ASTM QUALIFICATION PROCESS FOR SUSTAINABLE AVIATION FUEL

Abstract

The aviation industry alone contributes an estimated 2% to 3% of all carbon dioxide (CO_2) emissions. ASTM International's Subcommittee D02.J0 on Aviation Fuels has therefore developed standards to address the process to qualify environmentally acceptable, synthetic blend components (SBC) to be used in aviation fuels. This promotes the use of SBC as jet fuel blend stocks to produce sustainable aviation fuels (SAFs) ensuring that aviation fuels remain safe and reliable. This paper provides an overview of the challenges posed by uncontrolled CO_2 emissions and ASTM Internationals support of the aviation industry's initiatives to meet the International Civil Aviation Organization's goal of net zero CO_2 emissions by the year 2050.

Introduction:

In 2025, carbon dioxide (CO_2) emissions due to aviation continued to rise, beyond pre-covid levels, reaching 960 million tons with an increase in demand resulting in a 2.7% increase compared to 2019 as seen in Figure 1 [1, 2]. Energy related CO_2 emissions are also growing faster in other sectors like rail, road, and shipping [1, 2]. A report put out by the International Bureau of Aviation (IBA) in 2025 shows that while total CO_2 emissions have risen, the intensity varies by region as seen in Figure 2 [1]. Due to the impact that CO_2 emissions have on climate change, the scientific consensus is to reach net zero emissions by 2050 to reduce carbon emissions to amounts that can be absorbed and stored by nature and other CO_2 removal measures leaving no emissions in the atmosphere [3]. Aviation organizations, with the collaboration with airlines, have formed roadmaps to meet decarbonization goals. The International Air Transport Association (IATA) is a global organization representing airlines that promotes the adoption of SAF to help reduce the aviation industry's carbon footprint. They passed a resolution with member airlines committing to achieve net-zero carbon emissions from their operations by 2050 [4, 5]. The International Civil Aviation Organization (ICAO) is a UN specialized agency that sets global aviation standards and policies which have set the Carbon Offsetting and Reduction Scheme (CORSIA) that supports the use of SAF to achieve carbon reduction and offsetting goals, ensuring compliance and international environmental standards [4]. The roadmap has set a goal of 55 percent emissions reductions by 2035 [1, 2, 3]. Air travel has become more efficient however it is no longer sufficient, absolute emissions continue to rise alongside growth in passenger and cargo demand [1]. To meet the United Nation's Net Zero goals, aviation CO_2 emissions must be reduced rapidly. The most efficient road towards aviation decarbonization is dependent on sustainable aviation fuels [1, 2].

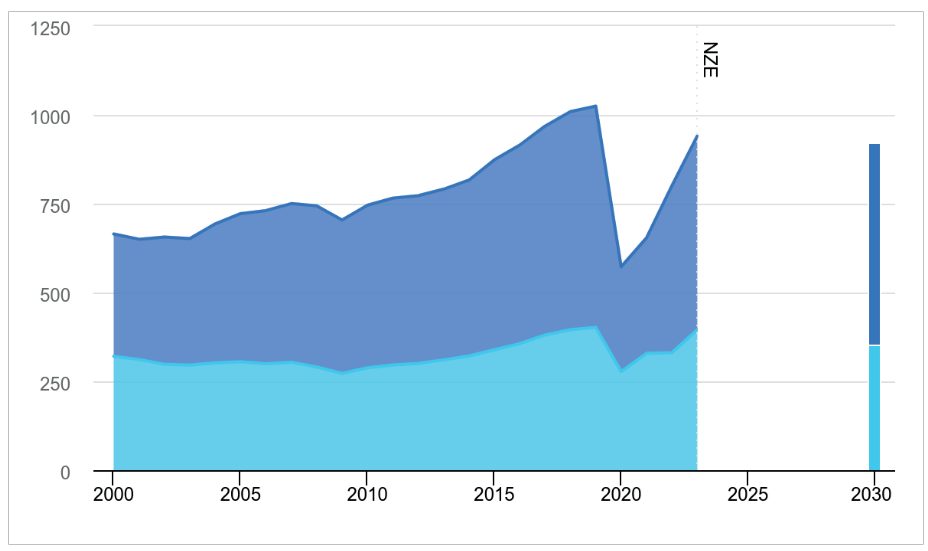

Figure 1: CO_2 emissions from 2000 to 2023 with estimated emissions for 2030 [1]

