristics of E-10 a potential danger consists in material deposits at the tank bottom that could be rinsed out and contaminate the fuel system. In further consequence it may result in blocking fuel filters.

  - Issue 32: Incompatibility of covering material and lacquering of skin of wing/body of aircrafts (RPN 112)
    Risk: During the refuelling procedure a decomposition of material coverings or lacquer may be induced by overflowing E-10 fuel. This can lead to aircraft strength problems.
  - Issue 34: Increased fuel consumption (RPN 192)
    Risk: Due to the smaller energy content of E-10 or because of inappropriate ignition timing an increased fuel consumption may be observed which consequentially leads to a reduced range of the aircraft.
  - Issue 35: Carburettor icing (RPN 216, see above)

- **Enforcement of operational / maintenance procedures**
  - Issue 1: Storage of fuel within tank top after production (RPN 108)
    Risk: The potential risk is to insert water during storage caused by potentially lacking operational management. Due to the chemical affinity of E-10 to water this could lead to a phase separated fuel that could influence the operation of the aircraft.
  - Issue 2: Mixing fuel products during filling the tank top (RPN 108)
    Risk: The potential risk is to mix different fuels in tank tops caused by human failures, especially at older tank tops that are not equipped with modern detection methods and do not comply with quality assurance processes.

- **Recommended regulatory action**
  - Issue 8: Cross-section diminution in fuel pipes (RPN 378)
    Risk: By the characteristics respectively the consequences of phase separated E-10 fuel, perhaps the danger of inward expanding rubber pipes exists, which can lead to a cross-section contraction and in further consequence to an influence of the engine operation.
  - Issue 9: Leakages within the fuel system (RPN 160)
    Risk: Probably the solvent characteristics of E-10 lead to decomposition of the base material, which could result in fuel system leakages and in further consequence to a potential fire risk.
  - Issue 15: Insufficient pre-heating of the intake air (RPN 189)
    Risk: Due to the increased evaporation enthalpy of E-10 a too low intake air temperature may be encountered, which could result in carburettor icing and consequentially lead to an engine shut down.
  - Issue 18: Incompatibility of composite material (CFK/GFK) (RPN 168, see above)
  - Issue 19: Embrittlement of fuselage tanks made of blown PE-HD or PE-LD (RPN 168, see above)
  - Issue 20: Swelling of NBR rubber material used for tanks (RPN 126, see above)
  - Issue 21: Difficult draining at NBR tanks (RPN 240, see above)
  - Issue 22: Damage of tank interior coatings (RPN 216)
    Risk: The solvent characteristics of E-10 in connection with mechanical load may induce a damage of the tank interior coatings. This could lead to a decomposition of the base material up to structural disruptions especially for GFK integral tanks.
  - Issue 23: Decomposition of the tank sealing material (RPN 192, see above) Issue 24: Chemical influence on the tank ventilation (aluminum, plastic or steel pipe placed into the air flow) (RPN 192, see above)

- Issue 25: Chemical influence on filler caps including sealing (e.g. NBR gasket, NBR O-rings, cork gasket, Viton) (RPN 120, see above)
- Issue 26: Chemical influence on fuel filler neck (NBR rubber material) (RPN 126, see above)
- Issue 27: Chemical influence on hoses and pipes (PTFE, NBR, Viton, BR, CR-Chloropren rubber) (RPN 378, see above)
- Issue 28: Chemical influence on electrical fuel pumps and check valves (RPN 160, see above)
- Issue 29: Chemical influence on sealing materials (O-rings, cork, paper, metal, copper, aluminium, ...) (RPN 200, see above)
- Issue 33: Influence on the operational behavior of the engine (RPN 392, see above)
- Issue 42: Chemical influence on sealing materials (e.g. NBR gasket, NBR O-rings, cork gasket, Viton) within oil and fuel system (RPN 225, see above) Issue 43: Incompatibility of rubber pipes (RPN 192, see above) Issue 44: Incompatibility of aluminum, steel, copper pipes (RPN 224, see above)
- Issue 47: Incompatibility of carburettor (RPN 240)
  Risk: By corrosion (and/or surface corrosion) and rinsed out deposits (due to solvent properties of E-10) filters can be blocked. Base material decomposition, embrittlement and/or swelling lead to leakages. In particular, leakages at the diaphragm or at the float needle valve may cause a malfunctioning of the carburettor.
- Issue 51: Incompatibility of (carburettor) rubber flanges (RPN 126, see above)
- Issue 52: Incompatibility of intake manifold (RPN 210, see above)
- Issue 55: Incompatibility of fuel injectors (RPN 280, see above)
- Issue 56: Incompatibility of fuel rails (RPN 240, see above)
- Issue 57: Incompatibility of fuel pressure regulator (RPN 168, see above)
- Issue 58: Incompatibility of quantity distributor (RPN 144, see above)
- Issue 59: Incompatibility of diaphragm (carburettor, pressure regulator, ...) (RPN 168, see above)
- Issue 60: Incompatibility of sensors (RPN 140, see above)

6.1.3 FMEA Conclusions

The FMEA has lead to a reassessment of the importance and fault potential of the gasoline delivery path. While the logistics of established distribution paths from refineries to individual gasoline stations seem mostly uncritical the individual, unreflected handling of the comparatively small amounts of gasoline needed for aircraft operation creates new threats when using ethanol-admixed fuels. Due to the altered properties of the new ethanol-admixed gasolines a differentiated view is required on potential non-conforming individual handling procedures, caused by lack of threat awareness.

The associated individual threats (phase separation, vapour locking, icing, material compatibility) were confirmed on the parts and functional levels by an expert group. The span of risks covers the range of “just a nuisance” to “deadly dangerous if not adequately and pro-actively handled”.

For the major threats a clustering of recommendations for a further treatment of the identified issues has been given. Some issues should be resolvable by raising public and professional awareness by respectively launched information campaigns after creating appropriate sets of information material.

Additional authority actions are recommended especially for the field of the compatibility of the aircraft's constructive materials. A general reassessment of fuel compatibility is suggested for all materials potentially coming into contact with new ethanol-admixed gasoline types. This process may be alleviated if respective choices of materials are backed by comparable choices in the automotive industry but should in general be mandatory.

The physico-chemical property changes of ethanol-admixed gasolines relative to former hydrocarbon-only types are rather intricate in the special light of usage in aircraft. Therefore not all experiences gathered from vehicle usage can be transferred to aviation. Accordingly, new research activities have been identified that should pinpoint qualitatively known threats in a more quantitative manner.

6.2 Task Spanning Activities for Experimentation

The investigations performed in the SIOBIA project required preparatory actions and anteceding logistics affecting several experiments. Most notably the basic object of experimentation are concerned (Fig. 25): AcUAS' flying lab, the MORANE was equipped with various sensors. A ROTAX 912 ULS engine was adapted to an engine rig and also equipped with several sensors and an exhaust gas analysis. Last but not least, a custom test rig for vapour bubble generation assessment was constructed, built, and operated. All experiments were accompanied by chemical analyses performed by PETROLAB.

Figure 25: *Principal experimentation objects put to work for the* SIOBIA *experiments.*

The general preparations undertaken are described in detail in Appendix D, pages 196ff.

6.3 Analysis of Phase Separation Hazard (T 2a, 2c)

6.3.1 Methodology and Approach

The threat of a gasoline phase separation, even though always based on the presence of water in the fuel, is a multi-facetted one. As long as the water content is not surpassing certain limits it is tolerable. The limit depends on several boundary conditions that are investigated with respect to their importance in several experiments, each of them highlighting a single of those facettes.

If an aircraft ascends to its service ceiling the fuel becomes cold. As shown in Sect. 5.1 the water carrying ability is strongly dependent on the fuel temperature. Therefore the cool-down effect is experimentally investigated in a flight experiment (Sect. 6.3.2).

Even if at the start of a flight there is not enough water in the tank to cause a phase separation the aircraft might collect additional liquid water during the mission if it is flown through condensing water vapour, i.e. fog, clouds, or rain. It may even, when climbing down from a cold service height, condense water vapour out of the ingested tank air into the fuel. Therefore a throughput measurement has been performed (Sect. 6.3.3).

If an aircraft is put away for a prolonged time the usual habit is to fill its tanks to prevent corrosion. As ethanol-admixed gasoline is at least slightly hygroscopic this may lead to a slow but steady intake of environmental water and lead to raised solved water contents that only appear at a tank cool-down, or to an actual incident of phase separation even before the start. The composition change for differently stored tanks is therefore investigated in Sect. 6.3.4.

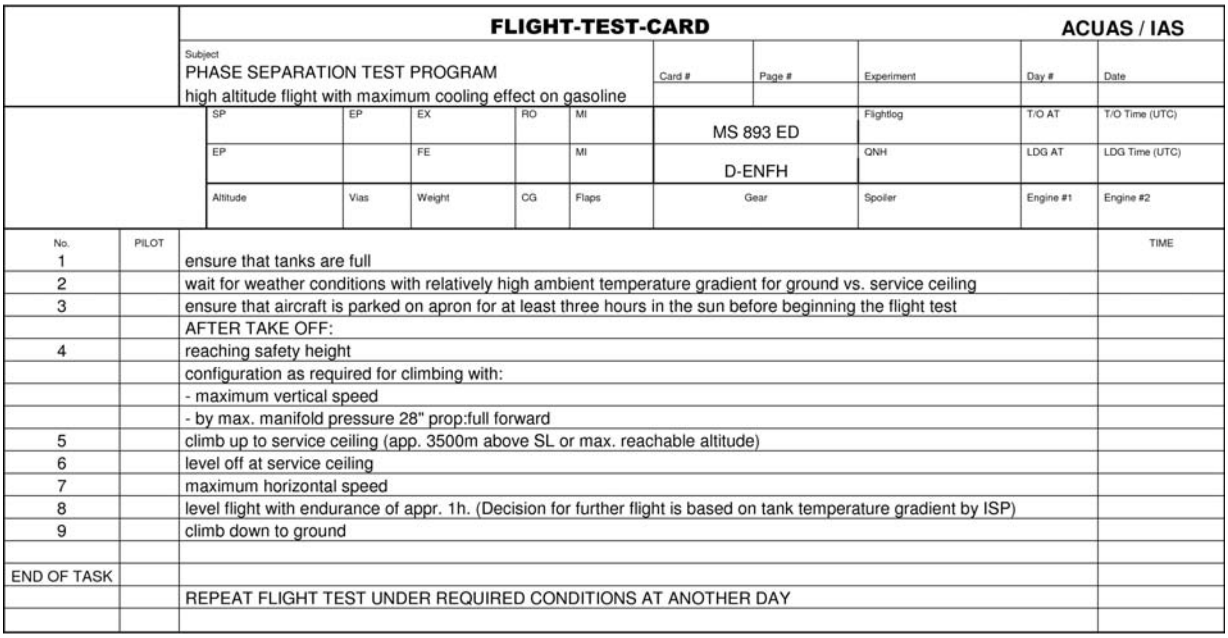
6.3.2 High-Altitude Flight Experiments for Cool-Down Experiments Boundary Conditions Determination (T 2a)

The cool-down experiment performed withe AcUAS's MORANE aims at a quantitative determination of the amount of heat drained from the fuel tanks into the atmosphere during a flight as long as possible under coldest conditions, at the same time striving for the largest possible temperature gradient between hot airfield and cold service condition.

The monitoring instrumentation (see section D.2, page 200) is used for the assessment of this purpose again. The respective flight test card (fig. 26) describes the foreseen operation.

The desired boundary conditions should ensure that the fuel in the tank experiences the largest possible cool-out during a flight mission. Therefore the aircraft is parked on the apron in the bright sunlight of a warmest possible day for some hours before the mission itself is flown. Fig. 27 shows the temperature development during this flight for the sensors positioned at the tank surface.

The temperatures measured at the bottom and the side of the tank (see sensor positions, Fig. 90) always are in good agreement until about the start of the descent. In the beginning until about 4000 sec they are well above the ambient tropospheric temperature derived from the standard temperature vs. elevation model. During the stay at service ceiling (4000 sec to about 5800 sec) the tank surface temperatures approach the ambient conditions but do not completely equilibrate. It is assumed that this effect is caused by the rather low exposition of the MORANE's tank to the surrounding air, opposite e.g. to aircraft equipped with wet wings. The thermo-element at the lower side of the tank exhibits a different behaviour. Up to 2400 sec its temperature readout is very much the same as that of the other sensors. After this time it separates and remains clearly above the others. Apart from the period 2400 to 3800 sec (see below) the cool-out follows its own



FLIGHT-TEST-CARD **ACUAS / IAS**

Subject
PHASE SEPARATION TEST PROGRAM
high altitude flight with maximum cooling effect on gasoline

Card # | Page # | Experiment | Day # | Date

SP | EP | EX | RO | MI | Flightlog | T/O AT | T/O Time (UTC)

MS 893 ED

EP | FE | MI | QNH | LDG AT | LDG Time (UTC)

D-ENFH

Altitude | Vias | Weight | CG | Flaps | Gear | Spoiler | Engine #1 | Engine #2

No.	PILOT		TIME
1		ensure that tanks are full	
2		wait for weather conditions with relatively high ambient temperature gradient for ground vs. service ceiling	
3		ensure that aircraft is parked on apron for at least three hours in the sun before beginning the flight test	
		AFTER TAKE OFF:	
4		reaching safety height	
		configuration as required for climbing with:	
		- maximum vertical speed	
		- by max. manifold pressure 28" prop:full forward	
5		climb up to service ceiling (app. 3500m above SL or max. reachable altitude)	
6		level off at service ceiling	
7		maximum horizontal speed	
8		level flight with endurance of appr. 1h. (Decision for further flight is based on tank temperature gradient by ISP)	
9		climb down to ground	
END OF TASK			
		REPEAT FLIGHT TEST UNDER REQUIRED CONDITIONS AT ANOTHER DAY	

Figure 26: *Flight test card developed for experiments on heat drain from the tanks due to a long-term flight at coldest conditions after a start from a warm airfield, potentially leading to a phase separation condition*

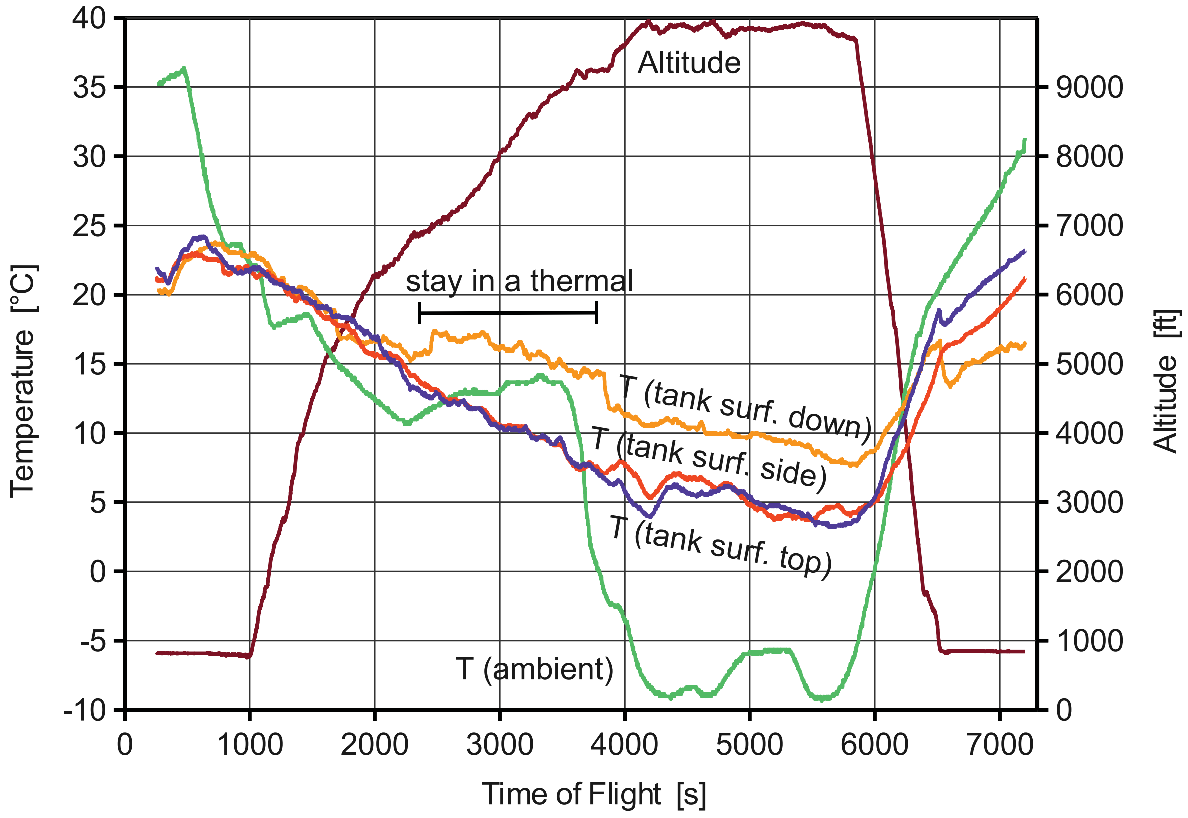


Figure 27: *Temperature developments at different positions on the fuel tank surface hull of the* Morane

curve. After 4000 sec it very much resembles the course of temperatures recorded for the upper thermo-element inside the fuel tank (Fig. 28) within a margin of about 2 degrees.

The upper element, while in close agreement with the lower one inside the tank up to 3600 sec,

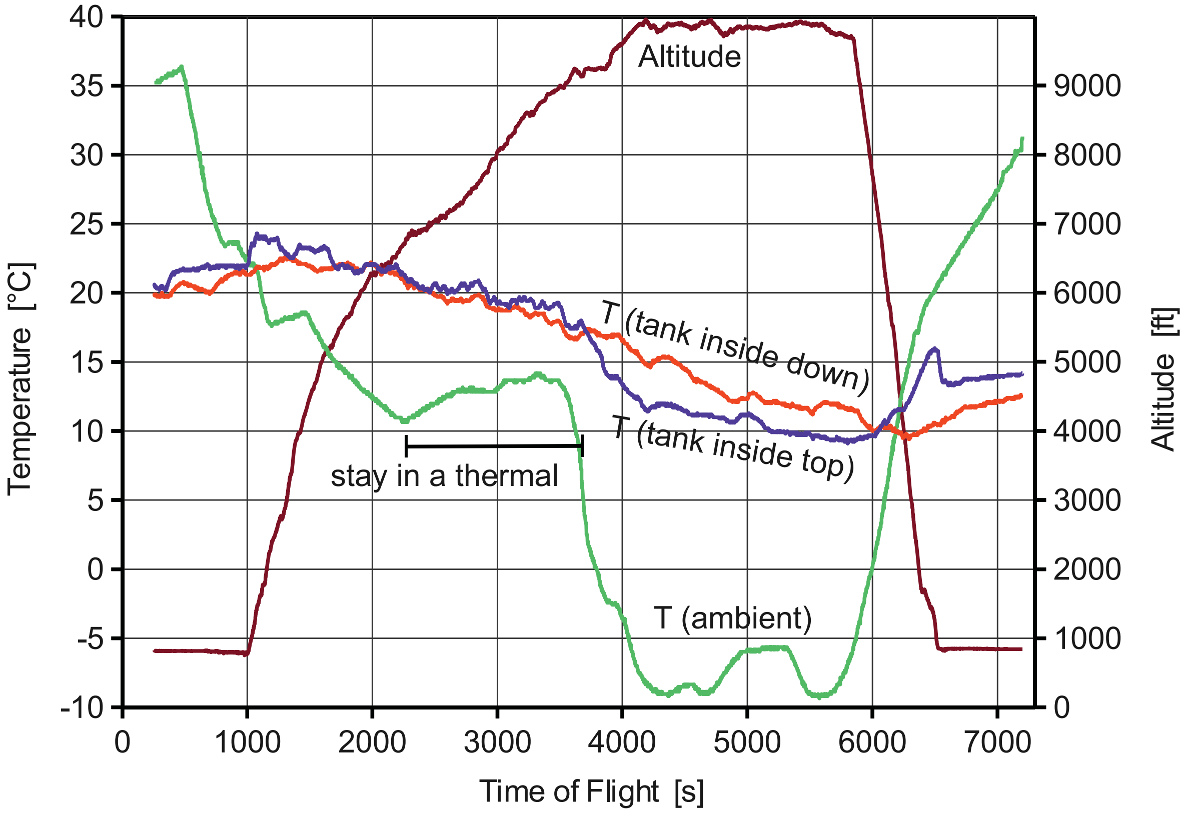


Figure 28: *Temperature developments at different positions inside the fuel tank of the* MORANE

separates for the later stage of the flight and drops below the latter's readout until some time point during the descent. This effect may well be interpreted as the upper thermo element surfacing for the state of being immersed in fuel up to about 3600 sec. Starting at that time it experiences no longer the warmth of the remaining fuel but mainly the temperature of the air slowly passing the fuel tank by its venting system.

During the descent the MORANE enters consecutively warmer atmospheric strata. Accordingly the relative temperature readouts of the two inner thermocouples change to the opposite direction, starting at the crossover point at about 6200 sec. While the lower thermocouple, still immersed in liquid fuel, heats up only slowly even when the aircraft is already on the ground the upper air-borne thermocouple inside the tanks shows a distinct temperature peak while ingesting the warm air at the airfield, before dropping again to a heat-up curve comparable to the lower thermocouple, but at an about two degrees higher level.

The ambient temperature given in the two diagrams is measured at the wing, hence far away from the engine. It shows that the aircraft stayed in a thermal for a while (2400 sec to 3800 sec) to support its ascend to service ceiling. Accordingly the other temperature profiles are affected as well. There is no decisive explanation, though, why this effect is predominantly visible in the temperature data taken for "fuel tank surface down".

6.3.3 Tank Air Throughput During a Flight (T 2a)

The humidity in an aircraft tank may stem from different sources. Both the water already present at the start of an aircraft and that picked up during the flight by condensation of atmospheric humidity may contribute. As the temperature of the fuel, the temperature of the air, the humidity of the air (clear air, clouds), the pressure depending on altitude and the fill grade of the tank change

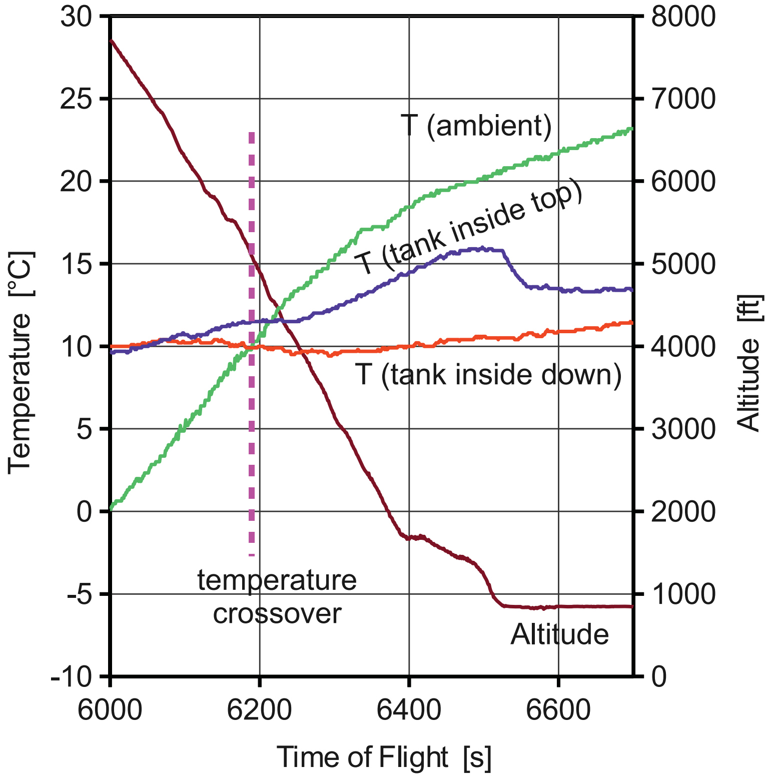


Figure 29: Temperature crossover of fuel temperature, and temperature of ingested air inside the fuel tank of the MORANE.

significantly during a flight there is no a-priori knowledge about the potential humidity exchange direction for this period. Therefore the ingestion was monitored on one of the MORANE's tanks during a flight mission.

First a second inspection of the temperature profile of the respective flight is made (Fig. 29, being an enlarged view of the descent phase of the complete profile shown in Fig. 28). Starting at about 6200 sec the temperature of any ingested air is higher than that of the fuel inside the tank. About 50 sec later the ambient temperature even surpasses the value shown by the unprecipitated temperature sensor in the empty tank space. As a consequence the air in this space is cooled down by the residual liquid fuel, being about 10 degrees colder. At about 6530 sec a distinct temperature drop of this readout is visible, presumably caused by the stopping ingestion of the warm ambient air as the aircraft has been landed.

Fig. 30 shows that during the whole flight without any exception an *ingestion into the tank* is observed. Especially the descent phase is interesting in this respect: Even though the ambient becomes gradually warmer, heating up a rather empty tank and its mostly gaseous content, this effect does not suffice to prevent further air from streaming into the volume. Rather, a precipitation of sufficiently humid ingested warmer air may take place for all times after the temperature crossover point until the aircraft reaches ground. The respective problematic range is highlighted as red region in Fig. 30.

6.3.4 Determination of Compositional Changes in Gasolines Stored in Aircraft Tanks for Prolonged Periods (T 2c)

Little is known about the composition change of the multi-component mixture "gasoline" during a vented storaging as it happens when an aircraft is parked in the hangar or on the apron with a

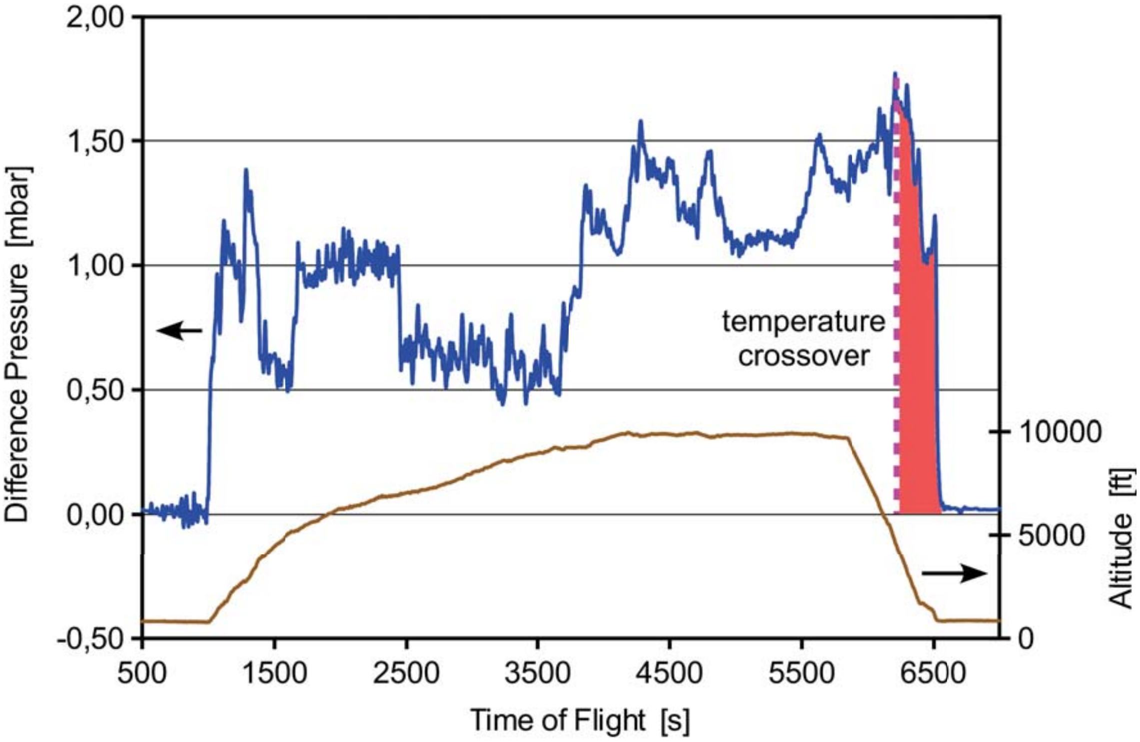


Figure 30: *Air ingestion by tank ventilation, measured during a long-distance flight in one of* MORANE*'s tank venting inlets. A positive value of the difference pressure indicates a flow into the tank. Humidity absorption endangered interval is painted red. For discussion see text.*

filled fuel tank. Even in the mineral oil industry such investigations are not usual as the handling procedures aim at relatively fast consumption of always freshly produced fuel.

With respect to ethanol admixed fuels several possible additional effects may happen:

- The hygroscopic behaviour of the ethanol content may draw in humidity from the air vented into the tank by temperature changes.
- The relatively low vapour pressure of the pure ethanol may lead to an increase of its share in the mixture due to an evaporation of the lighter gasoline components, or, on the contrary,
- the non-Raoultian behaviour of the sparse ethanol molecules in the gasoline environment may lead to their purge-out from the solution, resulting in decrease of the ethanol content.

To gain information on this process rather relevant for the General Aviation fleet an experimental long-time storaging is performed. In cooperation with Gomolzig Flugzeug und Maschinenbau GmbH, Schwelm, custom example tanks are fabricated exhibiting a surface/volume ratio comparable to the usual tanks encountered in smaller aircraft (fig. 31).

These tanks, sized approx. 30 l each, are filled and stored with Gomolzig in different ways, with the severest possible imposed change in mind. As the tank venting is supposed to be predominantly responsible for the composition change effect all tanks are filled to about 50 % of their volumes. The following table summarizes the boundary conditions:

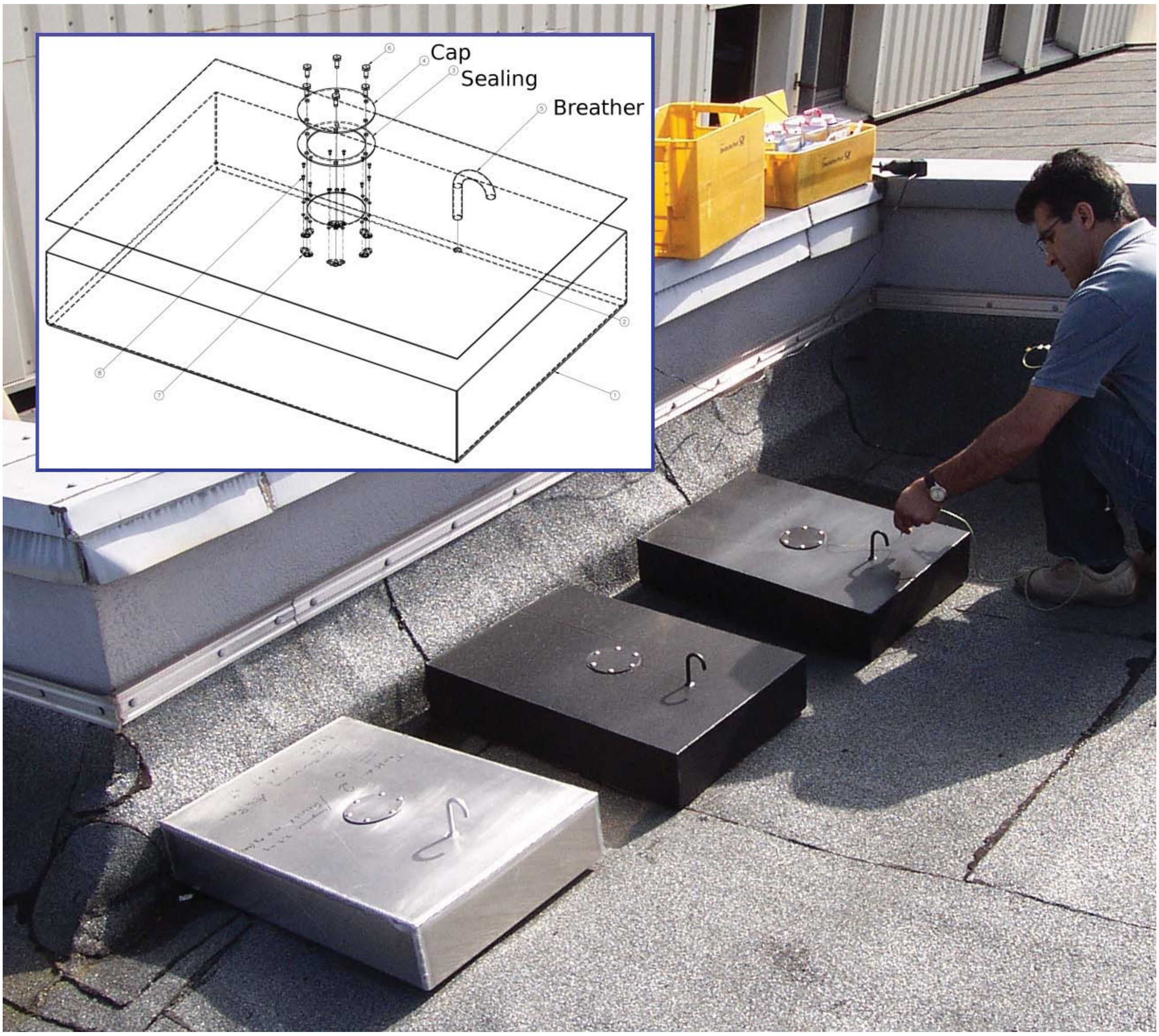


Figure 31: *Custom made aircraft wing tank simulation vessels with comparative volume/surface ratio, used for long-term storaging experiments. Tanks were donated and stored by Gomolzig Flugzeug und Maschinenbau GmbH, Schwelm. Shown are the three exposed tanks stored on the roof.*

protected storage in hangar	stored on building roof	
	black finish	bright finish
E-10	E-10	E-10
E-0	E-0	

Tanks have been filled and positioned at their locations on July, 8th 2009. Until the due date of this report (the storage experiment is continued beyond) three weighings of contents have taken place. The results are shown in Fig. 32.

Clearly, the storage inside the hangar results in the least loss of weight. Here the difference between E-0 and E-10 gasoline is negligible. The picture changes significantly for the tanks stored on the building roof that are exposed to the usual changing temperatures, bright sunlight, precipitation, etc.. Here the bright tank filled with E-10 is the least influenced, in good agreement with the assumption that imposed temperature changes should play the main role with respect to

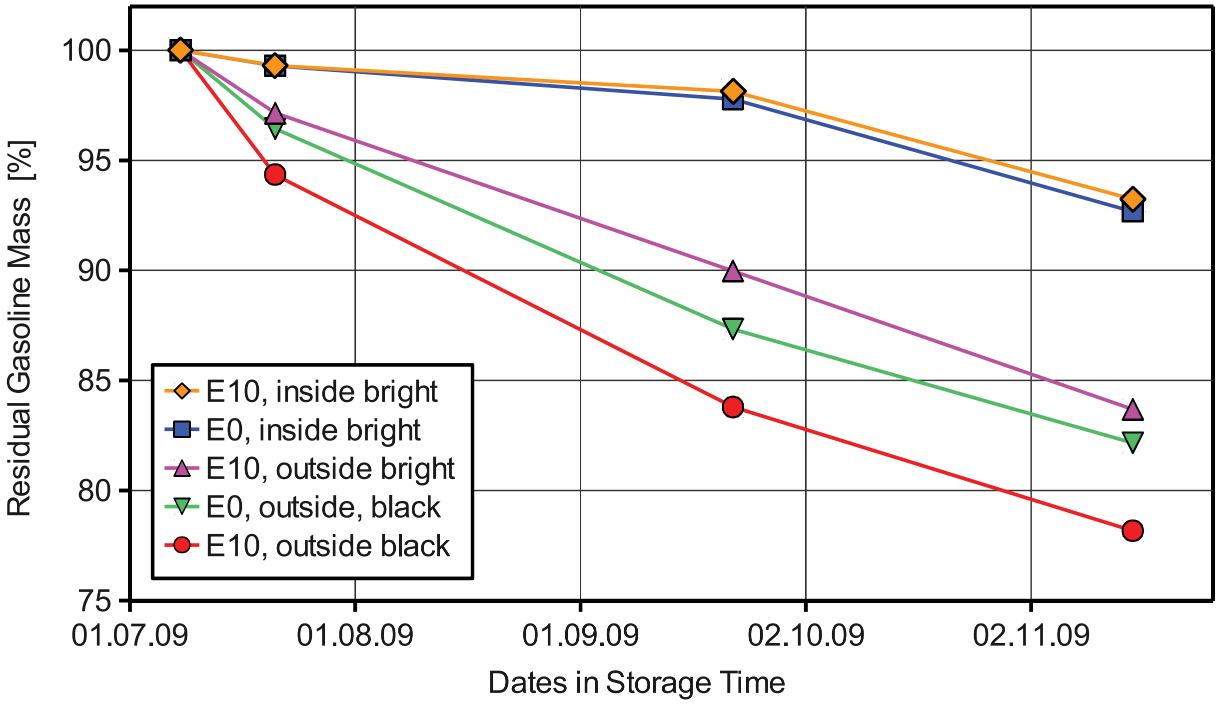


Figure 32: *Normalized residual gasoline masses observed for the different storage tanks.*

evaporation losses. After the storage period the black E-10 filled tank has lost much more of its former content.

In direct comparison of identical outside storage conditions the E-0 proves to be less volatile than the custom mixed E-10 gasoline. It should be kept in mind, though, that the custom mixing itself may have caused the volatility increase, as the non-adapted gasoline basestock (see Sect. 5.2) may have contributed to the effect.

Probes of the various stored gasolines, taken at intervals during the storage period were analyzed by PetroLab, Speyer, with respect to their compositional changes. The following tests were performed:

- density at 15 °C, according to EN ISO 12185
- sulphur content, according to EN ISO 20884
- bromium no., according to DIN 51774-1
- water content, according to EN ISO 12937
- distillation curve, according to ISO 3405
- composition by gas chromatography, according to DIN 51413 (aromats) and EN 1601 (oxygenates)

As a general observation no dramatic and indicative general compositional changes depending on ethanol content could be observed in this comparison. Slight changes in the evaporation characteristic and the densities are observed but vary inconclusively with storage manner and basic composition. A very slight tendency of the evaporation onset to higher temperatures with increasing storage time may be deduced but would have to be certified by a significantly larger statistical investigation.

An interesting yet constant result is the ethanol content over time: No E-10 probe showed a systematic change of ethanol content over time, even though the storage conditions were quite differing. It may be concluded that no ethanol-specific evaporation was induced in spite of the general rise of the vapour pressure (see Sect. 6.5.4) of the custom mixed gasolines. As a result the compositions seem stable over a longer period as may be the case in a small aircraft parked in a hangar and not operated e.g. during winter season.

The development of the water content of the probes does show clear-cut tendencies, although again not as systematic as anticipated, see Fig. 33.

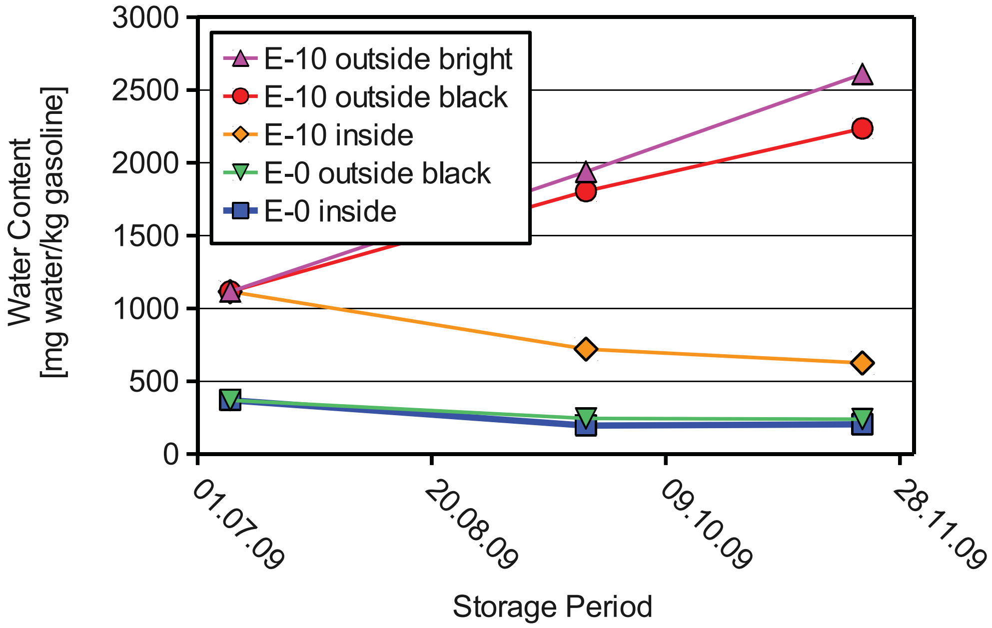


Figure 33: *Development of water contents for gasoline tanks stored under differing ambient conditions. Values represent always* solved water, *since a phase separation of the contents has not been observed.*

The E-0 probes seem rather unaffected by ambient humidity conditions as both probes for inside and outside storage even decrease their water contents slightly. This is expected, enviewing the general effect of water intaking: According to the delivery certificate and the subsequent analysis by PetroLab there is no potentially hygroscopic component in the mixture.

While the outside storage of the E-10 gasolines shows a significant increase in water content the tank stored inside even indicates a decrease. This points to a rather low hygroscopic tendency of the gasoline solved ethanol if the ambient humidity is moderate and the environment leveling out stronger temperature changes, as is the case in protected storage places. For a qualitative clarification of this process a consideration of the outside/ambient humidity and temperature developments of a nearby town (Fig. 34) may be taken into account: While in the summer months the average humidity stays at about 60 % it rises to about 90 % in winter time. Over the same interval the outside temperature decreases from about 24 °C to 10 °C. The “inside” storage location was a hallway of a larger production facility that would both raise and equilibrate the ambient temperature for the tanks relative to the outside conditions. While in summertime the large roller doors are frequently open for longer periods, thus creating ample equalisation with environment they are mostly kept shut in wintertime for energy conservation and comfort reasons. At the same time the facility’s interior is heated. This in turn, combined with the necessary air throughput for

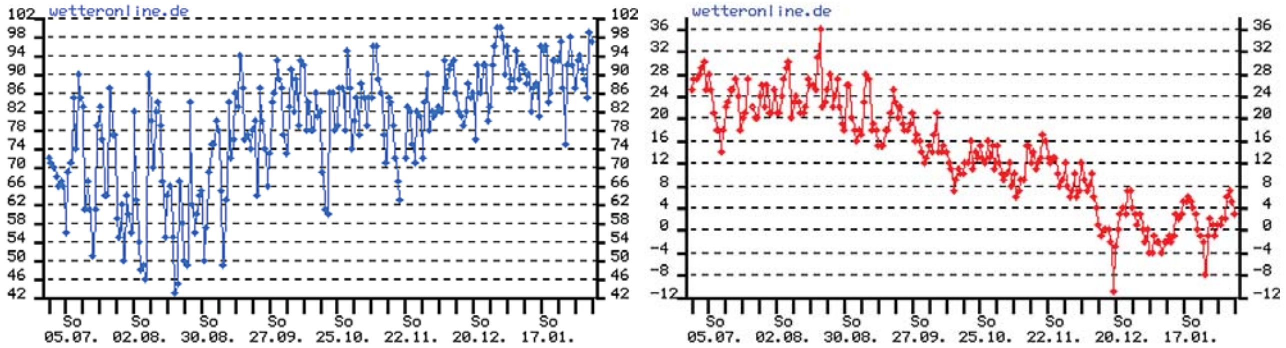


Figure 34: *Humidity (rel. humidity in %, left) and temperature (in °C, right) development for the storage time period in Dortmund, a town in the vicinity of the storage location in Schwelm. Source: Historic data provided by* WetterOnline.De

an active production facility reduces the ambient humidity significantly. It may be assumed that the relatively low humidity at the storage place is kept about at a more or less constant level of some 50 % or even less.

Different results have been reported for tanks of boats not operated in winter season. Here phase separated gasolines have frequently been observed [23] and form even an objective of novel, yet not very effective, remedy product designs. In comparison to the SIoBIA storage experiment the tanks of such boats are both unheated and subject to a near to 100 % relative humidity due to their immediate vicinity to open water.

6.3.5 Onset of Hazing in Custom Mixed Ethanol-Containing Gasolines (T 2a)

If too much water is present in the gasoline used in an aircraft the temperature dependency of the ternary mixing gap (see Sect. 5.1) may cause a phase separation in the aircraft tank cooling down. A first sign of immediate danger is the onset of a haze in the fuel, indicating a microscopic separation of a second water/ethanol phase, still spread out as a suspension in the beginning but likely to coalesce to a heavier bulk phase which can not be burnt in the engine.

PetroLab investigated the onset of hazing depending on ethanol content, water content, and temperature of the fuel. These measurements were carried out for E-0 to E-15 probes with temperature ranges down to -70 °C. Starting at higher temperatures a given probe with a fixed water content is cooled down until the point of a non-evanescent hazing is reached. This procedure resembles the practical case of an aircraft performing a high-altitude flight that cools down its fuel in the wing tanks with an constant amount of previously ingested water.

In parallel a very limited hazing control experiment was carried out by AcUAS. Here the methodology was chosen differently from the PetroLab experiment: Thermally equilibrated probes at 21 °C were subject to increasing amounts of admixed water, while again observing the onset of a non-disappearing hazing. This procedure resembles the practical case of an aircraft accumulating additional water during a flight at roughly constant temperature, e.g. by tank air ingestion condensation or intrusion of liquid water through a leaky filler cap.

The results of both experiments are shown both in Fig. 35 in a representation resembling the one of DGMK (p. 40). The onset of hazing in the water admixture experiment at 21 °C is rendered as unconnected orange symbols for the individual samples (E-0 to E-15) tested. The results of the cool-down tests are given as series of connected symbols for the different ethanol admixture levels.

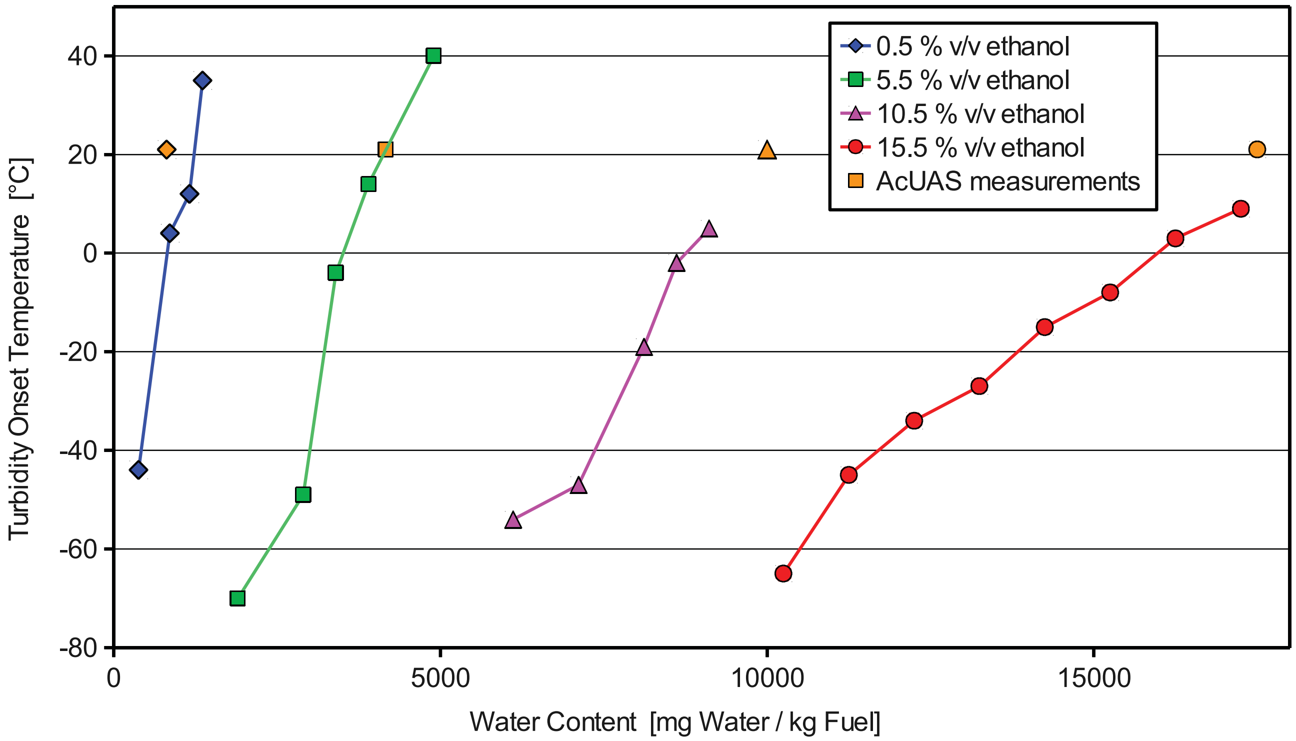


Figure 35: *Onset of phase separation hazing in water admixture (orange symbols,* ACUAS *measurements) and cool-down (connected symbols,* PETROLAB *measurements) experiments.*

First it may be concluded that the independently performed experiments agree surprisingly well with respect to the reported onset of the phase separation originating hazing. They almost meet for every ethanol content at the 21 °C temperature level. This points to a rather small hysteresis with respect to the differing separation schemas already discussed in Sect. 5.1. Accordingly, the same limits may be taken as valid for both lack of potential to absorb additionally ingested water and the danger of spontaneous disintegration into two phases in case of a temperature drop in an aircraft tank.

There is a certain discrepancy when comparing the experimental results with those reported in the literature [28], also shown in Sect. 5.1, p. 40: the DGMK numbers reported for water bearing are significantly lower. They reach roughly half the values obtained in the SIOBIA experiments, with deviations from this value over the investigated temperature range. Several causes for this difference may be sought. First, the base gasoline may be different from the one taken for the SIOBIA experiments. As there is no otherwise reported systematic survey of base gasoline composition influence this difference must be regarded as an open question. Second, the determination procedure reported in [28, p. 38] may not exclude a thermal non-equilibrium, with a certain gradient in the used test vessels. As the test vessels are cooled down by heat extraction through their walls the centrally positioned thermometer may not represent the correct readout, and a hazing near the walls may have been interpreted as an earlier disintegration.

While the AcUAS experiments on water admixture should share the same level of limited precision, although the constant temperature should rule out a thermal non-equilibrium, the systematic experiments by PETROLAB were performed in a custom circulatory thermally equilibrated device with a defined objective readout procedure. Thus potential non-equilibrium effects should have been ruled out as effectively as possible.

The acquired data allow a joint three-dimensional representation and the derivation of a bended interpolation plane (Fig. 36). The plane was computed for an assumed functional dependence of

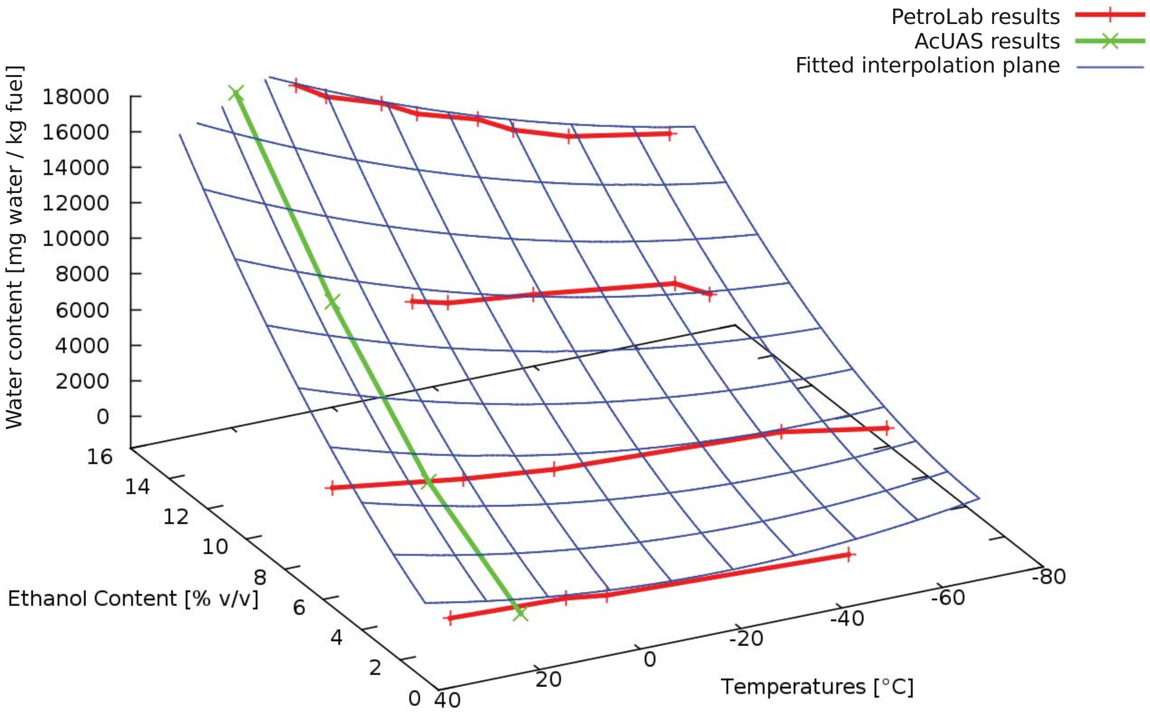


Figure 36: *Derivation of a three-dimensional approximation plane for the water bearing capability, taking into account the different ethanol admixture levels and gasoline temperatures. Combined display of* PETROLAB *(red lines, "+") and* ACUAS *(green line, "x") results, together with derived plane (blue).*

the limit water bearing capacity $w_l(T, x_{ethanol}) = c_1 + c_2(T + c_4) + c_3(T + c_4)^2 + c_5(x_{ethanol} + c_7) + c_6(x_{ethanol} + c_7)^2 + c_8(T + c_4)(x_{ethanol} + c_7)$. If a more detailed cross-correlation of temperature and ethanol content is assumed by introducing further product terms in T and $x_{ethanol}$ the interpolation would approximate the measurement data even better. Since the scope of the experimentation was rather limited and does not take into account further potentially important factors as base fuel composition and tank surface influence the current approximation should not be taken as a reference for a safety limit setting, though.

6.3.6 Phase Separation: Conclusion (T 2a)

Although the tank of the MORANE is thermally rather insulated, compared e.g. to a wet wing system, it cools down significantly during a longer flight. Accordingly, there is an actual threat of phase separation if the gasoline contains a significant amount of water. This water, even if not already present at the time of start, may enter the fuel tank by its venting opening. This danger exists despite the fact that low rates of water ingestion are observed in rain conditions, even if the aircraft traverses clouds or stronger rain. The amount of potential humidity condensation during the descent phase from cold and dry heights to humid warm air in lower strata should be scrutinized more thoroughly still. It will depend on the amount of air ingested by the tank venting system, the specific crossover temperature gap encountered during the last phase of descent, and the humidity of the air.

A tendency to an accumulation of water even in stronger ethanol-admixed gasolines (E-10) is only recognizable if the storage container (i.e. filled tank of the aircraft) is left in the open. If it is parked in a temperature change equilibrating hangar this effect is expected to be strongly reduced.

Experimentally determined water bearing capacities are larger than anticipated from former literature, although no principal clearance can be given, and the issue by itself remains critical. A phase separation in a water charged gasoline may occur during the cool-down of the tank content in mid-flight. Here another potential problem may arise, especially in future years, if automotive gasoline should be used uncritically and without at least an immediate pre-flight water content control: Since at present there is no normative upper limit of water content for the increasingly ethanol-admixed gasolines — only the absence of haze is required — some very competitive vendors may be tempted to deliberately exploit this boundary condition to a point where vehicles with their almost constant gasoline tank temperature will not experience any obvious disadvantage. Reported field tests with hydrous E-15 [21], saving the expenses of manufacturing super-azeotropic ethanol prior to gasoline admixing, already point in this direction. If such a gasoline with relatively high water content would be taken as aviation fuel the strong cool-down in exposed aircraft tanks may induce the phase separation effect. Since the absolute temperature dependence of the water tolerance increases significantly with a rising ethanol content (Fig. 35) this thread will grow significantly if a “non-disturbing water content” should be exploited commercially.

Consequently, both a static water content assessment of the tank contents of individual aircraft at the airfield and a monitoring of additional water input during the flight seem sensible to reduce the phase separation threat in case of ethanol-admixed gasoline usage. The presently available methods for such a determination are rather discouraging, though, as there is no immediate test procedure at hand — see Sect. 7.2.

6.4 Analysis of Carburettor Icing Hazard (T 2b)

6.4.1 Methodology and Approach

The effect of the ethanol's larger enthalpy of evaporation on the onset of a carburettor icing was investigated by measuring the temperature drop relative to an E-0 fuel, both for a test rigged ROTAX 912 ULS engine and the grounded MORANE's Lycoming engine type O 360 A1A.

Running the engine with different gasolines, namely E-0, E-5, E-10, and E-15, the temperature drop for various points of operation is monitored. The operating points are chosen to resemble typical practical operational modes of a typical flight: idle, taxi, take-off, and cruise.

6.4.2 Temperature Drop Determination in a ROTAX Engine

For definition of measurement boundary conditions see Fig. 92 in Sect. D.3. The engine is equipped with two thermo-elements (one in each two-cylinder manifold, on each sides of the engine) positioned at different heights in the fuel/air flow.

Fig. 37 shows the temperature drop at different engine speeds for a full load operation.

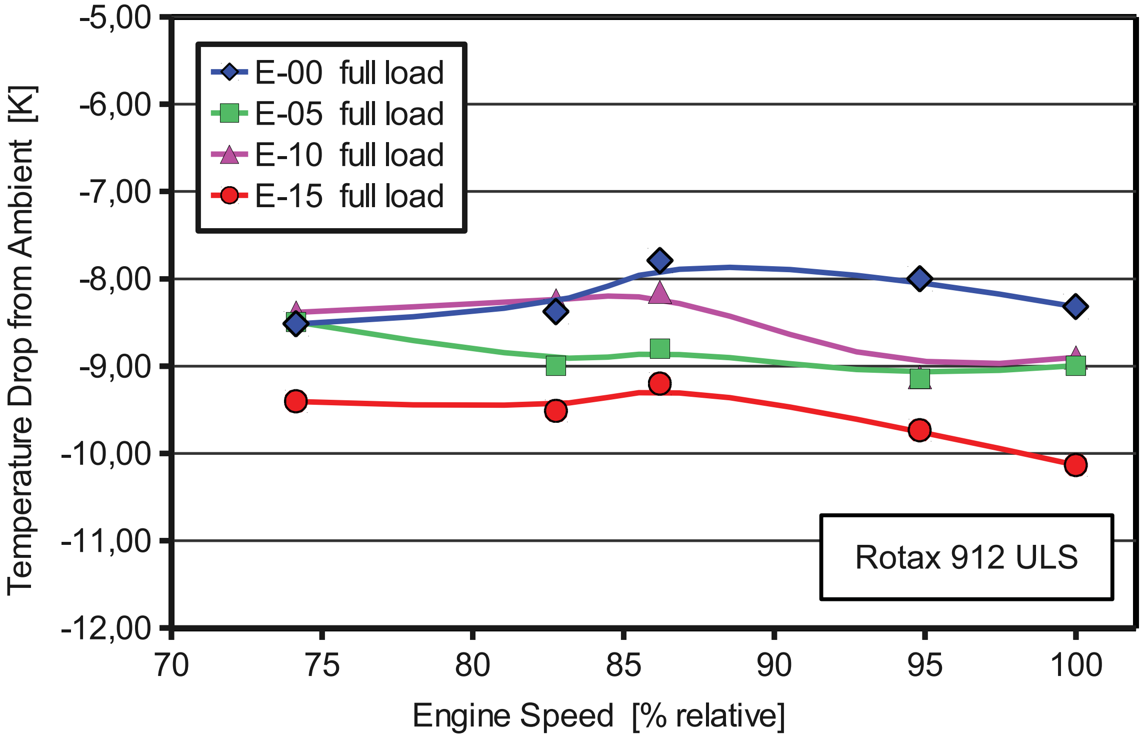


Figure 37: Temperature drop due to gasoline evaporation enthalpy in the intake manifold of the ROTAX *912 ULS engine under full load conditions. Ambient conditions: 24.3* °C, *98.4* kPa, *69.2* % *rel. humidity*

The curves are in good agreement with the expected tendency: With increasing abundancy of ethanol in the gasoline the temperature drop increases also. For full load the drops are not very strong, though: Even for the E-15 a drop of less than 2 °C was observed, while lower admixture amounts exhibited less than 1 °C in general.

The general correlation of ethanol ingredients and temperature drop is found as well for idle conditions (Fig. 38). The differences between the individual admixture levels tend to increase though, as do the absolute value of temperature reductions for higher idle speeds.

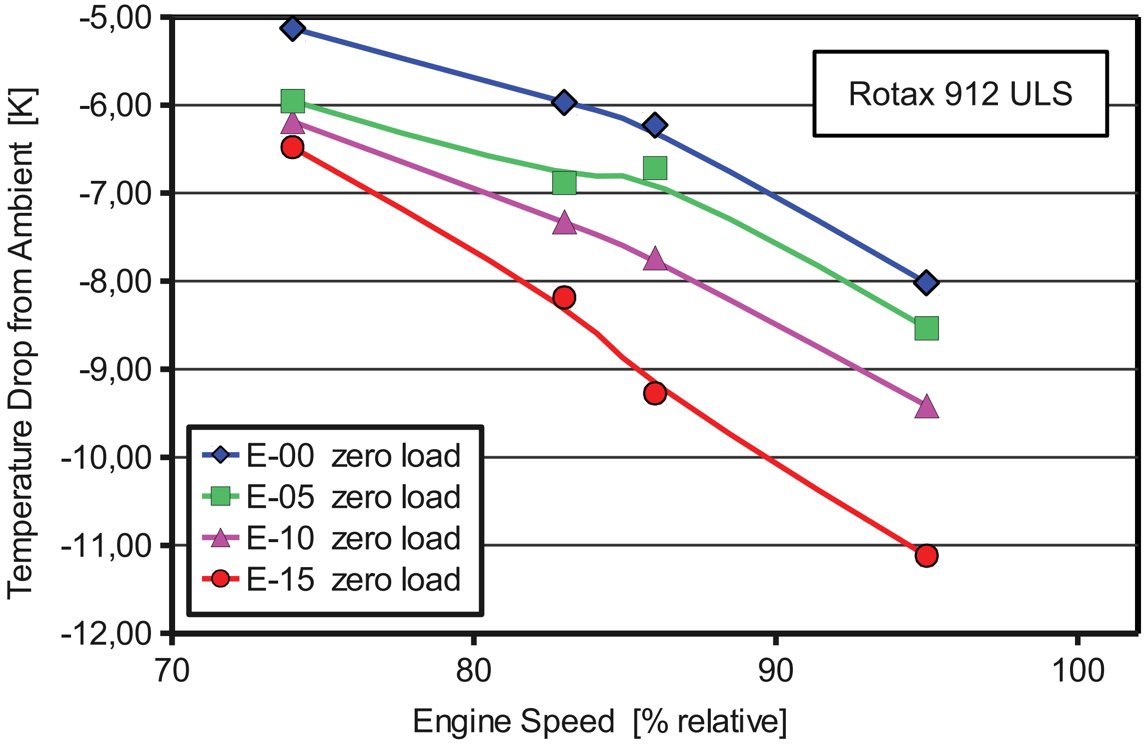


Figure 38: *Temperature drop due to gasoline evaporation enthalpy in the intake manifold of the* ROTAX *912 ULS engine under zero load conditions. Ambient conditions: 24.3 °C, 98.4 kPa, 69.2 % rel. humidity*

While the temperature drop observed for the smaller admixture amounts (E-5) is presumably negligible the larger admixtures exhibit a drop of up to 4 °C beyond that of pure gasoline. The most critical mode of operation with respect to a proneness for icing seems to be idle load condition at raised engine speed. This state is frequently assumed during begin of approach. Compared to the test rig installation an actual aircraft may even transgress the probed boundaries as the rig-mounted engine is not able to simulate a windmilling which in turn reduces the amount of ingested fuel even further.

6.4.3 Temperature Drop Determination in a Lycoming O 360 A1A Engine

Since the MORANE is not certified for MOGAS operation the investigations on the various ethanol admixed gasolines had to be performed with the grounded aircraft. A thermocouple was introduced into the intake manifold to measure the temperature drop, and the respective fuel was fed into the fuel system immediately in the engine section (Fig. 39).

In contrast to the ROTAX 912 ULS engine the MORANE pilot has an additional freedom of mixture setting. As there is no calibration of fuel/air mixtures the only points of reference are “full rich”, as used during a take-off, and “maximum exhaust temperature”, representing optimal cruise setting, with the usual “rich” position as some condition in between. The various operational states were scanned in qualitatively the same way as described for the ROTAX engine (cf. Fig 92), but with an additional variation of three points on the leaning gauge setting each.

Figure 39: *Morane icing test setup for operation with ethanol admixed fuels. The different gasoline compositions are taken from respective auxiliary tanks (red, left). They are fed by a bypass hose directly into the carburettor feed line. The aircraft is tied down to the ground with a strong rammed-in pole that is capable of supporting the full-power thrust of the engine.*

Presumably due to the additional freedom of mixture definition by the pilot and its differing absolute effects on the different load states the overall picture of influence is not so clear-cut as with the ROTAX engine with its self-adapting air-fuel ratio settings. Nevertheless there is a clear effect of icing tendency if the monitored temperature readouts for possible air-fuel ratio settings are compared at fixed intake manifold pressure levels for a given engine speed, as shown in Fig 40.

While the effect of a 5 % ethanol admixture in comparison to the approximately ethanol-free MOGAS is only marginal there is a distinct effect of higher admixture levels on the temperature drop. Both 10 % and 15 % admixtures create an additional drop of several degrees throughout, with their respective results quite near to each other but in the expected order. Similar results were obtained for direct injection engines operated with non-stoichiometric mixture compositions: Kar [20] reports disproportionate in-cylinder temperature drops especially for rich mixtures. As a potential cause high-temperature azeotropes of gasoline components and alcohols are suspected.

