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Preliminary Envelope for Large Transport Aircrafts Operating with Non-Primary Fuels AVGAS, MOGAS and F76-Dieso

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Abstract: This study explores the operational implications and safety considerations of using non-primary fuels—AVGAS, MOGAS, and F76 Dieso—in military transport aircraft, against the backdrop of standard aviation fuels. Through an analysis of fuel properties such as vapor pressure, density, viscosity, freeze temperature, water solubility, and thermal conductivity, this work outlines the operational envelopes for the mentioned non-primary fuels, highlighting the temperature and altitude limitations inherent to their use. The evaluation underscores the necessity of relevant testing, certification, and adherence to operational guidelines and constrains to ensure aircraft safety and reliability when standard fuels are unavailable, and hence, non-primary fuels may be required in special missions under emergency. Key findings include the specific altitude and temperature limitations for AVGAS and MOGAS to prevent fuel freezing and boiling, as well as the operational challenges posed by F76 Dieso due to its higher density and viscosity. The study also addresses the importance of managing water content in the fuel system, the flammability range of the non-primary fuels, and the considerations for fuel mixing to maintain aircraft performance and safety standards. This analysis aims to enhance the understanding of non-primary fuel usage in military transport aircraft, providing insights for system design, performance assessment, and the development of operational procedures to support military aviation in diverse operational scenarios.

Keywords: emergency fuels; operational envelope; fuel properties; military fuel system

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1. Introduction

In the context of aircraft fuel systems, the primary fuels commonly used include Jet A-1 (ASTM D1655-92), Jet B (ASTM D1655-92), JP4 (MIL-T-5624), JP5 (MIL-T-5624), JP8 (MIL-T-83133), and JP8+100 (MIL-DTL-83133). These fuels are classified as primary (or standard) fuels. In military operations, transport aircraft may need to use non-primary fuels, and given the special conditions of their use in emergency cases, such fuels can be also referred to as emergency fuels. Indeed, these fuels become crucial when primary fuels are unavailable during critical operations, enabling aircraft to take off and land at a secure nearby location. The emergency fuels discussed in this study include AVGAS (Aviation gasoline, ASTM D 910-06), MOGAS (Automotive gasoline, STANAG 7090), and F-76 Dieso (Def Stan 91-4/MIL-F-16884). Assessments of these emergency fuels are typically made by comparing their properties to those of standard fuels, thus determining the operational challenges relative to primary fuels. It is important to note that specific characteristics of emergency fuels such as their calorific value, chemical composition, manufacturing methods, performance characteristics, physical properties, and safety and handling procedures are provided in their respective specifications: ASTM D 910-06 for AVGAS, STANAG 7090 for MOGAS, and Def Stan 91-4/MIL-F-16884 for F-76 Dieso.

There are some interesting descriptions concerning the mentioned fuels. Indeed, Jet A-1 is similar to Jet A but with stricter freezing point specifications, suitable for use in regions with colder climates. Jet A and JP 8 are very similar fuels, with Jet A being primarily used in civilian aviation, while JP 8 is a military specification fuel commonly used by both fixed-wing aircraft and helicopters in military operations. JP 8 has similar characteristics to Jet A but with additives to improve its performance and stability under a wider range of operating conditions, including higher temperatures and pressures often encountered in military operations. JP 5 is a high-flash-point aviation fuel primarily used by the U.S. Navy and Marine Corps for shipboard operations and in some land-based aircraft. It has a higher flash point compared to other jet fuels, which reduces the risk of fire in hazardous environments such as aboard aircraft carriers. JP 5 is a specialized fuel formulated to meet the stringent safety requirements of naval aviation operations. JP 4 is a military specification aviation fuel primarily used by the U.S. Air Force for jet-powered aircraft. It is a high-performance fuel designed for use in military operations, including high-speed flight and aerial maneuvers. JP 4 has a relatively low freezing point, making it suitable for use in a wide range of operational environments. These fuels are formulated to meet the specific performance requirements and safety standards of military aviation, so as to ensure reliable and efficient operation of large transport aircraft in various mission scenarios.

In emergency cases, large military transport aircrafts may require the capability to operate with alternative or emergency fuels, like the previously mentioned AVGAS, MOGAS, or F76 Dieso. This capability is vital due to the diverse and sometimes unpredictable operating environments these aircraft encounter, which may limit access to standard aviation fuels.

AVGAS, primarily used in small, piston-engine aircraft, is a high-octane aviation gasoline. In emergency scenarios, AVGAS can be used in military transport aircraft equipped with compatible piston engines. The use of AVGAS in turbine engines, common in larger transport aircraft, is usually not recommended due to its lower flash point and different combustion characteristics compared to jet fuel. However, emergency situations may necessitate its use despite these differences [1]. MOGAS (Motor Gasoline) is another alternative fuel that may be utilized in certain military transport aircraft and under restricted operations. MOGAS is essentially automotive gasoline and can be a viable option for aircraft with engines that can tolerate its lower octane and different additives compared to AVGAS. However, its use is often limited by factors such as availability in remote locations and the need for specific engine modifications or certifications [1]. F76 Dieso, a type of naval distillate fuel, is also considered an emergency fuel for some military aircraft. It is similar to the more commonly used JP-5 or JP-8 in military aviation but has different characteristics, such as a higher flash point. F76 Dieso is typically used in naval vessels but may be utilized in aircraft when necessary and if approved; although, it may affect engine performance and maintenance requirements [2].