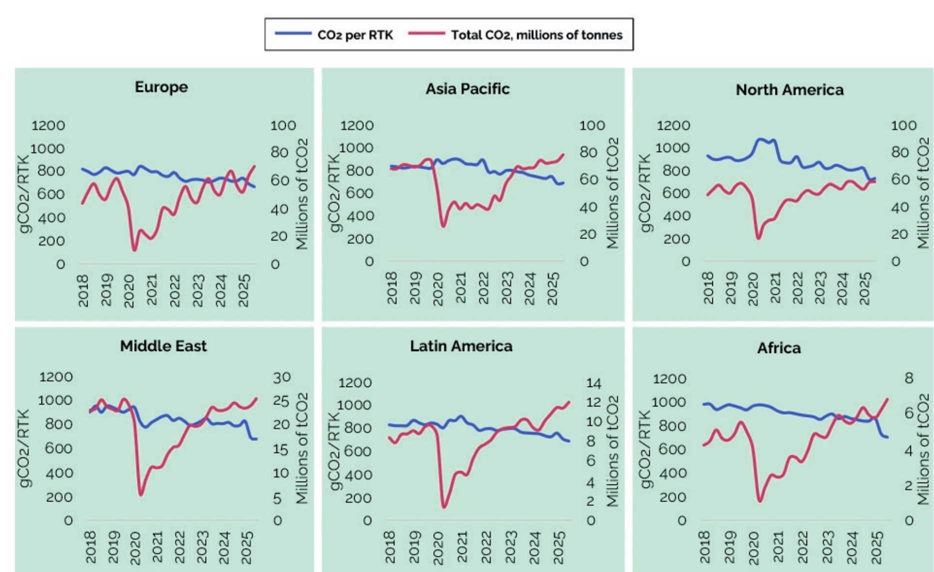

Figure 2: CO_2 intensity across various regions [2]

Sustainable Aviation fuels (SAFs) are synthetic biofuels used to power aircraft with properties like conventional jet fuels with a smaller carbon footprint [6]. SAF is made by blending conventional fuel with up to 50% Synthetic Blending Component (SBC) which is derived from renewable feedstocks like waste oils and biomass containing only no-fossil components [7]. No aircraft are certified to fly on just SBC currently and are instead used in the manufacturing of semi-synthetic jet fuel [8]. The most important criterion for SAFs is that they are drop-in fuels, they can be used in aircraft without the need for accommodations to the aircraft infrastructure [9]. According to current standards SAFs can be a blend of SBC in conventional fuel between 10% and 50% based on the feedstock and production process [10]. To further increase the impact of SAF, research is being done to facilitate the use of 100% SBC by 2030, without the need for blending [2]. With the aid of government policies and investments to the private sector for further research and development of SAFs, goals set by international climate agreements for decarbonization can be met.

The American Society for Testing Materials (ASTM) is the global authority in voluntary standards for materials ensuring consistent performance that can be trusted creating confidence in their products [11]. Their standards are developed through an open volunteer process where anyone can propose a new standard and then a dedicated technical committee dissects the proposal, refining it through multiple stages of review and feedback [11]. The standards define chemical, mechanical, and metallurgical properties allowing for consistency among products [11]. SBCs and SAFs must meet different ASTM standards, ensuring that SAFs are compatible with conventional aircraft and SBCs can be blended into conventional jet fuels as they are intended [9]. ASTM standards also determine the blend rates which range between 10% to 50% of SAF into conventional fuel, the limit is determined during the ASTM qualification process [10]. ASTM standards are crucial for SAFs and SBCs. ASTM standards and mandates are imperative for fuel manufacturers to be able to create quality fuel that is applicable across existing aircraft and infrastructure [10]. However, standards across the world vary and even ASTM standards are continuously updated to allow for advancements in technology causing complexities when candidate fuel producers are going through the rigorous and expensive ASTM approval process for SAFs making the process time consuming. With more government and private sector incentives towards renewable fuel research and development as well as ASTM approval process resources, these roadblocks could be avoided.

1. ASTM Qualification Framework

The American Society for Testing Materials (ASTM) formed in 1898 by Charles B. Dudley when 70 people met in Philadelphia [12, 13, 14]. In 2001 ASTM changed to ASTM international and launched a memorandum of understanding program with standards bodies worldwide [14]. ASTM international serves as the international standard for materials used in consumers products including jet fuel quality [12, 13]. ASTM standards are now accepted worldwide and cover areas such as metals, paints, plastics, textiles, petroleum, construction, energy, the environment, and consumer products [11, 12, 13]. These standards are developed through an open process which guarantees everyone the ability to participate, allowing anyone to propose a new standard often referred to as the candidate fuel producer [11]. A dedicated technical committee made up of industry stakeholders collaborated to define the standards for various materials, they dissected the proposal, refining it through rigorous stages of review and feedback [11,13]. For jet fuel, these industry stakeholders include original equipment manufacturers (OEMs), federal agencies, fuel suppliers, fuel producers, technology providers, and trade associations from across the world as seen in Figure 3 [12, 15]. Some international partners involved in global standard-setting include the Asia-Pacific Economic Cooperation (APEC), The International Finance Corporation (IFC), Millennium Challenge Corporation (MCC), and the United Nations (UN) [15]. ASTM plays an important role in ensuring safety, quality, and reliability of SBCs and SAFs [11,13]. For jet fuel, these standards include specifications that describe the requirements for material, system or service test methods used by manufacturers on their products and include expected results [16]. Furthermore, they provide instructions for procedures that help maintain a general practice in industry [16]. Companies that produce SBCs and SAFs, like SkyNRG, Roboze, benefit from ASTM standards, allowing them to meet the quality standards required for SAF to be used in aircraft, the standards include guidelines that aid these companies [12, 17].

