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Administration**

R&D Control Study: Plan for Future Jet Fuel Distribution Quality Control and Description of Fuel Properties Catalog

Broad Agency Announcement
Alternative Aviation Fuels

Submitted by Metron Aviation, Inc.

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Alternative Aviation Fuels BAA

B. Advanced Jet Fuel Quality and Performance Control Research and Development (R&D) Study

R&D Control Study: Plan for Future Jet Fuel Distribution Quality Control and Description of Fuel Properties Catalog

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Contents

1 Introduction

1.1 Background

In accordance with the Federal Aviation Administration's (FAA) NextGen Implementation Plan (NGIP), decreasing the environmental impact in the National Airspace System (NAS) while allowing for an increase in traffic is of strategic importance. The use of alternative fuels is one of the means that has the potential to limit the impact of aviation emissions on global climate. In addition, alternative fuels can contribute to energy security through diversification away from petroleum-based fuels. The support of the FAA and the John A. Volpe Transportation Systems Center (Volpe Center), part of the U.S. Department of Transportation's Research and Innovative Technology Administration (RITA), as well as support of the FAA through the Commercial Aviation Alternative Fuels Initiative (CAAFI), is of integral importance to the efforts of many stakeholders to produce and commercialize emissions-cutting alternative aviation fuels.

The impending introduction of alternative aviation fuels has the potential for introducing materials into the aviation fuel distribution system that have not been present historically. If not handled properly, there is the potential for these materials to impact aircraft operations as well as the fuel transportation and handling infrastructure. Furthermore, many of these alternative fuels will be produced by new entrants that have little or no experience in the monitoring and testing of aviation fuels as they enter the jet fuel supply chain. As a result, it is considered important to re-examine the existing framework for managing the fuel handling process to make sure that it is adequate for the new circumstances. A key aspect for the successful adoption of alternative aviation fuels is that they must be 100% compatible with the existing jet fuel infrastructure and equipment; therefore, the testing and certification framework assures users that these fuels are, indeed, 100% compatible.

1.2 Introduction to alternative jet fuels

In general terms, alternative jet fuels have the same performance characteristics as petroleum-based jet fuels, such as Jet A and JP 8, but are produced from non-petroleum feedstock using a number of different technologies. Feedstock for alternative jet fuels can be renewable (e.g., plant oils, animal fats, and biomass such as crop residues, wood chips, and prairie grasses) and non-renewable (e.g., coal and natural gas). Alternative jet fuels have different environmental and economic characteristics depending on the feedstock and technology process utilized.

There are several combinations of feedstock and production technologies, or "pathways," to produce alternative jet fuel, including:

- Fischer-Tropsch (FT) process which can be used to convert coal, natural gas, or biomass into liquid fuels such as diesel and alternative jet fuel.

- Hydroprocessed Esters and Fatty Acids (HEFA) process in which plant oils or animal fats can be converted into liquid fuels.

- Alcohols-to-Jet (ATJ) process that uses alcohols as feedstock to produce alternative jet fuel and other by-products.

The above processes are at different stages of maturity. FT fuels have been produced for decades; in fact, jet fuel from coal using the FT process has been in use in South Africa for many years and it was the first alternative jet fuel to be approved for use on aircraft. The HEFA process is more recent and was just approved for use on aircraft in 2011. The ATJ process is still in development and it is anticipated that ATJ fuels will be approved for use on aircraft in the 2014 timeframe. There are other pathways for producing alternative jet fuel, such as fermentation, catalytic conversion, and pyrolysis that are expected to undergo the approval process in years to come.

1.3 "Drop-in" alternative jet fuels

The aviation industry, including airlines, fuel distributors, and equipment manufacturers, have made it a priority to ensure that alternative jet fuels can be used in the existing infrastructure, airframes, engines, and other equipment without the need for any modifications. In other words, the industry wants alternative jet fuels that are fully interchangeable, or "drop-in," with petroleum-based fuels. Drop-in alternative jet fuels can, therefore, be used alongside conventional jet fuel or in isolation without changes to any infrastructure or equipment.

It is important to note the difference between drop-in blends and drop-in "neat" alternative jet fuel. Drop-in neat alternative fuels are defined as "a substitute for conventional jet fuel that is completely interchangeable and compatible with conventional jet fuel. A drop-in neat fuel does not require adaptation of the aircraft/engine fuel system or the fuel distribution network, and can be used "as is" on currently flying turbine-powered aircraft in pure form and/or blended in any amount with other drop-in neat, drop-in blend, or conventional jet fuels"[1]. As will be discussed in more detail in section 3, jet fuel is a complex mixture of different hydrocarbons, including iso and normal paraffins, napthenes, and aromatics. Some of the processes for alternative jet fuel do not produce as end produce a fuel that can replicate completely the composition and performance characteristics of conventional jet; therefore, those fuels need to be blended with conventional jet fuel to ensure the required specification is met. Those fuel blends, assuming they meet the required specifications, are known as drop-in blends.

1.4 Objective of the study

The main objective of this study is to investigate and provide recommendations for any unique quality control requirements that the production and distribution of alternative jet fuels may require, ultimately producing a quality control handbook for alternative jet fuel entrants and others along the supply chain. As experience is gained with the production and distribution of

[1] http://caafi.org/resources/glossary.html#D

alternative jet fuels, the quality control of those fuels can be examined relative to this handbook by the ASTM Aviation Fuels Subcommittee and by stakeholders that are engaged in the supply chain that produces, distributes, and uses jet fuel.

To reach the objective stated above, this study will a) highlight best practices for maintaining quality control of jet fuel, b) identify gaps in current quality and performance procedures that may emerge with the introduction of alternative fuels, c) suggest areas for improvement in current jet fuel quality control practices to accommodate the introduction of alternative fuels, and d) provide recommendations for an improved method of collection of fuel property and quality measurements.

1.5 Organization of the report

The report is organized in five main sections plus appendices and other supporting documentation. The main sections are described below:

Section 2, "Overview of Jet Fuel Specification and Standards," describes the system and organizations that issue specifications for jet fuel and the roles that different stakeholders play.

Section 3, "Jet Fuel Specifications and Testing Procedures," presents detailed information on jet fuel specifications and associated testing procedures.

Section 4, "Quality Control along the Supply Chain," describes the quality control procedures along the supply chain of jet fuel, from refinery production to aircraft delivery.

Section 5, "Considerations Regarding the Introduction of Alternative Fuels," discusses recommendations to the quality control system to address potential gaps in the existing jet fuel quality control system because of the introduction of alternative fuels.

Section 6, " Fuel Properties Catalog," describes the elements of a proposed fuel properties catalog, data requirements, and collection methods.

2 Overview of Jet Fuel Specification and Standards

Specifications and handling procedures for jet fuels are much more tightly controlled than for other fuel products, because minor changes in fuel properties, cleanliness, or contaminant levels can have drastic, unanticipated effects on engine performance. Based on many years of experience, a complex quality control system has been created. It starts with jet fuel certification at the production facility and continues along the entire supply chain from the refinery to the aircraft. This section provides an overview of jet fuel standards, certification requirements, and the role of different entities and organizations. A summary of the main organizations and documents involved in jet fuel quality control procedures discussed here is shown in Table 1:

Table 1: Summary of Common Documents Used in the U.S. Regarding Specification and Recommended Practices for Handling Jet Fuel

Organization	Document	Title
Jet Fuel Production Specification*		
ASTM	D-1655	Standard Specification for Aviation Turbine Fuels
ASTM	D-7566	Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons
U.K. Ministry of Defence	DEFSTAN 91-91	Turbine Fuel, Aviation Kerosine Type, Jet A1
Supply Chain Recommended Practices		
API	API 1543	Documentation, Monitoring and Laboratory Testing of Aviation Fuel During Shipment from Refinery to Airport
API	API 1540	Design, construction, operation and maintenance of aviation fuelling facilities (Model code of safe practice Part 7)
EI/HM 50	EI/HM	Guideline for the cleaning of tanks and lines for marine tank vessels carrying petroleum and refined products.
A4A	ATA 103	Standards for Jet Fuel Quality Control at Airports
IATA	IATA Fuel Quality Pool	Control of Fuel Quality & Fueling Safety Standards
JIG	JIG Sections 1 to 4	Guidelines for Aviation Fuel Quality Control and Operating Procedures for Joint Into-Plane Fueling Services
API	API 1595	Design, Construction, Operation, Maintenance, and Inspection of Aviation Pre-Airfield Storage Terminals
EI	EI 1530	Quality assurance requirements for the manufacture, storage and distribution of aviation fuels to airport
ICAO	Doc 9977, AN/489	Manual on Civil Aviation Jet Fuel Supply
SAE Aerospace	SAE- AS 6401	Storage, Handling and Distribution of Jet Fuels at Airports.

*There are other country or region specific aviation fuel specifications, but this study focuses on ASTM and DEFSTAN 91-91 since these are the most common in the U.S.

2.1 Jet fuel specification

At the top of the quality control pyramid for aviation fuel is the set of standards jet fuel must meet before it leaves the production facility and enters the supply chain. Jet fuel standards are revisited frequently to ensure they meet the requirements of current engines, and have evolved along with the development of the jet engine (see Section 3). Producers are required to test all jet fuel as it leaves the facility and to certify that it satisfies the appropriate specification (see Section 4.2). The quality control system in the supply chain relies upon this certification, because downstream tests do not cover all the standards mandated for the manufacturer unless the fuel fails a test at some point. In such case, the jet fuel needs to be fully re-tested and re-certified.

Specifications for jet fuel are established by standard-setting organizations such as ASTM International (ASTM) in the United States, and the United Kingdom's Ministry of Defence (DEFSTAN), which are recognized by aircraft and engine manufacturers and regulatory agencies around the world. Here, we focus mainly on the ASTM standards that are used for all commercial aviation fuels used in the United States; DEFSTAN and other standards are referenced but not discussed in as much detail.

In addition to setting performance standards, standard-setting organizations also specify which methods are acceptable to test the fuel. The most widely used commercial jet fuel specifications in use today, **ASTM D1655** *Standard specification for Aviation Turbine Fuels* (ASTM 2011) and **DEFSTAN 91-91** *Turbine Fuel, Aviation Kerosine Type, Jet A1* (MOD 2008), identify specific test methods to measure fuel performance. There are a few differences between the performance measures of the two standards, but the main differences have been with approved testing methods. The U.K. Ministry of Defence and ASTM have always cooperated with the intent of approving and incorporating each other's test methods to create a single global specification with a consolidated listing of approved instruments and methods. Their intent of recognizing and accommodating the availability of different testing equipment and technologies in different regions of the world will soon become reality as ASTM is balloting the addition of Institute of Petroleum (IP) methods in ASTM D1655 with the note that the ASTM methods will still be the reference methods in the US.

Other entities, such as the International Air Transport Association (IATA) and the Joint Inspection Group (JIG), issue recommended practices that are based largely on ASTM and DEFSTAN specifications. More information on these entities is presented below in Section 2.3.

2.1.1 ASTM International (ASTM)

ASTM develops and publishes the specification for turbine fuels that govern all jet fuels used in the United States. ASTM follows a consensus-based process for developing specifications. It has a long history going back to its origin in 1899 with Steel Industry Specifications for the railroad industry (ASTM 2001c). In 1921, the first petroleum standard was issued as **ASTM D86** *Method for Distillation of Petroleum Products at Atmospheric Pressure*, which became one of the most used ASTM standards and became a joint ASTM/Institute of Petroleum standard (Totten 2004). The second was **ASTM D445** *Method for Kinematic Viscosity of Transparent and Opaque Liquids*, which covered a long list of products including jet fuel, aircraft turbine lubricants, automotive and domestic fuel oils, diesel fuels, and hydraulic oils. D1655 is the standard for jet fuel in use today. It was first issued in 1959 and remains the exclusive specification for aviation turbine fuel in the United States. Since 1959, it has been reviewed, balloted, and revised to include and reflect the changes in quality requirements due to turbine engine modifications, new materials, and design improvements.

D1655 covers Jet A fuel, the most prevalent jet fuel in the United States, and Jet A1 fuel, which is used in most of the rest of the world. The only difference between Jet A and Jet A1 is that the freezing point of Jet A is -40 degrees Celsius versus the freezing point for Jet A1 of -47 degrees Celsius. D1655 also covers fuels from non-conventional petroleum sources such as oil sands or shale, and following DEFSTAN's lead, it was revised to include SASOL semi-synthetic fuel made from coal.

ASTM D7566 *Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons* (ASTM 2012) is the specification that applies to alternative jet fuels. To comply with ASTM D7566, neat alternative fuels must be blended with conventional fuel in a percentage approved by this standard. Since its approval in 2009 until its revision in 2013, this percentage has been set not to exceed 50% alternative fuel. It is important to note that D7566 Table 1 "Detailed Requirements of Aviation Turbine Fuels Containing Synthesized Hydrocarbons" (part 1 and 2) applies only at the point of blending of neat alternative fuel with conventional jet fuel. From that point onwards, the fuel is re-designated as D1655 fuel and treated as such throughout the supply chain.

The novelty of D7566 is that it includes two types of specifications: the specification for the blend of alternative and conventional fuel (Table 1 of D7566), and also the specification for neat alternative fuels, which are approved by production type. Individual process types are approved under Annexes to D7566; any new candidates for qualification and approval must follow the process described in ASTM D4054 -*Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives* [ASTM 2009]. The initial issue of D7566 approved in 2009 provides criteria for the production, distribution, and use of aviation turbine engine fuel produced from coal, natural gas or biomass using the Fischer-Tropsch process. In 2011, after two years of review, a new D7566 annex covering hydroprocessed esters and fatty acids (HEFA) was approved. It is expected that FT and HEFA will be followed by approvals for other production processes as they are developed, such as alcohol-to-jet (ATJ). Based on CAAFI's Fuel Readiness Level,[2] ATJ is expected to be qualified for approval by 2014.

[2] http://caafi.org/information/fuelreadinesslevel.html

2.1.2 United Kingdom Ministry of Defence (MOD)

Specifications published by MOD are used for most civil aviation fuels outside the United States. The first British jet engine fuel specification was introduced at the end of World War II. Following amendments and the addition of increasingly stringent requirements, the U.K. standard has evolved into today's commercial specification DEFSTAN 91-91.

The MOD was instrumental in pioneering the use of jet fuel from non-petroleum sources with the inclusion of sole site approval for SASOL's synthetic kerosene blends in DEFSTAN 91-91 in 1998. In 2008, following years of safe use of the blended fuel, DEFSTAN 91-91 approved SASOL's unblended synthetic jet fuel as Jet A-1 fuel for commercial use in all types of turbine aircraft (Sasol 2011).

2.1.3 Canadian General Standards Board (CAN CGSB)

The CAN CGSB is accredited as a Standards Development Organization by the Standards Council of Canada. Some of its specifications related to jet fuel include:

- CAN CGSB - 3.22, which covers wide-cut fuel (JetB) use in parts of Canada and Alaska
- CAN/CGSB - 3.23, which includes grades Jet A and Jet A-1
- CAN/CGSB - 3.24, which includes military grades JP-5 and JP-8

2.1.4 Russian specifications

The Russian Specifications are issued by Russia State Standard Committee. The Russian specification GOST 10227 covers the light kerosene-type fuel (TS-1 and RT) used in the countries members of Commonwealth of Independent States and parts of Eastern Europe. It is the only specification that uses different test methods.

2.1.5 Chinese specifications

Chinese specifications are issued by China's National Technology Supervisory Bureau. The GB6537 standard covers "No.3 Jet Fuel" which is basically equivalent to Jet A1 and is the predominant kerosene used in China.

2.2 Role of other entities

2.2.1 Regulatory Agencies

Regulatory agencies are involved in ensuring the ongoing safety of civil aviation, through rigorous processes of testing and certification of aircraft, issuing operating certificates to air carriers, and by ensuring that airports operate their fuel storage and delivery systems safely.

Aircraft and engines are generally certified for airworthiness by the national civil aviation authority in the country of manufacture. In the U.S., this is the Federal Aviation Administration (FAA). Federal Aviation Regulation 14CFR Part 25 (Airworthiness Standards: Transport Category Airplanes, 2010) include procedures to be followed for airworthiness certification of aircraft and 14CFR Part 33 provides airworthiness standards for certification of engines. In the case of aircraft engines, this includes extensive testing carried out by the original equipment manufacturer (OEM) and witnessed by the FAA, and when testing is successfully completed, a

"Type Certificate" is issued for the engine. This engine Type Certificate includes, among other requirements, the specification for the jet fuel approved by the OEM to be used in that equipment. Thus, the FAA does not directly regulate fuel standards; instead it refers to them in Type Certificates (Airworthiness Standards: Aircraft Engines, 2010).

