AEROSPACE INFORMATION REPORT

AIR790	REV. C
Issued 1964-04 Reaffirmed 1992-08 Revised 2006-08 Superseding AIR790B	

(R) Considerations on Ice Formation in Aircraft Fuel Systems

RATIONALE

The purpose of this proposed revision is to organize and combine the useful information from AIR790B and ARP1401 into the AIR790C and to expand the document with additional information on icing, fuel and water management and testing.

FOREWORD

This AIR is intended to provide useful information for the consideration of ice formation in aircraft fuel systems and includes suggested test procedures to demonstrate the suitability of fuel systems, sub systems and components in environments having the potential for ice formation. It does not include consideration of ice formation in aircraft engines or fuel tank vent systems nor does it include instructions for the use of anti-icing fuel additives.

This report was initially based on conclusions reached at a combined Air Force-Navy-Industry conference held in 1959 and subsequently updated to reflect current industry consensus and practice by the SAE Committee AE-5. It represents a summary of contributions, based on personal experience, from aircraft fuel system engineering representatives from the industry.

In the past, incidents and accidents occurred in the operation of military and civil aircraft which were attributed to the formation of ice in the fuel supply system resulting in intermittent or complete starvation of fuel flow. Considerable effort was devoted by many airframe companies, engine and accessory manufacturers, fuel system component suppliers and government agencies to study the problem of ice formation and to develop corrective measures. By its very nature, the problem of ice formation is very complex and difficult to analyze. However, corrective measures were developed which, for many years, have virtually eliminated serious icing problems in aircraft fuel systems.

Successful corrective measures are numerous and include, but are not limited to, the use of anti-icing fuel additives, aircraft fuel heaters, improved in-flight fuel and ambient temperature monitoring, appropriate corrections in route or altitude or air speed and improved water management and drainage provisions in aircraft fuel tanks and ground storage and delivery systems.

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1. SCOPE

Ice formation in aircraft fuel systems results from the presence of dissolved and undissolved water in the fuel. Dissolved water or water in solution with hydrocarbon fuels constitutes a relatively small part of the total water potential in a particular system with the quantity dissolved being primarily dependent on the fuel temperature and the water solubility characteristics of the fuel. One condition of undissolved water is entrained water such as water particles suspended in the fuel as a result of mechanical agitation of free water or conversion of dissolved water through temperature reduction. Another condition of undissolved water is free water which may be introduced as a result of refueling or the settling of entrained water which collects at the bottom of a fuel tank in easily detectable quantities separated by a continuous interface from the fuel above. Water may also be introduced as a result of condensation from air entering a fuel tank through the vent system.

Entrained water will settle out in time under static conditions and may or may not be drained, depending on the rate at which it is converted to free water. In general, it is not likely that all entrained water can ever be separated from fuel under field conditions. The settling rate depends on a series of factors including temperature, quiescence and droplet size. The droplet size will vary depending upon the mechanics of formation. Usually the particles are so small as to be invisible to the naked eye, but in extreme cases can cause a slight haziness in the fuel.

Free water can be drained from a fuel tank if low point drain provisions are adequate. Water in solution cannot be removed except by dehydration or by converting it, through temperature reduction, to entrained, then to free water.

Water strictly in solution is not a serious problem in aviation fuel so long as it remains in solution. Entrained and free water are the most dangerous because of the potential of freezing on the surfaces of the fuel system. Further, entrained water will freeze in cold fuel and tend to stay in solution longer since the specific gravity of ice is approximately the same as that of hydrocarbon fuels.

The elimination of undissolved water, to the extent practicable, in fuel storage, handling and delivery systems as well as in aircraft fuel systems can reduce or eliminate the potential for icing problems. Appropriate testing of fuel systems, sub systems and components under controlled icing conditions can establish confidence in the safe operation of the aircraft fuel system in such icing conditions. Considerations for these measures to control potential icing problems are addressed herein.

