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Systematic Review

Discussion of the Standards System for Sustainable Aviation Fuels: An Aero-Engine Safety Perspective

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Abstract: Sustainable aviation fuels (SAFs) are considered an important solution for reducing carbon emissions. Safety is the most important prerequisite for a new fuel to be used in an aero-engine. As a special component in aero-engines, fuel is required to comply with both airworthiness and technical standards. These two types of standard work together to guide SAF development. In this paper, the SAF safety issues related to aero-engines are first analyzed. Subsequently, SAF-related standard systems are analyzed in detail, and the different safety responsibilities of airworthiness authorities and industry associations are explained. Moreover, the relationships between airworthiness and technical standards are determined from the perspective of actual SAF certification. Furthermore, the revision of the standards is reviewed to summarize the historical evolution and outline the revision intention. Finally, the future SAF certification standards are discussed and prospected, including the blending ratio, property specifications, and testing equipment. According to the discussion, increased safety and fewer constraints are the principal objectives for the development of SAF standards. Analysis, review, and discussion of the SAF standards systems from an aero-engine safety perspective will contribute to the establishment of the next generation of standards to release the fuel potential and improve safety.

Keywords: sustainable aviation fuel; fuel assessment; aero-engine; certification standard; airworthiness

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1. Introduction

The combustion of aviation fuels emits greenhouse gases, such as nitrous oxide, carbon dioxide, and methane, as well as soot [1,2]. Prior to the COVID-19 outbreak, global commercial aviation's CO_2 emissions grew by approximately 30% in six years due to the continuous rise in global flights, from 707 million tons in 2013 to 920 million tons in 2019 [3,4]. Moreover, emissions from aero-engines act directly on the stratosphere, where the horizontal motion of airflow is significantly stronger than the vertical motion, and pollutants can spread rapidly with lateral winds over a wide area of similar altitude. Pollutants that are difficult to photodegrade [5] and do not react chemically with the main components of the air can persist and have a long-lasting effect on the environment. Therefore, the harmful effect caused by civil airliners is more serious [6,7] and difficult to monitor [8]. The aviation industry has been actively exploring clean, low-emissions energy technologies in recent years. Sustainable aviation fuels (SAFs) are alternative aviation fuels that meet sustainability criteria and are made from renewable or waste sources, and have been identified as one of the appropriate solutions for achieving aviation carbon-neutral targets because of their high potential for environmental sustainability [9]. An SAF with a well-established life cycle can achieve zero or even negative carbon emissions, as carbon capture and storage (CCS) are carried out in some stages [10–12]. Moreover, SAFs have more suitable energy densities and compatibility with existing aero-engines than electric or hydrogen energy [13]. However, the certification process for a new SAF should carry over 3–5 years and cost around USD 10–15 million [14]. The few SAFs that have been approved are not widely used because they are much more expensive than conventional jet fuel. At present, conventional jet fuel still dominates the aviation fuel market and SAF adoption is far below expectations. With the deadline for the carbon reduction targets set by the International Civil Aviation Organization (ICAO) approaching, there is an urgent need for the aviation industry to optimize the SAF-related standards system [15].

Safety is the most important prerequisite for a new fuel to be used on aero-engines. As the power source for aero-engines, the quality of the fuel has a direct impact on flight safety. Safety issues in aviation fuels include production, storage, transportation, and operation. Specific to aero-engine safety, the fuel affects ignition and re-ignition [16,17], flameout, combustion efficiency, and the hot-end component life [18,19], which may result in hazardous accidents in the worst conditions. Fuel experts from original equipment manufacturers (OEMs) have urged for a strengthening of the management and supervision of aviation fuels, due to the increase in unsafe incidents caused by these fuels [20]. Increasing attention is being paid to SAF safety issues, and SAF-related standards are being developed and revised.

For the past 20 years, several national and international organizations have developed SAF-related standards. To ensure that there are no safety issues with the application of SAFs to aero-engines, the airworthiness standards developed by airworthiness authorities require provisions of aero-engines that need to be compliance verified after the new fuel is applied. As a special component of aero-engines, the SAF also has to comply with the technical standards of industry associations such as those set by the American Society of Testing Materials (ASTM), which regulate the fuel properties. Airworthiness and technical standards together provide guidelines for the SAF. In practice, the standards intersect in their scope of application and refer to each other, creating the SAF-related standards system. However, there are significant deviations in the safety requirements of the SAF due to differences in the intents of airworthiness and the technical standards. The characteristics, advantages, and disadvantages of the two types of standard and their interrelationships need to be clarified to provide a basis for further improvements to the SAF-related standards system.

Several high-quality papers that contain reviews or discussions of SAF-related standards have been published in recent years, covering the certification, approval process, and specifications of technical standards [1,9,21–23]. However, few studies have taken airworthiness standards into account in SAF standards research, although airworthiness standards are more mandatory than technical standards. In contrast to other papers, this paper focuses on providing a comprehensive overview and discussion of the overall SAF-related standards system from the perspective of aero-engine safety. The main objective of this paper is to discuss how to reduce the cost of certification and the difficulty of compliance demonstration while ensuring the safety of aero-engines, as well as to discuss the further development prospects of the SAF-related standards system. The paper begins with a brief introduction to SAF and aero-engine safety. Next, we summarize SAF-related safety issues, especially dynamic safety issues in aero-engines. We then lay out the SAF-related standards system, including the relationship between technical and airworthiness standards in practice, their characteristics, and historical trends. Lastly, we discuss possible concessions and future amendments to the requirements of the standards system from the perspective of the aero-engine system safety.

2. Overview and Advantages of Sustainable Aviation Fuels

Green aviation energy technologies are generally classified into three main types based on the energy sources: electricity, hydrogen, and SAFs, as shown in Table 1. Both the first and second types have disadvantages in terms of energy density, which represents the energy storage capacity of an energy source, including mass energy density and volume energy density. If the mass energy density is too low, the aircraft will have to carry more mass of fuel or batteries in order to achieve the same range, which will reduce the payload of the aircraft. Correspondingly, a low volume energy density requires the aircraft to provide more space for the energy storage device, which will crowd the interior space if the shape of the aircraft is not changed. The volume energy densities of SAFs are about 10 times those of lithium-ion batteries and over six times those of compressed hydrogen. Moreover, both electric and hydrogen energy require changes to existing aircraft power systems due to differences in the operating principles [24], while SAFs can be used directly in aero-engines. SAFs have become the preferred solution for low-carbon aviation because of their high energy densities, flexible preparation methods, and compatibility with existing aviation power systems.

Table 1. Three types of green aviation energy.

Energy Type	Electricity (Lithium-Ion Battery)	Hydrogen (70 MPa Compressed)	SAF
Mass energy density (MJ/kg)	<1.8 [25]	≈142	≈43
Volume energy density (MJ/L)	<3.7 [26]	≈5.6	≈34.4
Compatibility with existing aero-engines			✓
No CO_2 emissions during application	✓	✓	
Lifecycle carbon capture			✓

SAF, sustainable aviation fuel.

Sustainable fuels, represented by biofuels, are already being studied extensively in several transport applications, including aircraft, marine, and automotive applications [27]. SAFs are defined as renewable or waste-derived aviation fuels that meet sustainability criteria [28]. As a sustainable alternative to fossil jet fuels, SAFs should be equivalent to conventional jet fuels in safety and performance. In particular, drop-in SAFs possess essentially identical compositions and physical properties as those of existing petroleum-derived fuels, and they can be employed seamlessly without any special handling, unique operating procedures, or modifications to aero-engines, aircraft, or infrastructure [29,30]. Accordingly, existing equipment and facility conditions can support the use, distribution, and storage of SAFs.

SAFs can achieve low or even negative carbon emissions through CCS [31–34]. Figure 1 summarizes the greenhouse gas (GHG) emissions of some SAF types, including hydrogenated esters and fatty acids (HEFA), catalytic hydrothermolysis (CH), hydroprocessed depolymerized cellulosic jet (HDCJ), Fischer–Tropsch (FT), alcohol-to-jet (ATJ), and direct-sugar-to-hydrocarbon (DSHC). As a comparison, the GHG emissions of conventional jet fuels are around 90 g CO_2/MJ. SAFs contain hydrocarbon compounds like conventional jet fuels, and they are not as carbon free as electric or hydrogen energy during the application process. However, the implementation of CO_2 capture and transformation technology provides a pathway for carbon reduction. The feedstocks for SAFs are sustainable, which are usually agro-forest residues, plants, old cooking oil, and tallow [35,36]. The carbon reduction of SAFs is even better than those of the other two from a whole life cycle view [37,38]. For the example of plant-based SAFs, as shown in Figure 2, energy plants absorb large amounts of CO_2 through photosynthesis during growth to realize carbon capture. The combustion process only re-emits part of the previously absorbed CO_2, and no additional CO_2 is emitted into the air.

The rest of the carbon residue is made into biochar, which can be used for fertilizer and building materials, to achieve carbon storage. Although there are in-process carbon emissions from transportation and refining, carbon capture may still exceed the total emissions with the help of carbon storage. Compared with fossil fuels, electricity, and hydrogen, SAFs can effectively reduce carbon dioxide and even achieve zero or negative carbon emissions over the whole life cycle [32]. Technical analysis conducted by the ICAO showed that SAFs have the greatest potential to reduce CO_2 emissions from international aviation.

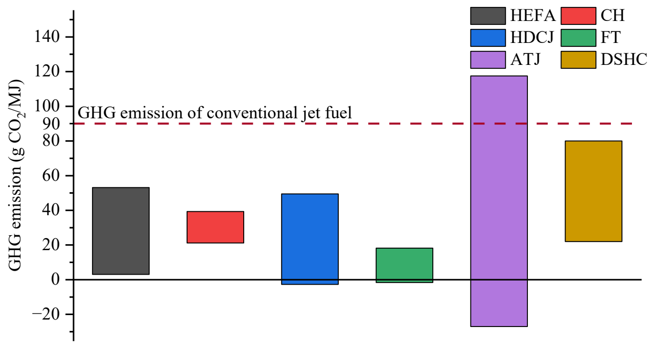

Figure 1. Summary of greenhouse gas (GHG) emissions of aviation fuels. SAFs have multiple feedstocks, and the figure shows the range covered by all feedstocks. The data were taken from [23].

