A PROPOSED ROUND ROBIN TEST PLAN TO EVALUATE CERTIFICATION TEST CONDITIONS FOR AIRCRAFT FUEL SYSTEM PIPE COUPLINGS

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ABSTRACT

There has been increasing interest in the prevention of ignition sources within fuel tanks due to lightning currents induced in fuel and vent tubes and other conducting objects within fuel tanks. The SAE fuel system committee, SAE G-3A (Aerospace Couplings, Fittings, Hose & Tubing Assemblies) has drafted a proposed environmental test standard [i] for fuel tube couplers that includes conduction of typical lightning currents through fuel tube couplings to verify that no arcing occurs that could ignite flammable fuel vapors. This paper describes a plan of exploratory tests to determine the conditions under which flames will and will not propagate to the ends of pipes attached to coupling specimens of various sizes. An initial series of tests will be conducted by igniting a hydrogen gas mixture with a small spark at the interior of tube specimens of various diameters to determine the conditions that let the flame appear at the open end of the pipe. A second group of tests will be conducted on couplings attached to short tube ends and arranged to produce an arc that is exposed to the interior of the coupling when typical currents are conducted through the coupling. Such an arc would have a higher energy dissipation than the 0.2 mJ spark often used to verify ignition sensitivity of flammable gasses, but most electrical arcs that might occur at fuel tube couplings would be significantly hotter, and more incendiary, than the standard 0.2 mJ spark. Several test laboratories are expected to conduct the same tests on identical couplings. If these "round robin" results are consistent, the results will be used to finalize the fuel tube coupling lightning test standard.

ACRONYMS AND SYMBOLS

AS	Aerospace Standard
SAE	Society of Automotive Engineers Inc.
EUROCAE	European Organization for Civil Aircraft Equipment
A	current (amperes)
C	capacitance (farads, or microfarads)
D	distance (m, cm)
I	current (amperes)
J	energy (joules)
mJ	millijoules (10^{-3} Joules)
mm	distance, millimeters (10^{-3} m)
US	United States of America
μF	capacitance (10^{-6} farads)
t	time (seconds)
μs	time (microseconds)
V	voltage (volts)
kV	Kilovolts (10^{-3} volts)

BACKGROUND

Fuel tube couplings are usually tested for ability to conduct small amounts of lightning currents without producing arcs or sparks that can ignite flammable fuel vapors. The most recent standard for these tests is included in the newly published aircraft lightning test standard [ii]. In this standard, fuel tube couplers are tested within a chamber filled with a flammable gas, so that if an incendiary electric arc or spark occurs at the coupling, it may be identified by the ignition of the chamber gas. This method of detecting ignition sources has long been used in fuel system lightning certification tests. Formerly, mixtures of hydrocarbon gasses such as propane and hexane with air have been used as the flammable gas. On occasion, evaporated aircraft fuel vapors have also been used. These gasses, however, do not ignite reliably at the 0.2 mJ spark energies commonly thought to be capable of igniting stoichiometric combinations of hydrocarbon vapors and air. Also, when these gasses do ignite, the resulting overpressures can damage test chambers. Recently, the hydrocarbon gasses have been replaced by a mixture of hydrogen, oxygen and argon, a combination that ignites reliably at 0.2 mJ and does not produce damaging overpressures [iii]. The hydrogen flames, however, can be quenched by the presence of cool surfaces such as metal fuel tank and tube walls. The possibility exists that a flame may be ignited by an arc on the interior of a coupling and be quenched before reaching the open end(s) of the coupled tube specimen and, therefore, not be detected by ignition of the gas surrounding the specimen in the test chamber.

OBJECTIVE

The primary objective of the tests described herein is to establish the diameter and length limitations of the tube ends that can be used to test fuel tube couplings for ability to conduct lightning currents without igniting flammable fuel vapors. A secondary objective is to verify that the test can be applied at different laboratories with the same test results.