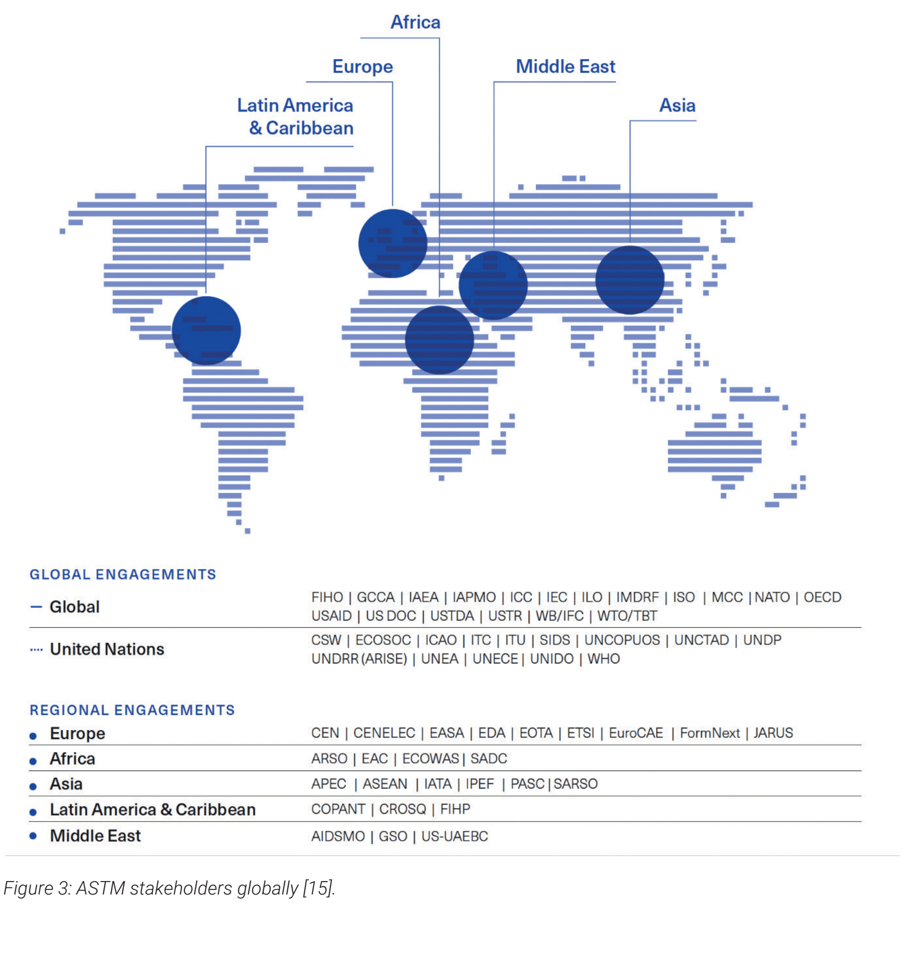

Figure 3: ASTM stakeholders globally [15].

1.1 Conventional Jet Fuel: ASTM D1655

Traditionally, aircraft utilize jet fuel derived from a kerosene base that is compatible with gas turbine engines. Kerosene is a distillation product of petroleum; it was once used as a pure product to power jet engines and now powers commercial airliners and other aircraft [18]. Aviation turbine fuel is a complex mixture mainly made of hydrocarbons which structures vary based on the manufacturing process [18]. In the United States there are three main types of jet fuel that meet the basic specifications: Jet A-1, Jet A, and Jet B described in Figure 4 [19]. Jet A is primarily used in the United States for domestic and international flights, does not contain static dissipater, and has a freezing point of -40℃ [18, 19]. Jet A-1 is turbine fuel with a lower freezing point at -47℃, containing static dissipater, and commonly used outside the United States [18, 19]. Jet B is not as commonly used and known for its enhanced cold-weather performance, giving it applications in colder climates with a freezing point of -50℃ or below [18]. Primary grades of jet fuel must meet the specifications of ASTM D1655: The Standard Specification for Aviation Turbine Fuels, the global basis of all jet fuel quality specifications for each batch produced [12, 18].

ASTM D1655 includes specifications that define the minimum property requirements for Jet A and Jet A-1 aviation turbine fuels, listing acceptable additives for use in civil and military operated engines [18, 20]. It was initially developed for civil applications but has now been adopted to be used for military aircraft [18]. The standard which previously included Jet B no longer does, as the FAA has issued a special airworthiness information bulletin, Jet B fuel now falls under ASTM D6615: Wide-cut Aviation Turbine Fuel [18, 20, 21]. This standard describes the quality of aviation turbine fuel from production to the aircraft, but it does not describe the quality assurance testing and procedure needed to ensure that the fuel complies with the specification [20]. The procedure is outlined in ASTM D4054: Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives [12].