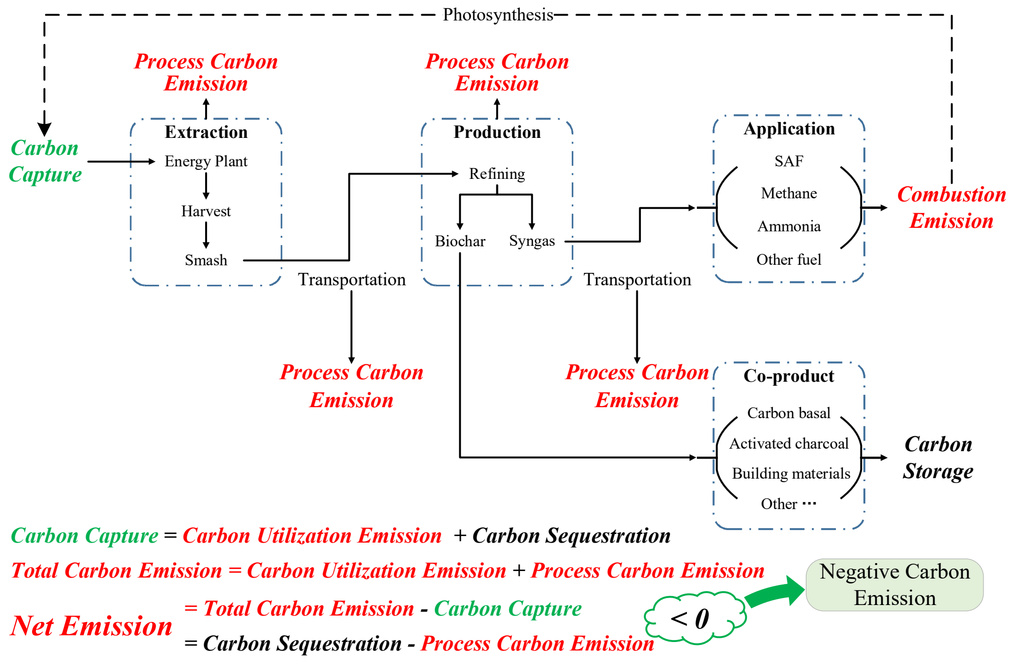

Figure 2. Life-cycle carbon emissions of plant-based sustainable aviation fuels.

These attributes make SAFs attractive to the civil aviation industry. The ICAO held the first Conference on Aviation and Alternative Fuels (CAAF) in 2009, which endorsed the use of SAFs as an important means of carbon reduction, and established the ICAO Global Framework for Aviation Alternative Fuels (GFAAF). At the 38th session of the ICAO in 2013, a series of measures were announced to ensure that the aviation industry meets its carbon-neutral growth targets, including a major expansion of SAF applications. The International Air Transport Association (IATA) estimates that SAFs will contribute approximately 65% to the achievement of net zero carbon emissions in 2050 [39]. Due to the continued growth in demand for aviation capacity [40], it is unlikely that the international aviation industry will achieve carbon neutrality solely through improvements in aero-engines, aircraft performance, and aircraft operation [24].

For the past several years, there have been many active efforts to promote SAF research. Researchers have conducted many SAF-related studies on synthesized materials [41]. For example, Figure 3a shows bio-aviation fuel production from lipids without hydro-cracking. Research in this area shows a clear tendency to avoid the non-selective cracking of fatty acids and to improve the product properties and process efficiency [21]. In terms of lignin and integrated biorefinery systems for jet fuel production, the different processing paths are shown in Figure 3b. Moreover, Figure 3c shows the reaction pathways of bifunctional catalysts for the single-step conversion of feedstock into jet biofuel. There are many more advances in synthetic materials that cannot be listed fully here [23,42–45].

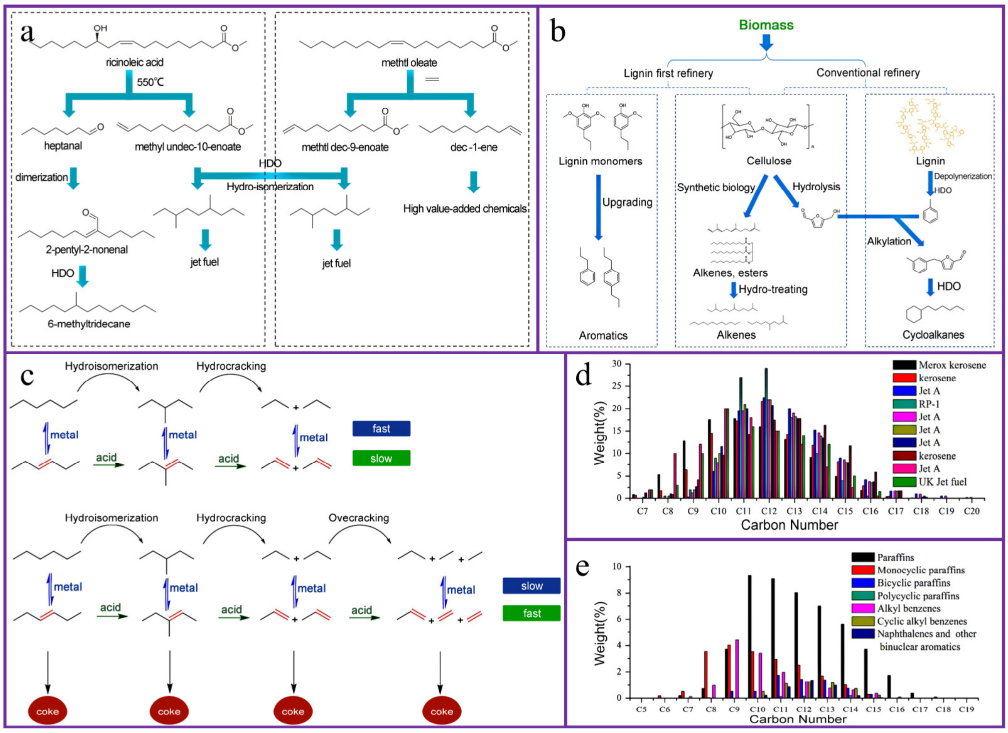

Figure 3. SAF-related studies on synthesized materials. (**a**) Bio-aviation fuel production from lipids without hydro-cracking [21]; copyright 2019, Elsevier Ltd. (**b**) Jet fuel oriented lignocellulosic biorefineries [21]; copyright 2019, Elsevier Ltd. (**c**) Reaction pathways of bifunctional catalysts for single-step conversion of feedstock into jet biofuel [46]. (**d**) Carbon distribution of different jet fuels and (**e**) carbon distribution of hydrocarbon types in Merox kerosene [47]; copyright 2015, Elsevier Ltd.

Several aircraft, aero-engine, and fuel companies are also involved in SAF research [48]. However, most of these promising research results cannot be applied. SAF application is far below expectations, and petroleum-derived fuel still dominates the aviation fuel market. Current global SAF production is less than 0.02% of the total aviation industry fuel consumption by year.

The most significant barriers to the widespread use of SAFs can be summarized in two main categories: refining and certification, and both are directly related to the standards. On the refining side, several standards require SAFs to be physicochemically equivalent to conventional jet fuel, which greatly increases the difficulty and cost of refining. Jet fuels can be classified into main groups, including paraffins, iso-paraffins, cyclic paraffins, and aromatics. The carbon distribution follows a normal distribution from C8 to C16 centered on C11 and C12, as shown in Figure 3d,e. The average aromatic concentration is 10% with the range of 1–20%, which is usually higher than that in an SAF. Carbon by hydrogen (C/H) ratio levels are typically in the range of 5.9–6.14 in jet fuel, while those of SAFs are usually in the range of 5.5–5.7 due to fewer aromatics and cycloparaffins [47].

In terms of certification, according to the International Council on Clean Transportation (ICCT), the refining cost of SAFs is about 2–8 times that of aviation kerosene. Moreover, the feedstocks that have both sustainability and favorable refining potential need to be further developed. SAFs are currently struggling to match fossil fuels in terms of both capacity and cost. The critical constraint to the SAF certification is the lack of data support caused by limited application experience. Several airworthiness authorities and industry associations are actively promoting the study of certification. However, current certification methods are often more difficult to specify than those for conventional jet fuel. There is an urgent need to find a balance between the stringency of certification and the promotion of the SAF industry.

3. Aero-Engine Safety

Safety is the freedom from conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment [49]. In civil transportation, the safety of aircraft and aero-engines is the most important attribute. Adopting any new technology at the expense of aero-engine safety is unacceptable. Therefore, the aviation industry has developed airworthiness standards and safety assessment methods to ensure aero-engine safety.

3.1. Aero-Engine Safety and Airworthiness

The implementation of aero-engine safety is subject to a series of technical, management, and cost factors. To protect the public interest and the orderly development of the aviation industry, the major aviation countries have adopted an airworthiness system to ensure the safety level of the whole process of the design, manufacture, and use of aero-engines. For an aircraft or aircraft component, airworthiness is the possession of the necessary requirements for flying in safe conditions, within allowable limits [50]. Airworthiness focuses on the main properties of safety and physical integrity, and the substantial intent of the airworthiness standards is to ensure that the risk of engine failure is acceptable.

Airworthiness authorities around the world promulgate various airworthiness standards and validation specifications to ensure the safety of aero-engine systems, e.g., FAR-33 Airworthiness Standards: Aircraft Engines issued by the U.S. Federal Aviation Administration (FAA), CS-E Certification Specifications for Engines issued by the European Union Aviation Safety Agency (EASA), and CCAR-33 Airworthiness Regulations for Aircraft Engines issued by the Civil Aviation Administration of China (CAAC). These airworthiness standards are the key to bringing civil aircraft to the public market. Airworthiness standards are the special technical standards and minimum safety standards established to ensure the implementation of civil aircraft airworthiness. Unlike other standards, civil aircraft airworthiness standards are part of national regulations and require strict enforcement [51]. Therefore, no modifications to the configuration, components, or control systems can take an aero-engine beyond the scope of the airworthiness standards. Even for an engine that has been certified as airworthy, the redesign of the components requires another appropriate airworthiness review. Although fuel is not a conventional component in aero-engines, as an essential part of aero-engine operation, SAFs need to meet the requirements of airworthiness standards when used in aero-engines.

3.2. Compliance Verification

To assess the risk level of an engine, a compliance verification exercise is required, which is mainly aimed at checking whether the verification object meets the airworthiness standards. The means of compliance (MC) is the verification method used by the applicant to demonstrate that the aircraft complies with airworthiness standards, which is also confirmed by the audit team through the documentation generated. MCs can be divided into four main categories based on the specific nature of the compliance work: engineering evaluation, tests, inspection, and equipment qualification. To unify the understanding of both sides of the review, airworthiness authorities further develop MCs and allocate the corresponding codes to each method, i.e., MC0-MC9, as shown in Table 2. There are slight differences in the formulations of MCs recognized by airworthiness authorities in the United States, European Union, and China, but the contents are basically the same. The effects of different fuels on an aero-engine are systemic. Components such as fuel systems, combustion chambers, and turbines may be affected, and verification of fuel airworthiness compliance often involves multiple MCs. Moreover, SAFs currently rely on test-type MCs due to the lack of safety data support. This will be further analyzed in Section 5 in conjunction with the standards for SAF safety verification.

Table 2. Means of compliance codes for the verification of compliance.

