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SYSTEM SAFETY-BASED SUSTAINABLE AVIATION FUEL SAFETY ASSESSMENT METHOD AND AIRWORTHINESS CERTIFICATION

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Abstract

The current certification process related to sustainable aviation fuel (SAF) has some problems to be solved, such as high testing costs, high testing fuel consumption, and the lack of safety criteria. In this paper, we proposed a system safety-based SAF safety assessment method and also offered a certification process for engine system safety. With the system safety of the engine as the top-level objective, the proposed method upgrades the similarity check from the fuel level to the engine level in the certification process. Not only the Safety Critical Parameters (SCP) are defined in this method, but also the SCP boundary for aviation kerosene is also used as a safety criterion for determining the safety of the SAF at the engine level. The adoption of the fuel technical standard orders (TSO) certification mode furthered the innovative concept of sustainable fuels as a special component of aero-engines, leveraging the experience of aviation kerosene operations and reducing certification costs. The certification process we proposed is capable of improving certification efficiency, reducing testing costs, and unlocking the potential of fuel components while maintaining system safety levels.

Keywords: System Safety; Airworthiness Certification; Sustainable Aviation Fuel; Safety Critical Parameter

1. Introduction

As civil aviation gradually becomes one of the main means of transportation for human beings to travel long distances, energy crisis, and environmental pollution gradually become major challenges that cannot be ignored by the aviation industry. The global aviation industry produced 915 million tons of CO2 in 2019 (before the COVID-19 outbreak), accounting for over 2.1% of all human-induced CO2 emissions. Within the transportation sector, aviation contributes 12 percent of CO2 emissions from all transportation sources [1]. Besides, passenger demand continues to grow rapidly, with a nearly 5% growth in revenue passenger kilometers (RPK) per year around the world [2][3]. It can be inferred that the global demand may be over 40,000 billion RPK in 2050, which would lead to global direct CO2 emissions of about 2500 million tons [4] barring any radical change to the aircraft technology, thus, the aviation carbon emissions reduction has gradually become a focus for researchers, policy-makers and international organizations [5].

Alternative aviation fuel (AAF) is treated as one of the potential solutions to achieve aviation carbon emissions reduction. The demand for alternative aviation fuels (AAF) in the aviation industry has increased significantly due to concerns over emissions. For the past years, there have been many active efforts to promote AAF research in several countries. However, the use of various aviation alternative fuels has fallen far short of expectations, including but not limited to sustainable aviation fuel (SAF), aviation kerosene still dominates the aviation fuel market. One of the reasons for this situation is that the current airworthiness certification process is not feasible for alternative aviation fuels due to the high testing costs, high testing fuel consumption, and the lack of safety criteria. As a result, few types of approved fuel are still difficult to be widely used because of restricted use conditions, insufficient safety assurance, and the cost of use which is far more than original aviation kerosene.

Airworthiness regulations are regulatory documents, which make a fundamental requirement for aviation safety. The FAR-33 Airworthiness Standards for Aircraft Engines [6], developed by the American Federal Aviation Administration (FAA), is one of the main representatives of aircraft engine airworthiness regulations. Due to the low demand for alternative fuels in the last few decades, current aero-engine airworthiness regulations, represented by FAR-33, do not consider alternative fuels certification. The regulation makers defaulted to the fact that aircraft would use a few types of aviation kerosene with a high degree of standardization. In practice, SAF is certified by organizations such as the American Society for Testing and Materials (ASTM) from the perspective of fuel components and physicochemical properties. In this way, it is difficult to ensure fuel safety requirements at the engine level.

To promote the development of SAF, and improve the safety level of engine systems for SAF applications, while unlocking the potential of SAF at the component and physicochemical property level, we will start with the certification process and assessment tools, and sort out the shortcomings of the alternative fuel assessment process in this paper. Based on the experience of using aviation kerosene, we will refine the criteria for determining the safety of alternative fuels in aviation engines, and establish the airworthiness certification system and safety assessment methods at the aero-engine level from the perspective of system safety.

2. Overview of current certification standards for SAF

2.1 The necessity of SAF airworthiness standards research

The aviation industry is identified as one of the most energy-consuming and pollution-intensive sectors [7]. In 2009, the International Civil Aviation Organization (ICAO) held the first Conference on Aviation and Alternative Fuels (CAAF), which endorsed the use of sustainable alternative fuels for aviation as an important means of reducing aviation emissions and established the ICAO Global Framework for Aviation Alternative Fuels (GFAAF). The International Air Transport Association (IATA) implemented a vigorous policy with three short-term and long-term goals for the global aviation sector: generating an annual energy efficiency improvement by 1.5% before 2020, achieving carbon neutral growth by 2020, and reducing 50% carbon emissions by 2050 compared to 2005 [8]. In 2013, the 38th of ICAO announced a series of measures to ensure carbon neutral growth targets for the aviation industry, including a major expansion of SAF applications for aviation [9]. In 2016, the 39th conference of the ICAO officially adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), forming the first global industry emission reduction market mechanism (ICAO, 2016) [10]. Appeals from international organizations such as ICAO and IATA have led to a growing focus on aviation carbon emissions. 121 states have voluntarily submitted their state action plan on emissions reduction to ICAO.