Jet Fuel	Description	Freezing Point
Jet A	Used Primarily in the United States and does not contain static dissipater as an additive.	-40℃
Jet A-1	Aviation turbine, normally containing static dissipater. This fuel is commonly outside the United States	-47℃
Jet B	Rarely used, known for enhanced cold-weather performance, giving it applications in cold climates. However, it is more dangerous to handle. It's mixture strongly differs from the two other grades, as it is defined as a "relatively wide boiling range volatile distillate"	-50℃

Figure 4: Jet Fuel specifications simplified through ASTM D1655

1.2 SAF ASTM Standards: ASTM D7566

SAFs utilized in aircraft are drop-in fuels allowing them to be used in aircraft infrastructure without the need for infrastructure accommodation [10, 12]. Neat SAF is produced through ASTM approved SAF production pathways under the ASTM D7566 standard: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons, it is the only globally recognized fuel standard for the qualification of SAF in the aviation industry [12]. This specification provides a standardized method to evaluate and certify SAFs, ensuring they meet safety requirements and their performance remains consistent [22]. It defines the minimum property requirements for aviation turbine fuel that contain synthesized hydrocarbons and lists acceptable additives for use in engines and aircraft [23]. ASTM D7566 is directed toward civil applications but may also be adopted for military, government, or other specialized uses [23]. All ASTM certifications are pertinent for building confidence amongst airlines, manufacturers, passengers, and regulators in terms of reliability and safety [22].

There are currently 11 approved pathways, listed in 8 different annexes as seen in Figure 5, the last pathway being approved in July 2023 [12, 24, 25]. An annex is an approved path or method of creating an SBC to add to conventional jet fuel [26]. Each annex includes the definition of allowable feedstock, conversion process, and blending component attributes and blending criteria [26]. All the annexes are for the same fuel just different synthetic production pathways controlled by individual annexes which produce SBCs [26]. There are two tables included in each annex: Table 1 and Table 2 used to identify the properties that must be tested for each SAF [7]. Table 1 specifies the key technical requirements for the SBC, including testing for critical properties like aromatics content, freezing point, viscosity, density, and flash point. The tests are conducted before the SBC is blended with conventional jet fuel to form SAF to ensure the SBC meets performance and safety standards [7]. The second table outlines the management of change (MoC) testing, and this is only required when significant changes occur in the production process like alterations in feedstock or technology [7]. SAF is a drop in fuel and has properties like jet fuel, SBC is blended with Jet A and Jet A-1 fuel which can be done after neat fuel is created at existing fuel terminals [10]. SBC in its neat form must meet the ASTM D7566 certification requirements [26]. Once the fuel is blended with Jet A and Jet A-1, the new fuel must meet the blend requirements and standards of the D1655 certification, used for conventional jet fuels as seen in Figure 6 [12].

ASTM approved SAF pathways

SAF Pathway	Abbreviation	Blending Limit	Feedstock	Description
Fischer-Tropsch Syntehtic Paraffinic Kerosene	FT-SPK, ASTM D7566 Annex A1	50%	Woody biomass: MSW, agriculutral wastes, forest wastes, wood, and energy crop	woody biomass converted to syngas using gasifaction which is then syntehsized through FT reaction to produce SAF
Hydroprocessed Esters and Faty Acids	HEFA, ASTM D7566 Annex A2	50%	oil-based feedstock	feedstock is hydroprocessed to break apart chain of fatty acids. Then Hydroisomerzation and hydrocracking occur to produce drop-in fuel
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins	HFS-SIP, ASTM D7566 Annex A3	10%	sugars	Microbial conversion of sugars to hydrocarbons. The feedstocs are pretreated to be eligible feedstocks.
FT-SPK with Aromatics	FT-SPK/A,ASTM D7566 Annex A4	50%	Woody biomass: MSW, agriculutral wastes, forest wastes, wood, and energy crop	Similar to FT-SPK but with aromatic components
Alcohol-to-Jet Syntehtic Paraffinic Kerosene	ATJ-SPK, ASTM D7566 Annex A5	50%	cellulosic biomass	feedstock is converted through series of chemical reactions: dehydration, hydrogenation, oligomerization, and hydrotreatment.
Catalytic Hydrothermolysis Synthesized Kerosene	CH-SK or CHJ, ASTM D7566 Annex A6	50%	Fatty acids, fatty acid esters, or lipids from fat oil greases: soybean oil, jatropha oil, camelina oil, carinata oil, tung oil	fatty acid oil extracted from processing waste oils or energy oils and is combined with preheated feed water. That is then passed through a catalytic hydrothermolysis reactor
Hydrocarbon-Hydroprocessed Ester and Fatty Acids	HC-HEFA-SPK, ASTM D7566 Annex A7	10%	triglyceride oil: Algal oil	triglyceride oil is converted to jet fuel through fractionations.
Synthetic Paraffinic Kerosene with Aromatics	ATJ-SKA, ASTM D7566 Annex A8	50%	Sugars, starches, Lignocellulosic biomass, and alcohols	similar to ATJ-SPK but with aromatizaiton step.
Fats, oils, and grease Processing	FOG(CO), ASTM D1655 Annex A1	5%	Fats, oils, greases	FOG processed with petroleum intermediates.
FT Co-processing	ASTM D1655 Annex A1	5%	FT biocrude	FT syncrude processed alongside petroleum crude oil to produce SAF
Co-processing of HEFA	ASTM D1655 Annex A1	5%	Renewable lipids: vegetable oils, used cooking oils (UCO), or animal fats	Blending Renewable feedstocks with fossil-based feeds in existing HEFA process

Figure 5: 11 ASTM approved SAF pathways, abbreviation, ASTM certification, blending limit, feedstock, and brief description [12, 24].

