Title: Opportunities for SATF Qualification Improvements

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Executive Summary:

Fuel qualification methods are comprehensive and effective but can continue to be improved.

- There is a well-established, evidence-based standard and a clearly delineated approach to the qualification of novel synthetic[1] aviation turbine fuels (SATF) that should be affirmed and supported (e.g. ASTM D4054 – Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives).
- As has happened over the last two decades, research and testing development can continue to improve, providing earlier insight into the viability of turbine fuel replacements or blending components, perhaps to the point of enabling more rapid and less costly qualification of SATF, as well as enabling more aggressive approaches toward broader applicability of molecules suitable for incorporation into turbine fuel, for blending restrictions, and use of advanced SATF production concepts.
- Governmental assistance is welcome in enhancing qualification of new SATF pathways, including:
  - Enabling SATF producers to produce test volumes of fuel, perhaps at dedicated Process Development Units
  - Assisting with the development of improvements of inspection and testing methodologies
  - Supporting one-stop clearinghouse efforts where SATF producers can get financial/technical assistance in testing/validation iterations to help finalize their production processes, and having research reports completed that thoroughly and appropriately document physical and fit-for-purpose properties necessary for qualification consideration by the broader aviation community.
- Specific areas likely requiring further government support and funding to enable concept enhancement (perhaps through another world-wide research effort) are outlined in the last section of this document, summarized in the following 4 themes.
  - Fuel Chemical Testing Refinement
  - Reducing Required Volumes for Fuel Testing
  - Correlation of Testing Data with Fit-For-Purpose Properties
  - Additional Risk Reduction

[1] Synthetic (or synthesized) is used in this context to refer to any turbine fuel that is derived from hydrocarbon sources other than conventional petroleum sources, including crude oil, natural gas liquid condensates, heavy oil, shale oil, and oil sands.

History and Background

Safety Assurance for Novel Fuels

Aviation fuel has an outstanding safety record supported by Airworthiness Regulations, which certify aircraft and engines to operate using specific fuel(s). This means the aircraft's design has been demonstrated to deliver the requisite performance, operability, safety, and efficiency defined by the certification regulations. Such fuel(s) is then considered an Operating Limitation which is specified by the original equipment manufacturer (OEM) as part of Airworthiness Standards. Airworthiness operating and flight rules require aircraft operators to use only the fuel(s) specified in the Operating Limitation. Fuels contained in Operation Limitation are controlled by a Fuel Specification which defines not only the critical properties of the fuel, but the appropriate methods for measuring those properties and the acceptable ranges to be measured.

The OEM group (consisting of the major airframe, engine, and systems manufacturers) plays a critical role in fuel review and approval. Because aviation turbine fuel is an Operating Limitation of Airworthiness Standards, as part of the type certification process, the OEMs have the necessary expertise to review and validate the compatibility of novel fuels with aircraft systems. Therefore, consensus among all major OEMs is required for the approval of new synthetic blending components and sustainable aviation fuels within turbine fuel specifications. Incorporating fuel specifications and approval pathways without OEM oversight is not advisable, as it could jeopardize safety and undermine performance standards in aviation. The aviation fuel industry, including fuel producers, distributors, regulators, OEMS, airlines, and many others, strive to ensure that fuel test methods and specifications control a fuel throughout the entire supply chain (refinery to aircraft fuel tank) to ensure that the fuel meets operational requirements for consistently safe use.

Integration of Novel Fuels through Fuel Qualification (ASTM)

Alternative fuel production processes have been under development for over a century, with dedicated efforts for aviation turbine fuels initiating during the oil shocks of the late 1900s, but then more earnestly in the early 2000s. These efforts focused on drop-in fuels, fuels that would not require changes to existing aircraft, fueling infrastructure, and other fuel delivery systems. SATF pathways represent a combination of fuel feedstock, production process, and final fuel characteristics. The first synthetic fuel pathway, Fischer-Tropsch synthetic paraffinic kerosene, was approved in 2009 and annexed under ASTM D7566[2]. This first pathway involved extensive testing to address many uncertainties within the fuel community, consuming an estimated

[2] ASTM Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons

710,000 gallons of fuel over several years and requiring coordinated efforts across various branches of government. Subsequent pathway approvals followed, and, thanks to improved testing and growing experience, fuel volumes used for each approval reduced over time, with some pathways using as little as 50 gallons.