In all cases, the use of emergency fuels in military transport aircraft is governed by strict regulations and standards to ensure safety and aircraft performance. Aircraft manufacturers and military organizations typically conduct extensive testing and certification processes to determine the suitability and operational limitations of using these fuels. These tests assess factors such as engine performance, fuel system compatibility and the potential impact on aircraft maintenance and operational life [1]. Moreover, the logistics of fuel supply in military operations often necessitate the consideration of emergency fuels. In austere or remote environments, where standard or primary aviation fuels are not available, the ability to use alternatives like AVGAS, MOGAS, or F76 Dieso can be crucial to reach a secure zone. This flexibility allows military transport aircraft to operate across a wider range of scenarios, ensuring operational readiness and effectiveness.

In summary, although standard aviation fuels remain the primary choice for military transport aircraft, the ability to utilize emergency fuels such as AVGAS, MOGAS, or F-76 Dieso is a critical component of military aviation. This capability ensures operational flexibility and readiness under various circumstances. However, using these emergency fuels requires careful consideration of factors such as aircraft performance, safety, and maintenance needs. At aircraft and fuel system design levels, it is typical to consider a design requirement stating the need of a military transport aircraft to operate with the mentioned emergency fuels. Military transport aircraft fuel systems may be engineered to function with these emergency fuels without the need to meet the operational or performance criteria set for primary fuels. The only criterion is the aircraft's capability to function with these fuels, acknowledging the limitations imposed by their physical characteristics.

2. Scope of the Analysis

In the context of military transport aircraft, the qualification of emergency fuels like AVGAS, MOGAS, or F76 Dieso involves a comprehensive process that includes both equipment qualification and an analysis based on the fuel properties and data provided by equipment suppliers. This process is critical for ensuring that the aircraft's fuel system can efficiently and safely handle different types of fuels, especially in situations where standard fuels are not available. The evaluation of a military transport aircraft's fluid mechanical system with respect to emergency fuels is a key part of this process. It involves assessing how the fuel system performs when utilizing these non-primary fuels. The results from such evaluations are essential for developing a system clearance report. This report defines the operational limitations of the aircraft's fuel system when using emergency fuels, ensuring that these limitations are within the safe operating parameters established during the aircraft's type certification. This approach to compliance and safety closely parallels the procedures used during ground and flight testing for type certification. These tests are designed to assess the aircraft's performance and safety under various conditions, including the use of different fuel types. The data gathered from these tests are crucial for understanding how the aircraft will behave in real-world scenarios, thereby ensuring the safety and reliability of the aircraft under diverse operational conditions. It is important to note that such assessments typically focus on the performance and safety aspects of using emergency fuels and may not cover other aspects like fuel management systems, which are often evaluated separately.

In this study, we aim to analyze the limitations in temperature and altitude when operating with emergency fuels. As mentioned, the characteristics of these emergency fuels differ significantly from primary fuels. Therefore, it is necessary to examine how the properties of these fuels directly affect the operational envelope of the aircraft to assess their viability. This viability in the use of emergency fuels is solely based on the analysis of their physical properties with potential impact on the envelope. Thus, our analysis does not focus on verifying the performance of the engine or the fuel system (such as pumps or measurement systems). Instead, we focus on defining a preliminary aircraft envelope in terms of temperature and altitude based on the inherent properties of the emergency fuels.

3. Methodology

The methodology for emergency fuel clearance involves a detailed comparative analysis with primary fuels. The approach is inherently conservative, prioritizing the evaluation of worst-case scenarios to ensure thorough coverage and robust safety measures under all operational conditions. This methodical analysis is essential and a substantial part for ascertaining the system's reliability and efficiency when using emergency fuels. Specifically, by employing comparison strategies with already approved primary fuels, we establish a solid reference point to determine the operational envelope of the aircraft. However, it is important to reiterate that the analysis presented in this study is a first step towards understanding the limitations in the aircraft envelope introduced by emergency fuels. With this notion in mind, it will be necessary to subsequently verify the performance of the fuel pumps, fuel measurement systems, and the engine itself. To ensure safety and system integrity, specific operational restrictions can be applied. These restrictions might include limitations on power, time, and altitude and are designed to mitigate any potential negative impacts on the aircraft's fuel system. The approach is to establish a balance between operational flexibility and maintaining the highest safety standards.

The assessment to come is based on several general assumptions and exclusions. Flight conditions are considered under $1g$ loading unless specified otherwise. The performance of emergency fuels is not expected to exceed that of a kind of JP4 fuel (which is actually the most volatile fuel of those targeted as primary); if they do, JP4 limits will be applied.

Ambient conditions are based on International Standard Atmosphere (ISA) data. Emergency fuels are preliminary required to meet the same temperature range requirements as primary fuels. It is also assumed that unleaded AVGAS has the same vapor pressure as MOGAS, leading to the application of MOGAS limits on unleaded AVGAS. Indeed, this approach is overly conservative.

Exclusions from this assessment include aerial refueling (both receiving and delivering), interactions between Ground Support Equipment and emergency fuels, and consideration of the fuel system's Fuel Quantity Management System. The Inerting System's clearance is not covered, as this system may limit the fuel system's emergency fuel clearance capabilities significantly. Aerodynamic heating of the aircraft structure is not considered, as the temperatures will be provided based on aircraft envelope and fuel properties associated with temperature (like the boiling point). In addition, it is typical that large transport military aircraft host a Cargo Hold Tank located in the cabin or cargo compartments. Our analyses do not consider the installation of any Cargo Hold Tank.

4. Fuel Properties

The clearance of fuel systems in aircraft, particularly for emergency fuels, hinges on a comprehensive understanding of various fuel properties and their implications on system design and safety. The key fuel properties considered for system assessment include vapor pressure, density, viscosity, freeze temperature, water solubility, and thermal conductivity. Each of these properties plays a relevant role in determining the fuel's behavior and compatibility with the aircraft's fuel system.

