



AEROSPACE RECOMMENDED PRACTICE

ARP1401™**REV. C**

Issued 1979-03
Reaffirmed 2007-12
Revised 2025-06

Superseding ARP1401B

(R) Aircraft Fuel System and Component Icing Test

RATIONALE

This revision is intended to address several industry challenges pertaining to the method of conducting fuel icing tests on fuel systems and fuel components. Some of the revisions pertain to defining the target water content considering variance in fuel types and batches, introduction of the slurry injection approach to deliver the required water content, and an additional test method, "Sustained Operation," that provides guidance to better align testing requirements with current FAA airworthiness certification standards. Additionally, methods for validation of the ice threat, clarity on test method applicability, and extensive organization to improve readability have also been included in this revision.

1. SCOPE

This SAE Aerospace Recommended Practice (ARP) covers a brief discussion of the icing problem in aircraft fuel systems and the different means that have been used to test for icing. Fuel preparation and icing test procedures for aircraft fuel systems and components are proposed herein as a recommended practice to be used for fixed wing and rotary-wing aircraft within their operational environment. This ARP mostly addresses aircraft fuel system level testing and provides a means to address the requirements of FAR 14 CFR § 23.951(c), § 25.951(c), § 27.951(c), and § 29.951(c). In the context of this ARP, the engine and the auxiliary power unit (APU) are not considered to be components of the aircraft fuel system. However, some of the methods described in this document can be applied to the engine, APU, and other aircraft (system or component level) icing tests.

This revision does not completely address new developments in ice accretion and release resulting from internal flow in tubing (see [2.3.6](#)). This will be addressed in a different document when more experimental data is available.

1.1 Purpose

The cold temperatures to which jet aircraft are exposed can have a detrimental effect upon the fuel system and its components by causing water entrained in fuel to form ice, clog filters and screens, or cause component or system malfunction. As a result, fuel flow to engines can be reduced, restricted, or stopped altogether, causing flameouts or loss of power which pose a flight safety hazard. Even though some aircraft normally operate with fuel treated with an anti-icing additive, also known as Fuel System Icing Inhibitor (FSII), fuel without this additive is routinely encountered.

Therefore, this ARP recommends practices for icing tests for aircraft fuel systems and fuel system components which helps avoid expensive overdesign and overtesting while ensuring the reliability of a fuel system in icing conditions.

Three icing test procedures are presented herein. The test paradigm used in this ARP is to create a representative icing threat that would simulate a typical aircraft mission. The aircraft mission and test profile/scenario should be developed to encompass all known icing threats and be agreed with the relevant certification authority. Although written primarily with system tests in mind, [1.1.1](#) through [1.1.3](#) can be applied to individual component testing to verify susceptibility to ice formation during specific aircraft operating conditions.

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1.1.1 Continuous Operation

This procedure is no longer a standalone means of certification for commercial aircraft fuel systems but may be utilized for non-commercial, development, engine, or component testing if applicable to the platform.

1.1.2 Emergency Operation

This procedure is no longer a standalone means of certification for commercial aircraft fuel systems but may be utilized for non-commercial, development, engine, or component testing if applicable to the platform.

1.1.3 Sustained Operation

This method is the primary means for certification of commercial aircraft fuel systems.

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 the 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 +1 724-776-4970 (outside USA), www.sae.org.

2.1.1 AIR790, Considerations on Ice Formation in Aircraft and Engine Fuel Systems

2.2 U.S. Government Publications

Copies of these documents are available online at <https://quicksearch.dla.mil>.

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

2.3 Other Publications

See individual reference publisher for document availability.

2.3.1 Langer, G. (1960). *JP-4 fuel system icing* (WADD Technical Report 60-826). Armour Research Foundation.

2.3.2 American Petroleum Institute. (1965). *The filtration of and water removal from aviation fuels* [API Bulletin].

2.3.3 Smith, M. (1970). *Aviation fuels*. G.T. Foulis and Company Ltd.

2.3.4 Krynitsky, J.A., Crellin, J.W., and Carhart, H.W. (1950). *The behavior of water in jet fuels and the clogging of micron filters at low temperatures* (NRL Report 3604). U.S. Naval Research Laboratory.