Type of Compliance	Means of Compliance
Engineering evaluation	MC0: Compliance statement MC1: Design review MC2: Calculation/analysis MC3: Safety assessment
Tests	MC4: Laboratory tests MC5: Ground tests MC6: Flight tests MC8: Simulation
Inspection	MC7: Design inspection/audit
Equipment qualification	MC9: Equipment qualification

MC, means of compliance.

4. Sustainable Aviation Fuel Safety Issues

The impact of fuels on the aviation industry is extensive, and the potential safety issues of fuels can be categorized as shown in Figure 4. This paper focuses on dynamic safety issues related to the operation of aero-engines, particularly in relation to combustion. Other dynamic safety issues related to the environment, aircraft, or static safety issues are not within the scope of this discussion. In addition, all aero-engines used proven standard aviation kerosene, such as Jet A, Jet A-1, and RP-3, before SAFs attracted widespread attention from the aviation industry in recent years. However, even with these conventional jet fuels, there are still flight accidents or faults directly related to the fuel. Examples include the 2008 Boeing 777 crash caused by fuel icing (UK), the 2010 Airbus A330 engine failure and forced landing due to contaminated fuel (China), and multiple aircraft engine failures in 2018 due to jet fuel contaminated with diesel exhaust fluid (America) [52]. The safety of SAFs is essential for their refinement, certification, and application. From the perspective of aero-engine system safety, SAFs may affect the aero-engine ignition and flameout performance, hot-end component lifetime, and overall aero-engine performance.

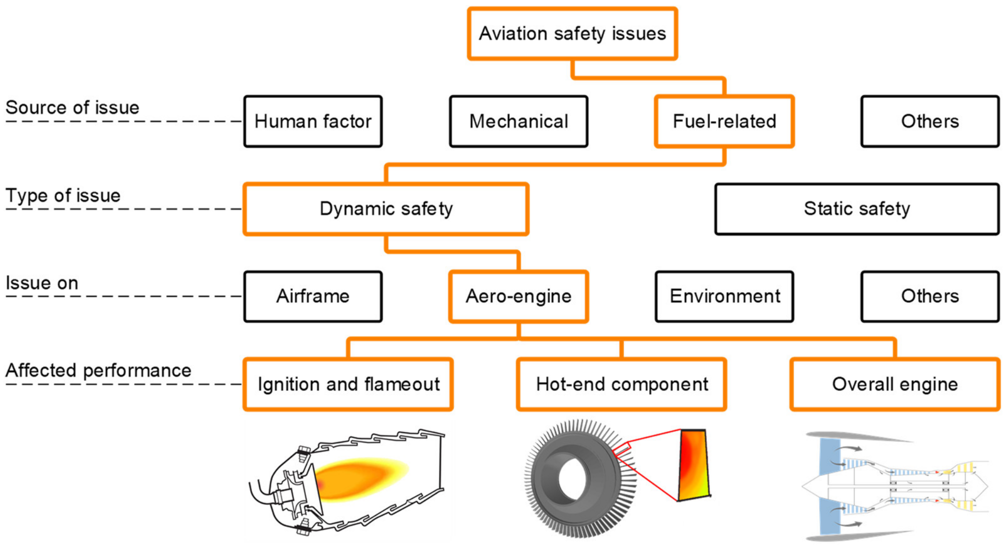

Figure 4. Classification of SAF-related safety issues.

4.1. Ignition, Re-Ignition, and Flameout Performance

Since SAFs can vary in composition compared to conventional jet fuels, some fundamental combustion properties may cause safety issues in aero-engines. Combustion responses can be very sensitive to the fuel composition and molecular structures, and they are directly linked to engine performances such as ignition, altitude re-ignition, and flameout [53]. Ignition and re-ignition are critical performance factors in determining the effectiveness of SAFs compared to that of conventional jet fuels [22]. In particular, the low-temperature ignition performance determines the stable operating range of the engine. In harsh conditions, such as cold launches in alpine regions where the temperature may be −40 °C, ignition is exceedingly difficult [54]. The ignition performance is affected by various factors, including the combustion chamber, fuel nozzle, and fuel. With a focus on SAF safety, several fuel properties contribute to the ignition performance by affecting the fuel vapor concentration in the vicinity of the ignition nozzle [55]. The most desired fuel quality for ignition is volatility, which indicates the tendency of the fuel to vaporize [53,56]. Even straight-chain alkanes in fuels can improve the combustion chamber ignition performance [17]. Figure 5a,d show the distillation data curves for different fuels, respectively [53,57]. For aviation turbine fuel, the temperature of 10% recovered (T10) is typically required to be no more than 205 °C, while the temperature of the final boiling point is typically required to be no more than 300 °C. Although fuels refined by different processes and feedstocks have different distillation curves, all turbine fuels except diesel meet the T10 and T90 maximum limit. Figure 5b illustrates the ignition delays for two alternative fuels (named C1 and C5) that were studied in the National Jet Fuel Combustion Program [14] compared to those of conventional Jet-A, JP-8, and JP-5 [58]. C1 is composed of 99% iso-paraffins whereas C5 is composed of 73% iso-paraffins and 27% trimethylbenzene. One of the important prerequisites for SAF safety is that the difference in fuel properties cannot deteriorate the ignition performance without changing the engine component design.

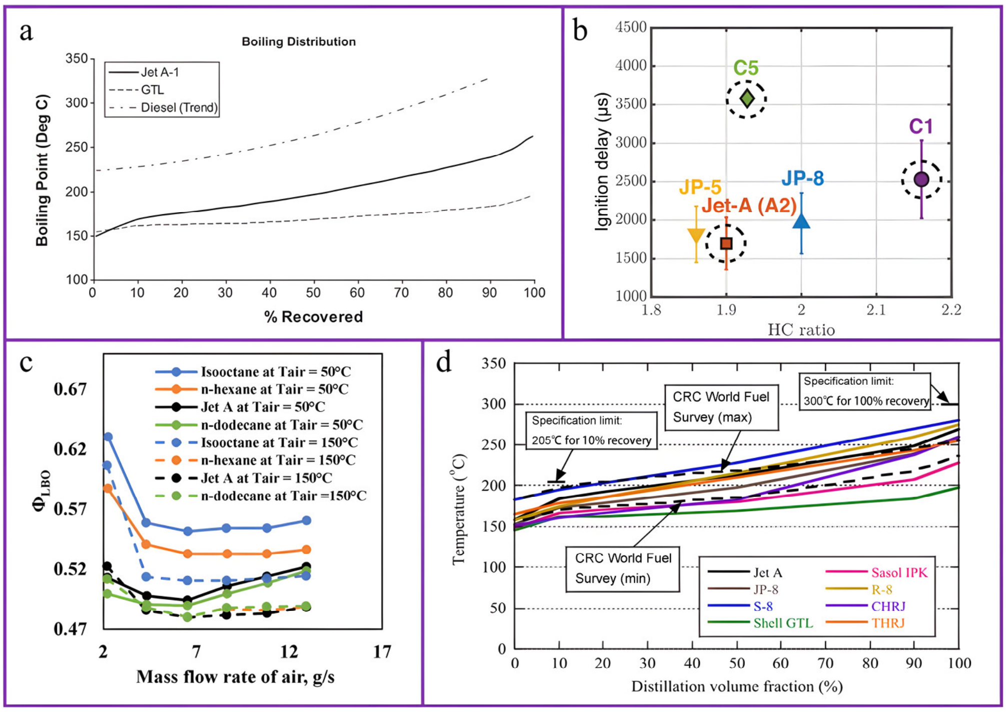

Figure 5. Several physicochemical properties of fuel are relevant to engine safety issues. (**a**) Boiling point distributions for a light gas-to-liquid (GTL) synthetic fuel, jet fuel, and diesel to indicate the relative volatility of the fuels [57]; copyright 2012, Elsevier Ltd. (**b**) Diagram of the alternative jet fuels (AJFs) compared with conventional jet fuels [58]; copyright 2020, Elsevier Inc. (**c**) Lean blow-out (LBO) results of fuels used at two air preheating temperatures [22]; copyright 2022, Elsevier Ltd. (**d**) Distillation data curves of conventional and alternative jet fuels [53]; copyright 2015, Elsevier Ltd.

In-flight shutdowns (IFSDs) caused by flameouts are not rare in civil aviation operations, especially lean blow-out (LBO), which is a phenomenon of interrupted combustion due to insufficient fuel supply, too much air, or ignition system malfunctions. Phenomena such as rain ingestion, hail ingestion, unstable combustion, and transient fuel supply shortages may cause aero-engine extinction at altitude. Although flameout is not listed as a hazardous top event in civil airworthiness standards, it is still one of the major subjects of fuel, combustion, and combustion chamber research [59]. LBO at altitude without adequate handling may even lead to a direct crash, which is more likely to occur in a single-engine aircraft. The LBO is one of the priority interests in current SAF research [60], and it is correlated with fuel properties including distillation characteristics, density, viscosity, flash point, and ignition delay [53,61]. Figure 5c shows the LBO equivalence ratios, the fuel-to-air ratio at the LBO limit to the ideal fuel-to-air ratio, for different fuels used at two air preheating temperatures [22]. A lower LBO equivalency ratio generally means that greater fuel flow or air flow fluctuations can be tolerated. When assessing the LBO limits of SAFs, the values of conventional aviation kerosene such as Jet A or Jet A-1 under the same conditions are used as an important reference. Furthermore, the ability to re-ignite at altitude is also one of the basic requirements for aero-engines to ensure that the IFSD can be recovered. Effective re-ignition performance can avoid most of the serious consequences of LBO at altitude.

4.2. Hot-End Component Lifetime

The life of an aero-engine is determined by both cold-end and hot-end components. The hot-end components include the combustion chamber and turbine. These hot-end components work under harsh environments for a long time and are subject to the compound effects of centrifugal force, thermal stress, aerodynamic force, vibration, and high-temperature corrosion, thus demanding more safety requirements. Metal materials working at high temperatures are more likely to reach fatigue or creep damage limits. The lifetimes of high-temperature components are usually lower than those of normal-temperature components. In addition, the failure rate and maintenance costs of hot-end components are noticeably higher than those of cold-end components. Therefore, the failure probabilities and lifetimes of hot-end components have always been the focus and challenge of system safety and airworthiness research. The airworthiness standards, e.g., 33.27, 33.63, 33.70, 33.88, and 33.94 in the Federal Aviation Regulations (FAR), are directly related to aero-engine hot-end components.

The fuel is combusted in the combustion chamber, and the generated high-temperature gas directly contacts the high-pressure turbine. Thus, the fuel properties have a significant impact on the lifetimes of these two hot-end components, mainly through the following aspects. The smoke point is correlated with flame radiation, engine soot, and smoke formation; as the smoke point goes up, the components' lives increase. The flame radiation increases significantly when the smoke point is below 18 mm. This is mainly due to the increase in solid particles represented by carbon black, the main source of flame radiation. The turbine component life decreases dramatically as a result. The hot-end component life may be halved if operated on a 16-mm-smoke-point fuel compared to an 18-mm-smoke-point fuel [62].