Several things happen to moisture laden fuel as the temperature is lowered, and an understanding of this helps to arrive at proper fuel conditioning procedures and subsequent testing for icing conditions. As the temperature of fuel is lowered, concentration of water droplets in the fuel begins to decrease in the vicinity of 40 to 50 °F (4 to 10 °C). Therefore, to get a reliable conditioning of fuel, samples should be taken and mixing of fuel and water should be accomplished before lowering the temperature further. Ice crystals begin to form as the temperature nears the freeze point of water; however, due to impurities in the water, this normally takes place at slightly lower temperatures (27 to 31 °F) (-3 to -1 °C). As the temperature is lowered further, the ice crystals begin to adhere to their surroundings in the form of ice. This is known as the critical icing temperature and occurs at about 12 to 15 °F (-11 to -9 °C). At temperatures below 0 °F (-18 °C), ice crystals tend to become larger and offer a threat to plugging small openings such as screens, filters, and orifices. The cooling rate and agitation or turbulence due to obstruction of flow have an effect on the type and size of ice formed, so it becomes important to test actual or closely simulated aircraft systems and to cool the fuel during tests at the aircraft cooling rate or practical simulation to obtain more accurate results.

2. APPLICABLE DOCUMENTS

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

ARP1401A Aircraft Fuel System and Component Icing Test

2.2 U.S. Government Publications

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, http://assist.daps.dla.mil/quicksearch/.

MIL-F-17874B Fuel Systems: Aircraft, Installation and Test of

3. STORAGE, GROUND HANDLING AND DELIVERY SYSTEMS

3.1 Undissolved Water

The fuel should be maintained with no detectable undissolved water at fuel ambient temperature.

3.2 Solid Contamination

Solid contamination should not exceed 4.0 milligrams per gallon of fuel.

3.3 Control Techniques

Procedures should be used to insure continuous compliance with the requirements of 3.1 and 3.2 at point of delivery to aircraft. Filtration to control the particulate contamination level of the fuel, and water coalescing type equipment to separate and remove undissolved water from the fuel should be employed in storage,handling and delivery systems to accomplish this.

4. AIRCRAFT FUEL SYSTEMS

4.1 Anti-Icing Fuel Additive

Icing inhibitor is included by specification requirement in some military aviation fuels. It is not included in commercial aviation fuels, however, it may be added by operators. The additive effectively lowers the freezing temperature of entrained and free water depending upon its percentage of concentration in the fuel. The additive is water soluble, therefore, its concentration and effectiveness may be reduced if settled free water is removed from low point drains. Use of the additive may allow low point drainage of free water in cold ground operations which might otherwise be frozen.

4.2 Fuel Heating

Dedicated engine accessory fuel heaters have been successful in eliminating icing problems downstream of engine feed lines.

Fuel can be heated by the use of circulation and transfer pumps and heat exchangers making maximum use of available heat.

In-flight corrections in route, altitude and air speed are commonly employed to control fuel temperature and avoid icing problems.

4.3 Water Management and Drainage

Minimization of free water can be achieved with proper design considerations and drainage provisions and procedures. The tank bottom surfaces and associated ribs, stringers and features should provide passages for free water to migrate to low point drains in water sumps of adequate capacity. Drainage provisions should be located for maximum free water removal, accessibility and ease of operation and should display prominent clearly defined markings.

Free water may also be routed to circulation or inter-tank transfer pump inlets or to engine feed pumps providing provisions exist for adequate mixing with fuel to prevent slugs of free water from entering the engine feed system.

Ejector pumps are often used to scavenge free water from trapped areas in fuel tanks to sumps or pump inlets.

4.4 System Components

Filters and screens which are not necessary for safety of flight should be eliminated. Use of a reliable by-pass design around filters or screens which, if clogged, could result in engine flameout or other safety of flight hazard should be mandatory. By-pass elements should be located to prevent backwashing of sediment. Multiple by-pass elements in a principle filter may be considered. An impending by-pass or by-pass activation warning device on principle filters or screens may be considered. Generally, No. 4 mesh screen or coarser is considered not subject to critical icing; however, this would depend on and should be demonstrated for the critical operating conditions such as mission profile, water content and environment. Filters and screens should be selected for adequate filtration and capacity based on engine requirements and should be subject to maintenance inspections per aircraft and engine maintenance manuals.

