

CRC Report AV-11-09

**DEVELOP AN AVIATION FUEL
COLD FLOWABILITY TEST TO
REPLACE FREEZING POINT
MEASUREMENT**

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Develop an Aviation Fuel Cold Flowability Test to Replace Freezing Point Measurement

CRC Project AV-11-09

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1 Background

The International Air Transport Association (IATA) technical fuel group through its Freezing Point Harmonisation Group investigated the viability of using a single grade of commercial jet fuel throughout the world, with respect to freezing point [1]. The group investigated a number of options for harmonisation of freezing points at, or between, current Jet A and Jet A-1 limits. The report concluded that a number of freezing point limit options were technically feasible. Therefore, further work was recommended to study which option would give the greatest commercial benefits to the industry. It was also reported that engine OEMs are more concerned about fuel viscosity at the engine intake rather than the freezing point of the fuel in the tanks. Furthermore, it was reported that “it is a generally accepted fact that the freezing point test is not an effective test for predicting fuel flow behaviour in the aircraft at low temperatures”.

These findings led to an IATA request, at the 2008 meeting in Shanghai, to investigate the possibility of a replacement for the currently used freezing point methods. The objectives of this CRC report are the first steps towards this goal.

This report aims to review all data currently available and identify any possible improved test methods. Based on this analysis, a programme of work to achieve a validated method is suggested. The project approach as requested by CRC was as follows (original statement of work can be found at Appendix A):

- The fuel system geometry and real life operating conditions thought to be the most severe were requested from the OEMs. The aim was to use this information to obtain a better understanding of what any test method has to emulate.
- ASTM, IP, and other methods were reviewed for potential use. These included freezing point, pour point, viscosity, and other low temperature flow measurements. These methods were assessed for applicability for predicting low temperature operations in OEM equipment.
- There have been various research projects investigating low temperature operations by OEMs and extensive research carried out by the US Air Force (AFRL). Much of the research sponsored by USAF was carried out through the University of Dayton. This research was reviewed and summarised along with other information found using literature searches.
- Possible ways forward for modifying specification test method requirements that may better predict low temperature operation were investigated and reported. Proposed ways forward were detailed along with further any work that may be required for the industry to use such methods.

2 Introduction

2.1 History

Early British jet fuel specifications were based on the properties of illuminating kerosine and this was reflected in the requirement for -40 °C maximum freezing point. By comparison, the first US military specifications for jet fuel were derived from aviation gasoline properties. Thus JP-1, JP-2 and JP-3 required -60 °C max. freezing point.

This not only put a restriction on fuel availability, but was later seen as being conservative with regard to operational requirements.

By the time the DERD 2494 specification (now superseded by Defence Standard 91-91) was introduced in 1957, it was recognised that long range flights, and turbo-prop aircraft, required $-50\text{ }^{\circ}\text{C}$ freezing point fuel. In the late 1970s, a jet fuel supply problem was perceived due to continually rising demand coupled with difficulties experienced by some refineries in meeting kerosine requirements, brought about by:

- demand for other products overlapping the Jet A-1 boiling range
- politico-economic restrictions on crude availability
- introduction of new and non-traditional crudes

The ASTM formed a task force at this time, responding to a proposal to raise the freezing point of Jet A-1 from $-50\text{ }^{\circ}\text{C}$ to $-47\text{ }^{\circ}\text{C}$ [2]. Its culmination was a Symposium on Jet Fuel Low Temperature Requirements held in December 1976, the theme of which was how to match the low temperature requirements of long-range aircraft with the flow properties of jet fuel. The results of detailed studies carried out by a number of airlines and by airframe and engine manufacturers were reported at the symposium. An availability gain of around 10% (percentage of jet fuel available from crude) appeared possible with a $3\text{ }^{\circ}\text{C}$ freezing point relaxation. Objections to this move came from international airline operators, having long flight routes where cold weather environments could result in fuel reaching critical low temperature conditions.

One of the studies presented was by The Boeing Company, who developed a computer programme to provide estimates of the lowest fuel temperature that might be encountered in their commercial aircraft. Fuel tank temperatures were predicted for a variety of flight and external ambient conditions that together represent the extremes of low temperature operations in the Northern Hemisphere. Route structures for the aircraft were superimposed over global weather isotherms, showing that minimum fuel temperatures of $-46\text{ }^{\circ}\text{C}$, $-41\text{ }^{\circ}\text{C}$, $-45\text{ }^{\circ}\text{C}$ and $-43\text{ }^{\circ}\text{C}$ could be expected for the 707, 727, 737 and 747 aircraft respectively. Boeing concluded that $-47\text{ }^{\circ}\text{C}$ freezing point fuel would not restrict any airline operation.

Other studies reached similar conclusions, which eventually led to the Jet A-1 limit in DERD 2494 and ASTM D 1655 specifications being raised to $-47\text{ }^{\circ}\text{C}$ in 1980.

More recently, in 1990, the IATA Fuel Trade Forum supported by several US airlines urged that the freezing point specification for Jet A-1 be changed from -47 to $-40\text{ }^{\circ}\text{C}$ to improve availability. It was claimed that the yield of fuel from an average barrel of crude oil would increase by about 10% by making this change (effectively producing Jet A instead of Jet A-1). The assumption was that fuel costs would then go down as a result of increased availability, thus alleviating some of the huge financial losses suffered by the airline industry at that time. It was suggested that IATA standardise on Jet A, with the proviso that Jet A-1 be provided upon the request or preference of an operator for those instances when it was required for specific aircraft, missions, or flying routes.

The proposal was strongly opposed by the international airlines and by Boeing. Extensive monitoring of in-flight fuel temperatures was carried out, showing that whilst some routes never presented incidents of low fuel temperature, all aircraft operating over long range routes in northern latitudes were subject to low temperature

occurrences. There were a significant number of cases where fuel tank temperature dropped below -37°C, the lowest operating temperature allowed with a -40°C specified fuel. It was eventually concluded in 1992 that there was insufficient justification for changing IATA Guidance Material freezing point from -47° to -40°C. The alleged fuel cost benefit from this change was also unproved.

2.2 Operation

Current aircraft are generally limited to operation under conditions where the measured in-tank fuel temperature is more than 3°C above the fuel specification freezing point. Thus aircraft are limited to fuel temperatures of -37C for Jet A and -44°C for Jet A-1. Certain routes at certain times of the year are most at risk of low fuel tank temperatures. Some measured aircraft fuel tank temperatures are shown in Appendix C.

3 OEM Fuel Systems

OEMs were contacted and asked to provide information on fuel system geometry; critical filter/mesh size; most severe low temperature operating conditions; and any low temperature certification tests. The OEMs contacted were GE, Rolls Royce, Boeing, Airbus, Honeywell, and BAe Systems.

3.1 OEM supplied information

GE reported [3] the following:

Fuel pipes (ss or Ti)	~½” diameter for most of run back to engine manifold then ¼” diameter pigtailed to the fuel nozzles.
Engine filters fixed wing	~35 µm absolute ¹ , ~25 µm nominal ²
Engine filters helicopters	~25 µm absolute, 10-15 µm nominal
Most severe starting conditions	12 cSt fuel, where engine bearings are -40°C or lower.
Certification	Certification of engine-airframe almost always requires an overnight stay at an airport where the ambient temperature is -40°C or lower and a start first thing in the morning.
Other information	It was noted that the filter holding capacity is important, but this information is proprietary.

Table 1, GE supplied fuel system information

¹ Defined as stopping 98% of particles at rating size or greater.

² Defined as stopping 95% of particles at rating size or greater.

Airbus reported [4] the following:

Tanks (metal or composite)	Flow paths provided through the ribs/stringers. Hole minimum diameter typically 8 mm.
Feed pipes (for engine feed)	2-2½" diameter
Feed pipes (transfer systems)	1½-2" diameter
Pump inlets	4/6/8 mesh filters
Qualification	Carried out by vendor down to fuel freezing point. Water tests also carried out with 260 ppm normally used. Long range flight tests also carried out.
Other information	Some fuel pipes can have no flow for long periods of time and subject to low temperatures. Some pipes can be near horizontal (through the fuselage) or rise at about the wing general dihedral angle. Normal envelope for operation -55°C on ground and -70°C in flight. These are ambient temperatures and do not include temperature recovery due to friction.

Table 2, Airbus supplied fuel system information

Honeywell reported [5] the following:

Honeywell engines and APUs (Auxiliary Power Units) are designed to start and operate with fuel viscosity up to 12 cSt. Most Honeywell propulsion engines have inlet fuel-oil heat exchangers upstream of the inlet fuel filter and fuel control and can generally operate with inlet fuel temperatures near the fuel freeze point (3 to 5°C above the freeze point), similar to propulsion engines used on large commercial transport type aircraft. Fuel temperature is raised above 0°C (32°F) in the fuel-oil heat exchanger to prevent inlet filter icing.