2.3.5 Wickwire, R.R. (1961). *Fuel system icing susceptibility test model A3D-2 tanker/receiver* (Report No. 20094). Douglas Aircraft Company, Inc.

2.3.6 United Kingdom Air Accidents Investigation Branch. (2010). *Aircraft Accident Report AAR 1/2010 - Boeing 777-236ER, G-YMMM, 17 January 2008*.

2.3.7 EASA. (2013). *Water in aviation fuel under cold temperature conditions* (EASA Research Project EASA.2010/01).

2.3.8 Coordinating Research Council, Inc. (2014). *Aviation fuel properties handbook, 2014 fourth edition* (CRC Report 663).

3. BRIEF HISTORY

As aircraft were operated at higher altitudes and in colder ambient temperatures, the cooler temperatures had an effect on water-saturated fuel and/or water entrained in the fuel. Valves, pumps, filters, and screens could become clogged with ice, resulting in failure of the aircraft fuel system. One case of failure through fuel icing occurred in 1958 when a large aircraft crashed short of a runway in South Dakota after power was lost on three engines. An inspection of the wreckage indicated that ice was blocking the engine fuel feed system. However, the cause of high water content was not determined. Other failures due to icing in the fuel system have been recorded (see [2.3.1](#) and [2.3.6](#)).

Water can be present in aviation fuels in two basic forms: dissolved or free water. Dissolved water is completely solubilized within the fuel, while free water (i.e., droplets) is that in excess of the solubility limit. Dissolved water is similar to humidity in the atmosphere. The amount of water which a volume of fuel will absorb and hold is dependent on both the temperature and the chemistry of the fuel. At 60 °F (16 °C), this may vary from less than 0.003% to approximately 0.010% by weight (~30 to 100 parts per million by volume [ppmv]), or almost 1 pint per 1000 U.S. gallons. Fuels may be partly or fully saturated with dissolved water. As with air, the higher the temperature of the fuel, the more dissolved water it can contain. Thus, whenever the temperature of a fuel saturated with dissolved water is lowered, some of the dissolved water will become free water.

Free water may be present as entrained droplets or as settled free water. Entrained water is water suspended in the fuel in minute globules (akin to an emulsion). At low concentrations, it may not be perceptible to the naked eye. At higher concentrations, it will cause the fuel to take on a hazy or milky appearance. Commercial aircraft fuel quality procedures require fuel to be “clear and bright” for use to limit free water content. Water may become entrained by the breaking up of water slugs through turbulence in a pump, throttling valve, in high velocity transfer operations, or by the reduction in temperature of a saturated fuel volume (see [2.3.2](#) and [2.3.3](#)). Condensation of moisture in the tank atmosphere due to low tank structure temperatures will result in water droplets that will settle rapidly on structures (ice formation) or along the tank bottom.

Though fuel filtration requirements limit the total water content during fueling, usually some small amount of free water remains. Once on board the aircraft, the primary process for additional water introduction is via fuel tank venting. Fuel systems draw outside air into the fuel tanks through their vents as fuel is consumed and as the aircraft descends in altitude. The fuel on board may absorb some of this moisture, depending on the saturation level of the fuel for its given temperature. If maintenance is performed, some water, which is free, might be drained from the tank sumps or separated from the fuel through a filter and then drained prior to flight; however, even if free water is drained, some water remains in solution in the fuel. This water, plus excess water which cannot be drained off, as well as that collected in flight, can pose a serious threat to proper functioning of fuel system components (see [2.3.1](#) and [2.3.4](#)). This situation is further aggravated as an aircraft climbs higher, cold soaks, and then descends to a lower altitude. Fuel tank vents expel fuel tank ullage vapors during climbs, then draw in outside ambient air during descents. Warm, moist air drawn in during a descent condenses when it comes in contact with the cold soaked tank and fuel, hence raising the water content.