System components should be located, as practicable, in favorable environmental locations to best utilize available heat. Insulation provisions may be considered where appropriate and practical.

Components should be designed to be tolerant to water and ice with provisions for water run-off and drainage of water traps. Materials and coatings which are non-ice adhering should be used where appropriate.

Low points in fuel lines where water can collect should be avoided wherever possible. Multiple vent system openings to atmosphere should be located such that no pressure differential exists between them to preclude continuous circulation of outside air which can introduce considerable quantities of water in some operating conditions.

5. FUEL SYSTEM OR COMPONENT TESTING

5.1 Testing Considerations

This section provides discussion and suggestions for the testing of fuel systems, sub systems and components and applies to all fuel flowing components and plumbing from fuel tank to engine, excluding engines.

The basic test methods presented herein are derived from previously published methods recorded in specifications MIL-F-17874 and ARP1401 which have served the industry as a baseline from which specific test procedures have been developed for specific systems and components. Icing test procedures must be tailored for the system, sub-system or component being tested. Continuous or intermittent operation, flow rate and temperature schedules should be developed to simulate actual aircraft operating conditions as closely as practicable.

Icing tests conducted in the industry have varied widely in the requirements and procedures used. There has been a lack of agreement on certain aspects of conducting tests including but not limited to general test set-ups, fuel conditioning, single pass test versus recirculating, use of anti-icing additive, test temperatures, test duration, water content analysis and post test requirements. With wide variations in test methods it is difficult to impossible to accurately compare test results from different sources and assess which most realistically represents actual aircraft environment or demonstrates acceptable performance. There is no optimum universal test set-up or detailed procedure to cover all systems and components, however, certain guidelines can be established, based on industry knowledge and experience, to minimize overdesign or overtesting while providing confidence in safe operation of a fuel system in realistic icing conditions. It is the intent of this report to provide such guidelines.

5.2 Test Set-Ups

Test set-ups should represent actual aircraft conditions as closely as practicable. The component or system installation should be representative of that in the aircraft in configuration and location relative to aircraft features which might influence the performance. For instance, for fuel pumps having inlets near the bottom of a tank, the tank bottom should represent the aircraft tank in size, geometry and contour and should include ribs and stringers which might collect water. Actual aircraft fuel tanks have been used as well as fabricated equivalents.

The test system as well as the test fuel should have the capability of being cooled at controlled rates and maintained at specified temperatures. Maintaining specified cooling rates and steady state test temperatures can be difficult and reasonable tolerances are advised considering wide variations in actual aircraft operations. Closed circuit refrigeration units with heat exchangers are commonly used for the fuel. Insulated enclosures cooled by cold nitrogen from a liquid supply have been used to cool systems as large as a full scale wing.

5.3 Test Facility

The test facility supplying fuel to the test system should be designed to provide and maintain specified fuel flow rates at specified temperatures and water concentrations. The facility and fuel delivery lines should be free of water traps and unnecessary restrictions. Insulation on lines will help control fuel temperatures. Line sizing should be considered to maintain fuel velocities sufficient to keep undisolved water in suspension and prevent settling in lower elevations.

Fuel conditioning and water content control can be accomplished in a number of ways, the merits of which have been widely debated. The proof lies in accurate and consistent laboratory fuel sample water content analysis. Common water injection methods are by atomizing water over the surface of the fuel and by simply feeding water into the suction side of a circulation pump. The test fuel should be kept agitated by circulation to keep undisolved water in suspension and uniformly distributed throughout the test system. Open vents are common in conditioning and test tanks, however, they should be small and breathing of outside ambient air should be limited to displacement of consumed fuel.