Always the richer compositions show a larger temperature drop effect which creates a remarkable effect on its dangerousness for aircraft operation: If the habitual modes of operation during a flight are envisioned the pilot usually approaches its destination still in cruise setting, so remaining on the EGT-max setting for some while. In the final stages of the descent the mixture gauge is reset to “full rich” in order to be able to obtain the full thrust if a critical situation should occur during

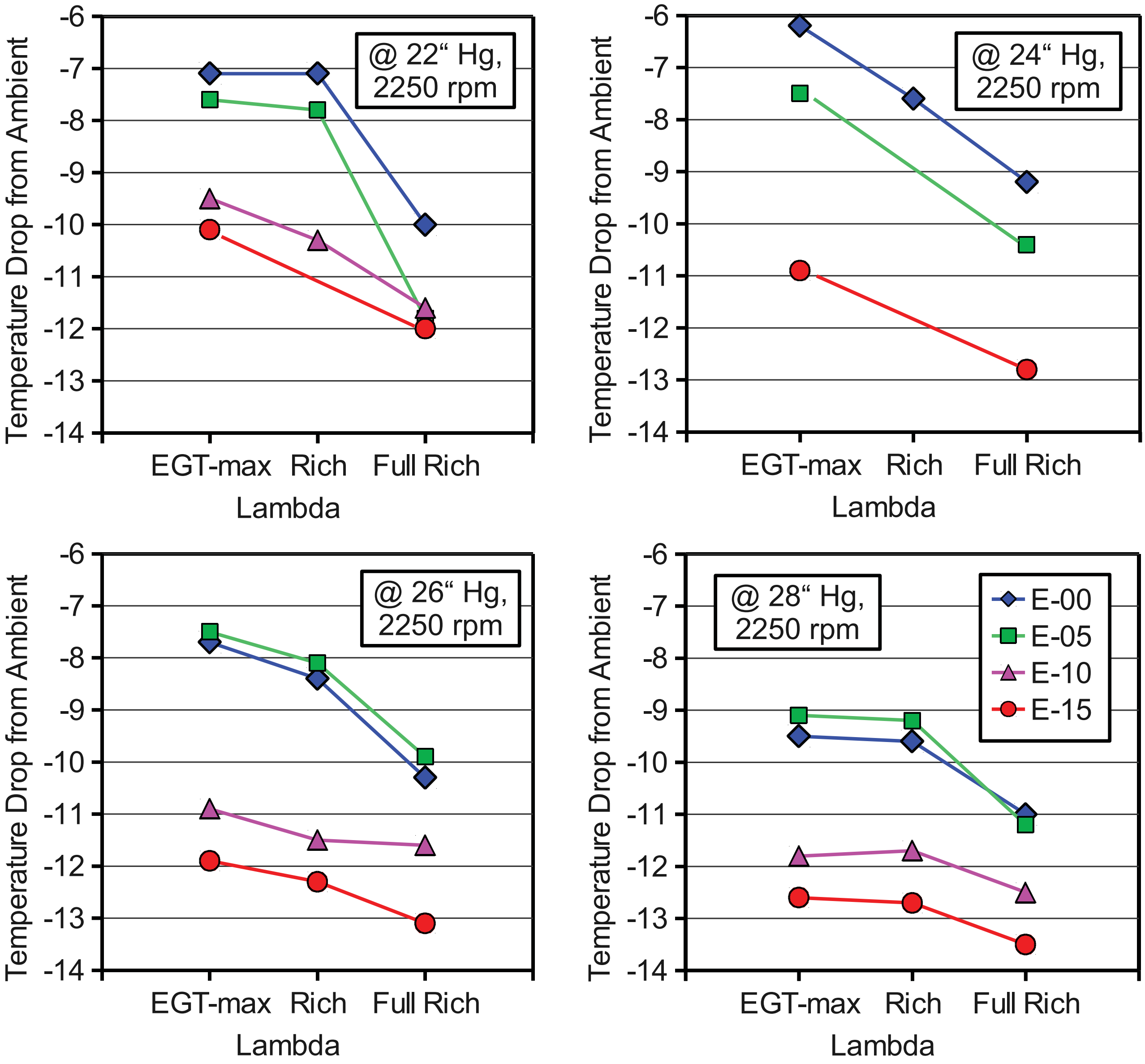


Figure 40: Temperature drop due to gasoline evaporation enthalpy in the intake manifold of the MORANE's Lycoming engine type O 360 A1A for various load conditions. The three states of air/fuel mixture settings can only be defined qualitatively and are likely to differ for the different admixture types due to slightly differing stoichiometric mass balances.

touch-down. At the same time the aircraft traverses the typically more humid lower strata of the atmosphere, thus being subject to additional water input into the intake manifold. At the same time the heat output of the engine is reduced due to its low power output during this phase of approach. All these partial effects may collaborate and lead to a sudden occurrence of a carburettor icing in the most critical stage of the flight, obstructing the possibility of requesting a sudden larger power output from the engine if required, e.g. for a touch-and-go operation.

6.4.4 Icing: Conclusions

The absolute value of the measured temperature drops are significant for all gasoline types, including E-0, and confirm the well-known general threat of carburettor icing. Additional effects of ethanol admixture appear insignificant for up to 5 % (v/v) ethanol, but become decisively stronger for larger admixtures. As the practical implications on the individual aircraft's operation strongly depend on further factors, like the fuel system and the engine integration design into the cell, it is near to impossible to define a limiting value for an ethanol admixture on a general basis. If a given aircraft has had any tendency to show an icing effect in the past when operated on AVGAS or MOGAS an urgent recommendation is given to install, or increase the power of, an air preheater to reduce the probability of icing prior to any try to operate on ethanol-admixed fuels. Here certification specifications CS-23 (especially the Induction System chapters — CS 23.1093 Induction System Icing protection and following paras CS 23.1095, CS 23.1097, CS 23.1099, CS 23.1101) should be revisited as a basis for design rules: If the aircraft is already equipped with a preheater its power should be increased at least by the factor that is numerically derived from the increased enthalpy of evaporation of the maximally ethanol-admixed gasoline to be used. Due to the fact that the effect to be expected is not a linearly superimposing one (cf. Sect. 5.3) the exact amount of additional heat required is still a matter of scientific investigation and can not be sharply defined yet. If the cited results are take as a basis the preheater power output shoudl be increase by a third of its original one.

If the icing prevention is attained by another method than a defined preheating additional tests will have to be made on the effectivity of this method on behalf of the additional heat demand in ethanol-admixed operation.

Even if an aircraft never has experienced icing and has been checked for further CS-23 compliance additional testing for the usage of ethanol admixed types should start with low admixture levels and only after due time advance to higher levels if no adverse icing effect has been noticed in the field.

6.5 Analysis of Intensified Vapour Locking Hazard Caused by Gasoline Mixing

As detailed in Sect. 5.2 *a mixing* of differently ethanol-admixed gasolines may result in an increased vapour pressure which in turn increases the danger of vapour-locking in general. Whether a certain aircraft is prone to be affected depends to a large part on its individual construction, especially with respect to its fuel system.

Several aspects of engine operation principally contribute to such a threat:

- If the fuel becomes too hot on its way from the tank to the engine bubbles of boiling gasoline may spontaneously emerge.
- If obstacles (reduced cross sections of fuel leading parts, clogged filters, etc.) impede the flow respective pressure drops may be imposed leading to local drops of pressure with similar results.
- Strong vibrations in combination with elevated temperatures may lead to bubble creation by a mixture of boiling and cavitation effects that have not been subjected to a more intensive theoretical scientific investigation.

Last but not least it should be kept in mind that the fuel system of a flying aircraft is operated in a highly unsteady mode: The fuel traverses its components (hoses, filters, switches, pumps, ...) with their specific heat transfer interaction surfaces with a certain velocity that limits both the time and the driving force for heat input.

In the actual specific aircraft these various conditions interact in a mostly non-replicable and abstractable manner. Therefore their effects can only be investigated exemplarically by monitoring temperature and pressure distributions in well-defined settings. Such experiments are performed with AcUAS's MORANE and by the application of a custom-built test rig with well-defined fuel flows under conditions of reduced ambient pressure. They are discussed in the subsequent sections.

Since no commercial defined E-10 and E-15 brands — that would have shown a reduced vapour pressure of the fossil basestock — are obtainable during the time of experimentation the admixed gasolines were created by custom mixing of pure ethanol with the Total Deutschland GmbH basestock (cf. D.1, p. 196). Due to the lacking consideration of the non-Raoultian vapour pressure increase relative to the original E-0 fuel this can be regarded as an intentional creation of a worst-case scenario.

6.5.1 Fuel Heat-Up Experiments with a MORANE MS 893 E-D Aircraft (T 3)

The effect of a heavy load operation with smallest possible cool-down possibilities on the fuel provision system is studied in an exemplaric manner by flight experiments with ACUAS's MORANE MS 893 E-D. The instrumentation for this task is described in full detail in sect. D.2.

The MORANE is put on the apron before the flight for several hours, and the wings parts containing the fuel tanks are covered with dark cloths to get the temperature up.

The goal of a maximum load condition with minimal cool-down is created by a sequence of consecutive starts, fast rises, fast descends, landings, and immediate consecutive starts. The aircraft is freighted to its maximum MTOM weight thus requiring the maximum take-off and climb power available.

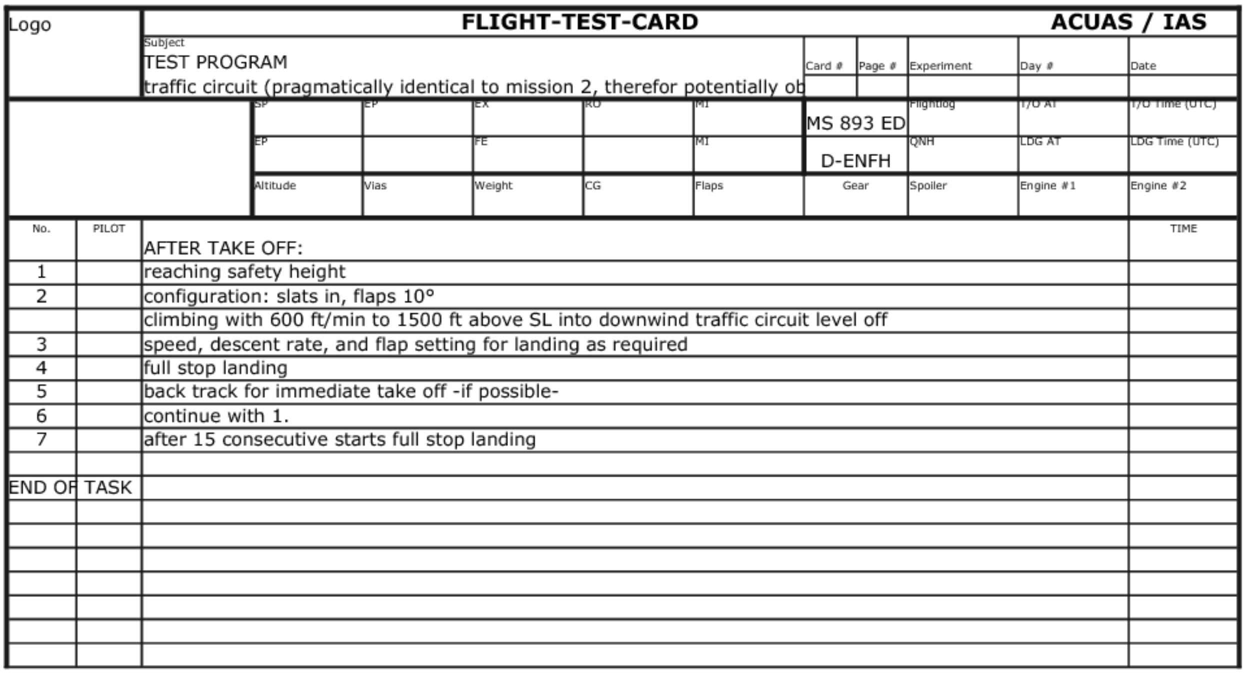
The actual execution of the respective test flights must take the statistical behaviour of the weather into accout. For the largest effect weather conditions should be as hot as possible. Apart from the really hot summer of 2006 weather statistics from the last years for the region of Aachen show just a few really hot days with temperatures exceeding 30 °C.

Therefore the flight mission was flown at a summer day at about 28 °C ground temperature with the option to repeat should some higher temperatures be forecasted. In the period available for test flights no hotter day has been met.

With respect to the vapour lock threat the main observation objective is the gasoline temperature as it approaches the carburettor. In order to assess the effect of heavy load operation on the temperature management of the MORANE a respective flight test card was defined (Fig. 41).

The result of this heavy load circuit operation is shown in Fig. 42. Starting at Merzbrück, an altitude of 3000 feet is repeatedly attained whereupon a steep descent and a landing follows. The aircraft is taxied to start position and takes off again.

The initially already quite warm gasoline (starting temperature about 31 °C due to anteceding parking on apron) is heating up fast already in the pre-flight check phase. At the time of take-off the fuel hoses at the electrical pump already show temperatures of 45 to 50 °C depending on the spatial position of the hose. Even though each climb is performed with maximum possible power the descent phases suffice to keep the hoses (and thereby assumedly the gasoline temperatures) in the range of 45 to 60 °C, depending on the hoses' position. It is worth noting that usually the highest temperatures are observed during the taxi operations on ground, not during the maximum load conditions during the climb. A maximum of slightly more than 60 °C is observed. As



Logo

FLIGHT-TEST-CARD **ACUAS / IAS**

Subject
TEST PROGRAM
traffic circuit (pragmatically identical to mission 2, therefor potentially ob

Card # | Page # | Experiment | Day # | Date

SP | EP | EX | RO | MI | MS 893 ED | Flightlog | T/O AT | T/O Time (UTC)

EP | FE | MI | D-ENFH | QNH | LDG AT | LDG Time (UTC)

Altitude | Vias | Weight | CG | Flaps | Gear | Spoiler | Engine #1 | Engine #2

No.	PILOT		TIME
		AFTER TAKE OFF:	
1		reaching safety height	
2		configuration: slats in, flaps 10°	
		climbing with 600 ft/min to 1500 ft above SL into downwind traffic circuit level off	
3		speed, descent rate, and flap setting for landing as required	
4		full stop landing	
5		back track for immediate take off -if possible-	
6		continue with 1.	
7		after 15 consecutive starts full stop landing	
END OF TASK			

Figure 41: *Flight Test Card for the heavy load circuit operation to perform a heat-up experiment.*

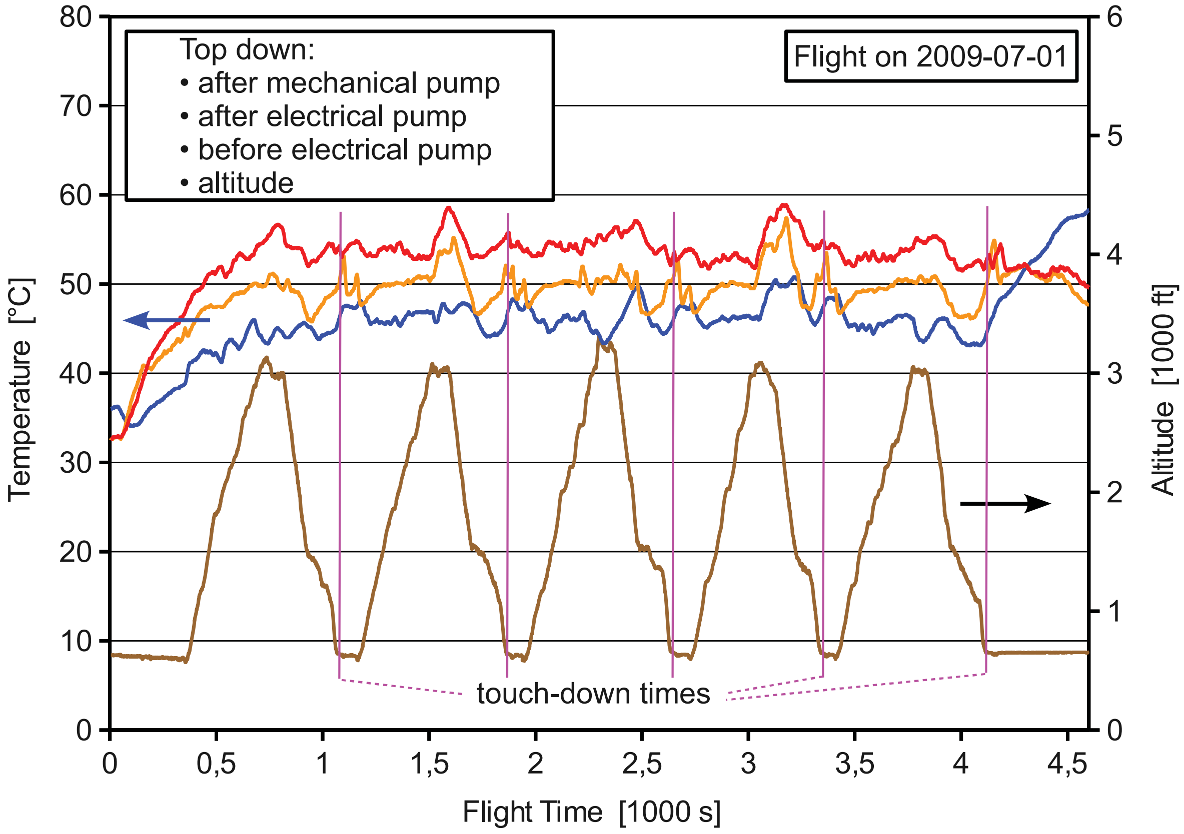


Figure 42: *Development of fuel hose temperatures near to the engine for a series of consecutive starts and fast touch-downs with AcUAS'* MORANE. *As defined on the original flight test card always the maximum flight height was selected*

Fig. 42 shows the temperatures in the fuel system begin to rise significantly already in the latest approach phase, during the last seconds before touch-down. Accordingly they may reach critical values especially in the critical phase of a necessary touch-and-go operation. This threat is even pronounced if the engine is stopped for a short time (e.g. for passenger exchanges at public flight days) and the aircraft is restarted and ascends at MTOW in a consecuting action.

The notion of already rising temperatures during the last stage of the descent and the assumption that the cooling effect of the cold high-altitude air lead to an alternative reiterated starting schema where the service ceilings were chosen consecutively lower, leading to the result shown in Fig. 43.

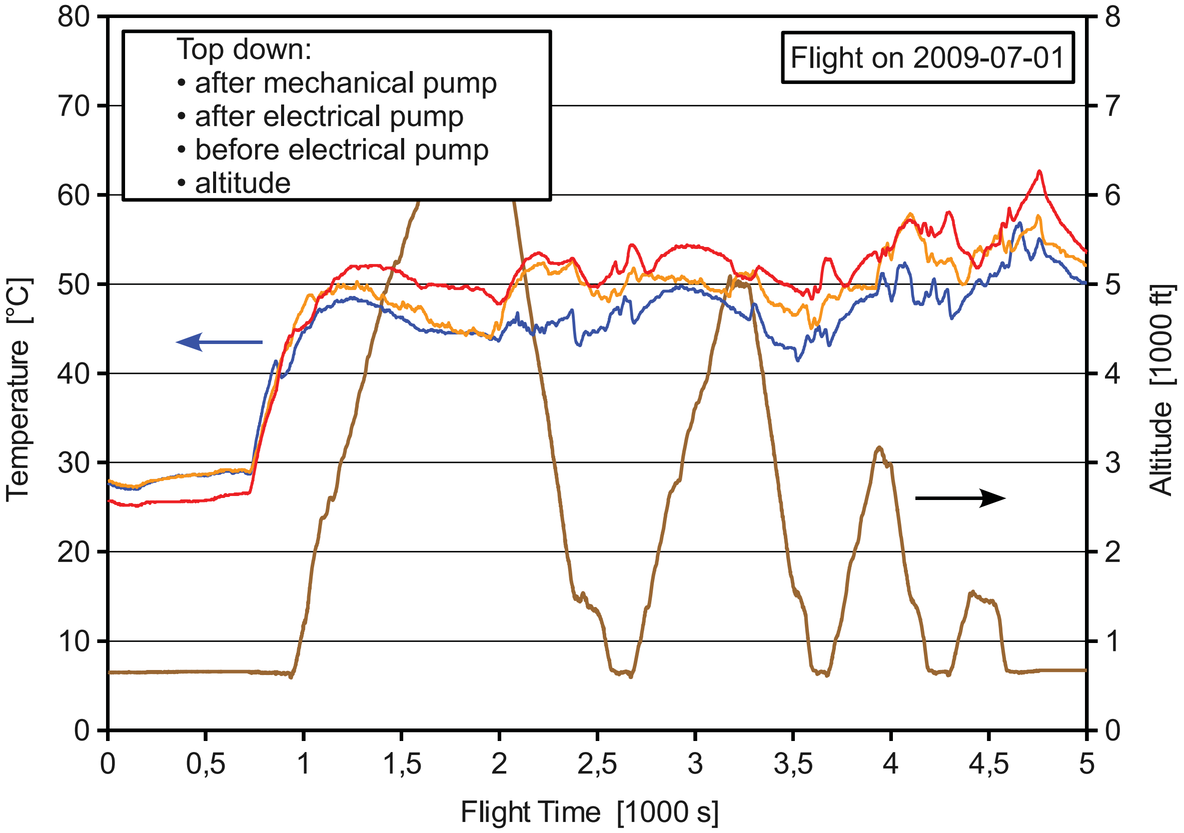


Figure 43: *Development of fuel hose temperatures near to the enginge for a series of consecutive starts and fast touch-downs with AcUAS'* Morane*. Deviating from the orginal flight card the zeniths were chosen consecuitvely lower.*

Starting with a slightly lower initial gasoline temperature the temperature levels of the former experiment are soon reached. The shorter intervals between the consecutive starts and the continuance in the warmer lower air strata leads to a gradually increasing gasoline temperature with a peak value above 60 °C.

Comparing these results to those of the bubble detection limits for gasolines in the vapour lock test rig (see Sect. 6.5.4) it should be keept in mind that the very high temperatures are encountered *after* the electrical pump, so in a region with an additional pressure imposed on the gasoline system (see Sect. 6.5.2). Accordingly the tendency of creating flow choking vapour bubbles is somewhat reduced. Nevertheless a temperature of about 55 °C *in front of* the electrical pump should not be disregarded, even without a threat of an increased vapour pressure due to a potential unlucky mixture of differently ethanol admixed gasolines.

6.5.2 Investigation of Pressure Drops in the Morane Fuel System Under Operating Conditions (T 3)

In combination with high intrinsic vapour pressures of the fuel, pressure drops imposed by bottlenecks in a fuel system as a consequence of a streaming liquid may create additional threats of bubble creation and hence vapour locking. An experiment was performed to quantify this effect in an exemplary manner for AcUAS's Morane.

At the time of the sensor instrumentation a modified fuel hose was installed in the Morane that enabled a readout of pressure values relative to the ambient before and after the electric pump (item E-pump in Fig. 90). With the aircraft rigged to the ground usual load conditions from idle to full load were set. The pressure drops were recorded both for the electric pump switched off and on. The result of this test run is shown in fig. 44.

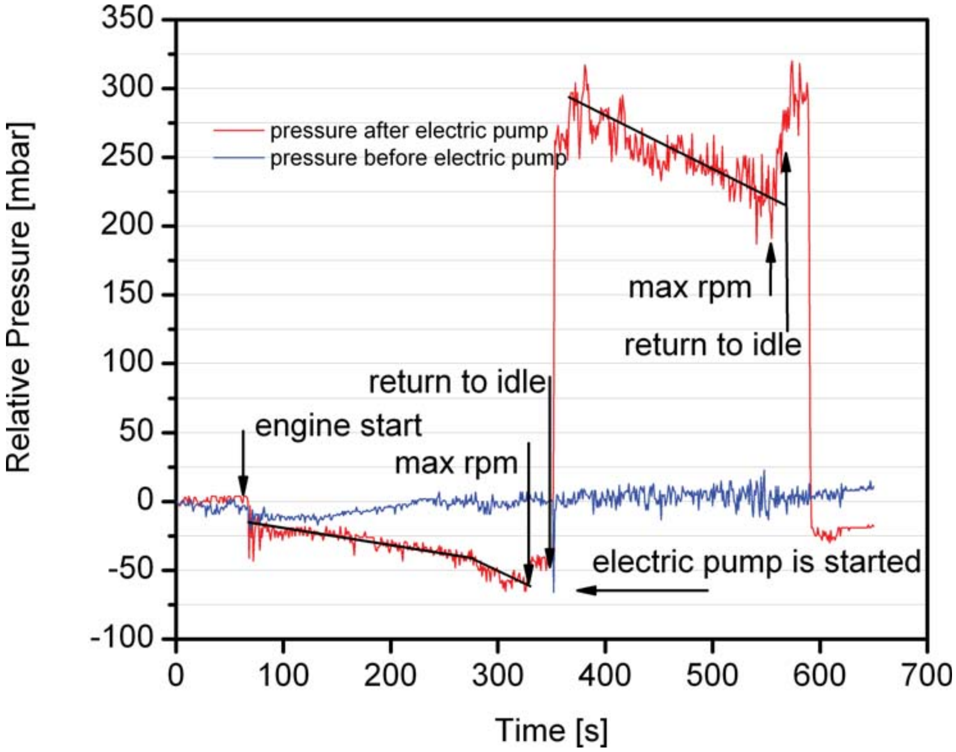


Figure 44: *Result of a pressure drop experiment on AcUAS's grounded* Morane*, operated on* Avgas*, for various load and pumping conditions.*

Only small dips of less than 10 mbar are noticed in front of the electric pump. Obviously the fuel system diameters are of sufficient size not to choke the flow in any remarkable way. The posterior side of the electric pump is more of interest, though. Here a clear influence of the load state of the engine is perceived, with even idle condition imposing a drop of some 25 mbar. For full load condition this adds up to about 50 mbar which is to be considered as significant.

After switching on the electric pump there is no noticeable additional drop on its anterior side. As expected, on the posterior side a pressure rise of some 300 mbar is produced. Even this pressure rise decreases again by about 50 mbar, in quite an agreement with the switched-off condition of this pump. Nevertheless the effect imposed by the electric pump is sufficient to raise the absolute pressure well above ambient conditions, thus taking care that additional pressure drops further downstream should not become detrimental.

With respect to safety aspects there is an interesting implication, though. The electric pump, being thought a redundant equipment part for the mechanical pump driven by the engine is no longer one in case of a vapour pressure rise caused by an accidental mixing of ethanol-free and ethanol containing fuel leading to an elevated vapour pressure value (see section 5.2). If such a mixing cannot be ruled out — and as a mishap it cannot, as long as AVGAS and ethanol-admixed MOGAS may be accidentally mixed — an additional electrical shunt pump would be required to provide the originally intended redundancy for fuel delivery to the carburettor.

6.5.3 Vibration Measurements in the MORANE Fuel System (T 3)

Dynamic pressure drops may be imposed on the liquid fuel by fast moving active parts like pumps, but also by orifices or vibrating fuel lines. Even though theoretical considerations for non-equilibrium liquid mixtures like gasoline are somewhat scarce experimental tests of vibration strengths were performed in some MORANE test flights. The respective instrumentation is shortly described in sect. D.2.

Since no theoretical evaluation and assessment of vibrational data for multi-component mixtures could be identified the consecuting data acquisition is reported here for further elucidation.

In the fuel a vibration, i.e. an acceleration of enclosing surfaces, acts as a bubble creating or at least promoting cause if the velocities of walls, imposing respective accelerations to the adjacent liquid volumina, become so strong that they tear apart the liquid. A well-known effect is the ultrasonically induced cavitation in cleaning baths. From basic physical theory it may be expected that

- for higher frequencies a smaller amplitude is sufficient to induce this effect (hence the choice of ultrasonic frequencies for the cleaner devices),
- for warmer liquids a lower tensile strength is required to tear the liquid apart.

As a first qualitative implication heated-up parts (e.g. in the engine compartment in front of the firewall) should not be exposed to too large vibrations, especially so, if the local system pressure is low at the same time.

The MORANE was equipped with acceleration sensors at the tank and at the electric pump (see Sect. D.2, page 201). Acceleration values were recorded for different directions. Since there was only one high temporal resolution data acquisition unit available respective measurements only could be performed as a sequence. Accordingly, the measurement results reported in the next figures are not recorded simultaneously but one shortly after the other from the same ascend interval of the same test flight. Due to changes in engine speed during this ascent the characteristic resonance frequencies of the individual measurement intervals are not immediately comparable.

An overview of typical frequency domain acceleration measurement results is shown in Fig.45. It should be minded that the ordinate scaling is logarithmic.

At the tank surface the recorded accelerations are quite high and reach values of up to 18 g (with g being the unit of the earth's gravity force). It should be noted, however, that the sensor is placed on the free surface of the tank, being able to vibrate without much hindrance and to respond to excitation frequencies coupled into the wing by the cell body. The gasoline in contact with respective surfaces is relatively cool and becomes even more so during a flight, so a vapour locking effect is not to be expected. Even if bubbles should be created they would collapse again before the fuel is ingested into the narrower parts of the fuel system.

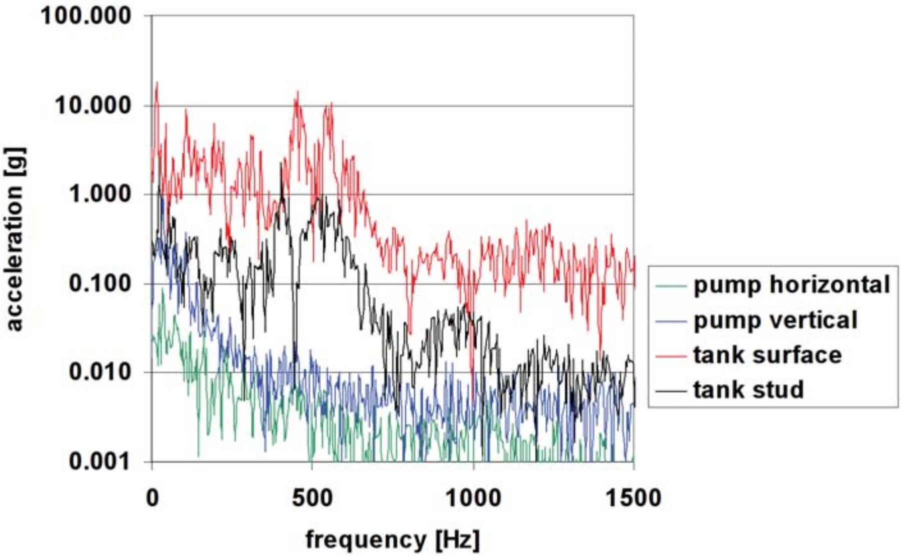


Figure 45: *Vibration frequencies and strengths at various positions of the* MORANE *fuel system, take-off condition.*

Vibrations at the tank outled stud are much smaller than those registered at the free tank surface, with the general layout of the spectrum quite similar. The governing (resonance) frequencies and their harmonics are slightly shifted, presumably due to a accordingly shifted engine speed.

Proceeding towards the warmer regions of the fuel system, the vibrations of the electrical fuel pump as a potential place of an additional pressure drop (see Sect. 6.5.2) are monitored both in vertical and horizontal direction. Again the acceleration amplitudes are decreasing compared to the tank recordings. While in vertical direction at least the lower frequencies, mainly representing the body vibrations of the cell, show amplitudes comparable to the tank stud ones, the horizontal vibrations are only marginal.

In conclusion it may be stated that in these measurements no extraordinary magnitudes of vibration have been found. The amplitudes tend to get smaller the nearer the location of the monitored spot is located towards the engine with its heat input. A in-depth evaluation of the vibration strengths would require a more detailed basic research of the material properties of the fuel, which is not yet available.

6.5.4 Vapour Locking Experiments on a Custom Test Rig (T 3)

At the time of the SIOBIA experiments taking place there were no certified commercial gasoline brands available that would guarantee a fixed ethanol content other than “less than 1 percent”. Accordingly, the investigators were not able to obtain a respective BOB that would yield commercially compliant ethanol gasolines. The mixtures to be investigated had to be custom-mixed from a certified winter quality E-0 gasoline provided by Total Deutschland GmbH, and from a stock supply of 100 % bio-ethanol provided by Crop Energies.

As a consequence it may be expected that the vapour pressures observed in these custom-mixed gasolines tend to be too high compared to a future commercial respective gasoline type obeying DIN EN 228. Nevertheless the custom mix can be taken as a conservative guess with respect to vapour locking threats.

The tendency of creating a vapour lock is investigated with the custom test rig described in

Appendix D.4. The imitated fuel system was kept as simple as possible, consisting only of a piece of fuel hose, an optical port for bubble determination by a straylight sensor, a viewing port for direct inspection and the system pump representing the suction pump of an aircraft.

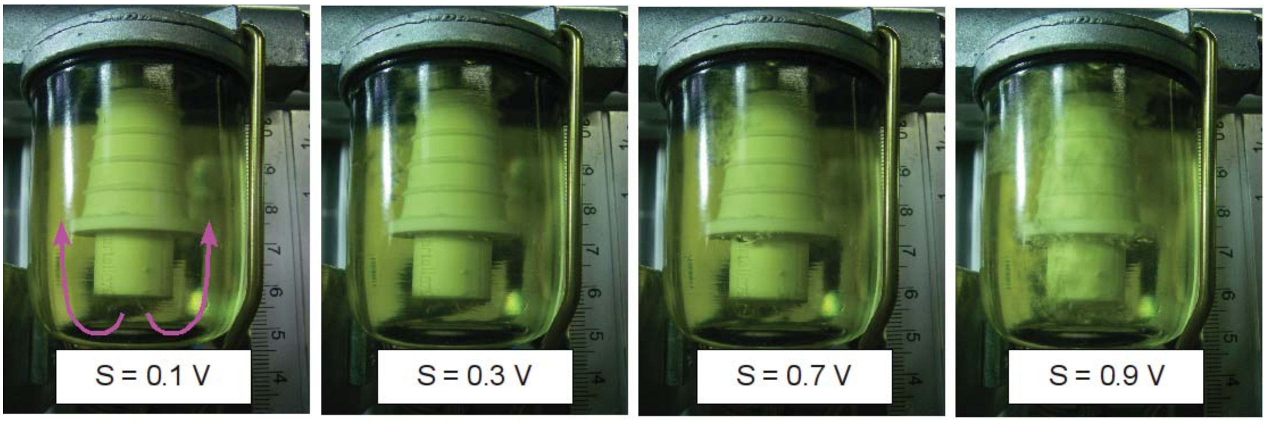


Figure 46: *Collection of bubble strength images seen through the viewport, relating to respective sensor readout values. The arrows in the first image show the flow direction*

Fig. 46 displays the optical impression of respective bubble sensor signal strengths, given as electrical voltage readouts that should be interpreted as arbitrary units, though. At 0.1 V only seldomly a bubble is observed. The gauge glass remains filled with liquid most of the time. At a signal level of 0.3 V bubbles appear quite frequent already. At 0.7 V there is an almost steady presence of a smaller bubble veil in the upper portion of the gauge glass. Finally, at 0.9 V the whole gauge glass is mostly filled with expanding rather than collapsing bubbles.

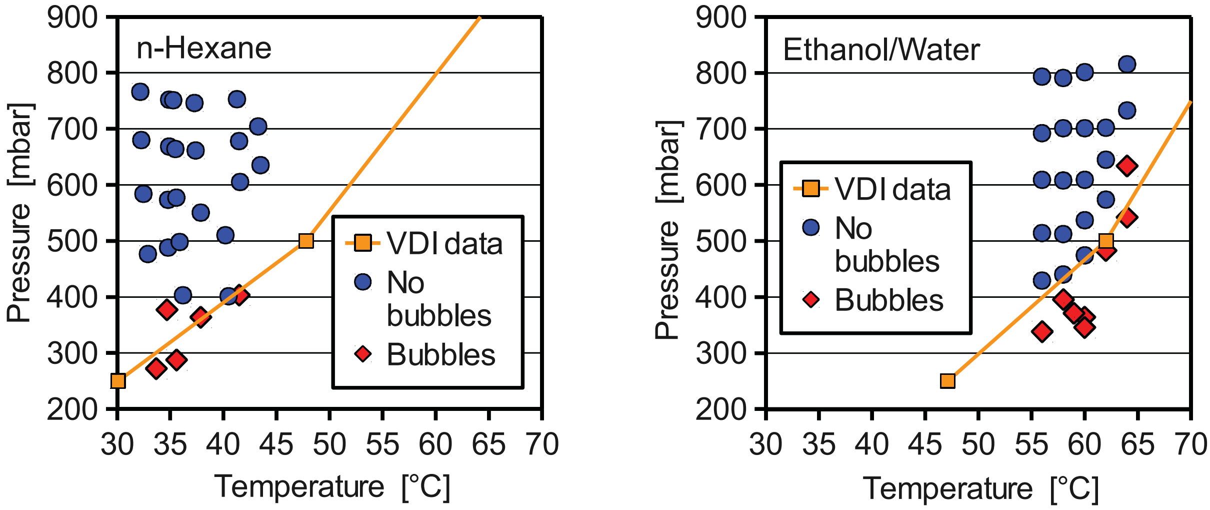


Figure 47: *Bubble measurement observations for n-hexane (left) and an azeotropic ethanol/water mixture (right) in combination with the governing theoretical evaporation curve for the respective substance [17].*

There is no clear indication what bubble sensor signal strength should be taken as a sign of immediate danger indication. For the pure calibration substances (see Fig. 47) a value of 0.3 V gave the best concordance with theoretical data. For multi-component mixtures this needs not be the same. Therefore a range of increasing danger is proposed, defined by the limits of 0.3 V and 0.7 V. It may be assumed that the actual point of imminent affection of engine operation is somewhere in between.

For comparison reasons the bubble signal diagram for AVGAS is included (Fig. 48). The field of sensible {p,T} points is automatically scanned and the sensor readout registered. According to the boundaries given above two lines in the resulting diagram of bubble strengths delineate the area where vapour locking is expected to start. Even for an assumed pressure drop of 0.3 bar, comparable to an altitude of about 10,000 ft, the gasoline may have a temperature of about 45 °C before a danger of vapour locking is to be expected. On the ground even a gasoline temperature of 55 °C does not seem to pose any problem.

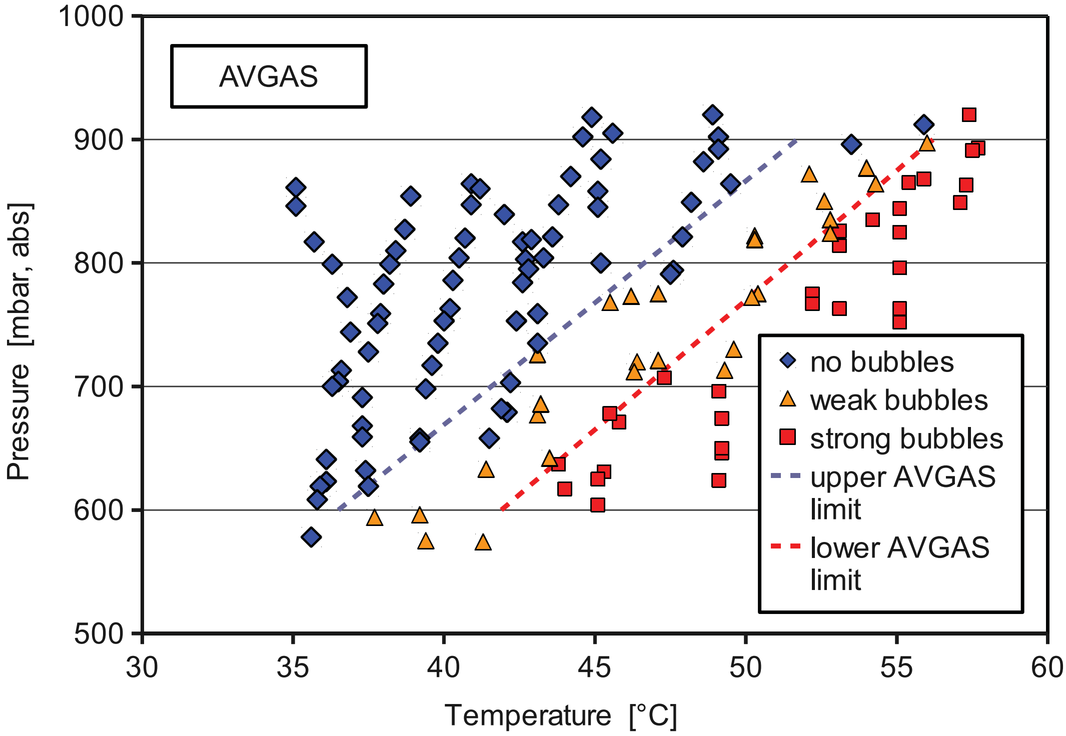


Figure 48: *Bubble sensor readouts for a {p,T} scan of* AVGAS. *Blue diamonds indicate a readout* $S < 0.3$ *V, orange triangles a value* 0.3 *V* $< S <$ *0.7 V, red squares indicate* $S >$ *0.7 V.*

The picture changes for the various MOGAS types under investigation. Fig. 49 and 50 depict the respective results.

Already for the E-0 quality (current MOGAS) the region of onsetting bubble creation moves further to the upper left of the diagram compared to AVGAS. Accordingly, the fuel may be safely operated only at lower service heights and/or lower temperatures. This is not astonishing and a commonplace experience with MOGAS using pilots. Proceeding to increasing ethanol admixtures this characteristic is pronounced further as shown in Figures 49 (bottom) and 50 for E-5 to E-15. For a given service height, defined by the respective ambient atmospheric pressure, is gradually declining when switching to higher admixture rates.

As already stated the practically endangering signal strength threshold cannot be sharply defined. Therefore the result data were evaluated for the limiting signal strengths of $S = 0.3$ V and $S = 0.7$ V with respect to a confidence temperature decrease for the different service heights.

Fig. 51 and 52 display this evaluation as a pragmatic conclusion of the bubble generation experiments. The exact onset of practical vapour locking with respect to observed bubble strengths cannot be defined — and it may even be different between different aircrafts. But it may be assumed that a dangerous state is reached somewhere in between the limits of 0.3 and 0.7. Regardless of the exact value a reduction of the temperatures for same bubble signal strengths is

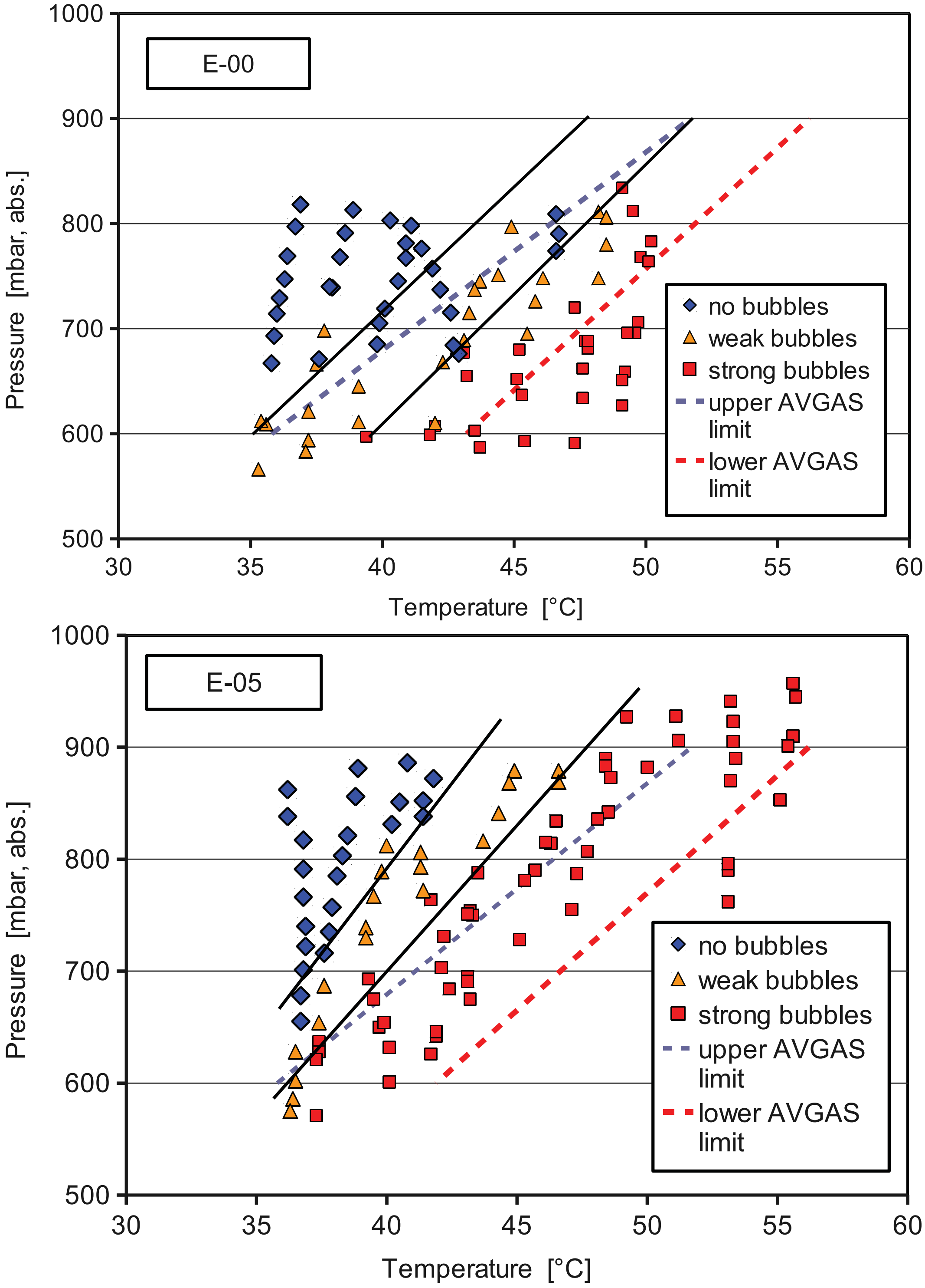


Figure 49: *Bubble sensor readouts for a {p,T} scan of E-0 (top) and E-5 (bottom). Blue diamonds indicate a readout $S < 0.3$ V, orange triangles a value $0.3\ \text{V} < S < 0.7$ V, red squares indicate $S > 0.7$ V. Averaged region borders are sketched as black lines. Respective borders for* AVGAS *(cf. Fig. 48) are additionally shown as dashed lines.*

recorded if a larger ethanol content is probed. In general the securely usable temperature resp. ceiling values decline with increasing ethanol abundancies in identical gasoline basestocks. This is not to be misinterpreted as a general rejection of ethanol admixed fuels for aviation usages, though: The results are only to be interpreted in the light of an unlucky mixing event of non-admixed fuel

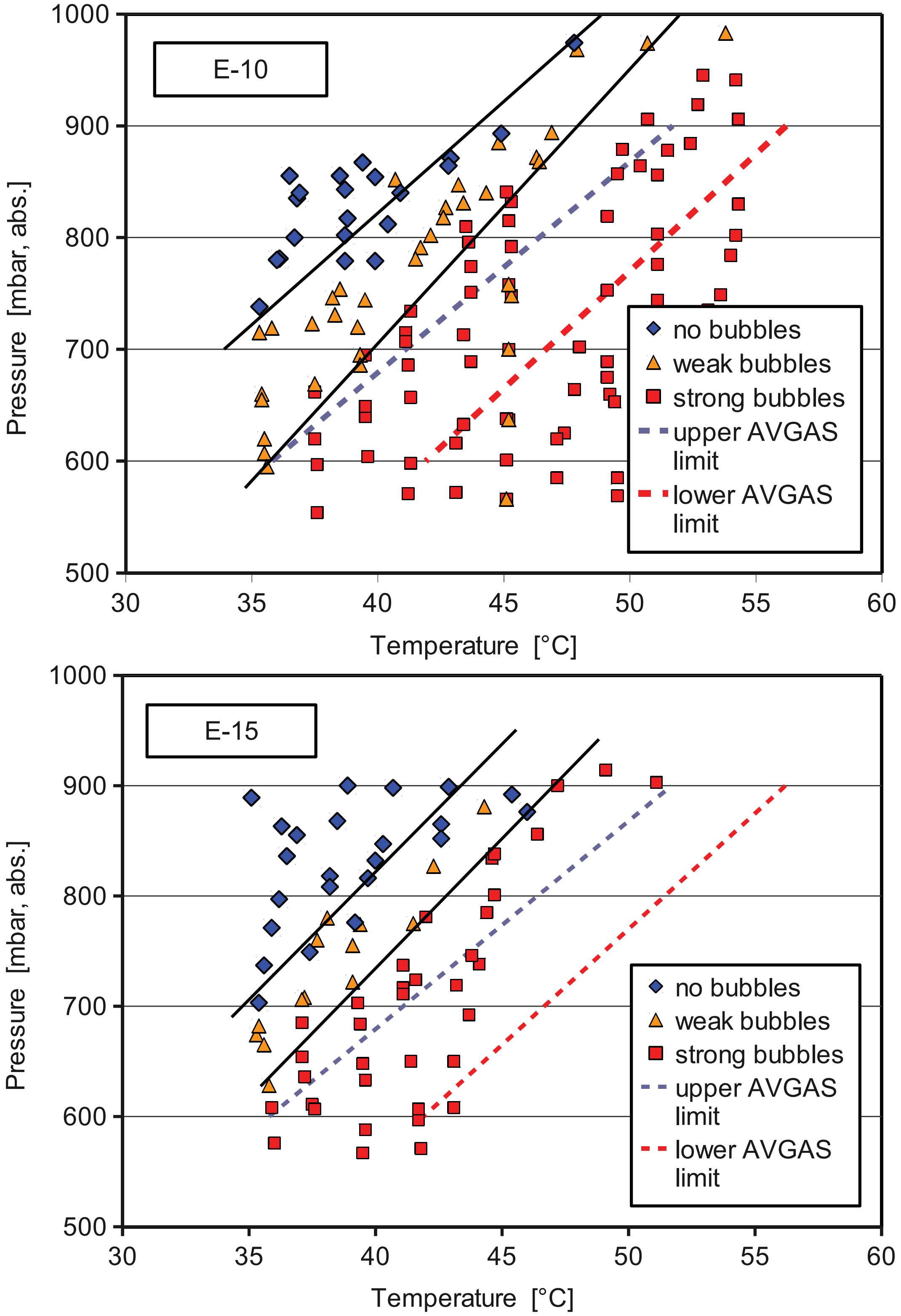


Figure 50: *Bubble sensor readouts for a {p,T} scan of custom mixed E-10 (top) and E-15 (bottom). Blue diamonds indicate a readout S < 0.3 V, orange triangles a value 0.3 V < S < 0.7 V, red squares indicate S > 0.7 V. Averaged region borders are sketched as black lines. Respective borders for AVGAS (cf. Fig. 48) are additionally shown as dashed lines.*

with an admixed one.

The reported results create a discrepancy to DGMK's results (see Sect. 5.2, page 46) for "cold"

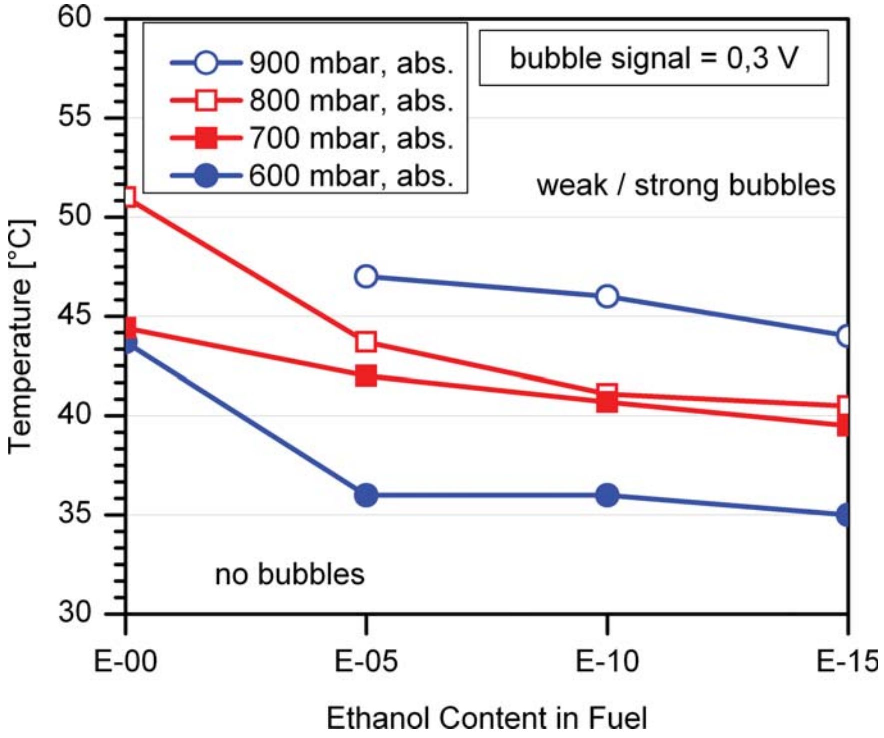


Figure 51: *Temperature limits derived for the investigated ethanol abundancies and ambient pressure levels for the lower bubble intensity level of 0.3 V sensor readout.*

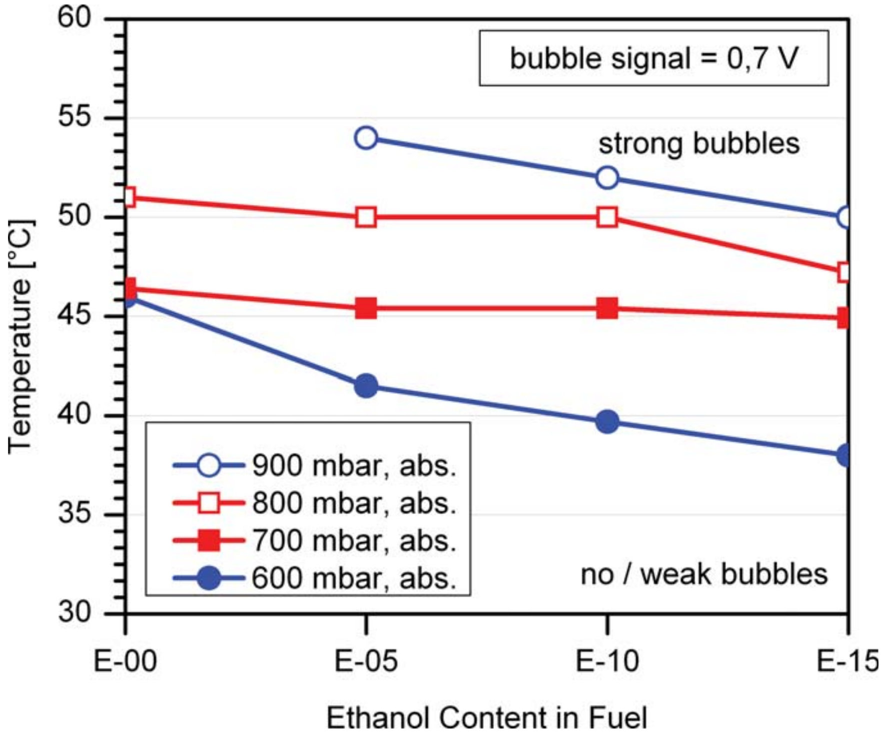


Figure 52: *Temperature limits derived for the investigated ethanol abundancies and ambient pressure levels for the higher bubble intensity level of 0.7 V sensor readout.*

gasoline where a share of larger than about 3 % of ethanol in gasoline should again decrease the tendendy of evaporation slightly. The DGMK reported vapour pressures are (kind of) equilibrium ones, though, not taking into account the faster heat transfer mechanisms experienced in perfused systems. In addition, DGMK's reported vapour pressure values almost form a kind of plateau in the scrutinized region. For elevated temperatures another source [20] reported a steadily increasing vapour pressure for increasing ethanol abundancies of up to 20 % in accordance with the measurements reported here. Therefore the authors of this report consider it likely that this report's results come closer to the reality of potential problems in flight operation.

It should be kept in mind, though, that the absolute volatilities of the tested custom mixed fuel qualities must not be taken as expected ones of commercial ethanol-admixed gasolines (see Sect. 5.2, p. 43). Nevertheless, they may resemble those after an accidental mixing of ethanol-containing and not containing brands.

6.5.5 Assessment of a Common Gasoline Volatility Test Device (T 3)

Depending on season MOGAS is distributed in different volatility classes (cf. Sect. 4.1.2, p. 31). As a sufficiently low volatility may be crucial for vapour lock suppression in aviation applications its control is already important without ethanol admixtures. Among others the so-called "Hodges Tester" (Fig. 53) is widely used for this purpose. It operates on the basis of a direct vapour pressure measurement.

__Figure 53:__ Hodges tester for gasoline volatility assessment.

A small amount (about 1 ml) of gasoline is sucked into an otherwise empty syringe. The inlet port is shut up by screwing a pressure gauge on it. Consecutively the syringe is drawn out further, creating a vacuum space that is filled with the spontaneously evaporated lighter constituents of the gasoline. These constituents determine the pressure drop observed by the gauge readout. It is a measure for the vapour pressure of the gasoline.

In the framework of SIoBiA the Hodges Tester was used on E-0, E-5, E-10 and E-15 consecutively, in ascending order, as theory would suggest a step by step increasing or at least stagnating vapour pressure. Between each individual measurement the syringe was rinsed out with E-0.

All experiments produced an identical vapour pressure value of -45 kPa relative to ambient pressure at a temperature condition of 21 °C (in the chemical laboratory). Some slight variations in the order of the width of the indicator needle were superimposed by typical handling dependent alterations: Gripping the syringe firmly with a warm hand obviously instead of touching just the orange handlebar added heat to the systme taken up by the liquid and leading to a slightly less pressure drop relative to ambient conditions.

These findings have to be compared to the results gathered with the vapour lock test rig (cf. Sect. 6.5.4) where clear differences in the bubble onset have been observed for the different admixture levels. As a result it must be stated that the device has proven too insensitive to identify the differences in the Exx levels.

6.5.6 Vapour Lock: Conclusions

The issue of vapour locking is an effect of various boundary conditions coinciding unluckily in a given flight situation. Respective temperature readout experiments performed with the MORANE showed fuel system peak temperatures around 60 °C in the proximity of the engine. First boiling bubbles observed in a test rig emerged at significantly lower temperatures for comparable ambient pressures for higher ethanol admixture values compared to both AVGAS and ethanol-free MOGAS. Accordingly it is to be expected that unlucky mixtures of different gasolines, especially one ethanol-free and one with shares of more than 5 % ethanol, will create a significantly higher vapour pressure compared to the initial components and are thus prone to vapour locks caused by gasoline boiling. This potential effect is to be seen in conjunction with a partially lacking compliance of actual gasoline vapour pressures with agreed-on maximum values — see Fig. 6 — that adds to the threat. Critical temperature conditions were experienced especially at the time of descent immediately before a touch-and-go restart.

Even though typical handheld devices are available to the pilots for vapour pressure assessment a frequently applied device did not exhibit the necessary sensitivity to detect the differences observed in the test rig experiments.

Should ethanol-containing gasolines be approved for aviation purposes in future it would be wise to define a “hot fuel testing” procedure that would take into account the worst possible boundary conditions that might be encountered in practice. As of today this worst condition is given if ethanol is directly admixed to a commercial ethanol-free gasoline in winter quality. For ambient conditions in which the aircraft will operate correctly with such a fuel, any future ethanol-admixed commercial gasoline should impose no stronger risk. This very conservative limit may be somewhat excessive, though, as commercial gasolines with noteworthy ethanol contents will feature lower base volatilities to meet the fugacity norms. Accordingly, any mixture of an ethanol-free gasoline with an ethanol-containing one will exhibit a higher boiling curve and hence less tendency of bubble creation.

So, with defined ethanol-containing gasolines appearing on the market, a number of tests should be performed to identify the worst potential *practical* bubble threat that may originate in mixing different brands. At the same time it should be communicated to all pilots never to prepare mixtures of gasoline and pure ethanol by themselves.

6.6 Material Compatibility of Common Constructive Materials for Aircraft Parts (T 4)

6.6.1 Approach / Methodology

The range of different materials lending themselves for the construction of aircraft parts is very large. Even though quite a lot of constructive elements of an aircraft may have contact with fuel and show a variety of reactions to its compositional change (see Sect. 6.1 and Appendix C) the main focus of the reported investigations lies on the elements of the fuel system. For an in-depth analysis the expertise of a cooperation partner, SGS Institut Fresenius, Dortmund, has been sought. Its report is reproduced in the consecuting section.

Since until recently the admixture of ethanol to vehicle gasolines was of minor concern and ethanol-free gasoline brands ubiquitous the manufacturers of General Aviation parts did not need to bother about this issue. A first bottom-up approach, to identify the materials used in a larger number of fuel system constructive parts researched from respective aircraft spare parts catalogues and contacting their manufacturers with targeted questions, had to get abandoned due to the prohibitively large number of individual parts in question.

Instead a top-down approach was chosen. In order to scrutinize the awareness of a changing fuel situation, at least for potentially MOGAS capable aircrafts, an internet questionnaire was created. About 550 companies busy in the aircraft parts domain were invited to participate in this interrogation. EASA assisted this approach with a Letter of Support that accompanied every invitation. The structure of the questionnaire and the obtained results are detailed in Sect. 6.6.3.

6.6.2 SGS Report on Plastic Materials Compatibility with Ethanol-Admixed Gasolines[5]

Smaller aircraft and engine-driven microlights are fuelled to some extent with gasoline. Both AVGAS and MOGAS are generally used. Due to the increased content of bioethanol in gasoline in the future, problems will arise especially concerning the material compatibility of polymers, elastomers and sealing material of aircraft which are in direct contact with the gasoline.

Polymers in the Aviation Industry

Polymers emerge from the interlinking of molecular chains. The single components of the molecular chains are called monomers and the interlinking process polymerisation. Polymers can be sub-divided into three classes depending on their type, structure and position of the molecular chains: Thermoplastics (amorphous and semi-crystalline), thermosetting plastics and elastomers. Table 10 summarises the different criteria of the polymer classes.

Elastomers

Elastomers are established in the aviation industry as follows:

- Hoses, partially as metal-plastic bonds (e.g. fuel hose, hydraulic hose)
- Seals and profiles (e.g. o-rings, tank sealing)
- Driving belts
- Flexible fuel tanks (e.g. in gliders)
- Tyres

Table 11 summarises the common elastomers with their German, English and French names. Tables 12 and 13 list exemplary trade names with their corresponding manufacturer.

Both tables are the basis for the identification of the elastomers used in the aviation industry. If there is no identification mark on the sample, identification is only possible with the help of suitable chemical analyses (e.g. infrared spectroscopy (ATR FT-IR)).

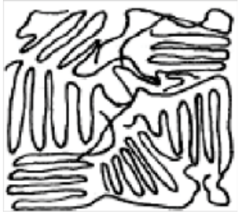
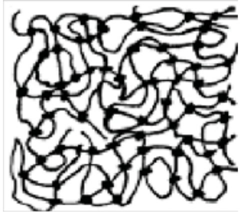
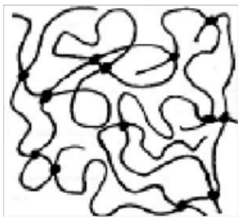
	Thermoplastics		Thermosetting Plastics	Elastomer
	Amorphous	Semi-crystalline		
Structure	 linear, unbranched chains, non-crystalline, uncured	 branched chains, semi-crystalline, uncured	 three-dimensionally cross-linked, non-crystalline	 loose cross-linked structure with wide meshes, semi-crystalline
Process-ability	meltable, ductily-deformable at elevated temperature, remeltable (recycling)	meltable, ductily-deformable at elevated temperature, remeltable (recycling)	only machining operation possible after curing, no remelting possible, not reusable	only elastically deformable, no remelting possible, tendency to thermal destruction at higher temperatures, not reusable
Heat distortion temperature	middle to high	middle to high	high	low
Mechanical behaviour	good combination of strength and toughness	good combination of strength and toughness	high strength, low elasticity	high elasticity low strength

Table 10: *Different polymer classes*

Tables 14 and 15, and Figures 56 to 56 summarise the properties and compatibilities of the most important elastomers.

As an example a potential replacement strategy observing specific properties of ethanol admixtures shall be discussed for the commonplace elastomers. In avionics most flexible hoses or junctions are made from nitrile rubbers or close derivatives (NBR, H-NBR and X-NBR). This is, in view of AVGAS or present-day MOGAS usage, unquestionably favourable: These rubbers yield a sensible temperature stability (Fig. 54), a low swelling rate (Fig. 55), and a good chemical resistivity against the typical, non-alcohol-admixed gasoline types (Fig. 56).

As soon as larger amounts of ethanol are present in the gasoline the picture changes, especially for the NBR materials' chemical resistance against this mixture: Fig. 56 (columns "gasoline-benzene-ethanol" in the sections of *CKD* and *Busak & Shamban* render them as unappropriate for such mixtures.

Instead of nitrile rubbers, fluoro rubbers as well as fluorosilicone rubbers (FFKM, FKM and FVMQ) are offering themselves as viable alternatives: While being chemically compatible with ethanol as well (Fig. 56) they offer a comparative or even better swelling behaviour (Fig. 55) and

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[5] This section is a slightly adapted version of the original SGS report which is enclosed for reference as a separate attachment to this report

Elastomer	Chemical name German	Chemical name English	Chemical name French
ACM	Polyacrylat-Kautschuk	polyacrylate rubber	caoutchouc polyacrylique
AEM	Ethylen-Acrylat-Kautschuk	ethylen-acrylate rubber	caoutchouc déthylèneacrylate
AU EU	Polyurethan-Kautschuk: Polyesterurethan Polyetherurethan	polyurethane rubber	caoutchouc de polyuréthane
BIIR	Brombutyl-Kautschuk (Brom-Isobuten-Isopren Kautschuk)	bromobutyl rubber	caoutchouc butylbromique
CIIR	Chlorbutyl-Kautschuk (Chlor-Isobuten-Isopren-Kautschuk)	bromchloride rubber	caoutchouc butylchlorique
CO	Epichlorhydrin-Kautschuk	epichlorohydrine rubber	caoutchouc épichlorhydrine
CSM	Chlorsulfonyl-Polyethylen-Katuschuk	hypalon	hypalon
ECO	Epichlorhydrin-Copolymer-Kautschuk	epichlorhydrine-copolymere rubber	
EPR / EPDM	Ethylen-Propylen-Dien-Kautschuk Ethylen-Propylen-Copolymer (EPR)	ethylene-propylene-diene rubber	caoutchouc éthylène propylène diène monomère
FFKM / FFPM	Perfluor-Kautschuk	perfluoro rubber	caoutchouc perfluoré
FKM	Fluor-Kautschuk	fluoro rubber	caoutchouc fluoré
FVMQ	Fluorsilikonkautschuk	fluorsilicone rubber	caoutchouc fluorosilicone
MQ	Silikon-Kautschuk Methyl-Polysiloxan	silicone rubber	caoutchouc silicone
VMQ	Methyl-Vinyl-Silikon-Kautschuk	methyl-vinyl silicone rubber	caoutchouc méthyl-vinyl-silicone
IIR	Butyl-Kautschuk (Isobuten-Isopren-Kautschuk)	butylene rubber	caoutchouc butylène
NBR	Nitril-Kautschuk (Acrylnitril-Butadien-Kautschuk)	nitrile rubber	caoutchouc nitrile
X-NBR	Carboxylierter Nitril-Kautschuk	carboxilited nitrile rubber	caoutchouc nitrile carboxylique
HNBR	Hydrierter Nitril-Butadien-Kautschuk	hydrogenated nitrile-butadiene rubber	caoutchouc nitrile hydrogénique
NR	Natur-Kautschuk	natural rubber	caoutchouc naturel
SBR	Styrol-Butadien-Kautschuk	styrene-butadiene rubber	caoutchouc styrène-butadiène

Table 11: *Common Elastomers*

the same appropriateness for cold ambient conditions. With respect to hot conditions they usually outperform the nitrile rubber variants (Fig. 54).