As ice forms within the fuel system, it may accumulate in certain places such as the tank bottom near a pump inlet. Therefore, a slush of ice and fuel may begin to build up. The turbulence produced by the action of the pump is considered to be the most severe inducement for the crystallization of ice from the water droplets within the fuel at subfreezing temperatures (see [2.3.1](#) and [2.3.4](#)). Under high fuel flows, it is expected that the ice formed will travel through the pump because it would not have an opportunity to accumulate and grow in size. At lower fuel flows, only a portion of the ice formed will travel through the pump with most of the ice accumulating about the pump or on its inlet or inlet screen. Additionally, with low velocity, ice accretion on interior surfaces, such as tube walls, increases. The worst flight condition may occur when after sustained low fuel flows under subfreezing conditions, a demand is made for high fuel flow. The slush formed during the low fuel flow could reduce or preclude flow. The pump and the rest of the system should function with no deterioration in performance that would result in a flight safety hazard or seriously compromising the mission.

Early solutions to the icing problem, many of which are still used, included enlarged screens, added bypass valves, and lower filter densities. Engine bleed air was used to heat the fuel near the engine but did not affect the fuel before reaching the engine area. Anti-icing additives (FSII) were developed for aircraft without fuel heaters. Commercial fuels, such as ASTM D1655 and D6615, deem the inclusion of an anti-icing additive as optional and not mandatory. As such, most modern commercial aircraft are designed, approved, and operated without the need for the additive. Therefore, icing tests for commercial certification purposes shall be undertaken without the additive unless the aircraft type certificate mandates that an anti-icing additive must be used. Military fuels such as MIL-PRF-5624 and MIL-PRF-83133 require the inclusion of an anti-icing additive. In specific conditions, e.g., military customers, the approved fuel types may be such that an anti-icing additive will always be present. In these circumstances, icing tests may be performed with the additive. When the additive is used, the concentration should be recorded.

The origin of the three icing test procedures within this document are detailed below:

3.1 Continuous Operation

Continuous Operation testing can be traced back to at least MIL-F-17874A, issued in February 1960. The latest revision of this document, B, was reaffirmed in 2019. The objective of the testing is to ensure satisfactory winter operation. This is achieved through demonstrating satisfactory operation for one design mission plus one in-flight refueling with fuel initially saturated at 80 °F and cooled to the most critical icing condition. In practice, at least three tests are undertaken. One at a fuel temperature of 28 °F, one at 15 °F, and one at the lowest fuel temperature experienced during flight. When running these tests, “the conditions of the apparatus should be such that ice from previous tests is not destroyed between test runs” (refer to para 4.17 of MIL-F-17874A). Note, the take-off and climb segments are typically rolled into one given their relatively short durations when compared to the cruise portion of a typical mission. Para 4.17 also states, “The most critical temperature from the icing standpoint occurs at about 15 °F according to the best information to date.” When this critical temperature was changed to the current 13 °F is currently unknown.

3.2 Emergency Operation

Emergency Operation testing can be traced back to at least MIL-F-17874A, issued in February 1960. The latest revision of this document, B, was reaffirmed in 2019. The objective of the testing is to ensure that “the aircraft and engine fuel system shall continue to operate in such manner that the safety of flight of the aircraft is not jeopardized” when operated with fuel fully saturated at 80 °F plus 0.75 cc/gal of free water and cooled to the most critical icing condition. This objective is achieved through demonstrating that the engine can maintain at least minimum flight power for 30 minutes at three different fuel temperatures (28 °F, 15 °F, and the lowest fuel temperature experienced during flight). When running the tests, “the conditions of the apparatus should be such that ice from previous tests is not destroyed between test runs” (refer to para 4.17 of MIL-F-17874A). Para 4.17 also states, “The most critical temperature from the icing standpoint occurs at about 15 °F according to the best information to date.” When this critical temperature was changed to the current 13 °F is currently unknown.

3.3 Sustained Operation

The Sustained Operation test procedure is designed to support turbine powered civil aircraft certification steady state icing resistance requirements of FAR 23.951(c), FAR 25.951 (c), FAR 27.951 (c), and FAR 29.951 (c), introduced in October 1974 through amendments 23-15, 25-36, 27-9, and 29-10, respectively. These requirements are intended to demonstrate uninterrupted functioning of the fuel system rather than require demonstrating operation for an indefinite time (refer to FAR 25 amendment preamble). The requirements state that “Each fuel system for a turbine powered engine must be capable of sustained operation throughout its flow and pressure range with fuel initially saturated with water at 80 °F and having 0.75 cc of free water per gallon and cooled to the most critical condition for icing likely to be encountered in operation.” Testing should be designed to ensure the fuel system functions properly under all probable operating conditions. Typically, tests are undertaken at fuel temperatures of 28 °F, 13 °F, and the minimum temperature as declared on the aircraft type certificate. The test profiles and durations to demonstrate “sustained operation” shall be established by the type certificate holder with agreement from the certification authority.