Single pass tests, where conditioned fuel is passed through the test system once are preferred, however, the quantity of conditioned fuel required for a simulated mission of a large transport, cargo or tanker aircraft can be prohibitive for most facilities. In this case, delivery systems which return fuel from the test system outlet to the conditioned fuel supply are commonly used. When such a recirculating system is used, the conditioned fuel supply should be as large as possible to minimize the quantity of recirculated fuel.

5.4 Laboratory Analysis

Fuel samples for laboratory water content analysis should be taken from points easily accessible during test. Assuming that samples are taken from valves, the valves should be opened and purged prior to collecting samples. Sample containers should then be rinsed with fuel and emptied prior to being filled with the laboratory sample. Laboratory sample containers should be kept sealed until analysis is performed. Laboratory water content analysis methods may vary, some reportedly more accurate with oversaturated fuel. The laboratory should be consulted and advised of the purpose of the analysis, the condition of the fuel samples and the predicted water content based on previous fuel conditioning. Consistent results in the expected range of water concentration establishes confidence in methods and procedures. Lower concentrations can be expected with low temperature samples as some water will freeze on internal surfaces of the system. Post test water content analysis should be considered for information only unless the entire system is such that all free water can be collected and measured.

5.5 Test Fuel

The test fuel should be certified as the primary fuel expected to be used on the aircraft. Anti-icing additives should be left out of the fuel so that a worst case situation will be simulated unless the aircraft is restricted to using anti-icing additives even under emergency conditions.

Test fuel may be procured from a refinery, an airport or a specialty hydrocarbon blender. Sample analysis at the source and at delivery should be considered as fuel has been contaminated during transit in multi-purpose tank trucks. Traces of anti-icing additives have been detected in commercial fuels processed at facilities which also process military fuels due to multi-purpose piping systems and tankage.

The amount of water required to saturate fuel at a given temperature varies with different fuel blends and with different batches of the same blend. This is due largely to the vast hydrocarbon variations of the crude oil, natural and introduced surfactants, aromatic content and additives. For icing tests, fuel which is saturated with 90 PPM minimum at 80 °F (27 °C) is preferred. Fuel with a lower saturation following initial conditioning is considered rare and simply adding more water for a total water content of 90 PPM has been practiced.

5.6 Fuel Flow Rates

Continuous and intermittent duty systems operating at one steady state flow rate should be tested at their specified conditions. Systems operating at various flow rates such as those associated with engine feed can be more susceptible to ice accumulation and need further consideration.

The turbulence produced by the action of a fuel pump is considered to be the most severe inducement for crystallization of ice from water droplets within the fuel at sub-freezing temperatures. At high flow rates it is expected that more of the ice formed will travel through the pump because it would have less opportunity to accumulate and grow in size. At lower flow rates more ice is expected to accumulate within the pump, particularly on inlet screens. The worst flight condition may occur when a high flow rate is initiated following a sustained low flow rate at sub-freezing conditions. Ice packed on a pump inlet screen may prevent the required fuel flow to an engine.

In general, icing test flow rates and durations for engine feed systems should simulate those expected during a typical flight. Following each test temperature phase, a high flow rate setting is recommended for long enough to evaluate system pressure drop characteristics which may be attributable to icing.

6. TEST METHODS

Three test methods are addressed for (1) continuous system operation, (2) emergency system operation and (3) component operation. Each test includes three test phase temperatures. A system should be subjected to the continuous and emergency system operation tests. The emergency system operation test is a short duration test at each temperature with a higher water content. Individual components are recommended to be tested at a still higher water content because, depending on their function and installation, they may be exposed to more severe icing conditions.

Caution is advised in developing icing test requirements as over testing often leads to invalid failures. The real aircraft operating conditions and environment must be considered. It has, however, become popular with some test operators to combine the continuous system operation and emergency system operation tests at the emergency operation test water concentrations. This practice is reported to be successful, a time saver and establishes a higher level of confidence in system operation in icing conditions.

6.1 Preparation of the Fuel

Proper conditioning of the fuel prior to test should be accomplished to establish a standard baseline so that valid results of the tests can be obtained and compared. A standard to start with is fuel that is saturated with water at 80 °F +10 °F/-0 °F (27 °C +5 °C/-0 °C). To obtain this condition, the specified test fuel should be procured in sufficient quantity for the total fuel capacity required for the test and conditioned as specified herein.