Honeywell APUs and some small propulsion engines do not have inlet fuel-oil heat exchangers, and starting and operation is limited to 12 cSt viscosity maximum. Since fuel viscosity is generally not known, Honeywell limits APU starting and operation based on fuel freeze point and viscosity considerations. Typical APU low temperature operating limits for commercial jet fuels are -37°C (-35°F) for Jet A, and -40°C (-40°F) for Jet A-1.

The APU is traditionally operated to provide a power source for the aircraft air-conditioning units and electrical systems during ground taxi and gate operations. The APU is also used to provide a power source for main engine starting. The APU can be used in-flight as an alternate electrical source in the event of a main engine system failure. APUs have more severe cold and altitude start requirements than main engines, typically having to start after extended cold soaks (up to 14 hours) and to altitudes over 40,000 feet. Main engine starting is typically limited to 25,000 to 30,000

feet. The APU is flight essential on some long flights for twin engine aircraft considered ETOPS flights (Extended Twin Operations).

APU low temperature light-off and blowout fuel schedules are set based on achieving adequate atomization with 12 cSt viscosity fuel. Start attempts with fuel viscosity higher than 12 cSt will result in either a no-start or slow and difficult starting, and repeated start attempts can result in hot section distress. The current viscosity limit in most commercial jet fuel specifications is 8 cSt maximum at -20°C (-4°F). A fuel at the specification limit for viscosity would reach the 12 cSt limit at -30°C (-22°F). Recent fuel surveys (CRC Report No. 647 World Fuel Sampling Program and PQIS 2009 Annual Report) show fuel viscosity is typically not at the specification limit. It is recommended that a more realistic low temperature viscosity limit be considered, such as 12 cSt maximum at -37°C (-35°F) for Jet A and 12 cSt maximum at -40°C (-40°F) for Jet A-1.

Moving from a fuel freeze point limitation to a cold flowability test would not adequately control fuel properties to insure reliable APU cold and altitude starting, unless the change to the low temperature viscosity limit described above is also made.

3.2 Other sources of Information

A 4 mesh screen is reportedly [6] used in the boost pump inlet on the Boeing 747.

3.3 Aircraft fuel system design with respect to particulate and ice

Although fuel physical properties are important for fuel system design, it should be noted that there are other considerations. Some of the most restrictive parts of an aircraft fuel system are designed to cope with the particulate and water within the fuel.

Particulate on delivery to aircraft should be below 1 mg/l and normally below 0.2 mg/l [7] and it is expected that further particulate may be picked up whilst in the aircraft fuel tanks. A previous CRC study [8] indicated that the finest engine fuel filters are generally 35 µm absolute, but some small aircraft use filters down to 10 µm absolute.

As the fuel in an aircraft cools during flight, the solubility of water in the fuel reduces. This reduction in solubility results in precipitation, which along with any free water already present is likely to form ice at some temperature below 0°C. These ice crystals have the potential to block fuel flow to the engine. Douglas Aircraft Co. found [9] that ice forms on tank pump inlet screens. This ice could readily block the fuel flow. It was found that screens with small meshes and small areas block most easily, additionally the distance between the screen and the lip of the inlet pipe was also critical. The work showed that a minimum distance between the screen and the inlet pipe as well as a large mesh size (1/4" mesh sizes inhibited ice blockage) were required to minimise flow reductions due to ice formation.

There are a number of solutions to icing problems, which may include enlarged screens, bypass valves, lower filter densities, using heat from engines, and using icing inhibitor additives. This means that aircraft fuel systems are likely to vary significantly. There is an SAE Aerospace Information Report [10] and an associated Aerospace Recommended Practice [11] which details testing aircraft fuel systems for ice accumulation. These documents detail fuel water mixes and critical icing temperatures

to test. They recommend that generally a number 4 mesh screen or coarser is considered to be not subject to critical icing, however this depends on the particular system being evaluated.

While suspended water freezing is not the same condition as fuel freezing and it generally occurs at higher temperatures, they can have similar results and solutions such that both need to be considered together in fuel system designs. A fuel cold flowability or freezing point test should not be sensitive to water content and/or freezing of suspended water.

4 Test Methods

Freezing point and viscosity are low temperature test methods currently used in jet fuel specifications. All the freezing point methods in section 4.1 apart from ASTM D4305 / IP 422 are currently allowed in ASTM D 1655 and Defence Standard 91-91. Viscosity at -20°C by ASTM D445 / IP 71 is also used in these specifications. Other methods detailed in this section are discussed for possible use within jet fuel specifications.

4.1 Freezing point methods

Freezing point is currently used in jet fuel specifications and is the test method that IATA have requested that a replacement is sought for. It is a measurement of the temperature at which wax crystals disappear as the fuel is warmed after previously being cooled. The manual method, described below, uses a visual method, however, a number of automated methods are also used in specifications to predict freezing point.

It should be noted that the automatic freezing point methods use a verification liquid that has been evaluated using ASTM D2386. To enable independent use of these methods (such as using them as specification referee methods) it may be necessary to develop calibration standards and procedures for these methods.

A number of tests, including freezing point, are often used for quality assurance purposes in the distribution system. The properties are monitored and if the properties for a particular batch of fuel differ significantly from the previous value, contamination is assumed as a possibility and further investigations are initiated. During an ASTM and Energy Institute round robin [12] the detection of gas oil contamination in jet fuel using freezing point methods was found to be variable. Following this study, only those methods which detected contaminated gas oil, at least as good as the manual method (ASTM D2386), were specified as alternative tests in the main jet fuel specifications.

The various freezing point methods are described below.

4.1.1 ASTM D2386 / IP 16, Determination of the freezing point of aviation fuels – manual method

This test is generally used as the referee test to determine the freezing point of jet fuel.

The test involves a sample tube, containing the test sample, a stirrer, collar and a thermometer, which is placed in a vacuum flask containing a coolant. During the cooling cycle the test sample is stirred vigorously and examined visually for the formation of wax crystals. When crystals are observed the sample tube is removed

from the coolant and allowed to warm. Stirring continues until the crystals disappear, at which point the temperature is recorded as the freezing point (this could be described as the melting point).

The method requires the tester to visually determine the freezing point and is therefore subjective. This subjectivity is likely to affect the precision of the test which is stated as having a repeatability³ of 1.5°C and reproducibility⁴ of 2.5°C. It is often suggested that due to the widespread use of automatic equipment there is no longer the expertise needed by technicians to carry out this test. However, it should be noted that the ASTM cross check programme shows that the majority of test results reported are carried out using the manual method. Furthermore, it is believed that the manual test is widely used throughout the world outside North America. Despite the subjectivity ASTM D2386/IP16 has successfully protected aircraft for many decades.

4.1.2 ASTM D4305 / IP 422 Determination of the filter flow of aviation turbine fuels at low temperatures (FFLT) (simulated freezing point method)

This test uses a 5 ml sample of fuel which is subjected to a programmed temperature cycle while a pump maintains an oscillating flow at a constant rate across a mesh filter. As the temperature falls (at a similar rate to ASTM D2386 cooling), separated wax tends to restrict the test filter causing an increase in pressure. When this pressure exceeds 1.33 kPa for more than 0.95 seconds the cooling is stopped. The pump continues to operate and exert pressure as the fuel sample is warmed. At the point when the test filter is unplugged (the pressure falls below 1.33 kPa for more than 0.95 seconds), the simulated freezing point is indicated.

The repeatability was 1.24°C and the reproducibility was 2.64°C. The method was briefly used in jet fuel specifications but was limited to fuels with a viscosity of 5 cSt or less. This method was removed from the main jet fuel specifications because it was found that it did not detect contamination at levels similar to ASTM D2386. Nevertheless this 'low temperature flow method' may more closely reflect fuel operations on-board aircraft than the conventional freezing point method.

4.1.3 ASTM D5972 / IP 435 Determination of the freezing point of aviation turbine fuels by automatic phase transition method

The method uses a small test portion cooled at 15°C/min by a peltier device, while continuously being illuminated and monitored by optical detectors. When the detectors record the presence of hydrocarbon crystals, the test portion is warmed at 10°C/min until the hydrocarbon crystals return to the liquid phase. The temperature at which the last hydrocarbon crystals disappear is recorded as the freezing point.