Elastomer	Trade name and manufacturer (examples)	
ACM	Noxtite-PA	Denki Kagugi Chemicals
	Hytemp	Zeon Chemicals
	Nipol AR	Zeon Chemicals
	Hycar	BF Goodrich
	Europrene AR	Enichem Elastomeri
	Cyanacryl	Enichem Elastomeri
	Vamac	Du Pont Dow Elastomers
	Thiacril	Thiokol Chemical Corp.
AEM	Vamac	Du Pont Dow Elastomers
AU EU	Pellethane	Dow Chemical
	Vibrathane	Uniroyal Inc.
	Urepan	Bayer
	Elastothane	Compounding Ingredients
	Adiprene	Uniroyal Inc.
	Desmopan	Bayer
	Vulkollan	Bayer
	Estanev	BF Goodrich
	Cyanaprene	American Cyanamid
BIIR		
CIIR	Esso Butyl H10	Esso
CO	Herclor C	Hercules Chemicals
SM	Hypalon	Du Pont Dow Elastomers
	Noralon	Denki Kagugi Chemicals
ECO	Hydrin	Zeon Chemicals
	Herclor H	Hercules Chemicals
	Gechron	Zeon Chemicals
EPR / EPDM	Dutral	Montedison, USA
	Keltan	DSM / Sabic
	Vistalon	Exxon Chemical Co.
	Buna EP / AP	Chemische Werke Hüls
	Nordel	Du Pont Dow Elastomers
	Royalene	Uniroyal, Inc.
	Epcar	Goodrich
	Epsyn	Copolymer Rubber
	Polysar-EPDM	Bayer
FFKM / FFPM	Isolast	Trelleborg Sealing Solutions
	Celrez	CKD Dichtungstechnik
	Kalrez	Du Pont Dow Elastomers
	Simriz	Simrit
	Chemraz	Greene Tweed
	Perlast	Precision Polymer Engineering
FKM	Dai-El	Daikin Industries
	Fluorel	3M Company (Dyneon)
	Tecnoflon	Montedison, USA
	Viton	Du Pont Dow Elastomers
	Noxtite	Denki Kagugi Chemicals
	Sylon	3M Corporation
	Aflas	Asashi Glass Co., Ltd.

Table 12: *Exemplary Trade Marks of Elastomers*

Elastomer	Trade name and manufacturer (examples)	
FVMQ	Silastic LS	Dow Corning
	FSE	General Electric
MQ		
VMQ	Rhodorsil	Rhone Poulenc
	Silastic	Dow Corning
	Silopren	Bayer
	Silplus	General Electric
IIR	Esso Butyl	Esso
	Exxon Butyl	Exxon Chemical Co.
	Polysar Butyl	Bayer
	Enjay Butyl	Enjay
	Bucar Butal	Columbia Carbon Co.
	Petro-Tex Butyl	Petro-Tex Chemical Co.
NBR	Breon	BP Chemicals
	Chemigum	Goodyear
	Elaprim	BF Goodrich
	Hycar	DSM Copolymer, Inc.
	Nysyn	Revertex
	Butakon	
X-NBR	Butacril	Was Ugine Kuhlmann
	Buna N	Chemische Werke Hüls
	Perbunan N / NT	Bayer
	Paracril	Uniroyal
	Krynac	Bayer
	Europrene N	Enichem Elastomeri
	Nipol N	Zeon Chemicals
HNBR	Therban	Bayer
	Zetpol	Zeon Chemicals
	Tornac	Bayer
NR	Crepe	
	SMR	
	SIR	
	Natsyn	Goodyear
SBR	Buna Hüls	Chemische Werke Hüls
	Buna S	Chemische Werke Hüls
	Europrene	Enichem Elastomeri
	Polysar S	Bayer
	Phioflex	
	Phiolite	Goodyear
	Stereon	
	Solprene	Fina Chemicals
	Rhodorsil	Rhone Poulenc
	Clariflex S	
	Plioflex	Goodyear
	Carom	Chemisches Kombinat

Table 13: *Exemplary Trade Marks of Elastomers (continued)*

Elastomer	Properties
ACM	• only medium strength, low elasticity, disadvantageous low-temperature performance • (very) good ageing, oxidation and ozone resistance • excellent resistance against heat and hot oil • application in automotive industry due to its very good heat resistance and its resistance against highly addivated lubricants
AEM	• good resistance against mineral oils, water and cooling agents, good weather and ozone resistance
AU EU	• very high tear strength, notch and friction resistance, high tensile strength, high breaking elongation, low compression set • EU has better hydrolysis resistance • good resistance against mineral oils, water and cooling agents, very good ageing- and ozone resistance • low expansion when exposed to e.g. alcohol
BIIR	• good resistance against acids, glycol brake fluids and hot water
CIIR	• good resistance against acids, glycol brake fluids and hot water
CO	• good high temperature properties • good weather and ozone resistance • good resistance against gasoline and mineral oils and mineral oil greases
CSM	Properties depending on chlorine content: • low chlorine content: best heat resistance and low-temperature flexibility, fair oil resistance • high chlorine content: better resistance against oils, less heat resistance and low-temperature flexibility • abrasion-resistant • good chemical, ageing and ozone resistance
ECO	• good low-temperature flexibility, good high temperature properties • good resistance against gasoline and mineral oils and mineral oil greases
EPR / EPDM	• high elasticity, good low-temperature behaviour • good resistance against hot water, very good ageing, weather and ozone resistance
FFKM / FFPM	• combines the high temperature toughness of a fluorocarbon elastomer with the chemi-cal inertness of Teflon • very good mechanical properties even at high temperatures, high tearing strength • mechanical properties depend strongly on composition • excellent resistance against almost all chemicals
FKM	• very good mechanical properties even at high temperatures, high tearing strength • very good resistance against oils and chemicals, heat resistant

Table 14: *Properties of elastomers*

Elastomer	Properties
FVMQ MQ VMQ	• good compression set, low strength, bad abrasion properties, good - very good low-temperature flexibility • FVMQ combine the good temperature properties of the silicones with the good chemical resistance of the fluorocarbones [F0E0?] advanced resistance against fuels and oils • high thermical resistance, ageing, ozone and weather resistant
IIR	• good resistance against acids, glycol brake fluids and hot water as well as good oxygen, chemicals, ozone and solvent resistance
NBR X-NBR HNBR	• good combination of low compression set, high tensile strength and good abrasion resistance, high shock resistance, low-temperature flexibility, however, properties depend on ratio butadiene:acrylonitrile (e.g. increasing butadiene content: resistance increases but low temperature flexibility decreases) • X-NBR is more abrasion resistant than NBR • HNBR: advanced mechanical properties (better abrasion resistance, low temperature flexibility, high impact resilience) • bad ozone, weather and ageing resistance for NBR, no direct exposure to sunlight, avoid contact with high-polar solvents • HNBR: advanced resistance against heat, oil, oil additives and ozone
NR	• good mechanical strength and elasticity, high flexural fatigue strength, very good abrasion resistance, low compression set, high tensile strength, high abrasion resistance and tear resistance • good resistance against organic acids, alcohol and brake fluids, bad resistance against e.g. sunlight, ozone and gasoline • flammable
SBR	• advanced abrasion and ageing resistance, good low and high temperature resistance • good resistance against brake fluids

Table 15: *Properties of elastomers (continued)*

As a conclusion it is recommendable to exchange nitrile rubbers as not being sufficiently qualified for their usage in the aviation industry if in contact with ethanol-admixed gasolines, against more resistant materials. Even though for most material changes recourses may be made to experiences gathered in automotive industries all newly introduced elastomers should generally undergo a sufficient qualification before they are assembled in aircraft, to exclude any potentially overlooked effects distinguishing avionics from automotive applications.

Not only the components of the fuel system but also those with an indirect contact with fuels (gaseous or liquid phase) should be critically inspected. All kind of sealings in the engine compartement as well as tyres are to be mentioned which can come into contact with fuels due to leakage or fuel-filling.

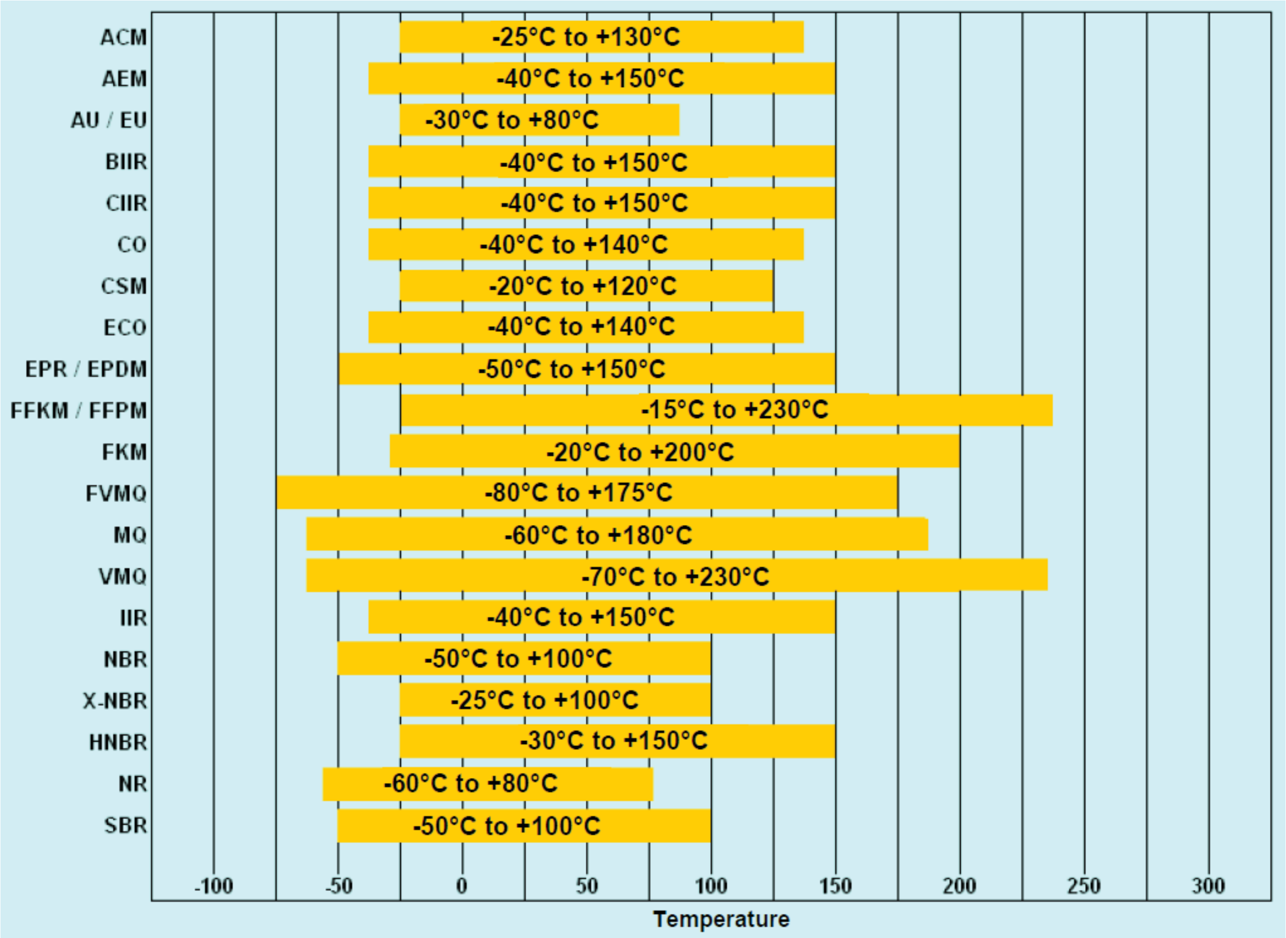


Figure 54: *Temperature resistance of elastomers*

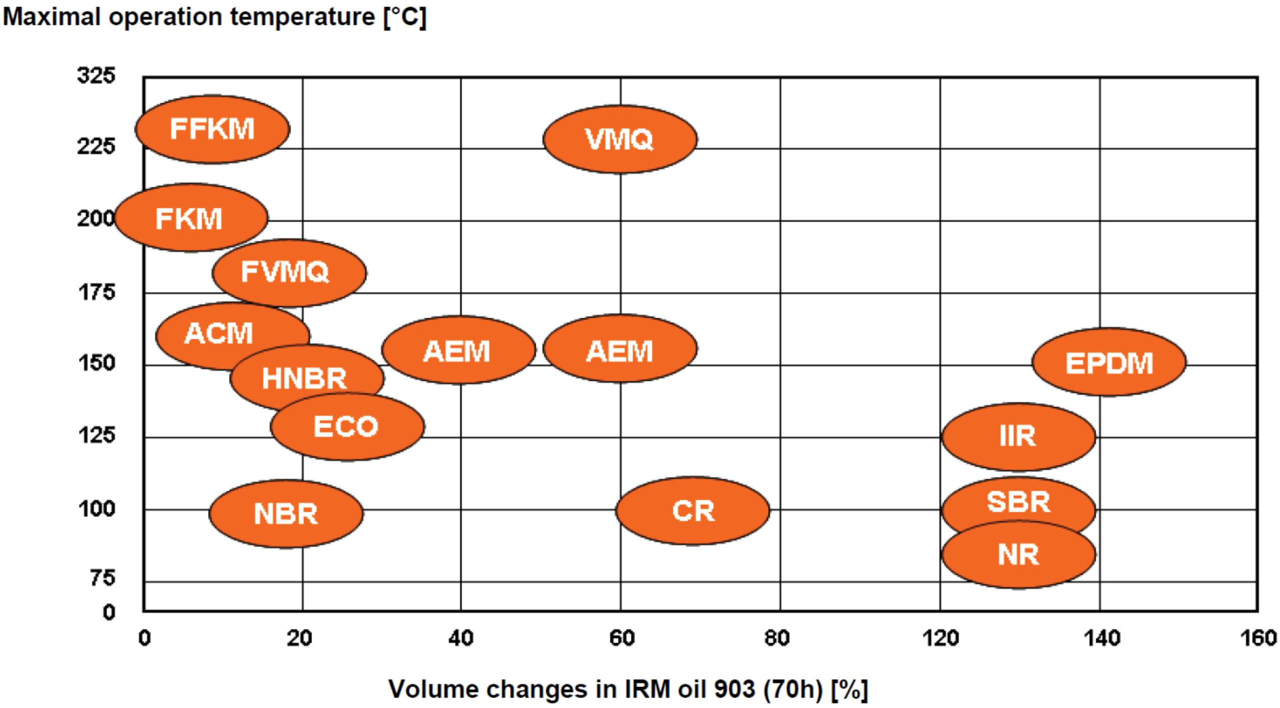
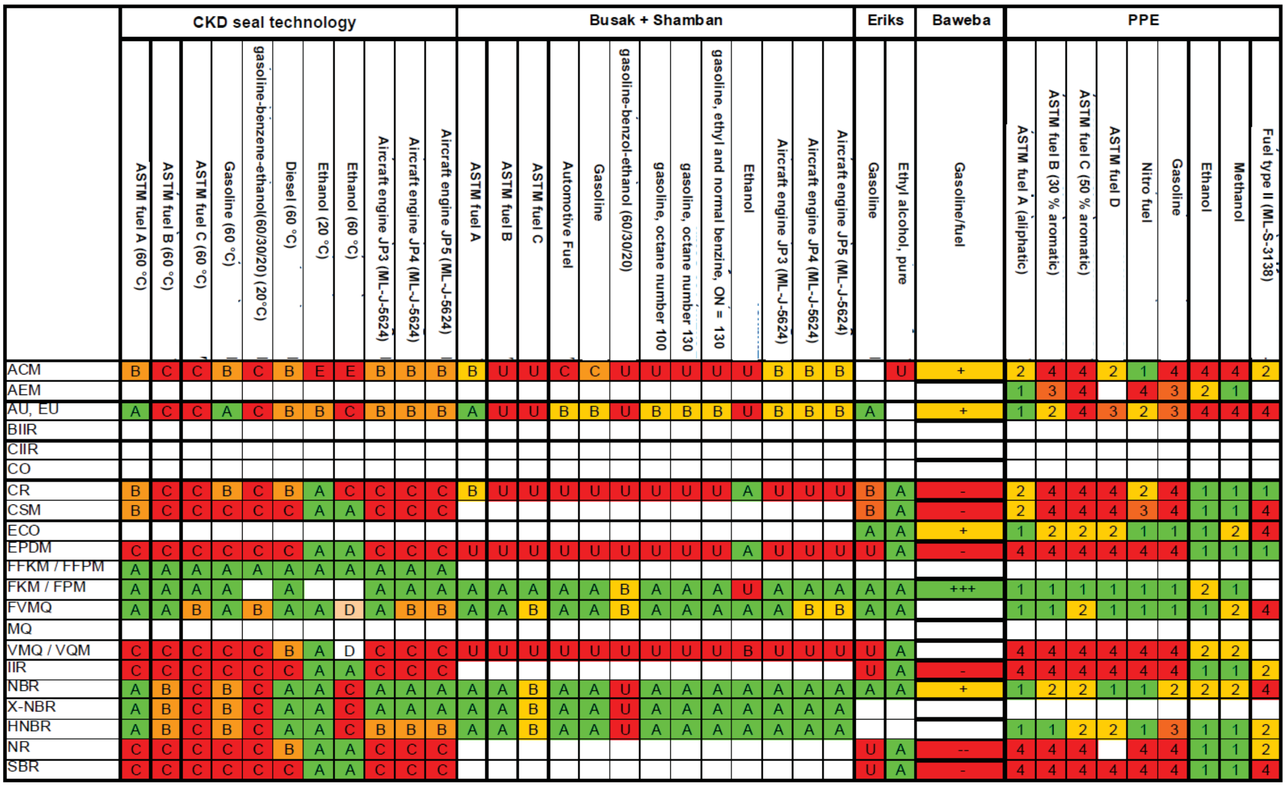


Figure 55: *Oil resistance of elastomers*



	CKD seal technology											Busak + Shamban													Eriks		Baweba	PPE								
	ASTM fuel A (60 °C)	ASTM fuel B (60 °C)	ASTM fuel C (60 °C)	Gasoline (60 °C)	gasoline-benzene-ethanol(60/30/20) (20°C)	Diesel (60 °C)	Ethanol (20 °C)	Ethanol (60 °C)	Aircraft engine JP3 (ML-J-5624)	Aircraft engine JP4 (ML-J-5624)	Aircraft engine JP5 (ML-J-5624)	ASTM fuel A	ASTM fuel B	ASTM fuel C	Automotive Fuel	Gasoline	gasoline-benzol-ethanol (60/30/20)	gasoline, octane number 100	gasoline, octane number 130	gasoline, ethyl and normal benzine, ON = 130	Ethanol	Aircraft engine JP3 (ML-J-5624)	Aircraft engine JP4 (ML-J-5624)	Aircraft engine JP5 (ML-J-5624)	Gasoline	Ethyl alcohol, pure	Gasoline/fuel	ASTM fuel A (aliphatic)	ASTM fuel B (30 % aromatic)	ASTM fuel C (50 % aromatic)	ASTM fuel D	Nitro fuel	Gasoline	Ethanol	Methanol	Fuel type II (ML-S-3138)
ACM	B	C	C	B	C	B	E	E	B	B	B	B	U	U	C	C	U	U	U	U	U	B	B	B		U	+	2	4	4	2	1	4	4	4	2
AEM																												1	3	4		4	3	2	1	
AU, EU	A	C	C	A	C	B	B	C	B	B	B	A	U	U	B	B	U	B	B	B	U	B	B	B	A		+	1	2	4	3	2	3	4	4	4
BIIR																																				
CIIR																																				
CO																																				
CR	B	C	C	B	C	B	A	C	C	C	C	B	U	U	U	U	U	U	U	U	A	U	U	U	B	A	-	2	4	4	4	2	4	1	1	1
CSM	B	C	C	C	C	C	A	A	C	C	C														B	A	-	2	4	4	4	3	4	1	1	4
ECO																									A	A	+	1	2	2	2	1	1	1	2	4
EPDM	C	C	C	C	C	C	A	A	C	C	C	U	U	U	U	U	U	U	U	U	A	U	U	U	U	A	-	4	4	4	4	4	4	1	1	1
FFKM / FFPM	A	A	A	A	A	A	A	A	A	A	A																									
FKM / FPM	A	A	A	A		A			A	A	A	A	A	A	A	A	B	A	A	A	U	A	A	A	A	A	+++	1	1	1	1	1	1	2	1	
FVMQ	A	A	B	A	B	A	A	D	A	B	B	A	A	B	A	A	B	A	A	A	A	A	B	B	A	A		1	1	2	1	1	1	1	2	4
MQ																																				
VMQ / VQM	C	C	C	C	C	B	A	D	C	C	C	U	U	U	U	U	U	U	U	U	B	U	U	U	U	A		4	4	4	4	4	4	2	2	
IIR	C	C	C	C	C	C	A	A	C	C	C														U	A	-	4	4	4	4	4	4	1	1	2
NBR	A	B	C	B	C	A	A	C	A	A	A	A	A	B	A	A	U	A	A	A	A	A	A	A	A	A	+	1	2	2	1	1	2	2	2	4
X-NBR	A	B	C	B	C	A	A	C	A	A	A	A	A	B	A	A	U	A	A	A	A	A	A	A												
HNBR	A	B	C	B	C	A	A	C	B	B	B	A	A	B	A	A	U	A	A	A	A	A	A	A				1	1	2	2	1	3	1	1	2
NR	C	C	C	C	C	B	A	A	C	C	C														U	A	--	4	4	4		4	4	1	1	2
SBR	C	C	C	C	C	C	A	A	C	C	C														U	A	-	4	4	4	4	4	4	1	1	4

🟥 not resistant
🟧 badly resistant
🟨 limited resistant
🟩 resistant

Figure 56: *Gasoline and ethanol resistance of elastomers*

Thermoplastics

Thermoplastics are materials which are soft or stiff at operation temperature. A transition area lies above the operation temperature where the thermoplastic starts to melt. Formed parts can be produced by e.g. compression moulding, extrusion, injection moulding in the softened condition. Fig. 57 illustrates the classification of the common thermoplastics.

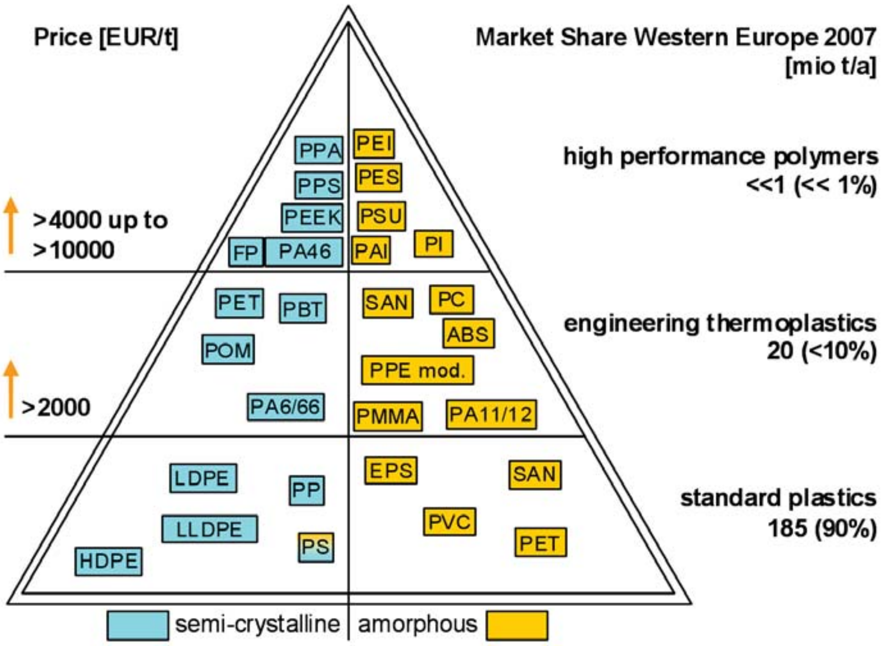


Figure 57: *Classification of thermoplastics*

Thermoplastics are used in the aviation industry for example as:

- Tank material (particularly in microlight aircrafts),
- Material / component in the fuel system (e.g. tank cap, tank ventilation valve, tank opening, filling-level meter, fuel pump, transfer pump, check valve, fuel filter),
- Material for housings of several electrical and electronical components in the motor compartment (e.g. engine control, sensors / actuator),
- Polymer pipe or fitting for different media,
- Fuselage material.

Table 16 summarises the common thermoplastics with their German, English and French names. Tables 17 to 20 list exemplary trade names with their corresponding manufacturers.

Tables 21 to 24 summarise the properties and resistances of the most important thermoplastics. The use of amorphous polymers, such as PC, PVC, PS, PPO and PMMA, should be avoided in contact with gasoline due to the potential effect of environmental stress cracking. Furthermore, the use of blend materials could be critical and is not included in the study.

It can be assumed that the mass product polyethylene (PE), the technical polymers polyamide (PA), polyethylene terephthalate (PET), polyacetal (POM), polybutylen terephthalate (PBT), polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS) as well as the special polymers polytetrafluoroethylene (PTFE), polyetheretherketone (PEEK), and polyphenylene sulfide (PPS) are assembled in systems with direct gasoline contact as these materials are resistant against conventional gasoline.

Elastomer	Chemical name German	Chemical name English	Chemical name French
PE	Polyethylen	polyethylene	polyéthylène
PA	Polyamid	polyamide	polyamide
PC	Polycarbonat	polycarbonate	polycarbonate
PVDF	Polyvinylchlorid	polyvinylidene fluoride	polyfluorure de vinylidène
PVC	Polyvinylchlorid	polyvinyle chloride	polychlorure de vinyle
PTFE	Polytetrafluorethylen	polytetrafluorethylene	polytétrafluoroéthylène
PU	Polyurethan	polyurethane	polyuréthane
PS	Polystyrol	polystyrene	polystyrène
SB	Styrol-Butadien	styrene-butadien	styrène-butadiène
PP	Polypropylen	polypropylene	polypropylène
PPS	Polyphenylensulfid	polyphenylensulfide	polyphenylene Sulfide
PPTA	Poly-p-phenylenterephthalamid	poly-p-phenylenterephthalamide	poly-para-phénylène téréphtalamide
PMIA	Poly-m-phenylene-isophthalamid	poly-m-phenylene-isophthalamide	poly-m-phénylène isophtalamide
PPO	Polyphenylenoxid	polyphenylenoxid	polyoxide de phénylène
PMMA	Polymethylmethacrylat	polymethylmethacrylate	polyméthacrylate de méthyle
PMP	Polymethylpenten	polymethylpentene	polyméthylpentène
PI	Polyimid	polyimide	polyimide
PIB	Polyisobutylen	polyisobutylene	polyisobutylène
POM	Polyoxymethylen	polyoxymethylene	polyoxyméthylène
PET	Polyethylenterephthalat	polyethylenterephthalate	polyéthylène téréphtalate
PEEK	Polyetheretherketon	polyetheretherketone	polyétheréthercétone
PEI	Polyetherimid	polyetherimide	polyéther imide
PBT	Polybutylenterephthalat	polybutylenterephthalate	polybutylène Téréphthalate
PB	Poly(ethylen-co-1-buten)	poly-ethylen-co-1-butene	polybutadièn de éthylène-co-1
PES	Polyethersulfon	polyethersulfone	polysulfone d'éther
PEO / PEG	Polyethylenoxid / Polyethylenglykol	polyethylenoxide	polyoxide d'éthylène
PMMS	Poly(methyl-stilbenmethacrylat)	polymethyl-stilbenemethacrylate	polyméthacrylate de méthyle-stilbène
PPMS	Poly(p-methylstyrol)	poly-p-methylstyrene	poly-p-methylstyrène
PAN	Polyacrylnitril	polyacrylonitrile	polyacrylonitrile
PBD	Polybutadien	polybutadiene	Polybutadièn
ABS	Acrylnitril-Butadien-Styrol	acrylonitrile butadiene styrene	acrylonitrile butadiène styrène
PSU	Polysulfon	polysulfone	polysulfone

Table 16: *Common thermoplastics*

Except for acrylonitrile-butadiene-styrene (ABS) and amorphous polyamide, all thermoplastics are resistant to ethanol as well. However, their suitability should be tested individually at any rate. All thermoplastics should generally undergo a sufficient qualification before they are assembled in

Thermoplastic		Trade name and manufacturer (examples)	
PE	LDPE	Flexirene	EniChem S.p.A. Italy
	LDPE	Ipethene	Carmel Olefins Israel
	LDPE	Trolen H	Dynamit Nobel (1960)
	LDPE	Lacqtene LD	Atofina GmbH
	LDPE	Mirathen	Dow Plastics
	LDPE	Baylon	Bayer AG
	LLDPE		
	MDPE	Neo-zex	Prime Polymer Co. Ltd.
	HDPE	Eltex	Solvay & Cie S.A.
	HDPE	Finathene	Petrofina SA
	HDPE	Fortiflex	Soltex Polymer (Solvay)
	HDPE	G_Flex	
	HDPE	Hival	General Corp. Polymers
	HDPE	Hostalen	Basell Polyolefin GmbH
	HDPE	Microthene	USI Chemicals (USA)
	HDPE	Ertalen HD	
	HDPE	Lupolen HD	Basell Polyolefin GmbH
	HDPE	Ripolen HD	
	HDPE	Lacqtene HD	Atofina GmbH
	HDPE	Trovidur HDPE	Metzeler
	UHMW	Chirulen	Poly Hi Solidur Deutschland
	UHMW	Hostalen GUR	Basell Polyolefin GmbH
	UHMW	Stamylan UH	Sabic Deutschland
PA	PA6	Durethan B od. BP	Bayer
	PA6	Akulon K	DSM
	PA6	Sustamid 6 (G)	Sustaplast
	PA6	Technyl C	Rhone-Poulenc Rhodia AG
	PA6	Miramid	Leuna Polymer GmbH
	PA6	Ertalon 6 (SA od. PLA)	Quadrant
	PA6	Maranyl 6	ICI America
	PA6	Grilon A	EMS Grivory
	PA6	Tecamid 6	Ensinger
	PA6	Nylatron 6 od. M	Polytron GmbH
	PA6	Ultralon	?
	PA6	Capron (today: Ultramid)	BASF
	PA6	Ultramid B	BASF
	PA66	Zytel	DuPont
	PA66	Maranyl	ICI America
	PA66	Ultramid A	BASF
	PA66	Tecamid 66	Ensinger
	PA610	Edgetek NI-10GF/000	PolyOne
	PA12	Lauramid	Evonik Degussa
	PA612	Vestamid	Evonik Degussa

Table 17: *Exemplary trade marks of thermoplastics*

aircraft (see end of this section, p. 6.6.2).

Thermoplastic	Trade name and manufacturer (examples)	
PC	Astalon	Marplex Australia
	Anjalon	J&A Plastics
	Calibre	Dow Plastics
	Lexan	G.E.
	Makrolon	Bayer AG
PVDF	Dyflor	Evonik Degussa
	Kynar	Arkema
	Solef	Solvay Solexis
	Foraflon	Atochem
	Hylar	Solvay
	Lutonal M	BASF
PVC	Apex	Teknor
	Apiflex	API SpA Italy
	Boltaron	Boltaron
	Kömacel (PVC-panels)	Kömmerling etc.
	Simocell	Simona etc.
PTFE	Teflon	DuPont
	Fluon	Asahi Glass
	Duraflon (Coating?)	
	Dyneon	3M
	Fulton	LNP Sabic
	Hostaflon TF	Ticona
PU	Elastollan Desmodur Desmophen Desmorapid	Elastogran GmbH Bayer Materialscience Bayer Materialscience Bayer Materialscience
PS	Avantra	Ineos Styrenics
	Cosden	BASF
	Daicel Styrol	PlastxWorld
	BASF Polystyrol	BASF
	Styrodur	BASF
SB	BASF Polystyrol	BASF
	Styrolux	BASF
PP	Adflex	LyondelBasell
	Addilene	Addiplast
	Adpro	Eastman
PPS	Ceramer	Ceramer
	Fortron	Ticona
	Tecatron VF	Ensinger (Fortron PPS)
	Bearec	
PPTA	Kevlar	DuPont
	Twaron	Teijin Ltd.
PMIA	Nomex	DuPont

Table 18: *Exemplary trade marks of thermoplastics (continued)*

Thermoplastic	Trade name and manufacturer (examples)	
PPO	Serpol	
	Noryl	General Electric
	PPOX	Oxford Polymers
	Artlex	Sumitomo Chemical
	Dianium	Mitsubishi Plastics
	Norpex	CustomResins
	Prevex	Sabic Innovative Plastics
	Vestoran	Evonik Degussa
PMMA	Diakon	ICI
	Lucite	DuPont
	Oroglas	Atochem
	Degalas	
	Delpet	Asahi Glass
PMP	Zeonex	
	TPX	Mitsui Petrochemical
	Crystalor	Chevron Phillips
PI	Kapton	DuPont
	Sintimid	Degussa
	Aurum	Performance Plastics
	Upilex	UBE Europe GmbH
	Upimol	UBE Europe GmbH
	Vespel	DuPont
PIB	Vistanex (production stopped?)	Exxon Mobile Efremov BASF
	Efrolen	
	Oppanol B	
POM	Bergaform	PolyOne Engineering
	Celcon	Ticona
	Dafnelan	NordColor SpA
	Ultraform	BASF
	Hostaform	Ticona
	Delrin	DuPont
PET	Terylene	Imperial Chemical Industries
	Aspect	
	Cleartuf	M&G Grupo Mossi & Ghisolfi / Goodyear
	Crystar	DuPont
PEEK	Victrex (PES?)	ICI America / Victrex
	Zyex	Zyex (?)
	Himod (discontinued)	Boedeker
	Gatone	Gharda Chemicals
	Ketron	Quadrant EPP
	Tecapeek	Ensinger (Victrex PEEK?)
	Vestakeep	Evonik Degussa
PEI	Ultem	G.E.
	Pebax	Arkema
	Tecapei	Ensinger (Ultem)

Table 19: *Exemplary trade marks of thermoplastics (continued)*

Thermoplastic	Trade name and manufacturer (examples)	
PBT	Duranex	PolyPlastics Co.
	Durlex	ChemPolymer Corporation
	Deniter	VampTech SpA
	Celanex	Ticona
	Ultradur	BASF
	Vestodur	Evonik Degussa
PB	Duraflex	Shell (?)
PES	Sumikaexcel	Sumitomo Chemical
	Talpa	Mitsui Toatsu Chemicals
	Ultrason E	BASF
PEO / PEG	Polyox	Dow
PMMS		
PPMS		
PAN	Acrilan	Monsanto
PBD	SEETEC BR 1208	Hyundai Petrochemicals
ABS	Retain	Dow Plastics
	Terulan	BASF
	Terlux	BASF
	Tecaron	Ensinger
	Satran	MRC Polymers
	Tarodur	Taro Plast
	Lustran ABS	Bayer MaterialScience
	Blendex	GE Specialty Chemicals
PSU	Ultrason S	BASF

Table 20: *Exemplary trade marks of thermoplastics (continued)*

Thermo-plastic	Properties	
PE	PE-UHMW	• semi-crystalline material • high molecular weight hence high abrasion resistance, wax-like soft surface • low density, good toughness, low strength and hardness, low temperature stability, very good chemical resistance but susceptible to environmenal stress cracking
	PE-HMW	• semi-crystalline material • Properties comparable to PE-UHMW
	PE-HD	• semi-crystalline material • wax-like soft surface, low density, good toughness, low strength and hardness, low temperature stability, very good chemical resistance but susceptible to environmenal stress cracking
	PE-LD	• semi-crystalline material • wax-like soft surface, low density, good toughness, low strength and hardness, low temperature stability, very good chemical resistance but susceptible to environmenal stress cracking
PA	PA6	• semi-crystalline material • coldresistant, shock resistant and impact resistant, abrasion-resistant and high work capacity, high moisture absorption
	PA66	• semi-crystalline material • higher heat distortion temperature than PA6, but lesser impact-resistance compared to PA6 • shock resistant, abrasion-resistant and high work capacity, high moisture absorption
	PA12	• semi-crystalline material • high low-temperature impact strength, good chemical resistance and les-ser moisture absorption, worse mechanical properties than those of PA 6
PC	• amorphous material • PC is a clear transparent material with extremly high impact strength high strength, high temperature resistance, good optical properties and self-extinguishing • Disadvantegeously high chemical incompabitility and high environmental stress cracking can lead to material failure. PC is not qualified for long-term stresses above 20 Mpa, (maximal 10 MPa under temperature influence), not qualified for high dynamic stress, notch-sensitive at edges and offset with small radius	
PVDF	• semi-crystalline material • PVDF combines excellent chemical resistance with good mechanical properties • high toughness, high creep resistance under long-term stresses, good low-temperature properties and high temperature resistance	

Table 21: *Properties of thermoplastics*

Thermo-plastic	Properties	
PVC	PVC-U Hard PVC	• amorphous material • Hard-PVC is a clear transparent polymer. It is hard and brittle at low temperatures. Operation temperature: up to ˜ 65°C, soluble in acetone and esters, resistant against acids, bases, alcoholes and oils
	PVC-P Soft PVC	• amorphous material • Soft-PVC is a rubber-like, flexible, scratch-resistant polymer. Not brittle at low temperatures when suitable plasticisers are added, weldable and glueable, soluble in acetone and esters, resistant against acids, bases, alcoholes and oils, low moisture absorption
	PVC-C post-chlorinated	• amorphous material • highest stiffness and toughness of all PVC-types, very high chemical resistance, operation temperatures up to 90°C, low coefficient of thermal expansion, good electrical isolating properties and low moisture absorption
PTFE	• semi-crystalline material • Polymer with the highest chemical resistance and extremely low adhesion, soft sintered material with low mechanical properties • Resistance against almost all chemicals, very high temperature resistance, non-flammability, low friction coefficient	
PU	• This material class comprises the area from rubber-elasticity to polyamide-hardness. Good resistance against weather as well as many solvents, fuels and lubricants. High elasticity and hardly any plastic deformation also at low temperatures. High damping and abrasion resistance.	
PS	• amorphous material • clear transparent material with high stiffness and hardness • only low toughness hence fracture to impact stress, clear transparent with a brilliant surface	
SB	• amorphous material • Mostly manufactured with injection moulding and foamed thermoplastic moulding (TSG). • extremely shock resistant and hence suitable for shock proof components, well suitable for low temperatures, not sensitive to notches , good electrical properties	
PP	• semi-crystalline material • Offers averaged strength, stiffness and impact resistance at a low price, low density, very good chemical resistance, very good environmental stress cracking resistance (better than PE) but very bad low temperature properties.	

Table 22: *Properties of thermoplastics (continued)*

Thermo-plastic	Properties
PPS	• semi-crystalline material • very stiff material, with many properties in the high performance area • high toughness, also at high temperatures, high dimensional stability, high temperature resistance, good electrical properties, high chemical resistance and flame resistant, tends to brittle fracture behaviour
PPTA	• Mostly used for fibres (z.B. Kevlar) • very high toughness, high impact resistance, high breaking elongation, good vibration damping as well as resistance against acids and bases, additionally very heat resistant and fireproof.
PMIA	• Mostly used for fibres (z.B. Nomex) • very high strength, high impact resistance, high breaking elongation, good vibration damping as well as resistance against acids and bases, additionally very heat resistant and fireproof.
PPO	• amorphous material • high heat distortion temperature and good dimensional stability
PMMA	• amorphous material • transparent, can be dyed with nearly every colour • hard and brittle with high strength and dimensional stability, good weather resistance (light resistance and colour resistance) and scretch resistance
PMP	• semi-crystalline material with high transparency (90 %) • lowest density of all thermoplastic polymers, very high gas permeability (appr. 10 times higher than for polyethylene), very low moisture absorption, high heat distortion temperature and very high resistance against acids and bases
PI	• Mostly used in foils (Kapton-foil) • very high temperature resistance (long-time stress 230°C, short-time stress up to 400°C), low outgassing, radiation resistance and isolating properties, hence mostly used in electronic, insoluble in all known solvents
PIB	• range of properties: viscous oil to plastic tough material to rubber-like material (depends on the degree of polymerisation) • low density, high tear strength, resistant against gegen acids and bases, not UV resistant
POM	• semi-crystalline material • low frictional resistance, good abrasion resistant abrasion strength, excellent spring properties, high fatigue strength at changing stresses, good electrical properties (high punch-though strength and low dielectrical loss factor), good chemical resistance (resistant against solvents), very resistant against stress cracking

Table 23: *Properties of thermoplastics (continued)*

Thermo-plastic	Properties
PET	• semi-crystalline material, alternative to polyacetal (POM) • very high dimensional stability, significantly better than those of POM, high strength and stiffness, but here worse than POM • low slip resistance, very abrasion resistant
PEEK	• semi-crystalline material • Properties comparable to those of POM or PET, but better mechanical properties and very good temperature strength • high strength, high stiffness, good chemical resistance, high radiation strength, hardly flammable, advantageous slip and abrasion behaviour
PEI	• amorphous material with amber-like transparency • unique combination of extraordinary tensile strength and high flexural modulus, also at maximal temperatures, high stiffness, dimensional stability and heat distortation temperture
PBT	• semi-crystalline material, alternative for polyacetal (POM) • comparable properties to PET, advantegous cooling behaviour and therewith better suited for injection moulding • very high dimensional stability, significantly better than POM, high strength and stiffness, but here worser than POM • low slip resistance, very abrasion resistant, advantageous electrical properties
PES	• amorphous material • PES is a transparent material with slight brownish colouration. Due to ist low smoke gas density and its good fire protection equipment preferable use in the interior of the aircraft.
PPMS	• semi-crystalline material
ABS	• amorphous material • Preferable used as housing material due to its high quality, matt-finished and scratch resistant surfaces, resistant against chemicals.
PSU	• amorphous material • PSU is a transparent material with brownish colouration. • Typical application: sterilisable components in the medical and food industry or as cask for hot water treatment (due to its low migration).

Table 24: *Properties of thermoplastics (continued)*

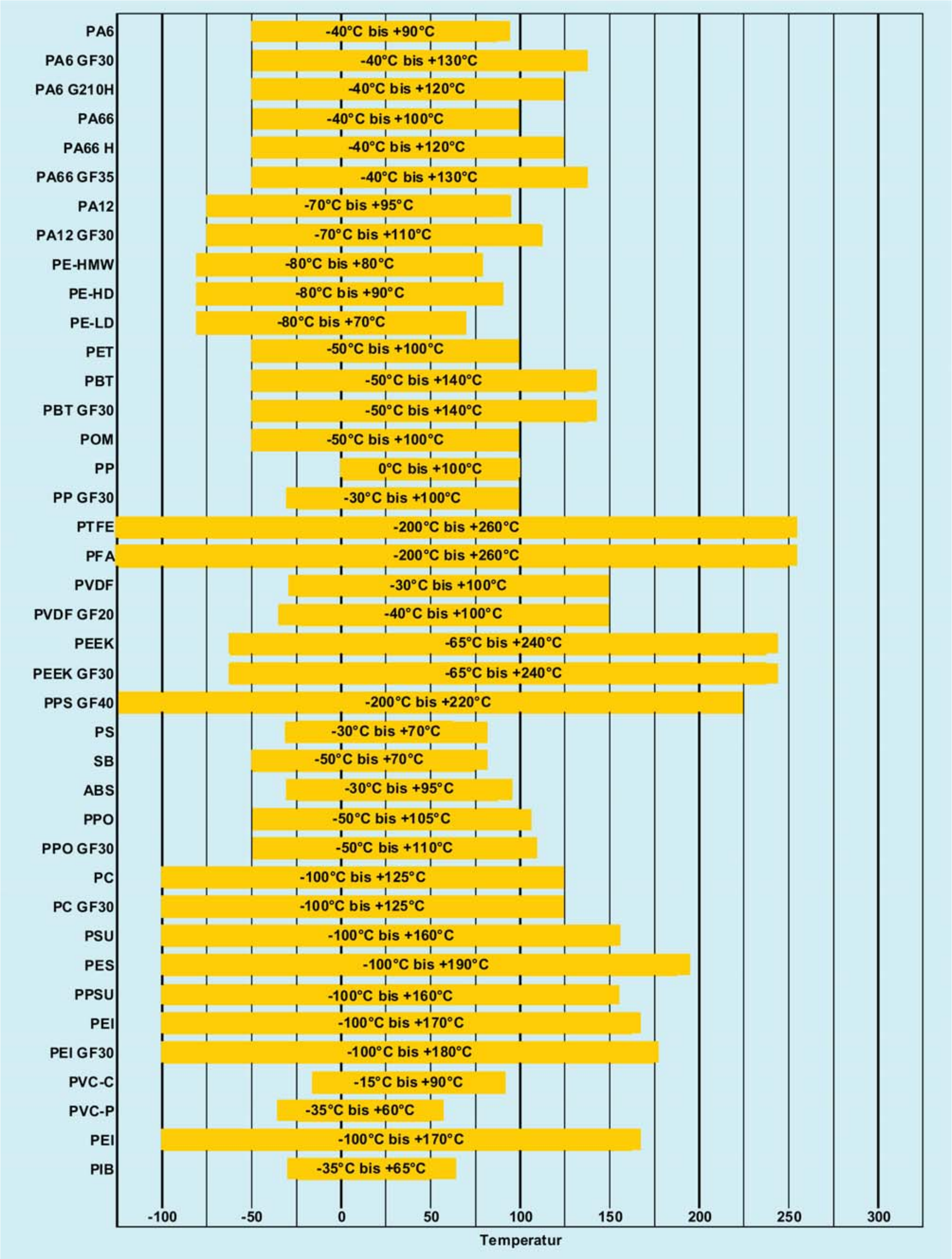
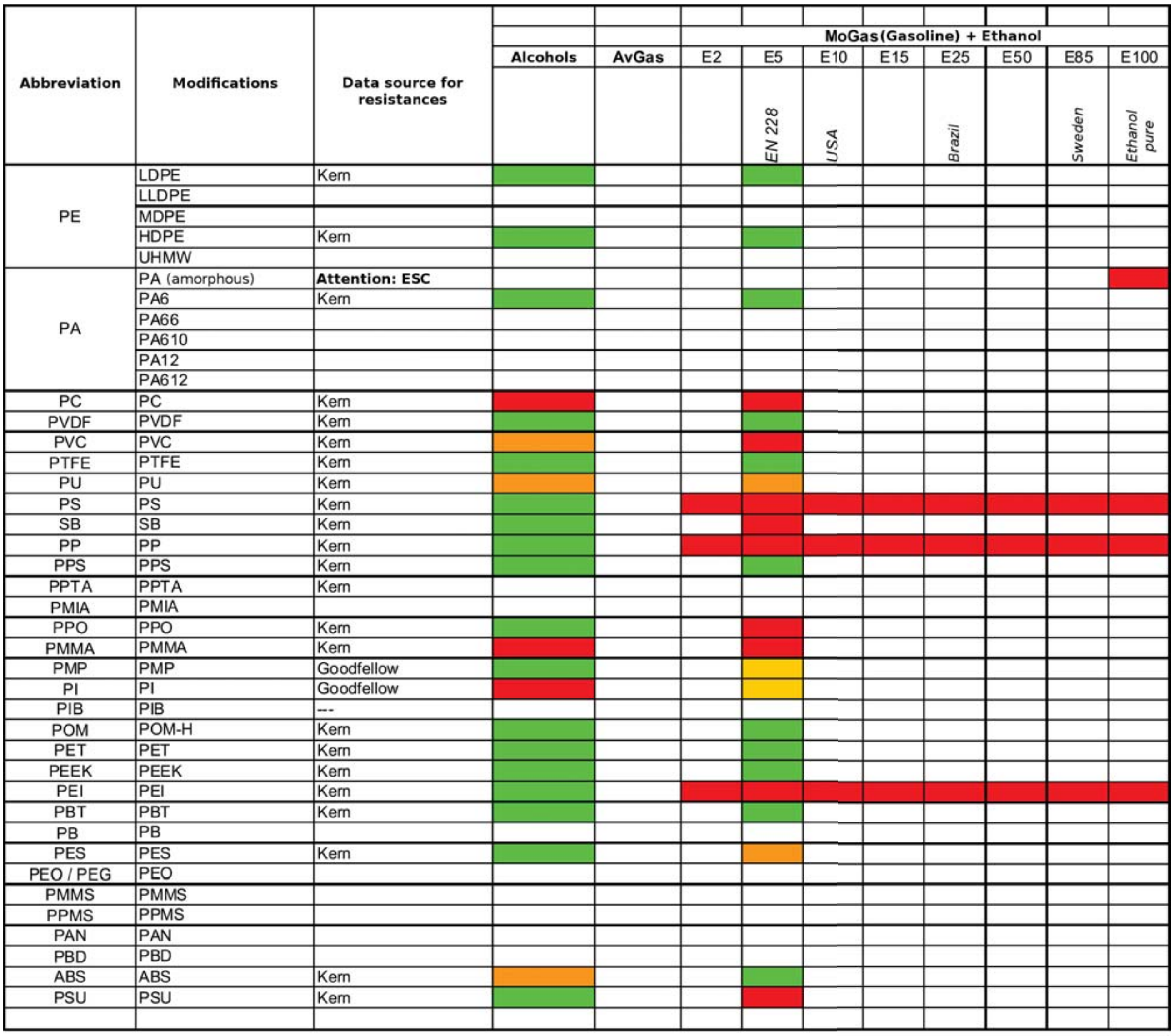


Figure 58: *Temperature resistance of thermoplastics*



Abbreviation	Modifications	Data source for resistances			MoGas(Gasoline) + Ethanol							
			Alcohols	AvGas	E2	E5	E10	E15	E25	E50	E85	E100
						EN 228	USA		Brazil		Sweden	Ethanol pure
PE	LDPE	Kern	🟩			🟩						
	LLDPE											
	MDPE											
	HDPE	Kern	🟩			🟩						
	UHMW											
PA	PA (amorphous)	**Attention: ESC**										🟥
	PA6	Kern	🟩			🟩						
	PA66											
	PA610											
	PA12											
	PA612											
PC	PC	Kern	🟥			🟥						
PVDF	PVDF	Kern	🟩			🟩						
PVC	PVC	Kern	🟧			🟥						
PTFE	PTFE	Kern	🟩			🟩						
PU	PU	Kern	🟧			🟧						
PS	PS	Kern	🟩		🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
SB	SB	Kern	🟩			🟥						
PP	PP	Kern	🟩		🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
PPS	PPS	Kern	🟩			🟩						
PPTA	PPTA	Kern										
PMIA	PMIA											
PPO	PPO	Kern	🟩			🟥						
PMMA	PMMA	Kern	🟥			🟥						
PMP	PMP	Goodfellow	🟩			🟨						
PI	PI	Goodfellow	🟥			🟨						
PIB	PIB	---										
POM	POM-H	Kern	🟩			🟩						
PET	PET	Kern	🟩			🟩						
PEEK	PEEK	Kern	🟩			🟩						
PEI	PEI	Kern	🟩		🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
PBT	PBT	Kern	🟩			🟩						
PB	PB											
PES	PES	Kern	🟩			🟧						
PEO / PEG	PEO											
PMMS	PMMS											
PPMS	PPMS											
PAN	PAN											
PBD	PBD											
ABS	ABS	Kern	🟧			🟩						
PSU	PSU	Kern	🟩			🟥						

🟥 not resistant
🟧 poorly resistant
🟨 partly resistant
🟩 resistant

Figure 59: *Resistance of thermoplastics against gasoline and alcohol / ethanol*

Thermosettings and Sealants

Resins are the most important thermosettings used in the aviation industry. Among these, the most common materials are the following: epoxy, phenol, melamine-phenol and polyester resins, which are also used as adhesives for carbon fibre reinforced and fibre-glass reinforced plastics (CFK / GFK).

Thermosettings are used in the aviation industry as e.g.

- Tank material (GFK tanks) and fuselage tanks respectively,
- Fuselage material,
- Material for wings,
- Material for panelings.

Table 25 shows examples of thermosettings together with trade name and manufacturer. The chemical names are again given in German, English and French.

Duroplast	Chemical name	Trade name	Manufacturer
EP	Epoxidharz (en: epoxy resins fr: résines époxy)	Araldite	Huntsman
		Epikote	Hexion Specialty Chemicals
		Epon	Hexion Specialty Chemicals
		Eponex	Hexion Specialty Chemicals
		Epi-Rez	Hexion Specialty Chemicals
		Epoxin	
		Epilox	Leuna Harze
		Lekutherm	
		Hysol 3450	Henkel
		Hysol 9492	Henkel
		Hysol 3425	Henkel
PF	Phenolharz (en: phenolic resins, fr: phenoplastes)	Bakelite PF31	Hexion Specialty Chemicals
		Bakelite PF31.5	Hexion Specialty Chemicals
		Bakelite PF51	Hexion Specialty Chemicals
MPF	Melamin / Phenolharz (en: melamine phenol formaldehyde resins, fr: résines de mélamine-phénol-formaldéhyde)	Melopas MP183	Raschig
UP	Polyesterharz (en: polyester resins, fr: résines polyester)	Ralupol UP4385	Raschig
		Atlac	DSM
		Palatal	DSM
		Synolite	DSM

Table 25: *Common thermosettings*

The resistances of the resins against different gasoline and ethanol mixtures are given in Fig. 60. They depend on the product variant which can be particularly seen for the epoxy resins Hysol of the Henkel company: Whereas Hysol 3450 and 9492 are resistant against gasoline E-5, type 3425 has only a limited resistance. Additionally the epoxy resins exhibit partially an incompatibility with water, especially at high temperatures and pressures.

The phenol and phenol-melamine resins are to a large extent resistant against alcohol and gasoline E-5. The polyester resins are clearly not resistant against these chemicals. Analogous to the elastomers and thermoplastics, the thermosettings should generally undergo a sufficient qualification before they are assembled in aircraft as well.

Abbreviation	Modification	Source Resistance	Alcohols	Water	MoGas(Gasoline) + Ethanol							
					E2	E5	E10	E15	E25	E50	E85	E100
						EN 228	USA		Brazil		Sweden	Ethanol pure
EP	Araldite											
	Epikote											
	Epon											
	Eponex											
	Epi-Rez											
	Epoxin											
	Epilox											
	Lekutherm											
	Hysol 3450	Henkel data sheet	🟩	🟥		🟩						
	Hysol 9492	Henkel data sheet		🟧		🟩						
	Hysol 3425	Henkel data sheet		🟩		🟧						
PF	Bakelite PF31	Kern	🟩			🟩						
	Bakelite PF31.5	Kern	🟩			🟩						
	Bakelite PF51	Kern	🟩			🟩						
MPF	Melopas MP183	Kern	🟩			🟩						
UP	Ralupol UP4385	Kern	🟧			🟩						
	Atlac	DSM				🟧	🟧			🟧		🟥
	Palatal	DSM					🟧			🟥		🟥
	Synolite	DSM					🟧			🟥		🟥
Polysulfide	Pro-Seal	PPG / PRC-DeSoto	🟩	🟩		🟩						

🟥 not resistant
🟧 partly resistant
🟩 resistant

Figure 60: *Resistance of thermosettings against gasoline and alcohol / ethanol*

Compatibility Test of Polymer Materials

The resistance of elastomers against fuels is tested with an exposure of the elastomer to the respective medium (e.g. E-0, E-5, E-10, E-24, E-85 and E-100) for different periods and temperatures. A compabitility test period may last to up to 5000 hours. For a quantitative evaluation of the effects of the medium onto the polymer mechanical, volumetric and gravimetric parameters are comparatively tested before and after the compability test.

Of particular interest are

- change of breaking elongation,
- change of tensile strength,
- change of density,
- change of hardness (with or without drying),
- change of weight and volume (with or without drying), as well as
- change of thickness.

Different materials or variant formulations can be compared with these test methods and therewith the adequate material can be chosen. Fig. 61 illustrates the results of a compatibility test with an exemplary chosen fluorocarbon elastomer (type: FKM 9022/60).

A further test for the characterisation of the environmental stress cracking sensitivity is recommended for thermoplastics. Environmental stress cracking is solely a physical process and not a chemical attack onto the polymer. Via small incipient cracks a medium penetrates the polymer surface. In combination with mechanical stresses the cracks are enlarged. Finally, a sudden fracture of the polymer occurs. The stresses can thereby be induced during operation (external stresses) or by the injection moulding (internal stresses). Particularly amorphous thermoplastics, like PC, PVC, PS, PPO and PMMA, are sensitive to this mechanism. A lot of liquid media (e.g. grease, oils, lubricants, but also ethanol) can cause environmental stress cracking.

For the testing of a possible effect of bioethanol-containing gasoline onto polymers, tensile bars are produced by injection moulding. These tensile bars are exposed to a defined bending load in a climate chamber. Part of the tensile bars are in contact with the medium. After the end of the test, tensile tests are carried out to detect a decrease of the mechanical properties as these are indicators for environmental stress corrosion. Fig. 62 describes the procedure of this test for polyphenylene sulfide (PPS) with a water-glycol-mixture (representing heat exchanger water from the automotive industry).

Another risk for polymer damage is hydrolysis induced by the presence of water at high temperature (vapour phase). Especially polymers such as PBT, PS, SB, PC, PVC, PMMA and PET are sensitive for hydrolysis damage. PA is basically sensitive at higher temperatures but stabilized in most cases.

Material	Medium	Sampling [h]	Breaking Elongation [%]	Tensile Strength [MPa]	Density [g/cm³]	Hardness	Hardness (without drying)	Mass Change (without drying)	Volume Change (without drying)	Mass Change [%]
FKM 9022/60	E 10	0	338	14,7	1,908	55	55	0	0	
FKM 9022/60	E 10	168	349	13,3	1,892	61	48	4,35	11,35	0,12
FKM 9022/60	E 10	500	327	9,4	1,882	59	49	4,09	10,78	3,30
FKM 9022/60	E 10	750	356	10,1	1,88	59	48	3,89	10,26	3,31
FKM 9022/60	E 10	1000	0	0	0	0	48	3,70	9,76	-100
FKM 9022/60	E 10	2000	0	0	0	0	51	3,78	11,00	-100
FKM 9022/60	E 10	3000	0	0	0	0	53	4,01	9,96	-100
FKM 9022/60	E 10	5000	0	0	0	0	49	4,63	12,58	-100
FKM 9022/60	E 24	0	338	14,7	1,908	55	55	0	0	
FKM 9022/60	E 24	168	344	13,3	1,895	59	47	4,83	13,28	-0,49
FKM 9022/60	E 24	500	340	9,7	1,89	57	47	4,64	14,37	3,18
FKM 9022/60	E 24	750	356	9,7	1,884	58	48	4,17	12,94	2,98
FKM 9022/60	E 24	1000	0	0	0	0	48	3,52	11,20	-100
FKM 9022/60	E 24	2000	0	0	0	0	49	3,41	11,37	-100
FKM 9022/60	E 24	3000	0	0	0	0	51	3,34	11,59	-100
FKM 9022/60	E 24	5000	0	0	0	0	46	2,20	9,47	-100
FKM 9022/60	E 85	0	338	14,7	1,908	55	55	0	0	
FKM 9022/60	E 85	168	364	13,4	1,916	60	49	2,94	8,06	-0,41
FKM 9022/60	E 85	500	377	10,4	1,883	58	49	2,86	8,74	2,07
FKM 9022/60	E 85	750	362	9,8	1,878	58	49	2,40	7,71	2,20
FKM 9022/60	E 85	1000	0	0	0	0	50	1,91	7,11	-100
FKM 9022/60	E 85	2000	0	0	0	0	51	1,60	6,97	-100
FKM 9022/60	E 85	3000	0	0	0	0	53	1,42	6,73	-100
FKM 9022/60	E 85	5000	0	0	0	0	51	0,43	5,22	-100
FKM 9022/60	E 100	0	338	14,7	1,908	55	55	0	0	
FKM 9022/60	E 100	168	355	13,4	1,911	60	51	1,64	3,91	-0,02
FKM 9022/60	E 100	500	369	10,7	1,885	59	52	1,99	4,84	1,47
FKM 9022/60	E 100	750	381	11,1	1,887	60	52	1,84	4,69	1,54
FKM 9022/60	E 100	1000	0	0	0	0	52	1,75	4,60	-100
FKM 9022/60	E 100	2000	0	0	0	0	53	1,75	4,73	-100
FKM 9022/60	E 100	3000	0	0	0	0	54	1,74	4,81	-100
FKM 9022/60	E 100	5000	0	0	0	0	56	1,27	4,05	-100
FKM 9022/60	Otto	0	338	14,7	1,908	55	55	0	0	
FKM 9022/60	Otto	168	326	12,9	1,895	60	50	3,37	9,06	0,06
FKM 9022/60	Otto	500	348	10,8	1,893	58	51	3,36	8,43	4,48
FKM 9022/60	Otto	750	348	11,1	1,882	60	50	3,31	8,74	-2,09
FKM 9022/60	Otto	1000	0	0	0	0	48	3,25	9,12	-100
FKM 9022/60	Otto	2000	0	0	0	0	50	3,39	9,29	-100
FKM 9022/60	Otto	3000	0	0	0	0	53	3,51	9,72	-100
FKM 9022/60	Otto	5000	0	0	0	0	54	3,16	8,13	-100

Figure 61: *Results of compabitility tests of a fluorocarbon elastomer in contact with different fuels (E-10, E-24, E-85, and E-100).*

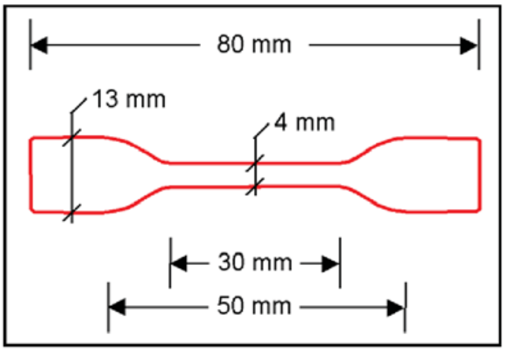
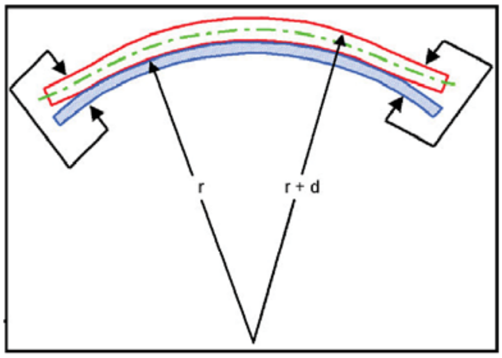
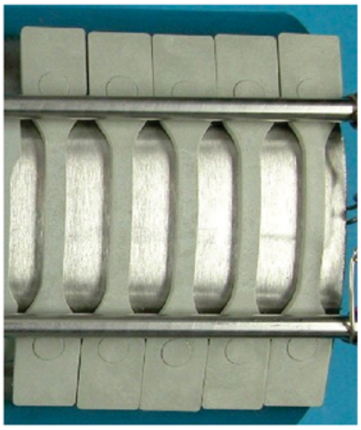
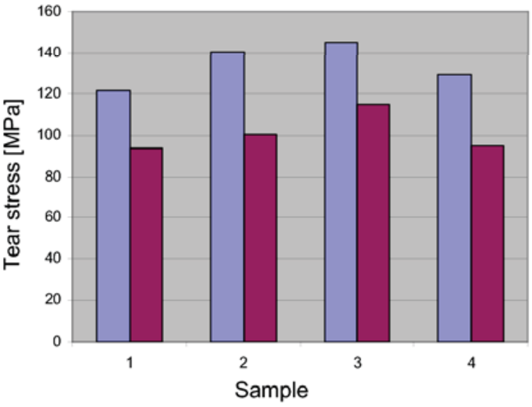
	Production of tensile bars of the tested material by injection moulding
	Bending of the tensile bars on a suitable bending template which generates an outer fibre strain according to the following formula $$\varepsilon_x[\%] = \frac{d}{2r+d} \cdot 100$$
	Illustration of tensile bars fixed on the bending template
	Results of the test of polyphenylene sulfide (PPS) in a water-glycol mixture at a temperature of 90 °C over a period of 500 h: Reduction of tear stress of up to 40% due to test (red bars).

Figure 62: Realisation of a test for environmental stress cracking

6.6.3 Survey on Deployed Materials for Fuel Systems

The assessment of material-originating hazards was undertaken by interrogating GA parts manufacturers and aviation OEMs with the help of a respective custom-built questionnaire. The questionnaire was set up as a web application to which potential respondents are directed via an individualized invitation letter. This letter was accompanied by a letter of support issued by EASA.

Questionnaire Outline

Addressing the issue of material compatibility and the assessing the awareness of aircraft and parts producers is somewhat difficult:

- At the time being there is a clear-cut difference between AVGAS and DIN EN 228 based MOGAS, with the latter being identified mainly as the quality "Super Plus, 98 RON". As until early 2009 no significant amount of ethanol was input into this gasoline quality, no practical experience could be gained with respect to adverse effects of elevated ethanol shares. With very few exceptions the ethanol content remained below the 1 % limit that all MOGAS capable aircraft would accept. Accordingly there was no issue of materials deterioration so far, and producers of aviation parts simply did not have to care about that.
- Even today the AVGAS oriented GA mainstream does not have to cope with ethanol as it is forbidden as an admixture therein, and there will be neither technical nor economical a necessity in the foreseeable future to put it in. In the respective EU regulations and their national ratifications fuels not dedicated to vehicle usage are explicitly unburdened from the admixing quota necessities, otherwise leading to financial penalties for the fuel producers (see Sect.3.3).

Accordingly no parts manufacturer can be regarded as negligent if it did not yet care about the ethanol issue at all. Nevertheless, with the time horizon of aircraft utilization periods it is quite certain that the issue *will* arise sooner or later, so it is interesting to check if manufacturers are already aware of it and if they actively work and develop with this future topic in mind. Such a survey has been undertaken by publishing a publicly accessible web-based questionnaire and addressing the respective companies by a dedicated direct letter to draw attention to it.

In Fig. 63 the structure of this questionnaire is detailed out. As the structure is organized as a hyperlinked system it is very likely that no respondent will see every branch of it. He will rather meet the questions suitable for his respective range of products. Accordingly is the number of answerers to each questions strongly differing.

The questionnaire is structured as follows: A first section of questions interrogates about the general awareness towards the issue "ethanol as a gasoline admixture". Only if the respondent has indicated at least a basic familiarity with the issue direct questions about compatibility of the materials utilized in his parts are asked. Each question has been carefully worded so as not to brusque the respondent in case of not knowing about the respective detail. The order of directly material related questions has been chosen in a way that anticipates the reception of the invitation letter in the individual companies: The questions tree spans out from the rather few practical items the companies manufacture or assemble (tanks, hoses, sensors, pumps, . . .) and goes down into the details of selected construction materials (see fig. 63).

For each question a statistical evaluation can be performed. The questionnaire tree shows the direction of the answer analyses in the boxes with the lighted bulbs for each question.

