Title: Alternative fuels specification and testing

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Gap/Problem statement:

One of the most consistently noted challenges in the development of alternative aviation fuels is the lack of clear definition of what is acceptable as an alternative aviation fuel to the OEMs and the aviation community. This lack of a well-defined accepted criteria or specification inhibits invention and investment, and allows efforts that may eventually prove unprofitable to be pursued.

Up until now, aviation fuel has been a petroleum distillate. Standards have been developed for the distillate, providing bounds on the natural variation due to source and process, but not specifying the chemical composition or even all the key characteristics required for use in a gas turbine. That aircraft fuels are petroleum distillates serves as the basis for the entire infrastructure of refining, fuel transport, filtration, testing, purchase, and refueling. The inherent assumption of fungible petroleum-based fuels has resulted in standards that are not suited to evaluate alternative processes and alternative sources. Whereas specifications that detail acceptable chemistries are what are desired by the developers.

Conversely, since the engineering of commercial aviation gas turbines has employed petroleum distillate fuels, the impact of fuels that differ significantly from distillates has not been characterized. Experience with the already occurring variation in distillates indicates that these variations influence combustor performance. Experiments and modeling with non-distillate fuels indicate that certain combustion characteristics are impacted, especially limit behavior, and that the performance of the fuel system or fuel transportation infrastructure can be impacted as well. The key question is which differences in fuel and combustion characteristics are acceptable and which are not. Historically, the only way to validate a proposed fuel has been to characterize the fuel according to the distillate standards, and then run an extensive and expensive series of developmental rigs and engines that were not designed to evaluate fuels, but rather to evaluate performance of the components. Pilot-plant quantities of the fuel are required for the rig and engine tests. Further, an industry-consensus test plan is required for each fuel, and the acceptance was limited to the proposed fuel only, and the particular rigs and engines used to validate the fuel.

In order to change from this laborious, expensive, and uncertain process, tests and testing procedures are required to be defined and accepted by industry that can clearly identify if a proposed fuel chemistry is acceptable or not and can do so in a reasonable time frame and cost with limited quantities of fuel.

Identifying either allowable chemical compositions or identifying proof tests that can be performed quickly with limited quantities of fuel would greatly accelerate the development of alternative fuels.

Background:

Petroleum distillates have been the basis of aviation fuels since the inception of aviation. Petroleum crudes vary widely in their properties and composition. Modern refinery processing reduces the variation in the different distillate products, but not all processes are alike. Recent surveys of the composition of jet fuels show a broad distribution of characteristics over the entire n-dimensional property space. In other words, jet fuels can be found that demonstrate the extremes of any particular allowed property or composition. Fuel producers and OEMs are aware of these variations and the aviation fuel infrastructure, aircraft systems and engines are engineered to operate safely and reliably with any jet fuel that satisfies the specifications.

The specifications for jet fuels have evolved with the jet engine. At one time, JP-4, a lighter cut of distillate, was allowed for use, especially in excessively cold weather such as Alaska. As the combustion systems for jet engines improved and the safety of a higher flash point product realized, the need to use JP-4 diminished, insomuch that it is not accepted by the OEMs for use on many current engines. Further, the definition of the specifications has been driven by incidents that have impacted the operability or safety of the aircraft. For example, the coking or thermal stability test has been refined to provide greater accuracy.

The following excerpts from BP's web site http://www.bp.com/sectiongenericarticle.do?categoryId=4503664&contentId=57733 titled the "The History of Jet Fuel" illustrate this evolution:

> "Gasoline was the fuel (first) used because of its ease of evaporation and known performance properties in piston engine aircraft. … Early proponents of the jet engine claimed that these new engines could operate on any fuel from whiskey to peanut butter. Although jet engines are much more tolerant than gasoline and diesel engines, the aircraft and engine fuel system are sensitive to the chemical and physical properties of the fuel. Early advances in engine and aircraft design greatly expanded the flight envelope which necessitated new standards for turbine engine fuel quality. This led to the introduction of a variety of fuel types for different purposes and to the development of specifications to ensure the fuel met equipment requirements under all flight conditions.
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> In 1944 the US published specification AN-F-32 for JP-1, a -60C freezing point kerosene. The freezing point so limited availability that is was soon superseded by various wide cut fuels; JP-2 (1945), JP-3 (1947) and JP-4 (1951 - avtag, NATO F-40). These wide cut fuels are mixtures of naphtha and kerosene which greatly increase availability. …