Improvements in fuel qualification are thanks in large part to continued government support and strong industry coordination. Today, these coordination efforts center around the ASTM D4054 Standard Practice, and several institutions and processes that support the guidelines therein (e.g. the ASTM D4054 Clearinghouses in the USA, UK and Europe; CAAFI's and Jet Screen's Pre-screening guidance and testing, led by Washington State University and DLR, …). The ASTM D4054 standard practice outlines procedures for evaluating new aviation turbine fuels and additives. Robust industry participation, including fuel testing and data review, ensures the safety and performance of novel synthetic aviation turbine fuels in the current fleet and future aircraft. Coordination across aviation OEMs, fuel producers, and researchers enables continued improvement in fuel qualification and testing methods.

Currently, there are eight pathway annexes under ASTM D7566 covering a range of feedstocks and production processes. These annexes define the feedstock, production process, physical and fit-for-purpose fuel attributes, and blending limit for a particular synthetic blending component (SBC). Blending limits vary across annexes, with some allowing as little as 10% SBC to be blended with conventional Jet A. The current maximum allowable blend limit under ASTM D7566 is 50% SBC with conventional Jet A. There are ongoing efforts to allow for higher blend limits, up to 100% synthetic fuels.

Enhancing the Understanding of the Performance of Novel Fuels

Based on qualification efforts between 2009-2013, it became increasingly clear that the industry needed to see some improvements in the basis of SATF qualification. Beginning in 2014, the FAA coalesced the interests of several US agencies, to fund the National Jet Fuel Combustion Program (NJFCP) through their Aviation Sustainability Center of Excellence (ASCENT)[3]. Prior to the NJFCP, the collective understanding of jet fuel properties variation and its effects on fuel systems and combustion was limited and largely concentrated within the minds of a few engineers who had little interaction with each other or with decision makers within other companies or government agencies. A typical combustor design engineer would have known that high fuel viscosity challenges atomization goals (with ignition implications) and

[3] Similar efforts were undertaken by other agencies in this timeframe, including, e.g., DLR-VT. FAA's contribution to these efforts exceeded $8M in direct funding, with other agencies (NASA, AFRL, DLA Energy, NavAir, DOE, ARL, NIST, and several additional governmental or academic institutions) contributing a combined equivalent amount. OEMs significantly supported this work through cost-share.

that high aromatics challenge the goal to minimize smoke emissions, but other intricacies of fuel property variation and property interdependencies were more veiled. Otherwise, the knowledge base was fractured and applied differently within different OEMs, and on the certification of different products.

Over the course of 7 years of effort on testing and analysis of various turbine fuel compositions, the NJFCP focused on how fuel properties affect gas turbine combustor operability. In one pillar of that research of note, gas turbine lean blowout was proven to be strongly influenced by the chemical reactivity of fuels, represented by derived cetane number (DCN), with an importance-scaling relative to the fuel's physical properties being dependent on combustor size and design. Forced ignition, on the other hand, proved to be primarily impacted by the fuel's physical properties; viscosity (principally), surface tension, density, and perhaps its distillation curve. These results were counter to the intuition of many combustion design engineers and design practices.

A new-to-some way of collecting and comparing ignition data was introduced and standardized during the NJFCP. The air pressure, temperature and flow rate as well as the spark frequency and energy are held constant in controlled experiments while the fuel flow rate is increased until ignition occurs, and the process is repeated several times to garner statistically meaningful data. The ignition probability is plotted as a function of fuel to air ratio (or equivalence ratio), with separate graphs for each operating condition. A surprisingly (to some) high difference between fuels was demonstrated in the NJFCP program, underscoring the importance of fuel properties on ignition. The spread between the best and worst conventional fuel was shown to be approximately 25% of the nominal, across all operating conditions that were tested.

Since the conclusion of the NJFCP, research on fuel properties variation and its effects on aircraft systems has continued informally. Industry now has a better understanding of the role that fuel composition variation (both bulk and trace) impacts turbine fuel property variation across a broad range of properties. For example, the impact of trace concentration of sulfur in jet fuel on contrail formation, size and duration has been characterized. Generally, the community has gained greater understanding of predictive model uncertainties and many laboratory-scale investigations have provided a greater understanding of issues such as materials compatibility, lubricity, viscosity as a function of temperature, vapor pressure and distillation curves, dielectric constant, freeze point, DCN, etc., as well as further detail relating to how fuel effects on combustion differ with respect to operating condition or combustor size and design. Additionally, significant advances have been made in low sulfur measurement capability and significant granularity has been added to bulk hydrocarbon composition determinations.