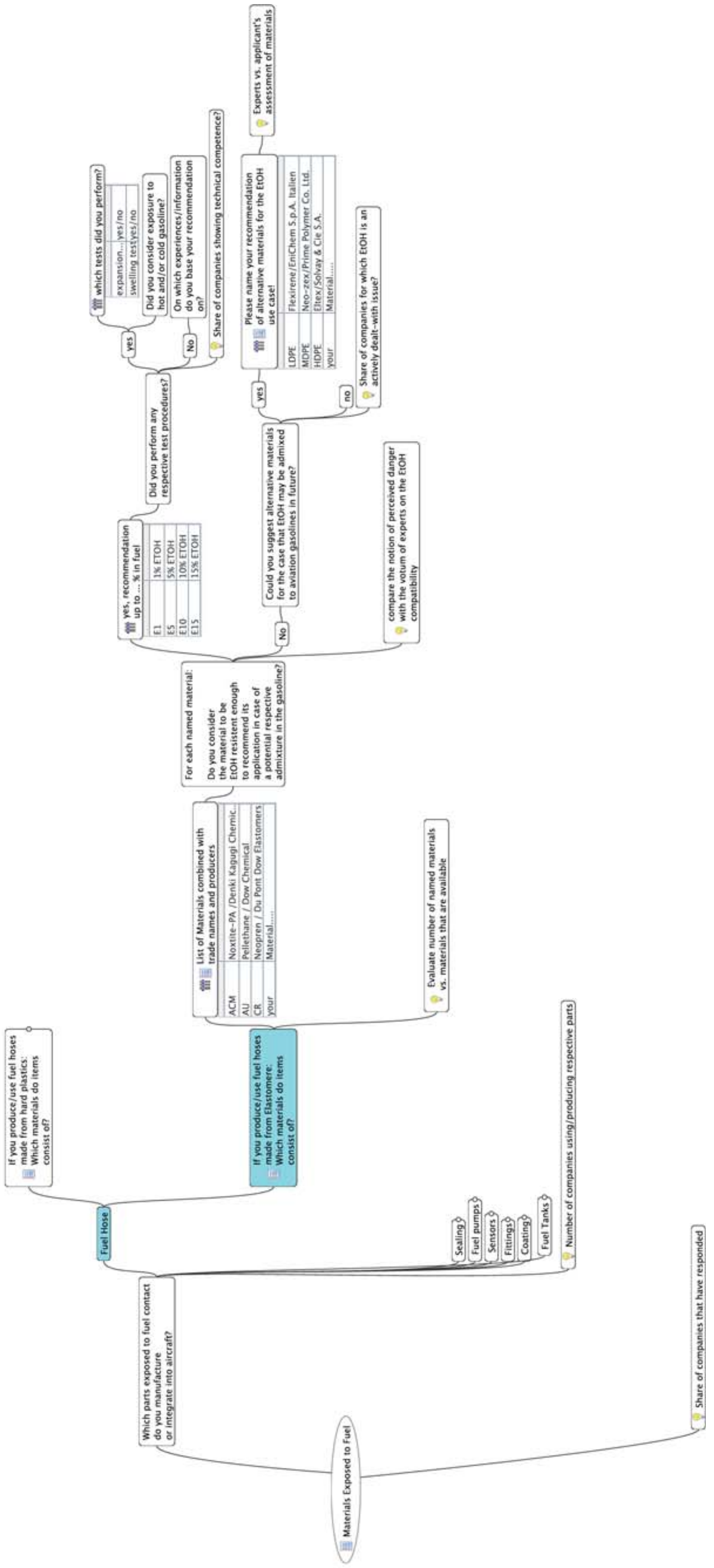


Figure 63: *Materials question tree, expanded for hoses made from elastomeres to its full depth as an example clip from the whole materials questions tree.*

Evaluation of Questionnaire Responses

For easiest possible participation of parts providers or assembling OEM companies across the world the questionnaire has been set up as an internet-based interrogation system accessible via a simple-to-recall URL (http://siobia.fh-aachen.de). 550 companies selected from the German LBA's Certified Aviation Parts Providers List, supplemented with a list of well-known manufacturers not listed therein, have been contacted by a paper mailing. Due to the limited detailedness of the list the type of parts a company produces or handles could not be determined. Accordingly, a certain but non-definable number of them is not involved in fuel related parts.

A small number of excuses were received for not taking part, mostly due to technical difficulties on the participants' side or because of the mentioned non-involvedness in the fuel-related parts sector. 55 participants could be identified that entered the questionnaire at least to a certain extent (Fig 64).

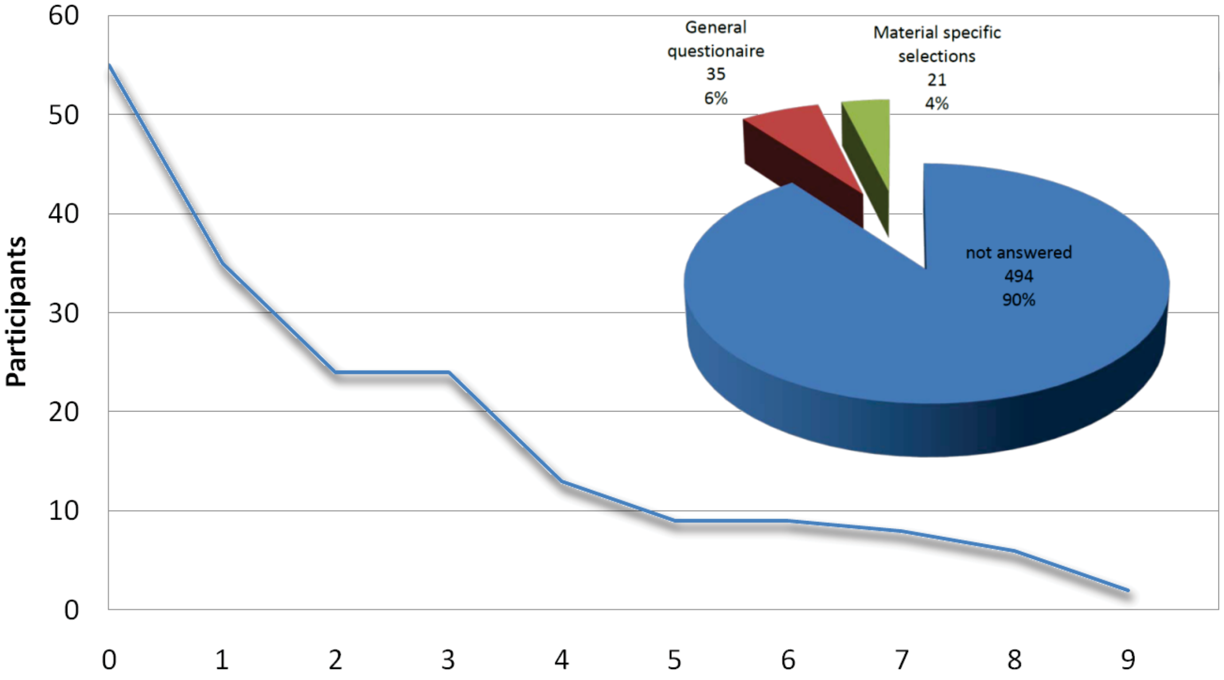


Figure 64: *Decrease of participants' number along the first general questions part of the questionnaire.*

From the starting 55 participants only a gradually decreasing number worked through the general awareness questions, with 21 of them entering the detailed technical questionnaire part. Some of the general questionnaire pages curtailed the interrogation if the given answer rendered a further persecution of the general part insensible, leading to a remaining final participation of only 3 that worked completely through the general part.

From the presented areas of potentially ethanol threat related parts the 21 participating answerers chose grossly an equi-distribution (Fig. 65). The differences in numbers are not statistically significant. It should be kept in mind that the potential answers are not mutually excluding, as the same company can deal with many, if not all, fuel related parts under investigation. Somewhat remarkable is the frequent mentioning of sensors.

Considering the materials or material combinations involved in the named parts again an almost equipartition is found (Fig. 66), with a slight less frequent mentioning of hard plastics.

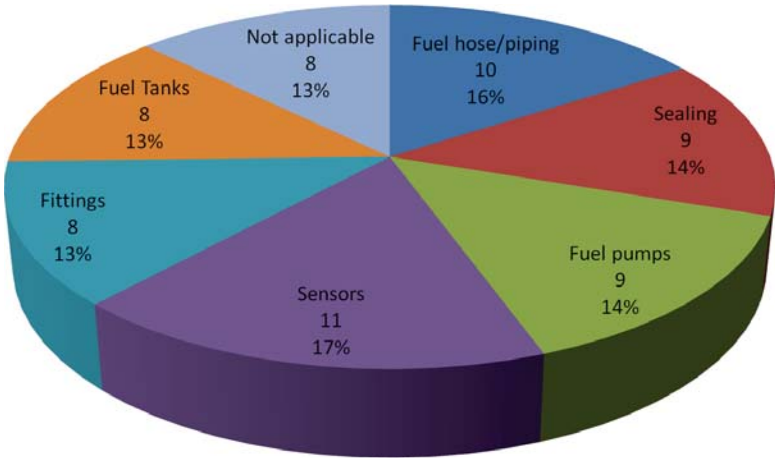


Figure 65: *Mentioned areas of parts production or application (not mutually excluding).*

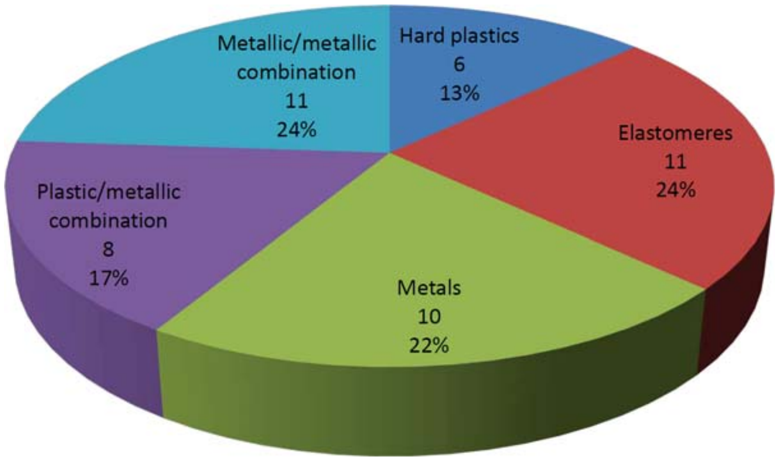
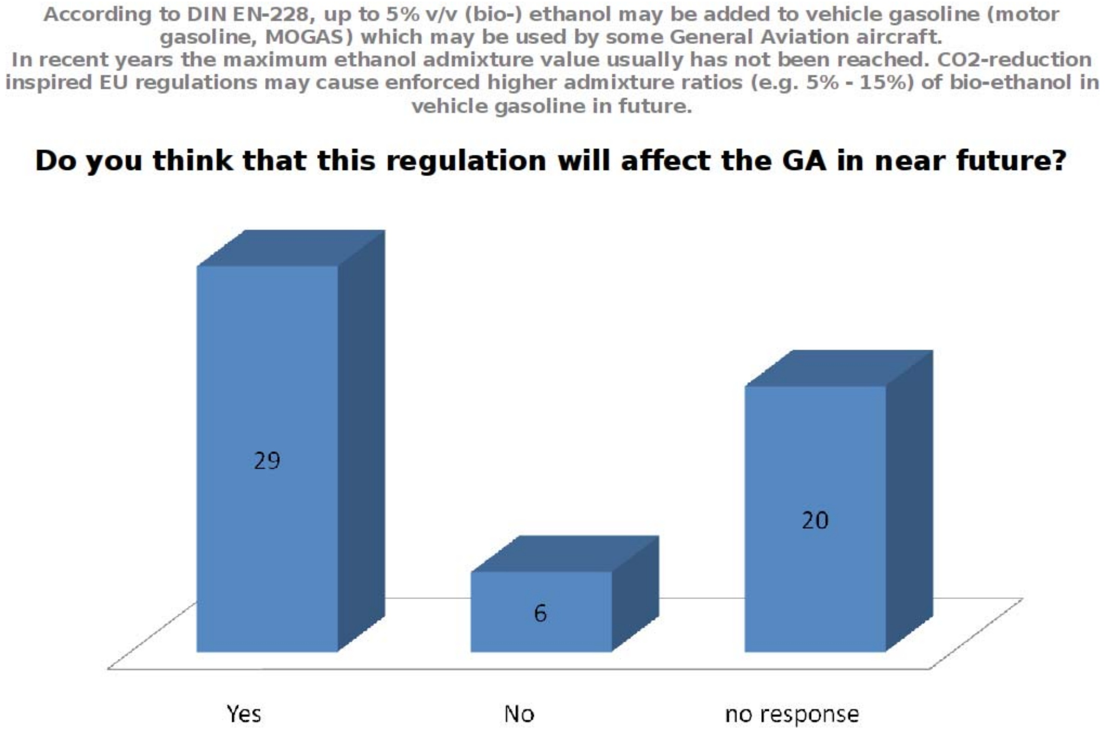


Figure 66: *Distribution of materials for aviation parts production or application (not mutually excluding).*

The main problem in further evaluating the detailed questionnaire part is the low number of mentioning of respective materials or material combinations. Again a wide-spread utilisation of materials is observed, leading to the fact that no listed material has been multiply named to a significant statistical level. Accordingly a further evaluation of individual material classes and their anticipated pontential threat impact is not possible for the data acquired.

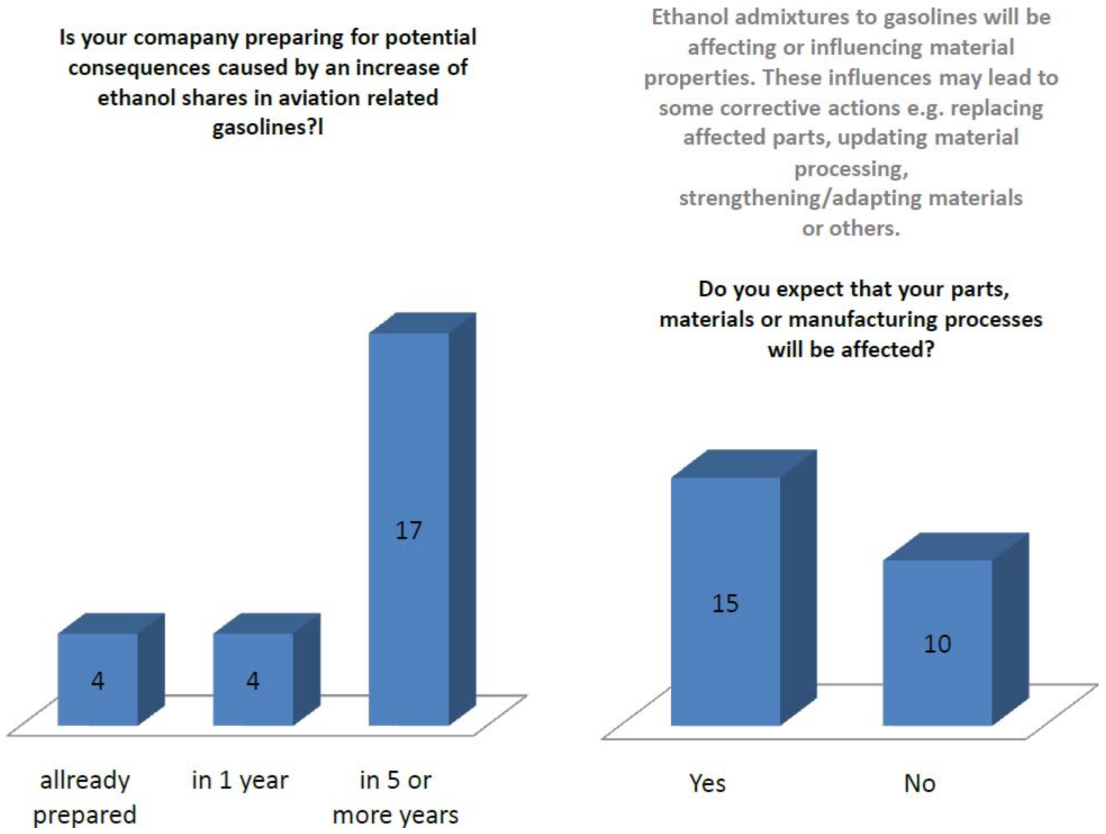
Back to the general awareness questions, quite a large portion of the participants (more than 80 % of those that pondered on the question) indeed expects effects of biogenic admixtures in vehicle gasolines also for aviation matters (Fig. 67). In spite of this large fraction the time horizon for dealing with these potential problems is rather wide: the vast majority expects respective effects no sooner than about 5 years in the future or at least foresees a commercial involvement at that time (Fig. 68). This reflects quite well the present situation for the majority of aircraft, usually oriented towards operating on AVGAS on a more global point of view.



According to DIN EN-228, up to 5% v/v (bio-) ethanol may be added to vehicle gasoline (motor gasoline, MOGAS) which may be used by some General Aviation aircraft.
In recent years the maximum ethanol admixture value usually has not been reached. CO2-reduction inspired EU regulations may cause enforced higher admixture ratios (e.g. 5% - 15%) of bio-ethanol in vehicle gasoline in future.

Do you think that this regulation will affect the GA in near future?

Figure 67: Estimate of an effect of ethanol admixture in vehicle gasolines on aviation affairs.



Is your comapany preparing for potential consequences caused by an increase of ethanol shares in aviation related gasolines?l

Ethanol admixtures to gasolines will be affecting or influencing material properties. These influences may lead to some corrective actions e.g. replacing affected parts, updating material processing, strengthening/adapting materials or others.

Do you expect that your parts, materials or manufacturing processes will be affected?

Figure 68: Valuation of potential consequences of ethanol admixture in vehicle gasolines on the products of the individual company.

6.6.4 Conclusions

The field of material compatibility is very complex and becomes even more so by the tendency of modern product design, to integrate different basic materials in so-called blends. This increases the amount of principally available construction materials immensely. The intention to combine the positive properties of the different materials has certainly been achieved in many cases. But the ultimate features of blended composites are very hard to anticipate, especially so if the material is exposed to hitherto unforeseen environmental influences like changed liquid solvents, other temperature ranges, increased radiation etc.. Accordingly materials, having proven their applicability in *similar* environments like the automobile industry, need not necessarily withstand the boundary conditions in aeronautical applications with the same sovereignty.

Special attention should be given to the ubiquitous rubbers. Here the state-of-the-art utilization of NBR and its derivatives for flexible hoses, sealings and similar fuel contacting construction parts could prove itself dangerous, especially for heat radiation exposed parts in the immediate vicinity of the engine.

The aviation part manufacturers' questionnaire did not reveal a new aspect in the general discussion of ethanol admixture utilization in the area of General Aviation. It may be concluded that the topic itself is noticed in general but not being worked upon besides companies presumably involved in designing and selling ultralight aircraft for low service ceiling operation with rather modern engine and fuel system designs. With respect to the large fleet of older aircraft with engine designs originating from several decades ago there is neither a sensitization nor an impulse detectable from the questionnaire results to consider future ethanol admixtures in gasolines potentially used in aviation as well.

Nevertheless the international awareness may have been raised by the existence of the questionnaire and especially its official backing by the regulatory authorities. It would be interesting if such an effect could be perceived by repeating such a survey after a certain period.

7 Metrological Aids for Gasoline Composition Assessment (T 6)

7.1 Determination of an Ethanol Share in Gasoline

The quantitative detection of the ethanol content is a growing issue for MOGAS users: While traditionally STC'ed MOGAS engines must obey the 1 % maximum ethanol content limit already today, some of the presently DIN EN 228 certified engines (especially in the Ultralights class) may have to check in future if the present 5 % limit on ethanol might be raised in the years to come. Even if an engine is suitable for arbitrary ethanol admixtures, concerns about the solved water issue (see sect. 5.1) will demand an at least semi-quantitative ethanol share determination as the water acceptance is strongly dependent on it.

There are primarily two very practical methods at hand for the pilot: i) colour indicator substances sensitive to the ethanol concentration in the gasoline, and ii) ethanol extraction by deliberately admixed water.

7.1.1 Colour Indicator Method

There are several colour indicator techniques that are sensitive for ethanol contents in gasolines. For demonstration purposes we investigated the discriminatory power of the "Bluebottle Ethanol Test" donated by B. Plumb. According to the accompanying leaflet it should detect any alcohol present in the gasoline. In a personal communication with a distributor a limiting value of 1 % was stated. The presence of ethanol is displayed as a discoloration of a small amount of gasoline in contact with a (solid) stain of blue colour at the bottom of a small (10 ml) bottle. For comparison purposes another empty bottle of same size has to be filled with another portion of the same gasoline. Starting with a value of 0.8 % ethanol in gasoline the tests were performed according to the schema defined in Fig. 69.

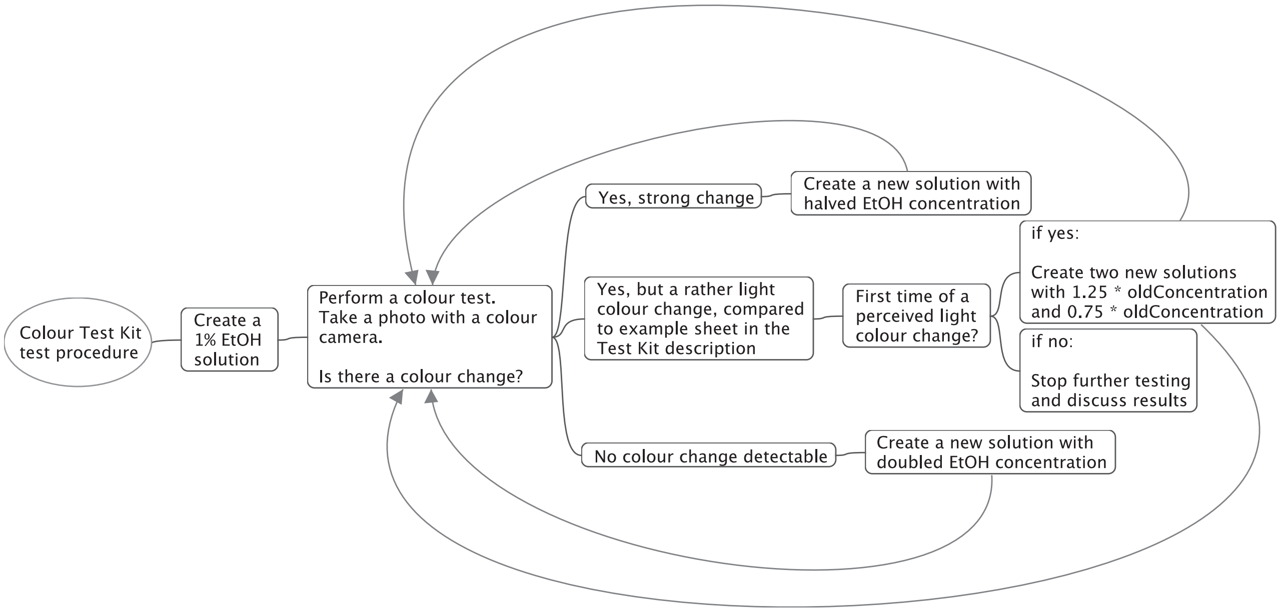


Figure 69: Sensitivity determination schema for an ethanol detection kit working on colour change reaction.

By consecutive narrowing of testing steps and comparison to the colourless gasoline the point of an emerging haze of blue colour in the gasoline could be fixed at about 2 %, with a confidence range of about 0.2 %. The investigated method works very quick and is, by the special chemical reaction to ethanol alone, selective for the required purpose.

The method is not applicable if a quantitative readout of an arbitrary ethanol share in a certain range is required, as may be the case for dielectrical sensoring based water detection systems that need ethanol abundancy values as correcting inputs.

7.1.2 Ethanol Extraction by Water

Various test methods are described that work principally on the phase separation effect described in detail in Sect. 5.1: As soon as a sufficiently large quantity of water is added to the gasoline to be investigated the contained ethanol is washed out and adds to the volume of the water. As the phase interface of ethanol/water vs. gasoline is quite well visible there is a possibility of directly assessing the volume increase of the former pure water.

The volumes of water and extracted gasoline do not exactly add up: The thermodynamic effect of the "excess volume" — in the case of a water/ethanol mixing being negative — reduces the appearent volume slightly (Fig. 70). Since the effect is less than 2 % for the complete range of possible mixing ratios an almost linear dependency may be assumed as a good approximation.

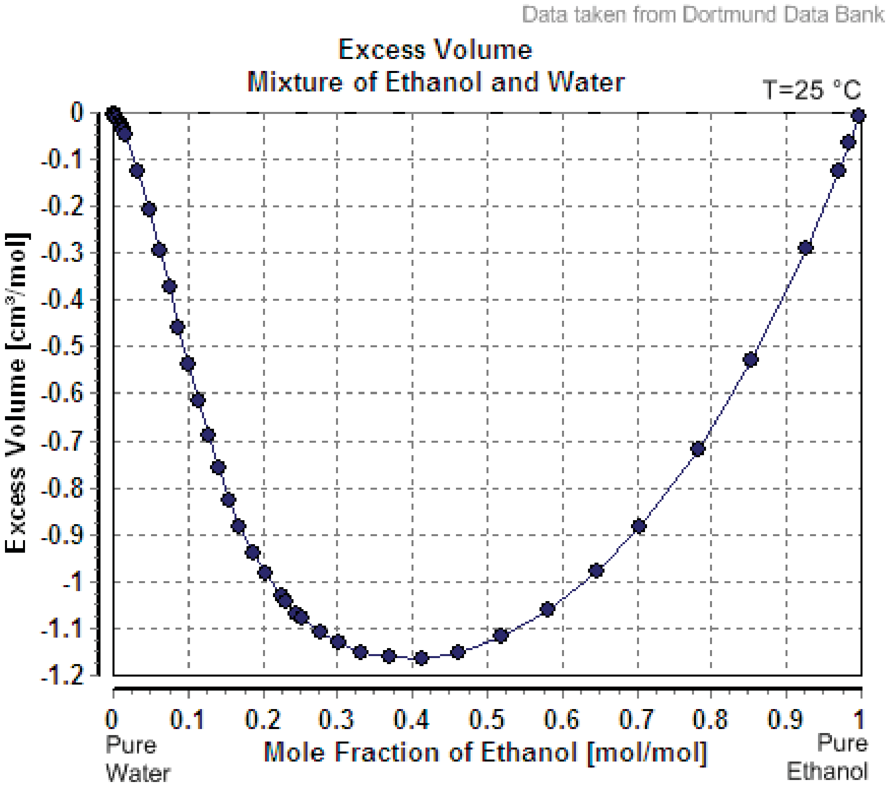


Figure 70: *Negative excess volume of a mixture of water and ethanol [34].*

There are methodological ethanol detection descriptions in circulation that base on rather similar amounts of gasoline and water being shaken vigorously in a chemical test tube for the ethanol extraction to take place. While they do basically work, they are much too insensitive to detect minor differences in ethanol abundancy as their readouts would differ in fractions of a millimeter only even for substantial changes. A secure control whether the ethanol share is less then 1 % or e.g. an already illegal 1.3 %, is not possible.

A better method is implemented in Maul's "Fuel-Alk Tester" (Fig. 71). Based on the same principle

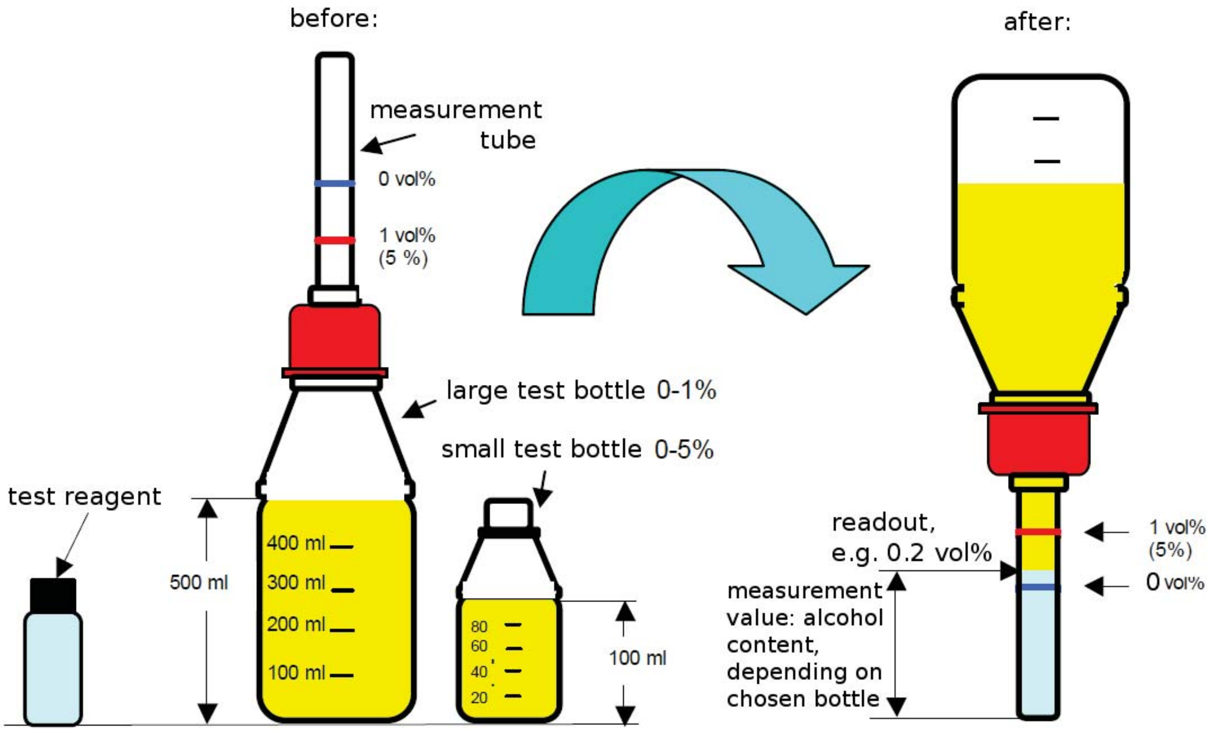


Figure 71: *Maul's Fuel-Alk Tester (after http://www.daec.de/te/downfiles/Fuel-AlkTester.pdf).*

the amount of gasoline taken as a probe is much larger, and the test tube placed on top of the test containment comparatively small. This yields a much larger readout sensitivity in the critical range around 1 % ethanol content. With a reduced absolute sensitivity the method is as well applicable to extended range of up to 5 % as presently allowed for EN 228 compliant vehicle gasolines.

While the purely mechanical readout resolution for a careful applicant should be about 1 mm, yielding a ethanol concentration resolution of about 0.02 %, the concentration determination repeatability in practical experiments a standard deviation of about 0.05 % for several identical samples of gasolines containing less than 1 % ethanol[6]. These tests were performed with identical samples of base gasoline. Accordingly, the method's repeatability would have to be qualified by larger test variations, especially taking into account compositional variations of the base gasoline.

7.2 Detection of Solved Water

Already for conventional gasolines the water content in the fuel system may exist both as an already separated and drainable water phase and/or as solved water in the gasoline phase. The separated water content must be drained prior to any flight as it may seriously affect the engine operation if the water phase is ingested while flying. Since the separated water is heavier than the gasoline and every small aircraft provides a respective tank drain opening this procedure is easy to perform.

The water solved in the gasoline creates no problem for the engine operation as long as it stays this way. Ethanol-admixed gasoline is even capable to dissolve significantly more water than an alcohol-free one, as is detailed in Sect. 5.1 and especially so in Fig. 12, p. 40. The main problem, however, is the fact that the amount of dissolvable water strongly depends on the gasoline's temperature (see e.g. Fig 12 on page 40), with a decreasing amount at decreasing temperatures.

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[6] Personal communication with vendor of *Fuel-Alk* test method

The problem is aggravated by the fact that in case of an emerging phase separation not only the water is purged. The water also drains the majority of the alcohol ingredients from the gasoline, yielding both an octane number reduced gasoline phase and a larger volumetric fraction of an uncombustible water/ethanol mixture. Accordingly, the detection of potentially dangerous *solved* water is relevant.

Compared to the drainage of already separated water from a tank system the detection of solved water is significantly more difficult. There are predominantly three general classes of water detection methods that lend themselves to further investigation:

- Chemical reactions that bind and display water contents of respective test probes. Chemical methods are favorable if static detection methods are sufficient.
- Optical analyses that rely on spectral differences between the usual gasoline components and water. Optical methods may be applied “in situ”, i.e. they may probe small amounts of fuel as it is sucked into the smaller compartments located between tank and carburettor or injection nozzle.
- Measurements of electrical properties, like capacitive resistance at different alternating current frequencies, or Ohmic resistance. A main obstacle for these methods is the electric similarity of water and ethanol and the fact that rather small amounts of water must be detectable in the presence of rather large, even not exactly specifiable abundancies of ethanol.

A further mainly electrically based class of methods, relying on additional electrical properties of the gasoline [22], may be ruled out by the fact that the measurable values vary to strongly in technical gasoline qualities for a sensible quantitative detection limit in the region of $< 0.1\,\%$.

Various commercial “water in gasoline” detectors are offered that operate on the so-called water activity and claim to detect water down to some ppm. Typical representatives are Vaisala’s MMT-330 or EESiFLo’s EASZ-1. At least one of the manufacturers claim that these sensors should be applicable even in the presence of alcohols if their operating values are adapted accordingly. Within the scope of SIOBIA one of these detectors is tested in the vapour lock test rig (see Appendix D.4).

The following sections investigate these different methodologies of water detection in more detail.

7.2.1 Chemical Water Detection

MLR Quik-Check Solution & Test Kit. MLR Solution (http://www.fueltestkit.com/) offers the “Quik-Check Solution & Test Kit”. It claims to check alcohol and water content at the same time. According to direct information from the vendors [27] the colour creating solution reacts identical to alcohol and water, so the sum of abundancies is “measured”. As the threatening water content is about one order of magnitude smaller than the potential ethanol content there is no sensitivity for water detection, and the result has no significance with respect to danger assessment.

Macherey-Nagel “Watesmo” indicator paper. According to the manufacturer the test paper allows the quick and easy detection of liquid water and (condensing) water vapour, even if solved in other substances. On contact with water the paper changes its colour. Besides other targets the test paper is intended to control the water content in solvents like aliphatic and aromatic hydrocarbons (gasoline, oil). If the paper remains uncoloured after evaporation of the solvent, the solvent is anhydrous. A false positive reaction is anticipated if methanol is present in the probed mixture. The test should be unsensible against higher alcohols.

A discussion contact with the manufacturer lead to a quick cross-check of ethanol sensitivity in their laboratories: Ethanol will create a false positive reaction, quite similar to the one reported for methanol. Again, the strong difference in ethanol vs. water abundance in typical gasolines impedes a direct application of the indicator paper. According to the discussion partnere there is no foreseeable chance to suppress this cross-sensitivity, so this indicator system is and will be not appropriate for the task.

Chromatographic tests. When discussing the Watesmo paper the Macherey-Nagel chemical analysis specialists also considered alternative methods, e.g. a chromatographic analysis. Again the molecular similarity of ethanol and water is considered as prohibitive for an application.

Karl-Fischer titration. A somewhat complex approach is a titration with special subtances. The method relies on the effect that iodine and sulphur dioxide react to iodide and sulphate only in the presence and by consumption of water [29]. It may be used to extract solved water quantitatively from solvents and at the same obtain a respective readout. This method requires several custom chemical reactands (Fig. 72) part of which require to be freshly prepared before the titration takes place. Within the scope of the present inquiry this methods seems to be the only practicable one to reliably probe solved water. It is by no means applicable as a “quick pre-flight check” for a pilot, though.

Figure 72: *Setup for a water detection by a Karl-Fischer titration. (Image source: Wikipedia)*

7.2.2 Optical Water Detection

Optical water detection relies on the spectral display of different molecular substances in the gasoline mixture. They show characteristical spectral bands over a larger spectral range from the ultra-violet to the far infra-red. Contrary to gaseous environments, rendering very sharp, well-defined and characteristic excitations bands, liquids show rather broad, diffuse and intermixing spectra. Nevertheless they may discerned against each other in many cases by intelligent algorithms and approximation calculations. In addition it might be expected that in the rather low water concentration domains the water molecules will not "see" each other any more and will deliver quite sharp bands.

Several spectrally sensitive methods exist: Raman spectroscopy, Coherent Anti-Stokes Raman Spectroscopy (CARS), absorption spectroscopy, LIDAR, fluorescence spectroscopy, and small angle scattering to name the most relevant. Their apparative expense differs strongly: while practical setups require quite powerful lasers for Raman spectroscopy and LIDAR, fluorescence spectroscopy and small angle scattering may be performed with filtered narrow-band emitting gas discharge lamps at least in some cases. The absorption spectroscopy, utilizing mostly calibrated lamps, will most probably create the least effort on the light emission equipment side.

The light created by excitation methods or transmitted in scattering or absorption methods in an optically accessible test cell must be analyzed with respect to the sought-for signals. Again comparatively expensive spectrally resolving instruments must be put to work. For **CARS** and **Raman spectroscopy** the spectral resolution usually must be quite high. In addition the background suppression of excitation light must be very good. Accordingly, the required equipment is quite costly.

An example of **LIDAR** application to a water analysis, although in the distinct field of pollution detection in sea water, gives a hint to the applicability of this measurement method [12]. The water, as the majority substance in the performed experiments, creates a small spectral peak on a vast and sloping underground of induced fluorescence originating from water pollution organic compounds. As the situation of majority/minority substances abundancies in gasoline composition identification is quite controversal the basic methods does not seem to be a promising approach.

Absorption spectroscopy is applicable in the various wavelength domains. Only regions where water displays significant absorption are interesting for the respective detection. In this respect the range from 1 μm to 3 μm is especially promising.

The structure of the spectral bands that water will exhibit as a minority component in an otherwise mostly homeopolar solution is not yet clear. The most prominent bands water shows are the ones for the intra-molecular OH bond. In liquid or solid water the sharpness of the gaseous spectra is strongly reduced due to intermolecular hydrogen bonds, yielding rather broad and diffuse absorption regions. The existence of the broadening is dependent on the amount of partners for cluster formation, though. So, if there are not enough other water molecules in the vicinity the formation of hydrogen bonds is respectively reduced, and the sharper peaks of the water vapour should become visible again.

Simultaneously present EtOH molecules lead to a problem, though, as their spectra show intramolecular OH bonds as well. They resemble those of the water rather strongly, and it remains to be investigated if they can be discerned from those orginating in the water with relatively simple means, leading to potentially affordable practicable measurement units for pilots.

The US patent no. 5,107,118, "Measurement of Water Levels in Liquid Hydrocarbon Media" from 1992 describes a measurement procedure based on infra-red absorption spectroscopy in the said region from 1 μm to 3 μm. A sensitivity of about 10 to 1000 ppm is achieved by applying rather simple narrow-band transmission filters. The evaluation is based on a ratio building of absorption band strengths determined with (scalar) integrating sensors. Contributions originating from EtOH are not considered.

Evaluating the relative intensities over a larger spectral region acquired by a line camera instead of single intensity peaks should yield the possibility of substracting even a sloping underground created by other gasoline components or potentially EtOH. In recent years the prices of the necessary electro-optic components (small form factor spectroscopes, line cameras, computerized evaluation kits) significantly decreased, so a measurement kit development seems probable.

As of today no such tests have been reported for the domain of ethanol admixed gasolines, though.

7.2.3 Electrical Water Detection

The distinction of water from gasoline components may be performed electrically by monitoring the dielectric constant of the medium under scrutiny, together with its ohmic resistance. Interrogation of different manufacturers of respective devices yielded a mixed resonance. Some dismissed the possibility of quantitative water assessment due to interferences with alcoholic ingredients of the liquid under investigation: The OH group coupled to an aliphatic rest acts electrically in mostly the same way as pure water does. Therefore some contacted distributors of respective measurement system outright declined any application in the desired direction.

Another manufacturer was in turn rather convinced that his device would be able to meet the challenge and sent an example device for custom tests. These were performed in the custom test rig (see Appendix D.4, page 205).

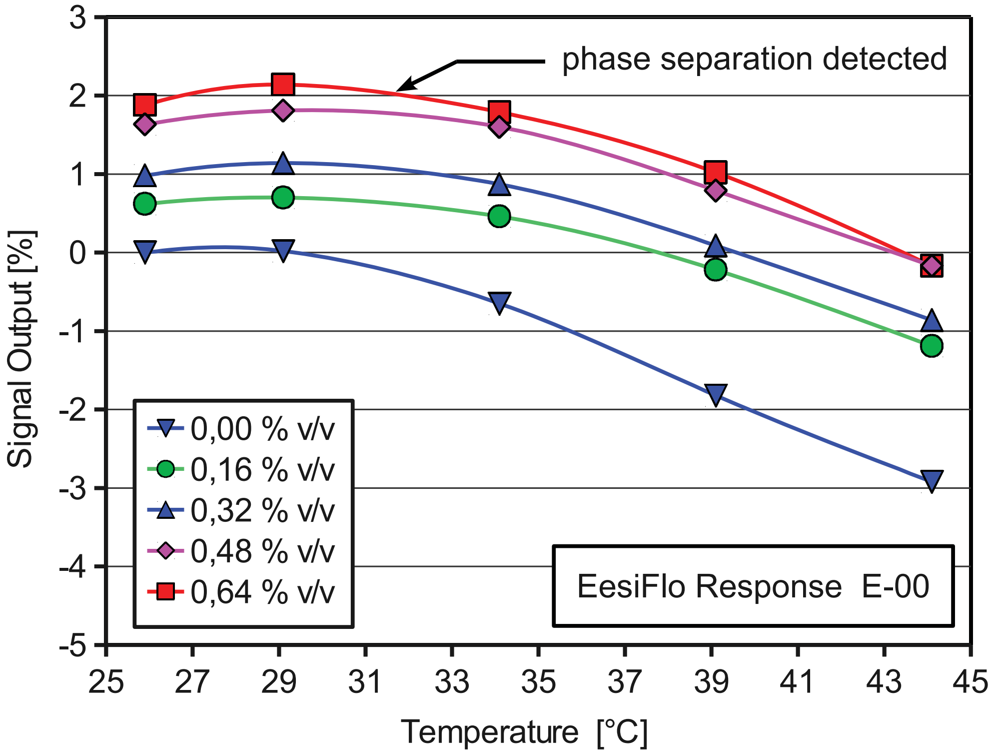

Figure 73: *Water detection with a dielectric monitoring device. Solvent: E-0 with increasing amounts of admixed water*

Results for E-0 are shown in Fig. 73. Clearly, for a given fixed temperature the electrical readout is strictly monotone with water abundance. There are reproducible deviations from linearity, though. Also, the signal readout for the same water content changes significantly with temperature in a range that may well be assumed by typical avionic boundary conditions.

The signal behaviour in the presence of ethanol is even worse[7]. As ethanol exhibits qualitatively the same dielectric properties, though at a weaker signal level, there is no secure means of discerning the water generated from the ethanol generated signal part. If there would be a quantitative measurement device for ethanol concentration assessment, working with an error margin roughly in the order of the required water amount distinction sensitivity, the setup of a respectively based water sensor would appear feasible. From the present state of experimental tests this is not to be expected.

7.2.4 Water detection by molecule-specific adsorption

Some chemical substances exhibit a strong tendency to adsorb water in their molecular or crystal structures like a molecular sieve. This effect may be utilized to quantitatively extract the water from the gasoline. One of those substances is zeolite. As a first test, the SIOBIA custom E-0 gasoline was mixed with ethanol and water to form a design-of-experiment inspired set of different probes. Table 26 shows the chosen combinations.

Probo no.	ethanol content [% v/v]	water added [ml]
1	5	0.6
2	10	0.3
3	10	1.3
4	15	1.0
5	15	2.0
6	0	0.0

Table 26: *Abundancy matrix for zeolite water absorption tests. The respective admixtures were given into 200 ml of gasoline each.*

Furtheron six probes of dried zeolite granules were prepared with differing masses in the range of 10 g to 15 g and matched randomly to the six gasoline probes. The amount of zeolite was chosen so that it would securely be able to absorb any water admixture of the gasoline probes. At the time of the experiment the airtight kept zeolite amounts were put into the gasoline bottles and vehemently shaken in order to provoke the largest possible absorption of water from the liquid (Fig. 74, left).

Subsequently the gasoline is filtered out of the zeolite samples, leaving the wet granules on a filter paper to dry out. In an exhaust hood the residual gasoline is slowly evaporating from the granules. With decreasing gasoline wetting the very strong absorption of air humidity increases that superimposes the water absorption from the gasoline and should be taken into account. The evaluated weighing event took place half an hour after probe filtering.

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[7] The tested device became dysfunctional before further measurement series with defined alcohol contents could be performed. Unluckily, the manufacturer was not able to provide a replacement item in time before the experimentation phase for this report had to be terminated.

Figure 74: *Zeolite water absorption experiment: Zeolite granules are given to gasoline probes (left). After vigorous shaking the zeolite is filtered, and the filter residues are weighed after some time of gasoline evaporative drying. Image right shows slightly differently coloured filtering samples with differing dry times.*

Regrettably there is no simple way of evaluation, as hoped for at first: No direct relation between probe water content and weight change of the respective filtering residue could be stated. The causal interrelations between the various contributing effects must obviously be taken into account:

- The boiling curve of the gasoline causes a slow fractionating evaporation, visible from the gradual change of the granules' colour. Directly after the filtration the grits are dark brown as is the colour in the mixture, seen also in the submerged sediments in the bottles of Fig. 74, left side. Some minutes later they become greyish and, after about 15 to 20 minutes, they change to a very light brown (cf. Fig. 74, right side).
- The ethanol may be absorbed differently compared to the base gasoline components, and also compared to the water.
- With ongoing desiccation the granule surfaces open towards the air humidity which is readily absorbed by zeolite.
- The indidivual grit does not have a well-defined surface. Instead the granules exhibit vast areas of internal ones. Accordingly, the absorption determining interface does not need to be proportional to the mass powered by 2/3, as is to be expected for typical ideal solid particles.

The potential effects are taken into account by defining a postulated theoretical zeolite residue mass formula with either three or four free parameters describing the contribution of the various effects. As approximation tool a evolutionary Pareto optimization was put to work, minimizing at the same time but independently the mean average error for all six probes and the maximum error that (at least) one probe would show for a given set of fitting coefficients. The result of this evalution is shown in Fig. 75.

If all the specified influences are considered but the results are thought as independent from the water content of the individual probes the red circle set of results apears, forming a trade-off curve of the two considered kinds of errors. Each symbol indicates an individual set of fit parameters. As a reading example, if we accept a mean error of 0.08 g zeolite weight for all the probes we will at the same time have to accept 0.15 as a maximum error that is found in at least one of the

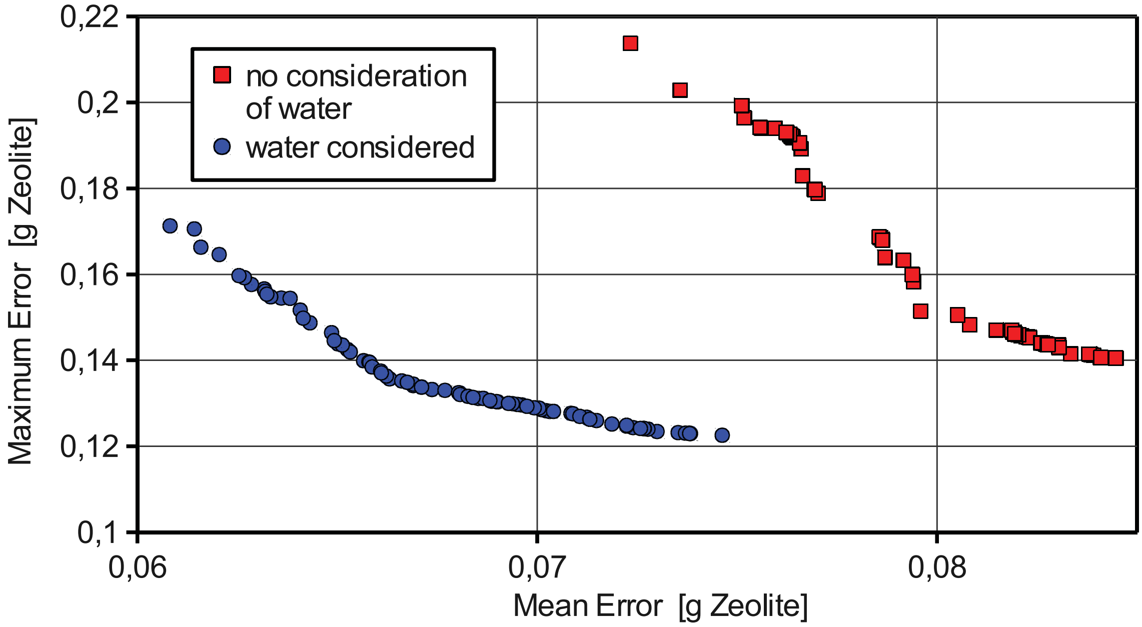

Figure 75: *Zeolite water absorption evaluation. Shown are two pareto sets for the respective fit parameters with and without consideration of the influence of water. Both average error and maximum deviation from the measured data are well reduced if a water influence is taken into account.*

probes. Lesser values for mean errors lead to larger ones for maximum errors and vice versa. For the given theoretical zeolite mass determination equation the red Pareto "curve" is the best we can reach with the assumptions made.

If an influence of the probes' water amount is taken into consideration by simply introducing an additional fit term of the form $\Delta m_{Zeo} = \alpha * m_{water}$, with α being subject to the optimizing variation, we arrive at the set of blue squares of results. Here we can e.g. achieve a mean zeolite mass error of about 0.07 g with at the same time limiting the maximum error for all probes to less than 0.13 g.

The consideration of the water influence yields definitely better approximations whereas an additional or alternative consideration of the ethanol content in the probes did not yield any change in the approximation quality. Accordingly, it is to be expected that by inversing the path of evaluation a comparably simple method of water content determination for gasolines may be developed from these basics. Many questions with respect to sensitivity, fault tolerances, base gasoline influence, experimental timing and many more remain, though, as the test was just a simple check of a measurement principle.

7.3 Detection of Solved Water: Conclusion

Several principles of solved water detection lend themselves to further scrutiny, but none of them provides an established means that is applicable as a simple yet effective testing device. The Karl-Fischer titration appears as the currently most promising candidate, with the molecular absorption by zeolite being presumably the most prospective one with respect to price per test. These candidates provide purely static measurement, though, to be performed as a pre-flight check. Water ingested during the flight itself cannot be assessed.

Optical measurements of spectral properties may be developed into online testing equipment that works continuously even during the flight. Since technical liquid media exhibit mostly broad absorption or scattering bands and are susceptible to staining, extensive theoretical and experimental investigations will have to be performed before any reliable testing method may evolve. Even though the necessary technical base devices (light sources, spectrometers, multidimensional detectors) become more and more available the system price for a potential test device will expectedly be rather high.

Testing procedures requiring additional input of mostly exact ethanol abundance will not alleviate the problem as there is no qualified method of such an anteceding measurement at hand either.

8 Life-Cycle Analysis of Ethanol-Admixed Gasolines (T 5)

8.1 Approach / Methodology

Due to the enforcement of the EU directive 2009/28/EC more oxygenates produced from organic materials like bioethanol will be added to the automotive gasoline. Some General Aviation aircraft equipped with spark ignited piston enginges are approved for operation with MOGAS. However, the majority of those approvals is limited to MOGAS containing a maximum of 1 % of ethanol while the current fuel specification EN 228 permits already up to 5 % (bio-)ethanol as fuel admixture. According to the longer-term policy of the European Union an increase of that number is to be expected in the years to follow, as gradually the lifetimes of older cars requiring low ethanol admixture shares will come to their ends.

Even though the share of gasoline used for non-automotive engine operation is explicitly excluded from the enforced biogenic admixture requirements, the share of gasoline consumed in aviation is so tiny that it seems economically prohibitive for the fuel provision companies to provide a custom gasoline brand outside the usual variations of automotive fuels. Accordingly, General Aviation will either have to adapt to the usage of ethanol admixed MOGAS in the future, or return in majority to the leaded AVGAS 100LL which, in spite of its “low lead” specification, contains quite a lot of it.

As the future mandatory ethanol admixture is mainly focusing on the reduction of CO_2 emissions and hence aiming at the amelioration of environmental conditions it is sensible as a look-ahead consideration to assess implications of ethanol fuel admixtures also on the various other influenced environmental properties. The life-cycle analysis section in this report scrutinizes this objective with a focus on the aviation related issues and peculiarities. Contrasting the focus of the whole report which is technically safety-oriented, the objectives of this section are targeted differently:

Based on identified knowledge gaps, and within the scope of this project, investigate the potential environmental benefits, using life-cycle analyses, from the production, supply and use of various biomass sources for biofuels.

In a subcontract to LUDWIG BÖLKOW SYSTEMTECHNIK, Ottobrunn, (furtheron called LBST) the consecuting objectives have been investigated in further detail. The self-contained LBST report, included as Appendix E, p. 213ff, is given as an attachment to this core part of the complete report.

The general topic of interest covers the complete lifecycle of biogenic ethanol as an admixture of aviation gasolines, so to say from seed to propeller. In the scope of the present research activities this admixture will only be considered for aircraft models presently already capable/permitted to fly on MOGAS.

On its way from the biogenic source to the airfield fuel station tank assumptions on the environmental impact are considered as comparable to those made for the usage of ethanol admixed fuel in automotive utilisation. The respective premises are particularized in the full report attached. They consider a variety of pathways (different crops and respective transport necessities) for bioethanol procuration.

There are certain differences in vehicle and aircraft fuel combustion, however: While practically all vehicles in the EU are equipped with catalyzers and hence produce very few exhaust emissions apart from CO_2 and H_2O, this is not the case for aircraft combustion systems where no catalyzers exist at all. In addition there are only a few load cases relevant in aviation usages (Fig. 76): Full load (take-off operation), best efficiency (cruising operation), part load (taxi operation on the airfield), and idle (warm-up on ground). Respective data have been recorded both for the ROTAX and the MORANEengines and have been provided as calculational basis to LBST.

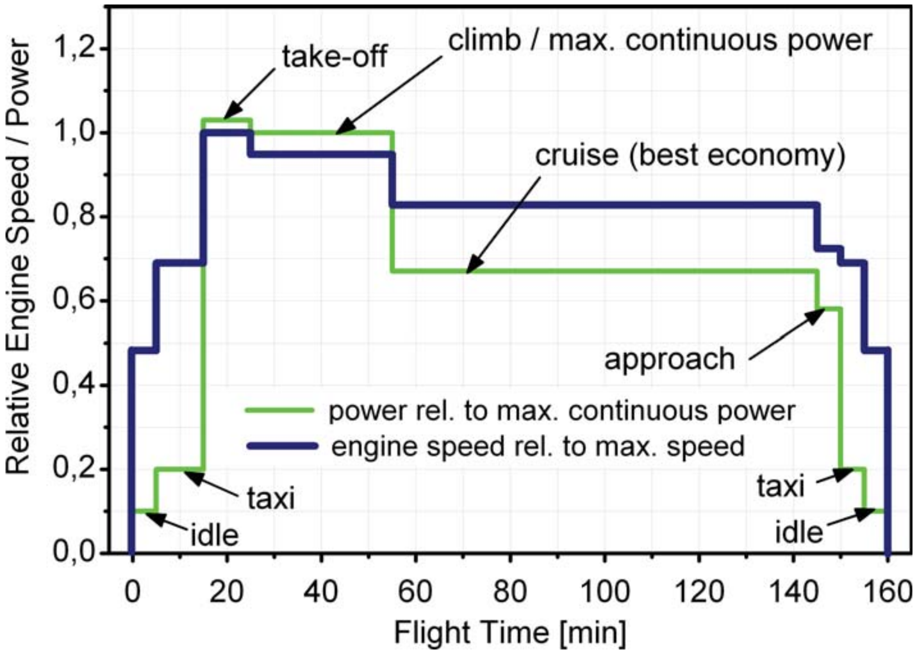

Figure 76: *Flight profile assumption for comparative LCA studies, representing the typical load states as relative values. For engine related definition of the respective operation points cf. Fig. 92, p. 204*

Accordingly, the next objective is to assess the difference of vehicle and aircraft combustion cases under the assumption of "average European gasoline" as the governing fuel for all gasoline usage scenarios (including the ethanol-admixed cases with accordingly less gasoline amounts in the fuel). The most prominent difference is the complete lack of catalyzers in aviation, leading to very different finally remanent emissions due to mostly sub-stoichiometric combustion in aircraft, different typical load scenarios.

In the light of dwindling chances to obtain STC compliant MOGAS (less than 1 % ethanol abundancy) a lot of pilots might become forced to return to AVGAS, restarting to emit vast amounts of lead as there is no practical alternative to the commonplace AVGAS 100LL. As a consequence the LCA is to consider the increase of lead contamination of the atmosphere, with the worst-case scenario being all (or most of) the aircraft returning to AVGAS usage.

8.2 Experimental Investigation of Exhaust Gas Emissions for a ROTAX 912 ULS Engine

For emission assessment the ROTAX engine is mounted on AcUAS's test rig as shown in Sect. D.3. The rig features a state-of-the-art measurement devices assortment for temperature, pressure, fuel mass flow, noise and vibration. The measured values are automatically sampled by Imps of Schlumberger and converted and indicated with an adequate post-processing system. For the SIOBIA project an electrically heated 20 m long exhaust gas analysis tube has been built and connected by an additional 5 m flexible hose to the exhaust gas analysis equipment in an adjacent laboratory.

The ROTAX is equipped with a carburettor system similar to those used in cars in pre-catalyzer times. In contrast to many larger US-American engines the mixture formation cannot be adjusted manually. Instead, the mixture characteristic is determined by the setting of the carburettor itself.

Accordingly, the actual fuel/air ratio changes over the range of load points, but stays constantly on the rich side of stoichiometry as can be derived from the exhaust gas analysis. It yields, together with the gasoline flow control, data on the following substances and physical combustion conditions: CO_2, CO, NO, NO_x, C_xH_y, O_2, $T_{exhaust}$, $\dot{m}_{fuel}$.

As the fuel/air ratio for stoichiometric conditions ($\lambda = 1$) is slightly shifting with the different ethanol admixtures ($\dot{m}_{air}/\dot{m}_{fuel} = 14.5$ for undoted E-0 fuel, 13.4 for E-15) the unchanged carburettor settings create accordingly differing stoichiometries — imitating the behaviour of a respective aircraft engine that is operated on changing fuel brands.

As an exemplaric result for the larger set of data fed into the subsequent theoretical life cycle analysis the measurement of exhaust temperatures and NO_x emissions is discussed.

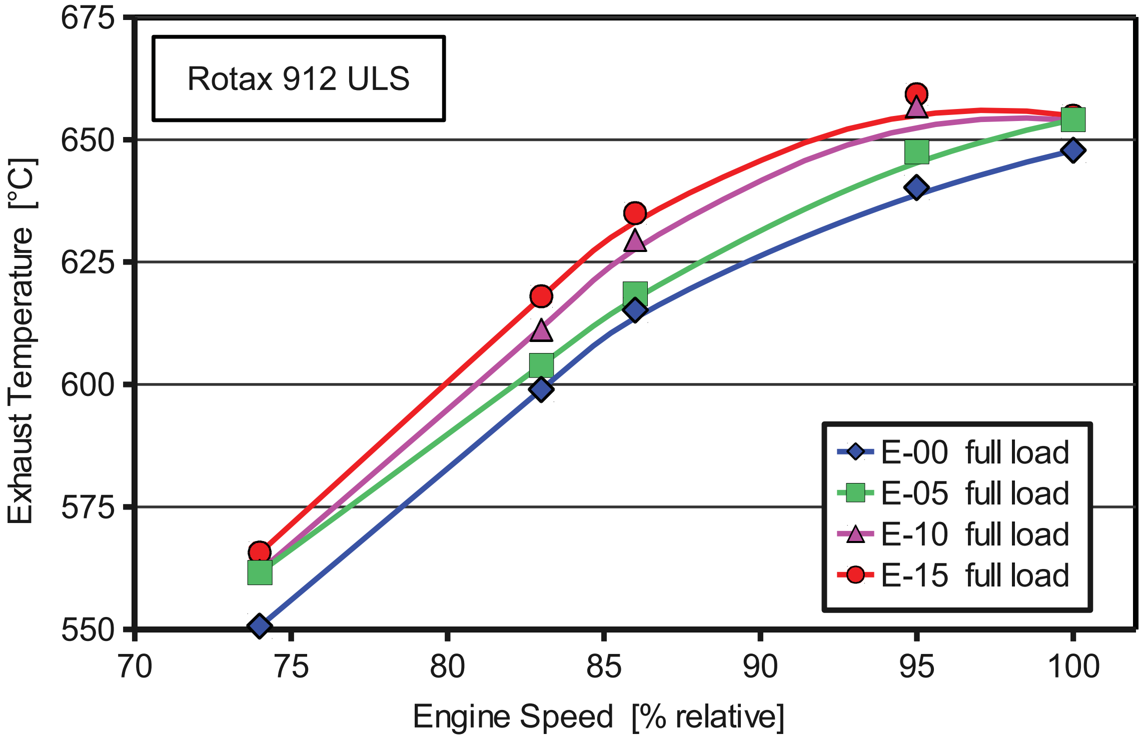

Figure 77: ROTAX *exhaust temperatures with ethanol admixed fuels. Unchanged carburettor settings for the different ethanol shares lead to slightly different actual fuel/air ratios in the comparation.*

First, different exhaust gas temperatures are observed for the different ethanol admixture ratios (Fig. 77). Larger ethanol abundancies lead to higher values. This is in accordance with the fact that the fuel/air ratio λ of the rotax was found to be always on the fuel rich side of stoichiometric balance. A feed with unchanged air mass per unit fuel due to the fluid dynamical setting of the carburettor will lead in consequence to an approximation of $\lambda \rightarrow 1$ with an expected related rise of exhaust gas temperatures.

As a consequence the NO_x emissions, being very much related to the exhaust gas temperatures, show an increase as well (Fig. 78). Since there is no such thing as a catalyzer in aircraft the raw emissions will enter the environment unreduced. Obviously in this case the "more biogenic" and therefore thought more sustainable fuel will create the larger environmental impact if no custom modification of the carburettor settings take place — as will be the typical case if changing ethanol admixture levels by different refuelling charges will be used.

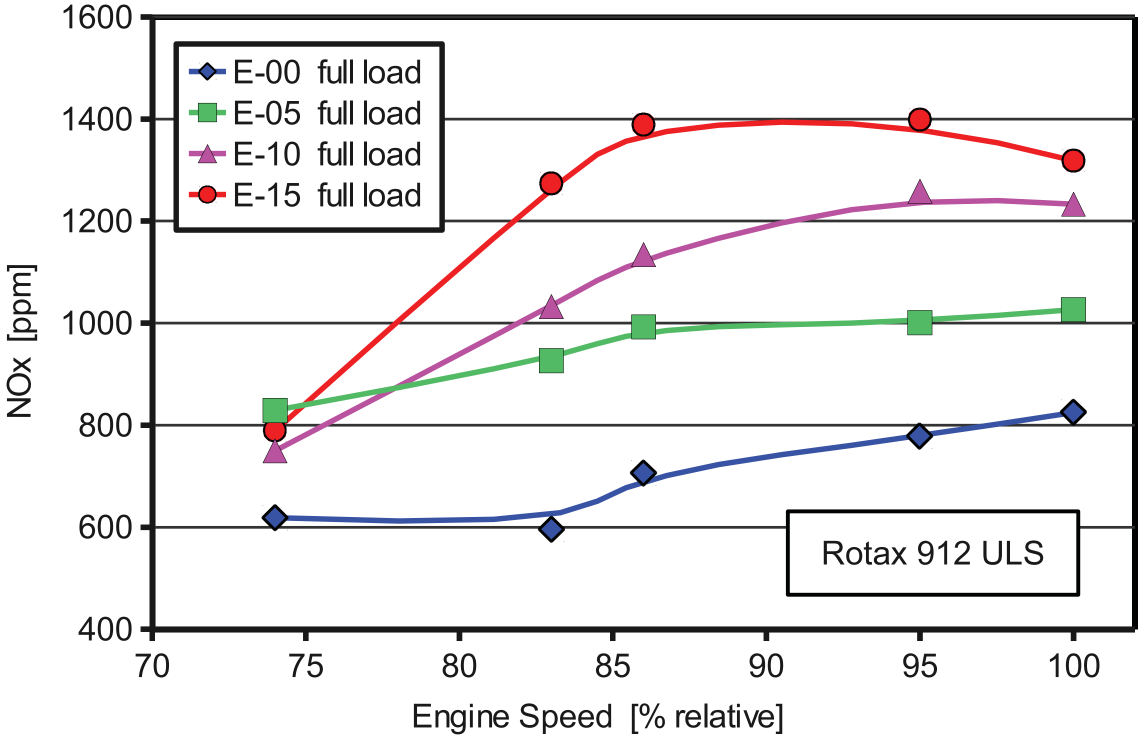

Figure 78: *ROTAX NO_x emissions with ethanol admixed fuels.*

8.3 Life Cycle Analysis of Measured Exhaust Gas Emissions of the ROTAX 912 Engine

The LBST report, included into this report as the comprehensive Appendix E, thoroughly scrutinizes the complete production part of ethanol derived from various kinds of crop (sugar beet, sugar cane, wheat, wheat straw, residual wood, farmed wood) together with differentiated methods of heat input for the processing chain.

Pathways	Fuel	Feedstock	Heat source for conversion process	By-products	Remark
No. 01	Gasoline EU	-	-	-	Reference
No. 02a	Ethanol	Wheat	Natural gas (boiler)	Substitution	Distillers Grains and Solubles as animal fodder
No. 02b	Ethanol	Wheat	Natural gas (boiler)	Allocation (1)	
No. 03a	Ethanol	Wheat	Natural gas (co-generation)	Substitution	Distillers Grains and Solubles as animal fodder
No. 03b	Ethanol	Wheat	Natural gas (co-generation)	Allocation (1)	
No. 04a	Ethanol	Wheat	Lignite (co-generation)	Substitution	Distillers Grains and Solubles as animal fodder
No. 04b	Ethanol	Wheat	Lignite (co-generation)	Allocation (1)	
No. 05a	Ethanol	Wheat	Wheat straw (co-generation)	Substitution	Distillers Grains and Solubles as animal fodder
No. 05b	Ethanol	Wheat	Wheat straw (co-generation)	Allocation (1)	
No. 06	Ethanol	Wheat	Biogas	Substitution	Distillers Grains and Solubles for Biogas
No. 07a	Ethanol	Sugar beet	Natural gas	Substitution	Beet pulp as animal fodder, slops to biogas
No. 07b	Ethanol	Sugar beet	Natural gas	Allocation (1)	
No. 08	Ethanol	Sugar cane	Bagasse	-	
No. 09	Ethanol	Residual wood	Wood (co-generation)	-	
No. 10	Ethanol	Farmed wood	Wood (co-generation)	-	
No. 11	Ethanol	Wheat straw	Wheat straw (co-generation)	-	

Figure 79: *LBST scenario overview over considered pathways and by-effects for biogenic ethanol production. For full explanation see Appendix E.*

An overview over the different ethanol production variants and usage by-effects like utilisation of by-products is given in Fig. 79. The resulting greenhouse gas emissions of this first part of the ethanol utilization chain analysis, so to say the well-to-tank analysis, is summarized in Fig. 80 in the form of CO_2 equivalents by assigning respective multiplicators to N_2O and CH_4 as the main climate relevant heat absorbers besides CO_2.