Of particular concern is whether tubes of small diameters will allow for the propagation of a flame front sufficient to ensure that an ignition source at the failure will be detected. SAE committee AE-2 and EUROCAE WG 31 have taken on the task to perform some experiments within various labs to ensure that the test article arrangement and lightning test method being proposed is technically feasible as well as repeatable at different laboratories.

It is expected that this “Round Robin” program will include performance of the same set of tests on similar coupling and tube specimens by up to four (4) participating laboratories, in the US and Europe, and the tests have been termed the *“Fuel Coupling Round Robin Tests”*. This is similar to previous round robin test programs that were sponsored by the SAE and EUROCAE lightning committees to develop improved methods for high voltage strike attachment testing of radomes [iv] and high current physical damage testing of aircraft skin specimens [v].

PROPOSED COUPLING LIGHTNING TEST METHOD BY SAE G-3A

SAE G-3A has proposed a standard [i] that defines requirements for a threadless, flexible, conductive, self-bonding coupling assembly which, when installed on fixed cavity ferrules, provides a flexible current carrying connection for joining tubing and components in aircraft fuel, vent or other systems. The assembled coupling is referred to as the assembly.

This proposed standard is a departure from prior qualification practices [vi]. Prior practice sought to validate the coupling design by a sequence of tests conducted to a set of coupling assemblies. There were multiple test sequences and a different set of coupling assemblies were tested with each sequence. Each of these test sequences challenged a particular design feature of the coupling. No single coupling was expected to survive all the required tests.

FAA regulations [vii, viii] together with the increasing use of carbon fiber reinforced composites (CFC) in fuel tank construction have established the need for a fuel tube coupling capable of safely conducting amounts of lightning current that may appear in fuel tubes. A coupling that required frequent inspection and maintenance to remain lightning capable for the life of the aircraft would be of little value.

The proposed lightning test is intended to insure that the coupling assemblies can withstand the predicted lightning transients over their service life without the creation of an ignition source under lightning strike conditions.

To ensure that a coupling is lightning capable for the life of the aircraft, it becomes important to simulate the wear that the coupling would encounter on the aircraft. The new standard proposed by G-3A simulates a worse-case wear situation for the installed coupling.

Briefly, the standard proposed by G-3A requires testing of eight coupling assemblies with end tube assemblies, tube end caps or plugs, coupling assemblies or similar retaining device and necessary clamp assemblies for each tube size, material and current level being tested. Four of the test specimens would be tested un-conditioned and four units tested after being conditioned by other test conditions described in the standard. Other features of the G-3A proposal are:

- For lightning tests, photography and flammable gas mixture shall be used with any ignition of the gas mixture being a failure and any light evident on the photos requiring a re-test of an additional four units. If the additional four units do not ignite yet still have light evidence, the units have passed

- Test experience has shown that hydrogen flames will propagate through aluminum tubes of greater than one inch (25 mm) in diameter, though this has not been demonstrated rigorously and documented. For metal tubes of diameters less than 1 inch (25 mm), the ability of the hydrogen flames to propagate after ignition and ignite the full chamber must be proven.

- The use of a common fixture for all testing (environmental, vibration, lightning etc.) is desired if the fixture allows for the tube ends to be un-constricted (i.e. no end plug) and fully exposed to the flammable gas.

- Lightning tests shall be performed per Section 7.3.3 of SAE ARP5416/EUROCAE ED-105 [ii]. The manufacturer's test setup shall be similar to Figures 1 and 2 with two coupling assemblies installed between two tube ends.