> … Even though the first US jet engines were direct copies of early British designs, these pioneering jet fuel specifications differed significantly in volatility, freezing point, specific gravity, sulphur and aromatic limits. The US specification was most likely derived from the aviation gasoline specification, while the British specification reflected the properties of illuminating kerosene.
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> High flash point kerosene was introduced as early as 1948 to reduce the fire risk aboard aircraft carriers. … A kerosene fuel very similar to commercial Jet A-1 , was developed by the USAF to reduce the fire hazards associated with wide cut fuels which became apparent during the Southeast Asian conflict. …"

The concern with safety is paramount. The particular distillate used as Jet A was chosen in part due to its safe handling characteristics – it has a high boiling point and a high flash point. From the CAAFI web site (http://www.caafi.org/information/pdf/Path_to_Aviation_Alternative_Fuel_Readiness_posted_2011_12.pdf):

> "First, and most importantly due to safety, the aviation industry has stringent requirements for aviation fuels that go beyond the properties listed in the specifications. Along with the well-recognized requirements of the fuel having sufficient energy density and the ability to remain liquid at very cold temperatures, other requirements are aimed at materials compatibility and fungibility with standard jet fuel. Materials compatibility issues include elastomer compatibility (to ensure o-ring seal swell within the fuel system of the airplane), engine and component wear, and compatibility with existing infrastructure. Fungibility is required due to the global nature of the aviation fueling infrastructure, the characteristics of airport fueling systems (which tend to have a single storage and distribution system for all vehicles) and the expense and slow replacement of the aircraft fleet."

Current Status:

Over these past 70 years, the process for reviewing and accepting either a new jet fuel or a new additive, was matured and codified. The "Path to Aviation Alternative Fuel Readiness" found on the CAAFI link shown above describes the intricacies of the current approval process. Further details may also be found in ASTM D4054 "Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives" available from ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428-2959 USA, www.astm.org.

Figure 1 illustrates the process.

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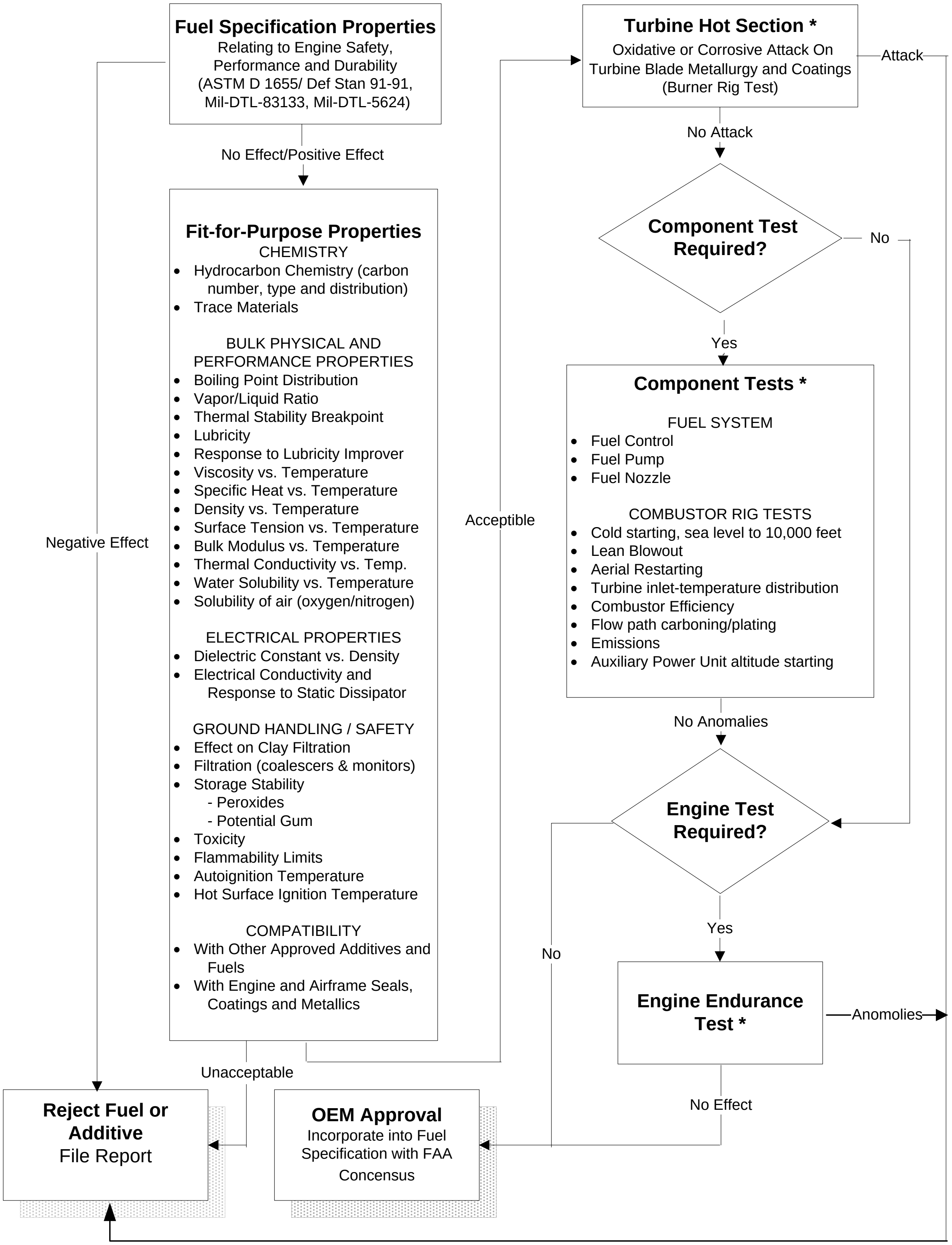