³ Repeatability is defined as the difference between successive test results, obtained by the same operator with the same apparatus under constant operating conditions on identical test material, in the normal and correct operation of the test method, would exceed the value in only one case in 20 (95% probability).

⁴ Reproducibility is defined as the difference between two single and independent results, obtained by different operators in different laboratories on nominally identical test material, in the normal and correct operation of the test method, would exceed the value in only one case in 20 (95% probability).

The precision of the method ($r=0.50^{\circ}\text{C}$, $R=0.8^{\circ}\text{C}$) is better than the manual method. ASTM D5972 has improved detection of contamination and tends to detect lower levels of high boiling material than the manual method. Although this could be useful for detecting contamination, there is the potential to cause problems when a fuel has been manufactured with some high boiling material. For example, a fuel specified using the manual method may fail the freezing point requirement when recertified using ASTM D5972.

Although not mentioned in the test method, the manufacturer's instructions allow the use of fuel pre-treatment using 'dry sacs'. The 'dry sacs' are designed to remove water from the sample and avoid interference from this water. The manufacturer claims the use of dry sacs does not change the result but improves the precision of a small proportion of susceptible samples. The Energy Institute is currently investigating the use of dry sacs with the final aim of clarifying their use within the test method.

4.1.4 ASTM D7154 / IP528 Determination of the freezing point of aviation turbine fuels – automatic fibre optic method

This test method uses a test portion in a test chamber and is continuously stirred. The temperature is reduced and the appearance is monitored using fibre optics. When hydrocarbon crystal formation is detected, the temperature is recorded, and the test portion is allowed to warm. The temperature at which the last hydrocarbon crystals disappear is recorded as the freezing point.

The test method is an automated version of the manual method, using the fibre optic detectors in place of the subjective visual assessment. This test has poorer precision than the other automated methods ($r=0.5^{\circ}\text{C}$, $R=1.9^{\circ}\text{C}$) allowed in jet fuel specifications.

4.1.5 ASTM D7153 / IP 529 Determination of the freezing point of aviation fuels – automatic laser method

This method uses a test portion placed into a cell and cooled while continuously monitored by optical detectors for the first formation of solid hydrocarbon crystals. The test portion is then warmed. The temperature of the test portion at which the last hydrocarbon crystal returns to the liquid phase is recorded as the freezing point. If the crystal disappearance temperature is colder than the crystal appearance temperature, reheating and cooling cycles are restarted, this time using a higher initial warming rate (this extra testing is rarely required to identify contaminated type samples).

This test has good precision ($r=0.6^{\circ}\text{C}$, $R=0.9^{\circ}\text{C}$) compared with ASTM D2386. ASTM D7153 identifies contamination more readily than the manual method and ASTM D7154. Due to the sensitivity to high boiling components, this method has the potential to erroneously detect contamination similar to that mentioned for IP 435 above.

4.2 Pour Point

Pour point has been used to evaluate low temperature performance of petroleum products for many decades. The method simply involves cooling a sample and determining the temperature at which it no longer pours from a container. As well as

the original manual method (ASTM D97) a number of automated methods are also available. These are described below.

As all of these methods were developed for use with other petroleum products, their use in jet fuel specifications may require further development and precision evaluation.

4.2.1 Pour Point ASTM D97 / IP 15 / ISO 3016

After preliminary heating, a sample is cooled at a specified rate and examined at intervals of 3°C for flow characteristics. The lowest temperature at which movement of the sample is observed is recorded as the pour point. An automated version of this method, ASTM D5950, is also available and a result can be determined to the nearest 1°C. Pour point is not normally carried out on jet fuel but used for other petroleum products. However, the test methods may be suitable for jet fuel use and have been used in low temperature jet fuel research [6].

Other test methods are commonly used to determine flow characteristics of petroleum products (but not normally jet fuel) which show some correlation to pour point and are often used instead of ASTM D97. Some of these are outlined below:

4.2.2 Hanovia Auto Pour

The Hanovia Auto Pour, uses a similar sample size and cooling rates but uses a probe which rotates in the sample. As the sample cools and solidifies the rotation stops at a given torque, and this temperature is equivalent to the pour point.

4.2.3 ASTM D5949 Standard Test Method for Pour Point of Petroleum Products (Automatic Pressure Pulsing Method)

ASTM D5949 determines the pour point of petroleum products by an automatic instrument that applies a controlled burst of nitrogen gas onto the specimen surface while the specimen is being cooled and detects movement of the surface of the test specimen with an optical device. The test method is designed to cover the range of temperatures from -57°C to +51°C.

4.2.4 ASTM D5985 Standard Test Method for Pour Point of Petroleum Products (Rotational Method)

ASTM D5985 covers the determination of pour point of petroleum products by an automated instrument using a rotation method. As the test specimen is cooled it is continuously tested for flow characteristics by rotating the test specimen cup at approximately 0.1 rpm against a stationary, counter balanced, sphere-shaped pendulum. The temperature of the test specimen at which a crystal structure or a viscosity increase, or both, within the test specimen causes the displacement of the pendulum is recorded with a resolution of 0.1°C. The test method is designed to cover the range of temperatures from -57°C to +51°C.

4.2.5 ASTM D6749 Standard Test Method for Pour Point of Petroleum Products (Automatic Air Pressure Method)

ASTM D6749 covers the determination of pour point of petroleum products using an automatic air pressure method. The test specimen is cooled and at specified intervals (typically 1°C) a slightly positive air pressure is gently applied to the surface of the specimen which is contained in an airtight test jar equipped with a communicating tube. Since the end of the communicating tube is inserted into the specimen while the other end is maintained at atmospheric pressure, a small amount of downward movement or deformation of the specimen surface, as a result of the application of air pressure, is observed by means of upward movement of the specimen in the communicating tube. The lowest temperature at which deformation of the specimen is observed upon application of air pressure is recorded as the pour point. The test method is designed to cover the range of temperatures from -57°C to +51°C.

4.3 Cloud point IP 219 / ISO 3015 / ASTM D2500

This test uses a sample which is cooled at a specified rate and examined periodically. The temperature at which a cloud is first observed at the bottom of the test jar is recorded as the cloud point. This test method measures properties similar to those measured in freezing point (ASTM D2386), however the cloud point sample cooling rate differs and it is not stirred. This test method was not developed for jet fuel, but may be useful for evaluation of jet fuel low temperature properties.

There are a number of automatic versions of this test. Furthermore, the test equipment used for freezing point in accordance with ASTM D5972 can be used to determine cloud and pour point equivalents using methods ASTM D5773 and ASTM D5949 respectively.

4.4 Shell Cold-Flow tester

The Shell Cold-Flow Test was developed due to a perceived need for a suitable procedure to characterise the low temperature flow behaviour of aviation turbine fuels [13]. The procedure does not measure any fundamental rheological property, although the test conditions are designed to represent as closely as possible those to which the fuel is subjected while flowing within a fuel tank towards the booster pump. The apparatus comprises two cylindrical chambers connected by a spring loaded poppet valve. The fuel sample is introduced into the upper chamber and the apparatus is immersed in a low temperature bath until the fuel and bath temperatures equilibrate. The poppet valve is then opened for a specified time, after which it is closed and the apparatus removed from the bath. The volume of the fuel remaining in the upper container is measured after the apparatus has warmed to assess the flow characteristic of the fuel at the test temperature.

A draw back of the Cold-Flow test is that the 'zero hold-up'⁵ temperature cannot be determined directly. The usual procedure is to plot the temperature dependence of the hold-up factor over a range of readily determined values (typically between 10-90% hold-up) and to extrapolate to zero hold-up to obtain the corresponding zero hold-up

⁵ Zero hold-up temperature is defined as the lowest temperature at which no fuel remains in the cooled fuel tank or test equipment.

temperature. To minimise errors, several determinations are required, particularly in the region of low hold-up factors.

The Cold-Flow test was evaluated during an Institute of Petroleum programme, and the method was adopted as a standard procedure (IP 217). The method was withdrawn in 1972, owing to lack of interest.

4.5 Air Probe Flow Monitor (APFM)

The APFM is based on pulsing a small bubble of air through a sample of fuel, which is cooled at a constant rate [13]. The uniform fluctuations of air pressure upstream and downstream of a glass capillary are monitored, the capillary acting as a fine control on the air pulse pressure. A change in the observed pressure profiles is observed when the air ceases to flow through the sample, and the temperature at which this occurs is recorded as the no-flow temperature. The inability of the air to flow through the sample is a direct indication to the loss of sample fluidity.