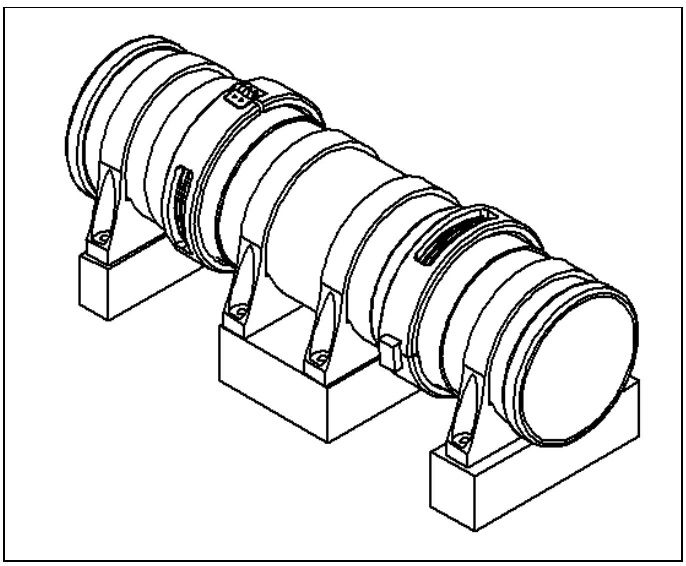

Figure 1. Lightning Test Setup Isometric

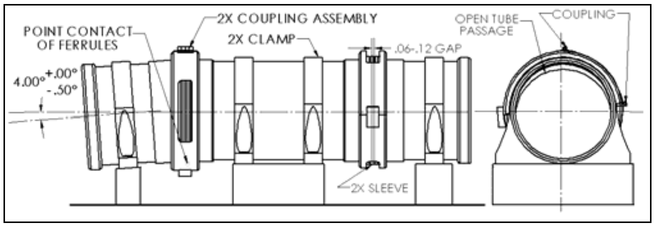

Figure 2. Lightning Test Setup Side View

- The first lightning test shall be with new manufactured specimens and shall have two specimens providing point contact between the tube ferrule flanges with a 3.5º to 4º angular offset of the ferrule flanges, and two specimens shall have a gap of 0.06 inch (1.5 mm) to 0.12 inch (3 mm) between the ferrules. The coupling assemblies and tube assemblies shall be supported in the test setup of Figures 1 and 2.

- The final lightning test shall test the remaining four specimens not tested in the first test and at least two of the specimens tested in the first test. Of the four not tested in the first test, two will provide point contact with a 3.5º to 4º angular offset and two will have a 0.06 inch (1.5 mm) to 0.12 inch (3 mm) between the ferrules. Of the two specimens tested in the first test, one will provide point contact with a 3.5º to 4º angular offset and will have a 0.06 inch (1.5 mm) to 0.12 inch (3 mm) between the ferrules. The second test shall have the same set-up requirements as the first.

- Lightning testing shall be performed in a chamber using an ignitable fuel mixture per [iii] to verify that no ignition sources are present. For this, it is necessary to insure that the ignitable fuel mixture is present inside the tube as well as in the test chamber, and that flames ignited within the tube can propagate to the tube ends and ignite the rest of the flammable gas in the chamber.

- Each specimen will be subjected to three lightning pulses in each polarity (a total of six pulses). After each lightning pulse, the tubes will be manipulated to break any weld points that may have occurred (and to simulate the effects of vibration).

- The pass criteria for each test specimen shall be no damage that compromises the functional capabilities of the coupling, and no ignition of the flammable gas. If no ignition has occurred due to the test, the gas shall be ignited by a Standard Voltage Spark Ignition Source (SVSIS) which produces a 0.2 mJ spark. If the gas fails to ignite when subjected to the SVSIS spark, the test is deemed inconclusive and the test specimen will have to be re-tested.

ROUND ROBIN TESTS

Two tests are proposed.

The first test is called the **tube test**, and a simple simulation of an ignition source of typical energy within a tube. This will provide an initial characterization of flame behavior within thin tubes in response to a standard ignition source.

The second test, called the **coupling test** is of a typical non-lightning rated coupling assembly arranged to produce an expected electric arc at point contacts at the interior of the coupling interface.

The tube test is to be done by placing an insulated wire with insulation 0.04 inch (1 mm) thick into the center of the tested tube that is placed within a chamber filled with flammable gas, so that a spark can jump from the end of the wire to the interior surface of the tube. The arrangement is illustrated in Figure 3. The tube is placed within a gas filled test chamber, so that ignition of the chamber gas can indicate that a flame propagated to the end(s) of the pipe.

Other arrangements for the gas filled chamber are to be as described in Section 7.7.2 of SAE ARP 5416/EUROCAE ED-105 [iii].