As emissions reduction targets loom, the aviation industry urgently needs new sources of power. SAF is emerging as a major approach to address aviation carbon emissions due to its advantages in moderate energy density, compatibility with existing aerodynamics, etc. The Volumetric Energy Density of fuel is more than ten times higher than that of lithium-ion batteries and about six times higher than that of compressed hydrogen (70MPa) [11][12]. At the Committee on Aviation Environmental Protection (CAEP) meeting in September 2017, it was proposed that aviation alternative fuels "must meet sustainability" based on satisfying technical specifications, i.e., SAF [13]. IATA estimates that the SAF will make about 65% contribution to achieving Net Zero Carbon in 2050 [14].

2.2 Current SAF Certification Process

In the last decade or so, countries have been continuously issuing and iterating alternative fuel-related regulations and certification processes. The most representative of these are ASTM-D7566 [15], a standard for synthetic hydrocarbon fuels published by the ASTM, and ASTM-D4054 [16], a standard for certification and approval processes for new aviation turbine fuels.

ASTM-D7566 reviews of physicochemical Specifications for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. As shown in Figure 1, the document provides boundary constraints for aviation turbine fuels containing synthetic hydrocarbons from dozens of physicochemical properties such as composition, volatility, fluidity, corrosion, and thermal stability.

TABLE 1 Detailed Requirements of Aviation Turbine Fuels Containing Synthesized Hydrocarbons[A]

Part 1—Basic Requirements			
Property		Jet A or Jet A-1	Test Method[B]
COMPOSITION			
Acidity, total mg KOH/g	Max	0.10	D3242/IP 354
Aromatics: One of the following requirements shall be met:			
1. Aromatics, volume percent	Max	25	*D1319* or IP 156[C]
2. Aromatics, volume percent	Max	26.5	D6379/IP 436
Sulfur, mercaptan,[D] mass percent	Max	0.003	*D3227/IP 342*
Sulfur, total mass percent	Max	0.30	D1266, D2622, D4294, D5453, or IP 336
VOLATILITY			
Distillation			
Distillation temperature, °C:			*D86*,[F] D2887/IP 406,[E] D7344,[G] D7345,[G] IP 123[F]
10 % recovered, temperature (T10)	Max	205	
50 % recovered, temperature (T50)		report	
90 % recovered, temperature (T90)		report	
Final boiling point, temperature	Max	300	
Distillation residue, percent	Max	1.5	
Distillation loss, percent	Max	1.5	
Flash point, °C	Min	38[H]	*D56* or D3828[I], IP 170[I] or IP 523[I]
Density at 15 °C, kg/m^3		775 to 840	D1298/IP 160 or D4052 or IP 365
FLUIDITY			
Freezing point, °C	Max	–40 Jet A[J] –47 Jet A-1[J]	D5972/IP 435, D7153/IP 529, D7154/IP 528, or *D2386/IP 16*
Viscosity –20 °C, mm^2/s[K]	Max	8.0	*D445/IP 71, Section 1*, D7042[L] or D7945
COMBUSTION			
Net heat of combustion, MJ/kg	Min	42.8[M]	D4529, D3338, *D4809* or IP 12
One of the following requirements shall be met:			
(1) Smoke point, mm, or	Min	25.0	D1322/IP 598
(2) Smoke point, mm, and	Min	18.0	D1322/IP 598
Naphthalenes, volume, percent	Max	3.0	D1840
CORROSION			
Copper strip, 2 h at 100 °C	Max	No. 1	D130/IP 154
THERMAL STABILITY			
2.5 h at control temperature of 260 °C, min			*D3241[N] /IP 323[N]*
Filter pressure drop, mm Hg	Max	25	
Tube rating: One of the following requirements shall be met:[O]			
(1) Annex A1 VTR, VTR Color Code	Less than	3 No peacock or abnormal color deposits	
(2) Annex A2 ITR or Annex A3 ETR, nm avg over area of 2.5 mm^2	Max	85	
CONTAMINANTS			
Existent gum, mg/100 mL	Max	7	*D381*, IP 540
Microseparometer,[P] Rating			D3948
Without electrical conductivity additive	Min	85	
With electrical conductivity additive	Min	70	
ADDITIVES		See 6.3	
Electrical conductivity, pS/m		[Q]	D2624/IP 274
Part 2—Extended Requirements			
Property		Jet A or Jet A-1	Test Method[B]
COMPOSITION			
Aromatics: One of the following requirements shall be met:			
1. Aromatics, volume percent	Min[R,S]	8	*D1319* or IP 156
2. Aromatics, volume percent	Min[R,S]	8.4	D6379/IP 436
VOLATILITY			
Distillation			D2887/IP 406[E] or *D86*[F] or IP 123[F] or D7344[G,V] or D7345[G]
T50-T10, °C	Min[S,T]	15	
T90-T10, °C	Min[S,T]	40	
LUBRICITY			
Lubricity,[P] mm	Max	0.85	D5001
FLUIDITY[U]			

Figure 1 - Detailed requirements of aviation turbine fuels containing synthesized hydrocarbons [15]

ASTM-D4054 verifies and approves new technologies that require approval, which specifies the certification process and criteria for new fuels. Figure 2 shows an overview of the Fuel and Additive Approval Process. In the initial stage of fuel certification, it is necessary to review the Specification Properties, followed by the Fit for Purpose Properties (FFP), and finally the Component or Rig Test, and Engine Test respectively. Approval of new fuels or additives is determined by the Original

Equipment Manufacturer (OEM) who lacks the incentive to use alternative fuels, with oversight from regulatory agencies such as the FAA and EASA.