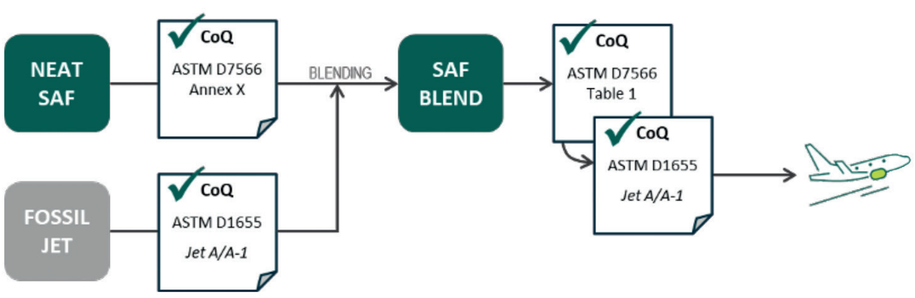

Figure 6: Flowchart of approval process required for drop-in SAF [12].

SAF is between two to five times more expensive to produce compared to conventional jet fuel and therefore is produced at lower quantities [27]. This is primarily driven by the cost of feedstock, which is expensive due to the inefficient supply due to the competition with other industries [27]. SAF is often made with virgin vegetable oil in the only commercially available production pathway, the Hydroprocessed Ester and Fatty Acids (HEFA) which is more expensive than the counterpart: conventional jet fuel made with kerosene [10, 12, 25, 27]. There are limited plants producing SAFs through the Alcohol to Jet (ATJ) and Fischer Tropsch (FT) pathways which are still being developed to reach commercial maturity [10, 12, 25]. For SAFs to be competitive with jet fuel, there must be more diversity in the pathways and feedstock used to produce them. There are currently 11 production pathways under evaluation, pending certification [25].

1.3 Approval Process: ASTM D4054

SAF production is currently not competitive with conventional jet fuel production; some of these barriers including feedstock and the lack of sufficient pathways to produce the SAF needed to meet CORSIA's decarbonization goals for the Net Zero Emissions Scenario. The diversification of SAF pathways can only occur through the approval of more pathways that meet the ASTM D7566 and ASTM D1655 specifications [22]. SAF approval must follow the process outlined by ASTM D4054: The Standard Practice for Evaluation of New Aviation Turbine and Fuel Additives [28]. This process involves several stages with the intent to permit a new fuel or additive to be evaluated and transitioned into fuel use [28, 29]. A new production pathway is introduced by the candidate fuel producer. The specifications in ASTM D4054 guide them through a clearly defined evaluation process with prerequisite testing [28, 29]. These tests assess the impact of the pathway or additive impact they have on the fuel due to alterations in production methods or transportation [29]. New SBCs and SAFs gain ASTM D7566 approval and subsequently ASTM D1655 approval [12]. The complete ASTM D4054 process is outlined by the flowchart in Figure 7 [30]. It is completed with collaboration between the candidate fuel producer and D4054 Clearinghouse which was established by the Federal Aviation Administration (FAA) under the Center of Excellence for Alternative Jet Fuels and Environment (ASCENT) program [28, 30, 31]. The process is necessary to ensure that the new production method or additive is compatible in commercial aviation gas turbine engines [30, 31].

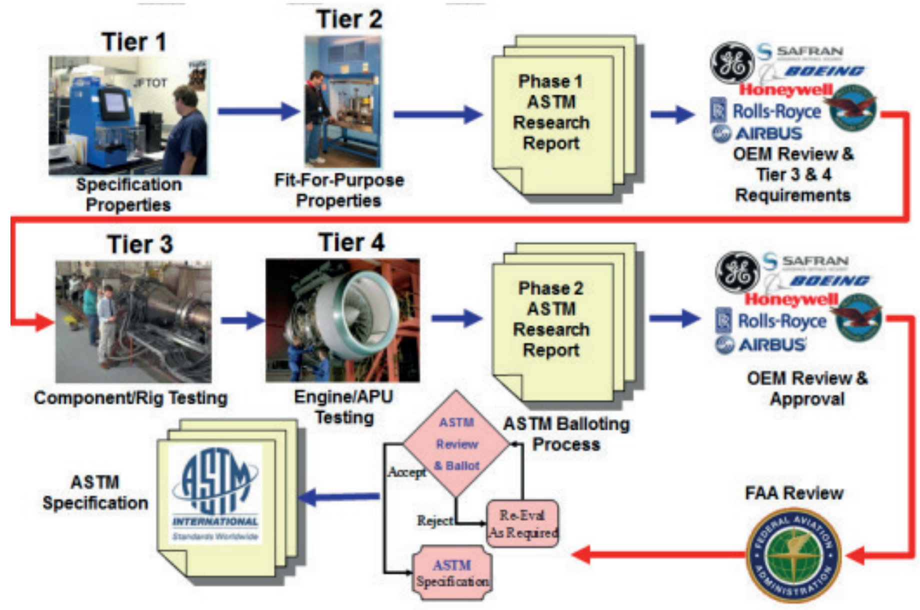

Figure 7: Complete ASTM D4054 qualification process [30].