4.6 Viscosity methods

The viscosity is a measure of internal resistance to motion caused by cohesive forces among the fluid molecules. It is strongly temperature dependent and increases as fuel temperature is lowered. A maximum viscosity limit at low temperature was part of the original jet fuel specification (DERD 2482 set in the UK in 1947) [2] in order to assure pumping and flow capabilities through the engine fuel system and to maintain adequate atomisation of the fuel at the burner nozzle.

The first limit of 6 mm²/s at -18 °C (6.5 mm²/s at -20 °C equivalent) was found to be more than adequate in practice. The ASTM kerosine specification in the 1950s used a slightly higher maximum limit of 15 mm²/s at -30 °F (8 mm²/s at -20 °C approximate equivalent) and the same limit was adopted by DERD in 1968. In 1978, the test temperature was raised to -20 °C to align with standard laboratory viscometry test conditions.

The current test method used is ASTM D445 / IP 71 / ISO 3104. The time is measured for a fixed volume of liquid to flow under gravity through the capillary of a calibrated viscometer under a reproducible driving head and at a closely controlled temperature of -20°C. The kinematic viscosity is the product of the measured flow time and the calibration constant of the viscometer.

The current specification test method measurement temperature of -20°C may not give an indication of a particular pumpability limit at a lower temperature. However, automated equipment developed in recent years may be able to test (with some modifications) for a temperature at which a fuel has a specific viscosity (such as a future specification limit). Such automated equipment have reportedly improved precision over manual methods [14]. A modified automated viscosity method based on ASTM D445 to predict a pumpability temperature would require assessment and standardisation for specification use.

A number of other viscosity methods are commonly used for various petroleum products. These are outlined below:

4.6.1 ASTM D7042 Standard Test Method for Dynamic Viscosity and Density of Liquids by Stabinger Viscometer (and the Calculation of Kinematic Viscosity)

ASTM D7042 describes a procedure for concurrent measurement of dynamic viscosity and density. The Stabinger viscometer uses a rotational coaxial cylinder measuring system. The outer cylinder (tube) is driven by a motor at a constant and known rotational speed. The low density inner cylinder (rotor) is held in the axis of rotation by the centrifugal forces of the higher density sample and its longitudinal position by the magnet and the soft iron ring. Consequently the system works free of bearing friction as found in rotational viscometers. A permanent magnet in the inner cylinder induces eddy currents in the surrounding copper casing. The rotational speed of the inner cylinder establishes itself as the result of the equilibrium between the driving torque of the viscous forces and the retarding eddy current torque. This rotational speed is measured by an electronic system (Hall effect sensor) by counting the frequency of the rotating magnetic field. The density is measured using a U-shaped oscillating sample tube.

The kinematic viscosity is calculated by dividing the dynamic viscosity with the density. The kinematic viscosity measured is equivalent to ASTM D445. This test method is not usually used for jet fuel viscosity measurements. However, a brief study [15] using a modified version of this test method in a temperature scanning mode showed this equipment has the potential for use with jet fuels. Some test results and notes can be found in Appendix B. This preliminary study included a review of the literature on behalf of the Energy Institute and the data of interest from that is recorded in this report.

4.6.2 ASTM D5133 Standard Test Method for Low Temperature, Low Shear Rate, Viscosity/Temperature Dependence of Lubricating Oils Using a Temperature Scanning Technique

ASTM describe two further methods using a type of rotational viscometer, ASTM D2983 describes a method for low temperature viscosity of lubricants measured by Brookfield viscometer. But probably more suitable for jet fuel purposes, a scanning rotational method, D5133, is available. This method was developed to provide measurements of low temperature, low shear rate, viscosity / temperature dependence of lubricating oils. This technique has the capability to rapidly measure viscosity as a function of temperature. As the sample is cooled the dynamic viscosity is measured continuously by the increasing torque generated by a spindle rotating in the fluid at a constant speed. This technique, though normally used to measure engine oil properties, has been used for jet fuel research [6,15].

4.7 Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) is a thermoanalytical technique in which the difference in the amount of heat required to change the temperature of a sample and reference is measured as a function of temperature. The technique can be used to yield information on phase transitions such as transition temperature and enthalpies. This technique has not been routinely used for jet fuel testing but has been used for research purposes [17,18].

5 Research into jet fuel low temperature properties

The University of Dayton has studied [19,20] the use of DSC as a rapid technique for evaluation of cold flow improving additives for jet fuel. It was reported that the rate of cooling can change the effects of supercooling and affect the crystallisation temperatures. The DSC freezing curves could be reproduced within $\pm 0.2^{\circ}\text{C}$. The work showed that the cloud and pour points, as measured by a Phase Technology Analyser, of each fuel measured, bracketed the DSC exotherm. The measured cloud points were found on the rising edge of the high temperature shoulder of each exotherm and the pour points were located on the low temperature side of the exotherm, near where the exotherm returns to the base line. The freezing points were 4-5 $^{\circ}\text{C}$ higher than the cloud points for each of the fuels studied. After measurements of normal alkanes were considered it was concluded that the exothermic feature observed when cooling fuels is mainly due to the crystallisation of the large normal alkanes present. It was shown however, that the addition of 'pour point improving' additives resulted in only small changes in the exotherms despite large changes observed in cold flow devices.

Boeing in a presentation to CRC [21] reported that low fuel temperatures are limiting some aircraft operations: Freezing point and pour point were used to describe fuel low temperature behaviour. Pour point was reported as lower than freezing point by between 4 $^{\circ}\text{C}$ and 20 $^{\circ}\text{C}$ depending on the fuel characteristics. Fuel will not flow to the boost pumps below the pour point temperature. Aircraft operating procedures instruct pilots to take action to keep fuel warmer than 3 $^{\circ}\text{C}$ above freezing point.

Low temperature behaviour of fuels in simulated aircraft tanks has been studied and reported in a CRC report [22]. Both Lockheed and Boeing each made a series of tests in aircraft fuel tank simulators to provide an understanding of the flowability and pumpability of jet fuels at low temperatures. Test fuels were chosen that were derived from widely differing crude sources and covered a range of freezing points. The simulations showed large temperature differences throughout the fuel when the wing outer sections were cooled, with the lowest fuel temperatures at the wing surfaces. Measurements were made to detect the level of hold-up at various temperatures when the fuel was pumped from the wing. Hold-up⁶ represented the separated wax plus entrapped liquid at the end of a particular time-temperature test. It was noted that it is impossible to prescribe an "acceptable" level of hold-up because the tolerance of a system depends on a particular tank design and system configuration.

The percentage hold-up appeared to be related to the tank skin temperature, the mid tank temperature and the low temperature properties of the fuel. The low temperature fuel property described was that temperature below which it does not exhibit significant flowability from the simulated aircraft wing. This temperature was named the solidification index (SI). The SI showed reasonable correlation with a function of freezing point and pour point, which was approximately the mean of these two values. It was noted however, that relatively minor differences in freezing point and pour point results (within method precision), caused significant errors in percentage hold-up predictions. To overcome this, a number of tests results were carried out to increase

⁶ Hold-up is the unpumpable fuel left in the wing presumably due to fuel waxing or high viscosity.

the precision⁷. It was also noted that this was an initial correlation study, and should not be interpreted as concluding that the ultimate choice in low temperature flow properties is the solidification index, to the exclusion of all other properties.

A number of other low temperature tests in addition to freezing point and pour point were carried out. These included the Shell cold flow test and the Setapoint test. These both appeared to show a relationship with SI, however none were able to accurately predict percentage hold-up. The Lockheed testing [23] reported a good relationship with freezing point. The CRC report [22] also describes a correlation of n-alkane content with various bench test methods. It showed similar results to a previously reported n-alkane correlation with freezing points by Petrovic and Vitrovic [24].

During the Boeing and Lockheed work [14] there was concern expressed about the reliability of data generated by repeated freezing of a given batch of fuel. When testing other heavier petroleum products there is often a requirement to increase the temperature of the product significantly above the pour point temperature to completely reconstitute the specimen. This need appears to arise due to the persistence of micro-crystals which serve as a condensation nuclei when the chilling cycle is repeated. This hysteresis effect has been showed to lead to variability in low temperature property measurements of other petroleum products. The Shell cold flow test procedure was used to test this and no significant hysteresis effects were evident with jet fuel.

Wax crystal growth and matrix formation during freezing of jet fuel is believed to be dependant on cooling rate. Therefore, consistent cooling cycles were attempted during the simulated aircraft tank studies. However, the effects of cooling rates were not extensively studied.