Furthermore, the FAA also issues Operating Certificates to airlines based in part on their operating manuals which include engine operating manuals that specify what fuel must be used in the aircraft. At regular intervals, the FAA conducts safety inspections of airlines to ensure they are operating in accordance with their operating certificate (FAR-121), which include a check on whether they have systems in place to ensure fuel being used complies with the manual specification, including being fit for use. Once again, the FAA refers to the ASTM specification rather than being directly involved in setting or approving the standard (FAA 2011).

2.2.2 Aircraft and Engine Manufacturers

Aircraft and engine manufacturers play a central role in the formulation of fuel performance standards developed and approved by the standard-setting organizations to ensure their products perform as advertised and are not harmed through the use of inappropriate fuels (ASTM D4054). Different engine manufacturers have their own specifications that are based on D1655 and DEFSTAN 91-91 and specific operating conditions for the equipment. This specification is included in the aircraft/engine operating manual and in the Aircraft Flight Manual (AFM) which must be followed by an aircraft operator to comply with their Operating Certificate.

2.3 Supply chain recommended practices

It is the responsibility of the final fuel delivery company to furnish on specification, "clean and dry" fuel to an airport. Organizations such as the American Petroleum Institute (API), the Energy Institute (EI) in the United Kingdom, and the Joint Inspection Group (JIG) have issued best practice handling procedures and testing guidelines to help achieve this goal, as discussed below.

2.3.1 American Petroleum Institute (API)/ Energy Institute (EI)

In the United States, the API published recommended practices for handling petroleum products. Starting in 2010, these publications have been taken over by the Energy Institute (EI 2011).

Publications of major interest to the aviation jet fuel community include:

API 1540 *Design, construction, operation and maintenance of aviation fuelling facilities* (API 1540): provides information for the proper siting, design, layout, and construction of aviation fueling facilities at the airport.

API 1543 *Documentation, Monitoring and Laboratory Testing of Aviation Fuel During Shipment from Refinery to Airport* (API 1543): discusses the fuel quality testing procedures necessary for the fuel to leave the refinery and flow through the supply chain to airport storage. The tests ensure that the product has not been contaminated or otherwise damaged in any way.

API 1595 *Design, Construction, Operation, Maintenance, and Inspection of Aviation Pre-Airfield Storage Terminals* (API 1595): describes best practices that should be followed in the handling of fuel and operation of storage facilities upstream of the airport.

EI 1530 *Quality assurance requirements for the manufacture, storage and distribution of aviation fuels to airport* (EI 2012): its stated objective is to provide a standard to help any company or organization involved in the production or handling of aviation fuel in the maintenance of aviation fuel quality. It covers the entire supply chain from point of manufacture to delivery to the airport. EI 1530 had not been released publicly at the time this report was prepared but a draft for stakeholder review was available.

2.3.2 Airlines for America (A4A)

To help ensure consistent fuel quality at airports throughout the U.S., airlines, under the auspices of their industry group Airlines for America (formerly known as Air Transport Association, ATA), organized a committee with representatives from airlines, oil companies and the independent airport fuel handling companies which created an all-encompassing standard fuel handling specification, known as ATA 103 (ATA 2009).

ATA 103 – *Standard for Jet Fuel Quality Control at Airports* (ATA 103): sets the standards not only for fuel quality control but for every aspect of getting fuel from the delivery point on the airport right up to the wing of the aircraft.

2.3.3 International Air Transport Association (IATA)

In its effort to institute global standards of fuel storage and handling, the IATA Fuel Quality Pool (IFQP) has set standards for fuel handling and inspected airports around the world (IATA 2011). IATA is currently updating the Provision Manual Standard 8 which is slated for publication in 2012. IATA is working with ICAO to implement these standards globally.

Furthermore, IATA published *Guidance Material for Aviation Turbine Fuels Specification* in 2008 which contains specifications for Jet A and Jet A1 based on both ASTM D1655 and DEFSTAN 91-91 (IATA 2008). It is intended to provide airlines a standard basis for jet fuel purchase contract specifications as IATA does not independently set fuel specifications.

2.3.4 International Civil Aviation Organization (ICAO)

ICAO recently published a *Manual on Civil Aviation Jet Fuel Supply(Doc 9977, AN/489)* to help member states, airlines, petroleum companies, and other stakeholders get a better and more uniform understanding of jet fuel quality control practices around the world (ICAO 2012). The document covers the handling of aviation fuels from the refinery production processes through the complete supply chain. It directs readers to the specific guidelines published by other agencies covering each segment of the supply chain (e.g., EI 1530, JIG, API 1543, API 1595, and SAE AS-6401). The document does not include information on alternative jet fuel.

2.3.5 Joint Inspection Group (JIG)

In 1974, a group of major oil companies formed JIG in order to develop a set of guidelines for handling aviation fuel at airports and upstream aviation fuel facilities (JIG 2011a). The intent was for these guidelines to be the basis to develop site-specific manuals at airports where joint fueling facilities were used. The Joint Guidelines include recommended practice for fuel sampling and testing, depot and fueling vehicle design features, and procedures for storage and delivery of aviation fuel to aircraft. These guidelines are updated regularly. At many commercial airports outside the U.S. where joint storage and hydrant systems are in place, airlines use the JIG Checklist to determine the quality system.

AFQRJOS – Aviation *Fuel Quality Requirements for Jointly Operated Systems* (JIG 2011b). This checklist combines the most stringent requirements of both ASTM D-1655 and DEFSTAN 91-91. One of its main benefits is that it broadens the approved test methods that can be used for the different quality tests, allowing a greater flexibility regarding approved equipment and technology.

2.3.6 SAE - Society of Automotive Engineers (1916)

SAE is an organization for engineering professionals in the aerospace, automotive, and commercial vehicle industries. The Society is a standards development organization for the engineering of powered vehicles, including cars, trucks, boats, aircraft, and others. SAE Aerospace Standards (AS) apply to missile, airframe, ground-support equipment, propulsion, propeller, and accessory equipment. Aerospace Recommended Practices (ARP) are recommendations for engineering practice, and are guidelines for design and production of aircraft and aircraft avionics systems. Aerospace Information Reports (AIR) contain generally accepted engineering data and information.

SAE Aerospace AS6401 - *Storage, Handling and Distribution of Jet Fuel at Airports* **-** was first issued in 2009. It is a very detailed guideline and aims to provide one single global standard for the handling of the aviation fuel, therefore to include all applicable guidelines published by others (EI/API, JIG, IATA, A4A) in a single publication. It covers the fuel supply chain from refinery certification to the wing of the aircraft.

3 Jet Fuel Specifications and Testing Procedures

This section describes the major characteristics of jet fuel that are addressed in jet fuel standards. We describe the performance characteristics that are required for a safe, effective jet fuel and briefly describe the tests that are specified in ASTM D1655 and D7566 to measure the fuel characteristics. Test methods are referred to by their title and code (e.g., DXXX). For more details on any tests, please visit the ASTM International website at: www.astm.org

3.1 Jet fuel performance characteristics

Jet fuel is a mixture of a large number (as many as thousands) of different hydrocarbon molecules, with carbon numbers mostly in the C_9-$C1_6$ range, a complex mixture of aliphatic and aromatic hydrocarbons and heteroatomic compounds, such as organonitrogen and organosulfur molecules. Jet fuels are composed mainly of three classes of organic compounds: about 60% iso and normal aliphatic alkanes (paraffins), about 20% cycloalkanes (napthenes), about 10-20% aromatics, and less than 1% olefins. The properties of each class of molecule influence the overall properties of the jet fuel and affect its performance in the turbine engine. When properties of jet fuels differ, it is because the fuels contain different proportions of compounds from these three classes. Furthermore, other properties of jet fuel are determined by individual components present in small, or trace amounts, and are not reflective of the typical composition of the mixture. The trace components may be present in the feedstock from which the jet fuel is produced or come from other sources such as additives or contaminants.

Modern analytical techniques are still not powerful enough to fully identify all the individual molecules that make up the jet fuel mixture. Therefore, jet fuel specifications and requirements are defined in terms of required performance rather than a strict target composition, although experience has proved that certain limits have to be set on certain classes of compounds.

It is important to understand that the specification for jet fuel is largely driven by the design of the jet engine and the fuel distribution system. To be acceptable for use on the current fuel infrastructure and equipment, any new fuel being considered must be capable of meeting the requirements specified for existing engine designs and existing fuel systems, in addition to environmental issues, such as limitation on sulfur content and other gas emissions. All key performance characteristics for jet fuel are translated and enforced by the specification requirements and they are measured by certain tests, as shown in Table 2:

Table 2: Performance Characteristics of Aviation Turbine Fuels. Source: ASTM D1655

Performance Characteristics	Test Method
Engine fuel system deposits and coke	Thermal stability
Combustion properties	Smoke point
	Aromatics
	Percent napthtalenes
Fuel metering and aircraft range	Density
	Net heat of combustion
Fuel atomization	Distillation
	Viscosity
Fluidity at low temperature	Freezing point
Compatibility with elastomer and the metals in the fuel system and turbine	Mercaptan sulfur
	Sulfur
	Copper strip corrosion
	Acidity
Fuel storage stability	Existent gum
Fuel handling	Flash point
	Static Electricity
	Water separation characteristics
	Free water and particulate contamination
	Particulate matter in fuel (contaminants)
	Membrane color ratings
	Undissolved water
Fuel lubricating ability (lubricity)	Fuel lubricity

Characteristics of jet fuels are discussed below:

3.1.1 Thermal stability

In normal operations, jet fuel is subject to temperature extremes between subzero temperatures in aircraft fuel tanks at high altitudes to very high temperatures in the combustor of the engine. In modern engines, fuel is used to absorb heat in different parts and stages prior to entering the combustor. At high temperatures, fuel can break down due to oxidation, which may be accelerated by the presences of certain dissolved metals, especially copper, that function as a catalyst. Thermal instability involves the formation of higher molecular weight compounds with limited fuel solubility, soluble gums, and, most critically, insoluble material that may either coat surfaces or form particulates. Commercial jet fuels should be thermally stable at temperature as high as 163 degrees C (325 degrees F).

The oxidative thermal stability is determined with the **Jet Fuel Thermal Oxidation Tests** (**D3241)**. It is a pass/fail run with the tube temperature at 260 degrees C to ensure compliance with minimum specification requirements.

3.1.2 Combustion

The combustion characteristics of a fuel depend largely on its molecular composition. Of the major organic class groups in jet fuel, paraffins have excellent burning properties, naphthenes have intermediate burning characteristics, closer to the paraffins, while aromatics have the least desirable combustion characteristics because they tend to burn with smoky flame and release a greater proportion of their chemical energy as undesirable radiation than other hydrocarbons. The specification limit for aromatics is a compromise between the combustion properties and the beneficial effect that the aromatics seem to have on certain fuel system seals. Similarly, for maintaining the desired combustion performance of the fuel, jet fuel specifications impose a limit on naphthalenes, which are heavy polycyclic aromatics (ASTM D1655 and DEFSTAN 91-91 have a limit of max 3% per volume for napthalenes).

Three combustion-related tests are: **Smoke Point (D1840); Percent Naphthalenes (D1840); and Aromatics content (D1319)**

3.1.3 Fuel metering and aircraft range

The overall design of aircraft and engines is based on the conversion of the heat of combustion of hydrocarbons in jet fuel into mechanical energy. A reduction in heat energy below the minimum specification would result in an increase in fuel consumption with corresponding loss of aircraft range and an increase in an airline's fuel cost.

Density (D1298, D4052) is a measure of fuel mass per unit volume, and is used for fuel load calculations. On the ground, jet fuel is bought on a volume basis, but in-aircraft fuel is measured by weight, so if fuel is of low density calculated loads may not be enough to complete the flight. Density is also useful in empirical assessment of heating value when used with other parameters, such as aniline point or distillation. For example, a low density may indicate low heating value per unit volume.

Net Heat of combustion (D4529, D3338, D4809) is the quantity of heat liberated by combustion of a unit quantity of fuel with oxygen. Heat of combustion directly affects the economics of engine performance. A reduction in heat energy would result into an increase in fuel consumption with corresponding loss or range. Refineries usually use the empirical calculation of the net heat of combustion based on correlations between sulfur content, gravity, volatility, and aromatics content.

3.1.4 Fuel atomization

Fuel volatility and ease of vaporization are affected by the hydrocarbon class type content of the jet fuel, and are determined by **Distillation (D86, D2887)** tests**.** The 10% distilled temperatures are limited to ensure easy starting. The Final boiling Point limit excludes heavier fractions that would be difficult to vaporize. **Viscosity at low temperature (D445)** is closely related to the pumpability characteristics over the temperature range. It is limited to ensure that proper fuel flow and atomization are maintained under all operating conditions and that fuel injection nozzles and system controls will operate at design conditions. Fuel viscosity can also influence the lubricating property of the fuel which affects the service life of fuel pumps.

3.1.5 Fluidity at low temperature

Jet fuel must have acceptable **freezing point (D5972, D7153, D7154, D2386**) and low temperature pumpability characteristics so that adequate fuel flow to the engine is maintained during long cruise periods at high altitudes. Freezing point is a property that depends on the molecular composition of the jet fuel: it increases with carbon number within each class, but is strongly influenced by molecular shape. Compounds with straight molecules such as normal paraffins and unsubstituted aromatics freeze at much higher temperatures than branched or circular compounds with the same carbon number. Normal paraffins in fuels have the highest freezing point, which means they will be the first to crystallize and come out of solution as wax crystals at low temperature, blocking fuel lines, filters, and nozzles (only 8-10% of normal paraffins in the fuel are required to form such a scenario).

3.1.6 Compatibility with elastomer and metals in the fuel system and engine

Aromatics (**D1319, D6379) -** Compatibility of jet fuel with the system materials involves primarily the effect on the systems elastomers, which are designed to swell in the presence of the fuel to seal systems. Although the role of specific compounds has not been well identified, experience has proven that aromatics have a beneficial effect on the elastomers in the system. Therefore a jet fuel with zero aromatics raises concerns over shrinkage of the seals and improper sealing of the system.

Mercaptan Sulfur (D3227) – These compounds are limited because of their odor, adverse effects on certain elastomers and corrosiveness with certain fuel systems materials, particularly cadmium.

Total Acidity (D3242) - Some petroleum products are treated with mineral acid or caustic, or both, as part of refining processes. Any residual acid or caustic is undesirable.

Sulfur (D1266, D2622, D4294, D5453) - Control of sulfur content is important for jet fuels because the sulfur oxides formed during combustion may be corrosive to turbine metal parts or copper or copper base alloys used in various parts of the fuel system. Direct corrosion of metals, especially copper, has been attributed to the presence of hydrogen sulfide or elemental sulfur at levels of 1 ppm or less. Rather than testing for these materials, the copper strip test is performed for jet fuel **(Copper Corrosion Test D130).**

3.1.7 Fuel storage stability

Jet fuel is usually stable when stored in normal conditions because it contains inhibitors to oxidation. However, processes like hydrocracking or high pressure hydrotreating used in refining can destroy the natural oxidation inhibitors in the fuel, so oxidation inhibitors are added to the fuel as early as possible, preferably into the line from the processing unit. The test for **Existent gum (D381, IP540)**, a nonvolatile residue left on evaporation of fuel, is a measurement of the fuel storage stability.

3.1.8 Fuel lubricity

Jet engine fuel systems rely on the fuel itself to lubricate moving parts. However the chemical and physical properties of jet fuel cause it to be a relatively poor lubricant material under high temperature and high load conditions. Furthermore, the deeper conversion processes in the refineries tend to destroy naturally occurring lubricity agents. Due to the nature of their petroleum source, some jet fuels naturally include enough sulfur or nitrogen compounds that act as lubricants. In other fuels, the problem may be corrected by adding lubricity additives, or blending low lubricity fuel with high lubricity fuel. Alternative fuel specification D7566 includes the requirement to test for lubricity (**Lubricity (D5001)** because fuels from bio sources are inherently lower in sulfur compounds than some petroleum-based jet fuels.