Current Efforts

Fuel Qualification Activities at ASTM

SATF Blendstock Pathways

The ASTM community continues to expand the specifications for new SATF pathways under the current model of qualifying blendstocks and associated blending requirements. To support these efforts, the FAA has, through the Aviation Sustainability Center (ASCENT), established the D4054 Clearinghouse, which has since been emulated with Clearinghouses in the UK and the EU.

The D4054 Clearinghouse roles are to:

- Facilitate the qualification process (i.e., data collection and OEM review)
- Provide trusted, third-party technical data for candidate samples
- Act as a liaison between fuel producers and OEM user community
- Educate stakeholders (e.g., new producers) about the SATF qualification process established by the aviation fuels community (i.e., ASTM D4054, D7566, and D1655).

Past and present producers who have submitted materials to the clearinghouse include international entities based in India, Japan, South Africa, Austria, Finland, Denmark, United States, and France to name a few. Some of the qualification advocates are large multinational corporations, and some are much smaller regional companies.

Currently, producers are pursuing nine unique SATF blending component (SATF-BC) qualifications through the U.S. D4054 Clearinghouse and one additional SBC qualification was started but has been placed on hold by the producer. The U.S. Clearinghouse anticipates an additional 5-6 producers to enter into active qualification for new pathways in 2026. Advance discussions with other researchers in industry and academia continue to occur, suggesting a considerable number of additional pathways will be pursued, corresponding to a range of feedstocks, conversion processes, and hydrocarbon molecules, some of which are not currently present in conventional jet fuel.

Drop-in 100%-SATF Specification (Fully-SATF)

In addition to the well-established approach of qualifying SATF-BCs through ASTM, the industry is seeking an option to qualify and use 100% synthetic fuels (fully-SATF). A fully synthetic specification would enable flexible utilization of synthetic fuels and would potentially simplify procurement and supply chain structure. A draft proposal has been developed for creating a specification for fully-SATF. The proposed draft specification centers on a fuel definition that targets a nominal/typical Jet A/A-1, rather than allowing for the full range of Jet A/A-1

attributes currently experienced with petroleum-based Jet A/A-1. The intent is to avoid marginal and unusual Jet A/A-1 characteristics in novel fuels, thereby reducing risk of safety or performance issues. The effort does not include options that would not qualify as Jet A/A-1 today (e.g., paraffinic-only fuel) or co-processing processed based fuels.
The draft proposal includes two separate approaches to qualify a drop-in fully synthetic fuel:

1) By utilizing a single pathway that could produce such a fuel. Currently, three out of the eight qualified pathways already generate products that consist of paraffinic and aromatic hydrocarbon fractions found in petroleum-based jet fuel and which are candidates for fulfilling a fully-SATF specification.
2) By blending two or more synthetic blending components, such as a paraffinic one with an aromatic one. In this approach, the industry initially needs a requirement ensuring that only already qualified synthetic blending components from ASTM D7566 with dedicated annexes could be used for blending.

At this time, OEM feedback on the draft fully-SATF specification has been received and is under evaluation to consider potential further adjustment to the proposal. When consensus is reached among the OEM community, a ballot will be advanced at ASTM.

Jet Fuel Co-processing

Jet fuel co-processing is a SATF production technique where alternate feedstocks are mixed and simultaneously processed with fossil streams in conventional refineries. By utilizing the scale of production at existing refineries, co-processing offers large-scale global SATF manufacturing without significant capital expenditure.

Currently, co-processing of lipids, Fischer-Tropsch hydrocarbons, and hydroprocessed fatty acid methyl esters are acceptable for jet fuel manufacturing at concentrations ranging from 5 to 30% by volume. Several new proposals for coprocessing materials have formal ASTM Task Forces, including the co-processing of waste plastics oil, pyrolyzed mixed plastics, and tire pyrolysis oil.