Corrosion and erosion are important factors affecting hot-end components, especially turbine blades. Gases from the combustion chamber may contain products that are harmful to the hot-end components. The fuel component determines to a certain extent the composition of the gas. For example, sulfur in fuel is often associated with corrosion, and the sulfur contents of aviation fuels are typically restricted to prevent corrosion of turbine blades by sulfur oxides. The cooling efficiency and turbine blade lifetime are also directly related. Turbine blade cooling schemes may be less effective, since different fuels may change the combustion characteristics and thereby impact the cooling requirements.

Deposits in the combustion chamber can significantly affect its performance and lifetime if in sufficient quantity. The performance may be adversely affected by interference with the aerodynamics of the chamber, and the creation of large local temperature gradients in the material may result in distortion and fretting [63]. Deposits are primarily derived from ash in fuels, metal contaminants, and carbon liberated during combustion. Most conventional aviation turbine fuels have low ash contents, but the development of SAFs requires this factor to be taken into account. The copper and zinc in the fuel catalyze oxidation reactions and lead to varnish-like deposits on the combustion chamber surface. Atomizers, igniters, and other combustor components are susceptible to carbon deposits. A comparison of several alternative aviation fuels with conventional jet fuel tests reveals that carbon deposits on the flame tubes, igniter, and fuel nozzles are significantly affected by the fuel [18,19]. The attainment of a satisfactory combustion chamber exhaust temperature distribution is important since a poor distribution can have adverse effects on the lives of turbine nozzles and blades. There is also some evidence that the degree of fuel atomization and fuel volatility can affect the distribution from a particular chamber to some extent [63].

4.3. Overall Engine Safety Issue

Differences in fuel properties can lead to some overall engine safety issues caused by system matching since aero-engines are highly integrated and strongly coupled complex systems [64]. Pressure loss is an important parameter of the aero-engine combustion process. The total pressure loss from the air passing through a combustion chamber derives, broadly, from two main sources: (1) the mixing and turbulence required to achieve satisfactory combustion and (2) the fundamental loss due to the heating of the air by combustion [63]. The increase in the total pressure loss leads to a decrease in the engine efficiency, and the turbine inlet temperature must be improved by more fuel supply to provide sufficient thrust, which hurts the overall engine safety.

Similarly, the temperature distribution causes a similar effect as the total pressure loss. As mentioned earlier, the fuel properties influence the combustion chamber exhaust temperature distribution, which also affects the high-pressure turbine efficiency. It increases the turbine inlet temperature if the control target of the system remains unchanged. Furthermore, properties such as the heating value, density, and C/H ratio can also have some overall safety influence. These properties affect the total mass or physical properties of the gas in the turbine, thus affecting the work capacity of the turbine, which also requires a higher turbine inlet temperature to compensate. Although these properties are usually governed by more important factors, there is always a possibility that the future development of SAFs may result in a recurrence of safety issues to some degree, and a focus on these safety issues from an aero-engine safety perspective would then be of some help.

Contaminants in aviation fuel have a direct impact on aero-engine safety. The philosophy in aviation fuels is that any material not originally part of the fuel is considered a contaminant and should not be there. Following this philosophy, contaminants that should not be present in jet fuel include free water, solid materials (such as rust, dust, or sand), microbial debris, other fuels, and unapproved additives, as well as other more unusual materials such as solvents and surfactant materials [62]. For example, solid materials can cause the engine control assembly to stick, and water contamination can lead to IFSDs and even accidents. It should be noted that many fuel properties, such as the flash point and volatility, may have a significant impact on ground storage, refueling, or tank systems, and the SAF safety requirement should consider all aspects together.

5. SAF-Related Standards

Safety is the most important prerequisite for a new fuel to be used on an aero-engine. The aviation industry regulates fuel development through a series of standards, and civil aviation in particular requires strict SAF-related safety standards to win public trust. Standards act in three ways. First, they provide a clear goal for new SAF research. Second, they integrally ensure the safety of all aspects of the SAF during its application. Third, they are the basis for the final system certification. A standards system is an important tool and necessary for technological development. Fuel can be considered a separate technology and a special component of aero-engines that is replaced most frequently. Therefore, SAFs are required to comply not only with airworthiness standards but also with the technical standards of industry associations.

5.1. Technical Standards for Aviation Turbine Fuel

Several countries and international organizations have developed fuel-related standards (Table 3) that include the American Society for Testing Material standard D1655 [65], D4054 [66], D7223 [67], and D7566 [68]; the UK Defence Standard DEF STAN 91-86 [69], 91-87 [70], and 91-91 [71]; the Chinese standards GB 6537 [72], MH/T 6106-2014 [73], CTSO 2C701a [74], and 2C702a [75]; the Russian and the Commonwealth of Independent States standard GOST 10227 [76]; the Canadian General Standards Board (CGSB) standards CGSB-3.23 [77] and CGSB-3.24 [78].

Table 3. International standards for aviation turbine fuel.

Standards System	Standard Code	Standard Full Name	Published Year	Application Scope	Technical Characteristics
ASTM	ASTM D1655-22 [65]	Standard specification for aviation turbine fuels	2022	Jet A and Jet A-1 aviation turbine fuel and acceptable additives	Requirements for fuel components and properties
	ASTM D4054-22 [66]	Standard practice for evaluation of new aviation turbine fuels and fuel additives	2022	Drop-in fuels, additives, and other fuels	Approval process, test program, and property requirements for new aviation turbine fuels and fuel additives
	ASTM D7223-21 [67]	Standard specification for aviation certification turbine fuel	2021	Specific types of aviation turbine fuels	Requirements for fuel components and properties
	ASTM D7566-22a [68]	Standard specification for aviation turbine fuel containing synthesized hydrocarbons	2022	Aviation turbine fuels containing synthesized hydrocarbons	Requirements for fuel production routes, components, properties, and blending ratio
MIL-DTL	MIL-DTL 5624 Revision W [79]	Detail specification, turbine fuel, aviation, grades JP-4 and JP-5	2016	JP-4 and JP-5 aviation turbine fuel	Requirements for fuel components and properties
	MIL-DTL 83133 Revision K [80]	Detail specification, turbine fuel, aviation kerosene type, JP-8, NATO F-35, and JP-8 + 100	2018	JP-8 and JP-8 + 100 aviation turbine fuel	Requirements for fuel components and properties
DEF STAN	DEF STAN 91-86 Issue 6 [69]	Turbine fuel, aviation kerosene type: high flash type, containing fuel system icing inhibitor	2009	High-flash-type aviation turbine kerosene, containing fuel system icing inhibitor	Requirements for fuel components and properties
	DEF STAN 91-087 Issue 7 [70]	Turbine fuel, aviation kerosene type, containing fuel system icing inhibitor	2022	Kerosene-type aviation turbine fuels	Requirements for fuel components and properties
	DEF STAN 91-091 Issue 14 [71]	Turbine fuel, kerosene type, Jet A-1,	2022	Jet A-1 kerosene-type aviation turbine fuel	Requirements for fuel components and properties
GB	GB 6537-2018 [72]	No. 3 jet fuel	2018	Jet fuel No. 3 processed from natural petroleum or its distillates	Requirements for fuel components and properties
MH/T	MH/T 6106-2014 [73]	Technological requirements of aviation turbine fuel containing synthesized hydrocarbons	2014	Aviation turbine fuels containing synthesized hydrocarbons	Requirements for fuel components, properties, and blending ratio
CTSO	CTSO 2C701a [74]	Civil aviation jet fuel containing synthetic hydrocarbons	2022	Jet fuels containing conventional jet fuels and synthesized hydrocarbons or co-processing aviation turbine fuels	Requirements for fuel production routes, components, properties, and blending ratio
	CTSO 2C702a [75]	Civil aviation jet fuel	2022	Jet fuel made from petroleum, natural gas condensate, heavy oil, shale oil, and oil sands	Requirements for fuel components and properties

Table 3. *Cont.*

Standards System	Standard Code	Standard Full Name	Published Year	Application Scope	Technical Characteristics
GOST	GOST 10227-86 [76]	Jet fuels specification	1987	TS-1 and RT aviation turbine fuel	Requirements for fuel components and properties
CGSB	CAN/CGSB 3.23-2019 [77]	Aviation turbine fuel (Grades Jet A and Jet A-1)	2019	Jet A and Jet A-1 aviation turbine fuel	Requirements for fuel components and properties
	CAN/CGSB 3.24-2018 [78]	Aviation Turbine Fuel (Military Grades F-34 and F-44)	2018	F-34 and F-44 aviation turbine fuel	Requirements for fuel components and properties

ASTM, American Society of Testing Materials; CGSB, Canadian General Standards Board.

The aforementioned fuel standards can be divided into three categories according to the application scope as follows:

1. The standards aimed at conventional petroleum-derived jet fuel—such as ASTM D1655, D7223, DEF STAN 91-091, and GB 6537—are applied on fuels refined from well-established processes and feedstocks, i.e., the primary specifications of fuel components and property requirements. Different standards have distinct test programs and methods, with overlaps in requirement properties. Currently, SAFs are usually blended with conventional aviation kerosene; the blended fuel still satisfies aviation turbine fuel standards such as ASTM D1655. Although the application object of these standards does not include SAFs, the requirements therein are also binding for SAFs.
2. The standards aimed at new aviation turbine fuels guide the manufacturers of new fuels through a defined evaluation process. ASTM D4054 is the most representative of this category, the evaluation of which many standards reference. To evaluate a new aviation turbine fuel, changing to an aviation turbine fuel or using a new or changed aviation turbine fuel additive is a standard procedural practice with associated test methods. Drop-in fuels are the primary objects of evaluation, but the standards can also be used for the evaluation of other fuels. A brand-new SAF generally requires the certification of such standards.
3. The standards, represented by ASTM D7566, are intended to regulate synthetic fuels whose production routes have been proven. These production routes have been evaluated and approved using standards such as ASTM D4054. At the time of writing this, seven blends of components or fuels in ASTM D7566 are available, namely Fischer–Tropsch hydroprocessed synthesized paraffinic kerosene (FT SPK), hydroprocessed esters and fatty acids synthesized paraffinic kerosene (HEFA SPK), synthesized isoparaffins (SIP), synthesized paraffinic kerosene plus aromatics (SPK/A), alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK), catalytic hydrothermolysis jet (CHJ), and synthesized paraffinic kerosene produced from bio-derived hydroprocessed hydrocarbons, esters, and fatty acids (HC-HEFA SPK). They are also currently internationally accepted alternative aviation turbine fuels. Accordingly, blended fuel would be considered a D1655 aviation turbine fuel after certification. These standards are formulated to regulate the quality of aviation turbine fuels and are therefore intended to provide specifications for fuel properties, in addition to being continuously upgraded alongside the development of aviation turbine fuel technology.