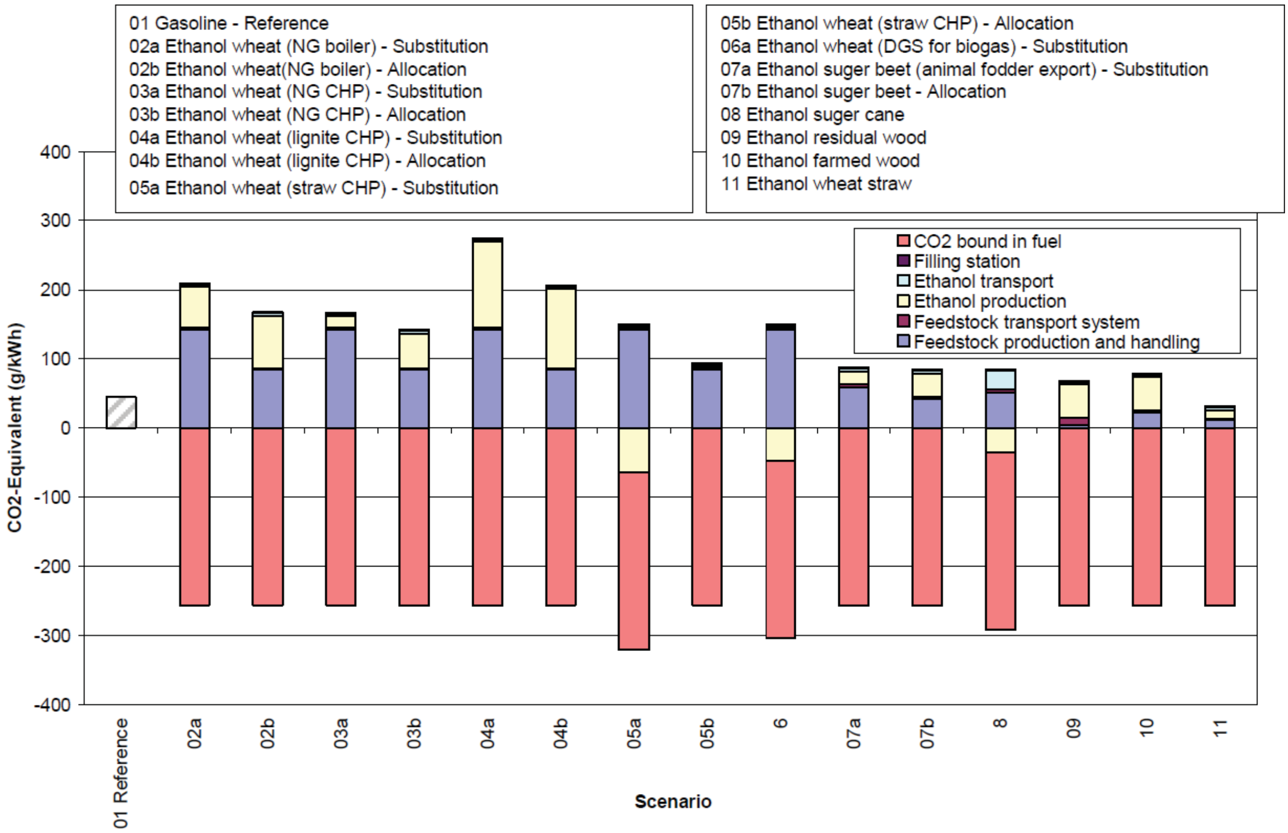

Figure 80: LBST well to tank greenhouse gas emission analysis results, comprising a variety of variants of process heat / steam generation for endothermic assisting processes (lignite cracking etc.). The various considered emissions (N_2O, CH_4) are introduced into the calculation as CO_2 equivalents.

The analysis shows a number of differentiated balances in comparison to the reference case of the amount of CO_2 being produced by simply bringing fossil gasoline to the tank (Fig. 80, leftmost column). CO_2 emission equivalents are sketched as positive, CO_2 savings (mostly by binding the carbon content into the ethanol and thereby reducing the entry into the atmosphere) as negative columns. It should be stressed, though, that *only the production and provisioning of the respective fuels* are balanced in these columns, not the subsequent combustion in the engine. The main result of the well-to-tank analysis is that most (but not all) methods of ethanol production lead to a certain reduction of greenhouse gases. Nevertheless the amount of CO_2 equivalents production in this process is non-negligible, and some methods of prepartion consume a larger part of the CO_2 bound in ethanol already.

Independent from the provisioning the tank-to-propeller GHG production analysis is performed. Changed emissions of ethanol admixed gasolines relative to ordinary fossil E-0 brands, measured by AcUAS for the ROTAX 912 ULS engine, are taken as a calculational basis when the final GHG reduction is calculated for the different szenarios. Fig. 81 shows the result for an E-15 gasoline, resulting in GHG savings in the order of 16 %. It should be noted that the GHG reduction potential, at least for some variants, is even slightly above the volumetric share of the ethanol in the gasoline even though the energetic share of the admixed gasoline is decisively smaller. Qualitatively, this

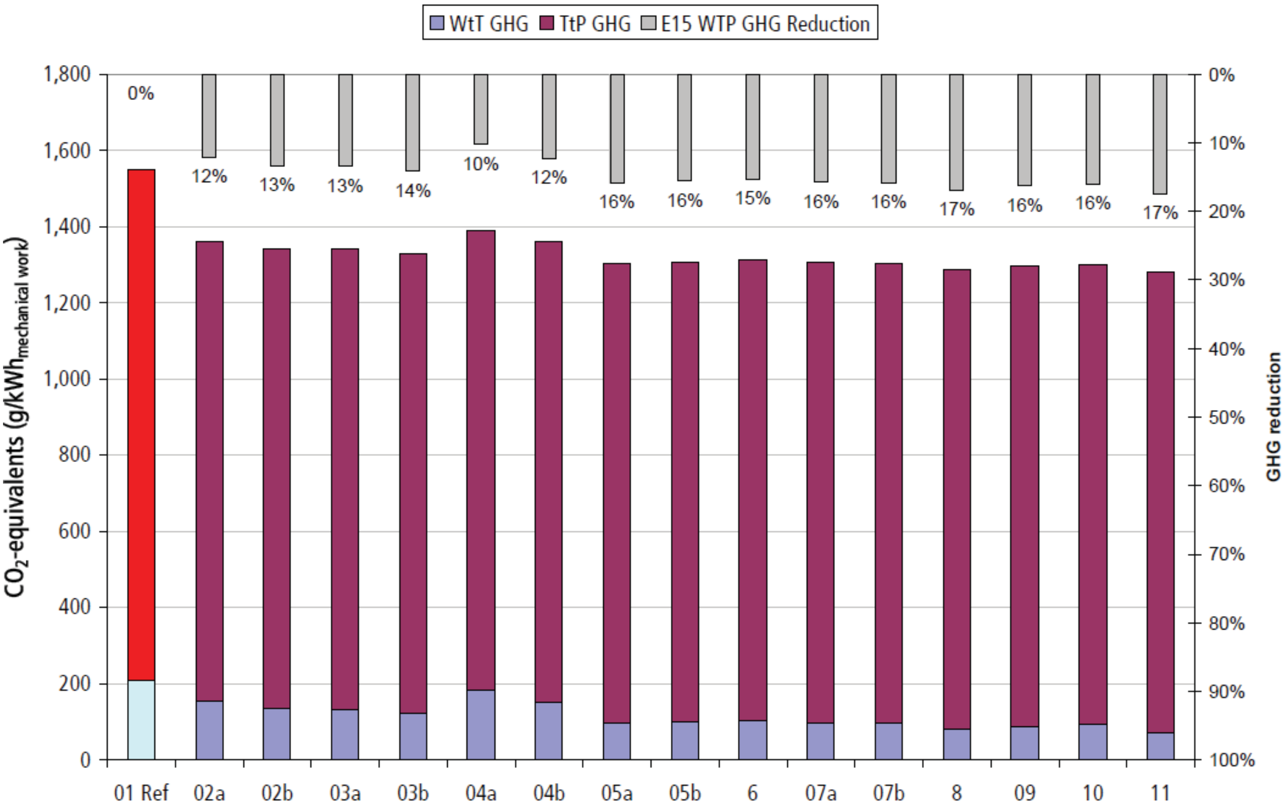

Figure 81: *LBST well to propeller greenhouse gas emission analysis results, shown here as an example for the analysis of E-15 combustion.*

may be tracked down to the fact that the combustion of the ethanol-admixed gasoline is partially cleaner than that of the basic MOGAS (E-0). Due to the non-existence of catalyzers this has a significant effect on the overall GHG balances, especially if the non-CO_2 pollutants are considered as CO_2 equivalents.

These further emissions, especially NO_x and NMVOC, are investigated in detail. Here the tank-to-propeller part is the by far dominating one due to the lack of catalyzer exhaust gas after-treatments in small aircraft. While NMVOC tend to decrease slightly with rising ethanol content the NO_x production even considerably increases. Here it should be emphasized that the carburettor and the setting of ignition timing of the ROTAX engine remained unchanged for the different E-*xx* gasolines and the operating points where chosen to deliver the same effective mechanical power.

Finally a lead analysis is performed for the scenario that the present MOGAS operated aircraft would need to return to AVGAS if the present ethanol STC restrictions cannot be met in the case of a general drop of ethanol-free gasoline. For that case an increase of the lead dispersed by avionic combustion of about 50 % is predicted. Taking into account the detailed flight hour data available for Germany this leads to an increase prognosis of presently about 12 t to 18 t per year for this country.

The full LBST report is reproduced in Appendix E on pages 213ff.

8.4 Conclusions

Depending on the method of biogenic ethanol admixture production quite different GHG savings are accomplishable. While some methods, exploiting mainly fruits of plants while discarding other plant components just about match the energetic input they still require for their production, novel techniques exploiting non-food plants and supplying required processing heat input by biogenic combustibles will increase the saving potential considerably.

Even for suboptimally produced biogenic fuel admixtures the overall balances indicate a substantial reduction of GHG emissions. This is caused by a change of combustion process emissions in the presence of ethanol in the gasoline. This effect is, to a great extent, not related to the biogenic origin of the ethanol, but to a shift in the operating point of the engine: the fuel-air ratio is changed slightly to a less fuel-rich setting, thus increasing the efficiency coefficient of the engine. If the engine is re-tuned to achieve the same maximum power output for ethanol-admixed gasolines the consumption and hence GHG emission reduction would lessen again considerably.

As the main parts of this report show, safety issues do exist if ethanol admixtures are present in gasolines used in aviation. Accordingly even presently MOGAS operated aircraft may be forced to revert to AVGAS utilisation if these issues cannot be overcome. In that case not only the small but perceptible potential GHG emission reduction is lost but also an increase of lead emissions of about 50 % relative to today's value is to be expected.

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A Engines and Cells Certified by the United States FAA

The consecuting list reports American FAA supplementary type certificates (STCs) for MOGAS usage.

The list does not raise the claim to be complete. It rather helps with identifying a certain aircraft as worthwile for interrogating the manufacturer on this behalf.

Certified Engines

Manufacturer	Continental
Series	Type
A-65-	1, -3, -6, -6J, -7, -8, (O-170-3, -7)-8F, -8FJ, -8J, -9, (O-170-5), -9F, -9FJ, -9J, -12, -12F, -12FJ, -12J, -14, -14F, -14FJ, -14J
A-75	-3, -6, -6J, -8, -8F, -8J, -8FJ, -9, -9J
C-75	-8, -8F, -8FH, -8FHJ, -8FJ, -8J, -12, -12F, -12FH, -12FHJ, -12FJ, -12J, -12B, -12BF, -12BFH, -15, -15F,
C-75	-8, -8F, -8FH, -8FHJ, -8FJ, -8J, -12, -12F, -12FH, -12FHJ, -12FJ, -12J, -12B, -12BF, -12BFH, -15, -15F,
C85	-8, -8F, -8FHJ, -8FJ, -8J, -12, -12F, -12FH, -12FHJ, -12FJ, -12J, -14F, -15, -15F
C-90	-8F, -8FJ, -12F, -12FH, -12FJ, -12FP, -14F, -14FH, -14FJ, -16F, C90-()
0-200	-A, O-200-B, O-200-C, RR O-200-(), RR O-300-()
C-115	-1, C-115-2, C-125-1, C-125
E-165	-2, -3, -4, E-185-1, -2, -3, (O-470-7, -7A), -5, -8, -9, (O-470-7B), -10, -11
E-225	-2, -4, -8, -9
O-300	-A, -B, -C, -D, -E, C-145-2, -2H, -2HP.
GO-300	-A, -B, -C, -D, -E, -F
O-470	-A, -E, -J, -K, -L, -R, -S. O-470-4, -11, -11B, -11-CI. -11B-CI, -13, -13°, -15, O-470
IO-470	-J & -K
W670	-6A, (R-670-3, -5), -6N, (R-670-4), -16 (R-670-8, -11, -11A), -23, -24, -K, -M

Manufacturer	Franklin
Series	Type
	6A4-150-B3, B4, B31, 6A4-165-B3, B4, B6, 4AC-176-B2, B3, BA2, (0-175-1), BA3, C2, C3, D2, D3, F2, F3

Manufacturer	Jacobs
Series	Type
	R-755, - All models

Manufacturer	Kinner
Series	Type
	R-5 Series 2, R-55, R-56, (R-540-1, -3)

Manufacturer	Lycoming
Series	Type
O-145	-B1, -B2, -B3, -C1, -C2, GO-145-C1, -C2,-C3, -A1, -A2
O-235	-C, -C1, -C1B, -E1, -E1B, -C1C, -C1A, -H2C, -C2A, -C2B, -E2A, -E2B, -L2A*, -L2C*, -M1*, -M2C*, -M3C*, -N2A*, -N2C*, -P1*, -P2A*, -P2C*, -P3C*, O-235-() nicht H
O-290	-A, -AP, -B, (O-290-1), -C, (O-290-3),-CP, -D, (O-290-11), -D2, -D2A, -D2B, -D2C
O-320	O-320-A1A, -A1B, -A2A, -A2B, -A2C,-A2D, -A3A, -A3B, -A3C, -B1A*, -B1B*, -B2A*,-B2B*, -B2C*, -B3A*, -B3B*, -B3C*, -C1A, -C1B, -C2A, -C2B, -C2C, -C3A,-C3B, -C3C, -D1A*, -D1B*, -D1C*, -D1D*, -D1F*, -D2A*, -D2B*, -D2C*, -D2F*, -D2G*, -D2H*, -D2J*, -D3G*, -E1A, -E1B,- E1C, -E1F, -E2A, -E2B, -E2C, -E2D, -E2F, -E2G,-E2H, -E3D, -E3H,-E1J
O-360	-B1A, -B1B, -B2A, -B2B, -D1A, -D2A,-D2B, -A1A*, -A1AD*, -A1D*,-A1F*,-A1F6*, -A1F6D*, A1H6*, -A1G*,-A1G6*, -A1G6D*, -A1H*, -A1H6*, -A1LD*, -A1P*, -A2A*, -A2D*, -A2E*, -A2F*, -A2G*, -A2H*,-A3A*, -A3AD*, -A3D*,-A4A*, -A4AD*, -A4D*, A4G*, -A4J*, -A4K*, -A4M*, -A4N*, -A5AD*, -C1A*, -C1C*, -C1E*, -C1F*, -C1G*, -C2A*, -C2C*, -C2E*, -C4F*, -C4P*, -F1A6*, -G1A6*, -J2A*, H0-360-C1A*, O-360B, D, A, C, F, HO360C
O-435	O-435-A, O-435-C (0-435-1),0-435-C1,(0-435-11), O-435-C2, (0-435-13)
O-540	-B1A5, -B1B5, -B1D5, -B2A5, -B2B5, -B2C5, -B4A5, -B4B5,-A1A*,-A1A5*,-A1B5*, -A1C5*, -A1D*, -A1D5*, -A2B*, -A3D5*, -A4A5*, -A4B5*, -A4C5*,-A4D5*,-D1A5*, -E4A5*, -E4B5*, -E4C5*, -G1A5*, -G2A5*, -H1A5*, -H2A5*, -H1A5D*, -H2A5D*, -H1B5D*, -H2B5D* -F1B5*, O-540B(), O-540-A(), -D(), -E(), -G(), -H()
R-680	-E3*, E3A*, E3B*, (R-680-9*, -13*) R-680, R-680-E1, E2, -6, -B6, -D5, -D6, -B2, -BA -2, -4, -B4, -B4B, -B4C, -B4D, -B4E, (R-680-5, -7, -8, -11, -17) R-680-5, -B5

Manufacturer	Pratt & Whitney:
Series	Type
R-985	-13, -17, -19, -23, -25, -27, -39, 39A, -48, -50, -AN-1, -AN-1M1,-AN-2,-AN-3,-AN-4, -AN-5, -AN-6, -AN-6B, -AN-8, -AN-10, AN-12, -AN-12B, -AN-14B, -AN-14BMI, T1B2, T1B3, B-4, B-5, SB, SB-2, SB-3
R-1340	-E, -19, -22, -29, -36, -40, -47,-49,-49M1, -51, -AN-1, -AN-2, -51M1, -53, -57, -59, -61, S1D1, S3H1, S3H1G, S1H2, S1H1, S1H4, S3H2
R-1830	-49, -53, -57, -82, -92, -92A, -96, SC-G, SC3-G, S1C-G, S1C3-G, S4C4-G, R-1830-43, -43A, -61, -65, -67, -75, -86M2, -90B, -90C, -90D, -94, -94M1, -94M2, -S3C4-G

Manufacturer	Ranger:
Series	Type
	6-440-C2 (L-440-1), -C3, -C4, -C5 (L-440-2, 3, 5, 7)

Manufacturer	Warner
Series	Type
	Super Scarab 40, 50 (R-500-2), 50A (R-500-4, -6) Scarab Series 28, 29, 30, 40, 50, Super Scarab 165 (R-500-1, -7), 165-A, 165-B, 165-D, 185, 185J (R-550-1, -3), 185K

Certified Cells

Manufacturer	Aeronca
Series	Type
	15AC, S15AC, 65-TC, YO-58, 65-TAC

Manufacturer	Aero Commander
Series	Type
	10, 100, 10A, 100A

Manufacturer	Air Tractor
Series	Type
	AT-300, AT-300

Manufacturer	Ayres Thrush
Series	Type
	S-2C and 600 S-2C, Serial Nos. 1163C & 600-1163C thru 1526C or 600-1526C only 600-S2D, S-2R, S2R-R1340

Manufacturer	Beech
Series	Type
	AT-11, SNB-1, D18S, E18S, C45G, TC-45G, C-45H, TC-45H, TC45J, UC-45J, (SNB-5), RC45J (SNB-5P), E-18S-9700, G-18S, H-18, URB-6, 3N, 3NM, 3TM, D17S, 35, A35, B35, C35, D35, E35, F35, G35, 35R, 35-33, 35-A33, 35-B33, 35-C33, E33, F33,

Manufacturer	Boeing
Series	Type
	75 (PT-13), A75 (PT-13A, -13B, -13C), B75 (N2S-2), E75 (PT-13D, NS2-5, PT-13D/N2S-5), A75J1 (PT-18), A75L300, A75N1 (PT-17, -17A, N2S-1, -4) B75N1 (N2S-3), D75N1 (PT-27), IB75A, E75N1, A75L3

Manufacturer	Bellanca
Series	Type
	7AC,7CCM,7EC,7ECA,7FC,7GCB,7GCBC, 11AC, S11AC, 11BC, S11BC, 11CC, S11CC

Manufacturer	Brewster
Series	Type
	Fleet7

Manufacturer	Callair
Series	Type
	A-9,A-9A

Manufacturer	Champion
Series	Type
	7GCAA, 7GCBC, 7AC, S7AC, 7BCM, 7CCM, 7DC, S7DC, S7CCM, 7EC, S7EC, 7FC, 7GC, (Aeronca) 7HC, 7GCA, 7JC, 7GCB, 7KC, 7GCBA, 7ECA, 8GCBC

Manufacturer	Cessna
Series	Type
	O-1D, O-1E, O-1F, O-1G, 120, 140, 140A, 150, 150A thru 150M, 152, A152, 170A, 170B, 172, 172A ... 172N, 172P, 175,175A, 175B, 175C, 177, 180, 180A, 180B, 180C, 180D, 180E, 180F, 180G,180H, 180J, 182, 182A, 182B, 182C, 182D, 182E, 182F, 182G, 182H, 182J, 182K, 182L, 182M, 182N, 182P, 188, 188A, 188B, 190,195, 195A, 195B, 305A, 305C, 305D, 305F, A150K, A150L, A150M, 305B, 305E, F172P, P172D, TO-1D, USAFO-1A

Manufacturer	Christen
Series	Type
	Husky A-1

Manufacturer	De Havilland
Series	Type
	DHC-2MKI

Manufacturer	Douglas
Series	Type
	DC3A-SCG, -SC3G, -S1CG, -S1C3G & -S4C4G, DC3C-SC3G, -S1C3G, -S4C4G, DC3C-R-1830-90C, DC3D-R-1830-90C

Manufacturer	Fairchild
Series	Type
	24R, 24W, 24C8C & 24C8CS

Manufacturer	Funk
Series	Type
	B, B75L, UC-92, B85C

Manufacturer	Grumman
Series	Type
	G-164, G-164A, G-164B, [G-21 (Goose), must have Pesco P/N 2E608 electric fuel pumps], AA-5, AA-5A (nur mitO-320-E2G)

Manufacturer	Gulfstream American
Series	Type
	AA-5, AA-5A

Manufacturer	Globe (Temco)
Series	Type
	GC-1A & GC-1B

Manufacturer	Gomolzig
Series	Type
	DR 300/108 -/125 -/180R, DR315, DR400/120(d) -/125 -/2+2 -/140 -/140B, -/180R

Manufacturer	Great Lakes
Series	Type
	2T-1A-1

Manufacturer	Harvard
Series	Type
	Mk 1 & Mk II (STA available on Mk IV)

Manufacturer	Howard
Series	Type
	DGA-15P

Manufacturer	Luscombe
Series	Type
	8 Series thru 8F and T-8F Models (must have gravity fuel feed wing fuel tanks as the main fuel supply to the carb)

Manufacturer	Maule
Series	Type
	M-4, M-4C, M-4S, M-4T, 5, 6, 7, MX7, M8 (See below for more Maule info)

Manufacturer	North American
Series	Type
	BC-1A, AT-6 (SNJ-2), AT-6A (SNJ-3), AT-6B, AT-6C (SNJ-4), AT-6D (SNJ-5), AT-6F (SNJ-6), SNJ-7, T-6G

Manufacturer	Piper
Series	Type
	PA-11, PA-11S, PA-12, PA-12S, PA-14, PA-16, PA-16S, PA-18, PA-18S, PA-18 "105", PA-18S "105", PA-18A, PA-18 "150", PA-18A "150", PA-18S "150", PA-18AS "150", PA-18S "135", PA-18AS "135", PA-18 "125", PA-18S "125", PA-18 "135", PA-18A "135", PA-19, PA-19S, PA-18A, PA-18A "135", PA-18A "150" restricted category, PA-20, PA-20S, PA-20 "115", PA-20S "115", PA-20 "135", PA-20S "135, PA-22, PA-22 ”15”, PA-22S ”15”, PA-22-108 (with gravity fuel system only), PA-22-135, PA-22S-135, PA-22-150, PA-22S-150, PA-22-160, PA-22S-160, PA-23-150, PA-23-160, PA-25, PA-25-235 (restricted and normal category), PA-23-150, -160, PA-28-140, PA-28-151, 150, 151, 160, 161, 180, 181, Warrior II & III, Archer II & III, PA-28-235, PA-36-285, J3C, J3C-65, J3C-65S, J4E, J4A-S, (L-4E) Petersen: PA-28-160, PA-28-180, PA-28-161, PA-28-181

Manufacturer	Robinson
Series	Type
	R-22 (See below)

Manufacturer	Ryan
Series	Type
	ST-3KR (PT-22, PT-22A)

Manufacturer	Stinson
Series	Type
	108, 108-1, 108-2, 108-3, L-5, -5B, -5C, -5D, -5E, -5E-1, -5G, SR-5, -5°, L-12, -5B, -5C, -5E.

Manufacturer	Spartan
Series	Type
	7W

Manufacturer	Taylorcraft
Series	Type
	BC-65, BCS-65, BC12-65, (ARMY L-2H) BCS12-65, BC12-D, BCS12-D, BC12-D1, BCS12-D1, BC12D-65, BC12-D, BCS12-D, BC12-D1, BCS12-D1, BC12D-85, BCS12D-85, BC12D-4-85, BCS12D-4-85, 19, F-19, DC-65 & DCO-65

Manufacturer	Varga
Series	Type
	2150°

Manufacturer	Waco
Series	Type
	UPF-7 & VPF-7, YKC, YKC-S, YKS-6, ZKS-6, YMF

Manufacturer	Weatherly
Series	Type
	620, 201, 201A, 201B, 201C

Manufacturer	Reims Cessa
Series	Type
	150G, H, J, K, L, M; FA150K, L, FA152, F152. F172D, E, F, G, H, K, L, & M, F172P, F182P

B Statistical Data on General Aviation and Ultralight Aircraft (T 1)

A statistical evaluation of available cell, engine and flight data was performed to assess the potential danger of faulty ethanol admixed MOGAS usage. As discussed with EASA available statistical base data are rather distributed for the different countries and, due to slightly differing boundary settings of individual aircraft classes, not well adapted to comparison purposes. Cell and engine resolved lists of operated aircraft and/or flying hours could only be obtained for Germany and the United Kingdom. Accordingly, an extrapolation for the whole European Union can be given only on some assumptions of an approximate equi-popularity of the different aircraft types throughout.

Only those aircraft types being presently able to fly on MOGAS are considered as potentially threatened by future ethanol admixtures. This assumption holds for the present state of affairs where there is a clear-cut difference between well-defined AVGAS with strict compositional restrictions and quality conformance processes throughout the delivery chain up into the individual aircraft, and rather arbitrary MOGAS qualities which may or may not contain certain amounts of alcohol. It cannot be ruled out that in the years to come some ethanol-containing AVGAS derivative may spring into existence, should the lead content of the standard AVGAS 100 LL be increasingly incriminated. As some adverse mixed fuel properties originate directly from the thermophysical behaviour of the gasoline the according threats would affect present AVGAS-only aircraft as well, even if the strict delivery rules for today's AVGAS would be analogously applied. Respective delivery rules would not eliminate hazards consecutive to a deteriorated technical state of the individual aircraft (e.g. porous filler cap sealings permitting water penetration into the tank).

The resulting workflow of statistical evaluation, to arrive at an at least educated guess, has been performed as follows:

(1) The number of GA aircraft for (most of the) European countries is taken from the IRCA/ICAO national registers worldwide (originating from 2005) [18].

(2) From the ECAC accident report for the European countries [13], determine the number of GA aircraft, subdivided into number of aircraft < 2.25 t and gliders.

(3) From (1) and (2) calculate the number of aircraft with MTOM < 2.25 t ("other A/C") for the countries given in (1).

(4) Estimate shares for the countries additionally found in (2), from the data calculated in (3). This yields an estimate of the total number of aircraft in Europe, subdivided into aircraft < 2.25 t, gliders and other aircraft by countries.

The resulting numbers, reported in Table 27 and Fig. 87 as a graphical representation of aircraft numbers throughout Europe, are definitely more realistic than those taken from other statistical database [24].

Now calculate the share of operative and potential EN 228 aircraft:

(5) For Germany: Reconciliation of the European type approvals [15] and the operating hours survey of the German LBA on the basis of engines and cells [11]. As a by-product, obtain statistics on widely used EN 228 aircraft types and engines in Germany. This leads to the numbers shown in Fig. 83 and Fig. 84, left side.

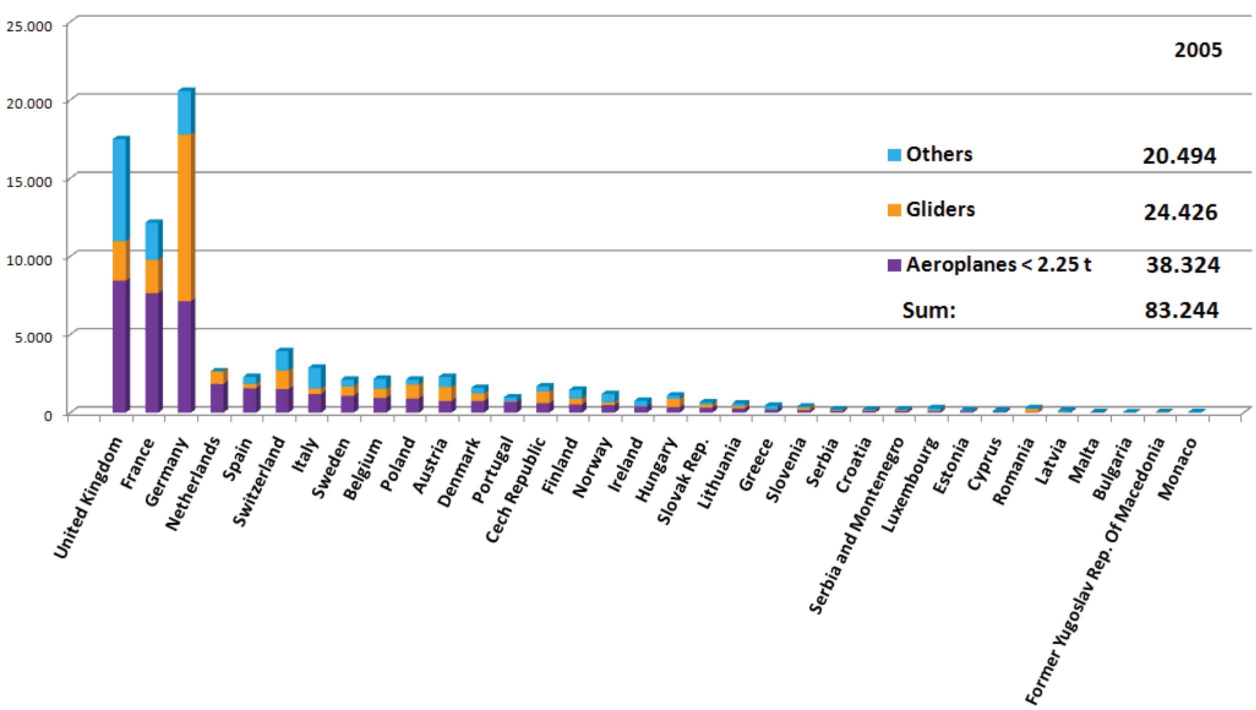


Figure 82: *Compilation of European General Aviation aircraft numbers as graphical representation, subdivided into estimated national shares and ordered by aeroplanes less than 2.25 t subtotals.*

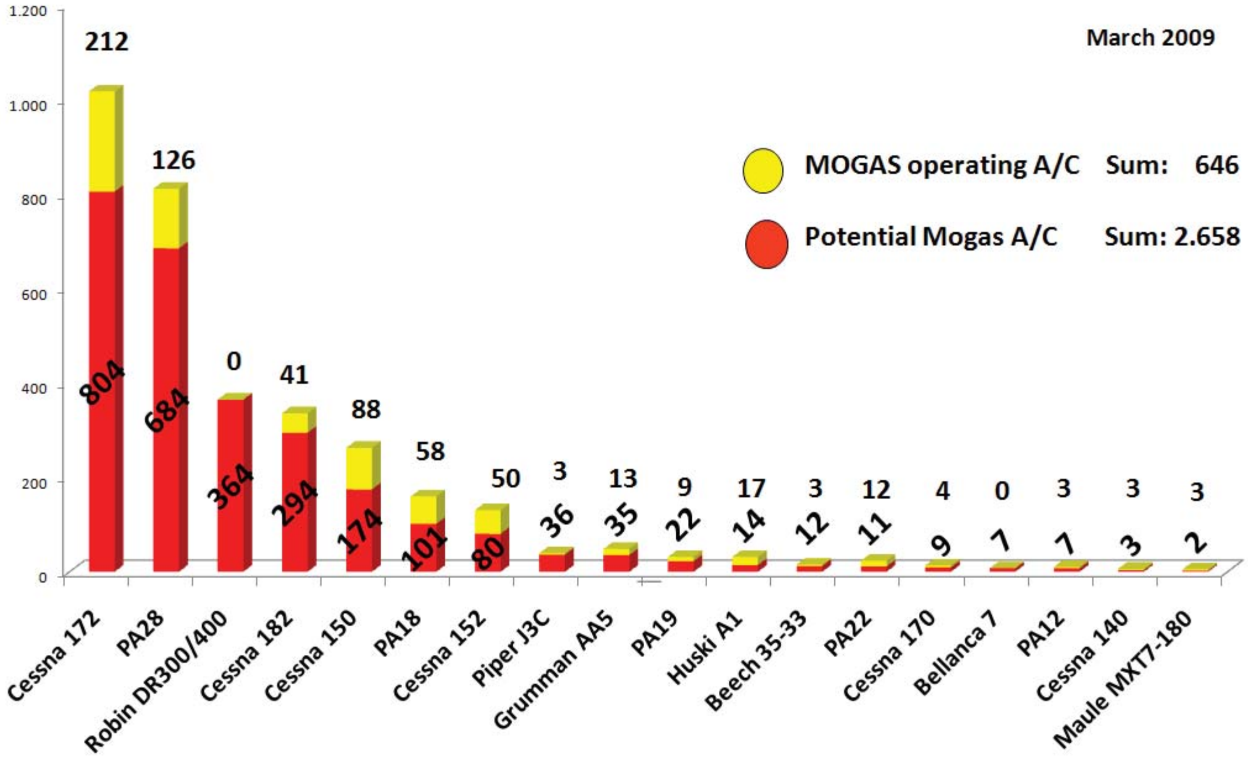


Figure 83: *Share of German* MOGAS *operated aircraft relative to the not yet (per STC) realized potential usage in same types.*

(6) For the UK: The share of certified and potential EN 228 aircraft (operable on <1 % ethanol, basis 2005 data) in General Aviation [4] is shown by numbers in Fig. 84, right side.

Country	All A/C, G/A	Aeroplanes < 2.25 t	Gliders	Others
United Kingdom	17.493	8.436	2.537	6.520
France	12.147	7.637	2.137	2.373
Germany	20.582	7.132	10.660	2.790
Netherlands	2.644	1.830	804	10
Spain	2.291	1.555	275	461
Switzerland	3.941	1.502	1.203	1.236
Italy	2.871	1.196	358	1.317
Sweden	2.112	1.067	620	425
Belgium	2.172	932	599	641
Poland	2.117	905	896	316
Austria	2.296	741	903	652
Denmark	1.586	734	494	358
Portugal	984	683	34	267
Cech Republic	1.681	599	744	338
Finland	1.461	519	386	556
Norway	1.194	488	172	534
Ireland	758	387	26	345
Hungary	1.092	350	522	220
Slovak Rep.	657	313	212	132
Lithuania	581	266	169	146
Greece	445	196	14	235
Slovenia	392	159	154	79
Serbia	218	112	62	44
Croatia	193	111	43	39
Serbia and Montenegro	209	108	59	42
Luxembourg	298	81	48	169
Estonia	144	70	28	46
Cyprus	117	66	1	50
Romania	299	38	201	60
Latvia	130	36	30	64
Malta	34	29	n/a	n/a
Bulgaria	27	20	2	5
Former Yugoslav Rep. of Macedonia	40	14	18	8
Monaco	38	12	3	23
Summarized values:	**83.244**	**38.324**	**24.426**	**20.494**

Table 27: *Tabular compilation of European aircraft numbers, subdivided into estimated national shares*

(7) Extrapolation of the shares calculated in (5) and (6) to the rest of Europe — it should be minded that UK and Germany together already accumulate nearly 50 % of all active General Aviation aircraft in Europe. It is worth noting that the shares of potentially endangered aircraft in the complete national engine-powered fleets in the UK and Germany are within a scatter of 50 – 70 % of the registered engine powered aircraft. Accordingly, the extrapolated numbers for the whole of Europe should not be too far from reality.

(8) On the basis of the analysis performed for the United Kingdom and Germany, estimate the total number of endangered EN 228 aircraft in Europe, shown in Fig. 85. It must be kept in mind that these estimated numbers do not include local national effects of EN 228 usage: it is often driven by fuel prices. Since for example the AVGAS price in France is quite low

and comparable to EN 228 gasoline the potential number of EN 228 aircraft is overestimated. This may as well happen in other European countries.

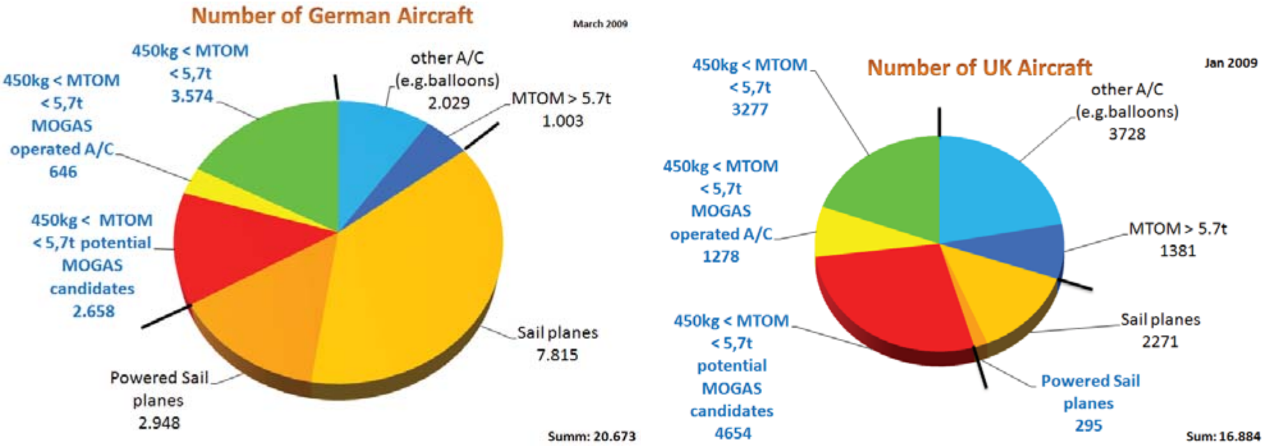


Figure 84: *German and United Kingdom numbers for the aircraft categories of interest. No distinction is made with respect to used fuel type.*

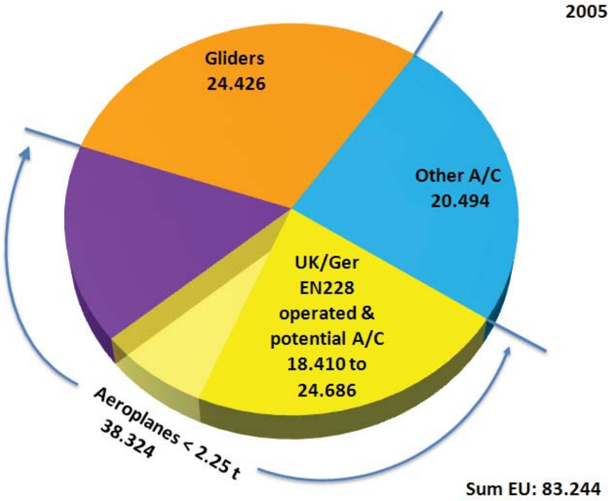


Figure 85: *Estimated European total numbers for the aircraft categories of interest*

The statistical basis also allows to attribute the actual utilization share of generally MOGAS capable engines for Germany. Fig. 86 shows that 18 % of the potential MOGAS engines are already operated on EN 228 fuel.

Additionally, the German statistics on operating hours [11] allow a rough estimate on the popularity of MOGAS operation: A comparison on the basis of "flown hours since last check" reveals that the actually EN 228 certified aircraft collect significantly more operating hours: While only 48 % of all General Aviation aircraft fall into the category of being principally MOGAS capable, 57 % of flight hours are delivered by the respective types if the comparison is performed on the basis of German data for flown hours since last check. This is not surprising since in Germany MOGAS is roughly only half the price of AVGAS, so even the costs of partial refurbishment to get an STC will be cost-effective for regularly operated aircraft.

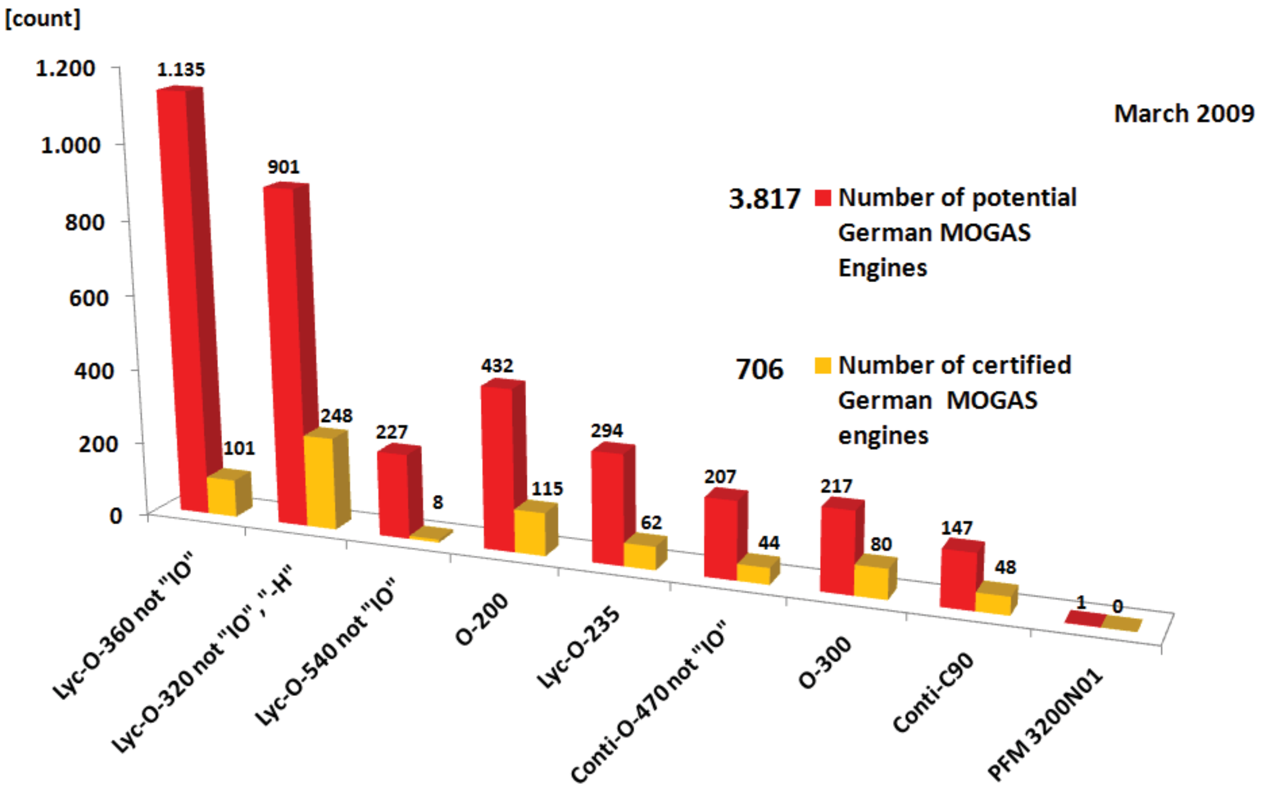


Figure 86: *Share of German* Mogas *operated aircraft engines relative to the not yet (per STC) realized potential usage in same types. Existence of respective cell certificates is not taken into account.*

It should be kept in mind, though, that the existence of an STC for a given aircraft does not always imply that all flight hours are actually flown on Mogas**. There are occasions when this fuel type is not available, so pilots have to revert to** Avgas **at least for some fillings.**

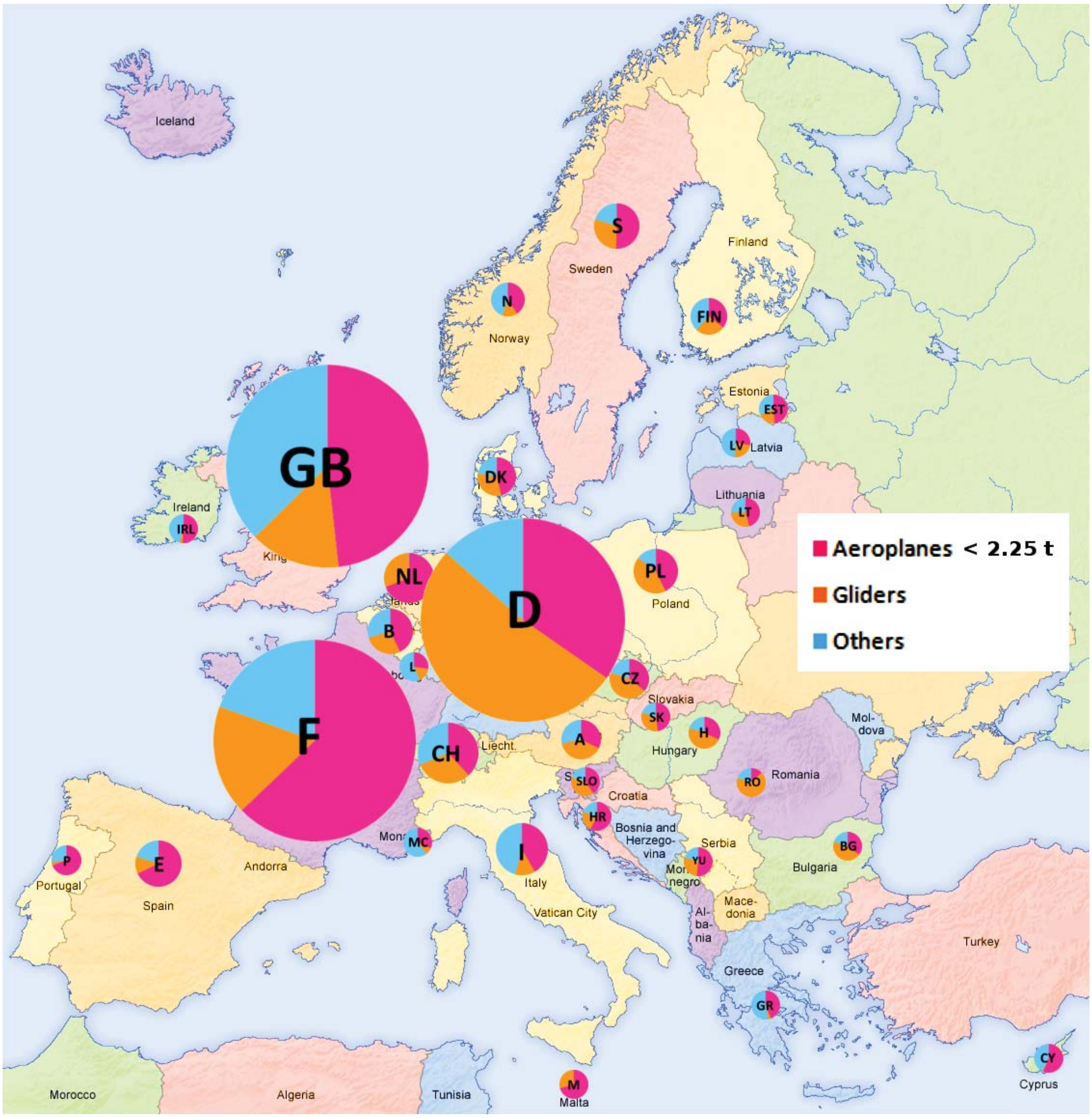


Figure 87: *Graphical display of the distribution of small aircraft (less than 2.25 t) in Europe. The three largest cakes (UK, D, F) are reduced to 70 % of their correct size whereas very small contributions (Malta, Estonia, ...) are disproportionally large to be able to display them at all. For comparative numerical data see Table 27, page 156.*

C Tabulated FMEA Results

On the subsequent pages the overview results of the FMEA are given. From the basic FMEA collection tables 63 issues with RPN values above 100 have been identified. The RPN is listed in the top right corner of every issue box there. Additionally the line numbers of the FMEA collection tables of the individual failure modes are given as line references for each issue.

As all participants of the workshops had German as their native language the practical FMEA fact collection was performed in German. Accordingly the raw FMEA tables (not included in this report, but obtainable as a separate appendix package) are given in this language. They can be obtained as a separate appendix and are not included in this report. The interpretation of the resulting issues is given in this report's section 6.1.

Executive Summary of the technical assessment for E10 blended fuels for General Aviation (GA)

Project:

SIoBiA - Safety Implications of Biofuels in Aviation

Sub-project:

**FAILURE MODE AND EFFECTS ANALYSIS (FMEA)
for the application of ethanol blended gasoline
in General Aviation**

TABLE OF CONTENTS

1. List of amendments

Issue / Revision / date	Remark	execution
A / 00 / 2009-08-12	new	OA/Ste
A / 01 / 2009-09-16	Several modifications after first review	OA/Ste
A / 02 / 2009-09-22	Corrections in english expressions	P. Roosen
A / 03 / 2009-11-03	Source inserted, and Release by BRP-Powertrain	OA/Felb
A / 04 / 2009-11-12	prepared for official SIoBiA Report	OA/Felb

2. Abbreviations

GA	**G**eneral **A**viation - Refers to all flights other than military and scheduled airline flights
MOGAS	**Mo**tor **Gas**oline vs. AVGAS (**Av**iation **Gas**oline)
SIoBiA	**S**afety **I**mplications **o**f **B**iofuels **i**n **A**viation
FMEA	Failure Mode and Effects Analysis
EASA	European Aviation Safety Agency
NBR	*Nitrile Butadiene Rubber (rubber)*
E10	Blend of 10% ethanol and 90% gasoline
FL	FMEA "**F**UE**L**LING"
AF	FMEA "**A**IRCRAFT INSTALLATION – **F**UNCTIONS"
AP	FMEA "**A**IRCRAFT INSTALLATION – **P**ARTS"
EF	FMEA "**E**NGINE – **F**UNCTIONS"
EP	FMEA "**E**NGINE - **P**ARTS"
PE-HD	Polyethylen - high density
PE-LD	Polyethylen - low density
PTFE	Polytetrafluorethylen
PA	Polyamid
###	Indication within an FMEA that the risk evaluation numbers (O, S, D, RPN) have been added afterwards based on the ratings of the expert team in the course of similar failure conditions.
xxx	Indication within an FMEA that the cell entry has been added afterwards based on the assessment of the expert team in the course of similar failure conditions.

3. Overview

1.1. Purpose and objectives

The purpose of this *Executive Summary Report* is to pinpoint the results of a *Failure Mode and Effects Analysis* (FMEA) whose objective was to identify potential hazards, failure conditions and the safety implications on aircraft and engine operation when using bio-ethanol blended fuel (up to 15% ethanol – E15) in comparison to MOGAS (<1% ethanol). In the course of the FMEA the term E10 is used representing the entire range of ethanol blended fuels up to E15.

This report represents a comprehensive abstract of the potential risks identified by the FMEA analysis and summarizes in-depth explanations for each failure condition if appropriate.

It takes into account aircraft and engine functions as well as essential components and systems to systematically determine the potential effects on materials and functions caused by the specific characteristics of fuel containing bio-ethanol.

Furthermore a step by step analysis of the fuelling process starting from the fuel production till the aircraft filling process has been accomplished to identify potential failures and its causes. The implications of failures during these processes could finally lead to operational irregularities induced by material incompatibilities.

Besides the summary of the failure conditions this report contains the general conditions of this FMEA such as project description, experts team selection, methodology, FMEA form description, and the project time frame.

1.2. SIoBiA project

In order to give appropriate recommendations on the usage of bio-ethanol blended fuel the EASA raised a project termed "Safety Implications of Biofuels in Aviation" (abbreviation: SIoBiA).

Its objective is to investigate the safety implications on aircraft/engine operation and on tanks, fuel pipes, seals and fuel systems of spark ignited piston engine powered aircraft and engines by using fuel containing bio-ethanol.

As an integrated part of this SIoBiA project amongst other surveys and studies a Failure Mode and Effects Analysis should determine bottom-up potential hazard conditions in order to give at least recommendations for the usage of bio-ethanol blended fuels in spark ignited piston engine powered aircrafts.

4. FMEA Process / methodology

An FMEA is a systematic, bottom-up approach to identify the failure modes of a system, piece-part or function and determining the effects on the next higher level.

It utilizes a tabular method to aid the thought processes accomplished by experts and specialists to determine potential failure modes and their effects. An FMEA is a tool to prevent risks by taking appropriate actions. It may be performed at any level within the system (e.g. piece-part, function, process, etc.).

Typically, an FMEA is used to address failure effects resulting from single failures and common mode failures.

1.3. FMEA team selection

Ideally the selection of specialists should cover the widest range of skill and experience. This expert's selection process has been performed in coordination between *FH-Aachen* and *BRP-Powertrain*. The selection criteria for that range of experts should cover the following domains and skills:

- Material properties and compatibilities
- Specification and characteristics of fuels used in aviation
- Fuelling process (production till aircraft fuelling)
- Aircraft installations regarding fuel systems
- Engine functionality and engine systems
- Engine and aircraft maintenance
- US aircraft engines (Lycoming, Continental …..)
- Science for aviation
- Performance of safety assessments and moderation (FMEA methodology)

By taking into account the identified selection criteria the responsible project leaders of *FH-Aachen* and *BRP-Powertrain* have chosen a team of specialists that participated the FMEA sessions.

BRP-Powertrain	Project leader FMEA (engine specialist)
BRP-Powertrain	FMEA-specialist, Moderation, engine experience, executive summary
BRP-Powertrain	Engine Expert, Aircraft installations, private pilot licence
Austro Engines	Engine specialist
Diamond Aircraft Industries GmbH	Aircraft installations
Diamond Aircraft Industries GmbH	Aircraft installations
Luftfahrzeug Wartungsbetrieb Krems GmbH	Aircraft Maintenance specialist / US engines
TOTAL Deutschland GmbH	Fuel expert, fuelling
SGS Institut Fresenius GmbH	Material specialist, material compatibilities
SGS Institut Fresenius GmbH	Material specialist, material compatibilities

FH-Aachen	Project leader SIoBiA Science for Aviation
FH-Aachen	Project leader SIoBiA Science for Aviation
g.o.e.the Gesellschaft zur Optimierung von Energiesystemen und thermochemischen Prozessen	Project Manager SioBiA Science for Aviation

1.4. Time schedule

Kick-off Meeting BRP	Definition of methodology, start of team selection, time schedule	16.3.2009
FMEA preparation	System determination, definition of functions, systems and parts	March – April 09
FMEA workshop #1	Fuelling systems Aircraft installation appraisal at LOLW (airfield WELS)	20.4.2009
FMEA workshop #2	Fuelling systems Aircraft installation	21.4.2009
FMEA workshop #3	Aircraft installation Engine - functions Aircraft installation appraisal at LOLW (airfield WELS)	8.6.2009
FMEA workshop #4	Engine – functions and parts	9.6.2009
Completion of FMEA	Analysis, evaluation, recommended actions	June – July 09
Preparation of Executive Summary	Incl. FMEA	June – July 09
Release of FMEA Executive Summary Report		13.8.2009

1.5. Used FMEA Software

For the preparation of the FMEA analysis a data based software tool termed ***SCIO-FMEA System 2.0*** (Plato AG, www.plato-ag.com) was used.

1.6. FMEA form description and rating tables

Enclosed the description of the particular columns within the FMEA form (from left to right):

Nr.
Consecutive number of lines containing potential failure scenarios for parts, functions or process steps. Shown are FMEA line reference to definitions within chapter 7 "Executive summary of potential risks". Note: This column is only visible within the FMEA software tool SCIO-FMEA.

Element / function
Name of the component and/or short description of the intended function, a part or a system has to perform (for piece-part or functional FMEA).
Description of the steps within a certain process (process FMEA)
Note: in some cases a specific description of the part and its function or the process step is essential. These comments are marked with "LK" (local comment).

Potential failure mode
This column lists potential failure modes for each item, function or process step so that the intended function the part has to fulfil could not be performed any longer.

Potential effects of failure
Description of the effect of the specific failure mode identified under "potential failure mode" on the next higher subsystem and/or on the uppermost system (e.g. engine or aircraft).

Potential causes
Potential cause for the specific failure mode.

Current actions
(P) Current checking actions that are already in place which help to detect the failure before it occurs. P-actions increase the detection probability (D).
(V) Design provisions that are already in place to avoid the described failure. V-actions decrease the occurrence probability.

Occurance (O)

Number from 1 to 10 stands for an estimated probability range specified for each failure considering potential causes and failure modes.

Probability of Occurrence (O)	O (Occurrence) number	Potential failure rate
Very high Failure almost unavoidable	**10**	≥ 1 of 2
	9	1 of 3
High Frequent respectively repeated occurrence	**8**	1 of 8
	7	1 of 20
Moderate Casual occurrence	**6**	1 of 80
	5	1 of 400
	4	1 of 2.000
Low Infrequent occurrence	**3**	1 of 15.000
	2	1 of 150.000
Very low Occurrence of failure unlikely	**1**	≤ 1 of 1,5 million

The occurance ratings in the chart are transferred from the automobile standard. The assessment can apply to several quantities (e.g. number of defective engines, defective devices or to flying hours) depending on the type of failure. The values provide as support to find the estimated occourance.

Severity (S)

Potential severity of the effect of the failure mode on the next higher subsystem and/or on the uppermost system (e.g. engine or aircraft).

Severity (S)	S (Severity) number	Closer description
Very high (Hazardous or catastrophic failure condition) Large reduction in functional capabilities or safety margins. Safety risk for the crew. E.g. Vehicle breakdown, fire hazard, structural fractures	**10**	Immediate occurrence without warning
	9	Immediate occurrence with warning
High (MAJOR failure condition) Significant reduction in functional capabilities or safety margins. Physical discomfort or a significant increase in workload. E.g. Engine shut down	**8**	Immediate occurrence without warning
	7	Occurrence with warning
Moderate (MINOR) Slight reduction in functional capabilities or safety margins. Slight increase in workload or use of emergency procedures. Repair required.	**6**	
	5	
	4	
Low (MINOR) Slight reduction of functional capabilities. Repair is	**3**	

required in the course of the next scheduled maintenance.	**2**	
Very low No effect on operational capabilities or safety. Almost not detectable by the pilot.	**1**	

Detection (D)

Evaluation of the probability to detect a failure.

Probability of Detection (D)	D (Detection) number
Very low Detection of the failure or the cause unlikely.	**10**
	9
Low Detection almost unlikely.	**8**
	7
Moderate Detection of the failure or the potential cause probable.	**6**
	5
	4
High Detection probability high.	**3**
	2
Very high Detection probability very high. Failure or the cause will be detected most likely.	**1**

RPN (Risk Priority Number)

The Risk Priority Number is the mathematical product of the numerical **S**everity, **O**ccurrence and **D**etection ratings.

RPN = Occurance (O) x Severity (S) x Detection (D)

This number is used to place priority on items that require additional actions.
RPNs above 100 are deemed to be critical and recommended actions have to be defined.

Recommended actions

Actions that are recommended to avoid or detect the potential failure or its potential cause.

5. Items of investigation – general

1.7. General

In order to determine the scope of the *Failure Mode and Effects Analysis* it is essential to define the items of investigation. These items could either be a processes, systems or single components, whereas each set of these kinds will form a dedicated and complete FMEA analysis.

The participating specialists have been selected to perform FMEA sessions on the consecutive list of investigation topics.

1.8. Scope of investigation

1.8.1. Fuelling systems

The fuelling process is to be scrutinized from the fuel production till the aircraft filling process, with the aim to identify potential process failures and its causes.

1.8.2. Aircrafts

The aircraft analysis should cover a preferrably wide range of different aircraft types in General Aviation that could use bio-ethanol blended fuels in future.

Amongst other components assessed during the FMEA the analysis should cover different kind of tanks, hoses and pipes, drainage, level sensors and fuel pumps.

1.8.3. Engines

The engine assessment should cover a preferrably wide range of different engine types in General Aviation that could use bio ethanol blended fuels in future. Following different kinds of engines should be considered:

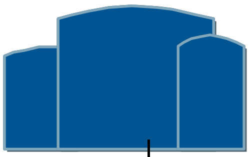
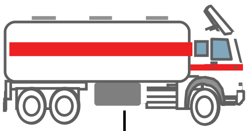
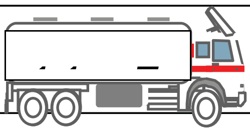
- Carburettor fed piston engines (2 and 4-strokes)
- Electronic intake-manifold fuel injection
- Mechanical intake-manifold fuel injection
- Wankel rotary engine

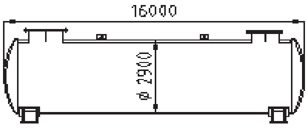
6. Items / functions description

1.9. Fuelling systems

1.9.1. General system description

The following sequence shows schematically the handling steps in the process of aviation grade fuel production down to the refuelling of the aircraft that had been taken into account during the FMEA assessment.

	**Refinery** repeated quality controls/analyses, sample, certificates
Transfer from refinery to storage   	**Means of transport** Cleanings is examined before loading.
	**Storage** duration of the deposit of the fuel tank truck = 1 hour Test of samples, storage into separated tanks. Storage of master samples. If the tank is full, recertification analysis of the commodity takes place via an independent supervisor, who gives the final release for distribution.
	**Loading for distribution to airfields** Within the fuel depot the vehicle is checked for cleanliness. After loading visual control of a sample from the fuel tank truck takes place. Master sample is kept 3 months.
	**Delivery** Fuel tank truck driver is trained and has written instructions for

 	procedure of TD. The connections with the customer tanks are separately characterized. Customer is obligated to the monitoring of the delivery procedure. Customer is trained and instructed of TD. TD had itself acknowledged the training. Feasting recovery each year. TD put a manual to customers at the disposal. The customer acknowledged. Customer and drivers pull samples from the TKW, before unloading. Spindling the density, control for water, sediments and colour takes place. Customer receives analysis certificate with delivery documents.

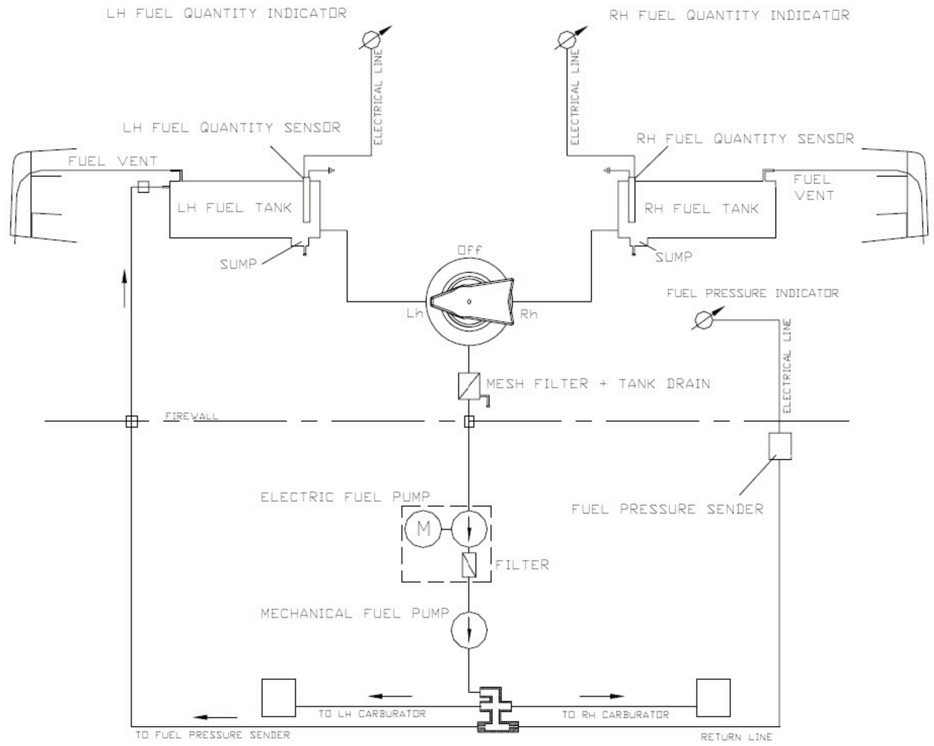
Source: provided by TOTAL Deutschland GmbH

The sequence above describes the transportation of aviation grade fuel (Mogas) from the refinery to the airodrome, and at least to the aircraft fuel tank.
Many aircraft operators are ordering fuel from automobile filling stations. They are refueling there aircraft fuel tanks with cans. This form of sequence is not displayed here. However this form of refueling is discussed and assessed in the FMEA (chapter 7.2.1, issue 3).

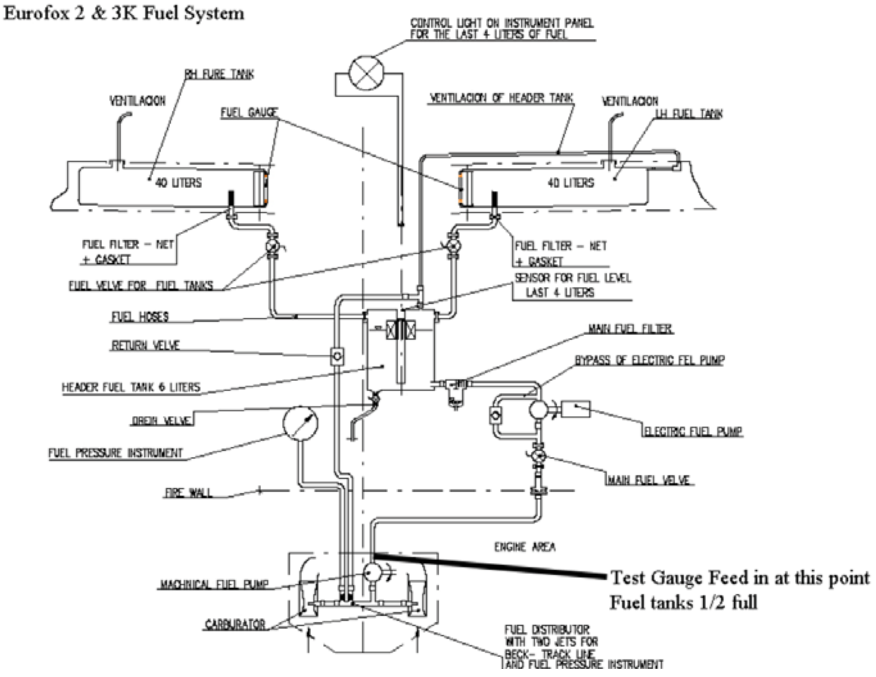
1.10. Aircraft

1.10.1. General system description

Following pictures are representing typical aircraft related fuel systems that have been investigated in the course of the FMEA analysis. They should be regarded as examples and do not exclude any other fuel system for aircraft engines.