1. Vapor Pressure: This is significant as it affects the fuel boil temperature and the pumps' ability to pressurize fuel without causing cavitation or vapor lock.
2. Density: It influences the optimal flow rate of fuel delivery and affects the vent system's ability to prevent over-pressurization.
3. Viscosity: The thickness of the fuel impacts its flow rate and the efficiency of the fuel supply.
4. Freeze Temperature: This property determines the minimum operating fuel temperature, crucial for cold-weather operations.
5. Water Solubility: It is vital for understanding the impact of water in the fuel system, including potential ice formation and the need for water drainage over extended storage periods.
6. Thermal Conductivity: It defines how the fuel interacts with the surrounding environmental temperature, gaining or losing heat.

The assessment aims to bracket the emergency fuels within the parameters set by the primary fuels, ensuring that the emergency fuels' properties are no worse than those already cleared. This approach involves a comparative study, where a read-across from existing primary fuels is possible, or an analytical assessment is required if the emergency fuels' properties differ significantly.

In designing aircraft fuel systems, considerations for safety, compatibility, reliability, and maintainability are paramount. For further details on fuel characteristics and their implications in aircraft fuel system design, the reader is referred to [1,3], where an extensive overview of fuel properties, system requirements, and safety considerations in aircraft design are provided. In the presented work, we adhere to these principles to ensure a robust analysis compliance with an appropriate level of safety margins.

5. Emergency Fuel Basic Data and First Operational Envelopes

The fuel properties for AVGAS, MOGAS, and F76 Dieso shall be carefully selected to avoid non-accurate conclusions at the analysis stage. It is important to note that, with the exception of AVGAS, these fuels are not traditionally intended for use as aircraft fuel. Consequently, the complete dataset required for aerospace applications may not be readily available for these fuels. To address this, the properties of these fuels have been compared to those of existing primary fuels, with data extrapolated as necessary. The fuel property data presented are considered to be the most accurate available at the time of writing, albeit being based on a series of outlined assumptions.

It is also observed that each fuel property has a range of data and this is particularly noticeable for some properties, which may reflect the different distillates of the fuel, such as summer and winter variants. In these instances, the assessment assumes the worst-case scenario for fuel properties. Additionally, it is highlighted that unleaded AVGAS has distinct properties compared to standard leaded AVGAS. Based on the analysis, unleaded AVGAS is recommended to be considered with a vapor pressure akin to that of MOGAS. Therefore, in this assessment, unleaded AVGAS is treated similarly to MOGAS, and this is actually conservative for our analysis.

Figure 1 presents the density measurements of the approved primary fuels and the emergency fuels across temperatures ranging from −50 °C to +50 °C. The data for the three emergency fuels are shown as a range, reflecting the minimum and maximum densities reported. For the purposes of this analysis, the highest density value is considered for each fuel to prepare for the worst-case scenario. In comparison to the already approved primary fuels (see reference [4] for additional details), F76 Dieso exhibits a higher density, while AVGAS and MOGAS (at its lowest density value) display lower densities. Since the densities of the emergency fuels do not fall within the range of the primary fuels, direct comparisons cannot be made without additional analysis.

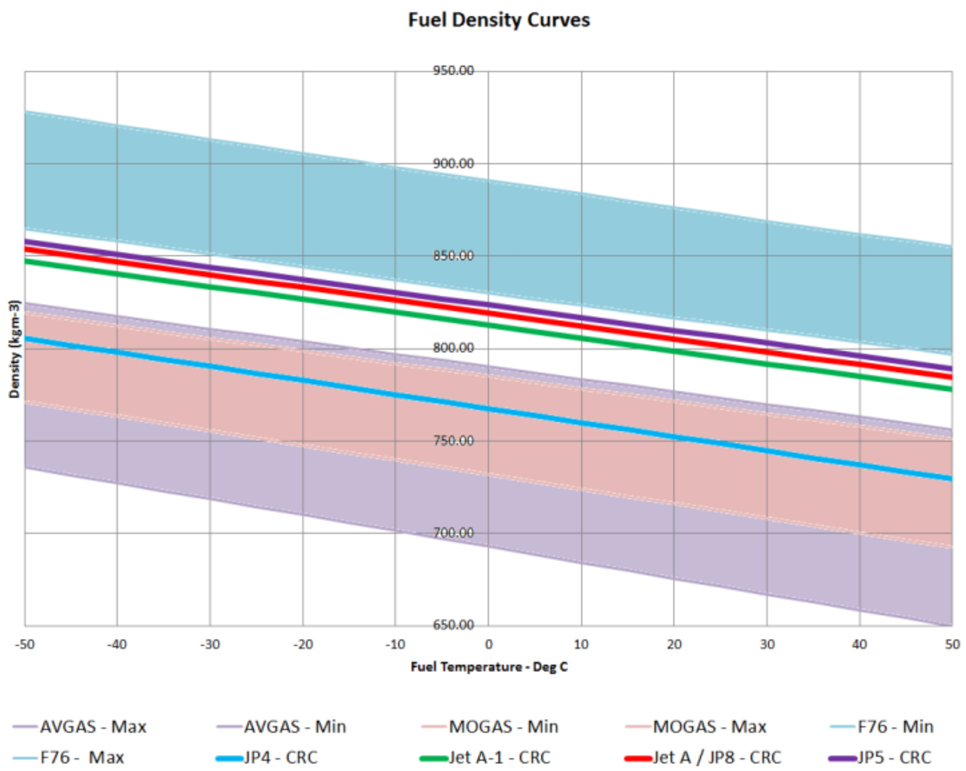

Figure 1. Fuel Density properties to be considered for our analysis.