5.2. Fuel-Related Airworthiness Standards and Their Relationship to Technical Standards

It is necessary to lay out the relationship between fuel-related airworthiness standards and technical standards, as they jointly regulate the development of SAFs. The FAR and ASTM standards are the most representative of the airworthiness standards and technical standards systems, respectively. This section uses these as examples to analyze the role of airworthiness and technical standards in the context of SAF certification.

The airworthiness authorities are responsible for reviewing the elements related to the safety assessment of aircraft and aero-engines, which include some fuel-related standards and sections, e.g., FAR-23.1521(d) [81], FAR-25.1583(b)(1) [82], FAR-33.7 [83], and FAR-34 [84]. However, the airworthiness authorities generally do not approve fuels directly, but reference technical standards set by industry associations and list the approved fuels in the type certificate data sheets (TCDS) of the aircraft or aero-engine.

Early airworthiness standards did not take into account fuels other than jet fuel produced from conventional raw materials. However, new processing techniques are emerging that will allow jet fuel to be produced from other raw materials, such as biomass, natural gas, or coal. With the increased demand for alternative fuels in aviation, the airworthiness system has added relevant requirements in the advisory circulars (ACs), which describe acceptable means. While guidelines in ACs are not mandatory, they are derived from extensive FAA and industry experience in determining compliance with the relevant standards. Applicants typically follow ACs to demonstrate airworthiness compliance and view them as a special extension of airworthiness standards and technical standards.

AC 20-24D [85]—which aims to approve aviation propulsion fuels, and provides guidance on fuel specifications, standards, and certification schemes—cites several fuel technical standards as references. In addition, the FAA has explicitly adopted ASTM's aviation fuel specification as an acceptable specification standard that is directly related to the aircraft's fuel operating limits. The requirements of the standards are clearly stated in official documents, but there is a complex correlation due to their cross-referencing. Therefore, the relationship between AC 20-24D and the ASTM standards associated with SAF certification (ASTM D1655, D4054, and D7566) has been laid out from the perspective of actual fuel certification, as shown in Figure 6.

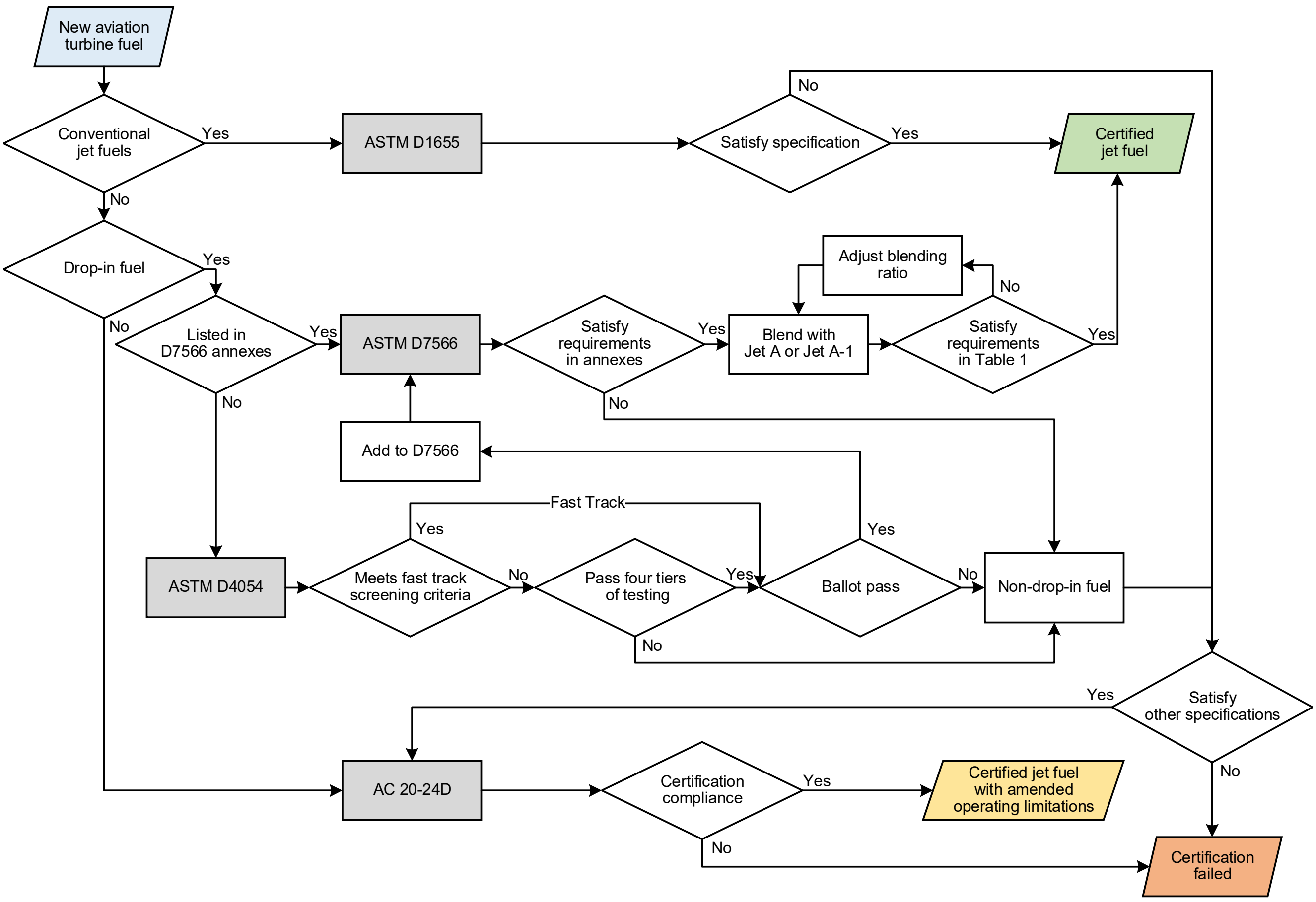

Figure 6. Relationship between fuel-related airworthiness and technical standards.

Several SAF production processes have been developed to meet sustainability requirements. Figure 7 illustrates seven ASTM certified conversion technology routes and three non-certified routes. For a new aviation turbine fuel, including fuel with a new process, manufacturer, or feedstock, the following procedures may be required before it is approved for aircraft, as shown in Figure 6:

- For jet fuel produced from a conventional feedstock such as petroleum, tar sand, or shale oil, testing must be conducted for fuel compliance with the specification criteria in ASTM D1655. According to the ASTM instructions, specifications for conventional jet fuel primarily rely on the measurement of performance properties to ensure that the fuel is suited to the purpose thereof. Compositional analysis generally has not been required due to years of experience with petroleum feedstocks and conventional processing methods.
- For synthetic jet fuel produced from non-conventional sources such as coal, natural gas, and biomass, it must be determined whether the objective of the certification is drop-in fuel, as both D7566 and D4054 are primarily aimed at drop-in fuels. Furthermore, a drop-in (the feedstock and process of which are listed in the annexes of D7566) is evaluated by the specifications of D7566. The neat new fuel must satisfy the corresponding annex requirements. After blending with D1655 aviation turbine fuel (e.g., Jet-A or Jet-A1) in a volume ratio not exceeding the constraint, the D7566 requirements must be satisfied; alternatively, the blending ratio must be reduced until the requirements are satisfied.
- For new drop-in fuel not included in the D7566 annexes, industry experience with new feedstocks and processes is not sufficient; thus, performance property measurements alone may not adequately demonstrate the fuel's abilities, which produces the need for evaluation by the D4054 standard practice. The standard practice consists of four tiers of testing with specification properties, i.e., fit-for-purpose (FFP) properties; component, rig, or materials testing; and engine or aircraft testing. The four-tier system provides a systematic approach for the evaluation of new fuel. Testing is typically performed in the sequence of the tiers and builds upon the successful completion of each. A Phase 1 review is conducted after the second tier to determine the recommended scope of testing for the final two tiers. A final ASTM research report for all four tiers is submitted to the OEMs and FAA for Phase 2 review. If acceptable, then a motion is made to the subcommittee to vote on the research report and the associated new specification or specification revision (referred to as the ballot in D4054). Fuels that pass the ballot are added to D7566. In recent years, testing and evaluation of alternative jet fuels have provided an experience base to allow ASTM to establish a fast track process with reduced testing requirements. The fast track process is only applicable to blendstocks and final aviation turbine fuel blends that satisfy compositional and performance criteria. Fuels that meet the fast track screening criteria can skip the four tiers of testing and directly proceed to the ballot.
- In the event that the objective of the certification is non-drop-in fuel or if the new fuel impacts the specification properties to the extent that the fuel does not conform to D1655, the fuel should be regulated as entirely new and re-validated by the aviation regulatory authorities. According to AC 20-24D, turbine engine fuel approval may involve compliance verification for 19 sections of FAR-33. Applicants must work with the FAA to develop their individual compliance plans. If the fuel can demonstrate compliance with the applicable sections and is approved by the FAA, it can still be listed in some specific engine and aircraft flight manuals. It should be noted that the standard practice of ASTM D4054 is generally one of the main bases for evaluation in AC 20-24D.
- A fuel is considered non-drop-in if the evaluation by ASTM D4054 or D7566 indicates that the fuel does not satisfy the test, ballot, or property requirements, or that the use of the fuel would require changes to the aircraft and engine operating limitations. However, AC 20-24D also allows other standards or specifications to be used as

operational limits for aviation fuels, with more stringency and testing requirements. If an applicant proposes to specify an aviation fuel identified by another governmental, military, or industry voluntary consensus-based standard, designation, or specification, then the applicant should present sufficient information to show that the specification provides an equivalent level of property, performance, and quality control. Moreover, the FAA has determined that independent fuel specifications may be acceptable for the definition of aviation fuel operating limitations if they provide an equivalent level of property, performance, and quality control to those of governmental, military, or industry voluntary consensus-based standards.