3.1.9 Fuel handling

Flash Point (D56) - To minimize the danger of accidental fuel explosions during handling, fuel should have as high a flash point (temperature at which the fuel vapor ignites) as possible, and the specified minimum flash point provides a reference for the maximum temperature at which to handle and store jet fuel to avoid fire hazards. The flash point is also used by local and regional regulations and insurance requirements to determine safe handling and storage practices.

Electrical Conductivity (D2624) - Hydrocarbons are poor conductors of electricity. Charges of static electricity, generated by fuel traveling through the system, may accumulate, and if static electricity dissipates through sparking this can create problems in the handling of aviation fuels. Usually electrical conductivity additives are added to dissipate charge more rapidly.

3.1.10 Fuel cleanliness and contamination

Modern aviation fuel systems require a fuel free of water, dirt and foreign contaminants. As jet fuel moves through the distribution and storage infrastructure, the chances for contamination exist. Therefore, tests have been designed to identify the following contaminants:

Water: Very small traces of free water can adversely affect jet engine and aircraft operation particularly by ice formation. Tests and controls are in place to reduce the risk associated with presence of water or particulate matter. Across the supply chain, the fuel is tested for cleanliness at various points for water and particulate matter contamination.

Microbial Contamination: Microorganisms that have become established in the fuel system can lead to problems such as corrosion, odor, filter plugging, decreased stability, and deterioration of fuel/water separation characteristics. Gross evidence of the presence of microbial contamination can include suspended matter in the fuel or at the fuel water interface and/or smell of rotten eggs, which is due to the presence of hydrogen sulfide. Usually, difficulties can be avoided by good housekeeping techniques, but major incidents in recent years have led to the development of biocides, as well as microbial monitoring tests for jet fuels. Fuel in tropical areas is particularly at risk because elevated fuel temperatures over time favors microbial growth.

Surfactants (D3948): A key element in preventing contamination is to minimize or eliminate surfactants, which can lower the ability of fuel handling systems to remove dirt and water. Surfactants can disperse dirt and water so finely that they pass through filters. They can also adsorb on the surfaces of filters and coalescers and interfere with water removal, and they can also lift rust from surfaces, increasing the amount of solids in the fuel.

3.2 Full conformity test

The set of tests required to confirm that fuel meets all the specifications in ASTM D1655 and D7566 is commonly referred to as a full conformity test. A list of the detailed requirements of the specifications and the approved ASTM test methods are shown in Table 3 and explained in more detail in the remainder of this section. Any of the listed test methods can be used; however, in case of discrepancy in test results, ASTM identifies some of the methods as referee methods to settle disputes.

Table 3: Detailed requirements for full conformity tests of aviation turbine fuels (Extracted from ASTM D1655 and D7566 Table 1; footnotes not included)

Requirement	Specification		ASTM Test Method
	D1655	**D7566***	
COMPOSITION			
Acidity, total mg KOH/g	max 0.10	max 0.10	D3242
1. Aromatics, vol %	max 25	max 25 **min 8**	D1319
2. Aromatics, vol %	max 26.5	min 8.4	D6379
Sulfur, mercaptan,[C] mass %	max 0.003	max 0.003	D3227
Sulfur, total mass %	max 0.30	max 0.30	D1266, D2622, D4294, D5453
VOLATILITY			
Distillation temp, °C			D86**, D2887
T10 (10 % recovered, temp)	max 205	max 205	
T50 (50 % recovered, temp)	report		
T90 (90 % recovered, temp_	report		
T50 – T10		**min 15**	
T90 – T10		**min 40**	
Final boiling point, temp	max 300	max 300	
Distillation residue, %	max 1.5	max 1.5	

Requirement	Specification		ASTM Test Method
Distillation loss, %	max 1.5	max 1.5	
Flash point, °C	min 38	min 38	D56 or D3828
DENSITY	775 to 840	775 to 840	D1298 or D4052
Density at 15°C, kg/m^3	775 to 840	775 to 840	D1298 or D4052
FLUIDITY			
Freezing point, °C max	−40 Jet A	−40 Jet A	D5972, D7153, D7154, D2386**
	−47 Jet A-1	−47 Jet A-1	
Viscosity −20°C, mm^2/s*l*	max 8.0	max 8.0	D445
COMBUSTION			
Net heat of combustion MJ/kg	min 42.8	min 42.8	D4529, D3338, or D4809
One of the following requirements shall be met:			
(1) Smoke point, mm, or	min 25	min 25	D1322
(2) Smoke point, mm, and	min 18	min 18	D1322
Naphtalenes, vol, %	max 3.0	max 3.0	D1840
CORROSION			
Copper strip, 2 h at 100°C	max No. 1	max No. 1	D130
THERMAL STABILITY			
Filter pressure drop, mm Hg	max 25	max 25	D3241
Tube deposits No Peacock or Abnormal Color Deposits	less than 3	less than 3	
CONTAMINANTS			
Existent gum, mg/100 mL	max 7	max 7	D381**, IP 540
Microseparometer, Rating			D3948
Without electrical conductivity additive	min 85	min 85	
With electrical conductivity additive	min 70	min 70	
Electrical conductivity pS/m (with electrical conductivity additive)	max 600	max 600	D2624
Lubricity mm		**0.85**	D5001

*Note: additional requirements in D7566 compared to D1655 are indicated in bold.

** Note: Referee methods in case of disputes.

As indicated in the table above, there are three expanded requirements in D7566 compared to D1655:

- **Aromatics** – For conventional fuel, only a maximum value for aromatics of 25 % by volume is stipulated. This is to ensure proper combustion without smoke, carbon, or soot deposition. There has not been a need to define a minimum aromatic concentration because petroleum-based jet fuel has a significant amount of aromatics, typically between 8 and 22 %. However, some alternative jet fuels do not have aromatics and, therefore, a minimum level of aromatics needs to be specified since aromatics are important for certain engine components such as elastomer seals.

- **Distillation –** Fuels certified to ASTM D7566 specifications have more specific and detailed requirements for distillation \ than conventional jet fuels. This is to ensure a proper and smooth boiling range distribution.

- **Lubricity –** Lubricity is specified for D7566 jet fuel because it is recognized that so far these fuels consist of a mixture of relatively pure hydrocarbons without the polar acids that enhance lubricity. Conventional fuel is a more complex mixture which naturally contains lubricating agents sufficient to ensure the smooth operation of the moving parts in engine fuel systems.

The test methods approved by ASTM to conduct a full conformity test of jet fuel according to the D1655 and D7566 specifications are discussed below. A basic description of the test and required test equipment is also provided. For more details on test descriptions, please visit the ASTM International website: www.astm.org

3.2.1 Composition

Acidity – Test method: ASTM D3242 *Test Method for Acidity in Aviation Turbine Fuel*

A weighed amount of sample is dissolved in titration solvent and titrated colorimetrically with potassium hydroxide. The result, expressed in mg/KOH/g, is the amount of acidity in the fuel.

The test is basic titration and does not need sophisticated equipment (see Figure 1):

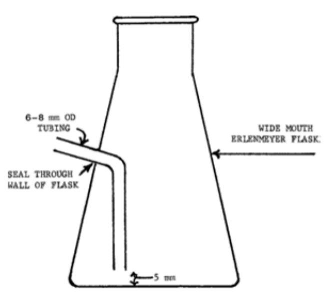

Figure 1: Titration flask for use in test method ASTM D3242 (Source: www.astm.org)

Aromatics – Test method 1: ASTM D 1319- *Hydrocarbon Types in Liquid Petroleum Products by Fluorescent Indicator Adsorption*

A small amount of sample is placed at the top of a capillary glass adsorption column packed with activated silica gel, after the top layer of the gel has been treated with fluorescent dyes. Isopropyl alcohol or isoamyl alcohol is used to carry the sample and the fluorescent dyes down the column. The hydrocarbons separate into bands of aromatics, olefins, and saturates based on their different affinity for the silica gel. The fluorescent dyes, which also selectively separate, make the boundaries of different type of hydrocarbons visible in UV light.

The test requires a set of adsorption columns with standard wall and precision bore (see Figure 2):

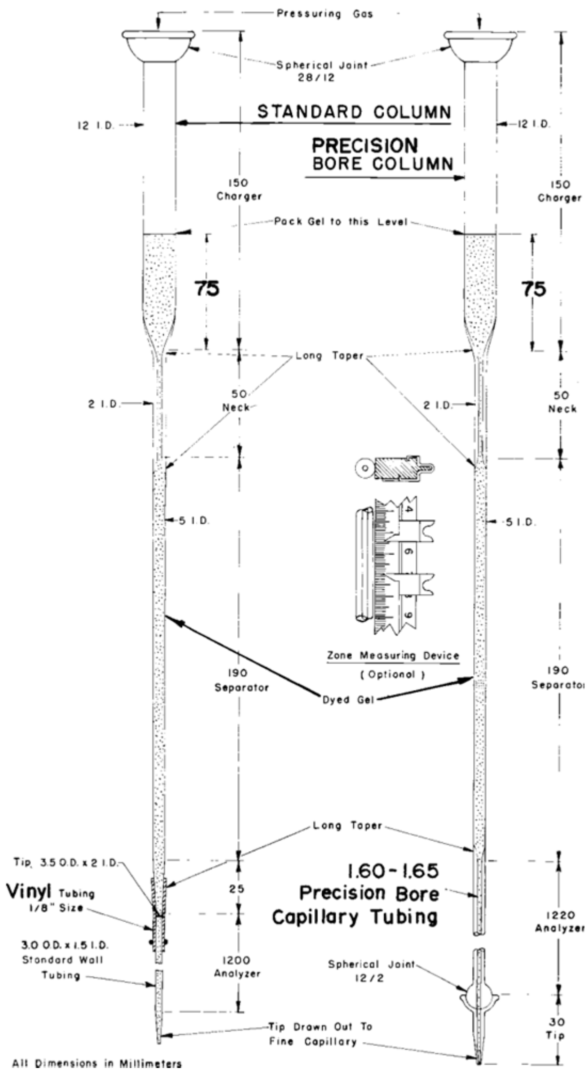

Figure 2: Adsorption Columns with Standard Wall (left) and Precision Bore (right) Tubing in Analyzer Section for use in test method ASTM D1319 (Source: www.astm.org)

Aromatics – Test method 2: ASTM D6379- *Test Method for Determination of Aromatic Hydrocarbon Types in Aviation Fuels and Petroleum Distillates Using High Performance Liquid Chromatography Method with Refractive Index*

A fixed volume of sample diluted 1:1 with the mobile phase (heptane) is injected into a high performance liquid chromatograph equipped with a polar column. The polar column has strong affinity for aromatic hydrocarbons; therefore the aromatics are separated from the non-aromatics into distinct bands based on their molecular structure. The refractive index detector connected to the column detects the components as they elute from the column. The data processor continually monitors the signals from the detector, compares them with the signals from a previously-run standard in order to calculate the percent of the individual aromatic hydrocarbon-types, which added give the result as total aromatics content.

Mercaptan Sulfur – ASTM D3227: *Test Method for (Thiol Mercaptan) Sulfur in Gasoline, Kerosene, Aviation Turbine Fuel, and Distillate Fuels*

A hydrogen sulfide-free sample is dissolve in alcoholic sodium acetate and potentiometrically titrated with standard silver nitrate solution. This precipitates the mercaptan sulfur as silver mercaptide, and the end point of the titration is indicated by a large change in the titration cell potential. The equipment as described in the procedure consists of any automatic titration system using the required electrode pair, and precision burette.

Note C of Table 1 in ASTM D1655 states that the Mercaptan sulfur determination may be waived if the fuel is considered ‘sweet” by the doctor test described in ASTM D4952 (see below).

Active Sulfur Species (Qualitative) ASTM D4952- *Test Method for Qualitative Analysis for Active Sulfur Species in Fuels and Solvents (Doctor Test)*

This is a very simple test Pass/ Failed test, requiring only test tubes and chemicals. A small amount of the sample is vigorously mixed with 5 mililiters (ml) of sodium plumbite solution and then a small amount of pure, sublimed flowers of sulfur. After a few minutes, two layers separate – the fuel on the top and the solution on the bottom – and a pass/fail result (reported as sweet/sour) is assessed based on the changes in color of the sulfur film. The change in color indicates that the reaction of mercaptan and sodium plumbite has occurred, which means mercaptan sulfurs are present in higher concentration than expected.

Sulfur – Test method 1: ASTM D1266 - *Sulfur in Petroleum Products (Lamp Method)*

A sample is burned in a glass lamp with a cotton wick to oxidize the sulfur to sulfur oxide. The combustion gases are bubbled through a solution of hydrogen peroxide to convert the sulfur dioxide to sulfuric acid. The amount of sulfuric acid formed is measured either by barium precipitation or by titration.

The test requires an assembled lamp unit (see Figure 3):

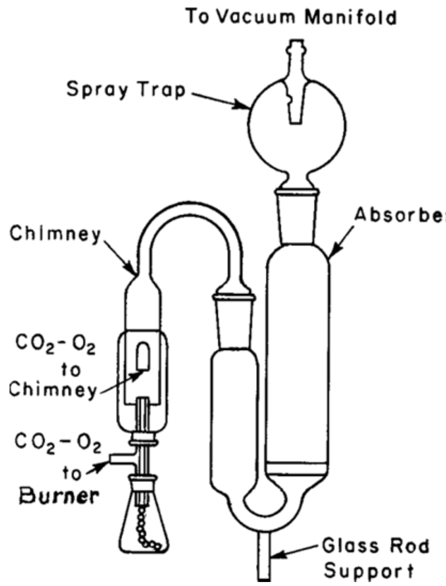

Figure 3: Illustrative Sketch of the Assembled Lamp Unit used in test method ASTM D1266 (Source: www.astm.org)

Sulfur – Test Method 2: ASTM D2622 - *Sulfur in Petroleum Products by X-Ray Spectrometry*

A sample is placed in an X-ray beam and the intensity of the sulfur X-ray fluorescence is measured and used to calculate the sulfur content of the sample. A Wavelength Dispersive X-Ray Fluorescence Spectrometer (WDXRF), equipped for X-ray detection in the wavelength range from about 0.52 nm to about 0.55 nm (specifically at 0.537 nm), is necessary for meeting the requirements specified in the method.

ASTM, under a note in the procedure, acknowledges that the equipment for Test Method D2622 tends to be more expensive than that required for alternative test methods.

Sulfur – Test Method 3: ASTM D4294 - *Standard Test Method for Sulfur in Petroleum and Petroleum Products by Energy Dispersive X-ray Fluorescence Spectrometry*

A sample is placed in an X-ray beam and the resultant characteristic X radiation is measured and used to calculate the sulfur content of the sample. The main equipment needed is an energy-dispersive X-ray Fluorescence Analyzer meeting the requirements described in the method.

Sulfur – Test Method 4: ASTM D5453 - *Standard Test Method for Determination of Total Sulfur in Light Hydrocarbons, Spark Ignition Engine Fuel, Diesel Engine Fuel, and Engine Oil by Ultraviolet Fluorescence*

A sample is burned to oxidize any sulfur to sulfur dioxide. The combustion gases are irradiated with UV light and the fluorescence of the sulfur dioxide is measured and reported.

The apparatus for this test includes (see Figure 4):

- a furnace held at a temperature of around 1075 degrees C sufficient to pyrolyze all of the sample and oxidize sulfur to sulfur dioxide,
- a quartz combustion tube,
- flow control to maintain a constant supply of oxygen and carrier gas,
- drier tube to remove the water vapor,
- UV Fluorescence Detector capable of measuring light emitted from the fluorescence of SO_2 by UV light,
- refrigerated circulator,
- and a balance.

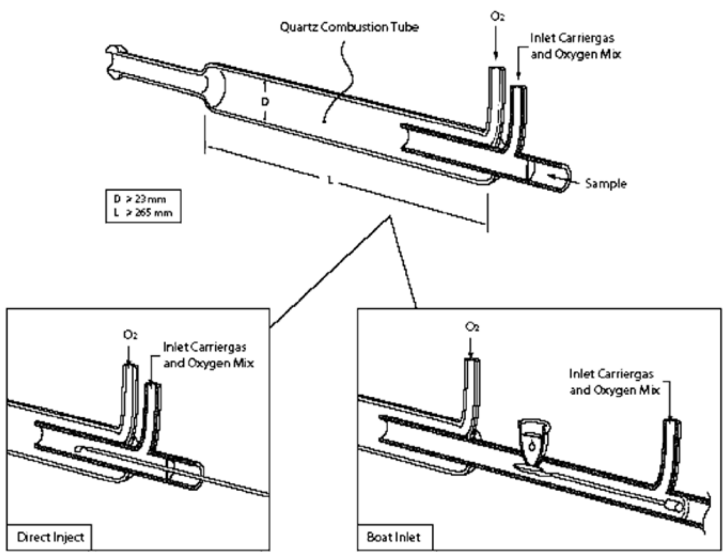

Figure 4: Conventional Combustion Tubes for test method ASTM D5453 (Source: www.astm.org)

3.2.2 Volatility

Distillation – Test method 1: ASTM D86- *Standard Test Method for Distillation of Petroleum Products at Atmospheric Pressure*

A 100 ml sample is placed in a round-bottom flask and heated at a rate specified for a sample with its vapor pressure characteristics. Vapor temperatures are recorded when the first drop of condensate is collected (initial boiling point) and at recovered volumes of 5 ml, 10 ml, 15 ml, 20 ml, and every 10 ml interval to 90 ml, 95 ml and at the end of the test (end point). The amount of sample remaining in the flask at the end of the test and the amount lost during the test (both in percent by volume) are recorded and calculated, respectively.