Figure 2 extracts data on the viscosity of standard aviation fuels from the CRC 635 fuel handbook [4] and includes specific data for AVGAS and F76 Dieso. It notes the absence of specific viscosity data for MOGAS in the specification STANAG 7090, yet it is inferred that MOGAS shares a similar viscosity profile with AVGAS. Consequently, for the purpose of this assessment, MOGAS and AVGAS are considered to have identical viscosity characteristics. The graph also delineates a viscosity range for F76 Dieso, reflecting its documented maximum and minimum values, with an assumption made here that F76 Dieso exhibits its highest viscosity. It is important to mention that temperatures below −3 °C are not considered for F76 Dieso due to its minimum pour point. In comparison to the primary fuels, F76 Dieso shows a significantly higher viscosity, while AVGAS and MOGAS's viscosity levels are positioned between those of JP4 and Jet A-1 fuels.

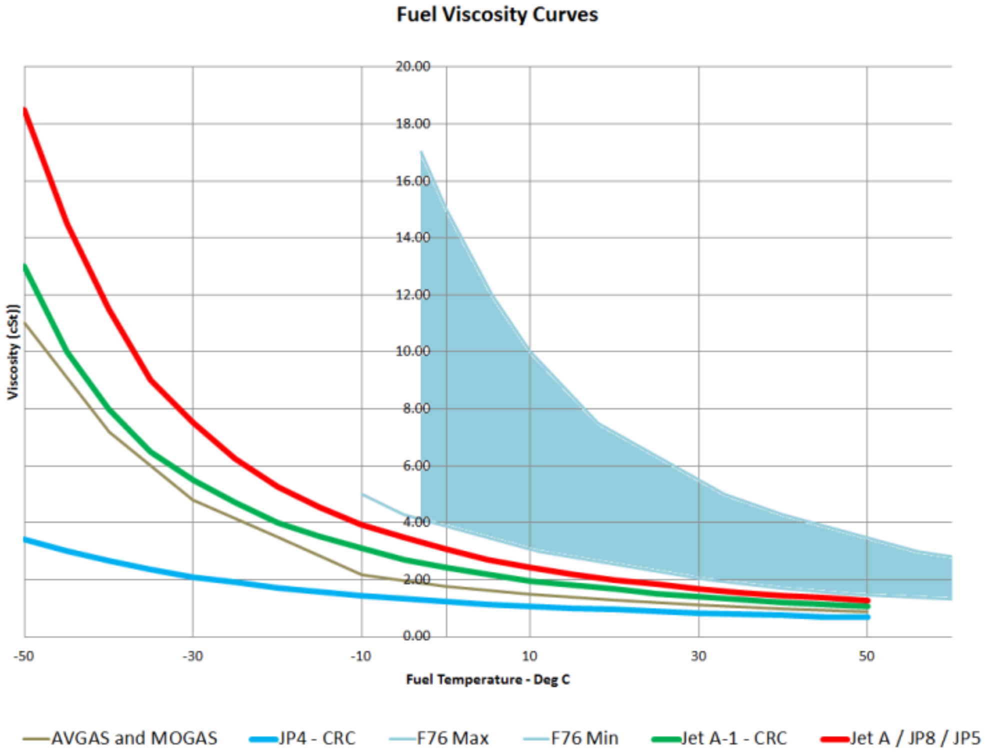

Figure 2. Fuel viscosity properties to be considered for our analysis.

Figure 3 details the fuel volatility of the currently cleared primary fuel JP4 and the emergency fuels AVGAS and MOGAS from the range of −50 °C to +50 °C. The data for AVGAS and MOGAS are taken from their respective specification as detailed in Section 3. Vapor pressure information on F76 Dieso is not available, but we consider that the vapor pressure of F76 Dieso is lower than that for Jet A-1. However the graph shows that compared with JP4, AVGAS, and MOGAS are considerably more volatile.

The operational limits for using emergency fuels are primarily determined by their freeze and boil temperatures. Typically, any fuel system is designed to operate with primary fuels adhering to a specified fuel temperature range. The minimum temperature is set at either −54 °C or the fuel's freezing point, whichever is higher, and the maximum temperature must not exceed +55 °C or 5 °C below the fuel's boiling point, whichever is lower. These criteria are also applied to emergency fuels, with their freeze and boil temperatures (−5 °C) establishing the initial boundaries for fuel temperature and altitude operation.

For AVGAS, its freezing point is identified at −58 °C, below the −54 °C operational minimum and the freezing points of approved Jet A-1 and Jet A fuels, meaning AVGAS's freezing point does not limit the aircraft's current flight envelope. MOGAS specification lacks a specific freeze temperature in the documentation, but a minimum operational temperature of −18 °C has been assigned, considerably higher than the freeze temperatures for Jet A-1, Jet A, and the −54 °C minimum stated in the technical specifications. Thus, MOGAS operations are restricted to temperatures not lower than −18 °C. F76 Dieso's freeze temperature is not directly provided, but with cloud and pour points at −1 °C and −3 °C, respectively, the cloud point is considered the operational minimum temperature. This temperature significantly exceeds the freeze temperatures of Jet A-1 and Jet A and the specified −54 °C minimum, restricting F76 Dieso operations to temperatures above −1 °C.