OEM approval defines success in this process for technical acceptance within aircraft fuel and engine systems. What is not explicit in the current flow chart is that while the majority of the “fit for purpose” tests can be conducted by any qualified laboratory, the determination of compatibility, the execution of turbine hot section tests, the component tests and the engine tests, can only be performed either by the OEM or by a laboratory or organization under the direct supervision of the OEM. This is because the materials, the coatings, the seals, the turbine configuration, and the combustor design, are all proprietary and perhaps unique to a particular OEM. As a whole, OEMs are very careful when approving tests or analyses performed for configurations that differ from their own, and will insist on performing the test on their particular component if the differences concern the experts at the engine company. Note that this practice is currently under review to include additional aspects such as fuel handling and distribution requirements. With respect to compatibility with fuel handling and distribution equipment, much work has been done by the American Petroleum Institute, UK Energy Institute and Military to define appropriate qualification tests for materials/hardware. These criteria are generally well defined and may be readily incorporated in a future edition of ASTM D4054.

The flow chart in Figure 1 does not specify the quantities of fuel required. While the initial fit for purpose test s can be conducted with under a few gallons of fuel, the burner rig tests take from a few hundred to a few thousand gallons of fuel to conduct. Engine testing can easily consume thousands of pounds of fuel an hour. For a just conceived alternative fuel process, a few gallons may be achievable, but hundreds and thousands of gallons are only attained with significant investment (on the order of 10’s and 100’s of millions of dollars), which can usually only be obtained with some certainty in the outcome, which can only be derived from the testing of large quantities of the proposed fuel. In addition, the OEMs have little incentive to perform the component and engine testing if a product is many years from the market and thus do not give it high priority. Further, the OEMs may require recompense to perform the tests, which can be on the order of millions of dollars.

Finally, the process only produces acceptance for a particular fuel or additive. Up until recently, there has not been any driver to apply the fuel to a wider class or source of fuels. Thus, a fuel producer may have identified an alternative fuel process, garnered investment, matured the process enough to produce tens of thousands of gallons, paid to have the fuel tested at the OEMs, suffered the delay that accompanies that testing, only to have to repeat the validation process if the alternative fuel feed stock or alternative fuel production process has to change in any significant fashion.

The OEMs aviation Industry has had to adopt this restrictive approach due to being caught between the requirement for safety and the lack of an absolute understanding of what fuel characteristics are linked to which particular combustion and performance behaviors. An example: the role of parts per billion of metal contamination may affect fuel thermal stability and impact 20,000 hour reliable engine operation. Another example: trace long chain hydrocarbons which may solidify at low temperatures and block filters.

Note that the recent approvals of SPK and HEFA as blending fuels have been accepted because the resultant blends have been deemed indistinguishable from petroleum distillate jet fuels, albeit low aromatic jet fuels. Testing and approval of Fischer-Tropsch fuels (Synthetic Paraffinic Kerosene – SPK) has given the manufacturers and the industry as a whole the substantiation to allow the acceptance of fuel blends that meet all traditional jet fuel specifications and which contain a range of aliphatic compounds similar to what is found in FT fuels. Hydroprocessed Esters and Fatty Acids (HEFA) were also accepted with a minimum of testing due to the hydroprocessing and distillation producing a fuel blending product similar to the range of aliphatic compounds found in jet fuels and thus deemed suitable for use in minority blends. They were not accepted because of a specific increase in knowledge about how the detailed compositional properties of jet fuels links to performance. If the blended fuels differed in some way outside the normal range of variability accepted for petroleum distillate kerosene, then those blends and those source fuels could not be accepted by the OEMs and the community, until suitable testing has been performed to insure that the difference does not challenge operability and safety.