ASTM D86 describes both manual and automatic procedures. A diagram of the apparatus for manual procedures is shown in Figure 5. All automatic equipment has to be approved by ASTM. The prices for the available and approved automated equipment start around $33,000. The automatic procedure requires minimal technician involvement.

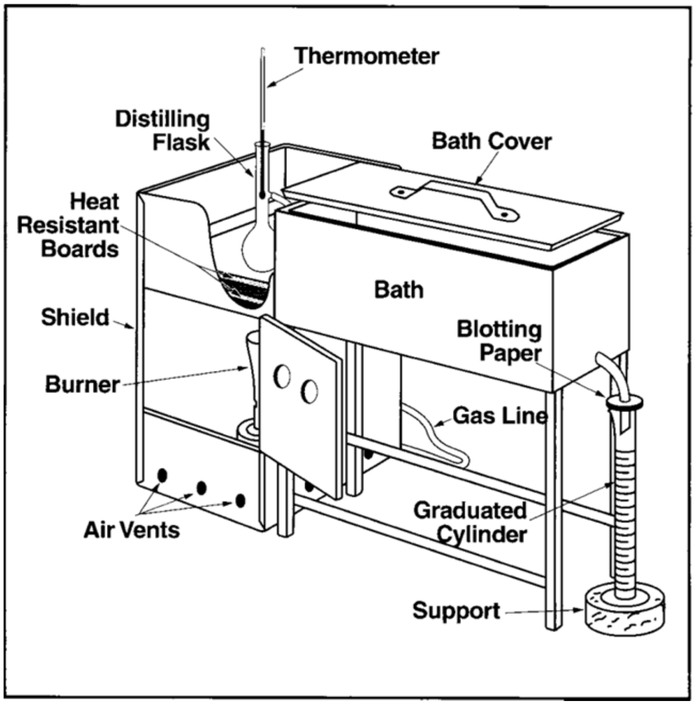

Figure 5: Manual Apparatus Assembly Using Gas Burner for test method ASTM D86 (Source: www.astm.org)

Distillation – Test method 2: ASTM D2887- *Standard Test Method for Boiling Range Distribution of Petroleum Fractions by Gas Chromatography*

The boiling range distribution determination by distillation is simulated by the use of gas chromatography. The hydrocarbon components of the sample are extracted in the column in order of increasing boiling point. The column temperature is raised at a reproducible linear rate and the area under the chromatogram is recorded throughout the analysis. Boiling points are assigned from a calibration curve obtained under the same chromatographic conditions by analyzing a known mixture of hydrocarbons. From these data, the boiling, range distribution can be obtained.

The equipment is a gas chromatograph with strictly imposed performance characteristics, specified in the test method.

Flash Point – Test method 1: ASTM D56- *Standard Test Method for Flash Point by Tag Closed Cup Tester*

A sample is placed in a lidded cup and heated at a slow, constant rate. At regular intervals, the lid is opened and an ignition source is directed into the cup. The lowest temperature at which the ignition source causes the vapor above the sample to ignite is the flash point.

ASTM D56 describes the procedures for both manual equipment and automatic equipment. The manual equipment is shown in Figure 6: Tag Closed Flash Tester (Manual) from ASTM D56. Any automatic equipment has to be approved by ASTM. The price of the automatic flash point apparatus (start at over $22,000) is over 10 times that of the manual equipment (about $2,000). For the automatic equipment the only task needed to be performed by a technician is to setup the sample. The equipment does all determinations and corrections.

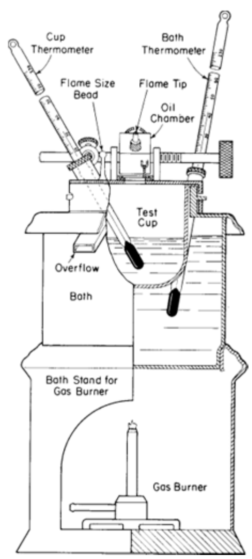

Figure 6: Tag Closed Flash Tester (Manual) from ASTM D56 (Source: www.astm.org)

Flash Point – Test method 2: ASTM D3828- *Standard Test Methods for Flash Point by Small Scale Closed Cup Tester*

This test specification covers two methods. Method A determines whether a product will or will not flash. For this test, a 50 ml sample is introduced, by syringe, into the test cup of the equipment that is set and maintained at a specific temperature. After a specified time, an ignition source is applied to determine if a flash occurred or not. Method B, which determines the flash point of the sample, is a repetition of Method A: the test is repeated with a fresh sample at other fixed temperatures until the flash point is established with the required precision.

D3828 covers both manual and automatic procedures. All automatic equipment has to be approved by ASTM. The price of the automatic equipment is much higher than the manual, starting at around $20,000.

3.2.3 Density

Density – Test Method 1: ASTM D1298- *Standard Test Method for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method*

Fuel is transferred to a cylindrical container and an appropriate hydrometer is carefully lowered into the cylinder and allowed to settle. After the temperature of the sample has equilibrated the value on the hydrometer scale is read as instructed in the method and reported. The result must be corrected to 15º C, and can be reported as API gravity, relative density or density in kg/m^3.

Equipment needed: appropriate cylinder, hydrometer, and thermometer.

Density – Test method 2: ASTM D4052- *Standard Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter*

A small volume of a sample is introduced into an oscillating tube held at constant temperature. The change in oscillation frequency caused by the change in the mass of the tube is related to the density of the sample.

The main part of the equipment is the Digital Density Analyzer - a digital analyzer consisting of a U-shaped, oscillating sample tube and a system for electronic excitation, frequency counting, and display. The instrument must be capable of meeting the precision requirements described in the test method.

3.2.4 Fluidity

Freezing point – Test method 1*:* ASTM D2386- *Standard Test Method for Freezing Point of Aviation Fuels*

A sample is placed in a special jacketed tube fitted with a stirring rod and a thermometer. The tube is placed in a low-temperature bath and stirred as the sample cools. When crystals of hydrocarbons appear, the tube is removed from the cooling bath and allowed to warm up slowly with continuous stirring. The temperature at which the hydrocarbon crystals completely disappear is the freezing point.

This manual test is laborious, requires continuous attention and a skilled eye when it comes to the determination of hydrocarbon crystal appearance. D2386 is the reference method in case of dispute.

Freezing point – Test method 2: D5972 *Standard Test Method for Freezing Point of Aviation Fuels (Automatic Phase Transition Method)*

A small portion of fuel is cooled at a constant rate and monitored optically. When the formation of hydrocarbon crystals is detected by the optical system, the sample is then heated at a constant rate until the crystals dissolve. The temperature of the fuel at this point is the freezing point.

A picture of the apparatus for test method ASTM D5972 is shown in Figure 7:

Figure 7: Apparatus Exterior from ASTM D5972 (Source: www.astm.org)

Freezing point – Test Method 3: D7153- *Standard Test Method for Freezing Point of Aviation Fuels (Automatic Laser Method)*

A 10 ml sample is injected with a syringe into the instrument. The sample is cooled at a certain continuous rate while at the same time being illuminated by a laser light source. The specimen is continuously monitored by optical crystal and opacity detectors for the first formation of solid hydrocarbon crystals. When these are detected the sample is warmed at a set rate. The temperature at which the last hydrocarbon crystals return to liquid phase is the freezing point of the sample. The price for the equipment starts around $40,000.

A picture of the apparatus for test method ASTM D7153 is shown in Figure 8:

Figure 8: Automatic Freezing Point Apparatus for test method ASTM D-7153 (Source: www.astm.org)

Freezing point – Test method 4: ASTM D7154- *Standard Test Method for Freezing Point of Aviation Fuels (Automatic Fiber Optical Method)*

A 25 ml of the test specimen is inserted into a test chamber. Then, the sample is cooled while being continuously stirred and monitored by a fiber optical system. When crystal formation is detected, the temperature is recorded and the specimen in the test chamber is warmed, while being continuously stirred and monitored by the optical system, until the crystals in the specimen completely disappear. The temperature of the measured when the last crystals disappear is recorded as the freezing point.

A picture of the apparatus for test method ASTM D7154 is shown in Figure 9:

Figure 9: Automatic Fiber Optical Freezing Point Apparatus for test method ASTM D7154 (Source: www.astm.org)

An ASTM inter-laboratory study was performed to evaluate the ability of freezing point methods to detect jet fuel contamination with diesel fuel. It was determined that the automated methods D5972 and D7153 provide significantly more consistent detection of freeze point changes caused by contamination than test method D2386 and D7154; however, in case of discrepancies, the referee method continues to be the manual method D2386.

Viscosity (at -20 degree C) Test method: ASTM D445- *Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)*

A sample is placed in a calibrated adequate glass viscometer and held at a closely controlled temperature. The time required for a specific volume of the sample to flow through the capillary under gravity is measured. This time is proportional to the kinematic viscosity of the sample.

3.2.5 Combustion

Net Heat of Combustion – Test method 1: ASTM D4529- *Standard Test Method for Estimation of Net Heat of Combustion of Aviation Fuel*

The neat heat of combustion of a sample is calculated based on the results of previous tests. These results include the sample's aniline point, density and sulfur content. The aniline point is the minimum temperature at which aniline and petroleum products or hydrocarbon solvents mix completely. It provides an estimate of the aromatic hydrocarbon mixture based on the different values for different hydrocarbon groups: aromatics have the lowest aniline point, paraffins have the highest, and cycloparaffins and olefins have values in between the two classes. The aromatic content is then used to calculate an approximate value for the heat of combustion

Net Heat of Combustion – Test method 2: ASTM D3338- *Standard Test Method for Estimation of Net Heat of Combustion of Aviation Fuels*

Similar to test method D4529, the net heat of combustion of a sample is estimated from another set of test results. Here, the results include the sample's API Gravity, aromatics content, and distillation profile.

Net Heat of Combustion – Test method 3: ASTM D4809- *Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)*

A weighed sample of fuel is placed in an oxygen bomb calorimeter under specified conditions. The fuel is ignited and the temperature increase of the calorimeter is used to calculate the heat of combustion.

Smoke Point – Test method: ASTM D1322- *Standard Test Method for Smoke Point of Kerosene and Aviation Turbine Fuel*

A set amount of sample is burned in a wick-fed lamp. The smoke point is the maximum height of flame that can be reached without smoking.

A picture of the equipment for test method ASTM D1322 is shown in Figure 10:

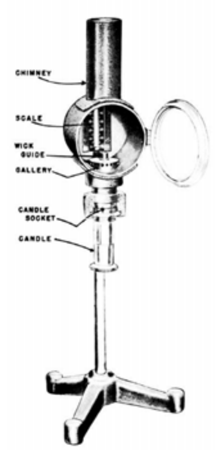

Figure 10: Smoke Point Lamp for test method ASTM D1322 (Source: www.astm.org)

Naphthalene – Test Method: ASTM D1840- *Standard Test Method for Naphthalene Hydrocarbons in Aviation Turbine Fuels by Ultraviolet Spectrophotometry*

A sample is dissolved in iso-octane at a known concentration and the absorbance of the solution at 285 nanometers is measured and used to calculate the naphthalene content.

3.2.6 Corrosion

Direct corrosion of metals by jet fuel, especially copper, has been attributed to the presence of hydrogen sulfide or elemental sulfur at levels of 1 ppm or less. Rather than testing for these materials, the copper strip test is performed for jet fuel.

Copper Strip – Test method: D130- *Standard Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test*

A polished copper strip is immersed in a sample for 2 hours at 100 degrees C and then removed and washed. The result is determined by qualitatively rating the copper surface by comparing it to the standard.

3.2.7 Thermal Stability

Test method: D3241- *Standard Test Method for Thermal Oxidation Stability of Aviation Turbine Fuels*

The instrument replicates the condition in the jet engine: fuel is pumped over a heated aluminum alloy tube at a constant flow rate for 2.5 hours at set temperature (260 degrees C). After contact with the tube, the fuel is filtered to collect any solid decomposition products. The pressure drop across the filter is monitored during the test. At the end of the test, the tube is removed and visually examined and rated by comparing it to a standard color scale. The visual rating and the pressure drop across the filter at the end of the test are reported as a pass/fail test results.

The equipment for this test is massive and the price starts around $75,000.

3.2.8 Contaminants

Existent Gum – Test method: D381- *Standard Test Method for Gum Content in Fuels by Jet Evaporation*

A measured amount of fuel is transferred to a weighed beaker, placed in a heated bath, and evaporated under a flow of steam. The resulting residue is weighed and reported as existent gum. The equipment (steam generator and heated bath) costs a minimum of approximately $20,000.

A picture of the equipment for test method ASTM D381 is shown in Figure 11:

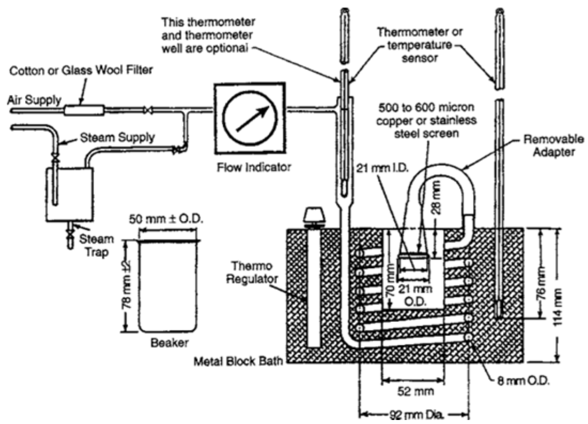

Figure 11: Apparatus for Determining Gum Content by Jet Evaporation for test method ASTM D381 (Source: www.astm.org)

Water Separation Characteristics – Test method: D3948- *Standard Test Method for Determining Water Separation Characteristics of Aviation Turbine Fuels by Portable Separometer*

Using a semi-automatic micro-separometer instrument, a fuel sample is mixed with water, forced through a fiber-glass coalescing medium, and rated. The MSEP rating indicates the relative ease of coalescing water from the sample. The instrument is calibrated with a water free fuel sample. The price for the instrument starts at around $10,000.

Electrical conductivity – Test Method: D2624- *Standard Test Methods for Electrical Conductivity of Aviation and Distillate Fuel*

A voltage is applied across two electrodes in the fuel and the resulting current is expressed in terms of the conductivity of the sample. In the case of portable conductivity meters, the current measurement is made immediately, and the instrument display is the reported result.

Lubricity

Test Method: D5001- *Standard Test Method for Measurement of Lubricity of Aviation Turbine Fuels by the Ball-on-Cylinder Lubricity Evaluator (BOCLE)*

In this test, a non-rotating steel ball is held against a cylindrical ring. The cylindrical ring is rotated at a fixed speed while partially immersed in the fuel sample. At the end of the test, the ball is removed and examined for wear. The size of the wear scar (measured in mm) is related to the lubricity of the fuel.

A picture of the equipment for test method ASTM D381 is shown in Figure 12:

Figure 12: Semi-Automatic Ball-on-Cylinder Lubricity Evaluator for test method ASTM D-5001 (Source: www.astm.org)

3.3 Eight-point test

A set of tests that are routinely used in the aviation industry to verify the quality of jet fuel is the so-called eight-point test. Once a batch of certified jet fuel is dispatched from the refinery, it will pass through the control of many different organizations before finally being loaded into an aircraft. Each stage of this delivery process offers the potential for contamination or degradation of the fuel. It is not feasible from a time or cost perspective to do a full conformity test of each batch of fuel at each of these points; however, based on the industry's experience of handling the fuel according to best practices, as few as eight tests can give a quick and reliable indication of the fuel's quality and cleanliness. This set of tests is required by ATA 103 before jet fuel is received at the airport and is referred to in API 1543, as well.