The two-phase process starts with the fuel screening stage where the candidate fuel producer provides ASTM D1655 Table 1 test data [30]. Table 1 details the requirements of aviation turbine fuel covering physical properties and expressions of the fuel's allowed composition as seen in Figure 8 [32]. D4054 Clearinghouse analyzes the data through a two-tier process leading to the Phase 1 ASTM Research Report as seen in Figure 9 [30]. The producer submits an overview of the candidate fuel production process including feed stocks and key process steps [30]. The first tier requires the measurement of the current jet fuel specification properties from the candidate fuel producer [20]. As seen in Figure 9, if there is a negative impact on the properties, the fuel does not progress further but if they have a positive impact, it moves to tier 2 [20]. Tier 2 testing is Fit-for-purpose testing which addresses fuel properties that are not listed in the specification but are important for design and performance of gas turbine engines including electrical properties, ground and handling safety, and compatibility properties [20, 31]. If the properties for FFP testing are acceptable the process moves towards the Phase 1 Research Report or the preliminary research report which is submitted by Clearinghouse to OEMs and includes data about airworthiness organizations, and international fuel specification standards groups, if the report is not accepted, the process restarts at Tier 1 testing [20, 30, 31]. The candidate fuel producer supports the OEMs review by providing answers to questions and data as needed [30]

Properties	Impact on Fuel
Thermal Stability	Reflects the fuel's resistance to oxidation and polymerization and its resistance to forming harmful deposits.
Smoke Point	High smoke point temperature means less chance of producing unhealthy smoke emission when burned
Aromatic Content	Influences smoke point: lower aromatic content results in less smoke and less carbon deposition
Density	Low Density: Fuel has low heating value, and aircraft will not travel too far. Density also determines how the fuel is metered in injectors
Distillation	Influences volatility of the fuel and vaporization.
Viscosity	Impacts fuel pumpability over the temperature range of its use. Also relates to keeping a consistent spray pattern from the injector nozzle

Figure 8: Table 1 properties and the impact they have on fuel [32]

Phase 2 of the approval process commences with the component testing which might be required if asked for by the engine OEMs [20]. Component tests are dependent on the results from the specifications and FFP tests done in phase 1, if component tests are found to be unnecessary, the process moves to the final research report [20, 30]. Tier 3 of tests starts with component and rig testing, these tests include an atomizer cold spray test, a combustion rig test, an ignition test, and emissions tests measuring thermal stability [20]. Tier 3 tests are conducted to establish compatibility with industry components [26]. If component rig testing is acceptable, the process moves to the fourth tier which is Engine/ Auxiliary Power Unit (APU) Testing [20]. Tier 4 carries out system-level testing including oxidative and corrosive tests on turbine blade metallurgy and coatings, fuel systems test, and combustor rig tests [26]. Tier 3 and 4 tests are done in collaboration with the OEMs and other test facilities facilitated by Clearinghouse [30]. It is the responsibility of the candidate fuel producer to deliver neat fuel and support any additional tests and data collection that might be necessary while Clearinghouse distributes the fuel to testing facilities [30]. Once the necessary tests are completed with satisfactory results, The phase 2 Research Report or the final research report is submitted to the OEM review panel [30].

Once the OEM panel is satisfied with the research report, the producer enters a motion with the ASTM D02.J6 subcommittee to ballot the final research report submitting a proposal ballot to the ASTM D02.J ballot secretary [30]. ASTM International D02 is the committee on petroleum products, liquid fuels and lubricants [26]. Clearinghouse supports the ballot process by providing resources to conduct further testing inhouse or through a third party [30]. If the pathway is accepted, a new jet fuel will be listed in ASTM D7566 as a new annex unless it is too similar to a previous pathway and if rejected, re-evaluation will be required [30].

2. Addressing Challenges

To meet the goals of the Net-Zero emissions scenario, SBC production must be scaled up to meet the decarbonization demands for aviation. There are 11 ASTM approved pathways as seen in Figure 5 and there are 11 more pathways under evaluation as seen in Figure 10 [10, 12, 24, 25]. There are many challenges hindering the scaling up of SBC production all branching from the fact that petroleum-based fuels are more cost effective than SAFs. Technical barriers start at the beginning of the process with feedstock diversity which is being addressed through various studies and investigations into alternative and less expensive avenues of feedstock [33]. The cost of SAF is primarily driven by the cost of its feedstock [27]. Currently, 82% of current SAF production is reliant on HEFA technology which is capped by the availability of used cooking oil (UCO), waste animal fats, and other lipid feedstocks [34]. First generation feedstock which were important to early stages of SAF development have fatty acids with saturated and unsaturated fatty acids which serve as an intermediate for the formation of aromatics [35]. Second-generation feedstock is often UCO and oil recovered from industrial waste [35]. Finally, third-generation feedstock is a major advancement as a potential source of lipid feedstock like microalgae which further minimizes competition with food crops [35]. Going into the future, feedstock quality and availability must be improved [35]. To meet decarbonization goals, another solution is to approve and commercialize more SBC production pathways to produce a larger amount of SBC per year [10, 36].