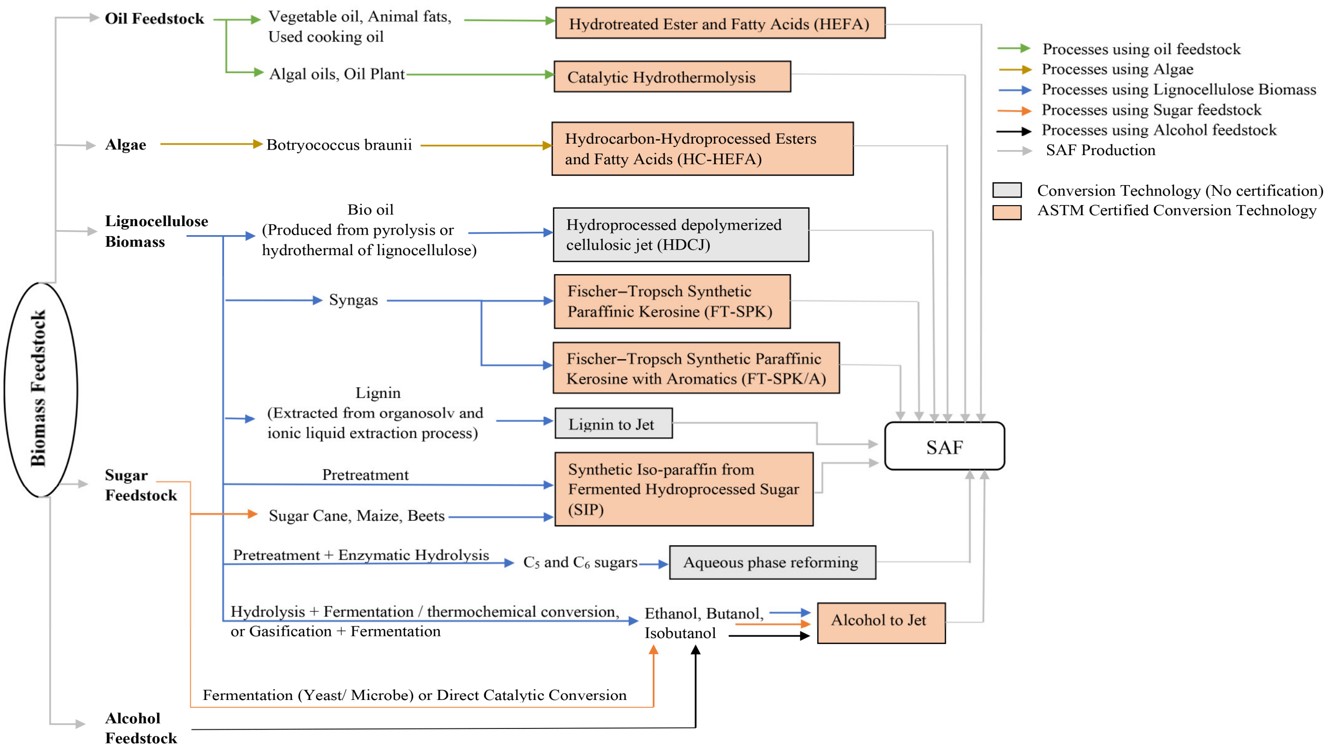

Figure 7. Biomass feedstock types and SAF production pathways [86]; copyright 2022, Elsevier Ltd.

5.3. Characterization of Standards for Aviation Turbine Fuel

For safety reasons, specifications and certification processes for aviation fuels are more tightly controlled than for other products [62]. Both technical and airworthiness standards for aviation turbine fuel are designed to evaluate aviation fuels but have different characteristics and emphases. Technical standards such as ASTM D4054 and D7566 are designed to provide the necessary criteria to determine if the fuel is suitable for existing aircraft, engines, and the aviation operational and supply infrastructure. Standard developers also need to consider the technical, legal, and financial interactions associated with aviation fuels and bring these different perspectives together. Despite the ASTM statement that these standards do not purport to address all safety concerns, safety is the major consideration in ASTM approval.

In terms of specifications, ASTM standards primarily focus on the properties of aviation fuels and specify boundaries for dozens of fuel properties, such as composition, volatility, fluidity, corrosiveness, and thermal stability, with conventional aviation kerosene as the benchmark. This constrains the potential of SAFs because it requires different feedstocks and processes to produce fuels that are extremely similar. It also makes the new SAF significantly more expensive than conventional jet fuel. However, tightly constraining the acceptable ranges of fuel components and physicochemical properties can effectively improve the universality of the certification and avoid issues of storage, equipment compatibility, and blending with existing conventional jet fuels.

The approval process described in the ASTM standards is a rigorous evaluation of alternative jet fuels that requires a significant amount of resources to accomplish [87]. From the viewpoint of airworthiness, the verification of SAFs in the ASTM standards involves several means of compliance, such as a compliance statement (MC0), a design review (MC1), laboratory tests (MC4), ground tests (MC5), and flight tests (MC6), and the test-type methods are dominant. The four-tier system in ASTM D4054 requires a large amount of test fuel. Fuel consumption increases tier by tier, and tier 4 testing can require up to 851,718 L of test fuel. In practice, fuels in the certification phase generally do not enter mass production, and high certification consumption significantly increases the upfront investment costs and development risks. While providing specifications and an approval process, these technical standards also raise the threshold for new SAF development.

Unlike technical standards, the airworthiness standards are evaluated for aero-engines rather than aviation fuels. The airworthiness standards for aviation turbine fuels are only focused on the safety and airworthiness of aero-engines with SAFs applied. The fuel components and physicochemical properties are not directly constrained, as long as the safety of the aero-engine is not negatively affected. As a result, some fuels that differ from existing petroleum-derived aviation turbine fuels but have no negative impact on aero-engine safety may be approved in the airworthiness standards. The need for specifications in AC 20-24D is greatly motivated by batch stability considerations to ensure that fuels produced based on these specifications are controlled in a manner consistent with the fuel used during the certification testing.

Airworthiness standards are more comprehensive in assessing aero-engine safety. Applicants should consider almost all factors related to aero-engine safety issues when demonstrating that an engine operating with a new fuel does not result in unsafe conditions. For example, differences or changes in the combustion characteristics, such as the temperature and pressure, deposit accumulation, fuel lubricity, fuel vaporization, and others should be evaluated by testing or analysis.

Technical and airworthiness standards have their strengths and limitations due to differences in the intent of the standards. Technical standards impose requirements on SAFs from the perspective of fuel properties. Fuels approved by technical standards are more universal, but there are problems such as severe physicochemical constraints and high certification consumption; as such, it is challenging to develop SAFs that satisfy technical standards with preparation costs similar to those of conventional jet fuel. While the airworthiness standards take aero-engine safety as the core requirement, the fuel safety assurance through airworthiness standards is more adequate. However, different types of engine need to be repeatedly demonstrated since the verification of these airworthiness provisions is difficult to extend between types. As the demand for SAFs in the aviation industry increases significantly, the optimization of SAF-related standards by combining the advantages of these two types of standard will be an important research direction in the future.

5.4. Historical Trend

Revisions of standards are not only a summary of experience but also a foreshadowing of the development trend. The SAF standards have been revised several times since their initial publication. The year 2009 was an essential point for SAF-related standards both in D4054 and D7566. In Figure 8, the important changes to the two technical standards from 2009 to date are laid out.

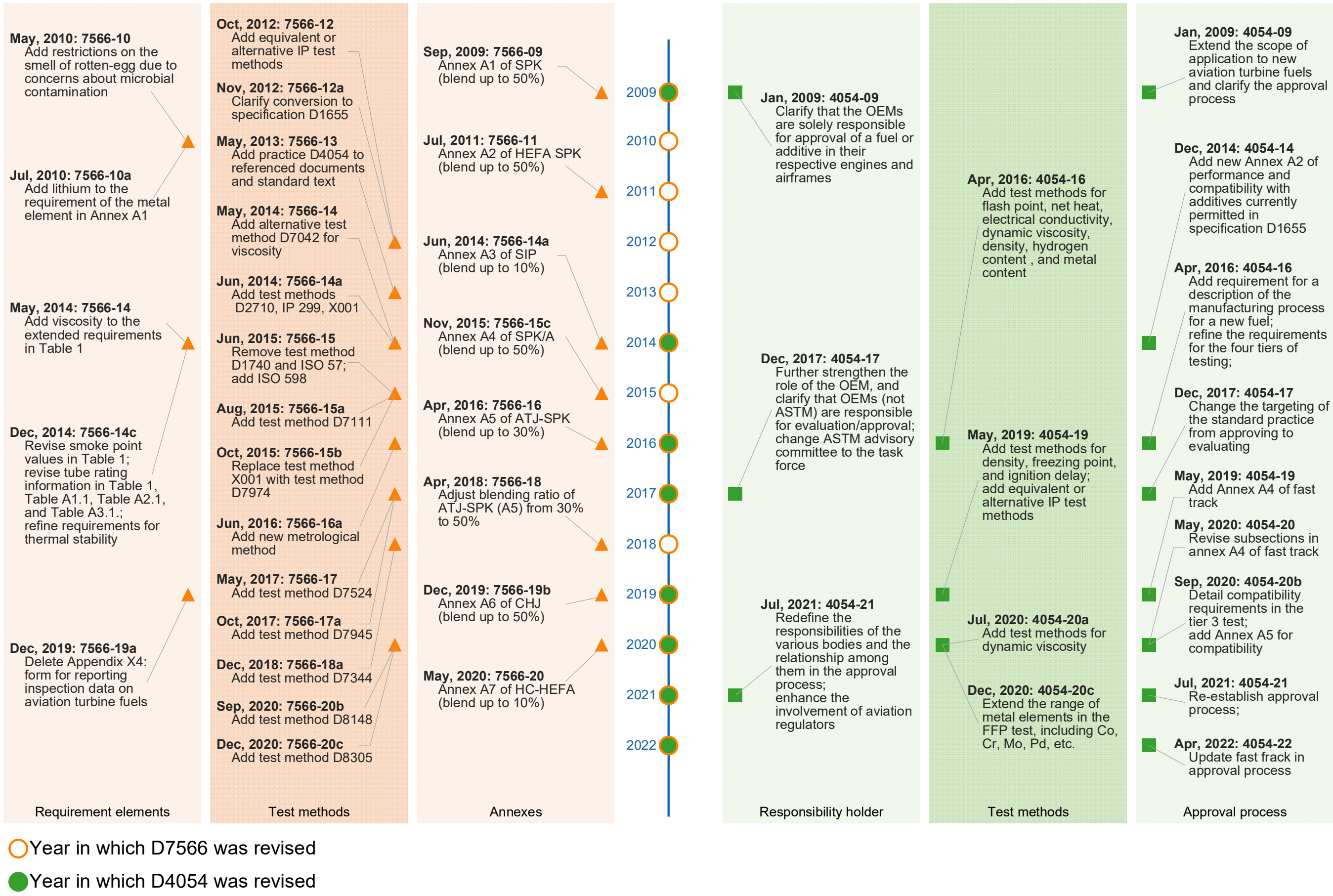

Figure 8. Historical revisions and important updates to technical standards.

5.4.1. ASTM D7566

D7566 was originally issued in 2009. It was updated every year until 2022, and in some years, such as 2014, 2015, and 2016, multiple amended versions were released. Sorting through the revisions to D7566 revealed three main trends: more annexes for approved synthetic blending components, more tests or metrological methods, and more requirement elements.

1. Annexes: The addition of the annexes is the most important part of the D7566 update, which means more synthetic blending components are defined, and more feedstocks are approved for SAF manufacturing.
    - Annex A1 of hydroprocessed synthesized paraffinic kerosene (SPK) was published with the first edition of D7566 and further specified in the 2011 revision as FT SPK.
    - Annex A2 of HEFA SPK was added in the 2011 edition.
    - Annex A3 of SIP from hydroprocessed fermented sugar was added in the 2014 edition.
    - Annex A4 of SPK/A was added in the 2015 edition.
    - Annex A5 of ATJ-SPK was added in the 2016 edition, and the blending ratio requirements were adjusted in 2018.
    - Annex A6 of CHJ was added in the 2019 edition.
    - Annex A7 of HC-HEFA SPK was added in the 2020 edition.