In the eight-point test, test results are compared with previous results that are contained in the batch transfer documents and compared with the applicable standards. At any stage, if any of these tests produces unexpected results, the tested fuel must be quarantined for a full conformity recertification under the original standard.

The tests as required by ATA 103 are listed below. The applicable ASTM test methods are also indicated. Apart from the visual appearance test, descriptions of the test methods have been included in Section 3.

a) Visual appearance in white bucket

   Color limits are not normally a specification item, but color deterioration can be a useful indicator of inter-product contamination or instability (gum formation), or cleanliness of the fuel.

b) Gravity (ASTM D1298 or ASTM D4052)
c) Distillation (ASTM D86)
   - 10%
   - 50%
   - 90%
   - Final boiling point
   - Residue
   - Loss
d) Flash Point (ASTM D56 or D3828)
e) Freezing Point (ASTM D2386, D4305, D5901, D5972)
f) Water Separation Characteristics (ASTM D3948)
g) Copper Corrosion (ASTM D130)
h) Existent Gum (ASTM D381)

3.4 Common testing procedures along the supply chain

Quality control processes in the fuel delivery system are designed to ensure the fuel is safe for aircraft operation. While this process starts at the refinery with the certification that fuel has been produced to meet D1655 or D7566 specifications, the fuel has to meet other requirements on delivery not included in the specification. In their simplest form, those requirements are called "clean and dry" and they ensure the delivery of a fuel free of contaminants that may be picked up in the fuel system anywhere between the point of manufacture until the fuel reaches the aircraft. These requirements are captured in a set of additional procedures including contamination tests and fatty acid methyl ester (FAME) tests. These tests and procedures are discussed below.

3.4.1 Contamination

Jet fuel contaminants can be divided into two broad categories: 1) solid contaminants and water, and 2) other fuels or materials that are soluble in jet fuel. Contamination tests are performed regularly in the industry without being included in the product specification. Some of the procedures that are performed at different points along the distribution system are not part of the specification and they have developed over the years from practical experience in the handling of conventional jet fuel. A recommended source of information on this type of procedures is the ASTM Manual 5, 4th edition: *Aviation Fuel Quality Control Procedures* (ASTM 2010). These tests include:

- Visual appearance is a gross measure of possible contamination with darker or dyed fuel, or solids or free water. Product color can be used for the detection of other petroleum products having darker colors than jet fuel.

- Solid particles are collected on special membrane filters of certain specifications. The solids content can be calculated by weighing the dried membrane or the dirt level can be described by comparing the membrane color to a standard chart.

- Free Water- there are a number of water detection methods ranging from water detecting paste which detects the depth of the water layer in a storage tank, to methods used to detect the suspended free water, usually at a level of 15 or 30 ppm (Shell Detector, Velcon Hydrokit, or Metrocator). The most sensitive method for undissolved water is the Aqua-glo test (ASTM D3240 detects undissolved water down to 2-3ppm. Water content can be also determined by Karl Fisher titration procedure (ASTM D6304).

- Microorganisms – microorganisms must have undissolved free water to grow and reproduce. As a result, most microbial growth is at the fuel-water interface. The products of active microbial growth tend to be corrosive to metal. They can act as surfactants, they from slimes or mats that can plug screeds or filters. There are few tests for determination of microbial contamination such as Hy-Lite kit recommended by IATA.

3.4.2 Fatty Acid Methyl Ester (FAME)

FAME, by nature, is a surface active agent, and theoretically can have an adverse effect on quality control equipment that relies on surface tension to separate water from fuel. Additionally, FAME contamination could cause deterioration in thermal stability resulting in oxidation and release of coke deposits in turbine engines, and could affect the freezing point of the fuel. FAME contamination can be an issue when transporting jet fuel in infrastructure that also transports biodiesel.

FAME is not a component in jet fuel produced from petroleum or via the Fischer Tropsch processes. For HEFA production process, due to the nature of the feedstock, ASTM D7566 Annex 2 specifies that production controls should ensure that the product contains less than 5 ppm of FAME. Two test methods are approved:

Test Method 1: IP 585 *Determination of fatty acid methyl esters (FAME), derived from bio-diesel fuel, in aviation turbine fuel - GC-MS with selective ion monitoring/scan detection method.*

Test Method 2: IP 590 *Determination of fatty acid methyl esters (FAME) in aviation turbine fuel - HPLC evaporative light scattering detector method*

4 Quality Control along the Supply Chain

The collaboration between the entities involved in the jet fuel industry – regulators, equipment manufacturers, fuel producers and handlers, and airlines – has evolved into a complex quality control system governed by best practices and guidelines that ensure robust quality control and safe handling processes. In this section, we more fully describe the responsibilities of the fuel producers and delivery companies.

4.1 Supply Chain Overview

Once a batch of fuel is dispatched from the refinery it passes through the control of many different organizations. It will be transported by pipeline, tanker truck, rail car, or even barge and may be stored in an intermediate storage facility before finally being delivered to the airport. Each of the entities along the supply chain has a responsibility for the ultimate delivery of ‘clean dry’ fuel. Consequently, jet fuel is tested according to each organization’s quality control process at points when it is handed off from one to another. The diagram in Figure 13 provides an overview of the entire jet fuel supply chain and identifies the most common fuel quality control standards that can be applied. Notice that these standards apply whether the fuel is being transported domestically or internationally. Depending on the country, there may be different or additional quality control criteria that need to be followed. International organizations such as IATA, EI, JIG, and A4A have been working diligently for many years to provide as much standardization as possible to simplify quality control procedures.

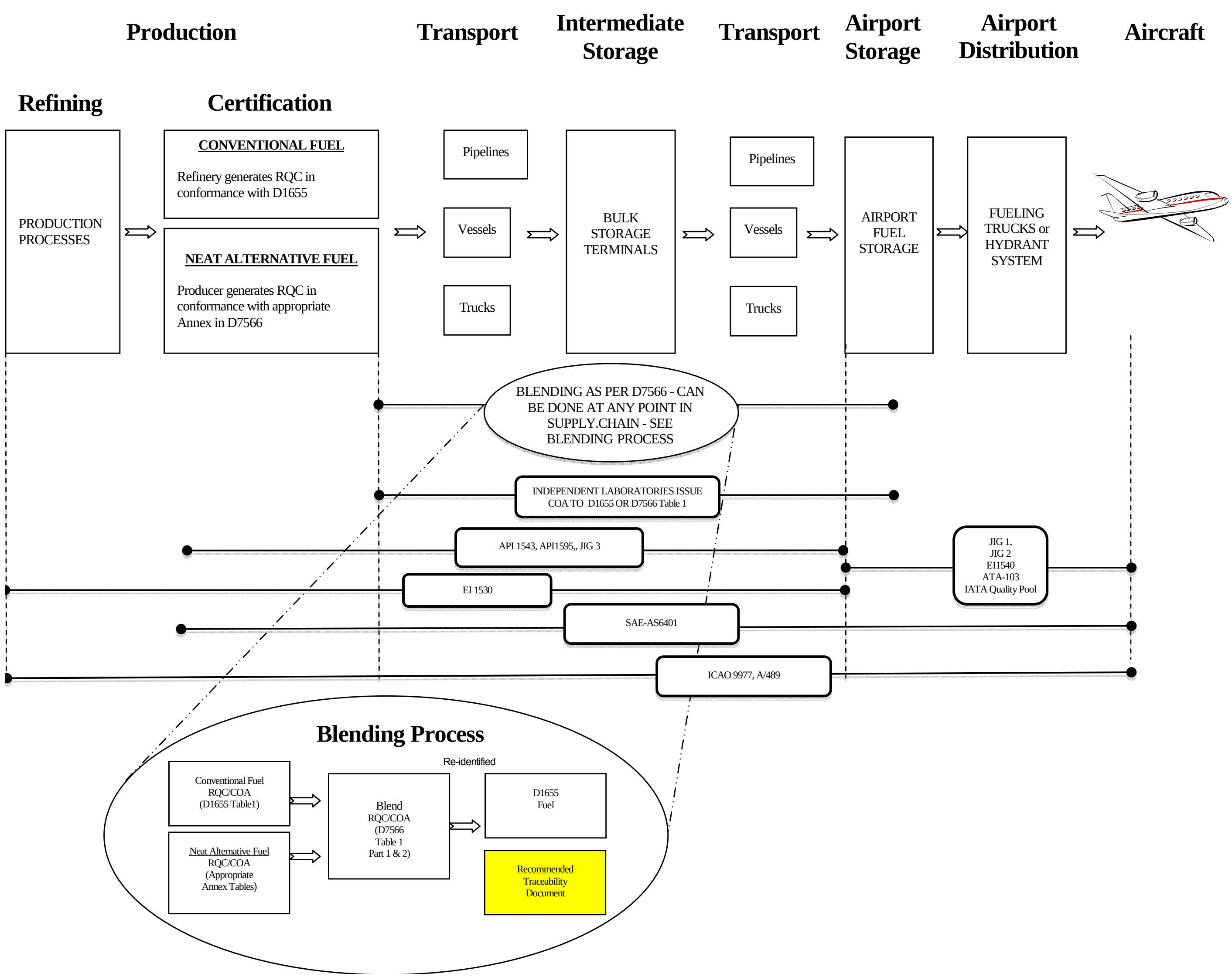

Figure 13: Jet fuel supply chain and quality control process overview

4.2 Refineries

The first step in the fuel quality control process is to certify that the fuel meets the applicable D1655 or D7566 specification. The refinery of origin is responsible for issuing the RQC and for keeping the production records for each unique batch and samples of each batch for a period in case unexpected issues arise downstream. The Certificate of Analysis (COA) is typically issued by an independent laboratory downstream from the point of manufacture. More detail on both documents is given below:

Refinery Quality Certificate: The RQC is the original document describing the quality of the fuel, and determinations of all the properties required in the relevant specifications (ASTM D1655 or D7566). It is prepared by the refinery manufacturing the product and must be signed by an authorized representative. It must include the following:

- Batch number
- Manufacturing refinery
- Documents the fuel specification manufactured against (D1655 or D7566)
- Details of additives used (including content of synthetic components if required by the specification)

Certificate of Analysis: The COA is issued by an independent laboratory after a complete specification analysis of the finished fuel, and is often issued at some point downstream of the point of manufacture. It is dated and signed by an authorized representative of the laboratory and includes the following:

- Batch number
- Manufacturing refinery
- Tested properties required in the relevant specification (D1655 or D7566 and appropriate Annex Tables)
- Need not necessarily contain details of additives used (this is a major difference with respect to an RQC)

Notice that for alternative fuel, the current D7566 specification states that the fuel must be blended up to 50/50 with conventional fuel. Thus, prior to an RQC or COA being generated, the alternative fuel has to be blended. This can occur at the refinery or at any other point in the supply chain. The implications of where the fuel is blended and, thus, certified, will be discussed in Sections 4.2.2 and 5.

Once the certified fuel leaves the point of manufacture or blending, handlers have to follow certain guidelines. EI 1530 applies from the point of manufacture to delivery at the airport. API 1543 and JIG 3 apply from when the fuel leaves the refinery to when it reaches airport storage.

JIG 1+2, ATA 103, or IATA Quality Pool apply once the fuel is received into airport storage and until it gets dispensed into the aircraft tanks.

4.2.1 Refinery batch traceability

During its journey from the refinery to the airport, the traceability of the jet fuel back to its manufacturing origin or the point at which it was last certificated is preferred. To this end, the refinery issues a unique and traceable batch reference number for each production batch and each batch of product is tested and certified as meeting the relevant ASTM specification.

Within the distribution network, batch integrity is maintained, monitored, and rechecked until the fuel is mixed with other fuel either at an intermediate storage facility or at an airport. From that point forward, batch identity is lost and the RQC is no longer applicable and a new COA needs to be generated. Chapter 2 of EI 1530 has detailed information on the types of documents required to accompany the batches on their journey to the airport according to the path traveled (e.g. if they were held in intermediate storage or were delivered directly to the airport). The same chapter in EI 1530 also includes information on the product audit trail necessary at each stage in the supply chain.

4.2.2 Process Control and Management of Change (MoC)

It is of critical importance for refineries to ensure that the fuel is manufactured consistently to meet the requirements in the chosen specification. According to EI 1530, “experience has shown that aircraft fuel-related problems can often be traced back to refinery processing deficiencies” (EI 2012). Therefore, the refining industry has created ways to anticipate and avoid problems related to the manufacture of the fuel. One of these ways consists of process control, i.e. identifying how different refinery processes are more likely to impact fuel properties. For example, Table 4 shows a number of refinery processes and their possible impact on several fuel properties. This type of refinery process to fuel property mapping is useful if the need arises to investigate deviations in certain properties of the finished fuel.

Table 4: Example of possible impacts of refinery processes on fuel properties (Source: Adapted from (EI 2012)).

Refinery process	Sensitive fuel property	Likely cause
Straight-run (untreated)	Mercaptan sulphur, acidity, thermal stability, odor, color	Crude selection
	Water separation properties, conductivity response	Impurities
	Salt content	Carryover from salt dryer due to improper operation or maintenance
Hydrotreatment/ hydrocracking	• Corrosivity (H_2S) • Peroxidation • Thermal stability • Color	• Insufficient steam stripping. • Insufficient or mis-applied antioxidant • Insufficient hydrotreatment of cracked components • Change of catalyst
Wet treatments Caustic wash (including use of sweetening unit without reactor step) Merox™ and similar sweetening units Sulphuric acid	Acid/base number (caustic carryover)	Insufficient water wash
	Water separation properties, color, conductivity response	• Impurities, surfactant formation • Deficiencies in caustic quality • Insufficient water wash • Spent clay treaters
	Salt content	Carryover from salt dryer due to improper operation or maintenance

Note that Table 4 is for refinery processes using conventional petroleum feedstock. As the alternative fuel industry expands and reaches commercial scale, similar process control mappings would be very helpful, especially for new fuel producers.

MoC recognizes that changes in one part of the refining operation or other elements of the supply chain (e.g. feedstock selection, processing steps, additives, blending, storage and handling infrastructure) may have unintended consequences downstream. MoC provides a system to identify, evaluate, authorize, and document changes in a consistent and systematic way to ensure that knowledge is captured and retained and that, ultimately, the quality of the fuel is maintained (EI 2012). EI 1530 has more details and an example review process. MoC will be particularly useful for alternative fuel producers as their production systems and supply chains mature.

Addition of MoC to ASTM D1655 happened in 2003, when ASTM approved to add a refinery MoC requirement. This MoC requirement is intended to control use of refinery processing additives that can potentially affect fuel quality if used improperly, without introducing onerous batch-testing requirements to the specification. The discussion that led to the introduction of the refinery MoC to the specification originated in a recommendation from the Australian Transportation Safety Bureau as an outcome of their investigation of a fuel contamination incident caused by a refinery corrosion inhibitor. Refineries in the US operate under OSHA Process Safety Management regulations that include a MoC requirement. Although the OSHA MoC requirement is directed at safety and health, it is expected that refineries will be able to comply with this proposal by adding a fuel quality element to their existing MoC process. The same language regarding MoC is used in DEF Stan 91-91 and has the same intent.

ASTM D7566 highlights the need for a Management of Change system that evaluates the impact of processing changes in manufacturing the different types of SPKs. Both ASTM D1655 and D7566 recommend that changes in the fuel handling system to be subject of a formal Risk and Management of Change Assessment to ensure product quality is maintain.

4.3 Blending

It is important to note the blending requirement of D7566 for alternative jet fuels. D7566 is based on a blended mix of the synthetic fuel with jet fuel conforming to D1655 with up to a maximum of 50% alternative fuel by volume. This means that the neat alternative fuel produced by the refinery will leave the manufacturing facility with a Quality Document issued against appropriate D7566 Annex Tables (for FT SPK the specification is D7566 Table A1.1 and A1.2, for HEFA SPK the specification is D7566 Tables A2.1 and A2.2), and must be blended with conventional jet fuel before the refinery issues its RQC or a COA against D7566 Table 1, part 1 and 2. In cases where the densities of the neat alternative jet fuel and the conventional blendstock are significantly different, care should be taken to ensure a homogenous blend.