Source: Tecnam P2002-JF – Flight Manual, first edition 29 March 2004, page 7-7



Test Gauge Feed in at this point
Fuel tanks 1/2 full

Source: Eurofox Maintenance manual, issue number 10/2008, page 11-6

1.10.2. Items / functions

Following typical and representative items and parts of the aircraft fuel related installation have been taken into account during the FMEA assessment:

- Different kind of tanks including accessories (venting, sealing, filler caps, ….)
- Hoses, tubes, fittings
- Valves and check valves
- Electrical fuel pumps
- Sensors
- Gaskets
- Pressure indications incl. inlet hoses
- Fuel selector valves
- Fuel cooler
- Fuel filters
- Skin of fabric and painting
- Exhaust system

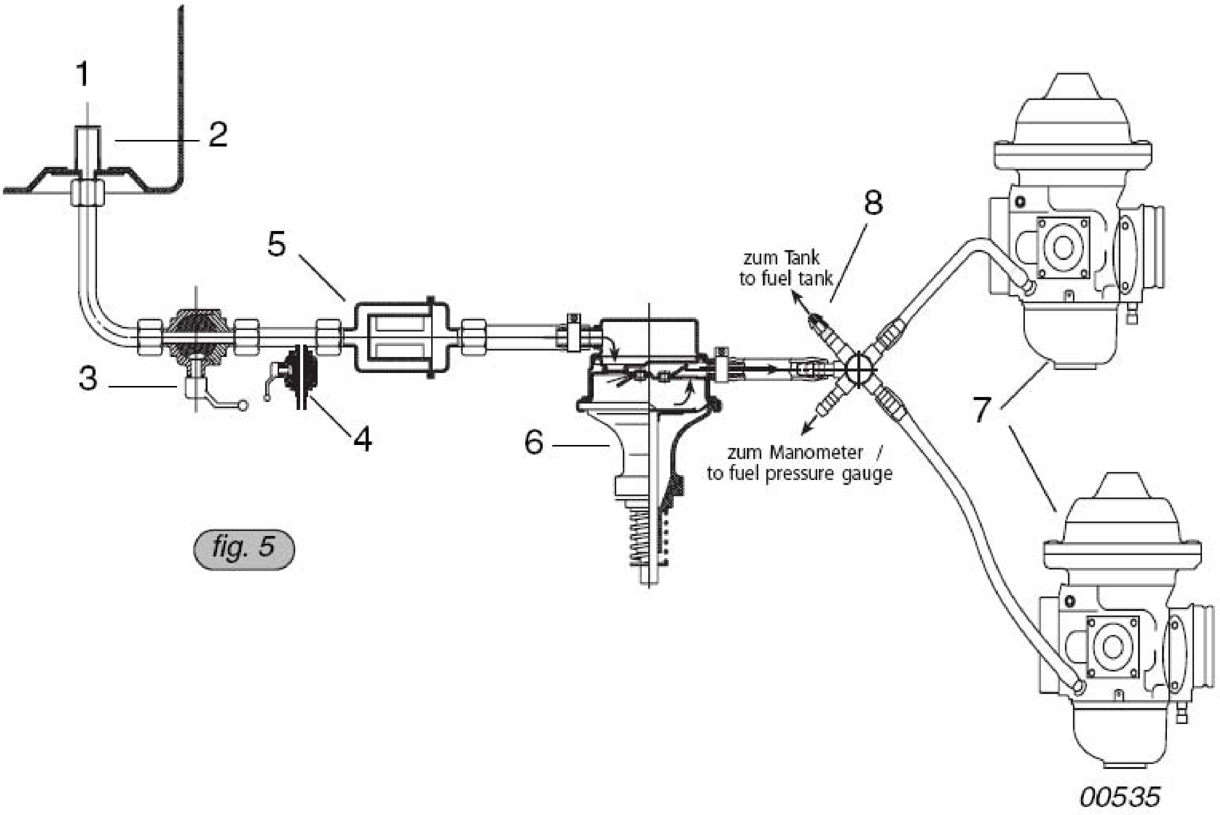
Following typical and representative functions of the aircraft fuel related installation have been taken into account during the FMEA assessment:

- Providing safe fuelling of the aircraft
- To allow longer non-usage periods of the aircraft
- To provide sufficient fuel for engine operation
- To avoid inadvertent discharge of fuel
- To provide fuel with sufficient quality for the engine
- Ability to cover the entire flight envelope
- To accept mixed fuels
- To keep fuel in liquid condition
- Pre-heating of the intake air

1.11. Engines

1.11.1. General system description

Following picture represents a typical engine related fuel system for carburettor equipped piston engines that have been investigated in the course of the FMEA analysis. This should be seen as an example and does not exclude any other fuel system for aircraft engines.



Source: Operators Manual for ROTAX engine type 912 series

Short description: The fuel flows from the tank (1) via a coarse filter (2) the safety cock (3), water drain cock (4) and fine filter (5) to the mechanical fuel pump (6). From the pump fuel passes on to the two carburettors (7). Via the return line (8) surplus fuel flows back to the fuel tank.

1.11.2. Items / functions

Following typical and representative items and parts of the engine related fuel installation had been taken into account during the FMEA assessment:

- Hoses, tubes, fittings
- Valves and check valves
- Mechanical and electrical fuel pumps
- Carburettors
- Airboxes and airfilters
- Primer
- Combustion chamber including spark plugs and storage spark plugs
- Spark plugs
- Injectors
- Fuel rail
- Fuel pressure regulator
- Different diaphragm materials
- Sensors
- Gaskets
- Fueltotalizer
- Engine oil (2 and 4 stroke)

Following typical and representative functions of the engine related fuel installation had been taken into account during the FMEA assessment:

- Cold start, warm start and restart
- Engine warm-up
- Cruising
- Max. take-off power (full load)
- Remain within the limits according operating manual (e.g.: fuel consumption, EGT, CHT, TIT…)
- Manual mixture adjustment
- Mixture admission within carburettor
- Shutdown
- Cover the entire flight envelope

- To allow suction of fuel
- Fresh oil lubrication
- Oil-in-gasoline lubrication
- To ensure lubrication of 4-stroke engine
- Powering and lubricating auxiliary drives
- Ensure function of the turbo charger
- Ensure leak-tightness

7. Results

1.12. Definitions

1.12.1. Phase separation

One of the substantial risk potentials when using ethanol admixtures is the separation of the phases into an alcohol/water mixture and a low-octane fuel at the upper phase. What particular conditions lead to phase separation and what its probability is, have to be determined by test and/or analysis.

The evaluation of the occurrence probability is currently an uncertain number and for the moment assessed with rather high evaluation characteristic numbers.

However, phase separation must be already prevented or detected as soon as it occurs anywhere in the aircraft fuel system. In particular, sections of the fuel system where larger volumes of fuel are accumulated are most vulnerable to separation effects (especially the tank).

1.12.2. Levels of risk potentials (red, yellow, green)

Basically the ***RPN*** evaluation of the potential failure conditions are highlighted with three different colours dependent on their risk potential, taking into account ***occurrence, severity*** and ***detection***.

RED: Failure conditions within an RPN range above 100 up to 1000 are deemed critical with respect to flight safety considering ***occurrence, severity*** and ***detection***. An appropriate counter measure is required to avoid or at least to detect the failure and/or its cause.

YELLOW: Failure conditions within a range of 80 and 100 are deemed uncritical but it should be observed not to increase to a higher level or taking appropriate actions to bring it to a RPN range below 80.

GREEN: Failure conditions within a RPN range below 80 are deemed uncritical. Nevertheless an action could reduce the risk to a lower level.

1.13. Executive summary of potential risks

The following list of issues contains only the main failure conditions of risk potentials classified as RED that had been identified by the FMEA. Green and yellow marked risk potentials are part of the FMEA itself (refer to APPENDIX A-E) and will not be outlined in this executive summary report.

Several topics are stated only once or summarized in the following listing even if these are found repeatedly in the FMEA. For details refer to the FMEA.

The ***FMEA line reference*** numbers refer to the corresponding ranges in the respective FMEA (only within the FMEA software), while the first two letters identify the FMEA part in which the lines will be found.

Example:

FL10 - FL15: line 10-15 within FMEA "**F**UE**L**LING"

AF10 - AF15: line 10-15 within FMEA "**A**IRCRAFT INSTALLATION – **F**UNCTIONS"

For further abbreviations, refer to *chapter 2 "Abbreviations"*

1.13.1. FMEA summary - Fuelling (production till aircraft fuelling)

Issue 1: Storage of fuel within tank top after production RPN 108

FMEA line reference: FL29 – FL30

Risk: The potential risk is to insert water during storage caused by potentially lacking operational management. Due to the chemical affinity of E10 to water this could lead to a phase separated fuel that could influence the operation of the aircraft.

Recommended action: Reinforced advice to comply with operational processes (e.g. JIG 3)

Issue 2: Mixing fuel products during filling the tank top RPN 108

FMEA line reference: FL41 – FL42

Risk: The potential risk is to mix different fuels in tank tops caused by human failures, especially at older tank tops that are not equipped with modern detection methods and do not comply with quality assurance processes.

Recommended action: Reinforced advice to comply with existing quality assurance requirements and implementation of processes also for older tank top systems.

Issue 3: Aircraft fuelling by using fuel from cans refilled at petrol stations. RPN 720

FMEA line reference: FL10 – FL22

Risk: The risk is to use fuel that is either contaminated by the can itself or has a poor quality because of mixed or long stored fuel. Longer stored E10 bio fuel can be phase separated and influence the operation of the aircraft.

Recommended action: Official recommendation by EASA. Release of a country specific fuel atlas.

Issue 4: Mixing fuel products during fuelling of the aircraft RPN 729

FMEA line reference: FL53 – FL56, AF42 – AF45

Risk: Potential risk is to have a remaining quantity of fuel within the aircraft tank and to refill with another product (e.g. mix AVGAS or E0 with E10) that could lead to operational problems of the engine.

Recommended action: Release of certain requirements for mixing fuels based on experimental substantiation

Issue 5: Insertion of water during fuelling of the aircraft RPN 729

FMEA line reference: FL57 – FL62

Risk: The potential risk is to insert water before or during the fuelling process by e.g. counter-sunk filler caps or damaged gaskets. Due to the water affinity of E10 a phase separated fuel influencing the operation of the engine is likely.

Recommended action: Regulations regarding the design of the filler caps and its gaskets in order to avoid insertion of water into the fuel system.

1.13.2. FMEA summary – Aircraft installation functions

Issue 6 : Sparking at refuelling RPN 180

FMEA line reference: AF4 – AF6, FL20 – FL22

Risk: The potential risk consists of the fact that due to the assumed smaller danger of the sparking with E10 the pilots probably abstain from grounding during refuelling despite existing regulations. In consequence the danger of sparking is higher than by fuelling MOGAS.

Recommended action: Instructions regarding accurate grounding when refuelling E10. Official EASA guideline must be compiled.

Issue 7: Corrosion of parts or materials during aircraft storage for longer periods RPN 360

FMEA line reference: AF7 – AF17

Risk: Due to the increased affinity for water, the probability of a phase separation and consequential contact corrosion (local cell), is larger with E10 than with MOGAS. With leakages of the fuel system additionally the danger of the chemical attack of surfaces exists (e.g. wood, lacquers, Aerodux 185 glues, covering, tire…)

Recommended action: Particularly in the winter months tests must be performed examining this danger potential and its effects. Additionally the compatibility of the listed materials on E10 must be ensured.

Issue 8: Cross-section diminution in fuel pipes RPN 378

FMEA line reference: AF18 – AF25

Risk: By the characteristics respectively the consequences of phase separated E10 fuel, perhaps the danger of inward expanding rubber pipes exists, which can lead to a cross-section contraction and in further consequence to an influence of the engine operation.

Recommended action: Material compatibility tests

Issue 9: Leakages within the fuel system RPN 160

FMEA line reference: AF26 – AF27

Risk: Probably the solvent characteristics of E10 lead to decomposition of the base material, which could result in fuel system leakages and in further consequence to a potential fire risk.

Recommended action: Material compatibility tests

Issue 10: Blocking filters RPN 144

FMEA line reference: AF28 – AF30

Risk: Due to the solvent characteristics of E10 a potential danger consists in the separation of material used in tanks or fuel pipes, which contaminate the fuel. In further consequence it can result in blocking fuel filters.

Recommended action: Investigations should be performed how quickly and intensively material separations within the fuel system may occur. Further on the tendency and speed of filter blocking is to be scrutinized.

Issue 11: Engine operation with phase separated E10 biofuel RPN 168

FMEA line reference: AF34 – AF35

Risk: By the increased affinity for water, particularly with longer aircraft storage times, a phase separation of the alcohol fuel may occur. This can lead in consequence to an influence of the engine operational behavior up to engine shut down.

Recommended action: Investigations must be performed concerning the probability of occurrence of phase separation respectively their effect on the engine behavior.

Issue 12: Higher vapor pressure of E10 RPN 648

FMEA line reference: AF36 – AF38

Risk: Particularly at low ambient pressure an evaporation of warm fuel may occur, flowing back to the tank. This can lead to a knocking combustion.

Recommended action: Continuative investigations specially in high altitudes

Issue 13: Efflorescence respectively harden from water in the fuel at low temperatures RPN 378

FMEA line reference: AF46 – AF48

Risk: Due to a potentially increased share of water in E10 an ice precipitation may occur, particularly at low temperatures. This could lead in further consequence to a blocking of fuel filters.

Recommended action: Continuative investigations particularly at low temperatures.

Issue 14: Higher vapour pressure due to mixing of different fuels (Avgas and Exx) RPN 378

FMEA line reference: AF49 – AF51

Risk: Due to non-linear mixing effects the vapour pressure of a mixture of E10 and a non-alcohol-admixed gasoline may surpass that of any single mixture component, leading to a reduced boiling point of the fuel. This can change the operational behavior of the engine.

Recommended action: Continuative investigations

Issue 15: Insufficient pre-heating of the intake air RPN 189

FMEA line reference: AF52 – AF54

Risk: Due to the increased evaporation enthalpy of E10 a too low intake air temperature may be encountered, which could result in carburettor icing and consequentially lead to an engine shut down.

Recommended action: Continuative investigations particularly with regard to carburettor icing

1.13.3. FMEA summary - Aircraft installation parts

Issue 16: Increased risk for corrosion with aluminum and/or steel tanks. RPN 189
Note: Similar risk potentials apply also to aluminum, copper and steel lines and metal fittings.

FMEA line reference: AP6 – AP12, AP105 - AP115, AP116 - AP126

Risk: By contact corrosion (local cell) or by electro-chemical corrosion caused by electrical level sensors surface corrosion may be induced, corrosion of the welding seams (if available) up to decomposition of the base material and/or to the pitting corrosion.

Recommended action: Continuative investigations regarding the difference of the oxide film decomposition characteristic with E10 and MOGAS (metal tanks, lines and fittings).

Issue 17: Deposits at the tank bottom may get rinsed out RPN 168

FMEA line reference: AP4 – AP5

Risk: Due to the increased solvent characteristics of E10 a potential danger consists in material deposits at the tank bottom that could be rinsed out and contaminate the fuel system. In further consequence it may result in blocking fuel filters.

Recommended action: Investigations should be accomplished, how quickly and intensively material separations within the fuel system occur. Further it has to be verified how fast this leads to blocked fuel filters.

Issue 18: Incompatibility of composite material (CFK/GFK) RPN 168

FMEA line reference: AP13 – AP23

Risk: The solvent characteristics of E10 in connection with mechanical load or caused by water in connection with high temperature may lead to a decomposition of resins and synthetic material. This on the one hand can result in leakages and on the other hand deposits rinsed out and probably blocking fuel filters.

Recommended action: Investigations should be performed how quickly and intensively material separations due to the solvent characteristics of E10 occur. Further it has to be verified how fast this leads to blocked fuel filters.

Issue 19: Embrittlement of fuselage tanks made of blown PE-HD or PE-LD RPN 168

FMEA line reference: AP24 – AP29

Risk: Due to the special characteristics of E10 a material embrittlement may occur, particular in PE fuselage tanks, which can lead in consequence to leakages. The exact effect currently is unknown.

Recommended action: Continuative investigations regarding the influence of E10 on poly-ethylene (e.g. used for fuselage tanks).

Issue 20: Swelling of NBR rubber material used for tanks RPN 126

FMEA line reference: AP35 – AP37

Risk: Presumably due to diffusion processes a penetration of E10 fuel into the rubber material may occur, which can lead in consequence to leakage and/or to the decrease of the mechanical strength of the tank.

Recommended action: Investigations regarding the swelling of rubber materials.

Issue 21: Difficult draining at NBR tanks RPN 240

FMEA line reference: AP38 – AP39

Risk: Phase separation of E10, particularly within NBR tanks, leads to accumulations of the water/ethanol mixture in bulges on the bottom of the tank. On the one hand this bulges filled with water/ethanol mixture could not be drained completely, on the other hand the quantity of the water/ethanol mixture to be drained is much larger than the proportion of water with MOGAS. Further, the remaining fuel after the draining has a very low octane rating and leads in further consequence to a knocking combustion.

Recommended action: Continuative investigations regarding material compatibility and difficult draining of rubber tanks.

Issue 22: Damage of tank interior coatings RPN 216

FMEA line reference: AP42 – AP49

Risk: The solvent characteristics of E10 in connection with mechanical load may induce a damage of the tank interior coatings. This could lead to a decomposition of the base material up to structural disruptions especially for GFK integral tanks.

Recommended action: Compatibility tests with tank interior coatings.

Issue 23: Decomposition of the tank sealing material RPN 192

FMEA line reference: AP50 – AP51

Risk: Due to the solvent characteristics of E10 the tank seal material may be decomposed. According to experts assumptions cork seals are deemed noncritical. Pro-seal, NBR and PRC (e.g. Company Desoto) are classified as critical. Note: Pro-seal consists of components (polysulphide rubber and a further component).

Recommended action: Continuative investigations with regard to the compatibility of tank sealing material.

Issue 24: Chemical influence on the tank ventilation (aluminum, plastic or steel pipe placed into the air flow) RPN 192

FMEA line reference: AP52 – AP59

Risk: Especially larger temperature variations may lead to a leaking of fuel via the tank ventilation. Material incompatibilities could consequently lead to an embrittlement or to pouring. Possibly the tank ventilation may become dysfunct which would have an effect on the engine behavior.

Recommended action: Continuative investigations with regard to compatibility of tank ventilation and E10.

Issue 25: Chemical influence on filler caps including sealing (e.g. NBR gasket, NBR O-rings, cork gasket, Viton) RPN 120

FMEA line reference: AP60 – AP63

Risk: The chemical influence on filler cap materials can lead to leakage (inward and/or outward) whereby inward is deemed to be more critical to evaluate.

Recommended action: Continuative investigations with regard to the compatibility of filler cap materials (incl. sealing).

Issue 26: Chemical influence on fuel filler neck (NBR rubber material) RPN 126

FMEA line reference: AP64 – AP66

Risk: The chemical influence on fuel filler necks made from NBR material (aluminium is deemed to be noncritical in that context) can lead to leakage of fuel into the airframe.

Recommended action: Continuative investigations with regard to the compatibility of fuel filler necks. Regulations regarding the exchange interval for rubber parts have to be determined.

Issue 27: Chemical influence on hoses and pipes (PTFE, NBR, Viton, BR, CR-Chloropren rubber). Note: Similar risk potentials also apply to PE and PA fittings and/or to very flexible hoses made of silicone for aerobatics tanks. RPN 378

FMEA line reference: AP93-AP104, AP127-AP134, EP4 – EP9

Risk: If there is an undesirable influence on hoses (also vacuum tubings), this possibly leads to pouring, embrittling or shrinking the material (CR and NBR rather most critically). The consequences are, dependent on the material and on the design, leakages, cross-section contractions and/or wall thickness reductions. The effect could be that the hoses detach from the fittings.

Recommended action: Continuative investigations with regard to the E10 compatibility of pipe and fitting materials.

Issue 28: Chemical influence on electrical fuel pumps and check valves RPN 160

FMEA line reference: AP135-AP151, AP164-AP179

Risk: Due to the undesired chemical influence on different materials (metals and/or synthetics) fuel leakage may occur, leading to functional deficiencies of the electrical fuel pump.

Recommended action: Investigations on E10 compatibility of electrical fuel pumps.

Issue 29: Chemical influence on sealing materials (O-rings, cork, paper, metal, copper, aluminium…) RPN 200

FMEA line reference: AP180-AP187, EP215 – EP222

Risk: Possible risks are embrittlement, swelling or decomposition of the basic seal material. The consequence of those would be a leakage and/or air ingress.

Recommended action: Investigations on the E10 compatibility of sealing materials

Issue 30: E10 fuel within sensor hoses ("dead end hoses") RPN 200

FMEA line reference: AP168-AP207

Risk: By the solvent characteristics of E10 and/or phase separated bio fuel there is a particular risk with “dead end hoses” where the fuel always remains the same. If there is an accumulation of water (due to the affinity of E10 for water) inside those "dead end hoses" the danger of freezing exists which consequentially lead to wrong indications.

Recommended action: Investigations regarding E10 in "dead end sensor hoses" especially at unfavourable climatic conditions.

Issue 31: Chemical influence on aluminium fuel coolers (required mainly for fuel injected engines). Note: Similar risk potentials also apply to finger filters or fine-meshed steel filters RPN 224

FMEA line reference: AP229-AP242

Risk: Due to the electro-chemical corrosion or oxide film decomposition a base material decomposition could occur at aluminum fuel coolers. Consequentially this could lead to fuel leakage.

Recommended action: Continuative investigations with regard to the E10 compatibility of aluminum fuel coolers.

Issue 32: Incompatibility of covering material and lacquering of skin of wing/body of aircrafts RPN 112

FMEA line reference: AP243-AP245

Risk: During the refuelling procedure a decomposition of material coverings or lacquer may be induced by overflowing E10 fuel. This can lead to aircraft strength problems.

Recommended action: Continuative investigations with regard to the E10 compatibility of covering material and lacquering of skin of wing/body of aircrafts.

1.13.4. FMEA summary – Engine functions

Only such topics are stated here that were not treated in the context of another FMEA yet. Potential risks e.g. to the topics "hoses, pipes, fittings etc." were addressed already and will not be re-iterated regarding the engine.

Issue 33: Influence on the operational behavior of the engine RPN 392

FMEA line reference: EF4 – EF54, EF61-EF70

Risk: By operating the engine with phase separated fuel impairments of the engine operational behavior may occur. This reaches from rough engine operation up to the stop of the engine. By operating the engine with undeteriorated E10 fuel its smaller energy content possibly leads to impairments of the engine characteristics. Further on, an increased burn temperature of E10 could result in a knocking combustion.

Recommended action: Phase separation must be prevented or detected by all means in the aircraft related installation of the fuel system. These applies particularly to fuel system sections where larger contiguous volumes of fuel are located (e.g. in the tank). With regard to the energy content of fuel the difference between E10 biofuel and MOGAS has to be determined. To avoid knocking due to the higher combustion temperatures of E10 the mixture calibration has to be adjusted. Generally it is essential to apply counter measures to avoid knocking (e.g. reduction of the compression, ignition, engine cooling, spark plugs …).

Issue 34: Increased fuel consumption RPN 192

FMEA line reference: EF55 - EF58

Risk: Due to the smaller energy content of E10 or because of inappropriate ignition timing an increased fuel consumption may be observed which consequentially leads to a reduced range of the aircraft.

Recommended action: Pilots must keep in mind that by using E10 the fuel consumption could be slightly higher than by operating with MOGAS. The differences have to be determined specifically for each type of engine.

Issue 35: Carburettor icing RPN 216

FMEA line reference: EF78 - EF83

Risk: Particular in case of adverse weather conditions such as very low temperatures and/or high humidity, carburettor icing due to the increased evaporation enthalpy of E10 may occur.

Recommended action: Determining the differences between MOGAS and E10 and giving appropriate recommendations.

Issue 36: Under certain conditions caused by the characteristics of E10 fuel can possibly not be ingested RPN 360

FMEA line reference: EF87 - EF97

Risk: Caused by frozen water in the fuel, corroded and/or rinsed out material and/or thereby blocked filters, the fuel can possibly not or not in sufficient quantity be ingested by the engine, which can lead in last consequence to an engine shut down. A further risk exists during switching the tanks: As hoses may have lost stability the depression caused by the switching process itself may lead to a hose contraction, leading to a blocking of the fuel flow.

Recommended action: Investigations must be performed on how quickly and intensively material separations and/or dissolving may occur, potentially leading to a blocking of fuel filters. Regulations regarding the exchange and inspection interval for filters have to be determined.

Issue 37: Reduced lubrication of the fuel pump RPN 315

FMEA line reference: EF96 – EF97

Risk: The probably worse lubrication characteristics of E10 (both in the normal condition and in phase separated condition) may lead to an insufficient lubrication of the fuel pump, potentially causing a loss of its function.

Recommended action: Continuative investigations with regard to the lubricating characteristics of E10 fuel.

Issue 38: Insufficient lubrication particularly at 2-Stroke engines RPN 270

FMEA line reference: EF98 – EF100

Risk: Particularly with 2-stroke engines with oil-in-gasoline lubrication, the more unfavorable lubrication characteristics from E10 may lead to a lack of lubrication, which can cause an engine shut down and damage.

Recommended action: Continuative investigations with regard to the interaction of fuel and oil especially at 2-stroke engines.

Issue 39: Insufficient lubrication of the engine including auxiliary drives particularly at 4-stroke engines. RPN 180

FMEA line reference: EF104 – EF112

Risk: A blow-by of E10 may reduce the lubrication of the engine and the associated auxiliary drives (e.g. governor, vacuum pump, hydraulic pump, starter, fuel pump, oil pump, alternator, magneto) too strongly.

Recommended action: Continuative investigations with regard to the interaction of E10 fuel and oil especially at 4-stroke engines

Issue 40: Chemical influence on essential engine parts (e.g. combustion chamber) especially at aircraft storage RPN 315

FMEA line reference: EF113 – EF117

Risk: Due to the increased water affinity of E10, incorporated water may lead to corrosion and/or base material decomposition of combustion chamber parts such as crank gear or valve train parts, resulting in an engine damage, particularly at longer aircraft storage intervals.

Recommended action: Investigations regarding corrosion of essential engine parts (e.g. combustion chamber, crank drive, valve train…) during aircraft storage.

Issue 41: Malfunction of the turbo charger RPN 120

FMEA line reference: EF118 – EF120

Risk: The slightly increased combustion temperature of E10 could lead to malfunctions of the turbocharger and consequentially to a loss of engine power.

Recommended action: Determine the differences of the combustion temperatures between MOGAS and E10.

Issue 42: Chemical influence on sealing materials (e.g. NBR gasket, NBR O-rings, cork gasket, Viton) within oil and fuel system RPN 225

FMEA line reference: EF126 – EF141

Risk: Due to the characteristics of E10 seal materials within the oil or fuel system may be disintegrated. After longer periods of time this could lead to leakages and the danger of fire.

Recommended action: Instructions for periodical maintenance interval for sealings and continuative investigations with regard to the E10 compatibility of sealing materials.

1.13.5. FMEA summary – Engine parts

Issue 43: Incompatibility of rubber pipes RPN 192

FMEA line reference: EP10 - EP17

Risk: If rubber hoses are not E10 resistant enough, this possibly leads to embrittling, swelling, or to base material decomposition. The consequences depend on the material, leakages and cross-section contractions. Leakage air may enter a porous fuel system. Cross-section contractions can impair the fuel flow, in the worst case leading to an engine stop.

Recommended action: Further investigations to the E10 compatibility of rubber materials.

Issue 44: Incompatibility of aluminum, steel, copper pipes RPN 224

Note: Similar risk potentials apply to fittings made of most diverse metals, check valves, fuel distributors

FMEA line reference: EP18 – EP28, EP29 - EP39, EP73 –EP89, EP90 – EP99

Risk: By corrosion (and/or surface corrosion) and rinsed out deposits (due to solvent characteristic of E10) filters can be jammed. Base material decomposition, pitting corrosion and increased corrosion within the range of welding seams lead to leakages.

Recommended action: Further investigations to the E10 compatibility of (welded) aluminum, steel, copper pipes, as well as fittings.

Issue 45: Incompatibility of electrical fuel pumps RPN 210

FMEA line reference: EP40 - EP56

Risk: The higher conductivity of E10 can lead to an increased wear of the carbon brush conductors. The (partial) degradation of different materials (metals and/or plastics) may lead to fuel leakages. Rinsed out deposits can block moving parts up to the loss of function of the fuel pump.

Recommended action: Investigations concerning E10 compatibility of electrical fuel pumps.

Issue 46: Incompatibility of mechanical fuel pumps RPN 280

FMEA line reference: EP57 - EP72

Risk: Worse lubrication characteristic of E10, corrosion, base material decomposition, frozen water in “dead end areas”, can result in a pump outage. Deposits rinsed out by E10 can block moving parts. Different degraded materials may cause leakages. Especially in the case of diaphragm pumps this may lead to the loss of function.

Recommended action: Investigations concerning E10 compatibility of mechanical fuel pumps.

Issue 47: Incompatibility of carburettor RPN 240

FMEA line reference: EP100 – EP114

Risk: By corrosion (and/or surface corrosion) and rinsed out deposits (due to solvent properties of E10) filters can be blocked. Base material decomposition, embrittlement and/or swelling lead to leakages. In particular, leakages at the diaphragm or at the float needle valve may cause a malfunctioning of the carburettor.

Recommended action: Investigations concerning E10 compatibility of carburettors

Issue 48: Material incompatibility with air boxes from composite material (CFK/GFK, …) RPN 224

FMEA line reference: EP115 - EP117

Risk: The solvent properties of E10 in conjunction with mechanical load, or water in conjunction with high temperature may lead to a dissolution and/or a separation of resins and fibers. This can cause leakages. Detached resins or fibers may end up in the combustion chamber, whereby damage to the engine can be caused.

Recommended action: Further investigations concerning the solvent characteristics of E10 and/or stability of composite materials

Issue 49: Material incompatibility with air boxes made of metal RPN 245

FMEA line reference: EP118 – EP120

Risk: The air box can become leaky by corrosion. Leakage in the air box leads to power loss with turbo engines, to undefined idle speeds with aspirated engines.

Recommended action: Further investigations concerning E10 stability of air box materials (metals)

Issue 50: Material incompatibility of the fuel return pipe check valve RPN 126

FMEA line reference: EP125 – EP126

Risk: Corrosion leads to a cross section enlargement in the check valve. This may cause a too low fuel pressure.

Recommended action: Further investigations concerning E10 stability of fuel return pipe check valve materials.

Issue 51: Incompatibility of (carburettor) rubber flange RPN 126

Note: Similar risk potentials apply to air intake hoses.

FMEA line reference: EP127 - EP133, EP134 – EP141

Risk: The rubber flange can become leaky by corrosion and/or base material decomposition. Leakage in the rubber flange, leads to power loss with turbo engines, to undefined idle speeds with suction engines. By swelling the air intake hose could be loosened from the connecting parts.

Recommended action: Further investigations concerning E10 stability of rubber flange materials

Issue 52: Incompatibility of intake manifold RPN 210

FMEA line reference: EP143 - EP153

Risk: Corrosion can affect the engine operation in two ways. There is a sensitivity to fuel mixture distribution, or detached particles can be carried into the combustion chamber. Also, the intake manifold can become leaky by corrosion/ base material decomposition, or by swelling/embrittlement of gaskets. Leakage in the intake manifold leads to power loss with turbo engines, to undefined idle speeds with suction engines.

Recommended action: Further investigations concerning E10 stability of intake manifold materials

Issue 53: Influence of E10 on combustion chamber parts RPN 256

FMEA line reference: EP162 - EP167

Risk: E10 could lead to increased valve seat wear. E10 could have negative influence on the engine oil. Bad oil can cause deposits in the valve guide. Malfunctioning of the valve guides results in loss of engine power.

Recommended action: Further investigations of the valve seat wear and the valve guide, in real engine operation. Particularly with air-cooled engines (worse convection)

Issue 54: Inappropriate spark plugs RPN 144

FMEA line reference: EP168 - EP171

Risk: Increased electrode consumption, inapplicable heat rating, leakage on sealing ring, inapplicable isolator.

Recommended action: Determine suitable spark plugs for E10 in real engine operation

Issue 55: Incompatibility of fuel injectors RPN 280

FMEA line reference: EP177 - EP185

Risk: Corrosion on the injection nozzle causes ill defined injection volumes. Further corrosion, base material decomposition, swelling or embrittlement can block moving parts, which causes a malfunction of the fuel injector.

Recommended action: Further investigations concerning E10 stability of fuel injectors

Issue 56: Incompatibility of fuel rails RPN 240

FMEA line reference: EP186 - EP191, EP192 - EP197

Note: Similar risk potentials apply to fuel distributors (in fuel injection systems).

Risk: Corrosion on the fuel rail causes cracks or leakage. This can entail fuel loss.

Recommended action: Further investigations concerning E10 stability of fuel rails

Issue 57: Incompatibility of fuel pressure regulator RPN 168

FMEA line reference: EP198 - EP207

Risk: Electro-chemical corrosion can cause base material decomposition. Leakages can result on the one hand from surface corrosion (at aluminum or steel components), on the other hand by swelling or embrittlement of seals.

Recommended action: Further investigations concerning E10 stability of fuel pressure regulators

Issue 58: Incompatibility of quantity distributor RPN 144

FMEA line reference: EP208 – EP214

Risk: A malfunctioning of the quantity distributor can be caused by a leaky diaphragm or from base material decomposition/corrosion. Causes for a leaky diaphragm can be embrittlement, swelling or attack on base material.

Recommended action: Further investigations concerning E10 stability of quantity distributors

Issue 59: Incompatibility of diaphragm (carburettor, pressure regulator, …) RPN 168

FMEA line reference: EP223 - EP230

Risk: Possible risks exist in embrittling, sources or base material decomposition of the diaphragm material, which would entail leakages and/or malfunctioning (e.g. supply pressure of the fuel pump cannot be held anymore, …).

Recommended action: Further investigations concerning E10 stability of diaphragm materials

Issue 60: Incompatibility of sensors RPN 140

Note: Similar risk potentials apply to fuel totalizers

FMEA line reference: EP231 – EP240, EP241 – EP250

Risk: Probably sensor lines and/or sensors are not compatible with E10. Additionally there is a potential risk in “dead end lines” where the fuel always remains the same. If there is an accumulation of water (due to the affinity of E10 for water) inside those "dead end hoses" the danger of freezing or even corrosion exists which consequentially could lead to wrong set values for the engine management system.

Recommended action: Execution of tests with unfavorable climatic conditions regarding E10 in “dead end hoses”

Issue 61: Influence of E10 on engine oil RPN 160

FMEA line reference: EP251 - EP263, EP264 – EP276

Risk: An ethanol share in the engine oil could probably extract certain components out of it. Also, due to the affinity of E10 for water, water can intrude. Thus the engine oil lubrication characteristics could deteriorate up to the point of malfunction. Reduced cooling characteristics or corrosion prevention properties (for combustion chamber parts, crankshaft drive, valve train) are possible.

Note: Particularly at 2-stroke engines with oil-in-gas lubrication the influence of E10 is deemed to be most critical.

Recommended action: Execution of endurance tests. During the test run the engine operational data (oil temperature, oil pressure, …) have to be compared between MOGAS and E10. Also the engine parts should be inspected after test run.

D Task Spanning Activities for Experimentation

In the consecuting sections actions specifically taken for the SIoBIA project are reported. Some of these relate to more than one specific practical task, like the instrumentation of the MORANE. Therefore they are discussed here before the targeted experimentation and results are given.

Experimental setups and details specifically set just for a single objective measurement are described with the individual results as they do not create implications for other tasks.

D.1 Acquisition and Handling of Test Fuels

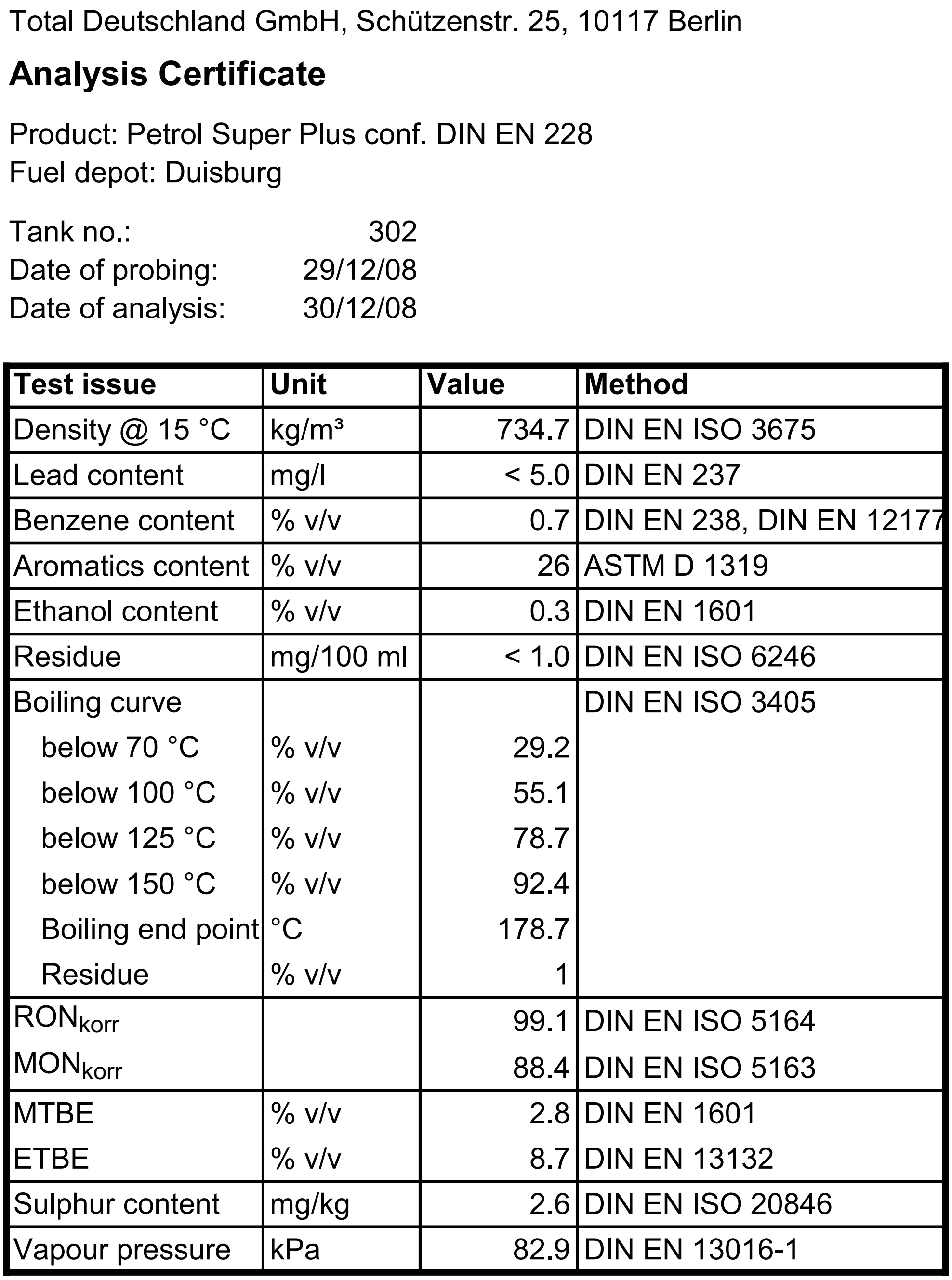
According to the FMEA discussions and further sources of information MOGAS types delivered to airports and airfields are not limited to summer quality, as is considered usual for Austria for vapour lock reasons in mountainous regions. Accordingly a stock of winter quality gasoline was storaged which all experiments on volatility and vapour locking experiments are based on.

The certified delivery (see Table 28) of 680 l "Super Plus" winter ware was obtained from Total Deutschland GmbH and is stored in closed tanks without ventilation in a custom-acquired fuel cabinet. This gasoline is taken as a basestock for bio-ethanol mixing even though commercial E*xx* mixtures will usually be different in order to conform to the DIN EN 228 vapour pressure limits. The experimenters would have liked to obtain such direct commercial E*xx* certified brands with defined ethanol concentrations but were not able to obtain them: As the spot checks on commercial qualities (see fig. 88) show the vast majority is exhibiting an ethanol content of well less than 1 % at the time being.

With respect to the main thermodynamical experiments on the problem of vapour locking this choice of winter quality as a basestock for admixing (Fig. 28) can be regarded as a conservative approach, as the rise in vapour pressure will surpass that of a commercially mixed gasoline and hence be more prone to the spontaneous creation of gasoline bubbles.

For admixture a delivery of 100 l of bio-ethanol was donated by Crop.Energies (http://www.cropenergies.com). The test gasolines for all experiments undertaken within the scope of SIoBIA (vapour locking in fuel system simulation test rig, icing on rotax test rig, long-time storaging in exposed simulation tanks, phase separation cool-down experiments) are performed with respective mixtures of the base gasoline and the bio-ethanol.

Table 29 shows the results of a chemical analysis of the custom mixed E*xx* gasolines.



Total Deutschland GmbH, Schützenstr. 25, 10117 Berlin

Analysis Certificate

Product: Petrol Super Plus conf. DIN EN 228
Fuel depot: Duisburg

Tank no.: 302
Date of probing: 29/12/08
Date of analysis: 30/12/08

Test issue	**Unit**	**Value**	**Method**
Density @ 15 °C	kg/m³	734.7	DIN EN ISO 3675
Lead content	mg/l	< 5.0	DIN EN 237
Benzene content	% v/v	0.7	DIN EN 238, DIN EN 12177
Aromatics content	% v/v	26	ASTM D 1319
Ethanol content	% v/v	0.3	DIN EN 1601
Residue	mg/100 ml	< 1.0	DIN EN ISO 6246
Boiling curve			DIN EN ISO 3405
below 70 °C	% v/v	29.2	
below 100 °C	% v/v	55.1	
below 125 °C	% v/v	78.7	
below 150 °C	% v/v	92.4	
Boiling end point	°C	178.7	
Residue	% v/v	1	
RON_{korr}		99.1	DIN EN ISO 5164
MON_{korr}		88.4	DIN EN ISO 5163
MTBE	% v/v	2.8	DIN EN 1601
ETBE	% v/v	8.7	DIN EN 13132
Sulphur content	mg/kg	2.6	DIN EN ISO 20846
Vapour pressure	kPa	82.9	DIN EN 13016-1

Table 28: *Fuel certificate values of the gasoline delivery by Total Deutschland GmbH, taken as custom basestock for oxygenated blending (BOB) for the vapour lock, storage and icing experiments*

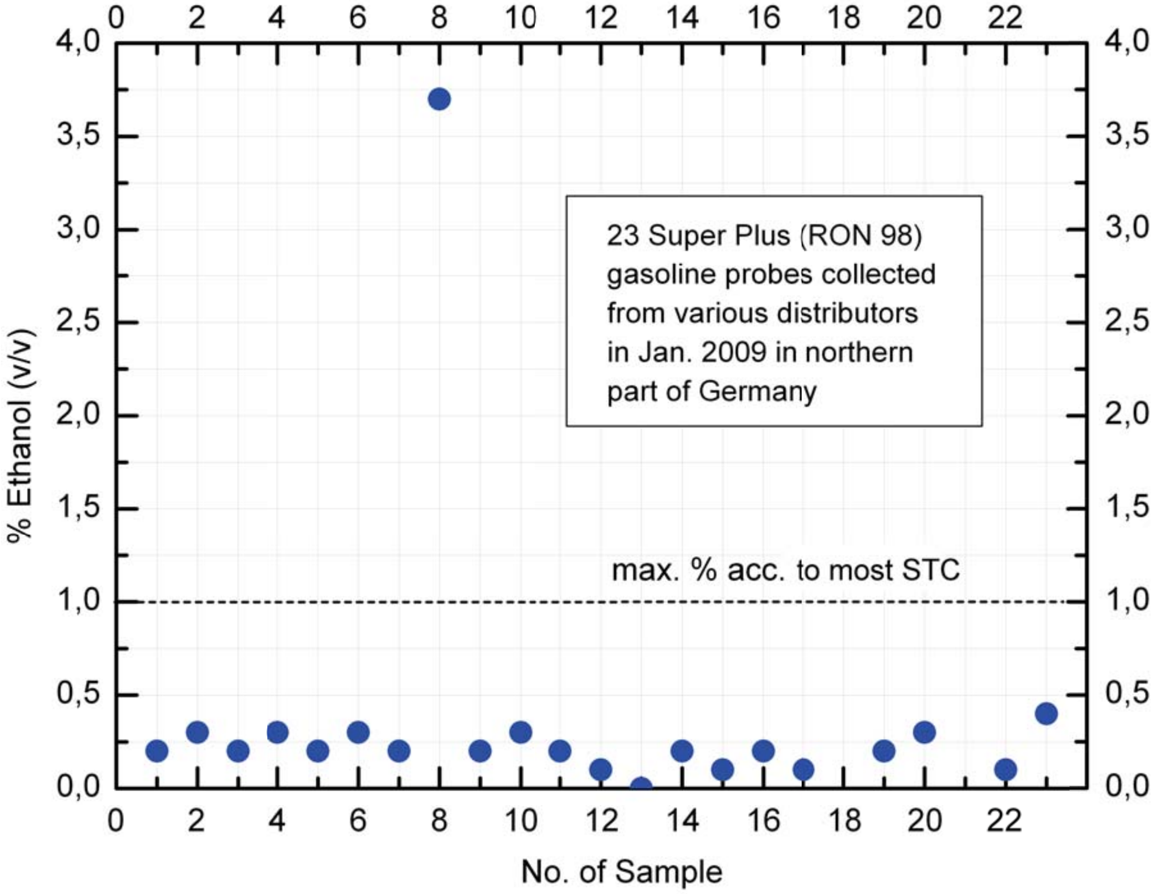


Figure 88: *Ethanol contents of 23 random commercial vehicle gasoline samples, taken in January 2009 in north-western Germany*

Quality criterion		Unit	Ethanol 00% v/v E0	Ethanol 05% v/v E5	Ethanol 10% v/v E10	Ethanol 15% v/v E15
Density at 15° C		kg/m^3	742.9	745.5	747.4	753.0
Sulfur content		mg/kg	5.2	4.9	4.6	4.1
Water content ratio (K.F)		mg/kg	380/360	900	1.115	1.125
FIA			corr	corr	corr	corr
• Aromatic		% v/v	24.8	23.3	21.7	20.8
• Olefin			8.9	8.4	7.6	6.9
• Total, Hydrocarbons			54.4	52.0	49.2	46.9
Aromatics						
• Benzene		% v/v	0.55	0.50	0.50	0.49
• Toluene		% v/v	7.4	7.1	6.5	6.4
• Ethylbenzene		% v/v	1.5	1.5	1.4	1.3
• p-xylene		% v/v	1.5	1.4	1.3	1.3
• m-xylene		% v/v	3.4	3.3	3.0	2.9
• o-xylene		%v/v	2.0	1.9	1.8	1.8
• Iso-Propylbenzene		% v/v	0.2	0.2	0.2	0.1
• n-Propylbenzene		% v/v	0.4	0.4	0.3	0.3
• 1,3-&1,4-Ethylmethylbenzene		% v/v	2.0	1.8	1.7	1.6
• 1,2-Ethylmethylbenzene		% v/v	0.5	0.5	0.5	0.4
• 1,3,5-Trimethylbenzene		% v/v	0.6	0.5	0.5	0.4
• 1,2,4-Trimethylbenzene		% v/v	2.1	2.0	1.9	1.8
• 1,2,3-Trimethylbenzene		% v/v	0.5	0.5	0.4	0.4
Total C-8 Aromatics		% v/v	8.4	8.0	7.5	7.3
Total C-9 Aromatics		% v/v	6.3	6.0	5.5	5.2
Total C-10 h.Aromatics		% v/v	1.6	1.1	1.4	1.4
Total Aromatics		% v/v	24.3	22.7	21.4	20.7
Alcohols						
• Ethanol		% v/v	0.8	5.2	10.7	15.3
Total Alcohol		% v/v	0.8	5.2	10.7	15.3
Ketones and Ethers						
• Methyl-tert-Butylether (MTBE)		% v/v	5.1	4.8	4.7	4.3
• Ethyl-tert-Butylether (ETBE)		% v/v	6.8	6.4	6.1	5.8
Total Ketones and Ethers		% v/v	11.9	11.2	10.8	10.1
Oxygen content		% g/g	2.31	3.79	5.77	7.30
Molecular weight		g/mol	96.8	94.2	91.4	88.9
Composition of sample	C	% g/g	83.7	82.38	80.45	78.97
	H	% g/g	13.8	13.81	13.76	13.71
	O	% g/g	2.32	3.81	5.79	7.32
Heating value (H_u)		MJ/kg	42.36	41.66	40.71	39.96

Table 29: *Physical and chemical composition of custom mixed Exx gasolines*

D.2 Instrumentation of ACUAS's flying lab, a MORANE MS 893 E-D

Flight experiments with ACUAS's MORANE MS 893 E-D (Fig. 89), equipped with a Lycoming engine type O 360 A1A, have been performed for investigation of potential vapour locking and phase separation threats. For this purpose the thermal behaviour of the fuel system components, including the tank and the carburettor, is to be monitored. In addition vibration levels and pressure levels are recorded.

Figure 89: *AcUAS' flying laboratory* MORANE *MS 893 E-D*

Figure 90 shows a schematic of the configuration of all sensors applied to the aircraft, with Table 30 defining the measurement values recorded at the respective locations. Temperatures are measured along the fuel system, starting outside and inside the tank and ending immediately before the carburettor (sensor no. 11). Sensor no. 12 is not installed for the flight experiments but is applied for icing experiments on the grounded aircraft.

For another experiment on the operative pressure drop in the fuel system the original fuel hoses connected to the electric pump are replaced by pressure sensors containing ones. This very special sensor instrumentation is not used for actual flight tests and is therefore described in the respective section 6.5.2, page 84.

The cables of all sensors applied to the MORANE are led into the cockpit and can easily be connected with the measuring instruments and the supply units, so that the normal flight operation independent of measurement instrumentation is guaranteed. All additional instruments are equipped with their own accumulators or are energized by a custom ISP power-box with 12 V d.c. voltage. A connection to the aircraft electric power system is not intended but can be realised easily.

Before a measurement flight is started the recording instruments only have to be switched on. In a data logger 20 measuring channels are continuously recorded. The measuring proceeds automatically without manual operations if desired, but can as well be influenced by a test engineer manually if necessary.

Corner values of the measurement instrumentation:

- sample rate: 1 measuring per second
- accuracy: 14 bit

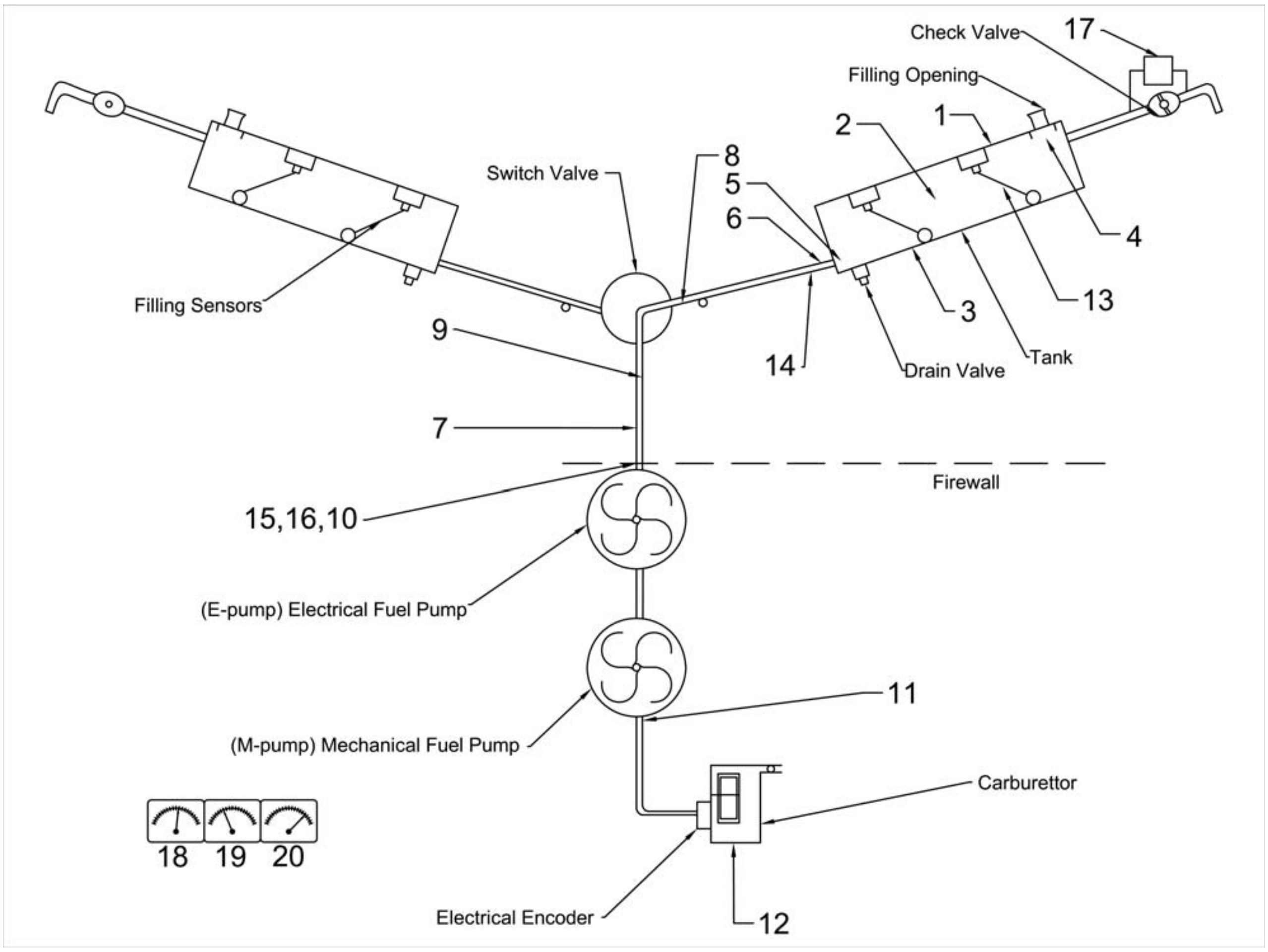


Figure 90: *Schematic of the fuel system of the* Morane *MS 893 E-D. Locations and types of sensors are given. For the technical specification of the sensors see table 30.*

- measurement period: max. 4 hours

During the measurement the correct operation of the additional instrumentation can be controlled on the display of the data logger.

In addition to the low-frequency data acquisition of temperatures and pressures the high-frequency read-out of vibration data is sampled for shorter periods of interest.

No.	Sensor-Type	Position	Compartment
1	Temperature	fuel tank top	wing tip
2	Temperature	fuel tank side	wing tip
3	Temperature	fuel tank bottom	wing tip
4	Temperature	fuel tank inside, top	wing tip
5	Temperature	fuel tank inside, bottom	wing tip
6	Temperature	fuel tank outlet	wing root
7	Temperature	before switch valve	wing root
8	Temperature	before electrical pump	engine
9	Temperature	after electrical pump	engine
10	Temperature	after mechanical pump	engine
11	Temperature	before carburettor	engine
12	Temperature	in carburettor (icing test)	engine
13	ΔP- Sensor	fuel tank air ventilation	wing
14	Vibration	fuel tank top	wing
15	Vibration	fuel pipe	wing root
16	Vibration	fuel pump vertical	engine
17	Vibration	fuel pump horizontal	engine
18	T ambient	inside fresh-air tube to	cockpit
19	P ambient	cockpit	cockpit
20	Relative humidity	cockpit	cockpit

Table 30: *Locations and types of sensor instrumentation as applied to the* MORANE

D.3 Setup, Instrumentation and Test Matrix of a Test-Rigged Rotax 912 ULS Engine in Propeller Operation

The AcUAS piston engine test bed was built in 1996 for ground testing and certification of propellered piston engines (Fig. 91). It is also possible to determine the propeller characteristic map. The test bed is designed for piston engines up to 300 kW and propeller diameters up to 2.1 m.

Figure 91: Rotax *912 ULS on test rig*

A multi fuel supply allows an alternating operation of one engine on different fuels with short switching intervals. For the SIoBiA project an additional fuel supply system has been installed being capable of providing ethanol admixed fuel types. The basic rack is variable and can be used for different kinds of piston engines and their peripheral aggregates. It is build as a plate profile to minimize the aerodynamic drag caused by the rotating propeller. At the assembly plate which is constructively similar to the firewall in an aircraft the engine itself is mounted.

Four independent linear bearings and two load cells allow the measurement of the thrust up to 20 kN and indirectly the propeller torque up to 1500 Nm. The rig features a state-of-the-art measurement devices assortment for temperature, pressure, fuel mass flow, noise and vibration. The measured values are automatically sampled by Imps of Schlumberger and converted and indicated with an adequate postprocessing system. For the SIoBIA project an electrically heated 20 m long exhaust gas analysis tube has been built and connected by an additional 5 m flexible hose to the exhaust gas analysis equipment in an adjacent laboratory. Gas analyses can be performed continuously during the engine operation.

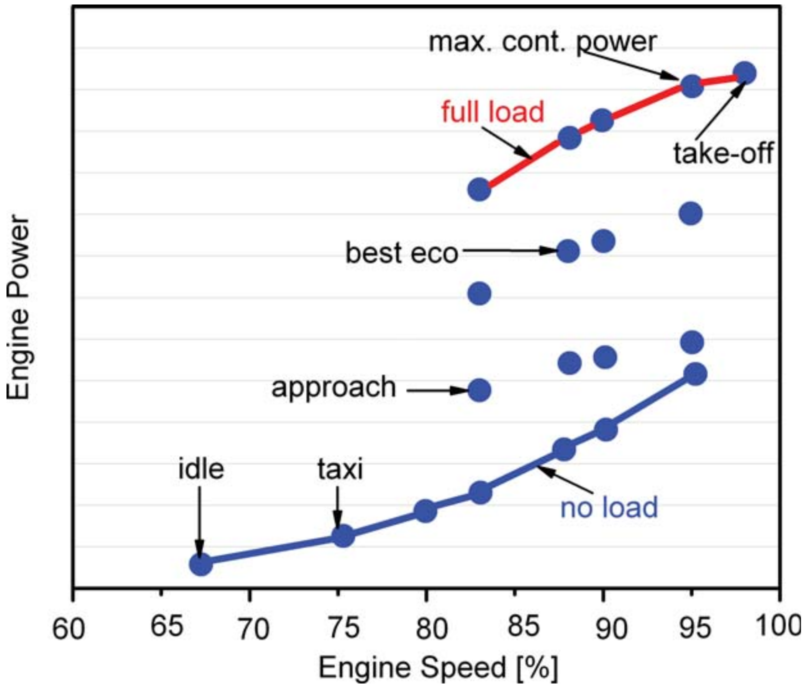


Figure 92: *Measurement points for temperature drop (icing) and exhaust gas composition (LCA) determination in the* ROTAX *912 ULS operating diagram. The named operating conditions denominate the respective engine states in the LCA flight profile (see Fig. 76, p. 138).*

Fig. 92 shows the test matrix for the icing experiments and for LCA exhaust gas data aquisition. As detailed in Sect. 8, Fig. 76 some standard comparison points have been defined representing typical engine load states. Besides the idle operation, keeping the engine alive, the taxi operation mode represents the typical load state when the aircraft is moving on the ground by its own power. At take-off the maximum power output is requested for a limited time, followed by a longer lasting period of maximal continuous power output that makes the aircraft climb to the service ceiling. Arriving there the engine is operated typically in the best economy mode, in order to make the most mileage from the available amount of fuel. Descending to touch-down the engine is throttled to the approach setting before another taxi-ing operation brings the aircraft back to the hangar.

D.4 Custom Designed Test Rig for Vapour Locking and Water Detection Experimentation

The fuel pump test rig, designed and engineered by ISP, Aachen, is a computer-controlled, programmable test control unit to perform parameter variations of fuel pressure, fuel temperature, and fuel flow velocity in almost arbitrary constellations of fuel systems mimicking those of small aircraft. In combination with an external shaker system like the one provided by AcUAS also the effect of vibration on component parts may be investigated. All infrastructural components for fuel conditioning are made from stainless steel and gasoline and ethanol resistant organic components (plastic parts, elastic hoses, sealings). Accordingly the test rig can be applied for the assessment of arbitrary gasoline-ethanol mixtures. Fig. 93 sketches the rig's layout.

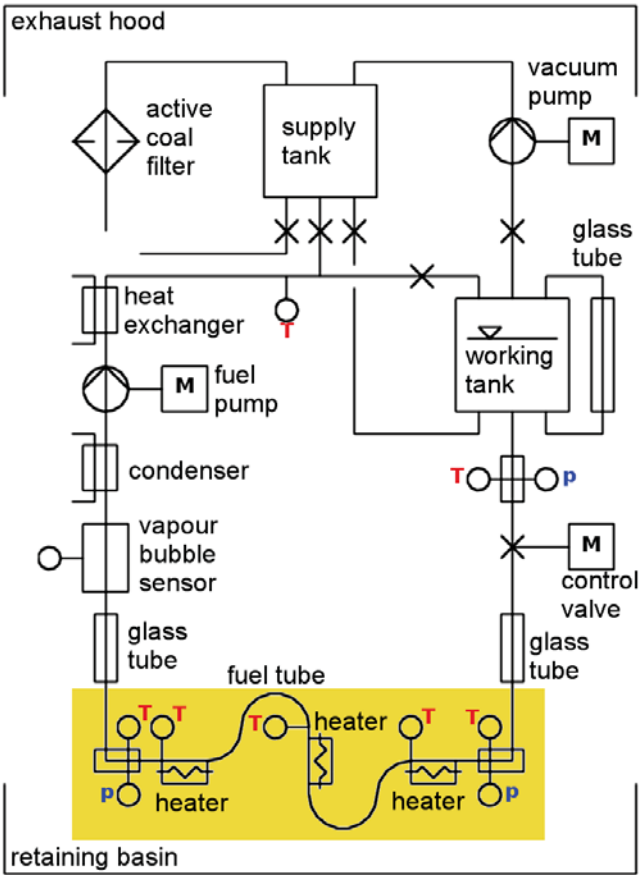


Figure 93: Schematic of the vapour lock test rig with its fuel conditioning instrumentation and an exemplaric assortment of fuel system parts inside the retaining basin.

The rig is designed as a self-contained, transportable unit. By connectors it is attached to a transportable cubicle. Operation requirements to be provided at the place of experimenting are the provision of three phase electrical current, water coolant and possibly an exaust gas connector. The test bench is operated by a computerized control unit and does not require manual control. The control PC operates on a visual program with screen graphics and graphical control parameter setting. The human operator can either set parameters manually or by programming a series of states that are processed automatically via a program flow. Remote control or remote monitoring is possible.

Electrical construction details and connected systems

The state of the fuel, especially with respect to the existence of vapour bubbles, may be determined by optical and capacitive sensors at the entry and the end of the fuel system test line. Arbitrary additional sensors can be applied and monitored by the data aquisition system connected to the control system.

- Rittal cubicle TS RAL 7035 800x1800x500 mm, with mobile base
- one main three-phase AC line 380 VAC, 32A, approx. 8 m
- Harting connectors to the test bench
- thermocouple connectors in the cubicle
- circuit breaker in the cubicle (VDE)
- emergency stop (VDE)
- gate and switch components for silicon oil heating
- frequency converter for silicon oil circulating pump
- Phoenix bus system
- Shuttle PC with Phoenix PCI card, monitor, keyboard and mouse

Mechanical Construction

The transportable test rig is constructed with frame and basic elements built of extruded aluminium sheaths with the maximum dimensions 900 mm × 1000 mm × 1850 mm, movable through a door and with pivoting and lockable wheels. The roof and three sides of the construction are covered with panes of Makrolon, the undercarriage with anodized aluminium plates. The interior is accessible by a swing door. Airtight collection pans underneath serve to absorb all liquids in case of spillage. A lid with a receptacle for an extraction hose closes off the test rig at the top.

The interior features cross-ties and beams to attach all components to be investigated, such as fittings, filters, tubes, switches, pumps, and the like. An oil conditioning unit is integrated into the undercarriage which can be detached to the sides in a userfriendly manner. The is designed to be operated in conjunction with the large shaker of AcUAS, so the fuel system components can be vibrated/accelerated during test runs. Fig. 94 shows the actual realisation of the rig.

Hydraulic Construction

The fuel-loop consists of the following components:

- 10 liters feeder tank (stainless steel) with activated carbon filter (stainless steel)
- 5 liters work tank (stainless steel)
- fittings and armatures, nickel-plated, cables VA D10
- main pressure control valve
- arbitrary (typically three) stainless steel heaters to heat fuel lines

Figure 94: *Actual vapour lock test rig with its fuel conditioning elements in place*

- condenser (stainless steel)
- controllable fuel pump
- controllable vacuum pump
- high quality fuel hoses

- 2 pcs. fuel-proof and compression-proof inspection glasses
- ISP capacitive vapour bubble sensors
- receptacles to integrate airplane components

D.4.1 Rig Control

The control system consists of the following single control units, each with selectable accesses:

- temperature control (PWM, single-point-method or PID)
- pressure control (PID)
- flow control (PID)

All controller parameters are adjustable. Range parameters can be used. A cascading of controllers is possible. The control systems are optimized for adjustment speed and, in second preference, for controller oscillation minimization. Ranges of tolerance can be edited. Accordingly it is possible to first run a test series with high ranges of tolerance quickly, and afterwards perform a test run with adjusted controller parameters and a decreased range of tolerance for more precision, but also of longer duration.

The test rig is controlled by a visual basic program. Input elements and notifications on the the screen enable the user to control all functions of the test bench and to meter the data. There is the possibility to steer the test bench manually or automatically, at which different inspection procedures can be loaded and completed.

The parameters of the inspection procedures, which are available as spreadsheet data, can be freely edited. Temperatures, compression, percolation and all other actuating variables can be set as parameters. Moreover, parameters can be defined as control variable.

A skip of certain check points can be timed or based on advanced tolerance range definitions. If a tolerance range cannot be reached, the check routine automatically jumps to another program step, which has been defined by the user. This schema permits a complete skip of the check routine after their initial loop is carried out once.

The pre-determined program flow is run automatically and does not require input of the user. All relevant input and data are saved as spreadsheet data in the course of the test run. A duration optimization of the test procedure is possible through a clever choice of check program ordering.

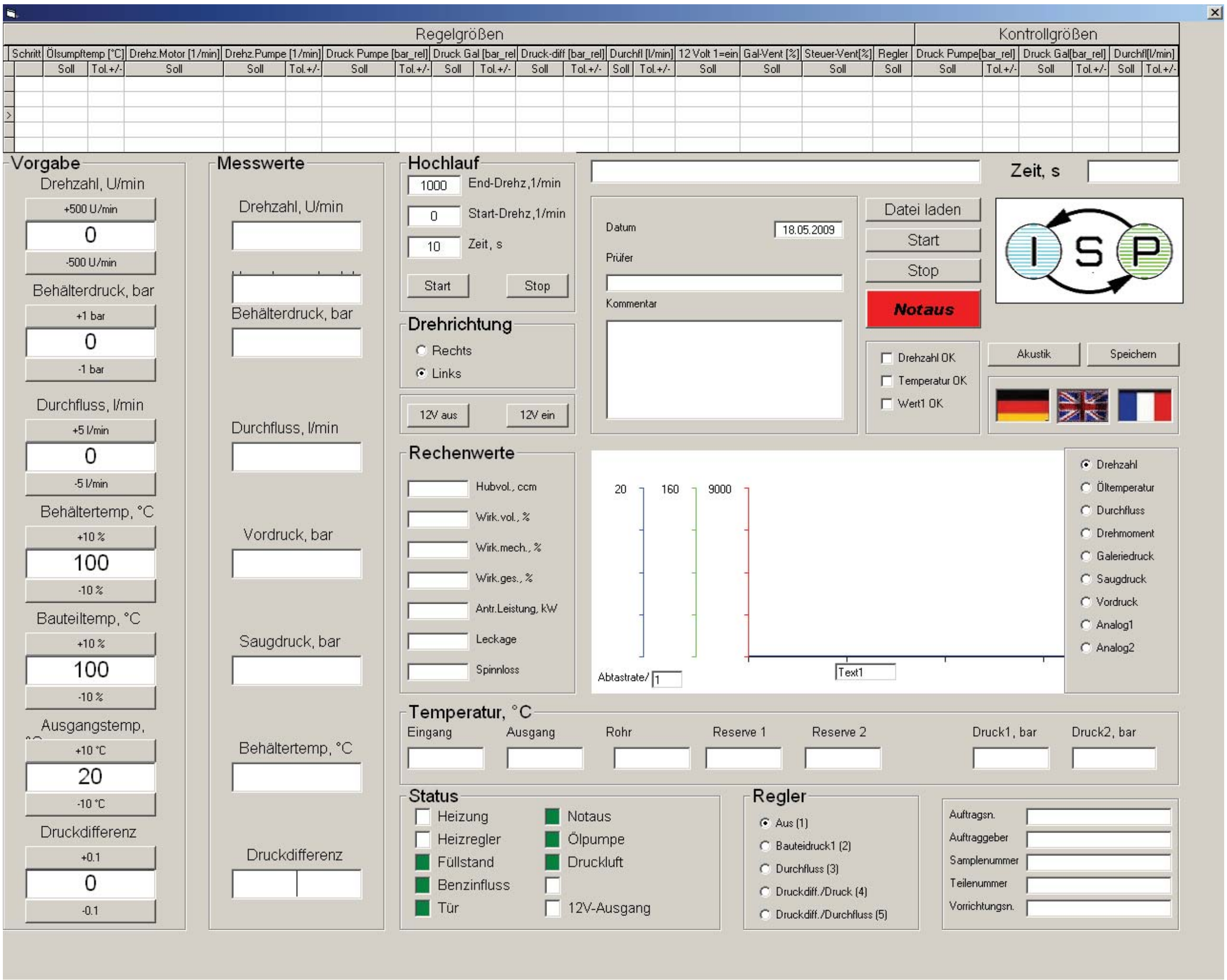
During the entire test procedure, security relevant parameters are continuously monitored. If the the maximum permissible value is exceeded, an immediate emergency stop os triggered and the test bench is lead to a defined security status.