4. TEST STANDARDIZATION

Historically, fuel icing tests can vary so greatly that it is difficult and sometimes impossible to accurately compare results from one test to another and to assess which process more appropriately represents the aircraft environment. Many reports and specifications have widely varying test temperatures and test durations or no clear statement of duration. Most reports show no schedule of temperature decrease. Fuel conditioning was accomplished by similar but still varying means. Therefore, a standardized icing test aids to eliminate or minimize this problem and give both manufacturer and customer more confidence in component and system integrity.

The specific type of ice, particle size, and accretion rate are partly dependent on the conditioning system. As stated, the interest lies in the macroscopic effect of possible ice formed in the aircraft fuel system or components through a standardized test procedure. Research of available information of actual and experimental system tests supports the procedures for aircraft system icing tests required in MIL-F-17874B (see [2.2.1](#)) as being the most concise procedures to date. These procedures and past test experience form the basis of the recommended tests within this ARP.

5. WATER TO ICE EVOLUTION

Several things happen to moisture laden fuel as the temperature is lowered. An understanding of this helps to arrive at proper fuel conditioning procedures and subsequent testing for icing conditions. For a fuel sample saturated with water at any temperature, water will come out of solution as the temperature of the sample is lowered. The concentration of water droplets in the fuel begins to decrease when the fuel sample reaches temperatures in the vicinity of 40 to 50 °F (4 to 10 °C). As the fuel temperature drops, ice crystals will begin to form at slightly below the freezing point of water (27 to 31 °F/-3 to -1 °C), due to impurities in the water. As the temperature is lowered further, the water becomes supercooled and easily adheres to its surroundings or other freezing nuclei similar to the Bergeron process (see [2.3.7](#)). At temperatures below 0 °F (-18 °C), ice crystals tend to become larger and offer a threat to plugging small openings such as screens, filter, and orifices (see [2.3.1](#) and [2.3.3](#)). Below -5 °F (-20 °C), most of the supercooled water has frozen, and so significant ice accretion is not observed below this temperature. The density of the ice is approximately the same as the fuel medium. Consequently, the ice will generally stay in suspension and drift within the fuel. As stated before, several references mention that the critical temperature is the point at which ice has the highest potential for obstructive accumulation.

The cooling rate and agitation or turbulence due to obstruction of flow have an effect on the type and size of ice formed. Consequently, it is desired to have a close representation of the actual aircraft when designing a test setup. If possible, target cooling the fuel during tests at a typical aircraft cooling rate to obtain more accurate results.

6. RECOMMENDATIONS

6.1 Test Method

Fuel icing testing can be performed using two different approaches based on the facility fuel tank volume and test requirements: single-pass or multi-pass testing. Alongside these approaches, water addition can also be performed via two methods: prior to fuel cooling in accordance with [6.4](#) and [6.5](#) or as a controlled water injection according to [6.6](#), also referred to as "slurry injection." Single-pass testing is the recommended but not a mandatory method (see [8.2](#) regarding tank sizing). All of these test method combinations are for conditioning fuel and performing system and component icing tests. Whichever test setup is used, low points and quiescent areas where water can settle must be avoided. In addition, the fuel tanks should have minimum venting to atmosphere to avoid changes in fuel water content. Prevention of water accumulation and settling in the conditioning system is critical to ensure that the required water content is transferred to the test article during testing.

[Figures 1](#) through [3](#) depict basic representations of a fuel icing test setup and are in no way complete or mandatory. Variations to these figures are acceptable as long as the test process as described can be accomplished with adequate validation of water content delivery.

6.1.1 Single-Pass Method

The intent of single-pass testing is to condition a main fuel supply tank (conditioning tank) with water and flow for the entire duration of the test, discarding the fuel into a “dump” tank. [Figures 1](#) and [3](#) depict rig setups for conducting single-pass testing. This method can greatly simplify controls, fuel management (water content and temperature), and post-test water validation.