The blending requirement has significant implications for production facilities of alternative jet fuel that do not have access to D1655 certified jet fuel. In that case, certification will need to occur at a blending location outside of the production facility. There, if the fuel does not meet the specification after blending, it will not be allowed to enter the jet fuel supply chain and will have to be quarantined. Based on the parameters that are out of specification, a decision will have to be made to either have the product returned to the production facility, sold as downgraded product, or disposed of in some other manner.

Another question associated with blending is the possibility of “re-blending.” D7566 allows a maximum blend ratio of 50/50 of alternative and conventional fuel. Once the fuel is certified to D7566, it is re-identified as D1655 fuel, and treated as such all throughout the Supply Chain. This means that the blended fuel, since it is now certified to D1655, could be considered blendstock. Thus, theoretically, a 50/50 blend could be re-blended with neat alternative fuel, resulting in a blend with more than 50% alternative fuel. Such eventuality has been anticipated by the D7566 specification. As mentioned earlier, alternative jet fuel has a lower density that conventional jet fuel. One of the reasons behind the 50/50 maximum in D7566 was to avoid re-blending since a blend with more than 50% alternative fuel is not likely to meet the density specification.

4.4 Transportation from the refinery to the airport

It is the responsibility of the final delivery company to furnish on specification, “clean and dry” fuel to an airport. Organizations such as API, EI, and JIG have issued best practices for handling procedures and testing guidelines to help achieve this goal, as discussed in more detail below.

4.4.1 Batch traceability

A significant portion of the jet fuel consumed in the U.S. is delivered by pipeline. Other transportation modes include tanker truck, rail car, and barge. In some of the larger metropolitan areas with several airports using large volumes of jet fuel, pipeline delivery is the only practical method. For example, in the New York metropolitan area, the three major airports (JFK, EWR, and LGA) consume several million gallons of jet fuel daily, all of which is delivered by pipeline.

In general, pipelines deliver a multitude of products (e.g., gasoline, diesel, home heating oil). Therefore, intermediate terminals are situated throughout the nation where several batches of product are stored and accumulated until sufficient demand is available for a large bulk delivery. For the purposes of quality control as defined by API (now Energy Institute, EI) in API 1543, a “batch” is a “distinct quantity of fuel that can be characterized by one set of test results including the type and amount of additives present” (API 2009). Accordingly, all batches of jet fuel leaving a refinery are certified by an RQC that specifies the properties of the fuel; however, once two or more individual batches enter a co-mingled storage facility, their batch identity according to the EI definition is lost. In order to assign a true batch number to a given volume of fuel leaving the co-mingled storage according to the EI definition would require a full conformity test and the issue of a COA. Those tests are more expensive and more time-consuming than the eight-point test currently approved to be performed in the absence of a COA. Therefore, the pipeline industry has developed a batch control and system of traceable codes that are not truly representative of the EI definition of a “batch”. These batch numbers are generated for volumetric accountability and do not carry over the certificate of analysis (COA) that accompanied the individual batches. The fuel leaving the facility is only checked with the eight-point test that does not provide all the information contained in a COA.

4.4.2 Testing along the supply chain

Once a batch of fuel leaves the refinery, its quality is rechecked at different times as it is handed off between different entities. During this time, the quality test lineup is experience-based and can differ from one company to another. Some of the most commonly used tests are:

- Density (D1298 , D4052)
- Distillation (D86, D2887)
- Flash Point (D56, D3828)
- Freezing Point (D2386, D4305, D5901, D5972)
- Existent Gum (D381)
- Copper Corrosion (D130)

- MSEP- Water Separation Characteristics by Portable Separometer (D3948)
- Color (D156)
- Electrical Conductivity (D2624)
- JFTOT- Thermal Oxidation Stability (D3241)

Some of these tests are also part of the set of tests required at a minimum by ATA 103 as part of the fuel check at the airport receipt, in case of a full COA is not available. The results of these tests are compared to expected results, and if the test results are outside the allowable specification limits, the fuel batch has to be segregated and quarantined until further testing has established that the quality is acceptable for aviation use. API 1543 requires that when a quality certificate does not accompany the product received into pre-airfield storage or one is not available, a full conformity test to the relevant fuel specification must be carried out before release. ATA 103 states that when batch traceability is lost during delivery, an eight-point test on receipt at the airport will suffice to test for acceptability.

According to API 1543 recommended practices, a Release Certificate is attached to every fuel transfer which is signed by an authorized person and certifies conformity with applicable specifications. It indicates:

- Time and date
- Product quality
- Batch number
- Density at 15 degrees C
- Service tank number
- Water check

Other recommended practices in API 1543 include:

Re-certification Test Analysis: This is used to check that the quality of the product has not changed and is maintained within tolerated limits. Full re-certification is not always mandatory but it is usually required after the use of non-dedicated transport. If the result of analysis does not match the tolerated difference between the re-certification analysis and the previous analysis, the product it is not used before the cause of the incident has been found and the other specifications match the limits.

Contamination Analysis: This is performed before the offloading of a sea vessel. A re-certification analysis is usually performed in any case at the end of the offloading.

Periodic Test Analysis/ Periodic Test Certificate: The Periodic Test Certificate confirms that the product in stock still matches the major aviation fuel specifications in case the product had been stored for a long period of time.

Visual Checks: These are performed on routine basis at all points during the supply chain. Visual checks are required to check that the product is free of:

- Water
- Sediments /particulate contaminant
- Obvious color bodies and have normal appearance /color

Acceptability Checks: These are performed usually on product receipt and include:

- Visual check, and
- Density measurement (density is compared with the density on the release certificate and the difference cannot surpass a set value)

Particulate Detection Checks: There are two types of checks, including a colorimetric and a gravimetric test. These give an indication on the solid particles content in the fuel. These are performed periodically and show evidence of the effectiveness of the filtration equipment and the validity of quality control procedures. Keeping the tests records provides a history of normal and abnormal filter and/or fuel conditions.

Electrical Conductivity Tests: These are performed at different times of the product life. They give an indication of whether more additives are necessary, or particular precautions should be taken in fuel handling.

4.5 Airport storage and delivery to wing

Once fuel is within an airport, the quality control processes are more systematic than during delivery. Even though each airline is ultimately responsible for the quality of the fuel in its aircraft, in reality it must often rely on an airport's fuel delivery system to ensure product safety. Today, at most airports around the world, fuel delivery is managed by an independent contractor that is responsible for ensuring fuel delivered to an aircraft meets specification. These fuel services companies are responsible for accepting delivery of and testing fuel that has been ordered by airlines, keeping records, and delivering safe clean fuel to an aircraft wing.

In the U.S., the A4A recommends that its members follow the ATA 103 guidelines for fuel handling at airports. ATA 103 designates use of the eight-point test to check on fuel quality at different points during the handling of fuel at the airport. In contrast to API 1543, which establishes more general minimum requirements for fuel handling, ATA 103 includes specific requirements for fuel handling and testing, including equipment, equipment checks, and record-keeping. Likewise, the procedures specified by JIG are very rigorous and they apply to jointly owned and operated systems. IATA Quality Pool is often used by foreign carriers.

Most U.S. and Canadian airlines reference ATA 103 in their certification manual and ATA 103 standards are contractually included in fuel delivery agreements. However, the ATA 103 standards are not specified in any government regulation. Federal Aviation Regulations reference fuel handling standards when carrying out airline safety inspections and the FAA will check that airlines have systems in place to audit the companies that are handling fuel delivery to ensure fuel is being appropriately tested; however, the FAA does not set the standards for an airport's handling or testing of fuel.

5 Considerations Regarding the Introduction of Alternative Fuels

This section discusses a number of considerations regarding the introduction of alternative fuels into the jet fuel supply chain. While no radical changes to the current quality control system are envisioned, the recommendations herein are meant to strengthen current practices.

5.1 Documentation for neat alternative fuel leaving a refinery

Consideration: This discussion pertains to alternative fuels that need to be blended with conventional fuels to meet the D7566 specification. The need for these fuels to be blended raises the question of the type of documentation that needs to accompany the neat alternative fuel as it leaves the refinery including for export across international borders. The current quality control system is based on the fact that any jet fuel leaving a refinery must be accompanied by an RQC certifying that it meets D1655 or D7566 or an equivalent standard; however, the neat alternative fuels will have to be certified against the appropriate Annex's Tables before the blending can take place.

Recommendation: This gap in the current system could be addressed by issuing a "document of quality" that includes the properties of the neat alternative fuel according to the appropriate annex in the D7566 specification. D7566 recommends the format for this type of document in Annex 4: Form 2 and Form 3. It is strongly recommended to use that format to structure the document of quality, including all the detailed batching and product type info, especially as the industry still gathers data in order to gain more experience in the use of the new type of fuels. This document of quality would become the RQC/COA of the neat alternative fuel. The main reason for blending alternative with conventional jet fuel is to meet the density, lubricity, and aromatics specifications. Knowing these properties for the alternative fuel would allow the blender to select an appropriate blend ratio to ensure the resulting blend meets D7566. For example, the density specification for conventional fuel in D1655 includes a given range. If the density of the blendstock is close to the lighter end of the density spectrum in the specification, the blend with neat alternative fuel may fail the density test because both the blendstock and the alternative fuel may not be dense enough. API 1543, ATA 103, EI 1530, and any other regulations or guidelines would have to be revised to incorporate requirements for batch traceability, certification, quality certification, and documentation for the neat alternative fuels. This "document of quality" can also facilitate and simplify export/import procedures for neat alternative fuels.

5.2 Information on feedstock and production process in RQC and COA

Consideration: When a batch of fuel is dispatched from the refinery into the distribution supply chain, its provenance, which includes the name of the production refinery and details such as any additives, is recorded on its RQC and COA. The current system assumes that all jet fuel is made from petroleum and, therefore, no information on the feedstock or production process is indicated in the RQC or COA. As alternative fuels start to enter the supply chain, it would be prudent to record the feedstock and production process used in the manufacture of all fuels. This information may be relevant for studies related to changes in fuel properties along the supply chain over time, for example.

Recommendation: Include information on feedstock and production process in the RQC and COA of any jet fuel, whether it was produced from petroleum or alternative feedstocks. For alternative fuels certified to D7566, this information should be referenced to the specific annex under which the fuel was certified. Note that this information is already contained in Forms 1, 2, and 3 of Appendix 4 in D7566. Also, for the batch generated after the blending, a traceability document should be issued to accompany the COA of the batch, and it should include information about the origination (feedstock, production process type and original batch numbers) of the blending components. To avoid the use of an extra document to accompany a batch, it is recommended to revise D7566 Annex 4, Form 1 - *Inspection Data on Aviation Turbine Fuel Containing Synthesized Hydrocarbons* to include the detailed information about both the neat alternative fuel and the conventional jet fuel in the blend: original batch numbers, feedstock information, and manufacturers/suppliers. This information is very important, again, as the industry gains experience and needs to build a database on the use of alternative fuels in aviation. Also, the use of this form recommended by ASTM should be strongly encouraged or required in applicable standards throughout the industry. Current standards documents should be revised to make it explicit that aviation jet fuel may be produced from feedstock other than petroleum.

5.3 Additional laboratory tests for D7566 fuels

Consideration: Fuel that is certified under D7566 must meet a specification standard for lubricity which is not part of the specification for D1655. Thus, laboratories that routinely issue COAs for conventional jet fuel may not have the equipment and training required to certify alternative fuels to D7566. This may result in delays and increased cost for fuel handlers if the laboratories they normally use are not in a position to perform fuel-conformity tests to D7566.

Recommendation: The presence of the additional test in D7566 compared to D1655 should be communicated clearly to laboratories that routinely issue COAs for conventional jet fuel. For experienced laboratories that routinely do D1655 tests, the barrier to expanding the capabilities for the extra test should be low.

5.4 Expansion of the Eight-point test

Consideration: As mentioned above, fuel that is certified under D7566 must meet a specification standard for lubricity and minimum levels for aromatics content, in addition to having an expanded distillation specification. These tests are not included in the eight-point test carried out today as defined by ATA 103. Since the eight-point test is a principal means to check the consistency of fuel properties without having to perform a full-conformity test, it would be important for the eight-point test to include lubricity and aromatic content. In addition, there may be other properties of interest, such as sulfur content, that could captured with an expanded eight-point test.

Recommendation: Expand the eight-point test as described by ATA 103 to include tests for lubricity, aromatics, and other properties of interest, such as sulfur content. In addition, replace the current distillation specification to the expanded version in D7566. Furthermore, it would be beneficial to include information such as feedstock and production method as part of product information that accompanies the documentation with results from the eight-point test.

5.5 Blend analysis

Consideration: In order to estimate and monitor the potential impact of the introduction of alternative fuels into the jet fuel supply chain, it is necessary to determine how much alternative fuel is present in each test sample. Unless this datum is present for each fuel sample, it will be impossible to attribute any changing characteristics in the jet fuel supply chain to the presence of alternative fuel. The recommendation above that the RQC and COA include the feedstock and production process for each fuel is only partially effective at capturing this information along the supply chain. As it has been explained, batch traceability is impossible under the current system as batch identity is lost as the fuel enters comingle storage.

An effective means to identify the presence of alternative fuel in a fuel sample is not a straightforward proposition at this time. Because the molecular constituents of alternative fuel vary only slightly from petroleum-based fuel and, moreover, the chemical makeup of petroleum fuels differs depending on the oil source, the presence of any particular molecule in a sample cannot indicate definitively whether it contains alternative fuel.

An approach to detect the presence of fuel made from biomass feedstock is to measure the relative amounts of different isotopes of carbon in the sample, as discussed below; however this method will not work for alternative fuel made from fossil feedstocks, whether coal, natural gas, or from CO_2 captured from industrial processes. For FT fuels, tests based on mid-infrared spectroscopy may be effective in determining the presence of alternative fuel.

Radiocarbon Analysis

There are the three naturally occurring isotopes of carbon: carbon-12 which comprises 99% of carbon in the atmosphere, carbon-13 which represents about 1 %, and carbon-14 which is radioactive and occurs in trace amounts in the atmosphere, about 1 part per billion (ppb).

Carbon-14, which has a half-life of 5,730 years, is constantly produced by cosmic rays in the upper layer of the atmosphere. From there it migrates into the lower atmosphere at a relatively constant rate, where it forms CO_2. CO_2 is the building block of biomass, and as long as they are alive, organisms incorporate carbon-14 into their structure in the same proportion that it is in the atmosphere. Upon death, the carbon-14 content of organisms slowly drops as carbon-14 decays into nitrogen. Radioactive decay occurs at a constant rate which means that the proportion of carbon-14 in a carbon sample can be used to determine its approximate age. Since the half-life of carbon-14 is around 5,730 years, all fossil fuel resources such as coal, crude oil, and natural gas, which are produced from organisms that died millions of years ago, no longer contains any C14. Based on this, the proportion of carbon-14 in a fuel sample can be used to indicate how much of the fuel is derived from biomass (high carbon-14 content) and how much from fossil (zero carbon-14) sources. This principle is used in the determination of the carbon-footprint in discharged carbon dioxide and how much renewable ethanol is contained in gasoline required by the Energy Policy Act of 2005. ASTM has a test method for radiocarbon:

Test method: ASTM D-6866 - *Standard Test Methods for Determining the Biobased Content of Solid Liquid, and Gaseous Samples using Radiocarbon Analysis*

Carbon-14/Carbon-12 and Carbon-13/Carbon-12 isotopic ratios are measured using accelerator mass spectrometry. The method requires modern, sophisticated equipment and results have to be carefully reviewed and interpreted, corrections made for background radiation and “the post-1950 bomb injection of Carbon-14 into the atmosphere” (ASTM D6866). One of the difficulties with this test is that some of the biobased products contain substantial amounts of inorganic carbonates. When preparing the samples for analysis, some or all of the carbon in the inorganic carbonates can be mixed into the samples to be analyzed and this can lead to incorrect results. For example, the USDA definition of “biobased content” requires the determination to be done only on organic carbon. D6866 describes the additional steps necessary to eliminate the errors in the results caused by the inorganic carbonates.

Mid-Infrared Spectroscopy

Another method for determining how much alternative fuel is in a sample is currently being researched by ASTM (ASTM 2010). This method uses a variable filter array infrared (IR) spectrometer. The instrument, a portable mid-infrared spectrometer, was chosen for its resolution and also because of its low cost and portability makes it a promising candidate for on-site testing of jet fuels. The method is currently being tested on blends of conventional jet fuel and FT alternative fuel, specifically a synthetic fuel made by the South African manufacturer Sasol.