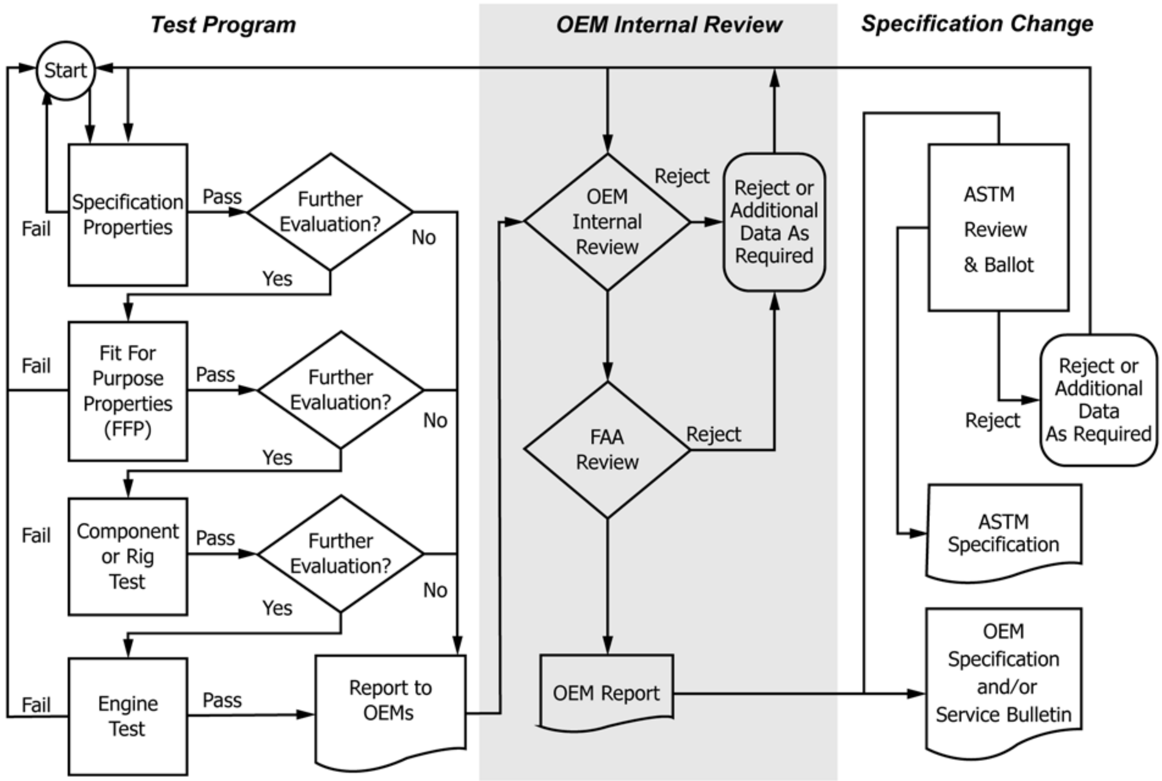

Figure 2 - Overview of fuel and additive approval process [16]

As shown in Figure 3 Test Program, the Fuel Specification Properties are based on the specification property tables in standards such as ASTM-D1655 [17]. The new fuel needs to demonstrate compliance with the constraints by comparison among more than thirty constraints on components and physicochemical properties. However, the comparison range of the constraints is based on the aviation fuel boundary generated by conventional aviation kerosene.

The FFP review shall examine each of these aspects, including chemistry, bulk physical and performance properties, electrical properties, and compatibility. When the results are formed, the OEM will determine whether the engine meets the requirements for use.

If the FFP is met, a component or rig test will be performed, and finally, an engine test which must be completed by the specified original equipment manufacturer because of proprietary issues and limitations of the test method. Completion of the entire experiment will consume a large amount of fuel. According to estimation by ASTM-D4054, specification property review requires approximately 37.8 liters, application property suitability review requires 320.8 liters, component or rig testing requires up to 37,854.1 liters, and engine testing requires up to 851,718 liters [16], for a total of approximately 900,000 liters. Current certification processes and criteria have created limitations in the development of alternative fuels for aviation.