In the current edition, when blended with conventional aviation turbine fuel, the blending ratios of A1, A2, A4, A5, and A6 are limited to up to 50%, while A3 and A7 are limited to up to 10%.

There has been a marked increase in the frequency of additions to the annexes after D4054 was added to the reference documents in 2013. With the help of the current seven annexes, feedstocks such as waste biomass, animal fats, sugars, and cellulosic biomass, have become feedstocks for SAFs. More production routes and feedstocks are expected to be approved and added to D7566 in the foreseeable future.

2. Test or metrological methods: More test or measurement methods have been added with the revisions of the standard. For example, D7566-12 introduced the Institute of Petroleum (IP) standards to the Energy Institute Standards referenced documents as alternative test methods; D7566-14 added an alternative test method (D7042) for viscosity; D7566-15a added test methods for metals; D7566-15b replaced test method X001 with test method D7974; D7566-17 and 17b added test methods for distillation characteristics and viscosity; D7566-20c added test methods for the flash point, freezing point, smoke point, and aromatics.
3. Requirement elements: The number of requirement elements of D7566 is increasing because more potential issues need to be regulated as new aviation fuels are being progressively applied. In D7566-10, the requirements for microbial contamination were further detailed, including suspended matter, the smell of 'rotten eggs,' and some semi-quantitative and quantitative techniques. Lithium was added to the metal element requirements for A1 in D7566-10a. D7566-14a added viscosity to the extended requirements. D7566-14c refined the requirements for thermal stability, materials, and manufacturing, and revised tube rating information.

There have also been some other revisions. For example, D7566-12a clarified the conversion to Specification D1655; D7566-16b defined the specification as the minimum property requirements for aviation turbine fuels rather than the specific type; D7566-22a replaced the term synthetic fuels with synthetic blending components throughout.

In summary, the range of requirements in D7566 has been increasing, and fuel blend specifications have become progressively tighter over recent years. However, more alternative test methods are permitted and more production routes are approved.

5.4.2. ASTM D4054

Although ASTM D4054 is now widely used by organizations to approve new aviation fuel processes, feedstocks, and products, it was originally an approval standard for additives, which is one of the reasons that new fuels have blending requirements, as they were originally treated as a special type of additive. D4054 was first issued in 1981, initially as Standard Practice for Evaluating the Compatibility of Additives with Aviation Turbine Fuels and Aircraft Fuel System Materials. In 2009, as the demand for new fuels increased, ASTM renamed the standard code to Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives. D4054-09 has changed radically, including the scope, requirements, approval process, and definitions. Accordingly, subsequent revisions have focused on the three main aspects: the responsibility holder, test methods, and approval process.

1. Responsibility holder: D4054-09 clarified that the OEMs are solely responsible for the approval of fuel or additive in their respective engines and airframes, and regulatory organizations such as the FAA and EASA participate in the process. D4054-17 further strengthens the role of the OEM in the process. Revisions were made throughout to generally change 'approval' to 'evaluation', clarifying that OEMs (not ASTM) are responsible for evaluation/approval. D4054-21 enhanced the involvement of aviation regulators. The subcommittee task group relies on the recommendations of the OEMs and the FAA to determine if data contained in the research report validate that the fuel or additive is acceptable for use on aircraft and engines.
2. Test methods: D4054-16 added more test methods for the flash point, net heat, electrical conductivity, dynamic viscosity, density, hydrogen content, and metal content. It also specifies the typical fuel volume requirements to evaluate a new fuel. D4054-19

updated the Energy Institute standard to the referenced documents and added test methods for density, freezing point, and ignition delay. D4054-20a added test methods for dynamic viscosity.

3. Approval process: D4054-09 introduced the first approval process for new aviation turbine fuels, which required significant resources to complete. However, extensive testing and evaluation of alternative jet fuels have provided a sufficient experience base to allow the establishment of a fast track process with reduced testing requirements [66]. The fast track and the corresponding Annex A4 were proposed in D4054-19 and were further standardized in D4054-20 and D4054-22. In D4054-20a, the target values for the fast track were changed to be used as guidelines rather than limitations, and they could be exceeded in some cases if deemed acceptable during this screening process.

The approval process has been substantially revised in D4054-21. Compared to the previous approval process, the current edition replaces the test-by-test evaluation with a review and data report every two tiers. This allows the internal review to be carried out earlier, rather than after all the test programs have been completed. Figure 9 shows a comparison between the original approval process and the current approval process with the fast track. To further promote the research and application of SAFs, institutions and researchers around the world are trying to optimize the approval process for faster and less time-consuming certification while ensuring safety. For example, the National Jet Fuel Combustion Program (NJFCP) in the US aimed to streamline the fuel certification procedures for alternative jet fuels [88].

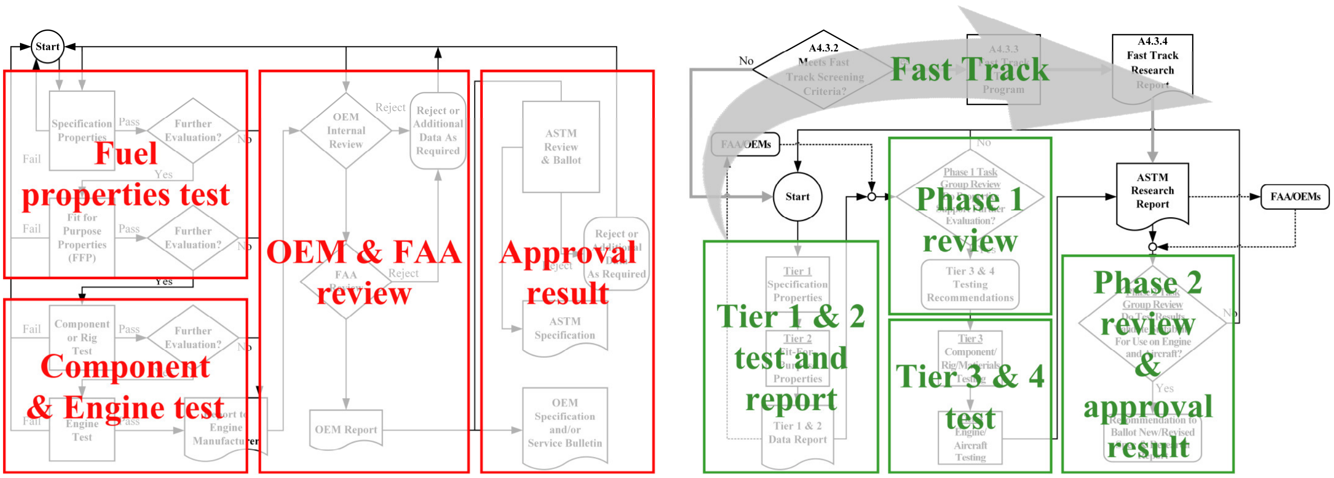

Figure 9. Comparison between the original approval process and the current approval process in ASTM D4054. Reproduced from [66,89]; copyright ASTM International.

6. Discussion and Perspective on the SAF-Related Safety Standards System

Despite the considerable progress made in SAF research with the help of technical and airworthiness standards, it remains a great challenge to produce an SAF that is safe, affordable, and sustainable. The standards need to minimize fuel constraints while ensuring safety. It is therefore useful to discuss the requirements of these standards from the perspective of aero-engine safety and to speculate about the possible future concessions and revisions.

6.1. Blending Ratio

The current technical standards require the blending of SAFs with D1655-compliant conventional jet fuels and impose an upper blending ratio constraint for each approved fuel. However, these blending ratio requirements seem to lack objective criteria. Practice has shown that the density, aromaticity, or other properties often limit the amount of SAFs that can be added to conventional jet fuel to less than the upper blending ratio [68]. With the development of SAF technology and a significant increase in market demand, aero-engines may use blends with SAF ratios higher than 50%, or even 100% pure SAF.

Several OEMs have already invested in 100% SAF aero-engine testing. In late 2020, Rolls-Royce used 100% SAF in the ground test of the technology demonstrator for its next-generation UltraFan engine program [90]. One Trent 1000 engine on a Boeing 747 platform in 2021 used 100% SAF for nearly 4 h of flight verification, and Rolls-Royce confirmed that all Trent engines will be 100% SAF compatible by 2023 [91]. The open rotor architecture engine, which is part of the 'revolutionary innovation for sustainable engines' program developed by Safran in collaboration with General Electric, will also support the use of 100% SAFs [92]. The use of 100% SAFs is the future trend for aero-engines, and removing the blending ratio constraint will further enhance the role of SAFs in emissions reduction.

Moreover, the blending ratio requirement also arguably involves a potential conflict of interest insomuch as it may not be in the commercial interests of a petroleum supplier to blend in SAFs produced by an independent bio-refiner, unless compelled to do so by some regulatory requirement [93]. Loosening or removing blending ratio constraints could also increase the motivation for independent bio-refiner development. Note that factors such as existing storage facilities and fuel compatibility should be considered in the process of revising blending ratio requirements [38].

6.2. Specification Properties

The specification property requirements in aviation fuel standards consist of elements and their ranges. Elements refer to the properties involved in the specification, while ranges refer to the upper and lower limits acceptable for each property. Taking into account the historical trends of the standard and the development prospects of SAFs, the requirements for fuels in future standards are likely to involve more property elements and wider or more specific property acceptability ranges.

More SAF-specific property elements may appear in future standards. The specification property elements in the current SAF-related standards evolved from D1655. With the increasing variety of SAF processes and feedstocks, more new properties will be required in the standard. This trend is also evident from the historical revisions of D7566. The range of properties permitted in the standard could be broader. D7566 defines the range of fuel properties using the boundaries of Jet-A and Jet-A1 as the reference. However, some properties may not have to be limited to the ranges of conventional jet fuels, and the margins on the actual properties with respect to standard limits are not defined [93].

Density is an example of a property whose range is likely to be extended. Both D1655 and D7566 contain requirements on the density of the fuel, with specific values for the upper and lower limits. The blended fuel density needs to lie between 775 and 840 kg/m^3. The main consideration for the lower limit of the density is its effect on the flight range. With a defined fuel tank volume and calorific value, a lower density will limit the range. However, it may be possible to reduce the density further if the calorific value is sufficiently large. The upper density limit, at least from the viewpoint of aero-engine safety, does not need to be bound. The upper density limit is more likely to be extended by combining other factors, such as storage, transport, and refinement.