Flammable gas. A hydrogen/oxygen/argon mixture (5% Hydrogen, 12% Oxygen and 83% Argon) is the preferred gas for the ignitable mixture testing. This mixture has demonstrated greater than 90% probability of ignition when exposed to a 0.2 mJ voltage spark. Procedures for setting this gas mixture and verifying the ignition sensitivity of this gas are given in Section 7.7.2 of SAE ARP 5416/EUROCAE ED-105 [iii]. Variations in the gas mixture may be tried, as well, if difficulties are found in propagating the flames to the ends of the tube specimens.

Ignition source. The ignition source for the first test should be a spark produced by a 0.1 µF energy storage capacitor chargeable to 10 kV. At 10 kV, this will produce a 0.5 J spark. This is higher energy than the 0.2 mJ spark that is acknowledged to be the minimum spark energy necessary to ignite hydrocarbon fuel vapors, but more like the energy associated with an electric arc that might occur at point contacts within a tube coupling.

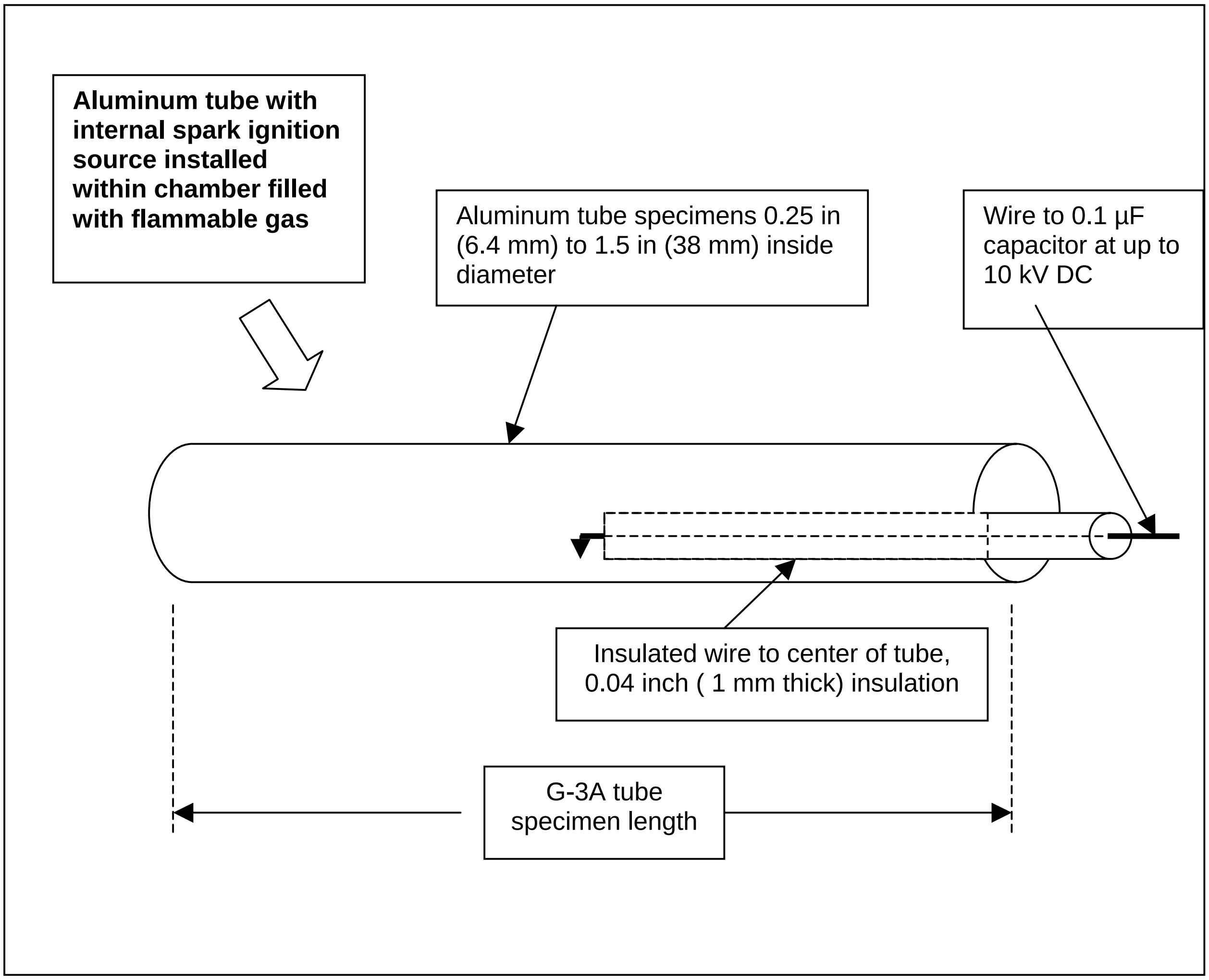

Figure 3. Arrangement of spark source within tested tube