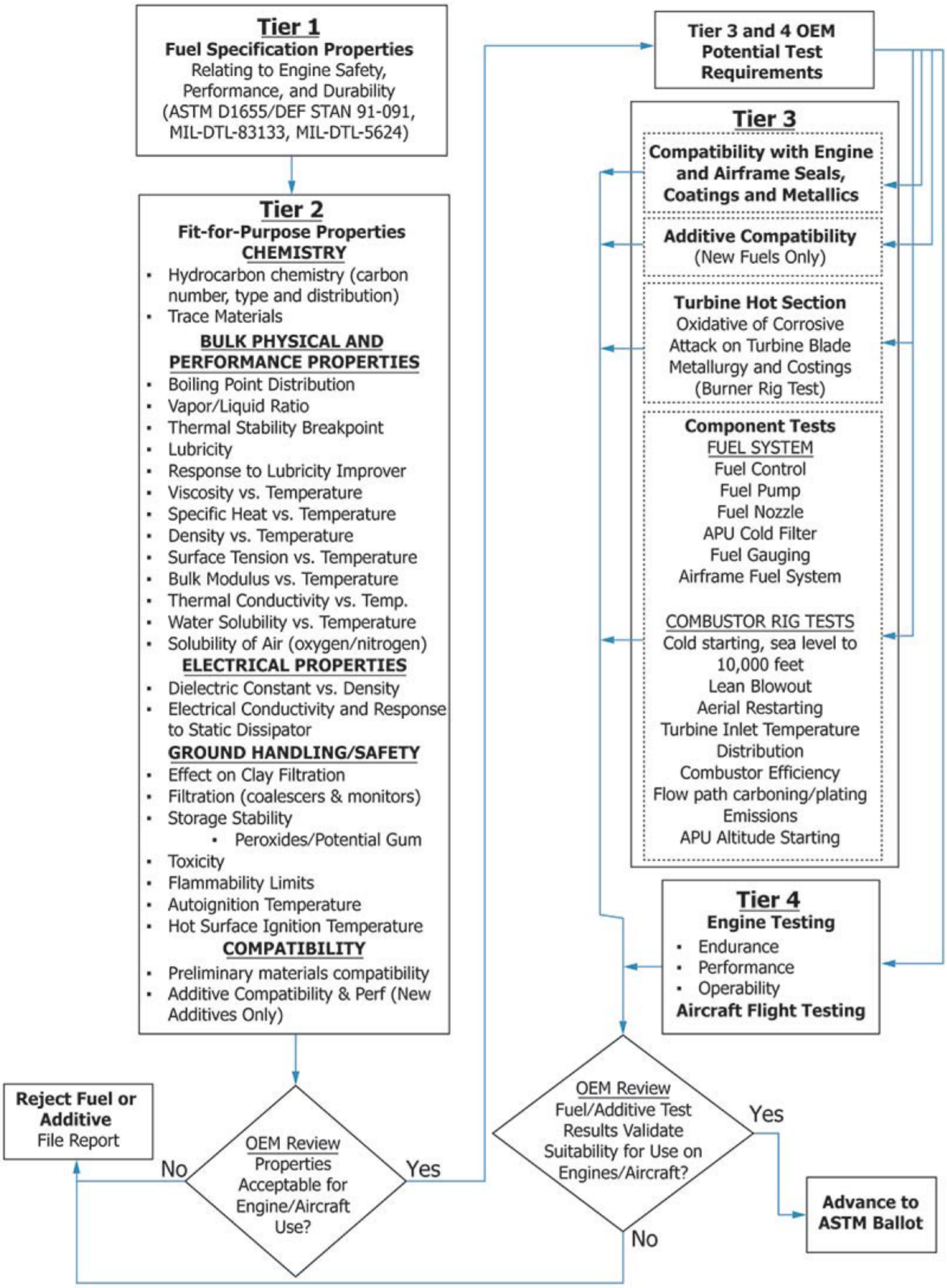

Figure 3 – Test program [16]

2.3 Bottleneck analysis

By analyzing the certification process, two major problems can be found.

- The cost of certified fuel is too high and lacks generalizability. ASTM-D4054 requires a large number of tests, and engine tests may require up to 851,718 liters. In practice, fuel in the certification phase usually does not go to mass production, and the high fuel consumption greatly increases the upfront investment cost and development risk. Furthermore, the existing certification process allows new fuels to be certified only on one specific type of engine. Duplicate certification is still required for different types and models of engines.
- Insufficient safety guarantee. Using aviation kerosene experience at the physicochemical property level, ASTM-D7566 specifies a range of specific physicochemical properties that indirectly constrain SAF to be a fuel highly similar to conventional aviation kerosene.

Nevertheless, SAF cannot be identical in chemical composition to aviation kerosene. Therefore, the certification process by physicochemical properties similarity check alone does not provide sufficient evidence of safety. Although ASTM-D4054 requires multiple levels of testing, the lack of engine level safety determination does not provide sufficient data to support its safety.

As the deadline for carbon emission reduction targets approaches day by day, the aviation industry urgently needs to establish a novel Certification and Safety Assessment Method for SAF certification at the engine system safety level from the perspective of aircraft engine airworthiness and safety.

The system safety assessment method takes the aero-engine as the main subject of analysis (instead of fuel), and system safety as the top-level objective (instead of physical and chemical characteristics similarity). It makes the SAF certification process and certification standard more reasonable and reduces the certification cost of SAF without reducing the level of engine system safety.

3. SAF System Safety Assessment Method

The Safety Assessment Method is designed to analyze the safety of all types of aviation fuels, including SAF, in terms of engine system safety.

3.1 Safety requirements

To ensure system safety, the safety requirements at the engine level need to be defined first. Based on the principle of similar analogy, the operational experience of aviation kerosene on engines is used as the safety boundary to compare the safety of SAF at the engine level.