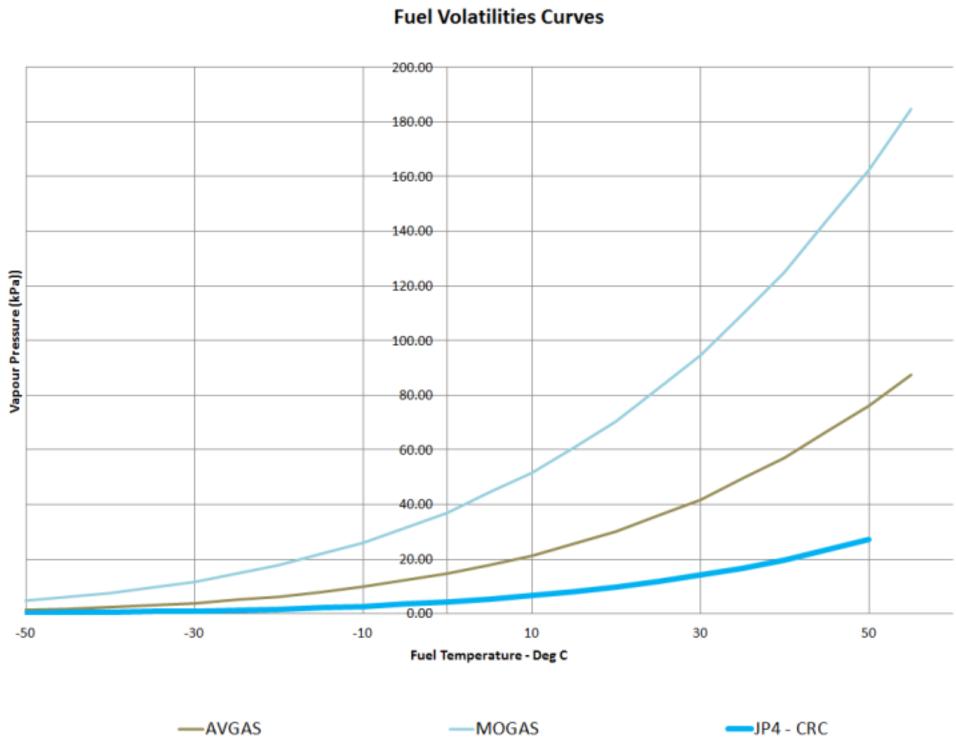

Figure 3. Fuel volatility properties to be considered for our analysis.

Regarding boil points, AVGAS and MOGAS are expected to boil with altitude because of decreased ambient pressure, necessitating then an evaluation of the maximum allowable altitude and temperature. F76 Dieso, conversely, mirrors the boiling temperature range of Jet A, suggesting it will not boil across the aircraft's flight envelope. The volatility of AVGAS and MOGAS is analyzed against the standard atmosphere pressure data to pinpoint the highest permissible fuel temperature at each altitude level, accounting for a mandatory 5 °C safety margin below the boiling point. Consequently, the maximum assessed fuel temperature for AVGAS and MOGAS is set at 50 °C, considering that the vapor pressure data extends up to 55 °C, thus requiring a 5 °C deduction once the boiling point is approached.

The flight envelope is determined by the boiling (refer to Table 1) and freezing temperatures of the emergency fuels. Figures 4–6 illustrate this operational envelope, factoring in both the freezing and boiling points (Table 1) of the fuels. Additionally, these plots include the International Standard Atmosphere (ISA) temperature profile, providing an expected ambient temperature at various altitudes. This approach offers a comprehensive view of how fuel properties influence the aircraft's permissible operational ranges.

Table 1. Emergency fuel boiling temperatures.

Altitude (Ft)	AVGAS Boil Temp (°C)	MOGAS Boil Temp (°C)
−2000	50	30
0	50	27
5000	49	21
10,000	42	15
15,000	35	8
20,000	28	2
25,000	21	−5
30,000	15	−11
35,000	8	−18
40,000	1	−24
45,000	−5	−31

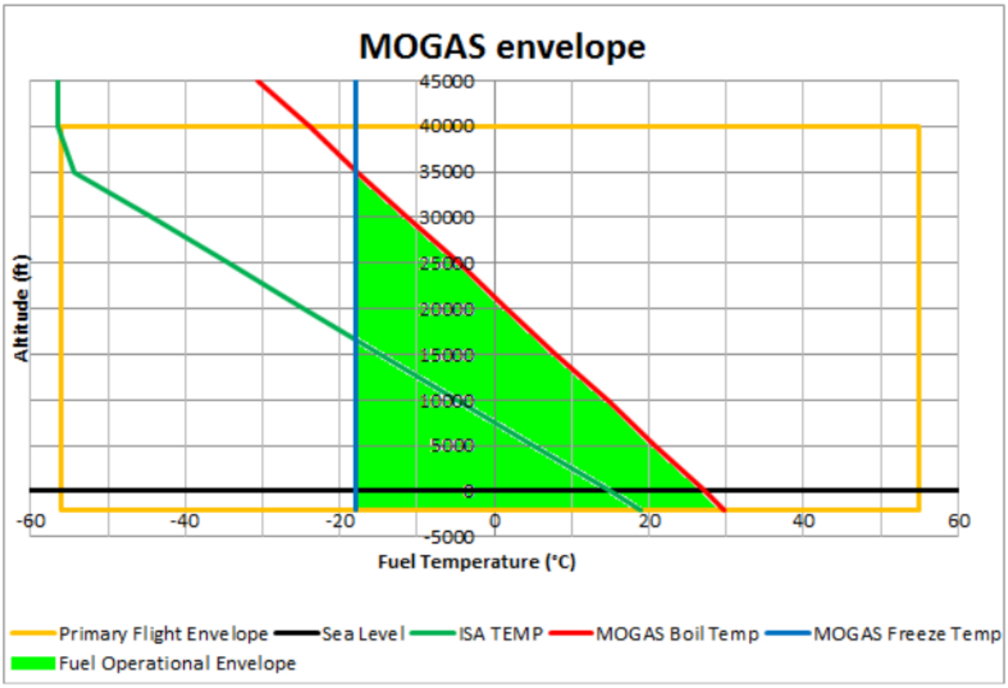

Figure 4. MOGAS boil and freeze envelope.