Aircraft fuel tank studies [25] have been carried out from the mid-1950s at Shell Thornton Research Centre. Due to the possibility of operational problems with two phase flow, later testing concentrated on the 'zero hold-up' temperature. This temperature represents the lowest temperature at which all the fuel can be recovered. In the studies, tanks in a cold room, were filled with fuel via a coalescer to remove water. The cold room temperature was then reduced to variety of temperatures down to -60°C. Upon reaching the required test temperatures, a boost pump was operated to empty the tank and the fuel was collected. Conditions were arranged so that cavitation occurred at the boost pump, and the variation of this condition with temperature was measured allowing the zero hold-up temperature to be determined.

Tests were carried out on a range of conventional Jet A/A-1 fuels and also on some specially blended 'experimental' fuels. These experimental fuels were prepared by blending varying quantities of heavier components into the kerosene fraction. The testing showed good agreement with the shell cold-flow test and with freezing point for conventional jet fuels. For the experimental fuels, the tank testing showed good agreement with the shell cold flow tests but did *not* correlate with the freezing point test results. The zero hold-up results could be as much as 20°C below the freezing point results. Shell concluded that the zero hold-up temperature provides a more realistic indication of the limiting temperature for unrestricted flow of the fuel under severe low-temperature conditions than does the freezing point.

⁷ These tests were probably carried out before various automated pour point testing with improved precision was widely available.

To explain the above test results Shell examined the influence of fuel composition in freezing point and low temperature flow tests. It was found that the least soluble straight chain paraffins (i.e., the longest-chain components), strongly influence the measured freezing point. In fact they suggest a more correct term for this test would be "low temperature solubility point". Therefore, it was shown that, unsurprisingly, the presence of low concentrations of straight chain paraffins do not necessarily reflect the bulk performance of the fuel, whereas a cold flow test successfully predicts the zero hold-up temperature. The work showed that fuels with a straight chain paraffin profile that is steep and symmetric showed good freezing point verses flow characteristics agreement. However, freezing point does not predict low temperature flow for fuels with asymmetric straight chain paraffinic profiles. A chart reproduced from reference [25] below shows a fuel with a steep and symmetric straight chain paraffin profile (FUEL A) and a fuel with an asymmetric profile (FUEL C).

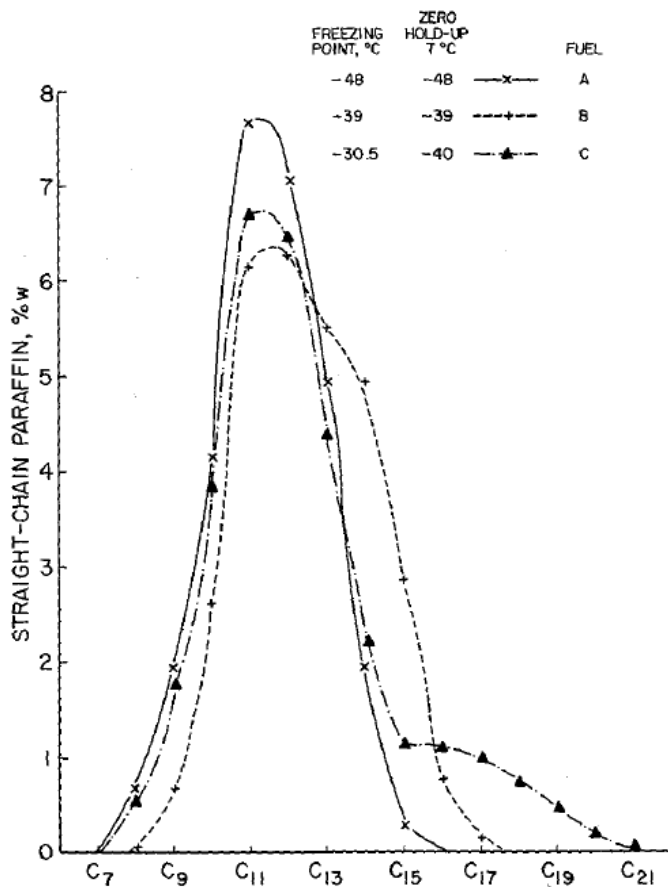


Figure 1, Showing straight chain paraffin distributions and their affects on cold properties.

Shell concluded that for many conventional fuels the use of a freezing point or a flow related criterion would be equally applicable. However, for some fuels the freezing point criteria could be unnecessarily restrictive as evidenced because they have satisfactory flow characteristics at temperatures well below their freezing point. For such fuels the use of a no-flow specification requirement would allow significant increases in the jet fuel yield to be obtained from refineries otherwise restricted by the need to meet a freezing point requirement.

The University of Dayton investigated [26] the use of a rotational viscometer to study low temperature jet fuel viscosity. A temperature scanning rotational viscometer which meets the requirements of ASTM D5133 was used for the studies. This equipment is normally used to measure low temperature properties of lubricants which have higher viscosities than jet fuel. Therefore, the most sensitive torsional spring available from the manufacturer was used. It was found that the technique was applicable to jet fuel provided the relative torque measurements were >6% of the full scale of the instrument to minimize uncertainty. The work concluded that the rotational viscometer was suitable for measuring the viscosity of kerosene-based jet fuels down to the cloud point of the fuel (several degrees below the freezing point temperature) with the equipment capable of providing continuous measurements from -20°C to the cloud point temperature. Furthermore, the viscosity measurements agree with other recognised viscosity techniques (commonly used for jet fuels) and previously published data.

Atkins & Ervin [27] conducted experiments using an optical cell with buoyancy-driven flow⁸. Buoyancy-dominated flow is expected in aircraft fuel tanks. It was suggested that as crystalline structures form at low temperatures, the structures are interlaced with liquid and were referred to as 'mushy' regions. Flow in mushy regions is analogous to flow in porous materials. The resistance to flow through the mushy region can be expressed in terms of permeability. The work showed that buoyancy-induced flow controlled the growth of wax structures and the flow enhanced the growth of wax structures on the cell surfaces for a Jet A fuel by increasing crystal interaction. Modelling the freezing process of jet fuel was accomplished using models similar to those used for metal alloy solidification. The optical cell experiments suggested that jet fuels with a wide distribution of small n-alkane species (<C₁₄) are likely to have desirable low temperature properties.

The University of Dayton Research Institute reported [28] studies to obtain fundamental information on the effect of low temperatures on fuel properties and behaviour. Scanning Brookfield viscosity studies were performed to measure the effect of temperature on fuel viscosity and compared this to flowability in an aircraft wing tank simulator. Quantitative analysis of fuels' normal alkanes were obtained by gas chromatography to help provide information on how the differences in chemical composition affects low temperature properties. In addition, freeze, cloud, and pour point data were obtained using a Phase Technology Petroleum Analyser.

The viscosity measurements show a gradual rise in viscosity as the fuel is cooled until a relatively sudden, rapid increase at the point microscopic crystal formation begins (generally at the fuel's cloud point). These studies primarily investigated fuel viscosity behaviour in the liquid phase unlike the Boeing and Lockheed studies [22,23] which investigated two phase flow.

A tank which simulates an outboard main tank (which are subjected to the coldest temperatures because they are not used until the end of a flight) on a Boeing 747 using actual fuel system components was cooled to various low temperatures. Fuel was pumped from the simulated wing tank and the flow was measured to evaluate the pumpability/flowability. The results show decreased pumpability with decreased temperature in agreement with the reduction in viscosity as measured by the scanning Brookfield method. Furthermore, it was noted that freezing point did not correlate with

⁸ Many fluid flows are driven by buoyancy, the tendency of hot fluid to be less dense and therefore rise, and cold fluid to sink.

the flowability. It was noted that one fuel with a freezing point of -53.1°C and a cloud point of -59.2°C displayed a viscosity of 46.4 cP at its cloud point, while another fuel which had a freezing point of -41.6°C and a cloud point of -46.1°C , had a viscosity of 11.7 cP at its cloud point. This factor-of-four difference in viscosity may have a significant effect on fuel flowability and pumpability. It should be noted that these fuels had similar viscosities at -40°C despite the differences at lower temperatures. It appeared that fuels with lower freezing points tended to exhibit the high viscosities near to their freeze/cloud points.

Analysis of normal alkane measurements indicates that those fuels with the highest concentrations of the larger normal alkanes (C_{16} to C_{19}) have the highest freezing points. Whereas, the viscosity and pumpability were reportedly mostly a function of the overall distribution of the normal alkanes. These findings are in agreement with the earlier investigations by Shell [25]. The report concludes that operating near fuel freezing point rather than the specification freezing point may reduce pumpability. However, the significance of pumpability reduction would be aircraft fuel system dependant and would need to be evaluated individually.