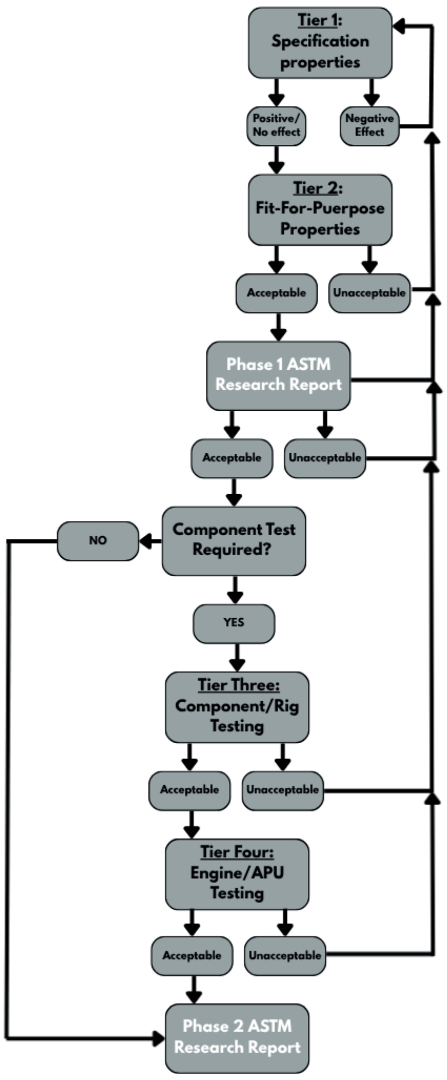

Figure 9: ASTM 4054 specified qualification process flow chart [20]

The certification and regulatory approval process is mandatory to ensure the safety and efficacy of the SBC; however, the process can be cost and time intensive [36, 37]. The approval timeline is lengthy, requiring extensive testing and approval phases which leads to delayed market entry and prevents aviation from meeting decarbonization goals [37]. Through the ASTM Practice D4054 approval process it can take several years to obtain approval for a new pathway or additive. This timeline reflects the comprehensive nature of the tests for new aviation turbine fuels and fuel additives [26]. As seen in Figure 7, the four tier testing process is a lengthy and resource-intensive process done as a collaboration between D4054 Clearinghouse and the candidate fuel producer [26, 37]. Furthermore, there can be discrepancies with regulatory frameworks based on time and location which can lengthen the certification process. There is a constant need for updates to standards which increase the operational complexity and the certification process requiring adaption from producers and airlines [37]. The Aeronautics Science and Technology Subcommittee of the Committee on Technology came up with federal Alternative Jet Fuels Research and Development Strategy which identified that cooperation between the federal government and the private sector are essential including non-governmental organizations (NGOs) and academia [33]. In the certification process, stakeholders like CAAFI and "Farm to Fly 2.0" are critical to coordinate the efforts between the public and private sectors [33, 38]. There are also varying international regulations between the public and private sectors [33, 38]. There are also varying international regulations between countries limiting global reach and SBC production [37]. This can be prevented by developing standards in a proactive manner by consulting international stakeholders and inviting them to participate in the process of creating new regulations [39]. This allows for international standards to be developed decreasing complexity among SBC Candidate Producers.

D4054 Clearinghouse and the candidate SAF producer collaborate to complete the required tests in-house or through a third party guided by the process outlined in ASTM D4054 for all four tiers of lab testing. These tests are often redundant and expensive, causing the approval process to be resource intensive. The Federal Alternative Jet Fuels Research and Development Strategy identifies research and development goals to assist in overcoming fuel testing and evaluate challenges [33]. Their effort focuses on facilitating approval of SBC production pathways through efficient evaluation through advancements to the certification and qualification processes and collection and analysis of data [33]. If testing is streamlined through a process involving the development of generic rig combustion and numerical modeling there will be a reduction in cost, time, and uncertainty of a certification and acceptance of candidate alternative jet fuels [33].

Another solution to reduce the time for the approval process is via the "Fast Track" program offered by Clearinghouse, described in ASTM D4054 Annex A4 [26, 40]. The program permits a limited test protocol of tier one and other further limited testing dependent on acceptable hydrocarbon bulk composition and trace material analyses [40]. This process avoids the cost and time that is needed for tier 2,3, and 4 testing [40]. However, due to the limited testing done in the "Fast Track" program, the blending percentage for SBCs are limited to 10 percent and require the blend stock to meet stringent specifications [40]. The ASTM "Fast Track" test bed is currently under development at Trinity College Dublin to perform the Fast Track Certification where the technical, business, and regulatory aspects of the program are all encompassed in one place [41]. Alternatively, prescreening can also be completed ahead of submitting the SBC into the approval process. This does not replace ASTM D4054 approval, but it provides the fuel developer confidence and an outlook on downstream challenges as well as helping to facilitate later qualification [40].