The approach is based on the fact that the Sasol fuel showed significant differences in spectral absorbance from conventional jet fuel in two areas within the infrared range. Alternative jet fuel is highly isomerized (i.e., it contains molecules of the same chemical composition but arranged differently) and is likely to have more branching in its hydrocarbons chains than conventional jet fuel. More branching in the fuel means that it will have relatively more CH_3 bonds (one at the end of each branch) than conventional fuel. This correlates with the fact that the main differences in infrared absorbance between the fuels was at the range thought to occur within CH_3 bonds. Further testing is required to determine if alternative fuel made through other FT processes and from other feedstock will also have significant variations in the IR spectrum, and to evaluate whether the approach is applicable to HEFA process fuels.

Recommendation: The ability to monitor the amount of alternative fuel in a jet fuel sample through testing is currently limited. While radiocarbon testing could be used to identify the presence of bio-derived alternative fuel, it cannot reveal the presence of FT fuels made from fossil, non-petroleum-based feedstock. Mid-infrared spectroscopy could be used to identify FT fuels and perhaps other types of fuel, as well. Developments in these areas should be monitored closely with the goal of choosing one or a series of tests that could identify the presence of alternative fuels.

5.6 Improved batch tracking

Consideration: As mentioned above, the current system of batch tracking makes it virtually impossible to identify the manufacturing location of a specific sample of fuel once it enters a co-mingled storage or fuel handling facility. This system has worked well because all jet fuel currently in the system is made out of petroleum; however, as alternative fuels are introduced into the supply chain, knowing the feedstock and production process of each fuel is necessary to monitor changes in fuel properties over time that may occur because of the presence of alternative fuels.

Recommendation: It is worth it to re-think the current system of batch traceability and to propose improvements based on the widespread availability of information management systems. Even though batch identity may be lost as fuel enters a co-mingled storage system, it should be possible to at least keep track of where the fuel came from originally and trace it back to individual refineries, feedstock, and production processes. This is an area that requires further research. As discussed earlier, after blending, the COA should be accompanied by a document describing the origination of the blend components.

5.7 Management of change

Consideration: As stated in Section 4.2.2, a Management of Change (MoC) evaluation is highly recommended whenever changes are introduced in the process to produce, transport, and handle jet fuel to ensure that the fuel remains fit-for-purpose. This applies to changes in a number of elements such as feedstock, processing steps, additives, blending, storage and handling infrastructure. The purpose of MoC is also to make all stakeholders aware that change in one area of the supply chain may have unintended consequences in other areas. MoC provides a system to identify, evaluate, authorize, and document changes in a consistent and systematic way to ensure that knowledge is captured and retained. This would be of great help to the industry as it gains experience with alternative aviation fuels.

Recommendation: It would be very beneficial to develop more specific MOC guidance specifically for D7566 in recognition of the potential lack of experience of new producers. This guidance could be tailored to these new and novel processes of producing synthetic jet fuel. EI 1530 has an extensive section on MoC (Section 3 – Management of Change/New Processes). At a minimum, a reference in D7566 to that particular section could be very helpful to new producers. Furthermore, encourage alternative fuel producers to institute MoC practices and to collaborate with other stakeholders along the supply chain to ensure communication flows and information exchanges whenever changes to the production or handling of fuels occur.

5.8 Compliance with guidelines and regulatory requirements

Consideration: There are a multitude of guidelines covering the supply chain: EI/API/ IATA/ ATA 103/ JIG/ SAE. It becomes very important, if not an issue, to identify which ones a company must take into consideration and adhere to fulfill its contractual obligation with its clients and other stakeholders.

Recommendation: Similar to the previous comment, it would be very beneficial to develop more specific guidance targeted at new producers that narrows down the important elements that new entrants should be aware of. For example, experience with previous airline initiatives has shown that thorough planning, training of all personnel, scheduling, and tight batch quality control contributed to gaining the trust of the stakeholders and in completing successful projects. Our team strongly recommends new producers that bring products to the market should consider having available detailed documentation regarding:

- Feedstock origin
- Sustainable jet fuel production
- Facts & figures, volumes, CO_2 , emissions, savings and costs
- Material Safety Data Sheets (MSDS), NFPA codes, or any other regulatory codes.
- Clear supply chain flow. If supplying to end users consider: blending and storage, analysis and certification, transport, transfers, fueling and flight.
- Batches traceability reports, or as recommended earlier the use of D7566 and/or D1655 forms for reporting the inspection results to include all batch info regarding feedstock, type of process, manufacturer, etc.

Also new producers and/or suppliers should plan ahead for Analysis and Certification. For example, some of the tests are not readily available or require extensive turnaround for results.

It is important to remember that every situation is different; each airport and airline have different issues and opportunities, therefore collaboration and clear communication must take place between the parties involved to rule out any confusion and avoid any possible bottlenecks in the process.

6 Fuel Properties Catalog

The characteristics of conventional jet fuel show a natural variability that is driven by different factors, including the type of petroleum (e.g., “heavy” or “sweet”) and refining process used to manufacture the fuel. To address this variability, current standards such as D1655 allow for a range of values for the different properties required in the specification. As non-petroleum fuels are introduced into the jet fuel supply chain, the aviation community would like to understand how the characteristics of the entire jet fuel supply pool may change over time. This would allow expert organizations, such as ASTM, to assess the adequacy of current specifications to anticipate the possible variability in jet fuel properties.

In the U.S., there is currently no consistent and widespread system for measuring and documenting the characteristics of jet fuel in storage at airports. Fuel service companies at an airport test batches of fuel as it is being delivered and sample fuel in storage tanks on a regular basis. The laboratories doing the tests record the results using diverse data collection software packages and report results back to the airports. This test data is retained for a certain time by the fuel service companies, in case of any fuel-related incidents and for auditing purposes, but we are not aware of any fuel service companies that monitor such test results over time.

This section presents an overview of a fuel properties catalog. This catalog is intended to capture the characteristics of the fuel pool as alternative fuels start being introduced; however, given the lack of such a comprehensive catalog for conventional jet fuel today, the catalog could also be useful for keeping track of conventional jet fuel properties even in the absence of significant amounts of alternative jet fuel.

As of the date of this updated report, a prototype fuel properties catalog was developed and implemented by the research team. Observations from implementation of the catalog are also discussed in the sections that follow.

6.1 What data to collect

In order to lower the barriers for implementation, it is recommended that data collection for the fuel properties catalog takes advantage of existing data to the extent possible. Two sets of data regarding jet fuel properties that are collected on a regular basis include the eight-point test and full-conformity tests. Jet fuel quality control tests can be expensive and, therefore, it is better not to require additional tests. For reference, a full conformity test costs between $1,000 and $2,000 and an eight-point test costs between $100 and $200.

The advantages and disadvantages of each test as a source of data for the catalog are discussed below:

Eight-point Test

As described elsewhere, airport fuel system operating companies regularly perform eight-point tests on fuel in their fuel tanks as part of their quality control process. Based on industry experience, it has been established that this set of data is sufficient to determine if the fuel is fit for purpose and its quality has not been altered since it was certified as meeting D1655 specifications; however, to ensure that the test samples are representative of fuel in airport storage tanks, only eight-point test results from tank tests should be collected, not those of incoming batches that are tested prior to acceptance.

The eight-point test results should be widely available, and monitoring these results over time would permit identification of variability trends. Furthermore, since these tests are performed very often, there would be a large amount of test samples to feed the catalog. A disadvantage of using the eight-point test is that it currently does not capture some of the key properties of interest to the jet fuel quality control community, such as aromatics content, distillation, net heat of combustion, and lubricity.

Full Conformity Test Data

An alternative to collecting eight-point test results is to collect full conformity test data. This would already contain the additional data on aromatics, distillation and lubricity that we recognize is missing from the eight-point test; however, full conformity tests are not conducted at all airports as part of quality control procedures. Some airports run these tests on random tanks once or a few times a week. Otherwise, they are usually only conducted on fuel that does not pass the eight-point test or at testing laboratories that issue COAs for batches of fuel on dispatch from refineries. Thus, the amount of data samples available would be far less than if the eight-point test is used.

Volume Data

Another piece of information that is desirable to collect is volume associated with each batch. This is to allow the calculation of volume-weighted averages of the different fuel properties for the combined fuel pool after batches are combined.

Recommendation for data to be collected

The research team recommends a dual approach for data collection. In the long term, the “expanded” eight-point test data that includes information on aromatics, distillation, lubricity, feedstock, production process, and blend level, if possible, should be enough for the purposes of the catalog. In the short term, while the expanded eight-point test is approved and implemented, the recommendation is to collect both the eight-point and full-conformity test data. While this may be cumbersome at first, this is the most practical approach to obtain significant number of test samples and the required information regarding aromatics, distillation, and lubricity. Furthermore, collecting both test data samples will allow a direct comparison that may, over time, indicate which one would be preferred. In addition to the eight-point test and full conformity data, basic information regarding fuel manufacturer, feedstock, and process should also be collected. Volume information specific to each batch represented in the eight-point or full-conformity test should also be collected.

Observations from implementation of the catalog

Through collaboration with a major U.S. airline, the research team was able to obtain information on conventional jet fuel properties for a number of U.S. airports. The type of data obtained changed from location to location, reflecting the variety of data collection in practice today. For most airports, COAs were available although, in some cases, eight-point tests were provided, as well. Batch volume information was not as easy to obtain but was provided in some cases by the FBO.

With respect to alternative fuels, results for only one test sample were obtained. The data was provided by another contractor in a different component of this BAA. An effort was made to collect test results on alternative jet fuel from other vendors and organizations; however, our requests were declined.

6.2 Where and from whom to collect data

There are a number of places along the supply chain where quality control test data could be collected. This implies that there could also be a large number of potential entities that would need to be engaged to collect the data. Possible data collection points are discussed below:

At the Airport

If the intent of the catalog is to monitor the variability jet fuel that is consumed on aircraft, the best place to gather the required data would be at the airport. At most airports in the U.S., jet fuel storage is comingled and, therefore, jet fuel from different manufacturers and points of origin gets combined and mixed together at the airport fuel farm. Therefore, collecting the fuel property data at the airport would give the best possible representation of the jet fuel being consumed.

The collection of fuel quality data at the airport should be fairly straightforward. As mentioned above, this information, in particular results from eight-point tests, is routinely gathered and archived as part of the quality control process of fuel service companies managing airport storage tanks. Furthermore, since at many airports fuel storage is typically managed by one company and sometimes two or three, identifying these companies would not be difficult. Finally, since these companies are hired directly by the airlines or the airports, and assuming the airlines and airports support the creation of the catalog, obtaining the support of these third-party companies should not be difficult.

Other points in the supply chain

As one moves upstream from the airport along the supply chain, it is more difficult to identify the best location to gather the fuel properties information for the catalog. As discussed above, fuel batches travel by different modes and may be co-mingled with other batches at different points in their journey from the refinery to the airport. Moreover, as the fuel moves along the supply chain, it changes custody multiple times and it may be difficult to identify the parties responsible for providing the test data.

At the refinery or blending location

Another possible location to collect fuel property data is at the refinery or blending location in the case of alternative fuels that require blending. Since an RQC or COA is required before the fuel can leave the refinery or blending location, the required information is generated and should be available, in theory. To collect this data, it would be necessary to request the collaboration of refiners and blenders.

Recommendation for where to collect the data

The research team recommends to collect the fuel property data at the airport fuel farm and, if possible, from refineries and blenders willing to participate. Collecting the data at the airport makes the most sense in terms of obtaining an accurate picture of the properties of the fuel pool being used on aircraft. In addition, existing quality control practices and the relatively small number of companies should make the data collection at the airport straightforward. With respect to refineries and blenders, while this data would be very useful, it is unclear how many of these organizations would be willing to cooperate with the catalog; however, an effort should be made to identify and contact them.

Prior to collecting the data, it will be necessary to identify the scope of the data collection effort in terms of number of locations and number of samples per time period (e.g., per week, per month) to ensure it is cost-effective. It is recommended to start with a small number of locations to test the process and then to expand it as more experience is gained.

Observations from implementation of the catalog

The data for the catalog on conventional jet fuel was collected essentially at the airport. In most cases, it was obtained directly from the fuel farm operator. In one case, it was provided by the testing laboratory performing the tests for the fuel farm operator. In another case, it was provided by the fuel supplier for fuel that was being held in storage just outside the airport. In all cases, the data collection of conventional fuel properties was made possible at the request of a major U.S. airline that collaborated with the research team. In the case of the one test result obtained for the alternative fuel, this was provided by the fixed-base operator (FBO) handling the fuel at the airport. This data was obtained through the assistance of the FAA.

6.3 How to collect the data

Producers, inspection companies, laboratories, airports, and airlines use computer systems to input the results of quality control tests and generate analysis reports. These tasks can be accomplished using simple spreadsheets or using more elaborated databases with multiple interfaces, e.g., gathering the results directly from the testing instruments. Specifications can also be built into the system and linked to the type of testing required, so that when a result is entered, the system compares it with the specification and flags it if is outside specification.

There are many custom systems on the market. For example, Nobil Petroleum Testing uses a proprietary software package engineered specifically for inspection companies and petroleum testing laboratories. It is structured based on the D1655 recommended format for reporting inspection data on aviation turbine fuels (see Figure 14). The form incorporates the requirements of the most common international specifications and IATA Guidance Material on Microbiological Contamination in Aircraft Fuel Tanks.

INSPECTION DATA ON AVIATION TURBINE FUEL

(Items in **bold** type are referenced in the specification)

MANUFACTURER/SUPPLIER ____________________
PRODUCT CODE/GRADE____________________
SPECIFICATION____________________
SAMPLE NUMBER____________________
DATE SAMPLED____________________
SAMPLING LOCATION____________________
BATCH NO.____________________
QUANTITY LITRES @ 15°C____________________
QUANTITY U.S. GALLONS @ 60°F____________________
LABORATORY____________________

DATE SAMPLED____________________
DATE RECEIVED AT LAB____________________
CONTRACT NO.____________________
ORDER NO.____________________
TANK NO.____________________
DESTINATION____________________
CRUDE SOURCE____________________
PROCESSING METHOD____________________
REMARKS____________________

Method			Result
		APPEARANCE	
010	D 156	Color (Saybolt)	◊◊◊
020	D 6045	Color (Saybolt)	◊◊◊
030	D 4176	Visual ("Pass" or "Fail")	◊◊◊◊
		COMPOSITION	
100C	**D 3242**	**Acidity, Total (mgKOH/g)**	◊●◊◊◊
110	**D 1319**	**Aromatics (vol %)**	◊◊●◊
112	**D 6379**	**Aromatics (vol %)**	◊◊●◊
115	D 1319	Olefins (vol %)	◊●◊
120	**D 1840**	**Naphthalene (vol %)**	◊●◊◊
130	**D 3227**	**Sulfur, Mercaptan (mass %)**	◊●◊◊◊◊
140	D 4952	Doctor Test (P = pos, N = neg)	◊
150A	D 129	Sulfur, Total (mass %)	◊●◊◊
150B	**D 1266**	**Sulfur, Total (mass %)**	◊●◊◊
150D	**D 2622**	**Sulfur, Total (mass %)**	◊●◊◊
150E	D 3120	Sulfur, Total (ppm)	◊◊◊◊
150F	**D 4294**	**Sulfur, Total (mass %)**	◊●◊◊
150G	**D 5453**	**Sulfur, Total (ppm)**	◊◊◊◊
160A	D 3343	Hydrogen Content (mass %)	◊◊●◊◊
160B	D 3701	Hydrogen Content (mass %)	◊◊●◊◊
		VOLATILITY	
200A	**D 86**	**Distillation by Auto/Manual (°C)**	◊
200B	D 2887	Distillation by GC (°C)	◊
201		Distillation by Initial BP (°C)	◊◊◊●◊
202		Distillation by 10 % Rec (°C)	◊◊◊●◊
203		Distillation by 20 % Rec (°C)	◊◊◊●◊
204		Distillation by 50 % Rec (°C)	◊◊◊●◊
205		Distillation by 90 % Rec (°C)	◊◊◊●◊
206		Distillation by 95 % Rec (°C)	◊◊◊●◊
211		Distillation by Final BP (°C)	◊◊◊●◊
213		Residue (vol %)	◊●◊
214		Loss (vol %)	◊●◊
220A	**D 56**	**Flash Point, Tag Closed (°C)**	◊◊●◊
220B	D 93	Flash Point, PM Closed (°C)	◊◊●◊
220C	**D 3828**	**Flash Point, Setaflash (°C), Meth A**	◊◊●◊
220D	D 3828	Flash Point, Setaflash (°C), Meth B	◊◊●◊
221	D 3828	Flash Point, Setaflash (Flash/No Flash)	◊
230A	**D 1298**	**Density @ 15°C (kg/m³)**	◊◊◊●◊
230B	**D 4052**	**Density @ 15°C (kg/m³)**	◊◊◊●◊
231A	D 1298	API Gravity @ 60°F	◊◊●◊
240A	D 323	Vapor Pressure, Reid (kPa)	◊◊●◊
240B	D 4953	Vapor Pressure, Dry Method (kPa)	◊◊●◊
240C	D 5190	Vapor Pressure, Automatic Method (kPa)	◊◊●◊
240D	D 5191	Vapor Pressure, Mini Method (kPa)	◊◊●◊
		FLUIDITY	
300A	**D 2386**	**Freezing Point (°C)**	-◊◊●◊◊
300B	**D 5901**	**Freezing Point (°C)**	-◊◊●◊◊
300C	**D 5972**	**Freezing Point (°C)**	-◊◊●◊◊
300D	**D 4305**	**Freezing Point (°C)**	-◊◊●◊◊
300F	**D 7154**	**Freezing Point (°C)**	-◊◊●◊◊
310	**D 445**	**Viscosity @ -20°C (mm²/s)**	◊◊●◊◊◊
311	D 445	Viscosity at other temp (mm²/s)	◊◊●◊◊◊
312	D 445	Temp (°C) of Item 311	◊◊◊◊