To accelerate co-processed jet fuel production, a "Generic Co-processing" ASTM Task Force has been developing a ballot that aims to significantly increase the pool of allowed co-processed feedstocks. The concept trades flexibility of applicable feedstocks with stricter manufacturing and finished product controls. This may allow more co-processing pathways to go straight into production without individual ASTM balloting. Currently, this proposal is for alternate feedstocks up to 5 % volume.

This Generic coprocessing taskforce is Chaired by an OEM (P&W) and co-chaired with a major oil producer (ExxonMobil). Two ASTM ballots have been submitted to date. The committee is working to resolve multiple negative votes from Q4 2025 balloting and is aiming for a third ballot to be issued in Q2 2026.

Where government support can enable continued progress

Funding universities and research laboratories to enhance test methods and improve the understanding of composition-property relationships is essential, as it will enable the development and adoption of sustainable aviation fuels. Further, driving down fuel volume required to achieve full testing will enable both more rapid and less expensive fuel qualification.

Fuel Chemical Testing Refinement

Significant progress has been made over the last 15 years in improving analytical test methods that focus on enhancing understanding of fuel chemistry and properties. For example, the development and adoption of two-dimensional gas chromatography (GCxGC) have been instrumental in improving the resolution of fuel composition down to the carbon number within each hydrocarbon class. Building upon detailed fuel composition has enabled the industry to conduct more precise research and enhance the understanding of composition-property relationships.

However, in some cases of evaluating unique blending components, greater molecular understanding is desired, coupling detailed chemical compositions and analyses to specification and fit-for-purpose properties. Significant progress has already been made in this area, with standard GCxGC hydrocarbon-type analysis now a new product line[4]. But additional studies coupling GCxGC with soft ionization and generating better spectroscopic databases for individual molecular constituents will illuminate how chemical constituents relate to properties of interest (e.g., coking, autoignition). Research and standard workflows need to be developed using soft ionization processes to identify specific heteroatoms in GCxGC chromatograms, and to link them to coking and other properties. Spectroscopic methods need to be continuously improved to identify specific isomers and propagate these compositions to properties of interest. Finally, this research needs to be coupled with AI for analysis, experimental design, and (potentially) operations in the lab. Ultimately, these research applications need to be developed into standard workflows that can be more broadly disseminated.

While some testing methodologies have received attention and have either been developed (e.g., GC x GC) or improved/automated (e.g., dielectric constant measurements), **several fit-for-**

[4] There is a company that is now offering a GCxGC-FID system for Hydrocarbon type analysis, designed for a specification lab.

purpose test methods critical for novel fuel review and approval by the OEMs have not received the necessary attention. These include, but are not limited to:

- Specific heat capacity
- Properties related to flammability: autoignition temperature, flammability limits, hot surface ignition
- Proxy properties (those which cannot today be specified in a practical standard), e.g.:
  - a property for auto-ignition temperature
  - flash point for flammability
- Volatility properties: vapor pressure, volume of gas over liquid ratio (V/L)
- Distillation profile controls to avoid unusual compositions such as a bimodal carbon distribution
- Properties relevant to combustor performance and operability (e.g., thermal conductivity)
- Material compatibility

Enhancing the accuracy and fidelity of these tests is essential for understanding the relationship between fuel composition and its properties, as well as their impacts on airframe and engine fuel systems. Additionally, recent method improvements have revealed inconsistencies where historical averages used for comparisons do not align with modern measurements, making data analysis complicated and inconclusive. **Furthermore, the rapid advancement of computational modeling generated additional demand for accurate data, further driving the need for improvements in test methods.**

Reducing Required Volumes for Fuel Testing

The biggest cost related to qualification of novel SATF routes remains the burden to produce sufficient volumes for candidate SATF materials for testing and qualification. Multiple producers have estimated the total investment to produce the first 100 gallons of material submitted to the Clearinghouse to be approximately $100 million (which often includes the cost of the plant or physical equipment). Over the last decade, there has been a focus on **reducing the overall volume of fuel required** at every stage of the qualification process. Significant progress has been made on understanding composition and fuel properties on the figures of merit in the NJFCP[5]. As an example, there has been a multi-year focus on reducing the test volumes needed for early-stage testing, i.e., pre-screening. As such, the volumes used in prescreening materials has reduced from several hundred milliliters to 60 mL for the same tests. These reduced volumes have matched testing requirements with common production methods, i.e., the volume of a Parr reactor. **Further research on fuel testing options to reduce**

[5] See this 2017 Status Update as an example: PowerPoint Presentation

initial fuel volume requirements would significantly reduce fuel qualification cost and shorten timelines for completion. However, the impression should not be given that all qualifications can be completed (with an annex issued) after making only lab-scale quantities of fuel. There is also an element of confidence amongst the aviation fuel community that needs to be addressed, that most new processes require demonstration of scale-up and commercial viability beyond lab scale experiments. And OEMs have clearly communicated that multiple batch-runs of test fuels using differing inputs or operating conditions increase the confidence that the process and management of change procedures are capable of maintaining statistical control of the final blending component properties.