Conversion process Under Evaluation	Abbreviation	Lead Developers
Synthesized aromatic kerosene	SAK	Virent
Integrated hydropyrolysis and hydroconversion	IH2	Shell
Single Reaction HEFA (Drop-in Liquid Sustainable Aviation and Automotive Fuel)	DILSAAF	Indian CSIR IIP
Pyrolysis of non-recyclable plastics	ReOIL	OMV
Co-processing of pyrolysis oil from used tires	TPO	Phillips 66
Increase in fatty acid/ester co-processing form 5% to 30%		
HEFA with higher cycloparaffins		Revo
Biomass pyrolysis		Alder
Biomass/Waste Pyrolysis		Green Lizard
Cycloalkanes from Ethanol		Vertimass

Figure 10: ASTM pathways pending approval [25].

3. Future Outlook

The aviation community has agreed that SBC is the key to meeting decarbonization goals set by ICAO and CORSIA. To meet these goals, SAF production will need to rise from 40,000 barrels per steam day (BPSD) in 2025 to about 400,000 BPSD in 2035 [42]. SkyNRG's 2025 market outlook reports that 82% of current SAF capacity relies on HEFA with demand set to outpace HEFA's production potential, which will create a projected 26 Mt gap between supply and demand by 2035 [42]. Stakeholders such as airlines, who are the primary buyers and organizations absorbing cost premium over conventional jet fuel, have set SBC goals for 2030. The costs to create SBCs are greater than conventional jet fuel due to the tension demand mandates and production incentives [34]. Making sure that SBC policies are consistent globally with clear structures is important to build SBC production to meet the demands for SAF [34]. This way, fewer resources are required in the approval process for new pathways allowing more of them to become available to diversify SBC production pathways, scaling up SAF production.

SBCs must be mixed with conventional jet fuel to be used in aircraft engines, as they lack aromatics leading to leaks [8]. There are other parameters such as viscosity and density that also make the blending step necessary [8]. However, there is currently research being done to increase blending limits of SBCs in jet fuel. During their production, SAFs rely on renewable feedstocks and energy which leads to fewer CO_2 emissions being released compared to the manufacturing of conventional kerosene-based jet fuel. In 2024, through the ECLIF3 study, an Airbus A350 powered by Rolls-Royce Trent XWB engines, followed by a DLR chase aircraft conducted flight with 100% SAF [43]. The results showed a reduction in soot particle emissions and formation of contrail ice crystals compared to the use of conventional aviation fuel [43]. Therefore, it was found that SAF in flight reduces the climate impact of aviation in the short term by reducing non-CO_2 effects such as contrails [43]. That same year in Georgia, Gulfstream Aerospace Corp, used neat SAF with no sulfur on the Gulfstream G700 powered by Rolls-Royce Pearl 700 engines [44]. Like the ECLIF3 study, results showed a decrease in the overall climate impact of aviation [43, 44].

Finally, there are 11 current SAF pathways that are currently under the approval process as seen in Figure 10 with additional qualifications being pursued as well. This lowers the cost of production through finding pathways that require lower temperatures, pressures, lower cost of materials, advanced catalysts and separation technologies, and more selective or retention of feedstock hydrocarbon structure [45]. ASTM international recently approved Honeywell's methanol-to-jet (MtJ) pathway which has been upgraded into a SAF with high yield and selectivity [42]. The technology and fuel samples were used in qualification, but the pathway will be available to all producers operating within the specifications [46]. Virent's synthetic aromatic kerosene uses aqueous phase reforming of sugars and catalytic processing; it is currently in stage 2 of the ASTM D4054 approval process [45]. The company advocates for drop-in fuels as a solution to avoid complications of introducing new fuel systems or the need for modifying current ones [47]. Another pathway currently going through the approval process is Shell IH2's SAF which is an integrated hydropyrolysis and hydroconversion of lignocellulosic materials [45]. With more pathways in the approval process additional investment must go into resources needed to speed up these processes to get more pathways producing SAF on the commercial scale.

Conclusion

The aviation industry has become increasingly efficient over the last decade; the carbon intensity is not up to par to meet the carbon emissions [10]. To meet decarbonization goals set by organizations like the ICAO and the UN, the easiest solution is to address turbine fuel to reduce the emissions created during production as well as combustion. Alternative fuel or SAFs are made from sustainable resources like used cooking oil, feedstocks that reduce the carbon footprint of the fuel [9]. SAFs are drop in fuels which must meet the specifications of ASTM D7566 ensure usefulness in established aircraft turbine infrastructure without the need for accommodation [12]. For fuels to be approved for SBC certification, they must go through a rigorous process requiring time and resources outlined in the specifications of ASTM D4054 [12, 13]. The fuel is proposed by a producer that collaborates with D4054 Clearinghouse for multiple tiers of testing with various resources gathered from the producer and Clearinghouse established through the ASCENT program of FAA [13]. Once the SBC is approved, it is blended with conventional jet fuel and must meet the specifications set by ASTM D1655 for conventional jet fuel [20]. This extensive multi-stage process is time consuming, with the urgent need for SAF scale-up, further resources are required like programs like the Fast-track program that Clearinghouse offers [26]. However, to meet the demand of decarbonization goals, government policies must be expanded and additional investments through research and resources must be made to the private sector, encouraging organizations to devote more time to SAF approval processes and production.

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