MOGAS operates within a limited flight envelope, peaking at an altitude of about 35,000 feet. It is observed that the ISA temperature drops below the minimum operational temperature of the fuel at altitudes exceeding 16,000 feet. Therefore, during flights above this altitude, the ambient temperature will gradually decrease the fuel temperature to below its operational minimum, affecting its performance.

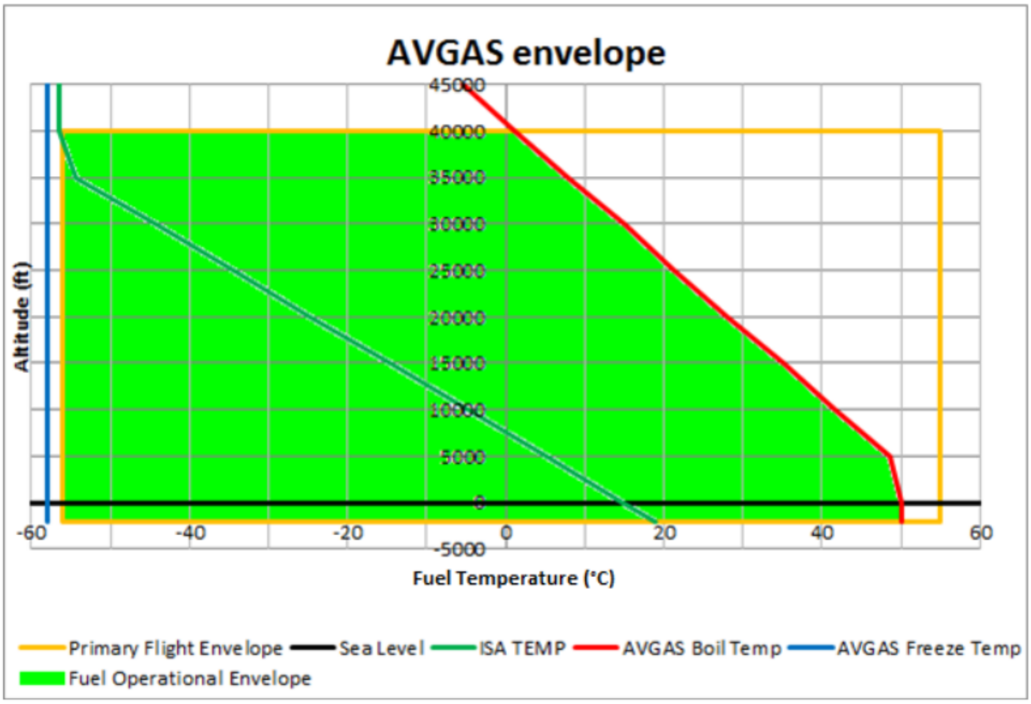

Figure 5. AVGAS boil and freeze envelope.

AVGAS boasts the most extensive operational range among the three fuels, extending up to 40,000 feet. Within the operational envelope, the ambient temperatures, as defined by the International Standard Atmosphere (ISA), remain above AVGAS's minimum fuel temperature threshold, ensuring its suitability across the aircraft's entire flight capability.

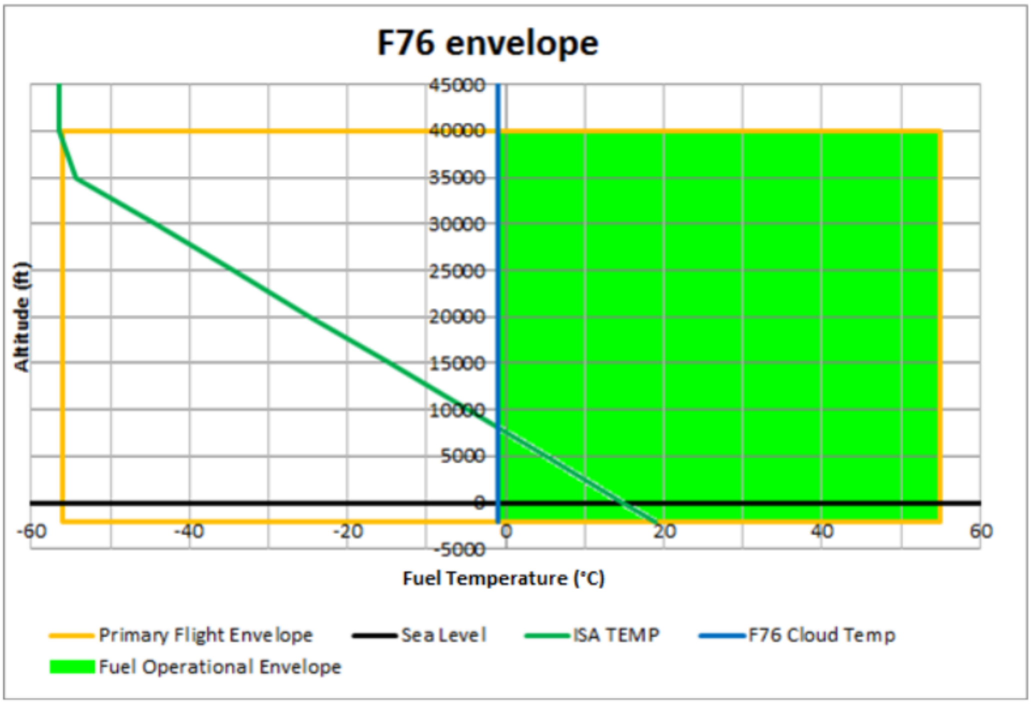

Figure 6. F76 . boil and freeze envelope.