6.1.1 Fuel Preparation for "Continuous System Operation" Test

The following fuel conditioning procedures are recommended for the continuous system operation tests:

a. Using Figure 1 as applicable, place the fuel in the storage tank and begin circulation from the tank through the heat exchanger and back into the storage tank using the circulation pump until the fuel is heated to 80 °F +10 °F/-0 °F (27 °C +5 °C/-0 °C).

b. While maintaining the circulation flow and the required temperature range, add 1 gallon (liter) of water per 1000 gallons (liters) of fuel at a rate of approximately 55 cc per minute. Use a method which produces a uniform distribution of water in the fuel (both spray bar and pump injection methods are indicated on figures).

c. After all the water has been added to the fuel, continue circulation for approximately 30 minutes to help insure complete mixing.

d. Transfer the fuel from the storage tank through the filter/water separator into the test tank. At this point, the fuel should be saturated. Commence step E as soon as practicable after transfer begins.

e. Establish and maintain circulation of the fuel in the test tank using circulation pump. The circulation should be from the tank through a cooling heat exchanger and back into the tank.

f. Analyze three samples from the bulk of the fuel for water content. If the average of the three samples is less than 90 PPM, additional water may be added as in step B for a total water content of 90 PPM.

g. Cool the fuel at the specified rate by circulation through the heat exchanger. To prevent water in the fuel from freezing on the walls of the heat exchanger, the difference in temperature between the fuel in the heat exchanger and the refrigerant should not be allowed to exceed 24 °F (13 °C). Once the test temperature is reached, the water content should be analyzed again.

h. After taking fuel samples for water content analysis, begin the test for "continuous system operation."

6.1.2 Fuel Preparation for "Emergency System Operation" Test

a. Prepare the fuel using the same procedure as for the "continuous system operation" test through step (g) except as follows:

b. During step (g), while the saturated fuel is being circulated in the test tank, add 0.75 cc of water per gallon (0.198 cc of water per liter) of fuel as in step (b). All water should be added before the fuel temperature in the test tank decreases below 45 °F (7 °C). Once the test temperature is reached, the water content should be analyzed again.

c. After taking fuel samples for water content analysis, begin the test for "emergency system operation".

6.1.3 Fuel Preparation for “Component” Testing

a. Prepare the fuel using the same procedure as for the “continuous system operation” test through step (g) except using Figure 2 and as follows:

b. During step (g), while the saturated fuel is being circulated in the test tank, add 2.0 cc of water per gallon (0.53 cc of water per liter) of fuel as in step (b). All water should be added before the fuel temperature in the test tank decreases below 45 °F (7 °C). Once the test temperature is reached, the water content should be analyzed again.

c. After taking fuel samples for water content analysis, begin the test for “component operation”.

6.2 Test Procedure

The fuel system or component should be operated as intended on the aircraft for the expected duration of a typical flight plus in-flight refuelings if applicable. The system or component shall function throughout the test with no deterioration in performance that would result in a flight safety hazard or compromise a mission.

Ideally, the entire test system with the conditioned fuel should be cooled down to the test temperatures together to provide a close simulation to what actually happens in an aircraft. While the tests are running, all surfaces of fuel system components in contact with the fuel should be at or below the test temperatures.

Tests should be conducted at nominal temperatures of 28 °F (-2 °C), at 13 °F (-11 °C) which is approximately the critical icing temperature and at the lowest fuel temperature experienced in flight (or on the ground). Test temperature tolerances should be established by applicable participating activities.

For continuous system and component operation tests the test phase durations should be approximately 25% at 28 °F (-2 °C), 50% at 13 °F (-11 °C), and 25% at the lowest fuel temperature experience in flight or on the ground.

For the emergency system operation test, the duration of the test should be 30 minutes at each test temperature. This test is not necessary if the continuous system operation test is conducted with fuel prepared for the emergency system operation test.