To be clear in the statement of the current situation concerning the evaluation of jet fuels: 1) There is no accepted chemical compositional standard, rather there is a set of specifications for a petroleum distillate. 2) Defined tests to evaluate a potential fuel to determine if it would achieve acceptance by the OEMs that can be performed with limited quantities of fuel at a qualified laboratory do not exist.

It is important to note that there is significant work on-going within the community to address these issues, such as the AFRL-sponsored Alternate Fuels “Rules and Tools” effort. However, these efforts are not necessarily comprehensive and at current funding levels and effort, resolution is still years away.

Solvability and Approaches

There are no current reasons to assume that a simplified, more rapid, lower cost testing procedure could not be developed, or that a set of specifications, such as chemical composition, could not be arrived at that would be applicable for alternative fuels, no matter the source or the process. The path to resolve these issues may include the following.

Consider the impact of critical fuel properties on key combustion characteristics. Fuel Physical properties such as density, surface tension, viscosity, and vaporization are known to impact combustion characteristics. Similarly, fuel chemical properties such as composition, trace compositional species, heat of reaction, and reaction rates, influence combustion. How might these characteristics differ in future fuels and what would be the impacts on combustion? How might these characteristics impact other engine characteristics such as fuel delivery and heat management systems?

Consider the purpose and rationale of current fuel evaluation methodology. Are the ASTM methods sufficient? Do the fit for purpose tests cover the necessary chemistry and bulk properties, performance, and fuel distribution characteristics? What is the purpose of each of the current component tests and how do they achieve it? What are the different combustor configurations currently extant and what are the future possibilities? What are the fuel impacts and combustor characteristics that are captured? Are the impacts of trace components captured?

Propose, define, fabricate and validate fuel evaluation combustor rigs. What would be the necessary operating parameters: pressure, inlet air temperature, f/a, etc.? What OEM-specific design characteristics can be addressed? What would be the suite of "standard" jet fuels? How would the OEMs validate the proposed rigs and approaches? What would need to be measured in order to achieve the required level of confidence that all safety concerns have been addressed?

Identify tool and approaches to convert test results into chemical specifications. How can specific chemical compositions be linked to critical parameters like spray characteristics, vaporization rates, and laminar flame speeds? How are these critical parameters linked to the more complex combustion behavior in gas turbine combustors? What ranges and blends of chemistry are acceptable to achieve the validated results?

Obtain industry consensus that this approach/procedure/specification addresses all concerns. How would each of the OEMs/industry members validate the tests, procedure and chemical composition? How all stakeholders become invested in the process? What is the ongoing role of the industry in the management and maturation of the potential process?

It is likely that not all of these efforts can be fully funded and staffed. What is required to create a specification or testing procedure that would insure the safety and operability of fuel processing, distribution, storage, and use in aircraft and engines, yet be simple, time effective, and clearly definitive?

Benefits to industry as a whole

Creating a simplified testing process and or chemical specifications would have enormous impacts on alternative fuel research and development.

First, if the definition of chemical compositions is possible, then each new chemical definition gives the community a new target at which to aim. Just as SPK prepared the way for HEFA, the definition of a chemical composition as acceptable would encourage the exploration of different fuel feedstocks and processes that might achieve that composition. Success could be measured with the quantities generated by a test tube and measured with a chromatograph/mass spectrometer.

Second, the development of alternative fuel evaluation tests that are simple, cost effective, linked to fundamental properties, and accepted by the engine manufacturers and industry, would shorten the time for approval, reduce the quantities needed for approval, and clarify the linkages between approval and fuel properties. This testing is still likely to require gallons and perhaps tens of gallons of fuel, but not 100's of thousands of gallons of fuel. Further, the successful completion of the tests, and the understanding gained by any accompanying modeling, could enable the definition of chemical compositions and thus the exploration of classes of fuels as enumerated above.

Such specifications and testing would energize the entire alternative fuel community and enable the development of fuels that may not mimic petroleum distillates but have equivalent performance and product cost.