F76 Dieso's operational range extends up to 40,000 feet, albeit with a constraint that temperatures must remain above −1 °C. It is observed that at altitudes beyond approximately 8000 feet, the ambient temperature, according to the International Standard Atmosphere (ISA), falls below the minimum allowable fuel temperature. Consequently, during flights at or above this altitude, the external temperature will gradually lower the fuel temperature below its freezing point, impacting its usability.

5.1. Thermal Conductivity Property

Regarding the thermal conductivity of emergency fuels, we shall refer to the CRC Handbook which indicates that all hydrocarbon fuels, including the primary fuels and the proposed as emergency fuels, have the same thermal conductivity. Therefore, it is considered in a first view that the emergency fuels will cool or heat similarly to the existing primary fuels.

5.2. Water Solubility

The civil requirements delineated in "CS25.951" of [5] state that each fuel system must function continuously across its entire flow and pressure range when utilizing fuel that is initially saturated with water at 26.7 °C (80 °F) with an additional 0.20 cm^3 (0.75 cc) of free water per litre (US gallon) added, then cooled to the most critical icing condition likely encountered during operations. In the experience of the author, during the design phase of large transport aircrafts (including military ones), it is common to consider a maximum water concentration of 260 ppm by volume. This interpretation is based on a fixed free water content of 0.20 cm^3 per liter (equivalent to 200 ppm by volume) plus the saturated water content at 26.7 °C, approximating to 60 ppm by volume for Jet-A fuels. To comply with this requirement for emergency fuels, their saturated water content at 26.7 °C must be evaluated, and this value combined with the free water content (200 ppm by volume) to ascertain the total water content.

The water solubility of AVGAS is lower than that of Jet-A and significantly less than Jet B. We also mention that the percentage of aromatics in AVGAS can vary, potentially leading to higher water concentrations than in Jet-A. Operational guidelines to manage water content when utilizing AVGAS are provided at the end of this section.

No data on the saturated water content of MOGAS or F76 Dieso are mentioned in their specifications. Nonetheless and according to [6], the diesel saturation point is of a maximum of 255 mg/kg at 313.15 K. In addition, the study [7] examines how water interacts with both conventional and alternative jet fuels, focusing on water solubility, settling rates, and interfacial tension to aid in fuel management and mitigation strategies. Key findings include a positive, nonlinear correlation between water solubility and both the aromatic content of the fuel and temperature (ranging from 0 to 50 °C). The settling rates of water in fuel align with Stokes' law, suggesting that the fuel's bulk chemical composition indirectly affects these rates through variations in density and viscosity. Additionally, there is a positive correlation between the surface tension of the fuel and its density, while interfacial tension depends on both the surface tension and the aromatic content of the fuel. Indeed, the aromatic content in fuels can serve as a basis to estimate their saturated water content. In this document, we propose an estimation of the saturated water content in fuels. This estimation is based on a model for predicting the solubility of water in fuels based on temperature and the content of aromatic hydrocarbons. The model considers an exponential relationship between water solubility (S) and temperature (T), where S increases with temperature according to a base constant (a) and an exponent coefficient (b) (refer to [7,8] for additional insights). Both a and b are functions of the aromatic hydrocarbon content (α), indicating that the presence of aromatic hydrocarbons affects the solubility of water in the fuel. The equations for a and b suggest that as the aromatic content increases, the base constant and the exponent coefficient adjust accordingly to model the impact on water solubility. Then, it holds that

$$S = a \times \exp(b \times T) \tag{1}$$

where

- S = water solubility (ppm (m/m));
- T = temperature (°C);
- a = base constant;
- b = exponent coefficient.

Constants a and b are determined using fitting equations considering raw data extracted from the field and following Equations (3) and (4). represented in the study [7]

$$a = 1.1327\alpha + 9.2721 \tag{2}$$

$$b = -0.00066782\alpha + 0.058620 \tag{3}$$

where

- α = aromatic hydrocarbon content (% by volume).

We consider that MOGAS may contain up to 35% by volume of aromatic hydrocarbons. In contrast, we note that the ASTM-D5186 method (see [9]) assessed the aromatic content of commercially available diesel to be 20.23% (by volume assumed), offering an approximation for F76 Dieso.

Thus, for MOGAS fuels with 35% (by volume) aromatic content and F76 Dieso with 20.23% (by volume) aromatic content, the calculations yield

- For MOGAS, $a = 48.92$ and $b = 0.035$;
- For F76 Dieso, $a = 32.19$ and $b = 0.045$.

Using Equation (1) at 26.7°C, the water solubility (S) for MOGAS is approximately 125 ppm m/m, and for F76 Dieso, it is about 106 ppm (m/m). Considering the worst-case densities of MOGAS and F76 Dieso at 767 kgm^{-3} and 871 kgm^{-3}, respectively, the water solubility per unit volume rounds up to 96 ppm (v/v) for MOGAS and 93 ppm (v/v) for F76 Dieso. Adding the 200 ppm (v/v) of free water results in total water contents of 296 ppm (v/v) for MOGAS and 293 ppm (v/v) for F76 Dieso, exceeding the 260 ppm (v/v) maximum requirement.