Correlation of Testing Data with Fit-For-Purpose Properties

One way to accelerate SATF qualifications is to develop a **compositional or more generalized specification where the end-product is controlled in the specification** to such a degree that it would allow especially the OEMs to relax the control of feedstock and/or production process. For this to take place, however, the technical community, especially the OEMs, need to have the level of confidence required in specification properties (current and new) being able to control the fit-for-purpose properties which require research testing techniques and cannot be practically measured on a production basis. The **correlation between these specification properties and fit-for-purpose properties needs to be firmly established/expanded**, at least for those properties that are deemed essential. This requires further research on topics such as:

- Impact of different paraffinic groups on fit-for-purpose properties. Although the iso- and n- paraffins ratio related impacts are understood to be under control by specification property requirements such as viscosity, cetane number, freeze point, etc., the demonstration of this might be needed.
- Isomer and dilution effect on fit-for-purpose properties. The synthetic pathways might lead to isomers of various hydrocarbon molecules with unique molecular structures that fall within jet fuel range in terms of type and carbon number, and their impact needs to be understood
- Material compatibility research on whether the 8% minimum industry consensus limit is sufficient or even whether a lower limit would be enough for proper functioning of certain legacy seal and O-ring materials.
- Further research on the potential to replace all or most of the aromatics (e.g. understanding attributes of naphthalenes versus naphthenes) with cycloparaffins and the impact on upstream fuel transfer components.

Additional Risk Reduction

There are several opportunities to provide additional risk reduction to new pathways.

- **Clearer expectations on target ranges of key properties**: Other properties not included or researched extensively, such as fit-for-purpose properties, are not clearly defined as to their expected ranges. This lack of clarity imparts uncertainty on new producers. Producers may generate sufficient volumes on these tests and may be able to tailor conversion processes, but do not know what 'mark' they need to hit to be confident before entering the ASTM D4054 process. There needs to be more standardization and clarity on what are in fact the expectations and ranges for this larger set of properties.
- **Prediction of additional properties**: Historically, there has been significant investment to predict many important bulk properties of jet fuel, such as Table 1 properties in D1655 and D7566. However, more investment is needed in the experimentation and prediction of many other properties. The ability to predict properties enables more producers to avoid certain problematic compositions and pursue a more rapid approval.

These items, along with the previous, suggest there may be a clear need for a second NJFCP type research effort over the coming couple years.

Final Thoughts

Several global entities have initiated efforts to participate in ongoing fuel qualification efforts, and some are evaluating whether additional fuel qualification approaches/systems, including 2025 efforts by the Economics Policy Branch of the OECD, can help address real or perceived challenges in current qualification. **CAAFI emphasizes that proliferation of standards introduces the risk of:**

- **agendas other than flight safety taking precedence (e.g., environmental, national, socio-economic, etc.)**
- **dilution of efforts/understanding of a limited number of global specialists**
- **compatibility and safety risks for existing aircraft systems**.

CAAFI recommends that OECD facilitate/recommend acceptance of current best practices based on the existing, well-established ASTM D4054 process and existing global fuel standards (ASTM D1655 and D7566 and DefStan 91-091). CAAFI further emphasizes that OEM engagement is key to ensure safety and global acceptance of fuels and SATF. The current approach (D4054) and specifications are sufficient, but can be improved if additional funding is provided, and even where there are other specifications (Def. Stan. 91-091, GB #3, etc.), they often mirror D1655/D7566.

Emphasis should be on improving the current approach instead of coming up with new fuel approval processes. OECD could be in a good position to convene an international workshop with representatives of ASTM, OEMs, airlines, and other stakeholders to recommend a practical path forward that focuses on R&D to address the issues and challenges highlighted in the above dialogue.