6 Discussion

6.1 Fuel Two Phase Flow

There have been a number of experiments detailed in the literature showing how fuel from aircraft tanks is held up at temperatures below significant wax formation. Although there was some correlation with various tests, there was little evidence of precise, accurate predictions. The effects of two phase flow in fuel systems is likely to be system dependant which could mean re-approval and possibly testing for every fuel system type. Furthermore, fuel system filters are likely to have been optimised to take a maximum level of particulate and water/ice whilst minimising size and weight. Therefore, an additional burden of wax crystals may require a redesign of many systems. These problems mean that it is probably not practical to consider any test method and specification limit that allows significant two phase flow.

6.2 Test Method Precision

Any test for freezing point or low temperature flow should have the best possible precision. This will allow refiners to cut their fuels closer to the specification limits with confidence and allow aircraft fuel system designers to minimise over engineering of equipment. Of the currently specified freezing point methods the manual method, ASTM D2386, has a reproducibility of 2.5°C whereas ASTM D5972, an allowed alternative method, has a reproducibility of 0.8°C. This could lead to suggestions that a lower specification limit could be used when using D5972. However, as the specification limits are absolute with no allowances for precision, this may not be relevant. Nevertheless, the use of more precise methods such as the currently allowed D5972 or D7153 should help refiners make fuels with freezing points close to the specification limits with confidence.

6.3 Test Method Accuracy

In addition to good precision any new test should have an improved prediction of aircraft low temperature flow characteristics. The literature shows that freezing point is not always a good predictor of low temperature flow. Low temperature flow tests have been shown to be improved predictors of fuel characteristics in aircraft fuel systems. Although other low temperature flow tests should not be discounted, a viscosity measurement is likely to be the best way forward because work has already shown this measurement to be relevant, and test methods already exist which can be used or easily modified.

Of the test methods available, the scanning Brookfield viscometer, based on ASTM D5133 appears to be a good choice. The University of Dayton has carried out work to show this method is suitable for fuel viscosity measurements from -20°C down to temperatures below the freezing point. They have demonstrated that the method predicts pumpability from an aircraft fuel tank simulator. Furthermore, test method D5133 is already used to predict low temperature properties of aviation products. It should be noted that although the method has been shown to predict fuel tank pumpability, it may not be relevant to all aircraft fuel systems. Input from OEMs is required to ascertain this.

Other viscosity measurements should also be considered. The method currently used in jet fuel specifications, ASTM D445, measures viscosity only at one temperature. Further measurements at other temperatures could be carried out but a large number of manual tests would be impractical. Furthermore, there is some evidence that the precision of manual measurements is not good. However, the emergence of some automatic methods appear to show much improved precision and one manufacturer claimed that their equipment could be easily modified to produce a temperature scanning device if this was required by the jet fuel industry. Therefore, this type of test method warrants further investigation.

The Stabinger type viscometer which is used in ASTM D7042 has not been used extensively for jet fuel. However, the limited work carried out shows promise if the equipment can be modified by the manufacturer to suite the requirements of jet fuel testing. This method therefore warrants further investigation.

6.4 Water/Ice

Water which turns to ice at low temperatures is known to have the potential to block or restrict fuel flow in aircraft fuel systems. The potential for such problems is tested for by the manufacturers. Dissolved and free water can affect low temperature test methods and as this water in a particular sample may not be relevant to conditions in the aircraft, the best option is probably to remove it as part of the sample preparation or ensure that any new test method is not affected by such water in the sample.

6.5 Specification Limits – equivalent to current limits

When considering a possible viscosity limit in place of the current freezing point limit, the first step should be the use of an 'equivalent limit'. This equivalent limit would be the currently acceptable viscosity of fuels, for example if the acceptable temperature for pumpability of a Jet A-1 fuel in an aircraft is -44°C ($-47^{\circ}\text{C} + 3^{\circ}\text{C}$), then viscosity at this temperature must, by definition be acceptable. Although some work has been carried out to investigate jet fuels viscosity at these low temperatures, particularly by the University of Dayton, it is likely that more data would be needed before any limits could be set. Any work programme to produce this data would need to show how freezing point and viscosity varied with fuel composition, and in particular, n-alkane distribution.

Adoption of a viscosity 'equivalent limit' would allow the use of fuels which were previously outside the specification requirements for freezing point, but still have the required fuel tank pumpability. This would allow refiners to have more flexibility when manufacturing jet fuel. However, the significance of this extra flexibility is not known. Perhaps, more importantly, the use of a viscosity limit and known viscosity values at various temperatures is likely to help with the design of equipment resulting in minimisation of over-engineering, with the potential for future equipment to be more efficient. Furthermore, the adoption of a specification parameter which more accurately predicts pumpability may be important at a time when the use of non-conventional fuels is challenging specification methodology. Table 3 shows a possible future specification requirement with viscosity limits yet to be determined.

Description	Method	Jet A-1 Limit	Jet A limit
Temperature at which fuel viscosity is xx cSt	Scanning low temperature viscosity DXXXX	-47°C max	-40°C max

Table 3, possible future specification requirement

The identification of a currently acceptable limit that does not change the ‘status quo’ of currently used fuel would likely be the easiest for the OEMs to agree. The adoption of an ‘equivalent limit’ should be acceptable with respect to low temperature pumpability. However, if, as the literature suggests, fuels previously out of specification would now be acceptable, a review of the risks of these fuels is necessary. The difference between these previously unacceptable fuels and current fuels appears to be the n-alkane distribution. The result of a viscosity ‘equivalent limit’ is likely to lead to a small proportion of fuels containing slightly higher concentrations of larger n-alkanes. These n-alkanes will not be new to OEM equipment but may have slightly higher concentrations. These changes are probably not likely to be significant. However, the risks need to be evaluated.

Although the adoption of an ‘equivalent limit’ would not change the ‘status quo’ with respect to flowability, Honeywell’s statements that some engines and APUs require a maximum viscosity of 12 cSt should be taken in to account. Therefore, Table 3 above may need to be modified to ensure the viscosities of Jet A at -37°C and Jet A-1 at -40 are no greater than 12 cSt (see Table 4 below).

Description	Method	Jet A-1 Limit	Jet A limit
Temperature at which fuel viscosity is xx cSt	Scanning low temperature viscosity DXXXX	-47°C max	-40°C max
Viscosity at -37°C	Scanning low temperature viscosity DXXXX	-	12 cSt max
Viscosity at -40°C	Scanning low temperature viscosity DXXXX	12 cSt max	-

Table 4, possible future specification requirement incorporating 12 cSt requirement

It should be noted that the current specifications do not adequately ensure that this 12 cSt limit is met at these temperatures. Furthermore, the temperature/viscosity relationships given in the CRC handbook [29], though generally correct, have been shown to be very inaccurate for some fuels. Therefore, setting appropriate viscosity limits at -37°C (for Jet A) and -40°C (for Jet A-1) should ensure improved operation safety for APUs and some propulsion gas turbines. As specifications do not adequately cover these requirements, the suggested changes may preclude some currently produced fuels, however, this is not likely to be significant.

6.6 Specification Limits – Relaxing the Specification

If a viscosity 'equivalent limit' as a replacement for freezing point is accepted by the aviation fuel industry, this would mean a more accurate estimate of low temperature fuel pumpability would be used. This could mean that OEMs could be less conservative with low temperature use limits and the 'viscosity limit' reduced from 'current levels'. This relaxing of the specification could result in additional flexibility for refiners with the possibility of more widely available and/or lower cost fuel. However, a significant change in the limit may be problematic, as mentioned earlier, as effects may be aircraft fuel system specific which could mean impractical approval requirements. Nevertheless, this should still be a consideration.

The allowance of fuel tank temperatures below current limits has been postulated provided the freezing point of the fuel used is known and is significantly lower than the specification limit. This, however, may be problematic because pumpability does not correlate with freezing point. Furthermore, it has been shown that some of the lower freezing point fuels have high viscosities close to their freezing points. However, if a viscosity test was adopted that correlates with pumpability, the possibility of using specific fuels with improved low temperature viscosity (additional to a future specification limit) may be a possibility. However, it should be noted that a scanning low temperature viscosity measurement at plane-side during fuelling may not be a practical option at this time.

6.7 OEM considerations

It is important that any significant change in specification testing and requirements has OEM agreement. Part of this study was to gather data from OEMs, and this data (as can be seen above) is limited. The lack of information provided from some OEMs appears to be due, in part, to commercial sensitivity. This leads one to believe that there is significant data held by OEMs that may influence any decision on the use of other methods in place of freezing points and possible future limits. It is therefore important that the recommendations contained in this report are reviewed and commented on by the OEMs to establish if these recommendations are a suitable way forward for the industry or otherwise.