As shown in Figure 4, the similarity check can be divided into four tiers, *Fuel, Fuel System, Combustor,* and *Engine*, based on the differences in the impact of the fuel. Similarity checks at tiers are available to support the certification of fuels to a different extent. The similarity check at the Fuel tier focuses on Compositions and Properties, where SAF is harmonized with aviation kerosene. The Fuel System tier focuses on Fuel System Performance and aims to ensure that the Fuel System is similar in operation. The similarity check at the Combustor tier focuses on Combustion Performance, which is concerned with the similarity of combustion performance and outlet distribution in the combustor. The Engine tier focuses on Engine performance and safety, with the criterion being the consistency of engine safety levels.

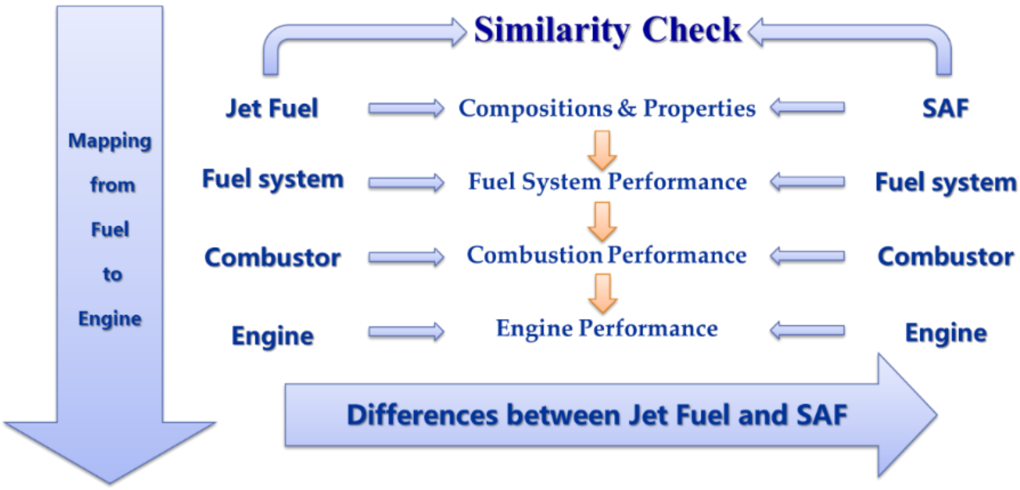

Figure 4 - Levels of similarity checking

The current certification standards ASTM-D7566 and ASTM-D4054 use a similar analogy at the Compositions and Properties level, using the range of physicochemical properties for aviation kerosene as the base assessment criteria and combining it with tests such as component test, engine test, and flight test for alternative fuel assessment. As noted in chapter 2.2, alternative fuels cannot be identical in chemical composition to aviation kerosene. Therefore, physicochemical properties alone do not provide sufficient evidence of safety.

According to the Society of Automotive Engineers (SAE) document ARP4761 [18] on guidelines and methods for conducting the safety assessment process on civil airborne systems and equipment, the objective of safety quantification is risk, i.e., the combination of the probability of a consequence occurring and the degree of hazard of the consequence. The essence of the safety requirements can be summarized as a risk matrix, and since there are no catastrophic events in aero engines, the aero-engine risk matrix is shown in Table 1. In the airworthiness regulations, engine level effects and assumed severity levels are defined by FAR-33 [6] Part E, Clause 75 Safety Analysis and follow the risk matrix for classification and probability requirements for aero-engine failure events.

Table 1 - Failure condition severity as related to probability objectives and assurance levels

Probability (Quantitative)		Per flight hour		
		$>10^{-5}$	10^{-5}~10^{-7}	10^{-7}~10^{-9}
Failure Condition Severity Classification	Hazardous	Unacceptable	Unacceptable	Acceptable
	Major	Unacceptable	Acceptable	Acceptable
	Minor	Acceptable	Acceptable	Acceptable

It is clear that the requirements of the airworthiness regulations for the safety of engine systems are the consequences of failure and their corresponding probability of occurrence relationships. Thus, it is more in line with the airworthiness requirement for the safety assessment of alternative fuels that use undegraded whole system safety levels instead of identical physicochemical properties as a safety assessment criterion. Moreover, in practice, the similarity check of safety parameters at the engine level can release the constraint at the fuel level. This means that sustainable fuel development potential is unleashed and fuel options are expanded without reducing the degree of system safety.

3.2 Safety Critical Parameters

According to ARP 4761, the consequences of failure and their occurrence probabilities are obtained by means of Fault Tree Analysis (FTA) or Failure Modes and Effects Analysis (FMEA), which rely on preexisting data and experience. The analysts estimate the failure probability of the bottom elements based on relevant experience and historical data. The probability of failure risk for the top-level event can then be derived by logical operations between the different elements through Boolean logic.

In actuality, it is difficult to directly use failure probabilities as a safety criterion for SAF certification. On the one head, using experience with alternative fuels is not enough to support safety assessment. On the other head, Failure probabilities are usually derived from qualitative judgments, and it is difficult to distinguish the degree of safety when there is no magnitude difference in the comparison terms. Critical parameters should be extracted and parameterized for safety assessment in order to achieve safety comparison with conventional aviation kerosene.