6.1.2 Multi-Pass Method

[Figure 2](#) depicts an alternate test setup which allows for multi-pass, a “recirculation” approach. Utilizing this method follows the same fuel preparation guidelines per [6.4](#) or [6.5](#) with exceptions as noted in [8.2](#). Once prepared for test, the fuel passes through the test article and then returns to the conditioning tank. Additional water may be injected during test to maintain water content. This setup is preferred when it is not practical to use a single-pass method given the amount of fuel that would be required to perform such a test. Recirculation often can create challenges with managing water content levels and fuel temperature during a test mission, especially if the test article imparts significant heat into the fuel.

6.1.3 Slurry Injection Method

[Figure 3](#) depicts an example of a single-pass method with controlled water injection per [6.6](#), commonly referred to as slurry injection. The slurry is a mixture of fuel and water within the slurry tank. The slurry tank is a heavily agitated tank where water is introduced into fuel via an atomization nozzle to promote water droplet suspension. To this point, the slurry tank is similar to the conditioning tank from the other test methods. However, the size of the slurry tank is generally small, while the water concentration is proportionally higher. The slurry tank is maintained at temperatures above 32 °F (0 °C) to prevent ice formation. The slurry is injected into the flow stream generated by the main conditioning tank that is flowing through the test article. The rate of the injection depends on the water concentration requirements, slurry tank size, and flow profile.

Using this method, the fuel in the conditioning tank is dry (at or below water saturation level) and then cooled to the target test temperatures with no additional water added. This alleviates the majority of challenges sustaining water content (ice) in a large system while below freezing temperatures for extended periods of time. Once at the desired fuel temperature, flow from the conditioning tank can be circulated through the test article to reach temperature stabilization. This flow poses little risk to the test article because the fuel is dry. When operators are ready, the icing test will begin upon initiating the slurry injection mixing with the cold fuel from the conditioning tank. The slurry system uses a controlled flow regulation to ensure the target water concentration is achieved upstream of the test article. The concentration is then verified by performing modified Karl Fischer titrations on fuel samples taken upstream of the test article at regular intervals.

Note that the slurry injection is generally proportional to the flow through the test article. This requires modulation in slurry flow if the flow profile through the test changes. For instance, transitioning from an “Idle” flow to a “Take Off” flow generally requires a proportional change in slurry flow. It is normally acceptable for the slurry flow to deviate from the target concentration for short periods of time while changes in flow occur so long as the total delivered water content meets or exceeds the requirement over the test period.

This injection system provides flexibility in controlling the water content and often permits variable control during a test to support changing flow conditions. This also can apply to multi-pass testing where the conditioning tank may increase in water concentration over time. Slurry injection can be used in single-pass or multi-pass configuration or included as an aid to control water content during tests preparing fuel in accordance with [6.4](#) or [6.5](#). Slurry injection can be used to control water concentration during all portions of a test.

The test setup must validate that the slurry mixture turns to ice and the total fuel flow achieves the target fuel temperature prior to reaching the test article. When slurry is introduced to cold fuel, the mixture temperature will increase. This resultant temperature must still achieve the targeted test parameters. The transition from water to ice can be validated by installing a temporary strainer or filter that will pass water but catch ice and can be visually inspected. Other means of validation may be approved by certification authorities.

Slurry injection has been utilized for component and engine testing extensively. However, for airframe fuel system testing, the slurry injection method is relatively novel in comparison to the legacy method of mixing the water and fuel prior to chilling. Therefore, it is recommended that the test facility provides evidence to validate that their test setup produces a fuel/water mixture that is equivalent to a fuel/water mixture that would be produced by the legacy mixing process. Agreement with the certifying authority would be required.