6.8 Recertification of Fuels and Contamination Detection

A reduced number of certification tests are often used for recertification of jet fuel (especially outside the US) to ensure a batch of fuel has not significantly changed. This process involves comparing test results, including freezing point, with those previously obtained for that batch. If the results are significantly different, then this could indicate contamination and further investigations are carried out. It has been shown that freezing point can detect contamination with higher boiling products such as gas oil.

If the freezing point test is replaced by a viscosity test, the use of this test as a recertification test should be evaluated and the risks of using an alternative test that might not show contamination with certain products, should be evaluated.

7 Conclusions

At temperatures below approximately the cloud point, significant two phase flow occurs. Setting methods and specification limits at these temperatures is probably not feasible.

It can be concluded from the literature that at low temperatures down to below the freezing point to approximately the cloud point of the fuel, a flow method such as viscosity, more accurately predicts pumpability from an aircraft fuel tank than freezing point.

Temperature scanning viscosity based on ASTM D5133 appears to be a suitable method for predicting fuel pumpability. Other viscosity methods such as automated, temperature scanning versions of D445 and D7042 warrant further investigation.

It may be possible to set a specification limit whereby, the 'status quo' will not change with respect to low temperature pumpability which will minimise the risks of specification change for OEMs. The risks of allowing slightly different fuel compositions would need to be assessed.

Some of the advantages and disadvantages of changing jet fuel freezing point limits and replacing with a viscosity test are listed below.

Advantages:

- Allows more flexibility for refiners
- More 'accurate' test may allow less conservative designs for future equipment
- One specification test to replace the two currently used (scanning viscosity to replace freezing point and viscosity at -20°C)
- More 'accurate' test may allow improved risk assessment of particular equipment and flight routes. For example actual viscosity, rather than specification limit may be applicable to use, giving airlines more flexibility.
- A test which better predicts pumpability may be important as more unusual fuels from unconventional sources are allowed in the jet fuel pool

Disadvantages:

- Cost of developing viscosity method and assessing suitable limits
- Costs of equipping laboratories with test method equipment
- The need to assess the risks of a slight fuel chemistry change
- The possible loss of a recertification test which can identify contamination

8 Recommendations

1. Development and assessment of a suitable low temperature scanning viscometer for jet fuel specification use. The most suitable method would have good precision and be an accurate predictor of low temperature pumpability. A method based on D5133 appears to be suitable but other methods such as ones based on D445 and D7042 may also be suitable.

2. Investigate and identify a 'viscosity equivalent' limit that may be used for specification purposes.
3. Investigation and quantification of the likely small chemistry change of fuel if a viscosity test replaces freezing point.
4. Engage with OEMs to evaluate their support for replacing freezing point with viscosity and to find out if further rig or aircraft testing would be necessary.

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Appendix A

EXHIBIT A

STATEMENT OF WORK

Develop an Aviation Fuel Cold Flowability Test to Replace Freezing Point Measurement

Relevant Strategic Objectives: Provide airlines and fuel manufacturers with a better method to assess fuel low temperature properties.

Background: At the 2008 IATA meeting in Shanghai, China the airlines requested that a fuel cold flow ability test be devised to replace the currently-in-use freezing point methods. This subject has been the object of a research program by the USAF within the past decade, and was the subject of significant discussion in 2007, but to no particular end. “Flowability” has different meanings to different equipment manufacturers, and for jet fuel it can be limited by both wax crystal formation (rate of formation and specific crystal structure) and fluid viscosity. For the Airframer, the limit is flow through small (quarter inch (?)) holes in the wing support structure running through fuel tanks, and isolated pipes that flow fuel intermittently during a flight. The APU manufacturer is concerned with fuel in piping from the source tank to the APU and fuel filters at their engine’s inlet. The engine manufacturer has concern for the engine inlet filters. It should be recognized that a total answer is, probably, not possible. Finding a satisfactory limit for the airframer/airlines that gets the fuel out of the tanks would be a good start. Further, whatever answer becomes the goal, free water in the fuel needs to be part of the solution.

Project Objectives: Using the available database, determine if there is a current test method or combination of test methods that could be used to assess jet fuel flowability limits, and/or develop a new method or technique to achieve this objective.

Project Approach: 1) Request a critical summary of the AFRL Fuel Tank Hold-up test results, (circa 1995 – 2003). Review this data to determine the specific program goal or test criteria.
2) Obtain from the different OEM’s the fuel vessel geometry and real life operating conditions thought to be most severe. This is to obtain a better understanding of what the test method has to emulate and/or what translation of test result to real world has to occur.
3) There exist within ASTM test methods several that could become models for moving forward. One is ASTM D4305, the filter flow test based on a set screen mesh and not currently in use due to a need to constantly adjust test parameters to match D2386 Freezing point. ASTM D5985, Standard Test Method for Pour Point of Petroleum Products (Rotational Method) which accounts for both viscosity and wax formation, albeit lacks a jet fuel precision statement. ASTM D97, STM for Pour Point of Petroleum Products. Inspect these test methods for possible usability and research the existent methods for any new technology which could also be of use.

4) Establish a test program with a method or methods selected from above or other sources. If a new method needs to be invented, describe the needed elements of that test and assemble an industry team to work it out.

Project Deliverables: Identify an improved test method(s) to determine jet fuel flowability, its applicability to airline operation and whether it can replace current freezing point methods. Identify a test program to validate this method.

Utilization of Deliverables: Harmonization of jet fuel specifications, provide airlines with improved capability to plan fuel loading for long range flight and provide improved in-flight operation as fuel cools to usable limits.

Relevant CRC Committee: **Low Temperature Group**

Appendix B

A small scale laboratory low temperature viscometer was identified. The equipment was an Anton Paar SVM 3000 which is a rotational viscometer with a cylinder geometry. It is based on a modified coquette principle with a rapidly rotating outer tube and an inner measuring bob which rotates more slowly. The instrument uses 2.5 ml of sample and determines dynamic viscosity, kinematic viscosity and density.

The equipment can be set up to measure at a set temperature or programmed to provide measurements at a number of temperatures. The lowest measuring temperature stated by the manufacturers is -56°C . However, there is no theoretical limit to the measurements and the QinetiQ laboratory carried out testing down to -60°C . Testing was labour intensive and problematic due to unusual testing procedures. Icing within the instrument housing caused difficulties and the software was very difficult to program. The manufacturer had no experience of such low temperature scanning applications. Nevertheless, it is expected that these problems could be readily solved by the manufacturers if given the incentive of large volume sales to the jet fuel industry.

Some test results can be seen in Figures A1, A2, and A3 below. Figures A1 and A2 show the viscosity of the fuel increase with decreasing temperature. The freezing point of the fuel was not reached for samples 1 and 2. Figure A3 shows increasing viscosity with decreasing temperature. A sharp increase in viscosity was observed approximately 2°C to 3°C below the freezing point. It was noted that the viscosity curve was smoother as the fuel warmed. This was only a preliminary study and no attempt was made to validate the results.