Safety critical systems occupy an important place in the safety analysis of complex systems, and safety critical systems analysis can significantly improve the efficiency of safety analysis [19-23]. We extend the concept of safety critical systems and define Safety Critical Parameters (SCP) to quantify and compare the safety performance of different fuels and to obtain a parametric safety boundary.

As shown in the figure 5. SCPs are parameters that contribute substantially to the safety of aero-engine systems and are derived from the Safety requirements. Single or combined variations in SCPs have a significant impact on critical failure consequences.

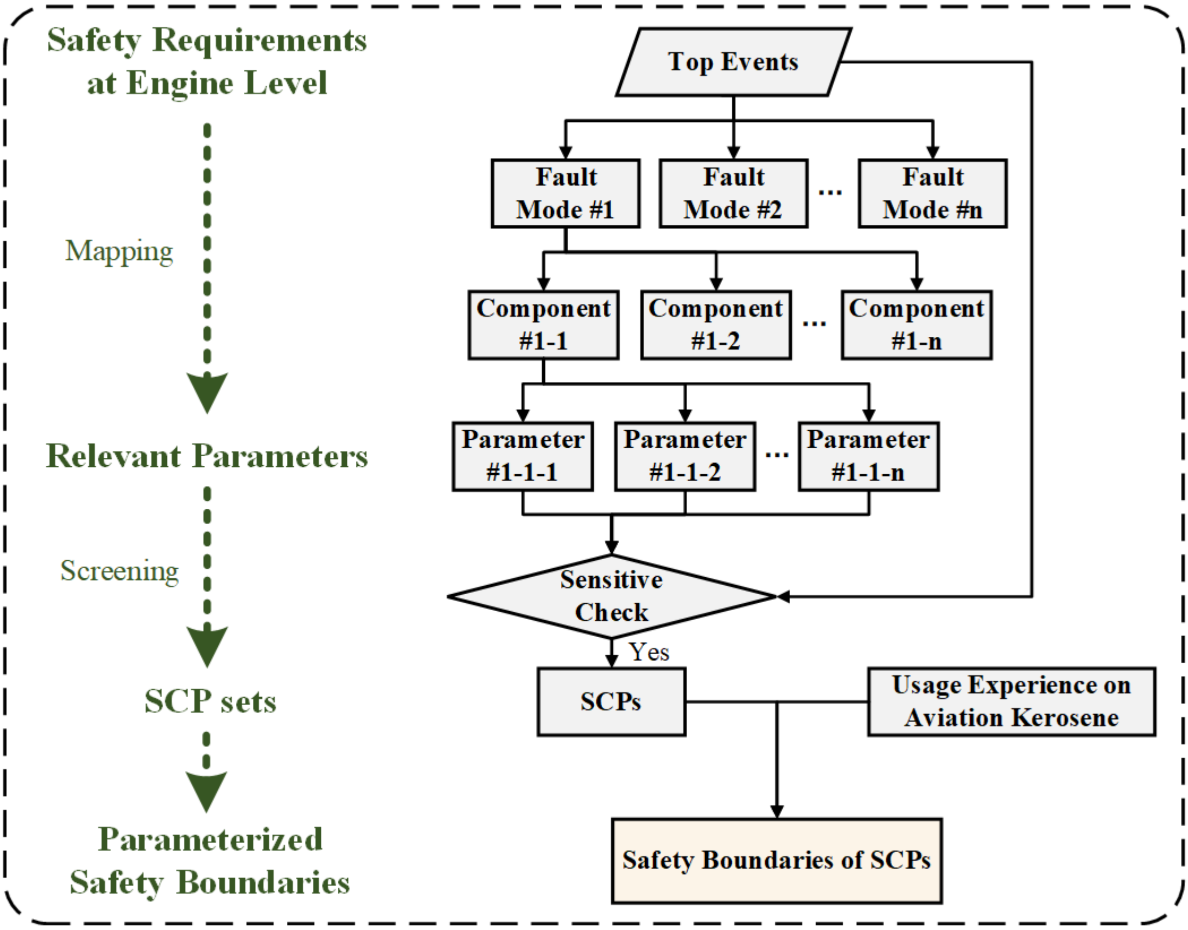

Figure 5 – SCP identification process

Fuel-related SCPs are extracted according to the Safety requirements. Based on historical empirical data for aviation kerosene, the safety boundaries of the SCPs are obtained as a criterion for safety determination, thus comparing kerosene with SAF at different levels.

3.3 Fuel-Safety Mapping

The methodology also requires the establishment of a mapping between the physicochemical properties of aviation fuels - volatility, fluidity, corrosion, etc. - and the safety of aviation engines.

The fuel properties can be mapped, level by level, to the engine level through numerical simulation, component testing and engine testing.

4. System Safety-Based SAF Certification

4.1 SAF TSO certification mode

As current SAF certification lacks generalizability in results, the complete certification process needs to be replicated for the same fuel for different engine models. Such duplication of work will significantly increase the time and fuel costs of certification. Moreover, there is a great deal of commonality in the elements that need attention in the certification process for the same fuel.