Another example is the freezing point. As the technology advances in SAFs, a variety of SAFs may be developed in the future. Fuel property requirements may be refined for air routes with different characteristics. For example, for some short-haul routes, the flight altitude is generally lower than that of international long-haul routes, and the freezing point requirement can be appropriately relaxed. Just as in conventional jet fuel, Jet A is permitted to have a relaxed freezing point requirement of -40 °C, compared to Jet A-1's freezing point of -47 °C because Jet A-1 is intended for long-haul flights [65].

In addition, requirements for aromatic content may become more specific. The current table of detailed requirements of aviation turbine fuels containing synthesized hydrocarbons in D7566 specifies only maximum values for aromatic content. However, if the aromatic content of the fuel is too low, it may lead to problems like fuel leakage. Currently, the safety of this regard needs to be verified by tests. If the minimum values for aromatics are specified in the fuel property requirements, it is beneficial to use less fuel, sooner, and to quickly assess the impact of the fuel on engine safety. Therefore, we believe that future fuel physicochemical property requirements may specify constraints on minimum values for aromatic content. In fact, the minimum aromatic content requirement has already been specified in Annex A6 for CHJ, but not in the Annexes for other fuels.

Future property ranges can be derived from aero-engine safety implications. For example, a mapping between the fuel properties and aero-engine safety-critical parameters (SCPs) can be established. The margins of SCPs are determined from historical data, and the extended ranges of fuel properties can be derived from the SCP boundaries [94]. This would help to ensure safety while reducing fuel property constraints.

6.3. Safety Approval

To ensure the safety of aero-engines after SAF application, more rigorous safety reviews are required to fit the more extensive range of fuel properties. As mentioned earlier, safety requirements at the fuel property level would constrain the potential for SAF development. A viable approach would be to place more responsibility for safety on airworthiness standards. The standards system uses the aero-engine as the subject of a safety review, thus minimizing safety constraints on components and physicochemical properties.

Aero-engine safety requirements need to be specified in the evaluation. Conventional jet fuel is considered as a base reference for safety, which can be used to determine safety boundaries. Current technical standards require SAFs to be identical to conventional jet fuels in terms of fuel properties, which is a fuel level similarity check. Following the same logic, similarity checking can also be performed at the engine safety level. With engine system safety as the top-level objective, a new path of SAF certification with safety equivalence as the only criterion can be established to enhance safety assurance.

Similarity checks at the engine safety parameter level rather than the fuel property level are more in line with airworthiness requirements. The potential for SAF development can be unleashed and fuel options can be expanded without compromising system safety. However, this also requires more ways to guarantee the universality of the fuel to avoid the differences in fuel application due to the specific design of the type of engine.

In the Horizon2020 project carried out by China and the EU, the technical standard order (TSO) mode—which is a minimum performance standard for the specified materials, parts, and appliances used on civil aircraft—is borrowed to establish a certification system for fuel 'components', which could solve the common problem of SAF application to similar engines. This would help to improve certification universality while reducing fuel certification consumption and difficulty.

6.4. Verification Methods

The preceding discussion showed that test-type methods are dominant in the validation of both technical and airworthiness standards for fuels, and this causes two issues. First, the test-type methods require extensive test fuel consumption, especially for the verification of engine endurance. This can significantly increase the cost of certification before the fuel has been mass produced. Second, the level of aero-engine system safety is a combination of the probability of failure and the severity of the consequences. The probability of failure results cannot be obtained through a limited number of tests, and it is difficult to provide sufficient evidence of safety with test-driven verification methods.

There are two potential directions for development in terms of verification methods to address these issues. On the one hand, future standards will likely reduce the test duration requirements for some certification processes. For example, the endurance test may be reduced from 150 to 50 h or less by increasing parameters such as the rpm transient rate and peak temperature. On the other hand, increasing the weight of analysis (MC2) and simulation (MC8) in certification methods is another way forward. A similar trend has been observed in recent years in airworthiness standards, where the role of system safety analysis methods in the airworthiness compliance demonstration process is gradually increasing. The combination of modeling, testing, and analysis will help to obtain the probability of failure results and provide more adequate safety assurances.

6.5. Testing Equipment

ASTM D4054 practice involves tests on components, rigs, or engines from OEMs. OEM review and evaluation of new fuels are required to ensure that engine operability, performance, and durability safety requirements are not impacted by the new fuel. However, test equipment is defined by OEMs each time rather than being fixed, and even components and engines could be sourced from different OEMs. Close coordination between the fuel manufacturer and OEMs is required to conduct testing. This process covers multiple OEMs, and the identification of test equipment for the new SAF can take a long time when balancing the potential benefits among OEMs. In practice, fuel manufacturers may have difficulties coordinating OEMs in different countries, including issues such as scheduling, policies, and interests.

For airworthiness standards, the specific engine and its components are usually used as test equipment. This ensures the safety of the engine after the SAF application. However, a similar certification process must be repeated before application to other engine types.

Future standards may include standardized test equipment dedicated to fuel certification, including components, rigs, and engines. Test equipment can be limited to engine types, power levels, and ranges of applications, e.g., equipment for SAF testing of turbofan engines with maximum thrusts of five to 10 tons and equipment for SAF testing of low-power turboshaft engines up to 500 kW. Smaller engines also help reduce fuel consumption, and many SAF studies have been conducted using micro-engines for similar purposes [48,64]. The standard equipment will be iterated gradually as aero-engine technology progresses, but in the short term, all SAFs will be tested using the same sets of equipment. Standardized test equipment could help to improve the efficiency of certification and also reduce the burden on OEMs in SAF approval. More importantly, this will facilitate the development and certification of SAFs by fuel manufacturers around the world, especially those from countries without OEMs.

6.6. Review Criteria

Technical standards have some links to be decided through discussion or ballot. The recommendations of the OEMs and the FAA are important references for the ASTM task group in determining whether the testing data indicates that the fuel is acceptable for further evaluation. In ASTM D4054, there are no objective criteria listed for the reviews, test requirements, or final ballot session for the new specification.

Admittedly, as there is still insufficient research experience (given that the SAF-related standards have only been in operation for fewer than 20 years), the current standards are hardly likely to present clear criteria in all review processes. With a discussion and ballot by multiple organizations, potential safety issues can be avoided as much as possible in the current stage. However, it is expected that more explicit criteria for review will gradually emerge in future standards as data accumulates, like quantitative ranges or qualitative expressions.

7. Conclusions

In this study, it was observed that carbon reduction has become one of the major trends in technology for the aviation industry. Moreover, SAFs are regarded as an important means of carbon reduction because they have a carbon-neutral or even carbon-negative potential throughout their lifecycles. Over the past years, considerable progress has been made in the use of SAFs. However, SAF application is far below expectations, and petroleum-derived fuel still dominates the aviation fuel market. Standards regulate the safety of SAFs, but some issues constrain the SAF potential.

The purpose of this paper was to summarize and discuss the SAF-related standards systems from the perspective of aero-engine safety, including airworthiness and technical standards. There were deviations in the safety requirements of SAFs due to differences in the intents of the standards. Airworthiness standards were specific to aero-engines and focus on the safety effects on the engine after SAF application. In contrast, ASTM standards have focused more on the fuel properties, and the requirements of physicochemical properties for SAFs have been constrained with Jet-A or Jet-A1 as the benchmark. A new SAF is required to satisfy both types of standard before being applied to aero-engines. In this study, the relationships between standards in the certification process for fuels as well as the approval routes for aviation fuels were summarized. Based on a compendium of standard characteristics and relationships, the SAF-related standards and related prospects were discussed together with the historical revisions of technical standards.

In light of the above, the future SAF-related standards system could move toward additional safety in aero-engine performance with fewer constraints on the fuel properties. The following changes are recommended.

- Blending ratio restrictions should be removed to promote the replacement of conventional aviation fuels with SAFs.
- More property elements and wider property acceptability ranges should be used to uncover SAF development potential and avoid potential safety issues.
- There should be more focus on aero-engine level safety reviews to fit the broadened fuel properties.
- With the need for test-based certification methods reducing, a more comprehensive system safety and less test fuel consumption could be achieved by combining simulations and safety analysis.
- More explicit review criteria and standardized test equipment should be established to encourage fuel manufacturers worldwide to study the next generation of SAFs.

In addition to the above, the following valuable research directions are identified for SAF-related standards and safety approval.

- System safety analysis methods applicable to fuel certification should be investigated. Notably conventional safety analysis methods like fault tree analysis (FTA) or failure mode and effects analysis (FMEA) are based on considerable experience, and may therefore be unfeasible for new fuels that lack operational data. Recently developed system safety analysis methods such as model-based safety analysis (MBSA) could be used to establish aero-engine-level safety criteria based on conventional aviation fuel operation data and to implement comparative safety analysis for SAFs.
- Aero-engine performance simulation tools with fuel property resolution should be developed. Importantly, combustion reaction simulations and aero-engine performance simulations are generally carried out independently, which is efficient for conventional combustion studies or aero-engine design. However, for SAF safety assessment, SAF combustion simulations should be embedded in the aero-engine performance simulation model to verify the impact on system safety.

Finally, combustion chambers and engines for SAF test approval must be designed, and the test equipment must reflect the characteristics of the same type of equipment to achieve certification universality, in addition to adequately representing the potential safety issues of SAFs.

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Abbreviations

SAF	Sustainable Aviation Fuel
ASTM	American Society of Testing Materials
CCS	Carbon Capture and Storage
ICAO	International Civil Aviation Organization
OEMs	Original Equipment Manufacturers
GHG	Greenhouse Gas
HEFA	Hydrogenated Esters and Fatty Acids
CH	Catalytic Hydrothermolysis
HDCJ	Hydroprocessed Depolymerized Cellulosic Jet
FT	Fischer–Tropsch
ATJ	Alcohol-to-Jet
DSHC	Direct-Sugar-to-Hydrocarbon
CAAF	Conference on Aviation and Alternative Fuels
GFAAF	Global Framework for Aviation Alternative Fuels
IATA	International Air Transport Association
FAA	Federal Aviation Administration
EASA	European Union Aviation Safety Agency
CAAC	Civil Aviation Administration of China
MC	Means of Compliance
US	United States
EU	European Union
LBO	Lean Blow-Out
IFSD	In-flight Shutdown
FAR	Federal Aviation Regulations
TCDS	Type Certificate Data Sheets
AC	Advisory Circular
FFP	Fit-for-purpose
SPK	Synthesized paraffinic kerosene
FT SPK	Fischer–Tropsch hydroprocessed Synthesized Paraffinic Kerosene
SIP	Synthesized Iso-Paraffins
SPK/A	Synthesized Paraffinic Kerosene plus Aromatics
ATJ-SPK	Alcohol-to-Jet Synthetic Paraffinic Kerosene
CHJ	Catalytic Hydrothermolysis Jet
IP	Institute of Petroleum
NJFCP	National Jet Fuel Combustion Program
SCPs	Safety-Critical Parameters
TSO	Technical Standard Order
MBSA	Model-Based Safety Analysis

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