6.2 Ambient and Surface Temperatures

The ambient temperature surrounding the test article may play a significant role in ice accretion, defrosting, and performance under fuel icing conditions. Therefore, careful consideration of ambient temperatures must be taken. Ideally, the ambient temperature should be controlled to provide a relevant simulation to what actually happens in an aircraft. Commonly, different fuel system components and tubing segments experience different ambient temperatures during flight based on which compartment they are within. These ambient conditions may be controlled individually to best recreate flight conditions. Alternatively, the entire system can be chilled to a single temperature. When managing temperatures around large systems, care must be taken to encourage consistent and homogenous ambient air temperatures. However, some test units may be located within a “hot” zone, or impervious to cold ambient air. In these cases, no ambient control or just insulation around the components may be satisfactory.

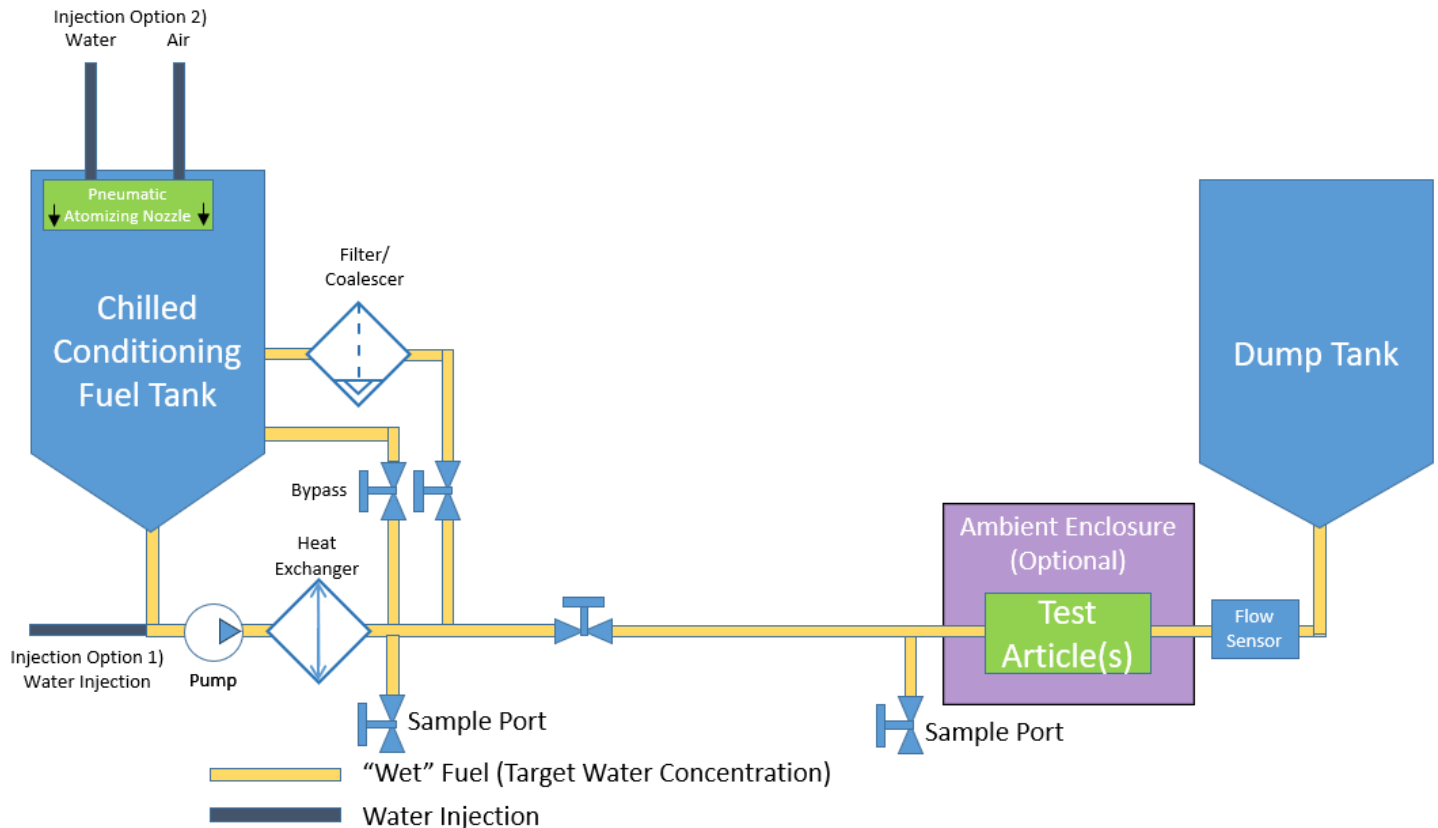


Figure 1 - Example single-pass setup with pneumatic atomizing nozzle

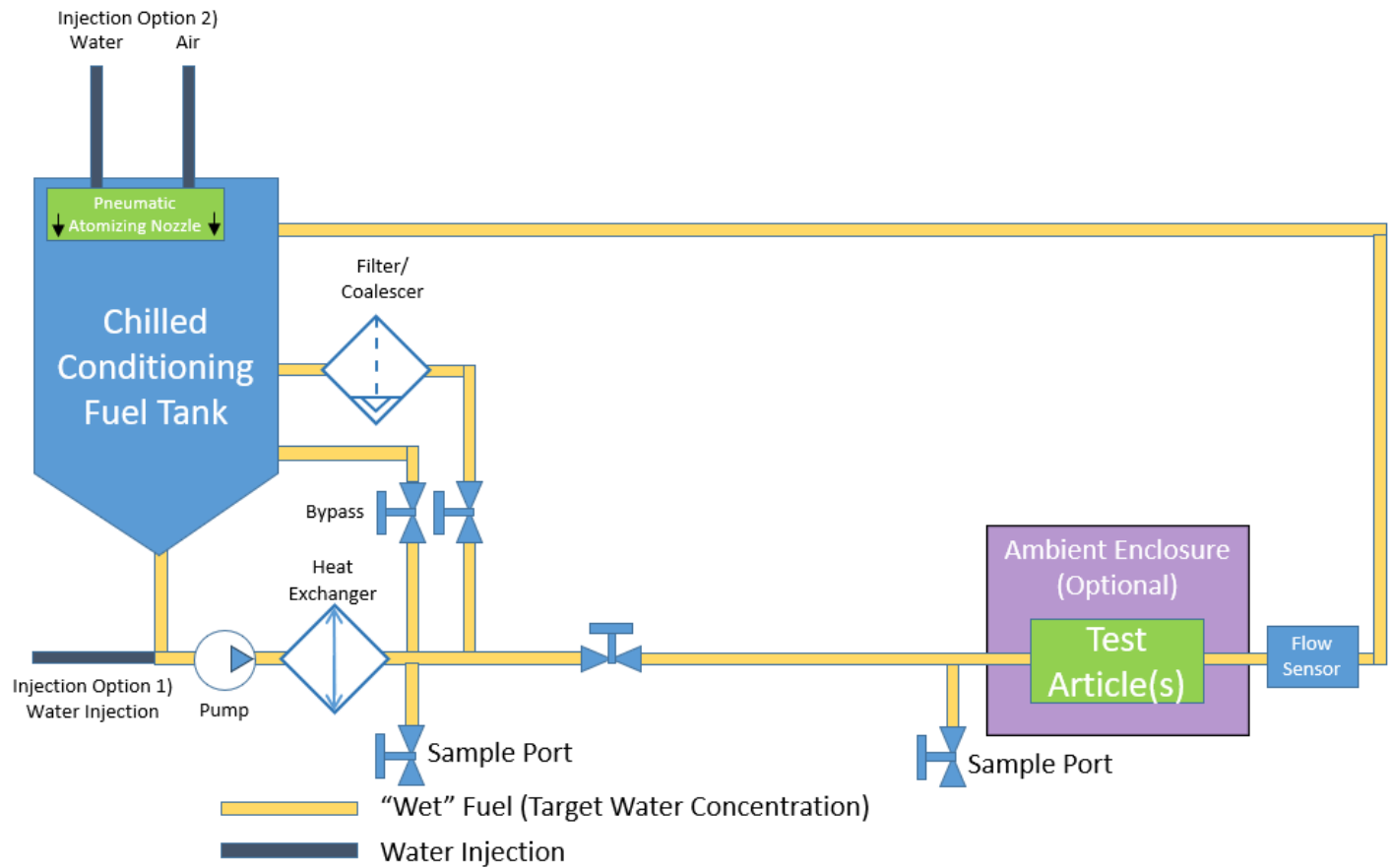


Figure 2 - Example multi-pass setup with pneumatic atomizing nozzle