Method			Brand	Result
		COMBUSTION		
400A	D 240	Net Heat of Combustion (MJ/kg)		◊◊●◊◊◊
400B	D 1405	Net Heat of Combustion (MJ/kg)		◊◊●◊◊◊
400C	**D 3338**	**Net Heat of Combustion (MJ/kg)**		◊◊●◊◊◊
400D	**D 4529**	**Net Heat of Combustion (MJ/kg)**		◊◊●◊◊◊
400E	**D 4809**	**Net Heat of Combustion (MJ/kg)**		◊◊●◊◊◊
410	**D 1740**	**Luminometer No.**		◊◊
420	**D 1322**	**Smoke Point (mm)**		◊◊●◊
		CORROSION		
500	**D 130**	**Copper Strip**		◊◊
510	IP 227	Silver Strip		◊
		STABILITY		
601A	**D 3241**	**Filter ΔP (mm Hg) @ other temp**		◊◊●◊
602A	**D 3241**	**Tube Deposit @ other temp**		◊◊◊◊
603A	**D 3241**	**TDR Spun Rating @ other temp**		◊◊
604A		**Temperature (°C) of above**		◊◊◊◊
601B	**D 3241**	**Filter ΔP (mm Hg) @ 260°C**		◊◊●◊
602B	**D 3241**	**Tube Deposit Rating @ 260°C**		◊◊◊◊
603B	**D 3241**	**TDR Spun Rating @ 260°C**		◊◊
		CONTAMINANTS		
700	IP 225	Copper Content (mg/kg)		◊●◊◊
710	**D 381**	**Existent Gum (mg/100 mL)**		◊◊◊
710A	**IP 540**	**Existent Gum (mg/100 mL)**		◊◊◊
720A	D 2276	Particulate (mg/L)		◊●◊◊
720B	D 5452	Particulate (mg/L)		◊●◊◊
730		Filtration time (minutes)		◊◊
740	**D 1094**	**Water Reaction Interferance Rating**		◊◊
750	D 3948	MSEP (With SDA)		◊◊◊
751	D 3948	MSEP (Without SDA)		◊◊◊
		ADDITIVES	**Brand**	
800		Antioxidant (mg/L)	[ ]	◊◊●◊
810		Metal Deactivator (mg/L)	[ ]	◊●◊
820		Static Dissipator Additive (mg/L)	[ ]	◊●◊
830A	(D5006)	FSII (vol%)	[ ]	◊●◊◊◊
830B	(FTM5327)	FSII (vol%)	[ ]	◊●◊◊◊
830C	(FTM5340)	FSII (vol%)	[ ]	◊●◊◊◊
840		Corrosion Inhibitor (mg/L)	[ ]	◊◊●◊
		OTHER TESTS		
900	**D 2624**	**Conductivity (pS/m)**		◊◊◊◊
901	**D 2624**	**Conductivity Test Temperature (°C)**		◊◊◊

Comments and/or Additional Tests:

____
____
____
____
____
____
____

CERTIFIED BY ____________________

Figure 14: Form for reporting inspection data on aviation turbine fuels, pp 12 to 15. Source: ASTM D1655 (2011).

Recommendation for how to collect the data

Efficient routine collection of fuel test results will require the design and ongoing management of a computer-based reporting system, and the development of tools to analyze the accumulated data. Even in these times of inexpensive data storage, the more data that is collected, the higher storage fees will be. The research team recommends a two-step approach for implementing the catalog:

- *Step 1: Demonstration catalog* – For the initial version of the catalog, the team recommends to use a system similar to the one used currently by Nobil Petroleum Testing. This system is field-tested and can be modified to capture the additional properties indicated in the expanded eight-point test. Initially, we anticipate that test results will be provided on a voluntary basis, either from fuel service companies or directly from testing laboratories. We will need to discuss what formats will be appropriate with the providers based on their individual test reporting procedures, and may have to develop simple software solutions to accommodate material in different formats.

- *Step 2: Long-term catalog* – Further recommendations regarding long-term collection and compilation of a broad sample of fuel characteristics will be based on experience gained in compiling the demonstration catalog for twelve months. The initial period will allow the team to obtain a better understanding with the practical challenges of collecting, storing, and analyzing fuel test data from many providers across the country.

Observations from implementation of the catalog

A number of lessons learned from the catalog implemented in this project with respect to data collection and recommendations for a long-term catalog are presented below:

- **Test results and data format:** The research team received the data in one of two ways, either electronically as a .pdf file or by fax (in the case of one airport, a research team member could access the data through their automated computer systems). Thus, in the majority of cases, the data in the catalog had to be input manually into the spreadsheet-based catalog. For the purposes of this project, manual input of the data was manageable because we were only receiving data from a number of airports; however, to establish a more comprehensive catalog, it will be important to coordinate with data suppliers to obtain the data in a way that does not require manual entries. Manual entries are slow and prone to errors.

- **Check for data consistency:** It is important to check the data in the catalog for consistency and to identify possible typing mistakes (especially in the case of manual entries). In particular, it is recommended to check that all units used in the catalog are consistent, as several test results can be reported with different units.

- **Coordination with data providers:** As mentioned above, the data provided to the research team was supplied by fuel farm operators, testing laboratories, or fuel companies. It is important to keep in close contact with them to ensure that the data continues to be provided. In the relatively short span of this project, there were certain changes that led to a discontinuation in the data collection. For example, there was a change from one testing company to another at a fuel farm and the new testing company was not aware of the data feed for this project. For the purposes of establishing a more comprehensive catalog, this is an important area to keep in mind to ensure data continuity.

6.4 Potential uses for the catalog

There are many potential uses for the fuel properties catalog. A main goal for creating the catalog is to monitor the variability in jet fuel properties over time, especially as alternative jet fuels get introduced into the jet fuel pool. Nobil Petroleum has been maintaining a catalog of jet fuel properties for over ten years and has experience analyzing and visualizing trends in jet fuel data. For example, using data collected from eight-point test results of conventional jet fuel samples from airports in the New York metropolitan area, Nobil Petroleum produced two charts showing the variability in freezing point and density over a twelve month period (see Figure 15 and Figure 16, respectively). Although individual test results appear to vary, all these samples were within specification and demonstrate the natural variability in conventional jet fuel properties.

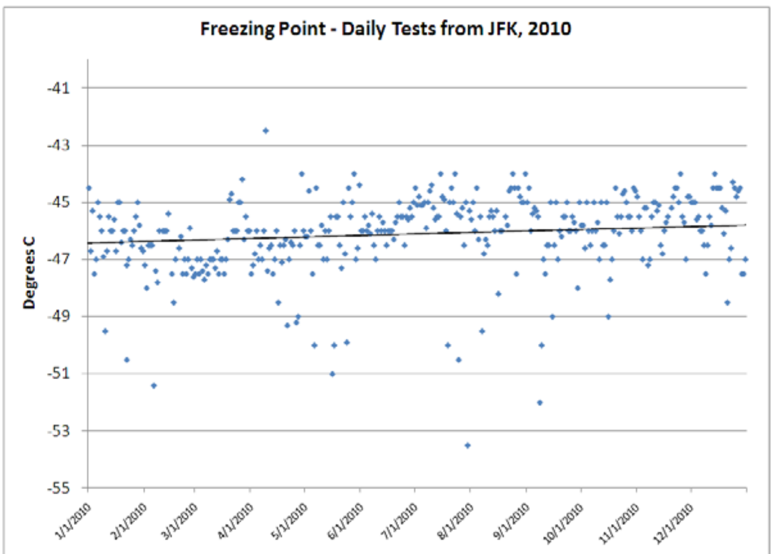

Figure 15: Variability in freezing point for a set of fuel samples collected in 2010.

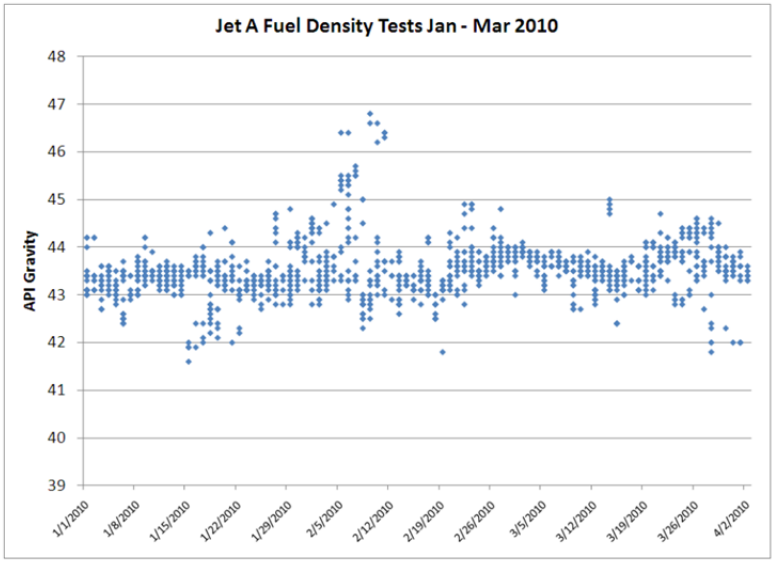

Figure 16: Variability in density for a set of fuel samples collected in 2010.

Another potential use for the catalog would be to serve as a repository of fuel properties data for different types of users. For example, airlines and airport operators may be interested in gaining a better understanding of fuel properties across the U.S. For example, airlines that want to purchase alternative jet fuel would benefit from understanding where conventional jet fuel with high density is more likely to be available to use as blendstock. Other properties, such as freeze point, can also be important for airline dispatchers as they plan flight routes, in particular polar routes. Airlines for America operates a jet fuel information dashboard (the Fuel Portal) and it could serve as a convenient outlet for the information contained in the catalog.

The catalog could also be available to non-airline and non-airport users. For example, alternative fuel producers would be interested in understanding the variability of jet fuel properties across the country. Furthermore, making the fuel properties catalog available to academia and the general public may spur further research and innovation related to jet fuel distribution and handling. Two possible outlets for a "public" version of the catalog are the Commercial Aviation Alternative Fuels Initiative (CAAFI, www.caafi.org) and the Department of Energy's Alternative Fuels and Advanced Vehicles Data Center (http://www.afdc.energy.gov/afdc/applications.html).

Observations from implementation of the catalog

The airline that facilitated obtaining the data on conventional jet fuel to populate the catalog has been very interested in the ability to analyze the data for the identification of potential trends. More data needs to be collected in order to have large enough sample sizes to perform analysis with statistical significance. Furthermore, in order to identify seasonal variations, it will be necessary to collect data spanning a number of years.

6.5 Access to data

We did not anticipate any problems in the collection of limited amounts of data to populate the prototype catalog. Our approach was to collaborate with a major U.S. airline to get access to the information.

Observations from implementation of the catalog

In our experience, the key to obtaining the data was for an airline to request a fuel supplier, fuel farm operator, or testing laboratory to make it available to us. As long as the airline communicated with those entities, there were no difficulties in collecting the data.

7 Glossary

Term	Definition
AFM	Aircraft Flight Manual
AFQRJOS	*Aviation Fuel Quality Requirements for Jointly Operated Systems*. JIG checklist for fuel handling at airports.
Alcohol to jet (ATJ)	Synthetic jet fuel made from alcohols.
API	American Petroleum Institute
API 1543	*Documentation, Monitoring and Laboratory Testing of Aviation Fuel During Shipment from Refinery to Airport*: recommended practices for shipment of fuel.
API 1595	*Design, Construction, Operation, Maintenance, and Inspection of Aviation Pre-Airfield Storage Terminals*: recommended practices for handling of fuel and operation of storage facilities.
ASTM	ASTM International, a voluntary standards development organization, develops specifications used for the certification of jet fuels with input from government agencies, fuel manufacturers, aircraft and engine manufacturers, and airlines.
ASTM D1655	ASTM jet fuel specification
ASTM D7566	ASTM approved a new fuel specification, "Aviation Turbine Fuel Containing Synthesized Hydrocarbons."
A4A	Airlines for America
ATA 103	*Standard for Jet Fuel Quality Control at Airports*: This sets the standards for every aspect of getting fuel from the delivery point on the airport up to the wing of the aircraft.
Biofuel	Fuel produced from biomass, which is organic matter available on a renewable or recurring basis, including agricultural crops, wood and wood residues, plants (including aquatic plants), grasses, animal residues, and municipal waste.
CAAFI	See "Commercial Aviation Alternative Fuels Initiative."
Certificate of Analysis (COA)	Paperwork issued for each batch of fuel by an independent fuel testing laboratory to certify the fuel meets specification.
CO_2	Carbon dioxide
Commercial Aviation Alternative Fuels Initiative (CAAFI)	A coalition of airlines, aircraft and engine manufacturers, energy producers, researchers, international participants and U.S. government agencies working to further the deployment of alternative jet fuels for commercial aviation.
DEFSTAN 91-91	*Turbine Fuel, Aviation Kerosene Type, Jet A*, which is the specification used for most civil aviation fuels outside the United States. It is published by the UK Ministry of Defence.
Drop-in fuel	Nonpetroleum fuel that is compatible with existing infrastructure and uses for petroleum-based fuels.
EI	The Energy Institute (UK)

Term	Definition
FAA	United States Federal Aviation Administration
Fermentation Renewable Jet	Biofuel created by a synthetic biology process in which metabolic processes involved in fermentation have been co-opted by genetically modifying organisms to produce hydrocarbons in place of ethanol.
Fischer Tropsch Process	A catalyzed chemical reaction in which synthesis gas, a mixture of carbon monoxide and hydrogen, is converted into liquid hydrocarbons of various forms.
FT	Fischer-Tropsch.
GHG	Greenhouse gas
Greenhouse gases	Gases that trap heat in the atmosphere. Principal greenhouse gases caused by human activities are carbon dioxide, methane, nitrous oxide and fluorinated gases.
HRJ	Hydrotreated Renewable Jet.
HEFA (also Hydrotreated renewable jet)	Synthetic fuel made from hydroprocessed esters and fatty acids (biological sources).
ATJ	Alcohols-to-Jet -process that uses alcohols as feedstock to produce alternative jet fuel and other by-products.
IATA	International Air Transport Association.
ICAO	International Civil Aviation Organization.
JIG	Joint Inspection Group
JIG 1	Guidelines for Aviation Fuel Quality Control & Operating Procedures for Joint Into-Plane Fueling Services.
JIG 2	Guidelines for Aviation Fuel Quality Control and Operating Procedures for Joint Airport Depots.
JIG 3	Guidelines for Aviation Fuel Quality Control and Operating Procedures for Jointly Operated Supply and Distribution Facilities
OEM	Original equipment manufacturer; in this document refers to aircraft and or engine manufacturing companies.
Refinery Quality Certificate (RQC)	Original Document describing the quality of the fuel, and determination of all properties required in the relevant specification,
Release Certificate	Is attached to every fuel transfer; signed by an authorized person and certifies conformity with applicable specifications as per API-1543 recommended practices
SPK	Synthetic paraffinic kerosene.
SAE	Society of Automotive Engineers

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