D.4.2 Procedures of Test Rig Operation for Nucleation Assessment

First the test rig is checked for all functions without any fuel system components: All control unit settings with its parameters and their specific reactions upon changes are checked. Subsequently the components specific to the fuel system under observation are inserted into the measuring circuit.

A layout change of the hydraulic system or a change of fuel composition consumes more time than for example a scan of various pressures or temperatures in the test loop. Self-defined testing schedules should take these dependencies into account (fig. 95).

Accordingly, pressure and temperatures, are specified in a matrix while the fuel composition is not changed. If steam bubbles occur, the part of the test (further reduction of pressure or increase of temperature) is skipped. In doing so, a limiting curve for nucleation is established. With the results won from this, a test run with a finer resolution is edited, so that the limiting curve can be collected more precisly (± 2 °C; ± 2 mbar).



Regelgrößen																				Kontrollgrößen			
Schritt	Ölsumpftemp [°C]		Drehz.Motor [1/min]	Drehz.Pumpe [1/min]		Druck Pumpe [bar_rel]		Druck Gal [bar_rel		Druck-diff [bar_rel]		Durchfl [l/min]		12 Volt 1=ein	Gal-Vent [%]	Steuer-Vent[%]	Regler	Druck Pumpe[bar_rel]		Druck Gal[bar_rel]		Durchfl[l/min]	
	Soll	Tol.+/-	Soll	Soll	Tol.+/-	Soll	Tol.+/-	Soll	Tol.+/-	Soll	Tol.+/-	Soll	Tol.+/-	Soll	Soll	Soll	Soll	Soll	Tol.+/-	Soll	Tol.+/-	Soll	Tol.+/-

Vorgabe
Drehzahl, U/min: 0
Behälterdruck, bar: 0
Durchfluss, l/min: 0
Behältertemp, °C: 100
Bauteiltemp, °C: 100
Ausgangstemp, °C: 20
Druckdifferenz: 0

Hochlauf
1000 End-Drehz,1/min
0 Start-Drehz,1/min
10 Zeit, s

Drehrichtung
○ Rechts
● Links

Datum 18.05.2009

☐ Drehzahl OK
☐ Temperatur OK
☐ Wert1 OK

Abtastrate/ 1

● Drehzahl
○ Öltemperatur
○ Durchfluss
○ Drehmoment
○ Galeriedruck
○ Saugdruck
○ Vordruck
○ Analog1
○ Analog2

Status
☐ Heizung
☐ Heizregler
🟩 Füllstand
🟩 Benzinfluss
🟩 Tür
🟩 Notaus
🟩 Ölpumpe
🟩 Druckluft
☐
☐ 12V-Ausgang

Regler
● Aus (1)
○ Bauteidruck1 (2)
○ Durchfluss (3)
○ Druckdiff./Druck (4)
○ Druckdiff./Durchfluss (5)

Figure 95: Example screen for the parameter setting of automatized test runs of the test rig

New test runs are performed for changed fuel compositions. Likewise the mechanic and hydraulic construction is changed and tested with varying fuel mixes in an outer loop.

D.4.3 Functions

The components to be checked are fixated at the test rig. Their tightness is tested with compressed air. The fuel to be tested is poured into the feeder tank (approx. 10 l).

The fuel system can now be evacuated and possibly be filled with inert gas. The working tank (approx. 5 l) is fed from the feeder tank via a ball cock. After visual check of the flow loop with respect to its tightness the test rig is operable. The doors are monitored for their closed position.

Operating pressure (mimicking flight altitude), fuel percolation and temperature can now be preselected and tuned. Settings and results can be saved via keystrokes. Now the test bench does not require manual operation anymore and can be switched to automatic operation. The automatic test run can be started.

The existence of vapour bubbles is monitored by optic turbidity sensors. The substances escaping the liquid loop as vapour in the testing section is liquified in a reconditioning condenser and refed into the fuel.

D.4.4 Measurement Options

Pressure sensors: Stainless steel, accuracy 0,5 %, measurement range 0 . . . 1 bar, current output 4 . . . 20 mA. The entire measuring chain can be calibrated.

Temperature sensor: 3 mm mineral isolated thermocouple type K NiCr–Ni, accuracy of measurement conforming to DIN or better. The entire measuring chain can be calibrated.

Coriolis flow rate sensor: Provided by AcUAS to measure the percolation. The test rig incorporates interfaces to import all relevant data of this sensor (mass flow, density, temperature). This data can be converted online and utilized by the control circuits.

Gear-wheel flowrate sensor for discharge measurement.

ISP laser scatter light sensor: A laser driven scatter light unit measures the turbidity at two parts in the fuel system. With bridge-balancing measurements the exact onset of turbidity and the first appearance of vapour bubbles can be detected.

D.4.5 Environment Protection and Safety Arrangements

For a retainment of bad smell and potential air contamination, the work tank is drained through an activated carbon filter. Airtight collection pans underneath serve to absorb all liquids in case of a spillage. The lid of the test rig can be connected to an exhaust fan via an air separator vent pipe. The test bench is barred on all sides with Makrolon- panes or aluminium plates. A bursting of tubes of a leackage of fuel can therefore not lead to injuries or scaldings. These protection are adequate as no fast moving engines or oscillating weights are present in operation.

In case of fire, an extinguishing agent can be directly injected into the rig through a security opening in the side panel. The doors can stay shut.

D.4.6 Bubble Sensor Design

The bubble sensor custom-designed by ISP operates on the principle of straylight detection caused by liquid/vapour interfaces. It consists of a stainless steel cube with bores at right angles, perpendicular to the flow direction. Optical access to the probe volume is provided by two borosilicate glass windows closing the bores. Light originating from a solid state laser is shone at a right angle into the liquid material. On the opposite side an absorber catches the remaining light not deflected or absorbed. Vertical to the laser beam a photo diode collects the light reflected or scattered by obstacles in measurement volume.

If a clear liquid or gas is streaming through the sensor only a minimal amount of parasitic light enters the photo diode. If there is a fluid with scattering interior interfaces in the sensor volume, like a liquid with bubbles, a measurable amount of light is scattered and detected by the diode, depending on bubble size and number. After amplification and low-pass filtering the signal is fed into the test rig processing unit. If a certain limiting value is transgressed the control program changes to the next probe cycle by either reducing the temperature or increasing the system pressure, to reduce the bubble generation.

D.4.7 Calibration of the Test Rig

For calibration the test rig without attached aircraft components is filled and actuated on substances with well-defined characteristics. First the imposed pressure is measured. Thereafter the fuel conditioning system is heated until the onset of vaporization can be registered. The recorded operating points are checked against the well-defined thermodynamic characteristics of the test fluid. The various sensors will be tested on a periodical basis with certified calibration standards to guarantee continuous high measuring accuracy.

	temperatures		
substance	20 °C	30 °C	50 °C
n-pentane (boiling point 36 °C @ 1 bar; $d = 0{,}63$ kg/l)	562 mbar	820 mbar	1585 mbar
n-hexane (boiling point 96 °C @ 1 bar; $d = 0{,}66$ kg/l)	162 mbar	248 mbar	540 mbar
ethanol, azeotropic 94 % (boiling point 78,4 °C @ 1 bar; $d = 0{,}79$ kg/l)	58 mbar	100 mbar	293 mbar

Table 31: *Boiling pressures of test rig calibration substances. Reference: GESTIS table of properties (http://www.dguv.de/bgia/de/gestis/stoffdb/index.jsp#)*

As calibration substances, n-hexane, and azeotropic ethanol are be used (Table 31, lines in Fig. 96). Their boiling pressure dependencies on the prevalent temperature resemble the ones of the more volatile gasoline components.

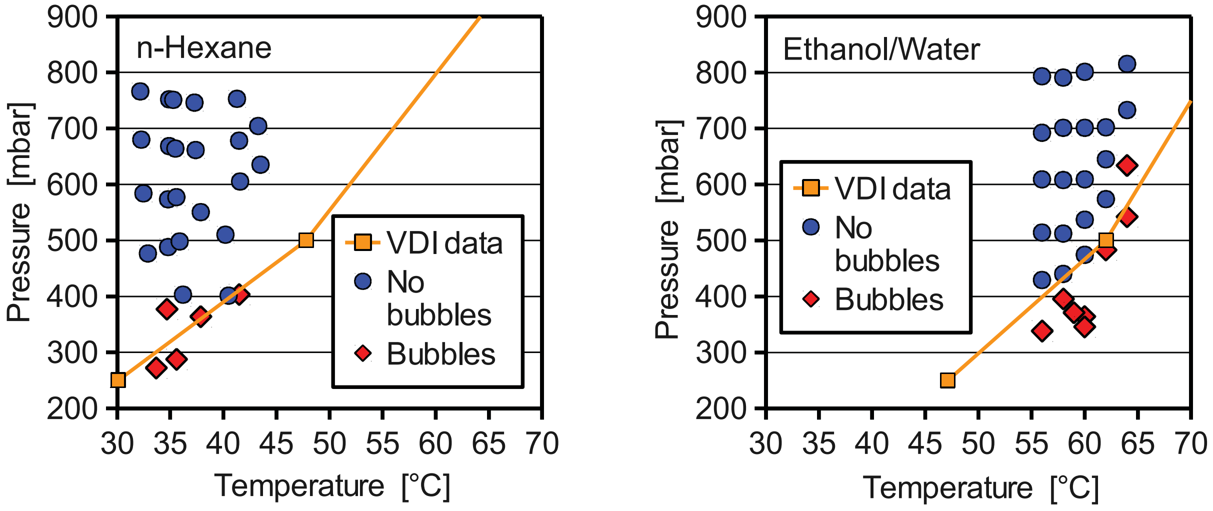


Figure 96: *Bubble measurement observations for n-hexane (left) and an azeotropic ethanol/water mixture (right) in combination with the governing theoretical evaporation curve for the respective substance [17].*

For calibration purposes the test rig is operated automatically in the same way as afterwards for the gasoline measurements. For the given calibration substance (T, p) pairs are scanned until a certain amount of bubbles, represented by a respective readout value, appears in the optical bubble sensor. Fig. 96 shows these results for a bubble value of 0.3 (in sensor specific units).

E Life-Cycle Analysis of Ethanol-Admixed Gasolines — Report by LUDWIG BÖLKOW SYSTEMTECHNIK

The consecuting pages include the self-contained LBST report as provided. Parts of this report, together with additional interpretations and subsumptions, are integrated in the main report body in Section 8, page 137.

FRAMEWORK PROJECT OF THE EUROPEAN AVIATION SAFETY AGENCY (EASA)

"SIOBIA: SAFETY IMPLICATIONS OF BIOFUELS IN AVIATION".

LIFE CYCLE ANALYSIS FROM THE PRODUCTION, SUPPLY AND USE OF VARIOUS BIOMASS SOURCES FOR ETHANOL AS AN AVIATION FUEL

STUDY COMMISSIONED BY

ACIAS – AACHEN INSTITUTE OF APPLIED SCIENCES E. V.

FINAL REPORT

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December 2009

ludwig bölkow
systemtechnik

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REPORT

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CONTENTS

TABLES

FIGURES

ACRONYMS AND ABBREVIATIONS

AcIAS	Aachen Institute of Applied Sciences e. V.
AVGAS	Aviation gas
CaO	Calcium oxide (commonly known as burnt lime, lime, or quicklime)
CCGT	Combined cycle gas turbine
CFCs	Chlorofluorocarbons
CH_4	Methane
CHP	Combined heat and power
C_xH_y	Hydrocarbons
CO	Carbon monoxide
CO_2	Carbon dioxide
DCA	Dichloroethane
DDGS	Dried distillers grains with solubles
DGS	Distiller's grain and solubles (
EASA	European Aviation Safety Agency
EDB	Dibromoethane
EtOH	Ethyl alcohol, (Bio)Ethanol, C_2H_5OH
FFB	Fresh fruit bunches
GHG	Greenhouse gases
HFC	Hydrofluorocarbons
ICE	Internal combustion engine
IPCC	Intergovernmental Panel on Climate Change
K_2O	Potassium oxide
LBST	Ludwig-Bölkow-Systemtechnik GmbH
LCA	Life-cycle analysis
LHV	Lower heating value
LL	Low lead
LTO	Landing and take-off
LUC	Land use change
MOGAS	automotive gasoline
MSF	Multi-stage flash distillation
MWV	Mineralölwirtschaftsverband
N	Nitrogen
N_2O	Nitrous oxide
NG	Natural gas
NH_3	Ammonia
NMVOC	Non-methane volatile organic compounds
NO_x	Nitrogen oxides

P_2O_5	Phosphorus oxide
Pb	Lead
PM	Particulate matter
ROZ	Research Oktan Zahl (German: research octane number)
SF_6	Sulfur hexafluoride
SO_2	Solfur dioxide
TCDD	Tetrachlorodibenzodioxin
TEPb	Tetra-ethyl-lead
TtP	Tank to propeller
VOC	Volatile organic compounds
WtP	Well to propeller
WtT	Well to tank

EXECUTIVE SUMMARY

This study investigates the potential environmental impacts, using life-cycle analyses (LCA), from the production, supply and use of various biomass sources for ethanol used as a gasoline admixture in general aviation aircraft equipped with spark ignited piston engines.

The analyses includes well-to-tank (WtT) greenhouse gas (GHG) and other air pollutant emissions for various bioethanol pathways, tank-to-propeller (TtP) emission values based on actual aircraft engine combustion data. Well-to-tank and tank-to-propeller data are combined in to a comprehensive well-to-propeller (WtP) LCA data set. Additional to GHG emissions, NO_x, NMVOC, SO_2, and dust/particulate matter are covered, and the emission impact of the use of lead containing aviation fuel on the environment is considered.

Using bioethanol admixtures generally leads to a reduction in GHG emissions, but to higher NO_x emissions.

1 SCOPE AND METHODOLOGY

1.1 Scope

Due to the enforcement of the EU directive 2003/30/EC more biomass derived fuels like bioethanol will be added to automotive gasoline. Some general aviation aircraft equipped with spark ignited piston engines are approved for operation with automotive gasoline (MOGAS). However, the majority of those approvals are limited to MOGAS that does not contain more than 1% volume per volume (v/v) ethanol. The current fuel specification EN 228 allows already up to 3% v/v (bio-)methanol or up to 5% v/v (bio-)ethanol as fuel component. Several refineries have already started the supply of E5 (gasoline containing 5% v/v ethanol) and B5 or B7 (diesel containing 5% or 7% v/v biodiesel, respectively) fuels. A further increase of the amount of ethanol is expected, e.g. E10 or E15 gasoline blends.

This report contributes to a research project by the European Aviation Safety Agency (EASA) aimed at investigating possible safety implications on aircraft/engine operation and on tanks, fuel pipes, seals, and fuels systems of spark ignited piston engine powered aircraft and engines by using fuel containing bioethanol. In addition, the potential environmental impacts (positive and negative) are considered. This work supports Task 5 of the project: "Based on identified knowledge gaps, and within the scope of this project, investigate the potential environmental benefits, using life-cycle analyses (LCA), from the production, supply and use of various biomass sources for biofuels."

The analyses are structured as follows:

- **Well-to-tank**: greenhouse gas (GHG) emissions and other air pollutant emissions are given for various bioethanol pathways from wheat, sugar beet, sugar cane (ethanol imported from Brazil), from lignocellulosic waste (waste wood, residual straw) and from lignocellulosic biomass from short rotation forestry.
- **Tank-to-propeller**: based on actual aircraft engine combustion data, tank-to-propeller emissions are estimated where accurate data is lacking.
- **Well-to-propeller**: well-to-tank and tank-to-propeller data are combined in to a comprehensive well-to-propeller LCA data set.
- **Other emissions**: additional to GHG emissions, NO_x, NMVOC, SO_2, and dust/particulate matter are covered.
- **Impact of the use of lead containing aviation fuel on the environment**: lead emissions are estimated, and the effect of returning from MOGAS to AVGAS is considered.

1.2 Methodology

This report evaluates gasoline–(bio)ethanol blends and their production pathways together with the fuel use in the general aviation aircraft equipped with spark ignited piston engines, comparing it to conventional MOGAS in a well-to-wheel-type "well-to-propeller" analysis. The evaluation comprises the emissions of greenhouse gases (GHG) and air pollutants of fuel supply and use.

The energy requirements and GHG emissions resulting from the construction and decommissioning of the fuel production plants are not considered. Also not considered are the energy requirements and emissions resulting from the manufacturing and decommissioning of the aircraft.

1.2.1 Pathways considered

The set of pathways considered in this report has been chosen to cover all relevant (bio)ethanol production sources and technologies including (bio)ethanol produced in the European Union or bought in the European Union and produced in exporting countries. This same set of ethanol pathways is also covered in the European Renewable Energy Directive [RED 2009]. Starting point for the evaluation are assumptions regarding individual processes and chains made in the CONCAWE/EUCAR/JRC well-to-wheel study [CONCAWE 2007], [CONCAWE 2009]. For this present study many of the original pathways defined in [CONCAWE 2007] and [CONCAWE 2009] are modified and additional pathways not considered in the cited study are newly modelled based on data from the aircraft industry and data provided by AcIAS – Aachen Institute of Applied Sciences e. V.

Pathways have been modelled and calculated using LBST's E3database tool.

The study covers the following groups of pathways:

- Gasoline pathway (MOGAS) (Reference, based on [CONCAWE 2007])
- (bio)ethanol production pathways
  - Ethanol from wheat (process heat demand covered by natural gas fuelled boiler)
  - Ethanol from wheat (process heat demand covered by combined heat and power production fuelled by natural gas)
  - Ethanol from wheat (process heat demand covered by combined heat and power production fuelled by lignite)
  - Ethanol from wheat (process heat demand covered by combined heat and power production fuelled by wheat straw)
  - Ethanol from wheat (process heat demand covered by biogas from distillers grains and solubles)
  - Ethanol from sugar beet (process heat demand covered by biogas from slops)

- Ethanol from sugarcane (process heat demand covered by bagasse)
- Ethanol from residual wood (process heat demand covered by combined heat and power production fuelled by the ligneous residue)
- Ethanol from farmed wood (process heat demand covered by combined heat and power production fuelled by the ligneous residue)
- Ethanol from wheat straw (process heat demand covered by combined heat and power production fuelled by the ligneous residue)

Any by-products in the pathways listed above are balanced by using the substitution method and allocation by energy method. Therefore each pathway has two variants (a) for substitution and (b) for allocation by energy. In the case when substitution is not applicable only allocation was used.

This report documents the assumptions used in modelling the fuel pathways and also the calculated results.

The calculations of energy use and GHG emissions are based on the lower heating value (LHV).

1.2.2 CO_2 equivalents

Greenhouse gases considered in this study are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)[1]. The global warming potential of the various greenhouse gases is expressed in CO_2 equivalents. Table 1 shows the global warming potential for a time period of 100 years according to the Intergovernmental Panel on Climate Change (IPCC).

Table 1: Global warming potential of various GHGs [IPCC 2007]

GHG	CO_2 equivalents
CO_2	1
CH_4	25
N_2O	298

In the evaluation only CO_2 generated by the combustion of fossil fuels is considered. The combustion of biomass is CO_2 neutral because the amount of CO_2 emitted during the combustion of the biomass is the same as the amount of CO_2 which has been removed from the atmosphere during the growth of the plants.

---

[1] Other greenhouse gases are CFCs, HFCs, and SF_6; these are not relevant in the context of this study.

1.2.3 Methodology for the accounting of by-products

Many processes produce not only the desired product but also "by-products". This is the case for biofuels from traditional crops such as FAME from rapeseed or ethanol from wheat. Two different methods are widely used to account for these by-products, the substitution method, and the allocation method.

Substitution method

For the calculation of a credit the energy requirements and GHG emission values are used from the production of the product which realistically is replaced by the by-product. This method is called „substitution method". The substitution method has also been used in [GM 2002], [CONCAWE 2007] and [CONCAWE 2009].

A typical by-product in ethanol production from wheat is DDGS (Dried Distillers Grains with Solubles), the dried residue remaining after the starch fraction of wheat is fermented, which is generally used in livestock feeds.

Figure 1 shows an example for the calculation of the credit (DDGS replaces animal fodder from wheat and imported soybeans).

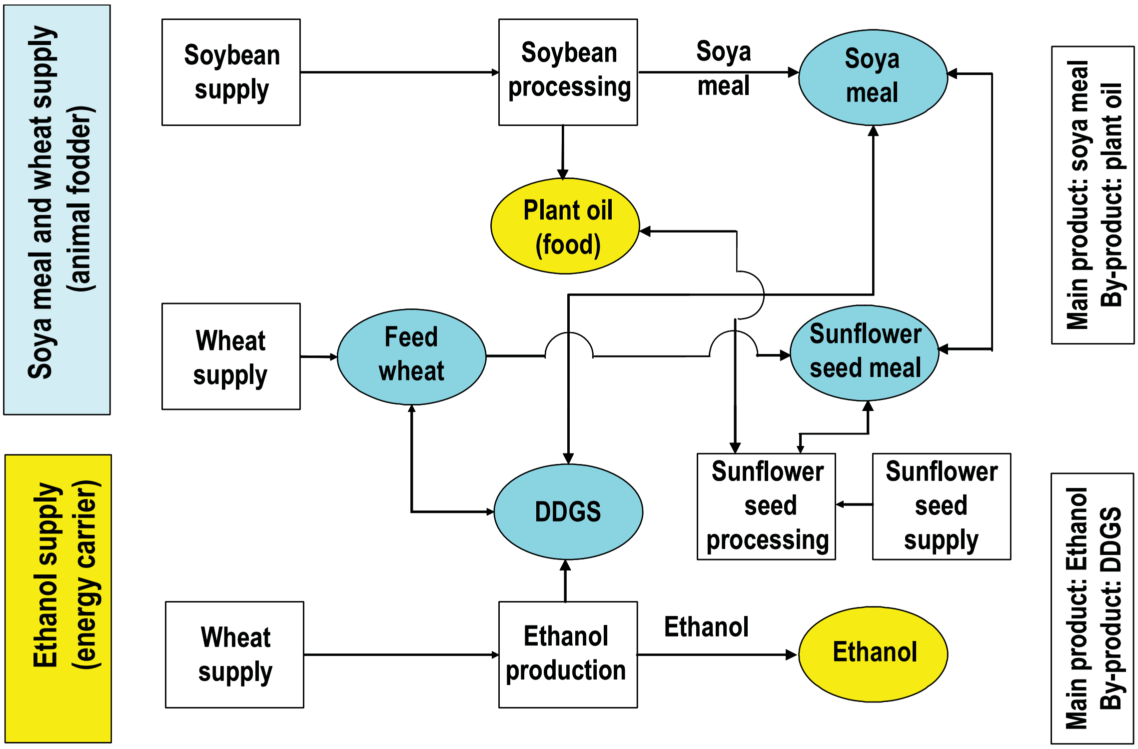

Figure 1: Calculation of a credit for the by-product DDGS for the production of ethanol from wheat

The by-product DDGS replaces animal fodder from wheat grain and imported soybeans, and as a result saves the associated emissions for the supply of wheat grain and soya meal. The production of soya meal for animal fodder leads to the by-product soybean oil which is used in the food industry and replaces sunflower oil. The production of sunflower oil itself produces the by-product sunflower seed meal which is used as animal fodder and replaces animal fodder from wheat and soya meal. This leads to a loop in the calculation leading to a net credit for the supply of ethanol from wheat.

Allocation by energy:

Another methodology to take by-products into account is to allocate the input of energy sources and materials and the GHG and air pollutant emissions to the products by energy content (allocation by the energy content of main and by-product).

$$Specific\ input = \frac{Input}{LHV(main\ output)} \cdot allocation\ \ factor$$

$$Specific\ input = \frac{Input}{LHV(main\ output)} \cdot \frac{LHV(main\ \ product)}{LHV(main\ output) + LHV(by\text{–}produc(s))}$$

In case of ethanol from wheat the main product is ethanol and the by-product is DDGS. The LHV of ethanol amounts to about 26.8 MJ/kg and the LHV of DDGS amounts to about 16 GJ/kg. About 1.14 kg DDGS is produced per kg of ethanol. The steam input is indicated with 9.75 MJ per kg of ethanol. Then the net input of steam per unit of ethanol would be:

$$Steam = \frac{9.75\,\frac{MJ_{steam}}{kg_{ethanol}}}{1\,kg_{ethanol} \cdot 26.8 \cdot \frac{MJ}{kg_{ethanol}} + 1.14\,kg_{DDGS} \cdot 16.0\,\frac{MJ}{kg_{DDGS}}} = 0.216 \cdot \frac{MJ_{steam}}{MJ_{ethanol}}$$

This allocation by energy is proposed in the EU Renewable Energy Directive [RED 2009] for the assessment of GHG emissions for the supply of biofuels. Allocation by energy shall be applied for by-products such as rapeseed cake (not relevant in this study), sugar beet pulp, and DDGS, but not for excess electricity.

In case of excess electricity from combined heat and power (CHP) plants the substitution method should be applied. According to the EU Renewable Energy Directive excess electricity shall replace electricity using the same fuel as the CHP plant itself.

[RED 2009] ANNEX V, C Methodology, No. 16 states: "Emission saving from excess electricity from cogeneration, eee, shall be taken into account in relation to the excess electricity produced by fuel production systems that use cogeneration except where the fuel used for the cogeneration is a co-product other than an agricultural crop residue. In accounting for that excess electricity, the size of the cogeneration unit shall be assumed to be the minimum necessary for the cogeneration unit to supply the heat that is needed to produce the fuel. The greenhouse gas emission saving associated with that excess electricity shall be taken to be equal to the amount of greenhouse gas that would be emitted when an equal amount of electricity was generated in a power plant using the same fuel as the cogeneration unit".

1.2.4 Other emissions

In this study the emission of the following other air pollutants is investigated:

- NO_x
- PM (particle matter)
- NMVOC (non-methane volatile organic compounds)
- SO_2

1.2.5 Calculation tool

For the calculations the E3database tool developed by LBST is used. This tool was also used in the CONCAWE/EUCAR/JRC study [CONCAWE 2007], [CONCAWE 2009].

2 FUEL PROPERTIES

Table 2 shows the properties of the investigated fuels regarding energy content and CO_2 emissions.

Table 2: Fuel properties

	LHV				CO_2	
Fuel	**[kWh/l]**	**[MJ/l]**	**[kWh/kg]**	**[MJ/kg]**	**[g/kWh]**	**[g/MJ]**
Gasoline	8.9	32.2	12.0 (11.77)	43.2 (42.36)	264	73.3
Ethanol	5.9	21.2	7.45	26.8	257	71.3

The data for the lower heating value (LHV) and CO2 emissions of gasoline and ethanol shown in Table 2 also have been used as in the CONCAWE/EUCAR/JRC study [CONCAWE 2007], [CONCAWE 2009]. The CO2 values represent complete stoichiometric combustion. The numbers for the lower heating value of gasoline in () are based on data from [Esch 2009] and have been used to convert the gasoline consumption of the aircraft engine expressed in kg into kWh.

The influence of the octane number on the lower heating value and the carbon content of the gasoline are negligible, see Table 3.

Table 3: ROZ (research octane number) and LHV of fuels

	MOGAS	**Normal unleaded**	**Super unleaded**	**AVGAS 100 LL**
ROZ	95 - 98	91 - 94	95 - 98	n. d. a.
LHV (kWh/kg)	12.00 (11.77)	12.20	12.00	12,14

Source: http://www.schmidtler.de/html/ht_technik/kraft.htm ; () [Esch 2009]

The combustion of biomass is CO_2 neutral because the carbon is removed from the atmosphere during growth of the plants and emitted as CO_2 during aircraft operation. In case of biomass derived fuels, the CO_2 emissions are subtracted at the WtT stage.

3 REFERENCE GASOLINE PATHWAY

3.1 Crude oil extraction and transport to refinery

Crude oil is extracted and transported to a refinery. For the supply and use of gasoline in the EU the energy requirements and associated GHG emissions for the supply of the crude oil are derived from [CONCAWE 2007], [CONCAWE 2009].

Table 4: Energy input and GHG emissions from crude oil extraction

	I/O	Unit	Amount
Crude oil	Input	$kWh/kWh_{crude\ oil}$	1.025
Crude oil	Output	kWh	1.000
CO_2 equivalent	-	$g/kWh_{crude\ oil}$	12.0

The crude oil input includes the LHV of the delivered crude oil.

Table 5: Energy input and GHG emissions from crude oil transport

	I/O	Unit	Amount
Crude oil	Input	$kWh/kWh_{crude\ oil}$	1.000
Heavy fuel oil	Input	$kWh/kWh_{crude\ oil}$	0.010
Crude oil	Output	kWh	1.000
CO_2 equivalent	-	$g/kWh_{crude\ oil}$	2.85

The heavy fuel oil input is connected with the supply of heavy fuel oil.

3.2 Crude oil refining

In the refinery the crude oil is converted to gasoline and diesel. The refinery data are derived from [GM 2002] and [CONCAWE 2007], [CONCAWE 2009].

Table 6: Technical and economic data for gasoline from crude oil refining

	I/O	Unit	Amount
Crude oil	Input	$kWh/kWh_{gasoline}$	1.08
Gasoline	Output	kWh	1.00
CO_2	-	$g/kWh_{gasoline}$	25.2

3.3 Distribution of final fuel

The gasoline is transported to a depot via pipeline, barge (distance: 500 km) and rail (distance: 250 km). The share of gasoline transport via pipeline is 60%, the share of inland navigation is 20% and the share of rail is 20%. The same assumptions have been made in [CONCAWE 2007] and [CONCAWE 2009].

The electricity consumption for the transport of gasoline via pipeline is about 0.0002 kWh/kWh of gasoline.

About 0.042 tkm/kWh of gasoline are required for the transport of gasoline via barge over a distance of 500 km. Table 7 shows the fuel consumption and the GHG emissions of a typical barge. The return voyage (empty) is considered for the fuel consumption of the barge.

Table 7: Fuel consumption and GHG emissions of the barge

	I/O	Unit	Amount
Diesel	Input	kWh/tkm	0.140
Distance	Output	tkm	1.000
CO_2	-	g/tkm	38.0
CH_4	-	g/tkm	0.03

For rail transport of gasoline over a distance of 250 km about 0.021 tkm/kWh of gasoline are required. The electricity consumption of the train is ca. 0.058 kWh/tkm. The electricity requirement of the train is met by the EU electricity mix.

The electricity consumption of the depot is about 0.0008 kWh/kWh of gasoline. From there the gasoline is distributed to the filling stations via truck over an average distance of 150 km. The electricity for the depot and the filling station (0.4 kV level) is derived from the EU electricity mix.

Table 8: Technical and economic data for gasoline dispensing

	I/O	Unit	Amount
Gasoline	Input	$kWh/kWh_{gasoline}$	1.0008
Electricity	Input	$kWh/kWh_{gasoline}$	0.0034
Gasoline	Output	kWh	1.0000

3.4 End use

The gasoline is used in piston engine aircrafts. The combustion of gasoline leads to about 264 g CO_2 per kWh of gasoline.

3.5 Results

Table 9 shows the overall WtP GHG emissions for the gasoline pathway. It has to be noted that Table 9 shows the GHG emissions per kWh of the final product (gasoline). Therefore, the GHG emissions of the different process steps presented in Table 9 are not necessarily the same as the GHG emissions of the single processes presented above.

The emission values of the processes are multiplied by the input/output ratios (including all inputs, outputs, by-products) trough all processes starting at the end of the chain calculating upstream to the first link. Therefore, energy requirement and emissions of a process step shown in the results table (e.g. crude oil extraction) strongly depend on the processes downstream in the chain. In this pathway the energy requirement and the emissions of all upstream processes such as the crude oil transport and the supply of crude oil has to be multiplied by the crude oil requirement of the refinery (1.06 kWh per kWh of gasoline).

Table 9: GHG emissions for the supply and use of gasoline

	CO_2-Equivalent/$kWh_{gasoline}$
Crude oil extraction	13.0
Crude oil transport system	3.3
Crude oil refinery	25.2
Gasoline distribution	0.9
Filling station	2.7
Total emissions gasoline supply	**45.2**
Combustion	**264**
Total emissions supply and combustion	**309**

4 ETHANOL PATHWAYS

The elements of a bioethanol life-cycle are shown in the Figure below.

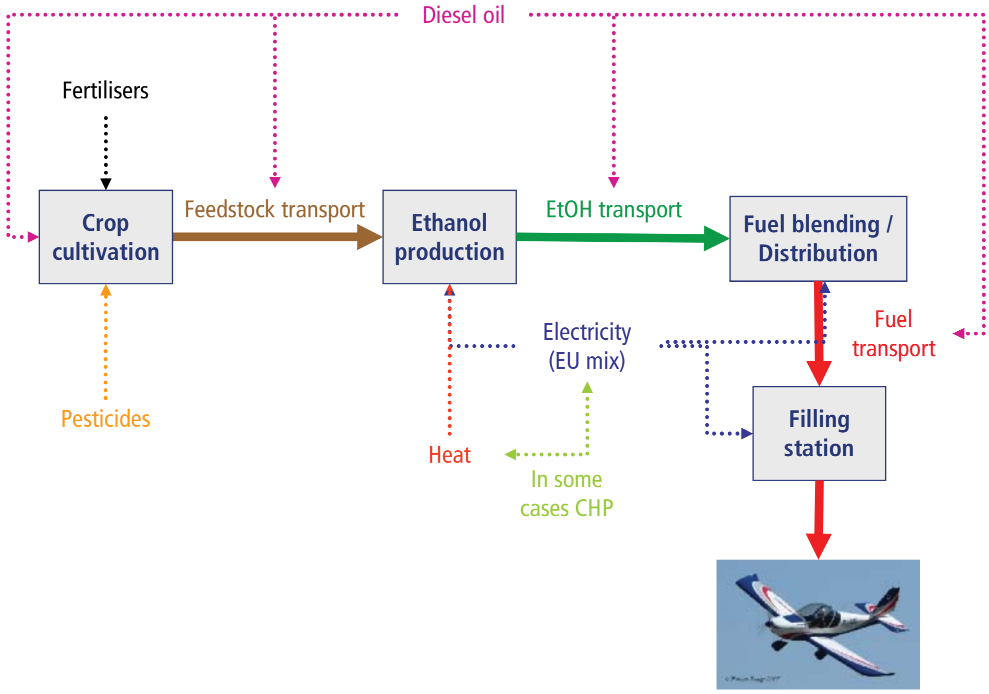

Figure 2: Bioethanol life-cycle

In the following sections, the life-cycle elements are described quantitatively for each individual bioethanol pathway.

4.1 Ethanol from wheat

4.1.1 Biomass supply

According the European Fertiliser Manufacturer Association (EFMA) the average yield for wheat grain in the EU amounts to about 5.2 t per ha and year based on a water content of 13.5% [EFMA 2008]. The LHV of wheat grain is 17.0 kg/kg of dry substance [Kaltschmitt 2001]. For the operation of farming machines 3,590 MJ [Crop Energies 2008] to 3843 MJ [ADEME 2002] diesel per ha and year are required. The average value of 3717 MJ per ha and year leads to a specific diesel requirement of about 0.0486 MJ/MJ of wheat grain.

The emissions of N_2O from the plantation of energy crops consist of the direct N_2O emissions, indirect N_2O emissions from emitted NH_3 and NO_x, and indirect N_2O emissions from leaching/runoff (soil N_2O emissions). The soil N_2O emissions are calculated using the European Soil Model in [CONCAWE 2009].

The input of nitrogen fertiliser is indicated with 109 kg N per ha and year based on the fertiliser use in 2005/2006 [EFMA 2008]. Furthermore, about 16 kg K_2O fertiliser [EFMA 2008], 22 kg P_2O_5 fertiliser [EFMA 2008], 2.3 kg pesticides [Crop Energies 2008], and 120 kg seeding material [ETSU 1996] are required per ha and year.

Additionally, there are N_2O emissions from the production of synthetic nitrogen fertiliser. The N_2O emissions from the production of synthetic nitrogen fertiliser are accounted for in the upstream process (see chapter 4.6 for data).

Table 10 shows the input and output data for the cultivation of wheat.

Table 10: Input and output data for the cultivation of wheat (per kWh of wheat grain)

	I/O	Unit	Amount
Diesel	Input	kWh/kWh_{wheat}	0.0486
N fertiliser	Input	$kg N/kWh_{wheat}$	0.00514
K_2O fertiliser	Input	$kg K_2O/kWh_{wheat}$	0.00077
P_2O_5 fertiliser	Input	$kg P_2O_5/kWh_{wheat}$	0.00102
Pesticides	Input	kg/kWh_{wheat}	0.00011
Seeding material	Input	kg/kWh_{wheat}	0.00565
Wheat	Output	kWh	1.0000
Emissions			
CO_2	-	g/kWh_{wheat}	12.8
CH_4	-	g/kWh_{wheat}	0.005
N_2O	-	g/kWh_{wheat}	0.085
NO_x	-	g/kWh_{wheat}	0.187
SO_2	-	g/kWh_{wheat}	0.000
NMVOC	-	g/kWh_{wheat}	0.029
Dust/PM	-	g/kWh_{wheat}	0.028

The energy requirements, GHG emissions and air pollutant emissions for the supply of fertilisers, pesticides, seeding material and diesel are accounted for in the upstream processes (see chapter 4.6 for data).

4.1.2 Transport to the ethanol plant

Storage and handling of the wheat grain leads to an electricity requirement of about 0.0004 kWh per kWh of wheat grain.

The wheat grain is transported to the ethanol plant over a distance of 50 km via 40 t truck. The payload of the truck is 25 t of wheat grain.

4.1.3 Ethanol plant

For the ethanol plant five variants have been considered for the calculation of the energy requirement of the ethanol plant:

- Conventional natural gas fuelled boiler
- Natural gas fuelled combined heat and power (CHP) plant
- Lignite fuelled CHP plant
- Straw fuelled CHP plant
- Energy requirement of the ethanol plant met by biogas from distiller's grain and solubles (DGS)

The by-product DDGS (dried distillers grain and solubles) is used as animal fodder (except in case where the DGS is used as feedstock for biogas generation). The DDGS replaces animal fodder from wheat and imported soybeans.

Table 11: Input and output data for the conversion of wheat to ethanol

	I/O	Unit	DDGS as animal feed	DGS to biogas
Wheat	Input	$kWh/kWh_{ethanol}$	1.864	1.864
Steam	Input	$kWh/kWh_{ethanol}$	0.364	0
Electricity	Input	$kWh/kWh_{ethanol}$	0.054	0.018
Ethanol	Output	kWh	1.000	1.000
DDGS	Output	$kg/kWh_{ethanol}$	0.153	-
N	Output	$kg/kWh_{ethanol}$	-	0.00897
K_2O	Output	$kg/kWh_{ethanol}$	-	0.00218
P_2O_5	Output	$kg/kWh_{ethanol}$	-	0.00352

The steam requirement is met by a natural gas fuelled boiler with an efficiency of 90% (Table 12), a natural gas fuelled combined heat and power (CHP) plant, a lignite fuelled CHP plant or a straw fuelled CHP plant. The electricity requirement is met by electricity from the EU electricity mix (10 to 20 kV level). The biogas residue which contains N, K_2O and P_2O_5 is returned to the field and is used as fertiliser.

Table 12: Input and output data for steam generation via a natural gas fuelled boiler

	I/O	Unit	Amount
NG	Input	kWh/kWh$_{steam}$	1.111
Electricity	Input	kWh/kWh$_{steam}$	0.020
Steam	Output	kWh	1.000
Emissions			
CO_2	-	g/kWh$_{steam}$	226
CH_4	-	g/kWh$_{steam}$	0.010
N_2O	-	g/kWh$_{steam}$	0.004
NO_x	-	g/kWh$_{steam}$	0.224
SO_2	-	g/kWh$_{steam}$	0.002
NMVOC	-	g/kWh$_{steam}$	0.010
Dust/PM	-	g/kWh$_{steam}$	0.001

According to the assumptions in [CONCAWE 2007] and [CONCAWE 2009] for the calculation of the energy requirements and GHG emissions from the supply of natural gas, a distance of 4000 km is assumed for the transport of natural gas from the natural gas fields to the EU via pipeline.

Table 13: Input and output data for the combined heat and power (CHP) plants

	I/O	Unit	NG CHP [Punter 2004]	Lignite CHP [CONCAWE 2009]	Straw CHP [Punter 2004]
Fuel	Input	kWh/kWh$_{steam}$	1.866	1.405	2.132
Steam	Output	kWh	1.000	1.000	1.000
Electricity	Output	kWh	0.662	0.222	0.361
Emissions					
CO_2	-	g/kWh$_{steam}$	379	582	-
CH_4	-	g/kWh$_{steam}$	0.056	0.008	0.021
N_2O	-	g/kWh$_{steam}$	0.017	0.045	0.004
NO_x	-	g/kWh$_{steam}$	1.128	0.543	0.819
SO_2	-	g/kWh$_{steam}$	0.003	0.388	0.264
NMVOC	-	g/kWh$_{steam}$	0.282	0.008	0.082
Dust/PM	-	g/kWh$_{steam}$	0.028	0.050	0.067

The (excess) electricity replaces electricity from a power plant using the same fuel. In case of the natural gas fuelled CHP the excess electricity replaces electricity from a natural gas fuelled combined cycle power plant (CCGT) with an efficiency of 55%. In case of the lignite fuelled CHP the excess electricity replaces electricity from a lignite fuelled steam turbine power station with an efficiency of 41%. In case of the straw fuelled CHP the excess electricity replaces electricity from a straw fuelled power station with an efficiency of 31.5%.

Table 14 shows the input and output data for the power stations used to take into account excess electricity from CHP plants. The input and output data for the straw power station is based on a straw fuelled steam turbine power station in Sangüesa in Navarra, Spain with a capacity of 25 MW_e.

Table 14: Input and output data for the power stations

	I/O	Unit	NG	Lignite	Straw
Fuel	Input	$kWh/kWh_{electricity}$	1.818	2.439	3.175
Electricity	Output	kWh	1.000	1.000	1.000
Emissions					
CO_2	-	$g/kWh_{electricity}$	369	1004	-
CH_4	-	$g/kWh_{electricity}$	0.027	0.016	0.031
N_2O	-	$g/kWh_{electricity}$	0.016	0.028	0.006
NO_x	-	$g/kWh_{electricity}$	0.550	0.706	1.219
SO_2	-	$g/kWh_{electricity}$	0.003	0.710	0.393
NMVOC	-	$g/kWh_{electricity}$	0.027	0.014	0.122
Dust/PM	-	$g/kWh_{electricity}$	0.003	0.089	0.100

According to the assumptions in [CONCAWE 2007] and [CONCAWE 2009] for the calculation of the energy requirements and GHG emissions from the supply of natural gas, a distance of 4000 km is assumed for the transport of natural gas from the natural gas fields to the EU via pipeline. The lignite is derived from lignite mines in Lausitz region in Germany.

4.1.4 Distribution of final fuel

The ethanol is transported to a depot over a distance of 150 km via truck. At the depot the ethanol can be mixed with gasoline. The electricity consumption of the depot is about 0.0008 kWh/kWh of ethanol. From there it is transported to the filling stations over a distance of 150 km. The electricity consumption of the filling station is 0.0034 kWh/kWh of ethanol. The electricity is derived from the EU electricity mix (0.4 kV level).

Table 15: Technical and economic data for ethanol dispensing

	I/O	Unit	Amount
Ethanol	Input	$kWh/kWh_{ethanol}$	1.0000
Electricity	Input	$kWh/kWh_{ethanol}$	0.0034
Ethanol	Output	kWh	1.0000

4.1.5 End use

The ethanol is used in a piston engine aircraft.

4.2 Ethanol from sugar beet

4.2.1 Biomass supply

According the European Fertiliser Manufacturer Association (EFMA) the average yield for sugar beet in the EU amounts to about 68.9 t per ha and year based on a water content of 75% [EFMA 2008]. The LHV of sugar beet is 16.3 kg/kg of dry substance [Dreier 1998]. For the operation of farming machines 6,330 MJ of diesel per ha and year are required [Dreier 1998].

The emissions of N_2O from the plantation of energy crops consist of the direct N_2O emissions, indirect N_2O emissions from emitted NH_3 and NO_x, and indirect N_2O emissions from leaching/runoff (soil N_2O emissions). The soil N_2O emissions are calculated using the European Soil Model in [CONCAWE 2009].

The input of nitrogen fertiliser is indicated with 120 kg N per ha and year based on the fertiliser use in 2005/2006 [EFMA 2008]. Furthermore, about 400 kg CaO [Dreier 1998], 138 kg K_2O fertiliser [EFMA 2008], 60 kg P_2O_5 fertiliser [EFMA 2008], 1.3 kg pesticides [Kaltschmitt 1997], and 6 kg seeding material [Dreier 1998] are required per ha and year.

Additionally, there are N_2O emissions from the production of synthetic nitrogen fertiliser. The N_2O emissions from the production of synthetic nitrogen fertiliser are accounted for in the upstream process (see chapter 4.6 for data).

Table 16 shows the input and output data for the cultivation of sugar beet.

Table 16: **Input and output data for the cultivation of sugar beet**

	I/O	Unit	Amount
Diesel	Input	kWh/kWh_{beet}	0.0226
N fertiliser	Input	$kg\ N/kWh_{beet}$	0.00154
CaO fertiliser	Input	$kg\ CaO/kWh_{beet}$	0.00513
K_2O fertiliser	Input	$kg\ K_2O/kWh_{beet}$	0.00173
P_2O_5 fertiliser	Input	$kg\ P_2O_5/kWh_{beet}$	0.00077
Pesticides	Input	kg/kWh_{beet}	0.000017
Seeding material	Input	kg/kWh_{beet}	0.000077
Sugar beet	Output	kWh	1.0000
Emissions			
CO_2	-	g/kWh_{beet}	6.0
CH_4	-	g/kWh_{beet}	0.002
N_2O	-	g/kWh_{beet}	0.042
NO_x	-	g/kWh_{beet}	0.087
SO_2	-	g/kWh_{beet}	0.000
NMVOC	-	g/kWh_{beet}	0.014
Dust/PM	-	g/kWh_{beet}	0.013

The energy requirements, GHG emissions, and air pollutant emissions for the supply of fertilisers, pesticides, seeding material, and diesel are accounted for in the upstream processes (see chapter 4.6 for data).

4.2.2 Transport to the ethanol plant

The sugar beet is transported to the ethanol plant over a distance of 30 km via 40 t truck. The payload of the truck is 26 t of sugar beet.

4.2.3 Ethanol plant

The ethanol plant generates ethanol as main product and sugar beet pulp as by-product (the by-product slop is converted to biogas which is used for heat supply for the ethanol plant). The by-product sugar beet pulp is used as animal fodder. The sugar beet pulp replaces animal fodder from wheat and imported soybeans. The plant data have been derived from [Kaltschmitt 1997].

Table 17: Input and output data for the conversion of sugar beet to ethanol

	I/O	Unit	
Sugar beet	Input	$kWh/kWh_{ethanol}$	1.840
Steam	Input	$kWh/kWh_{ethanol}$	0.104
Electricity	Input	$kWh/kWh_{ethanol}$	0.040
Ethanol	Output	kWh	1.000
Sugar beet pulp	Output	$kg/kWh_{ethanol}$	0.100

The steam requirement is met by a natural gas fuelled boiler with an efficiency of 90% (Table 12). The electricity requirement is met by electricity from the EU electricity mix (10 to 20 kV level).

4.2.4 Distribution of the final fuel

See chapter 4.1.4.

4.2.5 End use

The ethanol is used in a piston engine aircraft.

4.3 Ethanol from sugar cane

4.3.1 Biomass supply

The sugar cane yield amounts to about 68.7 t per ha and year within a six year cycle (82.4 t per ha and year within five years, in one year after a five year cycle no sugar cane is harvested) [Macedo 2004]. The water content of sugar cane is 72.5% [Kaltschmitt 2001]. The LHV is 19.6 MJ/kg of dry substance [Dreier 2000].

The use of synthetic nitrogen fertiliser amounts to about 75 kg nitrogen per ha and year in years where sugar cane is harvested (or 62.5 kg per year within a six year cycle). Furthermore, within a six year cycle about 367 kg CaO fertiliser, 74 kg K_2O fertiliser, 28 kg P_2O_5 fertiliser, 2 kg pesticides, and 2 kg seeding material are required per ha and year.

Table 18 shows the requirements of diesel, fertilisers, pesticides and the GHG emissions from the plantation of sugar cane e.g. in Brazil.

Table 18: Input and output data for the plantation of sugar cane

	I/O	Unit	Amount
Diesel	Input	$kWh/kWh_{sugar\ cane}$	0.0053
N fertiliser	Input	$kg/kWh_{sugar\ cane}$	0.000608
CaO fertiliser	Input	$kg/kWh_{sugar\ cane}$	0.003565
K_2O fertiliser	Input	$kg/kWh_{sugar\ cane}$	0.000719
P_2O_5 fertiliser	Input	$kg/kWh_{sugar\ cane}$	0.000274
Pesticides	Input	$kg/kWh_{sugar\ cane}$	0.000019
Seeding material	Input	$kg/kWh_{sugar\ cane}$	0.000019
Fiter mud cake	Input	$kg/kWh_{sugar\ cane}$	0.005833
Vinasse	Input	$kg/kWh_{sugar\ cane}$	0.256968
Sugar cane	Output	kWh	1.0000
Emissions			
CO_2	-	$g/kWh_{sugar\ cane}$	1.4
CH_4	-	$g/kWh_{sugar\ cane}$	0.19
N_2O	-	$g/kWh_{sugar\ cane}$	0.0198

Filter mud cake and vinasse are residues. The energy requirement for the supply of seeding material, filter mud cake, and vinasse consists of the diesel requirement for the transport and distribution to the sugar cane fields.

4.3.2 Transport to the ethanol plant

The sugar cane is transported to the ethanol plant over a distance of 20 km via truck [Macedo 2004}.

4.3.3 Ethanol plant

Table 19 shows the input and output data for the conversion of sugar cane to ethanol. The energy requirement is fully met by the residues from the ethanol production. There is even some excess heat which can be exported. About 91.8 l ethanol is generated per t of sugar cane [Macedo 2004]. The water content of the sugar cane is 72.5% [Kaltschmitt 2001]. The LHV of the sugar cane is 19.6 MJ/kg of dry substance [Dreier 2000]. The LHV of ethanol is 26.8 MJ/kg and the density of ethanol is 0.79 kg/l.

Table 19: Input and output data for the conversion of sugar cane to ethanol

	I/O	Unit	Amount
Sugar cane	Input	$kWh/kWh_{ethanol}$	2.772
CaO	Input	$kg/kWh_{ethanol}$	0.0017
Cyclehexane	Input	$kg/kWh_{ethanol}$	0.000102
H_2SO_4	Input	$kg/kWh_{ethanol}$	0.0015
Lubricants	Input	$kg/kWh_{ethanol}$	0.000025
Ethanol	Output	kWh	1.000
Heat	Output	$kWh/kWh_{ethanol}$	0.115

The excess heat replaces heat from a diesel oil fuelled boiler as assumed in [CONCAWE 2007] and [CONCAWE 2009].

4.3.4 Transport of the ethanol to the EU

The ethanol is transported to the export terminal via truck over a distance of 700 km. At the export terminal the ethanol is stored at a depot (electricity consumption: 0.0008 kWh/kWh of ethanol).

From there the ethanol is transported via ship over a distance of 5,500 nm (10,186 km) to the EU. The ship is fuelled with heavy fuel oil with a sulphur content of 3.5%. The ship used for ethanol transport (Table 20) is a product tanker with a payload of 50,000 t.

Table 20: Input and output data for the product tanker

	I/O	Unit	Amount
Heavy fuel oil	Input	kWh/tkm	0.0344
Distance	Output	tkm	1.0000
Emissions			
CO_2	-	g/tkm	9.9
CH_4	-	g/tkm	0.000
N_2O	-	g/tkm	0.000
NO_x	-	g/tkm	0.188
SO_2	-	g/tkm	0.188
NMVOC	-	g/tkm	0.007
Dust/PM	-	g/tkm	0.008

The fuel consumption of the ship is calculated for the roundtrip (return voyage included). At the import terminal in the EU the ethanol is stored in a depot.

4.3.5 Distribution of final fuel

For the distribution the same assumptions are made as for the distribution of ethanol from wheat (chapter 4.1.4).

4.3.6 End use

The ethanol is used in a piston engine aircraft.

4.4 Ethanol from wood

4.4.1 Biomass supply

The production of the wood chips from residual wood is carried out onsite in the forest or onsite in the wood processing plant (e.g. a saw mill). Depending on the wood chipping equipment and the degree of comminution, the diesel consumption for wood chipping ranges between 50 and 70 MJ per t of wood which is about 0.3 to 0.5% of the energy content of the wood based on the LHV [Hartmann 1995].

For the plantation of fast growing trees small amounts of synthetic N fertilizer are required. According to [Murach 2003] 20 to 30 kg N per ha and year are required for a yield of about 10 t dry substance per ha and year. According to [Kaltschmitt 2001] the lower heating value of wood from poplar is 18.5 MJ per kg dry substance.

N_2O emissions are released from fertilized soils. In [IPCC 2006] the N_2O emissions are classified into direct N_2O emissions, indirect N_2O emissions from emitted NH_3 and NO_x, and indirect N_2O emissions from nitrogen leaching/runoff. The direct N_2O emissions have been derived from [Flessa 1998] and the indirect N_2O emissions are derived from [IPCC 2006].

Table 21: Input and output data for the plantation of fast growing trees (short rotation forestry

	I/O	Unit	Amount
Mechanical work	Input	kWh/kWh_{wood}	0.0015
N fertiliser	Input	kg/kWh_{wood}	0.00049
Wood	Output	kWh	1.000
Emissions			
N_2O	-	g/kWh_{wood}	0.0091

The mechanical work is supplied by a diesel engine with an efficiency of 30%.

4.4.2 Transport to the ethanol plant

Lignocellulosic ethanol plants are relatively large plants requiring a large amount of biomass. In [CONCAWE 2007] and [CONCAWE 2009] for residual wood a longer transport distance has been assumed than for woody biomass from short rotation forestry. In case of residual wood the wood chips are transported to a midland port via truck over a distance of 50 km. From the midland port the wood chips are transported via ship to a gasification plant over a distance of 400 km. The ethanol plant is located nearby a river. In case of wood from short rotation forestry the wood chips are transported via truck directly to the ethanol plant over a distance of 50 km.

4.4.3 Ethanol plant

The wood chips are converted via a lignocellulosic ethanol plant. The input and output data for the conversion of wood to ethanol via hydrolysis and fermentation have been derived from [Wooley 1999]. Table 22 shows the input and output data for the conversion of wood to ethanol.

Table 22: Input and output data for the conversion of wood chips to ethanol

	I/O	Unit	Amount
Wood chips	Input	$kWh/kWh_{ethanol}$	2.909
$(NH_4)_2SO_4$	Input	$kg/kWh_{ethanol}$	0.0025
CaO	Input	$kg/kWh_{ethanol}$	0.0047
H_2SO_4	Input	$kg/kWh_{ethanol}$	0.0126
NH_3	Input	$kg/kWh_{ethanol}$	0.0097
Diesel	Input	$kWh/kWh_{ethanol}$	0.0360
Ethanol	Output	kWh	1.000
Electricity	Output	$kWh/kWh_{ethanol}$	0.099

The electricity replaces electricity from a wood chips fuelled steam turbine power station with an efficiency of 32%.

4.4.4 Distribution of final fuel

For the distribution the same assumptions are made as for the distribution of ethanol from wheat (chapter 4.1.4).

4.4.5 End use

The ethanol is used in a piston engine aircraft.

4.5 Ethanol from straw

4.5.1 Biomass supply

Removing straw reduces soil nutrients which need to be compensated by an additional fertiliser. Therefore, as done in [CONCAWE 2007] and [CONCAWE 2009], a fertiliser debit is calculated for the removal of straw from the field. The fertiliser debit is expressed as a fertiliser requirement for the supply of straw.

Table 23: Fertiliser debit

	I/O	Unit	Amount
K2O fertiliser	Input	kg/kWh_{straw}	0.00255
P_2O_5 fertiliser	Input	kg/kWh_{straw}	0.00048
Straw	input	kWh/kWh_{straw}	1.000
Straw	Output	kWh	1.000

For the production of straw bales about 0.011 kWh diesel/kWh of straw is required [GEMIS 2009].

4.5.2 Transport to the ethanol plant

The straw is transported to the ethanol plant over a distance of 50 km via truck. The LHV of wheat straw is 17.2 MJ/kg of dry substance [Kaltschmitt 2001]. The water content of the transported straw is about 15%.

4.5.3 Ethanol plant

The input and output data for the conversion of straw to ethanol via hydrolysis and fermentation are based on data from Iogen which also have been used in [CONCAWE 2007] and [CONCAWE 2009].

Table 24: Input and output data for the conversion of straw to ethanol

	I/O	Unit	Amount
Straw	Input	$kWh/kWh_{ethanol}$	2.377
CaO	Input	$kg/kWh_{ethanol}$	0.0086
H_2SO_4	Input	$kg/kWh_{ethanol}$	0.0147
Ethanol	Output	kWh	1.000
Electricity	Output	$kWh/kWh_{ethanol}$	0.052

The excess electricity replaces electricity from a straw fuelled steam turbine power plant with an efficiency of 31.5% (see chapter 4.1.3).

4.5.4 Distribution of the final fuel

For the distribution the same assumptions are made as for the distribution of ethanol from wheat (4.1.4).

4.5.5 End use

The ethanol is used in piston engine aircraft.

4.6 Supply of fertilisers, pesticides and seeding material

The following tables show the input and output data for the supply of fertilisers, pesticides and seeding material as indicated in [Kaltschmitt 1997].

Table 25: Energy requirements and GHG emissions for the supply of N-fertiliser [Kaltschmitt 1997]

	I/O	Unit	Amount
Hard coal	Input	kWh/kg_N	1.097
Diesel oil	Input	kWh/kg_N	0.239
Electricity	Input	kWh/kg_N	0.174
Heavy fuel oil	Input	kWh/kg_N	1.217
NG	Input	kWh/kg_N	9.167
Emissions			
CO_2	-	g/kg_N	2468
CH_4	-	g/kg_N	0.45
N_2O	-	g/kg_N	9.63
NO_x	-	g/kg_N	10.7
SO_2	-	g/kg_N	3.32
NMVOC	-	g/kg_N	0.21
Dust/PM	-	g/kg_N	0.774

Table 26: Energy requirements and GHG emissions for the supply of CaO-fertiliser [Kaltschmitt 1997]

	I/O	Unit	Amount
Lignite	Input	kWh/kg_{CaO}	0.0639
Hard coal	Input	kWh/kg_{CaO}	0.0261
Diesel oil	Input	kWh/kg_{CaO}	0.0514
Electricity	Input	kWh/kg_{CaO}	0.111
NG	Input	kWh/kg_{CaO}	0.0833
Emissions			
CO_2	-	g/kg_{CaO}	65
CH_4	-	g/kg_{CaO}	0.0039
N_2O	-	g/kg_{CaO}	0.016
NO_x	-	g/kg_{CaO}	0.25
SO_2	-	g/kg_{CaO}	0.012
NMVOC	-	g/kg_{CaO}	0.027
Dust/PM	-	g/kg_{CaO}	0.541

Table 27: Energy requirements and GHG emissions for the supply of K_2O-fertiliser [Kaltschmitt 1997]

	I/O	Unit	Amount
Diesel oil	Input	kWh/kg_{K2O}	0.15
Electricity	Input	kWh/kg_{K2O}	0.061
NG	Input	kWh/kg_{K2O}	2.0833
Emissions			
CO_2	-	g/kg_{K2O}	453
CH_4	-	g/kg_{K2O}	0.021
N_2O	-	g/kg_{K2O}	0.0094
NO_x	-	g/kg_{K2O}	0.69
SO_2	-	g/kg_{K2O}	0.015
NMVOC	-	g/kg_{K2O}	0.087
Dust/PM	-	g/kg_{K2O}	0.535

Table 28: Energy requirements and GHG emissions for the supply of P_2O_5-fertiliser [Kaltschmitt 1997]

	I/O	Unit	Amount
Hard coal	Input	kWh/kg_{P2O5}	0.1583
Diesel oil	Input	kWh/kg_{P2O5}	0.3111
Electricity	Input	kWh/kg_{P2O5}	0.445
Heavy fuel oil	Input	kWh/kg_{P2O5}	1.3889
NG	Input	kWh/kg_{P2O5}	0.875
Emissions			
CO_2	-	g/kg_{P2O5}	700
CH_4	-	g/kg_{P2O5}	0.023
N_2O	-	g/kg_{P2O5}	0.042
NO_x	-	g/kg_{P2O5}	9.7
SO_2	-	g/kg_{P2O5}	13.61
NMVOC	-	g/kg_{P2O5}	0.32
Dust/PM	-	g/kg_{P2O5}	0.968

Table 29: **Energy requirements and GHG emissions for the supply of pesticides [Kaltschmitt 1997]**

	I/O	Unit	Amount
Hard coal	Input	$kWh/kg_{pesticides}$	2.12
Diesel oil	Input	$kWh/kg_{pesticides}$	16.14
Electricity	Input	$kWh/kg_{pesticides}$	7.91
Heavy fuel oil	Input	$kWh/kg_{pesticides}$	9.03
NG	Input	$kWh/kg_{pesticides}$	19.83
Emissions			
CO_2	-	$g/kg_{pesticides}$	4921
CH_4	-	$g/kg_{pesticides}$	0.18
N_2O	-	$g/kg_{pesticides}$	1.51
NO_x	-	$g/kg_{pesticides}$	6.92
SO_2	-	$g/kg_{pesticides}$	17.4
NMVOC	-	$g/kg_{pesticides}$	0.29
Dust/PM	-	$g/kg_{pesticides}$	0.983

Table 30: **Energy requirements and GHG emissions for the supply of seeding material for winter wheat [Kaltschmitt 1997]**

	I/O	Unit	Amount
Hard coal	Input	kWh/kg_{seeds}	0.028
Diesel oil	Input	kWh/kg_{seeds}	0.194
Heavy fuel oil	Input	kWh/kg_{seeds}	0.083
NG	Input	kWh/kg_{seeds}	0.333
Emissions			
CO_2	-	g/kg_{seeds}	130.1
CH_4	-	g/kg_{seeds}	0.0
N_2O	-	g/kg_{seeds}	0.4
NO_x	-	g/kg_{seeds}	0.9
SO_2	-	g/kg_{seeds}	0.3
NMVOC	-	g/kg_{seeds}	0.1
Dust/PM	-	g/kg_{seeds}	0.0

5 WTT RESULTS

Table shows Well-to-Tank the main GHG emissions components of the selected bio-ethanol pathway 02a.

Table 31: Detailed GHG emissions of pathway 02a

Well-to-Tank Chain name	**CO2-Equivalent g/kWh**
02a Ethanol from wheat (NG fueled boiler) - Substitution method	
Wheat cultivation	142.0
Wheat transport system (50km)	2.3
Ethanol production	60.1
Ethanol transport (1)	4.0
Filling station	1.6
CO2 bound in ethanol	-256.5
Total emissions	**-46.6**

(1) Transport to a depot via truck: 150 km; depot; transport from the depot to the filling station via truck: 150 km

For all pathways the same lifecycle-stages have been used. Figure 3 shows the WtT GHG emissions for the supply of the most common bio-ethanol blends as well as for the gasoline reference. WtT data show the GHG emissions associated with producing the fuel - GHG released into the atmosphere during production shows up as positive emissions resulting from feedstock production and handling (see e.g. chapter 4.3.1), feedstock transport (see e.g. chapter 4.3.2), ethanol production (see e.g. chapter 4.3.3; use of by-products for energy supply may lead to negative emission values), ethanol transport (see e.g. chapter 4.3.4 and 4.3.5), and from the filling station (see e.g. chapter 4.1.4); any CO_2 bound in the plants used as feedstock or any by-products used as energy supply in the production process show up as negative, as it was previously removed by the plants from the atmosphere through photosynthesis.

Contributions from production and transport of feedstock and for the production and transport of ethanol are colour coded for each path as well as the biogenic CO_2 bound in the fuel.

The total emission results from the sum of positive (production, distribution, use) and negative emissions (biogenic CO_2 bound in fuel, use of by-products in ethanol production).

Consequently, the carbon emitted as CO_2 during combustion of the fuel (as per Table 2) is not accounted for in these WtT data. It would be released upon burning the fuel, and shown in TtP and WtP results.