Similar to the application of fuel to aircraft engines, the application of one engine to multiple aircraft types also requires a suitability assessment. Because the consequences of engine failure may be reduced or increased by the aircraft, the classification of the severity of the effects of aircraft-level failure is difficult to apply directly to engine safety assessments. In the FAA's airworthiness system, FAR-33 is adopted as the aero-engine airworthiness standard for engine airworthiness certification. The engine airworthiness certification process does not take into account the engine's installation effects, and the engine's suitability for the aircraft is verified in the FAR-25 [24] Subpart E-Powerplant.

In order to reasonably reduce the cost and difficulty of SAF certification, we treat the SAF as a special component of the aero-engine. SAF certification and fuel-engine application certification are carried out separately. Fuel certification is primarily used to assess common safety issues for SAF. In contrast, fuel-engine application certification is assessed for the particular characteristics of the target engine type. Fuel characteristics dependent on the combustor and engine construction will be analyzed in this process.

4.2 Standard Combustor and Standard Engine

Fuel safety certification cannot be separated from the combustor and engine, so standard combustor and standard engines are also required for compliance verification at the combustor level and engine level respectively.

Design the standard combustor based on the typical combustor configuration of existing aircraft engines. The focus of the combustor level compliance verification is on the effect of fuel on combustor safety, including chamber wall temperature, maximum temperature in the chamber, combustion efficiency, lean blow-out margin, rich extinction margin, temperature distribution, pressure distribution, etc.

As the engine type may affect the SCP boundary, separate standard engines are created depending on the engine type. Engine level compliance verification focuses on the impact of fuel on engine performance and safety including combustor pressure recovery factor, hot spot temperature, turbine inlet temperature distribution, turbine inlet pressure distribution, thrust (output power), etc.

Standard combustor and standard engine tests are carried out on aviation kerosene and alternative fuel combustion chambers to obtain performance-related and safety-related parameters based on which the variability of the different fuels can be analyzed.

4.3 System safety-based SAF certification process

As shown in Figure 6 The certification process is divided into two main parts, namely *Combustor Level Compliance Analysis* and *Engine Level Compliance Analysis*.

During the Combustor Level Compliance Analysis process, the aviation kerosene and the SAF to be certified are required to complete four projects respectively: *Basic combustion test, Standard combustor test, Fuel - Combustor SCP analysis,* and *Combustor working boundary analysis*. The working boundary of aviation kerosene was used as the combustor level safety boundary and the working boundary of the SAF to be tested was analyzed for comparison.

If the fuel fails to meet the boundary coverage requirement, i.e., the working boundary of the SAF exceeds the combustor level safety boundary, perform a sensitivity analysis of the working boundary to physicochemical properties. Based on the results of the sensitivity analysis, the SAF system safety can be improved by optimizing the physicochemical properties of the fuels that have a significant impact on the working boundary through the feedstock, refining process, or fuel system design. Conversely, it is also possible to release constraints on the physicochemical properties of low sensitivity, thereby reducing the cost of SAF preparation.

For those that meet combustor level compliance analysis, engine level compliance analysis with three projects can be performed. Parallels to combustor level compliance analysis, engine level compliance analysis contains *Standard engine test, Fuel – Engine SCP analysis,* and *Engine working boundary analysis*. The Safety Boundary Check has been repeated at the engine level. For meeting the boundary coverage conditions, the fuel is deemed to be TSO certified. Otherwise, a sensitivity analysis at the engine level is carried out and fuel improvement recommendations could be given.