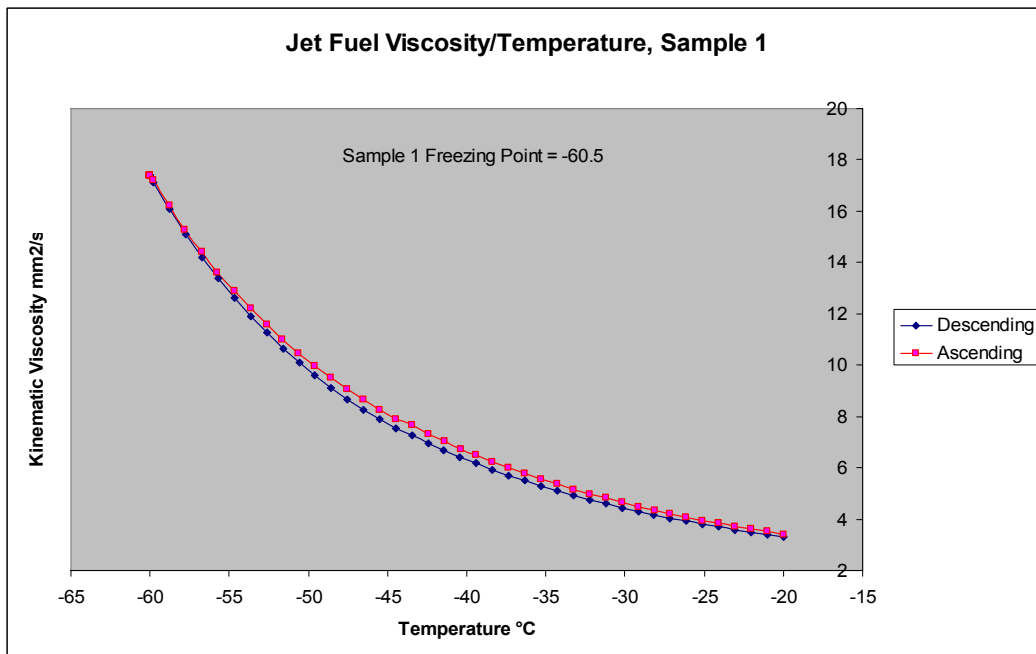


Figure A1, Sample 1 Test Results using the Anton Paar SVM 3000 Viscometer

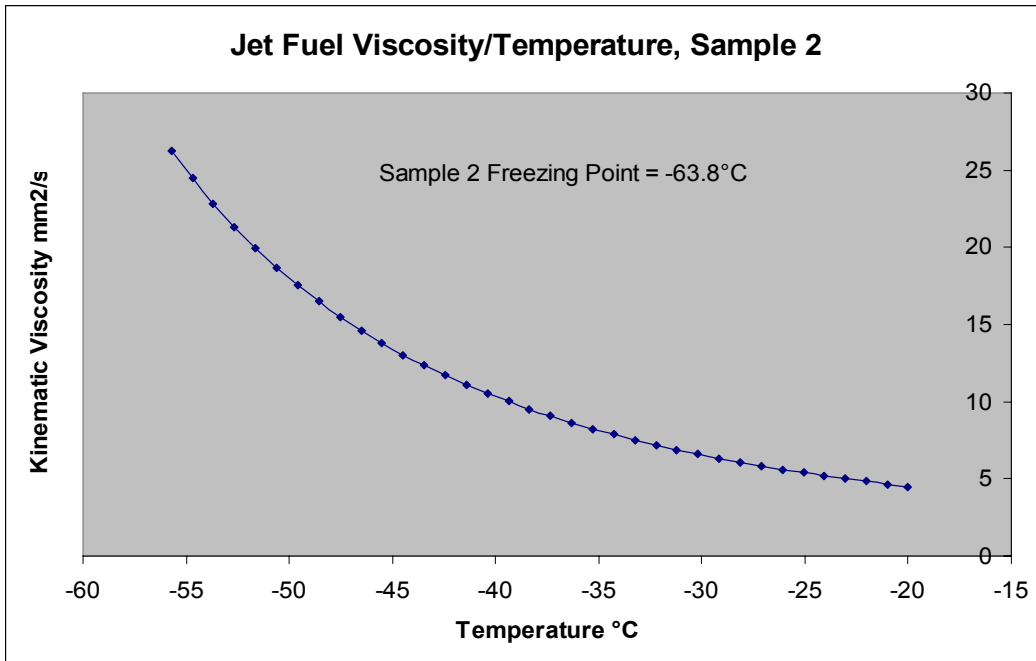


Figure A2, Sample 2 Test Results using the Anton Paar SVM 3000 Viscometer

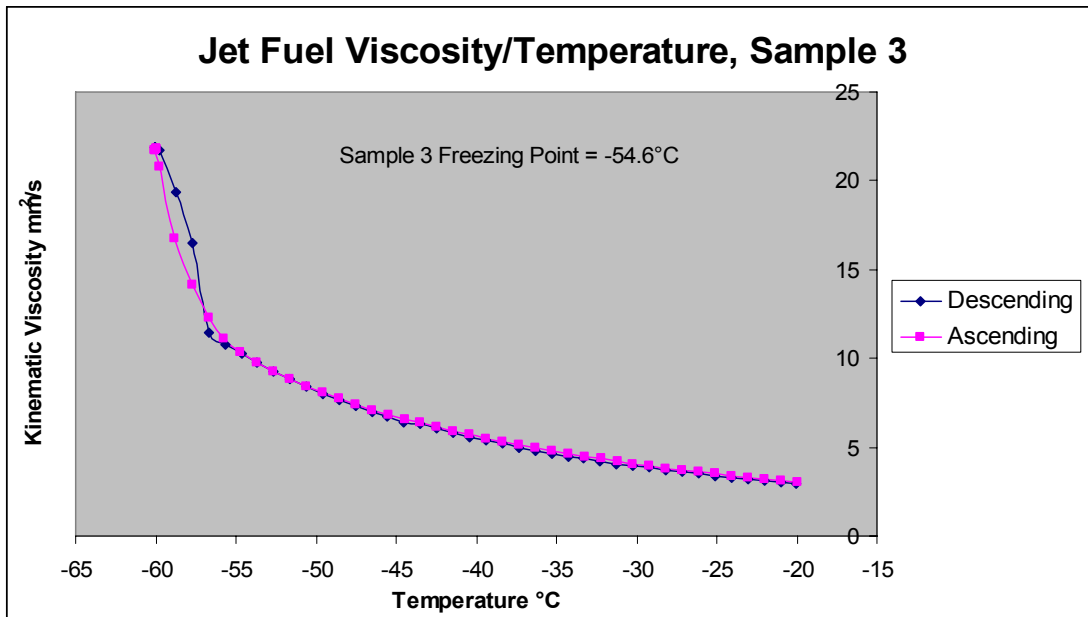


Figure A3, Sample 3 Test Results using the Anton Paar SVM 3000 Viscometer

Appendix C – Aircraft Fuel Tank measurements

The following results show fuel tank temperatures courtesy of Peter Westphal, Lufthansa. These show the lowest temperatures recorded on a low temperature route during Winter 2007/2008.

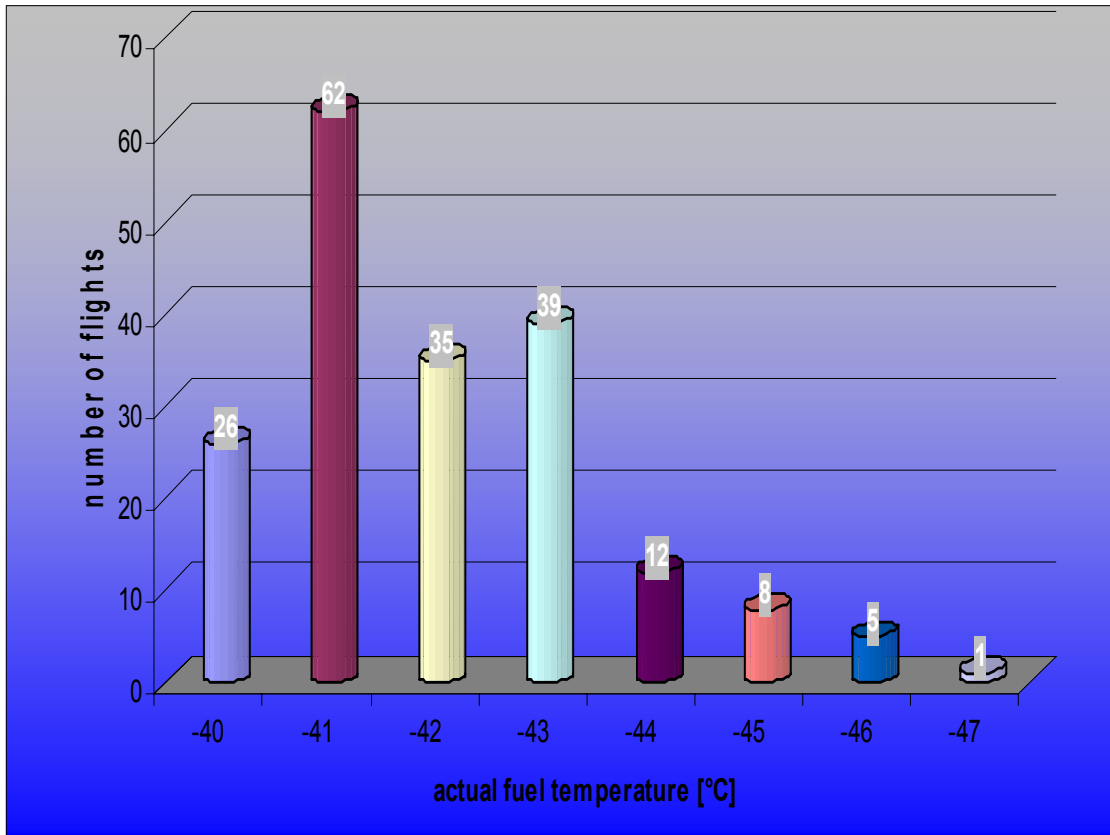


Figure B1, Fuel tank temperatures recorded on a low temperature route during Winter 2007/2008