To address water contamination in fuel and ensure compliance with the "CS25.951" requirement (refer to [5]), it is important to implement procedures that effectively remove water from the fuel system. The presence of water in fuel can lead to engine damage, reduced efficiency, and operational issues. Some typical methods to detect water contamination involve checking for water droplets or separated layers in the fuel filter or drained fuel, as well as looking for moisture or condensation within the fuel tank.

5.3. Consideration for Fuel Mixing

In the operation of large transport aircraft, the utilization of various fuel types can lead to the amalgamation of different fuels within the fuel system. When emergency fuels are utilized and subsequently followed by primary fuels, the resulting mixture can influence the expected performance parameters of the aircraft during operation on primary fuels. It is also observed that this blending of fuels may extend the flammability range, thereby increasing the risk of an explosive environment within the fuel tank's ullage.

In scenarios necessitating emergency fuel usage, combining primary and emergency fuels is deemed acceptable, with the understanding that the aircraft's performance should not deteriorate beyond the levels observed with emergency fuels alone. Nonetheless, to maintain adherence to the fuel system specifications for primary fuels, it is advisable to cleanse the aircraft's fuel tanks of any residual emergency fuels before transitioning back to primary fuel usage. This precaution ensures that the fuel system's integrity and performance criteria are upheld during regular operations.

6. Fuel Flammability

The flammability range, as provided in Table 2, indicates the conditions under which a fuel/air mixture in the fuel tank's ullage (the space above the liquid fuel) becomes explosive upon introduction of an ignition source. A mixture outside this range is either too rich (upper limit) or too lean (lower limit) to ignite. The explosiveness of the ullage varies with changes in aircraft altitude and fuel temperature, affecting the fuel/air ratio.

Table 2. Flammability limits for primary and emergency fuels. The lower (lean) and upper (rich) limits are given in (Vol %). The fuel temperatures are given in (ºC) at a pressure of 1 atm.

Fuel Types	Lower Limit	Upper Limit	Lower Fuel Temp	Upper Fuel Temp
MOGAS	0.0	7.0	−58	−4
AVGAS	1.2	7.0	−44	−12
Jet B / JP-4	1.3	8	−23	18
F76 Dieso	0.6	0.47	57	102
Jet A / JP-8	0.6	4.7	57	77
JP-5	0.6	0.46	64	102

Table 2 compares the flammability limits of primary and emergency fuels, drawing data from the CRC Handbook [4] and information compiled by the author based on each emergency fuel specification (ASTM D 910-06, STANAG 7090 and Def Stan 91-4/MIL-F-16884). The fuels are ranked by their flammability temperature ranges, from the lowest to the highest. It is important to note that the data represents fuel vapors in equilibrium with the liquid phase in a sealed environment at atmospheric pressure, and dynamic effects could cause variations. Thus, the table primarily serves as a comparative tool between primary and emergency fuels.

AVGAS and MOGAS are found to have similar flammability properties. Their flammability limits occur at lower temperatures compared to AVTUR (aviation turbine fuel), aligning more closely with AVTAG fuels like Jet B. F76 Dieso exhibits a higher flammability range, akin to Jet A fuel.

Additionally, in the design of large transport aircraft, assessing the fuel system's ability to resist direct lightning strikes and Electrostatic Discharge (ESD) is a critical safety consideration. This evaluation is integral to ensuring the aircraft's operational integrity under various environmental conditions. Such aircraft undergo comprehensive testing to certify their resistance to ESD, employing simulations of the worst-case conductivity scenarios. These tests are designed to confirm the safety of the fuel system, especially when using emergency fuels, by demonstrating its capability to manage the risks associated with ESD effectively.

However, configurations that include Flight Test Installations (FTIs) and are governed by an Aircraft Configuration List (ACL) may impose specific restrictions on fuel conductivity. For example, there may be a prohibition against using fuels with conductivity lower than a certain threshold, such as 50pS/m. This restriction aims to mitigate the risks associated with low fuel conductivity, which can increase the aircraft's susceptibility to ESD and lightning effects. Consequently, aircraft adhering to such ACL guidelines are precluded from using certain emergency fuels that fail to meet these conductivity requirements.

7. Conclusions

This study emphasized the importance of assessing the operational constraints associated with using emergency fuels such as AVGAS, MOGAS, and F76 Dieso in military transport aircraft. AVGAS and MOGAS demonstrated potential for use in emergency scenarios, though with specific altitude and temperature limitations to prevent fuel freezing and boiling. F76 Dieso, with its higher density and viscosity, required careful consideration of its freeze temperature to maintain performance. The study also highlighted the importance of managing fuel temperature within operational limits to avoid adverse impacts on aircraft performance. Further, the analysis addressed issues such as thermal conductivity, water solubility, and fuel flammability. The equal thermal conductivity of emergency and primary fuels suggested similar cooling or heating rates, while the water solubility analysis indicated challenges in managing water content within the fuel system, necessitating effective water removal strategies. The flammability range analysis illustrated the need to manage ullage conditions to prevent explosive environments, particularly when transitioning between fuel types. The considerations for fuel mixing underscored the practical aspects of using emergency fuels, stressing the importance of purging the fuel system of emergency fuels before returning to primary fuel use. This approach ensured that the blending of fuels did not compromise the aircraft's operational integrity or expected performance parameters. For future research, it is imperative to conduct further experimental validation to better understand the specific behaviors of these emergency fuels under varied operational conditions. Long-term performance evaluations are also necessary to assess the sustainability and reliability of using these fuels over extended periods. Additionally, assessing the environmental impact of these emergency fuels will be crucial in understanding their broader implications on military operations and sustainability. This future research will help solidify the framework for using emergency fuels in military aircraft, ensuring safety, efficiency, and environmental stewardship.

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