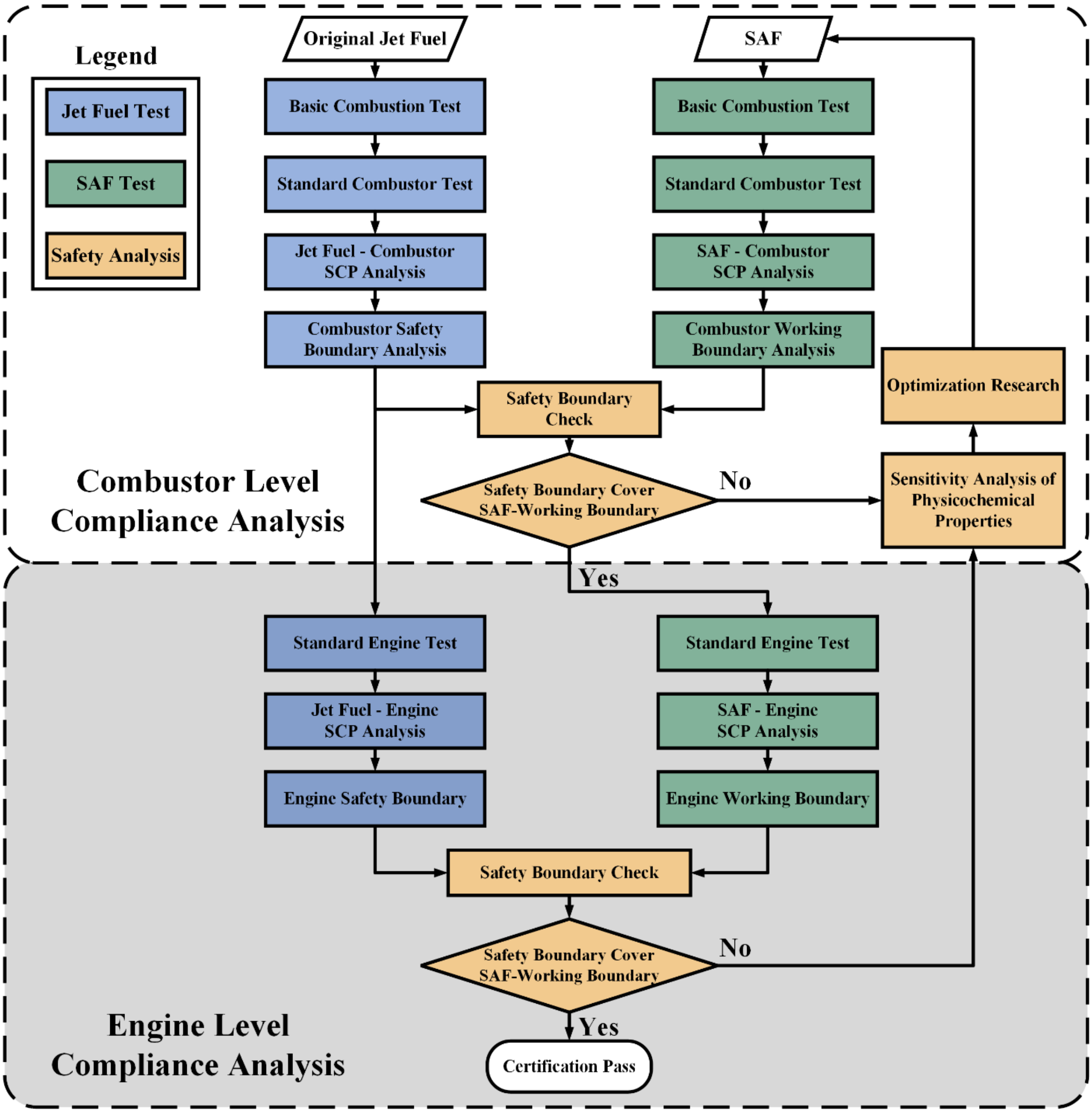

Figure 6 - SAF certification process

4.4 Advantages of the new certification method

System Safety-Based Sustainable Aviation Fuel Safety Certification has several advantages over the current certification standards:

- Low certification cost. The method treats fuel as an aero-engine particular component and uses fuel TSO certification to address common issues thereby reducing the fuel and time costs of the fuel certification process.
- Efficient utilization of aviation kerosene experience. The method aims at engine level system safety and performs similarity checks at the combustor and engine level. It solves the problem that relies on physicochemical properties alone would not provide adequate safety criteria. At the same time, the potential for fuel development is unlocked by reducing physicochemical constraints on fuels without reducing safety levels
- Sensitivity analysis feedback. The certification process is carried out in stages with Combustor Level Compliance Analysis and Engine Level Compliance Analysis. Fuel suppliers can use sensitivity analysis to recommend optimizations that will reduce refining costs and expand feedstock sources

5. Application and Outlook

Nowadays, increasing countries and organizations treat the SAF as one of the main directions for aviation development. Several airlines and airports have already put SAF-blended jet fuel into service. SAF-related industries are gradually forming. However, the number of certified SAF types is still insufficient. There are many low-carbon environment-friendly fuels to be applied in the aviation industry. The certification of new fuels remains a major bottleneck in the development of SAF. The certification and safety assessment methods we proposed cannot solve all the problems in the certification. But the constraints on the fuel source and refining method can be reduced by decreasing the restrictions on the physicochemical properties of the fuel in terms of safety and airworthiness.

Both plant-based fuels and fossil fuels have carbon solidification processes. However, this process for fossil fuels typically takes millions of years, while energy plants solidify carbon much more quickly, by way of photosynthesis. However, the certification problem makes it difficult to use in aviation. China is conducting botanical research and establishing industrial chains for energy plants such as Bamboo Reed, Miscanthus, and Pennisetum. Preliminary calculations show that the carbon uptake of some plants can approach or even exceed the carbon emissions during their entire life cycle, including cultivation, processing, refining, and use. Negative carbon emissions are achieved in the form of biochar formed from fuel refinery residues. Furthermore, these plants can be grown on non-cultivated land like saline land.

The certification methods of composition and physicochemical levels hinder the development of plant-based fuels, due to the native differences between plant-based and fossil fuels. The engine level certification method, with system safety as the top-level objective, frees up a portion of the fuel constraint to make more plant-based fuels potentially sustainable for aviation.

6. Conclusion

This paper presented a System Safety-Based Sustainable Aviation Fuel Safety Assessment and Certification Method, which combines the engine system safety method with SAF safety assessment. Based on standard combustor and standard engine, a new fuel certification process is also provided for improving SAF safety levels and promoting SAF development.

With the system safety of the engine as the fundamental goal, the method we proposed upgrades the similarity check from the fuel level to the engine level. The safety requirements are clearly defined and the boundary of the SCP for traditional aviation kerosene is used as the quantitative safety criterion.

There are still some open questions left to be solved for the proposed Safety Assessment and Certification Method. As part of the future work, we will investigate the ways of identifying SCPs for each engine type for further improving coverage of fuel types and engine types. Further investigation about certification process optimization would be conducted in our future work.

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8. Copyright Statement

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