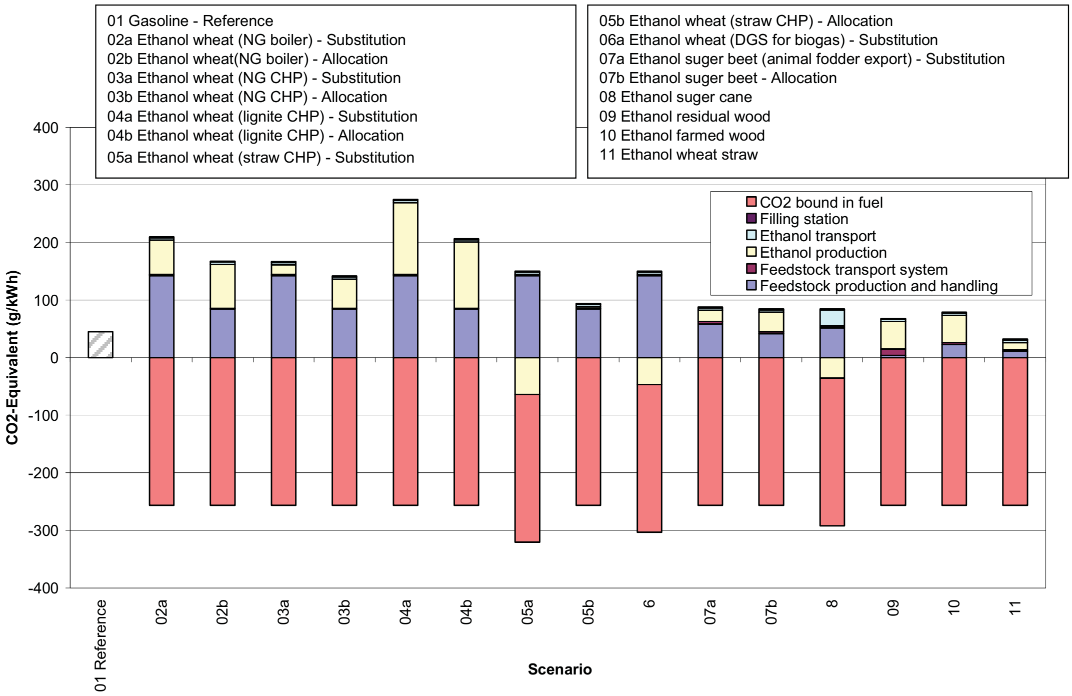

Figure 3: WtT GHG emissions

6 TTP RESULTS

Emission measurement data from a Rotax 912ULS piston engine on a test stand (see Figure 4) have been supplied by Prof. Dr.-Ing. Thomas Esch, Aachen University of Applied Sciences (FH Aachen), Institute for Applied Thermodynamics and Combustion Technology.

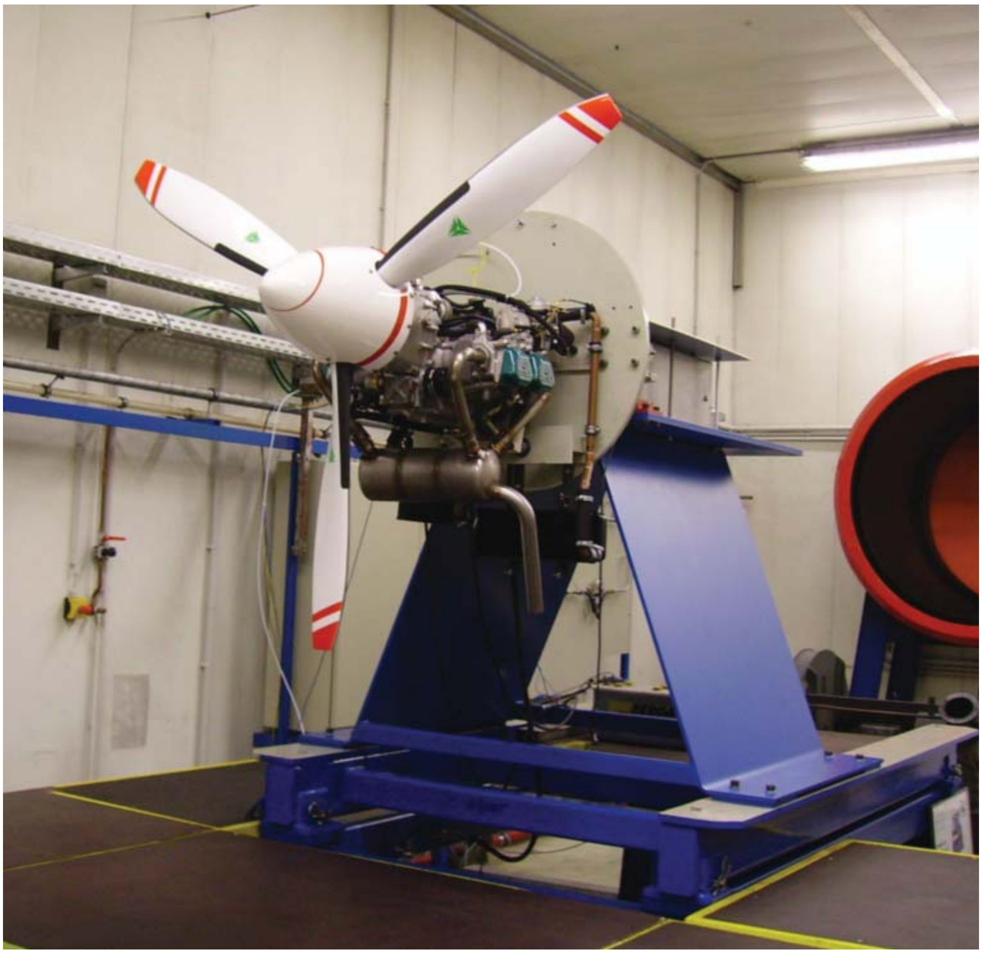

Figure 4: Piston engine test stand at FH Aachen

Figure 5 shows the LTO (landing and take-off) cycle used during the emission measurements. Six different operation modes have been used: idle, taxi, take-off, maximum continuous power, best economy cruising, and approach. Emission results for the cycles have been weighted by their respective duration and averaged for the TtP results. Resulting emissions are shown in Figure 6.

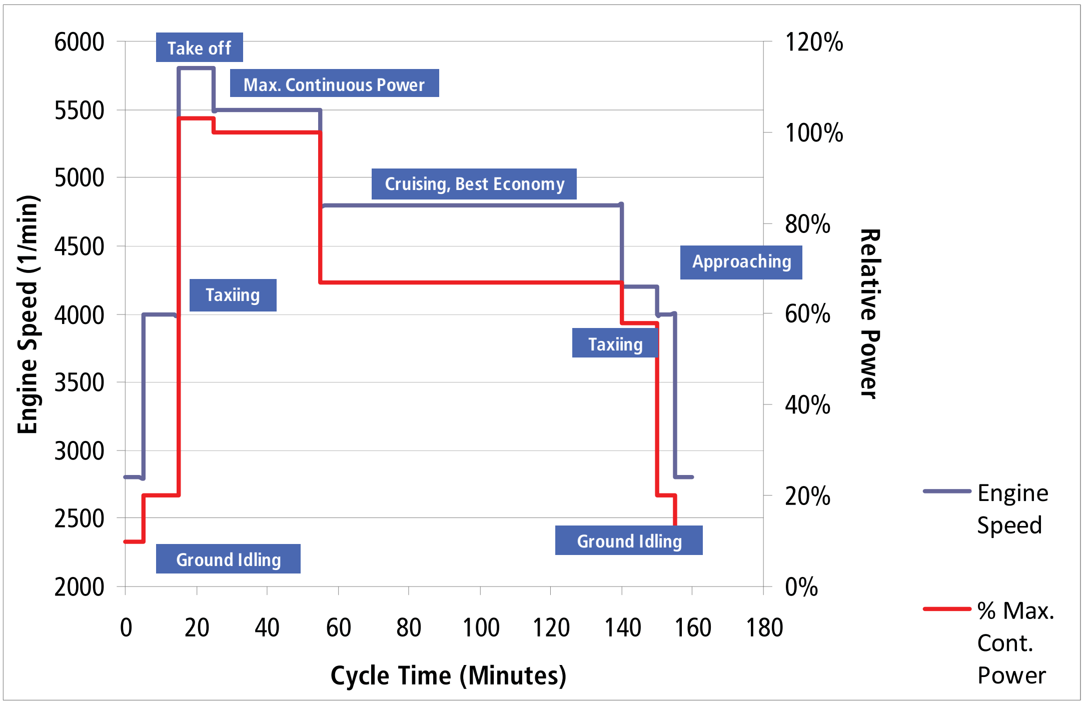

Figure 5: LTO cycle for engine emission measurements

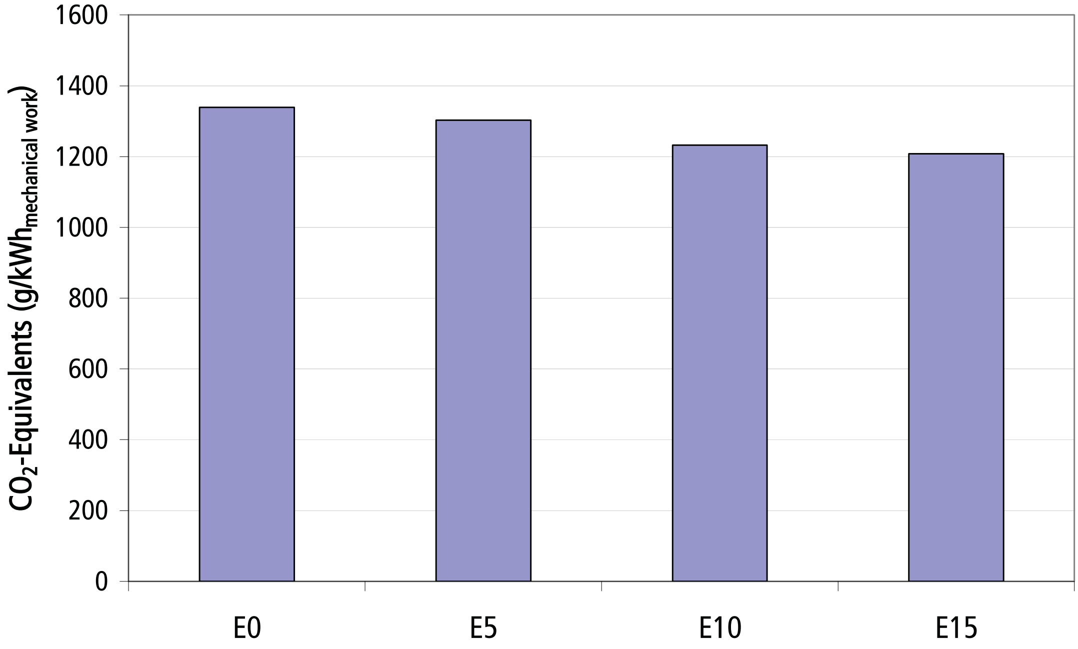

Figure 6: TtP GHG emissions from FH Aachen measurements (LTO cycle)

For the calculation of the energy related fuel consumption the different LHV of gasoline and ethanol has to be taken into account (gasoline: 12 kWh/kg; ethanol: 7.45 kWh/kg).

Measured hydrocarbons (C_xH_y) have been assumed to consist of 15% methane[2] (CH_4), which has been factored into the CO_2 equivalents shown. The significant amounts of emitted CO measured are assumed to eventually oxidize into CO_2 in the atmosphere and are accounted for accordingly.

Table 32: TtP fuel consumption, GHG emissions and air pollutant emissions (the SO_2 and PM emissions are approximately zero)

Blend	Mode	Fuel consumption	CO_2-Equivalent	NMVOC	NO_X
		$kWh_{fuel}/kWh_{mech. work}$	$g/kWh_{mech. work}$	$g/kWh_{mech. work}$	$g/kWh_{mech. work}$
E0	Idle	12.44	3,812.77	63.25	0.45
E0	Taxi	7.04	2,121.29	18.45	0.55
E0	Take off	3.84	1,094.61	4.91	4.81
E0	Max Cont	3.72	1,064.04	4.79	4.51
E0	Best Eco	3.83	1,068.53	5.75	5.18
E0	Approach	3.87	1,056.46	5.94	3.67
E0	**Total LTO cycle (weighted average)**	**4.65**	**1338.77**	**10.31**	**4.21**

Blend	Mode	Fuel consumption	CO_2-Equivalent	NMVOC	NO_X
		$kWh_{fuel}/kWh_{mech. work}$	$g/kWh_{mech. work}$	$g/kWh_{mech. work}$	$g/kWh_{mech. work}$
E5	Idle	11.21	3,814.60	53.45	0.60
E5	Taxi	7.40	2,113.65	16.66	0.65
E5	Take off	3.90	929.23	4.80	6.16
E5	Max Cont	3.47	971.65	5.23	5.46
E5	Best Eco	3.68	1,056.66	6.10	5.71
E5	Approach	3.67	1,026.42	6.33	4.18
E5	**Total LTO cycle (weighted average)**	**4.47**	**1302.33**	**9.82**	**4.80**

Blend	Mode	Fuel consumption	CO_2-Equivalent	NMVOC	NO_X
		$kWh_{fuel}/kWh_{mech. work}$	$g/kWh_{mech. work}$	$g/kWh_{mech. work}$	$g/kWh_{mech. work}$
E10	Idle	11.37	3,498.85	71.48	0.31
E10	Taxi	6.99	1,936.14	15.00	0.77
E10	Take off	3.63	974.67	4.23	6.65
E10	Max Cont	3.61	989.74	4.31	6.90
E10	Best Eco	3.67	991.87	5.03	6.64
E10	Approach	3.62	938.18	5.11	4.72
E10	**Total LTO cycle (weighted average)**	**4.45**	**1232.25**	**9.94**	**5.62**

Blend	Mode	Fuel consumption	CO_2-Equivalent	NMVOC	NO_X
		$kWh_{fuel}/kWh_{mech. work}$	$g/kWh_{mech. work}$	$g/kWh_{mech. work}$	$g/kWh_{mech. work}$
E15	Idle	11.61	3,380.13	51.73	0.51
E15	Taxi	6.71	1,985.77	15.70	0.81
E15	Take off	3.57	981.13	4.19	7.65
E15	Max Cont	3.47	962.18	4.19	7.94
E15	Best Eco	3.50	960.46	4.81	7.57
E15	Approach	3.46	943.77	5.06	6.10
E15	**Total LTO cycle (weighted average)**	**4.30**	**1208.38**	**8.63**	**6.48**

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[2] This value is based on private data from the automotive industry.

7 WTP RESULTS

WtT and TtP results are combined for WtP data in the following way:

- WtT data are calculated for each ethanol admixture by appropriately combining gasoline and ethanol WtT values (45.2 g CO2 equiv per kWh for gasoline, respectively the appropriate negative value for the bio-ethanol path chosen) weighted with their respective shares (e.g. for
- The average fuel consumption ($kWh_{fuel}/kWh_{mechanical\ work}$) is derived from the measured piston engine data by averaging consumption over the different LTO cycles, weighed by cycle duration (see Table 32).
- Multiplying these average fuel consumptions ($kWh_{fuel}/kWh_{mechanical\ work}$) by the WtT emission values yields specific WtT GHG emissions per kWh of mechanical work.
- TtP GHG emissions are added.

Results are shown in the table and figures below.

Table 33: WtP GHG emissions [g CO_2 equivalent/kWh_{mech}]

	01 Ref	02a	02b	03a	03b	04a	04b	05a	05b	06	07a	07b	08	09	10	11
E05 WtT GHG	210	188	182	182	178	198	188	169	170	172	169	169	164	166	168	161
E05 TtP GHG	1339	1302	1302	1302	1302	1302	1302	1302	1302	1302	1302	1302	1302	1302	1302	1302
E05 WtP GHG	1549	1490	1484	1484	1480	1500	1490	1472	1473	1474	1472	1471	1466	1469	1470	1463
E10 WtT GHG	210	173	159	159	152	193	171	134	137	140	135	134	123	129	132	118
E10 TtP GHG	1339	1232	1232	1232	1232	1232	1232	1232	1232	1232	1232	1232	1232	1232	1232	1232
E10 WtP GHG	1549	1405	1392	1391	1384	1425	1404	1366	1369	1372	1367	1366	1355	1361	1364	1350
E15 WtT GHG	210	153	133	133	122	182	151	96	100	104	97	95	79	88	93	71
E15 TtP GHG	1339	1208	1208	1208	1208	1208	1208	1208	1208	1208	1208	1208	1208	1208	1208	1208
E15 WtP GHG	1549	1361	1342	1341	1330	1391	1359	1304	1308	1312	1305	1304	1287	1296	1301	1280

Pathways	Fuel	Feedstock	Heat source for conversion process	By-products	Remark
No. 01	Gasoline EU	-	-	-	Reference
No. 02a	Ethanol	Wheat	Natural gas (boiler)	Substitution	Distillers Grains and Solubles as animal fodder
No. 02b	Ethanol	Wheat	Natural gas (boiler)	Allocation (1)	
No. 03a	Ethanol	Wheat	Natural gas (co-generation)	Substitution	Distillers Grains and Solubles as animal fodder
No. 03b	Ethanol	Wheat	Natural gas (co-generation)	Allocation (1)	
No. 04a	Ethanol	Wheat	Lignite (co-generation)	Substitution	Distillers Grains and Solubles as animal fodder
No. 04b	Ethanol	Wheat	Lignite (co-generation)	Allocation (1)	
No. 05a	Ethanol	Wheat	Wheat straw (co-generation)	Substitution	Distillers Grains and Solubles as animal fodder
No. 05b	Ethanol	Wheat	Wheat straw (co-generation)	Allocation (1)	
No. 06	Ethanol	Wheat	Biogas	Substitution	Distillers Grains and Solubles for Biogas
No. 07a	Ethanol	Sugar beet	Natural gas	Substitution	Beet pulp as animal fodder, slops to biogas
No. 07b	Ethanol	Sugar beet	Natural gas	Allocation (1)	
No. 08	Ethanol	Sugar cane	Bagasse	-	
No. 09	Ethanol	Residual wood	Wood (co-generation)	-	
No. 10	Ethanol	Farmed wood	Wood (co-generation)	-	
No. 11	Ethanol	Wheat straw	Wheat straw (co-generation)	-	

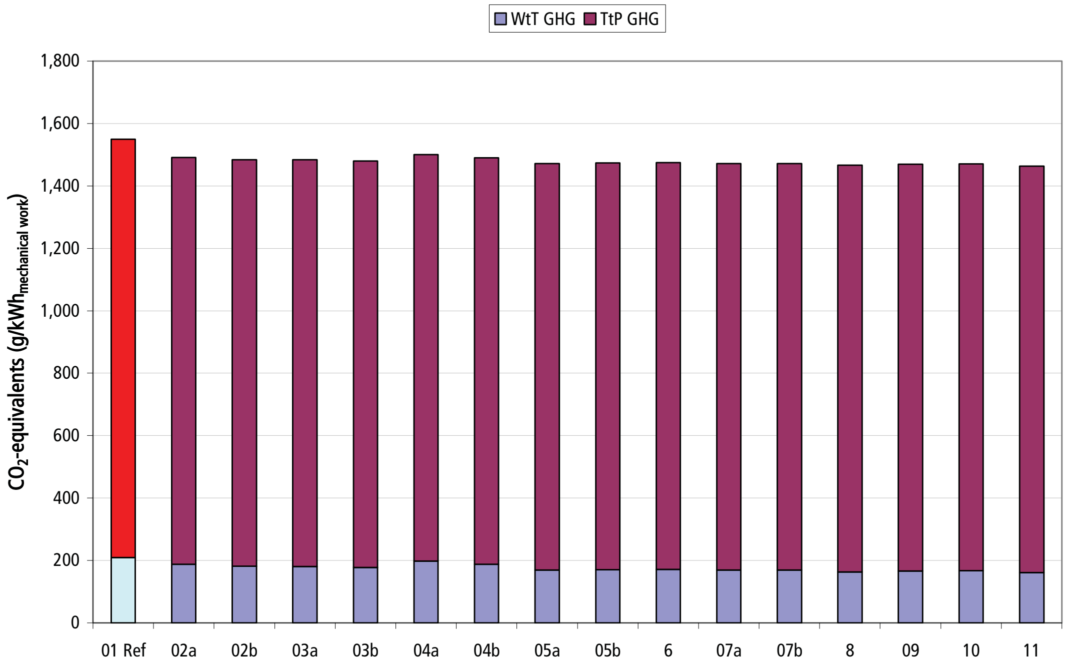

Figure 7: GHG emissions WtP E05

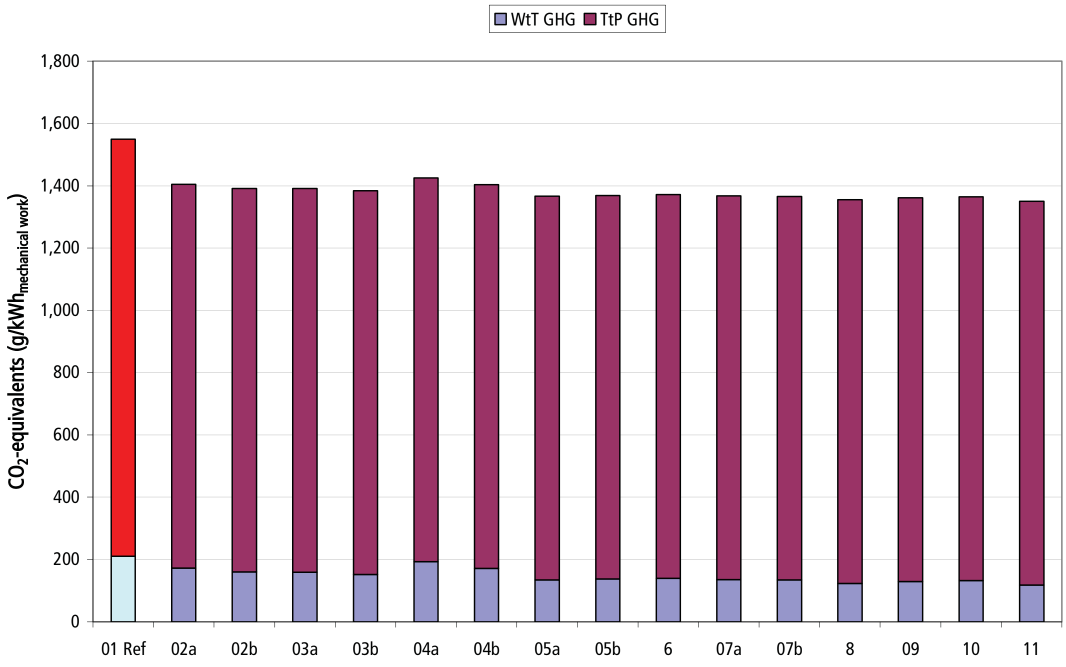

Figure 8: GHG emissions WtP E10

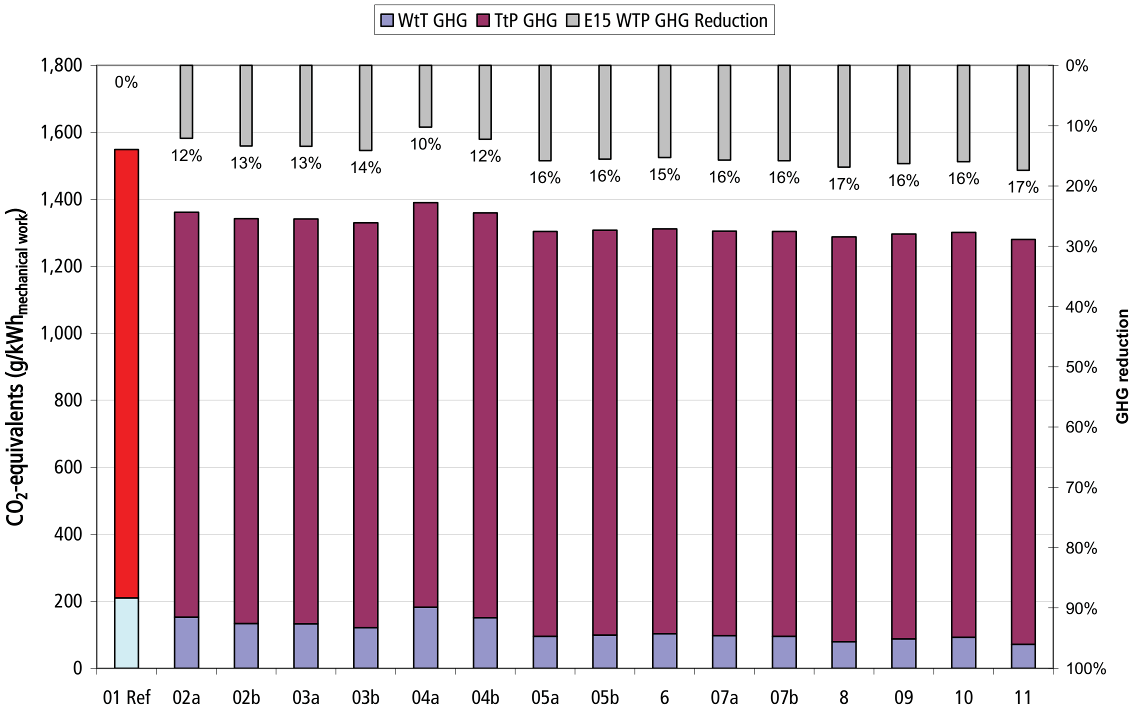

Figure 9: GHG emissions and emission reduction compared to reference WtP E15

8 OTHER EMISSIONS WTP

Volatile Organic Compounds (VOC) and Nitrogen Oxides (NO_X) have been measured by FH Aachen, and are also accounted for in the WtT data. Resulting emissions are calculated in the same way as described in Chapter 7. Measured C_xH_y results have been reduced by 15% assumed CH_4 (as Chapter 6) content to get the amount of Non-Methane Volatile Organic Compounds (NMVOC). Results are given below; pathway numbering according to the same scheme as above (see Table 33).

Figure 10 and Figure 11 show NMVOC and NO_x emissions separately for the WtT and TtP paths on the same scale (WtT emissions are shown exemplarily for E05; they do look very similar for E10 and E15). Clearly, NMVOC and NO_x emissions are dominated by the TtP emissions.

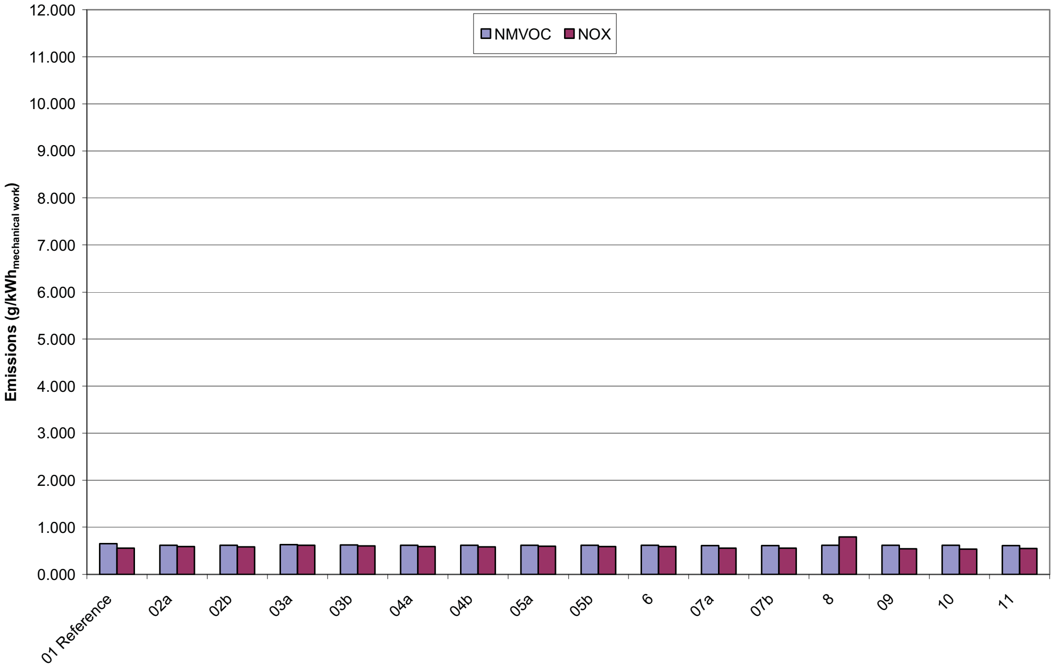

Figure 10: NO_x and NMVOC WtT emissions for E05

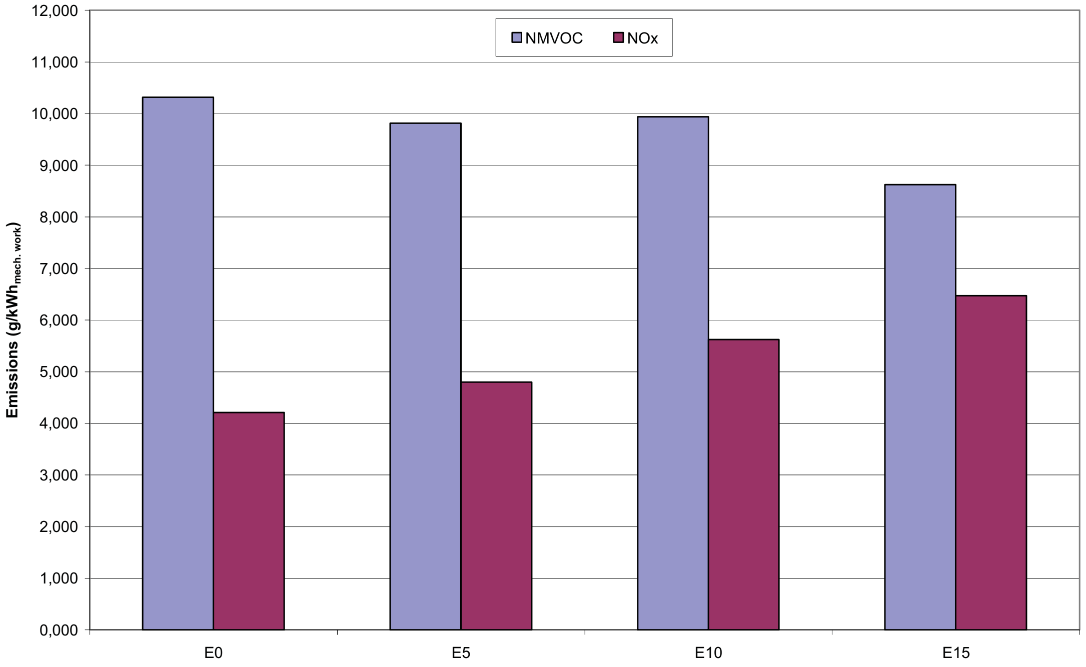

Figure 11: NO_x and NMVOC TtP emissions

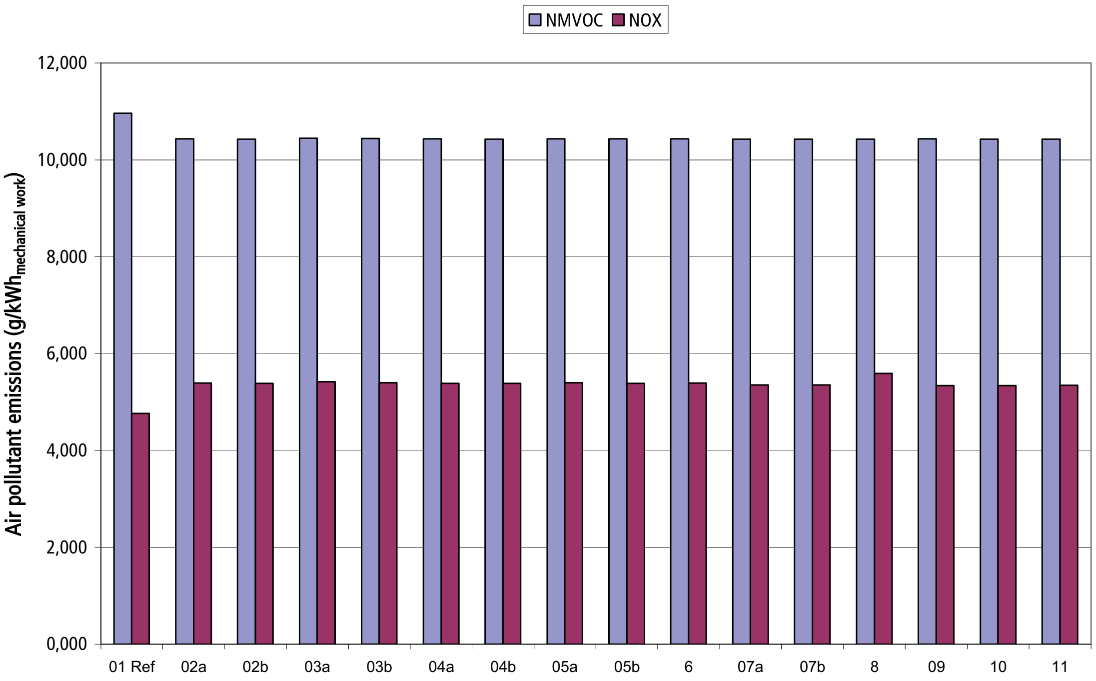

Figure 12: NO_x and NMVOC WtP emissions for E05

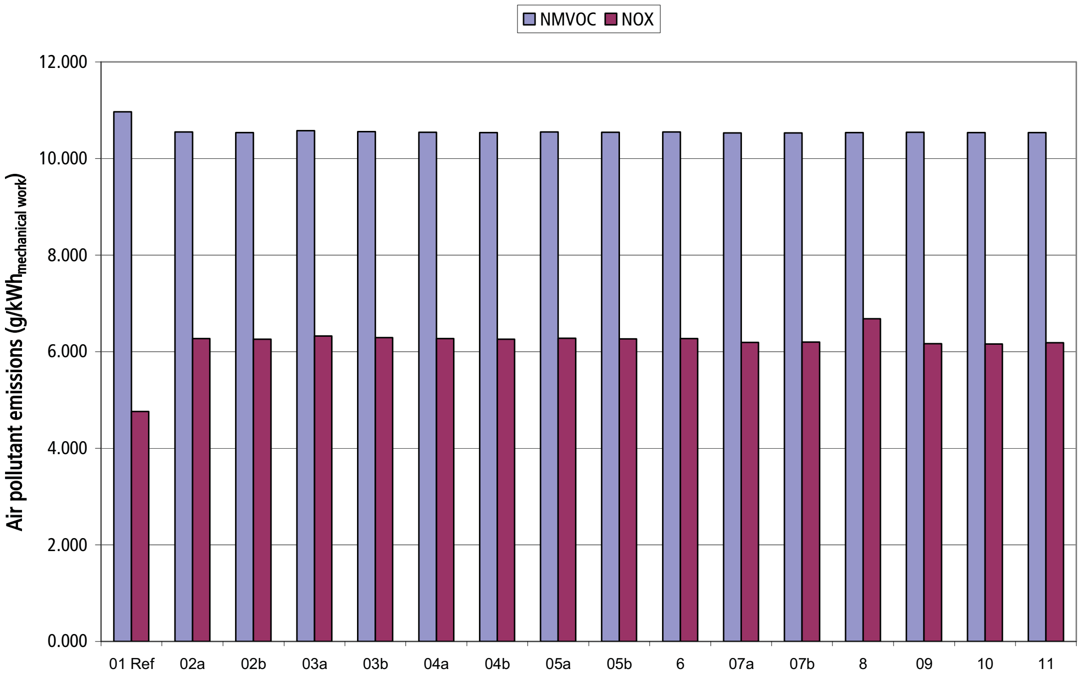

Figure 13: NO_x and NMVOC WtP emissions for E10

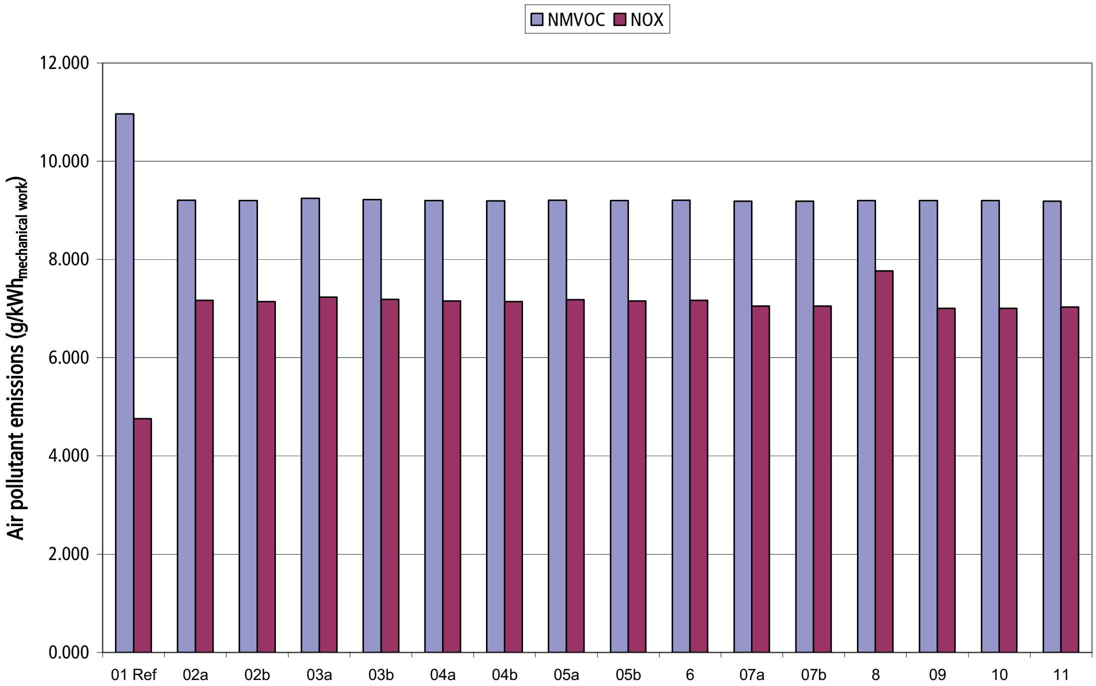

Figure 14: NO_x and NMVOC WtP emissions for E15

For Sulphur Dioxide (SO_2), and dust/particulate matter (PM), only WtT data are available. Sulphur Dioxide content in European MOGAS is very low (<50ppm)[3], and most SO_2 emissions occur WtT, with significant amounts mainly resulting from heavy fuel oil used in tankers for long range transport.

Dust/particulate matter (PM) emissions are fairly well known WtT; however, few data for aircraft piston engines are available. [Rindlisbacher 2007] have made measurements, exhibiting a significant deviation between different MOGAS fuels used and between different engines. However, absolute particulate emissions are low, and higher emission data being caused by lead containing fuels (the use of aviation gas with 0.7 g Pb per kg fuel leads to about 58 mg Pb emissions per kWh of fuel or about 276 g per kWh of mechanical work over the LTO cycle). The Rotax 951 has only shown emissions between 1 and 3 mg/kg fuel (ca. 4 to 12 mg/kWh$_{mech}$), being the best engine in the field. Most other engines had values around 30 mg/kWh$_{mech}$ emissions, and only the Rotax 582 DCDI was an outlier with up to 400 mg/kWh$_{mech}$. Hence, we can assume that in most cases, from a WtP perspective, the lion's share of particulate emissions is expected to result from the WtT path.

WtT results for Sulphur Dioxide (SO_2) and dust & particles (PM) are shown in below. The only point of note is the higher emission in the sugarcane path 08. The source of SO_2 and PM emissions occur in the conversion process of sugarcane-ethanol by burning bagasse[4] for process heat production.

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[3] Measured sulphur content of the fuels used in the TtP measurements is actually below 5ppm.

[4] Bagasse: fibre remaining after the extraction of the sugar-bearing juice from sugarcane.

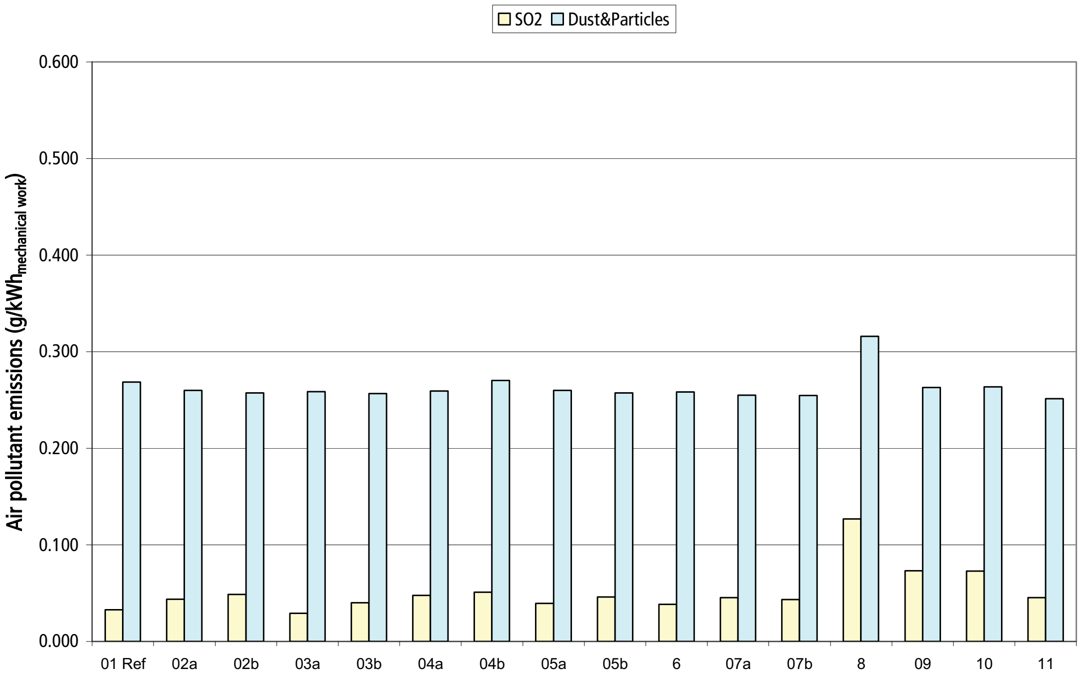

Figure 15: SO_2 and dust/PM WtT emissions for E05

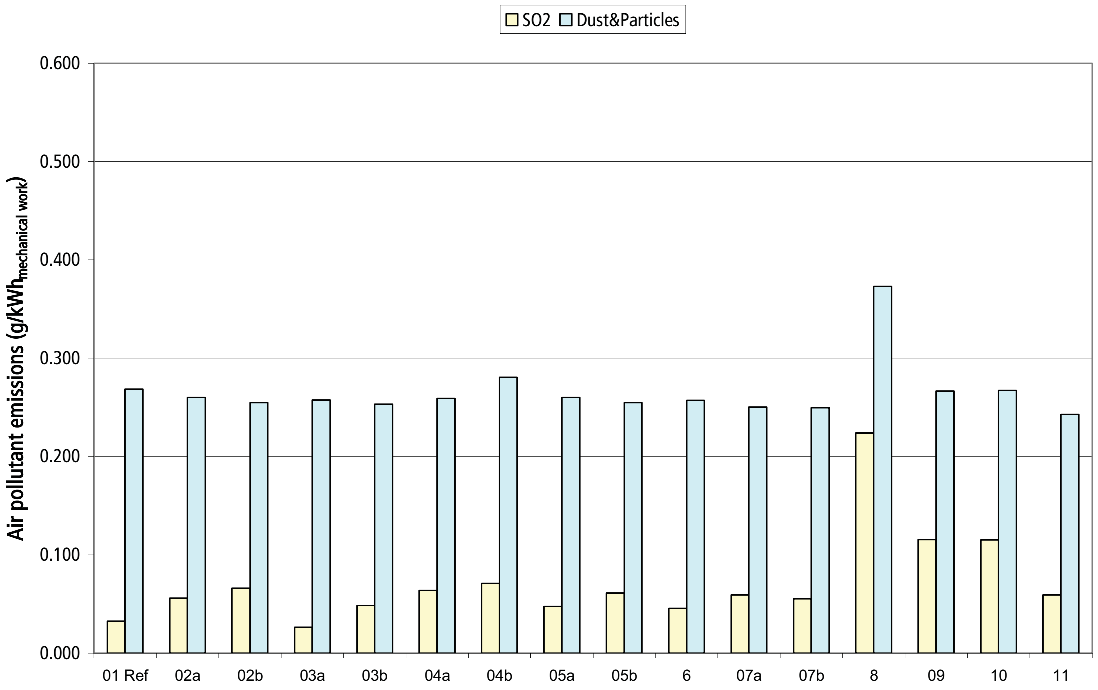

Figure 16: SO_2 and dust/PM WtT emissions for E10

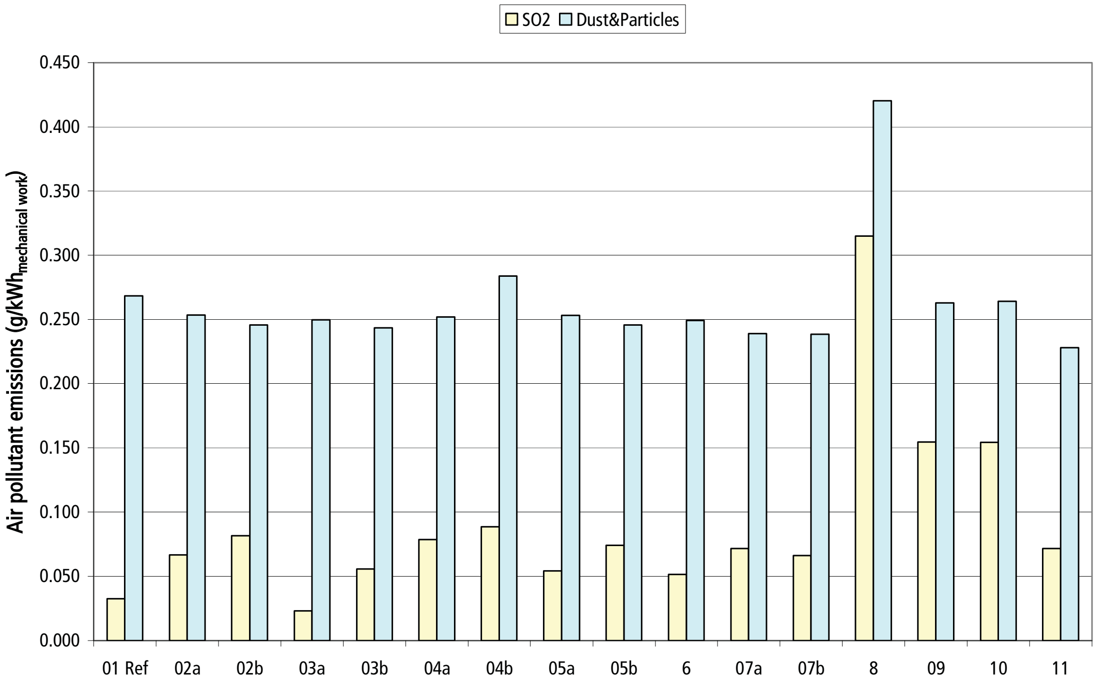

Figure 17: SO_2 and dust/PM WtT emissions for E15

9 WTP EMISSIONS EXPRESSED IN E0 EQUIVALENTS

In this chapter the WtP emission results are presented converted to E0 equivalents i.e. in kilograms of MOGAS based on the LHV of the blends.

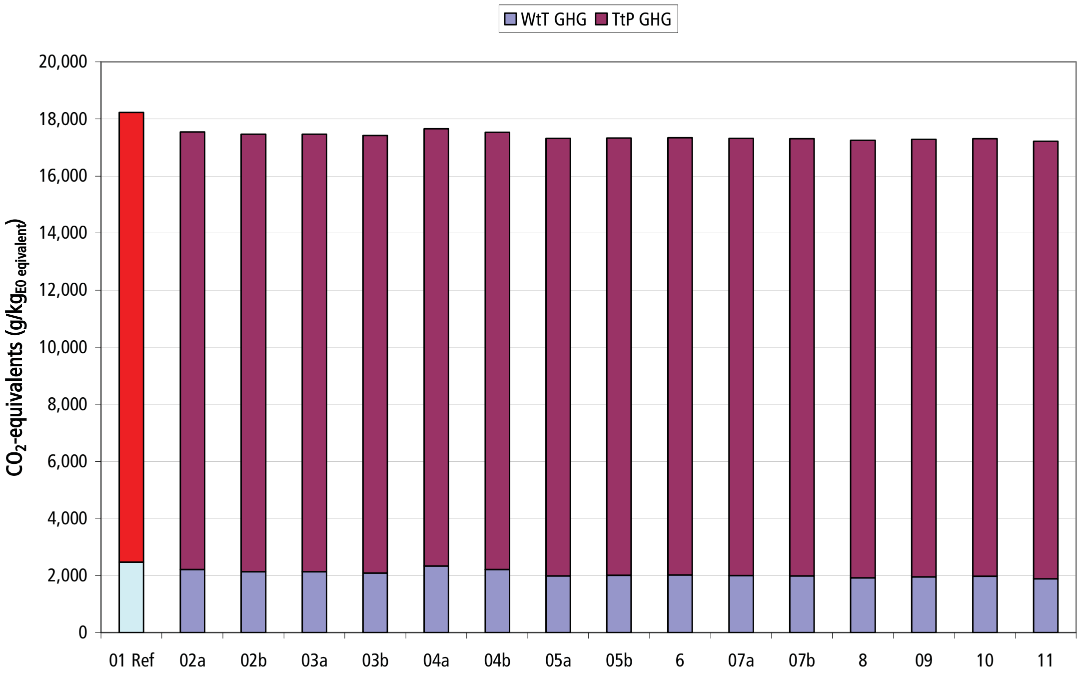

Figure 18: GHG emissions of E5 compared to reference WtP expressed in E0 equivalents

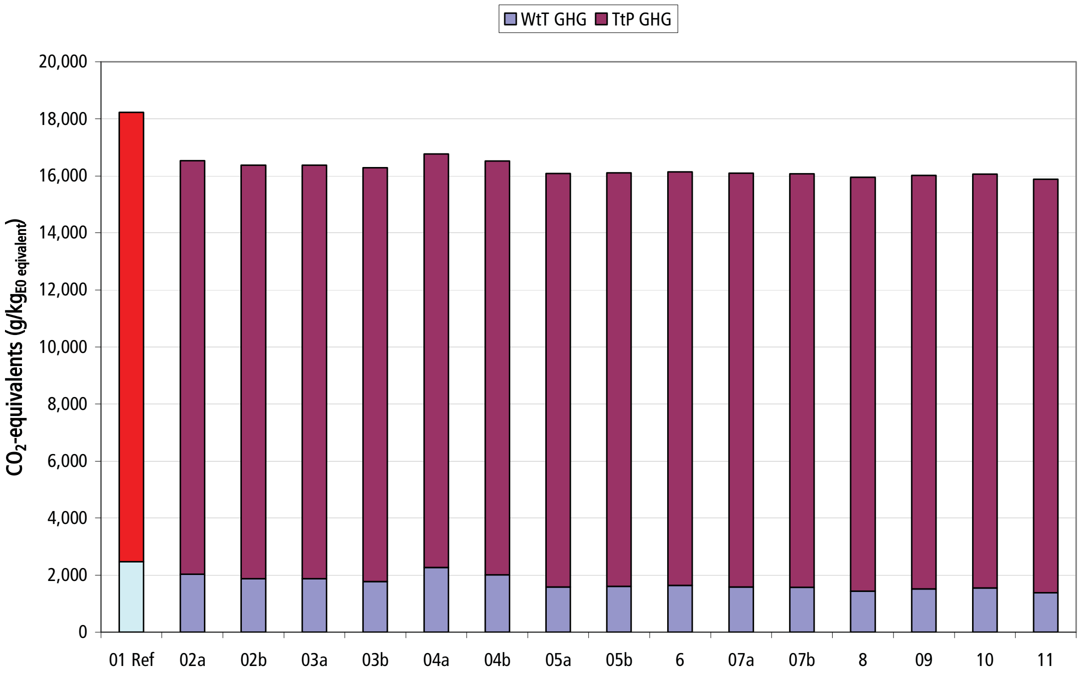

Figure 19: GHG emissions of E10 compared to reference WtP expressed in E0 equivalents

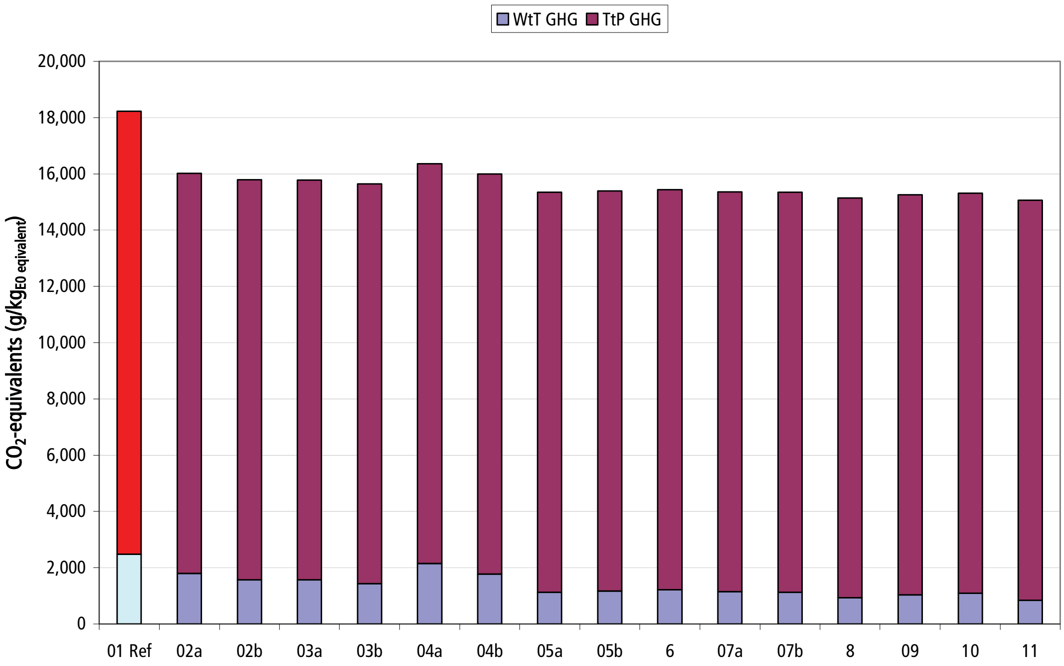

Figure 20: GHG emissions of E15 compared to reference WtP expressed in E0 equivalents

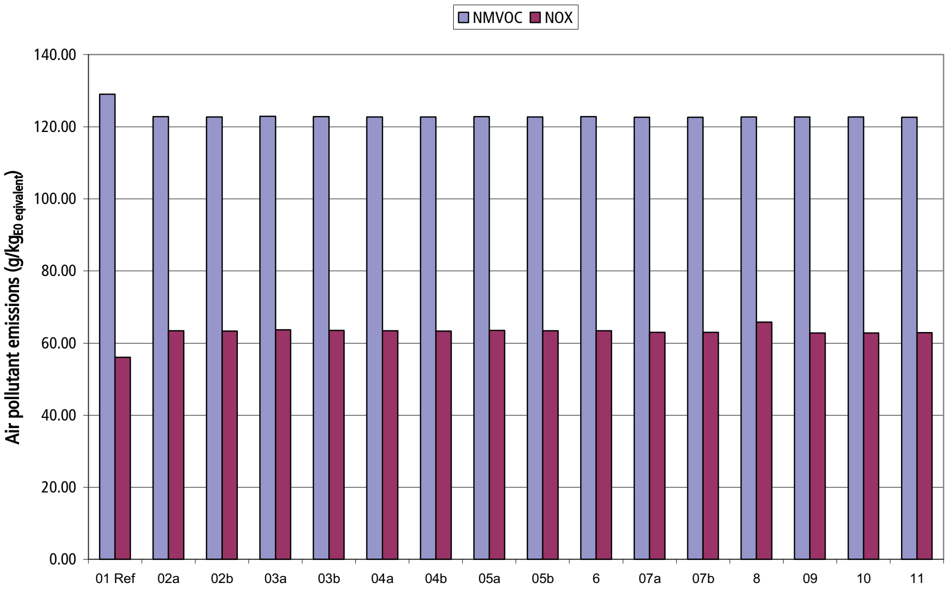

Figure 21: Air pollutant emissions of E5 compared to reference WtP expressed in E0 equivalents

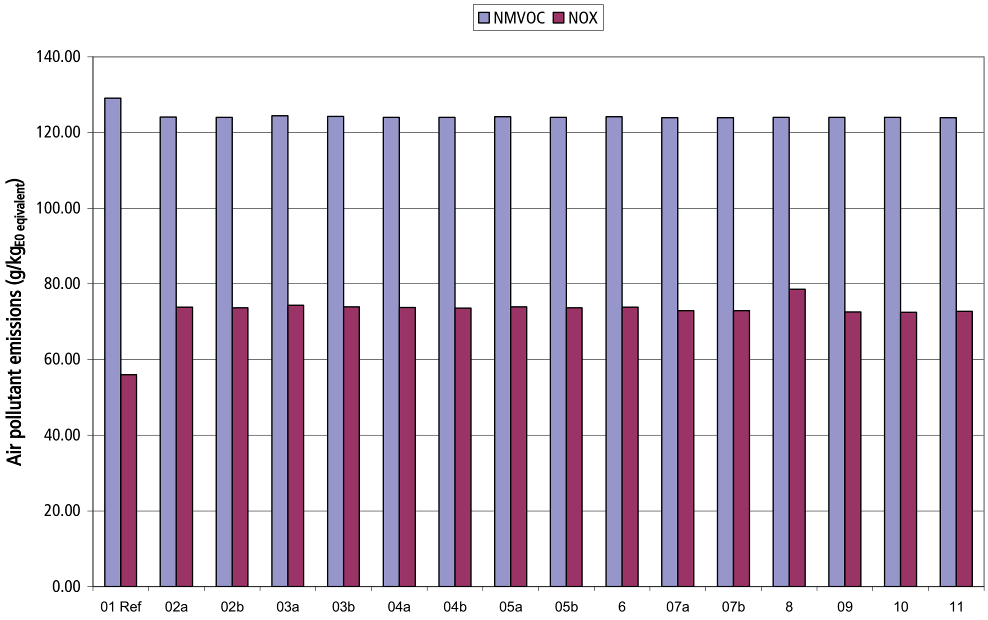

Figure 22: Air pollutant emissions of E10 compared to reference WtP expressed in E0 equivalents

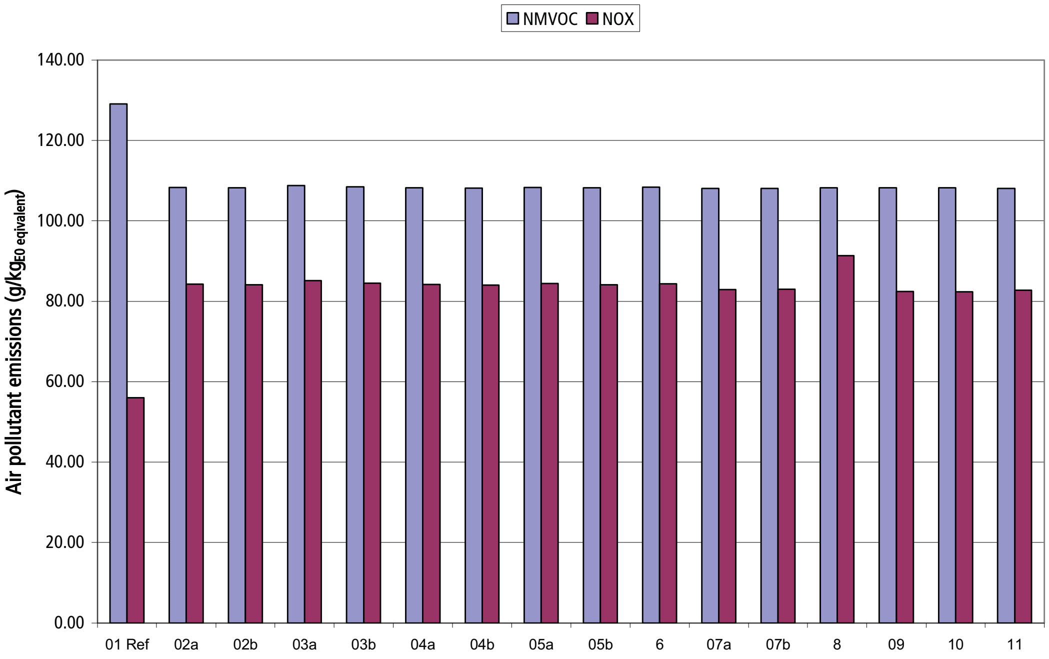

Figure 23: Air pollutant emissions of E15 compared to reference WtP expressed in E0 equivalents

10 LEAD EMISSIONS

When using aviation gas (AVGAS) as fuel, (TtP) emissions of lead (Pb) occur as AVGAS contains about 0.7 g Pb per kg of fuel. The main origin of particulate matter (PM) emissions from gasoline (AVGAS100 LL) fuelled piston engines are the lead particles from the anti-knock agent tetra-ethyl-lead (TEPb). The "Low Lead" (LL) aviation gasoline contains about 0.8 g TEPb per kg of fuel. The particle diameter ranges between 49 and 108 nm.

Table 34: TtP emissions of lead (Pb)

Blend	Mode	Lead	Lead	Lead
		g/kg_{fuel}	g/kWh_{fuel}	$g/kWh_{mech.\ work}$
E0	Idle	0.701	0.058	0.727
E0	Taxi	0.701	0.058	0.412
E0	Take off	0.701	0.058	0.225
E0	Max Cont	0.701	0.058	0.217
E0	Best Eco	0.701	0.058	0.224
E0	Approach	0.701	0.058	0.226
E0	**Total LTO cycle (weighted average)**	**0.701**	**0.058**	**0.272**

According to data from the German Mineralölwirtschaftsverband (MWV)[5], about 15,400 t and 17,400 t of AVGAS have been consumed in Germany in 2007 and 2008, leading to lead emissions of about 11 and 12 t, respectively.

Between 1996 and 2000 the annual consumption of aviation gasoline in Germany did not vary much over the years, amounting to around 25,000 t [Hellrigel 2003]. Assuming that before 2000 no motor gasoline (MOGAS) has been used for aviation, and that the overall consumption level has not significantly changed, it can be concluded that about 10,000 t of MOGAS are being used for aviation. If all aircraft would have to use lead containing aviation gasoline again due to safety issues with too high ethanol content in MOGAS lead emissions in Germany would increase from roughly 11 to 12 t today to about 18 t per year.

It has to be noted that the fuels which contain tetra-ethyl-lead also contain the lead scavengers 1,2-dibromoethane (EDB) and 1,2-dichloroethane (1,2-DCA), which lead to the emissions of dioxins and furans including the most toxic dioxin 2,3,7,8-Tetrachloro-dibenzodioxin (TCDD).

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[5] Statistics available on http://www.mwv.de/cms/front_content.php?idcat=10;
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F Keywords and Abbreviations Index

Abbreviation	**Meaning**
ASTM	American Society for Testing and Materials (see: http://www.astm.org/)
AVGAS	Aviation gasoline: gasoline for aviation purposes, strictly specified with respect to permitted constituents and handling from refinery to aircraft tank. AVGAS is available in different types, mainly discerned by their octane numbers
BtL	Biomass to Liquid (fuels): Fuels or fuel components produced exclusively by general biomass conversion, in contrast to a production exclusively from fruits or smaller distinct parts of vegetables.
CAA	(United Kingdom) Civil Aviation Authority. The abbreviation is, in conjunction with other national relations, also denominating aviation authorities of other countries.
CPE	Chlorinated polyethylene
DGMK	Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. (German Society for Petroleum and Coal Science and Technology, see: http://www.dgmk.de/)
DIPE	Di-isopropyl Ether
DVPE	Dry vapour pressure equivalent. Also see RVP
e/e, m/m, v/v	Abbreviation for energy percentage, mass percentage, volume percentage
E-5, E-10, E-85 etc.	Types of gasoline with respective volumetric shares of ethanol.
ECAC	European Civil Aviation Conference
EN 228	European norm for gasoline properties and compositions
ETBE	Abbreviation for Ethyl-Tertiär-Butyl-Ether. ETBE is a common gasoline admixture serving as octane number booster to reduce the knock tendency of the fuel. It is regarded, due to its chemical production path, as containing 47 % m/m bio-ethanol. DIN EN 228 allows an amount of 15 % v/v in vehicle gasolines. For environmental reasons ETBE nowadays replaces most of the former MTBE (Methyl-Tertiär-Butyl-Ether) admixtures already forbidden in the USA.
Ether	Chemical substance class of specific organic compounds with a characteristic molecular structure. Compared to alcohols (like methanol, ethanol) they exhibit a decisively smaller polarity and are miscible in arbitrary amounts with ordinary gasoline. Most popular delegates are MTBE and ETBE. They are counted (in part) as biogenic if they are produced from respective source materials.
FAA	Federal Aviation Administration of the USA
FBP	Final Boiling Point: Denotes the temperature at which no further evaporation (of a fuel) is observed. A non-volatile residue may remain.
FFV	Flexible Fuel Vehicles: Vehicles that may be operated on (almost) arbitrary mixtures of gasoline and ethanol. At least an ethanol range of up to E85 is covered.

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FMEA	Failure Mode and Effects Analysis
GA	General Aviation
GEW diagram	Ternary diagram for the mixture gasoline – ethanol – water
GHG	[Emissions of] Greenhouse Gases, substances that affect the re-radiation of infra-red wavelengths from earth into space, the most common being CO_2 and CH_4.
LBA	Luftfahrtbundesamt Deutschland (German Aviation Authority)
LCA	Life Cycle Analysis
m/m, v/v, e/e	Abbreviation for mass percentage, volume percentage, energy percentage
MOGAS	Motor gasoline: Officially not sharply defined appellation of vehicle gasoline that is intended for aviation usage. Within this report “mogas” denominates vehicle gasoline conforming to the requirements of most european STC, especially a limitation of its ethanol content to 1 % v/v. Please note that this upper ethanol limit is *not specified / valid* for the majority of recent aircraft that may explicitly be operated on EN 228 specified vehicle fuel.
MON	Motor octane number: measure of engine knock resistance for a fuel under heavy load conditions. For a comprehensive discussion, see page 32.
MTBE	Abbreviation for Methyl-Tertiär-Butylether, a colourless volatile liquid with a characteristic ether smell. It is highly inflammable and explosive. MTBE was predominantly used for octane number boosting in vehicle gasolines. Being quite toxic, it was replaced by ETBE especially in the USA due to environmental reasons.
MTOM	Maximum take off mass
NBR	Nitrile rubber: a very frequently used synthetic elastomer for fuel leading elastic hoses
NTSB	National Transportation Safety Board (an independent U.S. Federal Government Agency, see http://www.ntsb.gov/)
Octane numbers	Measure of engine knock resistance for a fuel. For a comprehensive discussion, see page 32.
Oxygenate	Oxygen-containing fuel additives that reduce the caloric value of the fuel. As examples, the computational mass-related oxygen content is 50 % for methanol, 34.7 % for ethanol, 18.2 % for MTBE, and 15.7 % for ETBE.
RON	Research octane number: measure of engine knock resistance under low load conditions. For a comprehensive discussion, see page 32.
RPN	Risc priority number, see FMEA section, pp. 6.1ff
RVP	The Reid Vapour Pressure is the result of a volatility measurement that has been performed according to internationally standardized procedures. Due to the complex multi-component evaporation properties of common fuel compositions the RVP cannot be identified with a concrete physically interpretable equilibrium vapour pressure, but is recognized as valuable measure for the evaporative properties of aviation gasolines. RVP is frequently used as synonymous for DVPE.

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SIoBiA	Safety Implication of Biofuels in Aviation
STC	Supplementary Type Certificate
TAME	Tertiary amyl methyl ether
TBA	Tertiary butyl alcohol
TEL	Tetra-ethyl-lead. An organic lead compound frequently used for octane number boosting in former times, but incompatible with vehicle catalyzers and therefore banned from ordinary vehicle gasoline. It is still in use for most aviation gasolines.
v/v, e/e, m/m	Abbreviation for volume percentage, energy percentage, mass percentage
VLI	Vapour Lock Index, a number representing the proneness of a fuel to produce dangerous vapour bubbles in the fuel supply system of aircraft.

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