Tube Dimensions. The standard proposed by SAE G-3A describes tube ends in Figure 1 of 4 inches (100 mm) long as shown in Figure 4. If two couplings are tested in series, a center tube 7.43 inches (190 mm) long is to be inserted between the two couplings. Thus, the total length of the center tube and both tube ends is 15.43 inches (390 mm). It would be advantageous, though not mandatory, to demonstrate that a flame ignited at only one coupling could propagate past the other coupling to the opposite tube end, a distance of 7.43 + 4 inches = 11.43 inches (290 mm).

The tube diameters included in the proposed G-3A standard are listed in Table 1.

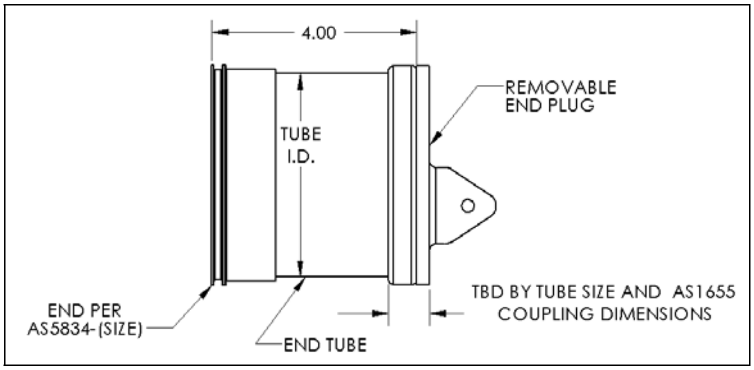

Figure 4. Tube end. End plugs will not be included in test [i]

Table 1. Standard tube diameters and wall thicknesses [i]

Coupling Dash Size (Ref)	Tube Size Inches (Ref)	Tube Wall Thickness /1/
-08	0.500	0.028
-10	0.625	0.028
-12	0.750	0.028
-16	1.000	0.028
-20	1.250	0.035
-24	1.500	0.035
-28	1.750	0.035
-32	2.000	0.035
-36	2.250	0.042
-40	2.500	0.042
-48	3.000	0.042
-56	3.500	0.049
-64	4.000	0.049
-72	4.500	

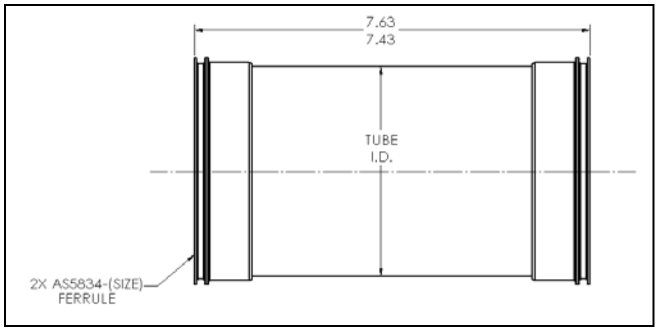

Figure 5. Center tube [i]

Experience has shown that flames ignited at the interiors of couplings on tubes of 1 inch (25 mm) or larger diameter will propagate out of the tube ends and ignite the chamber gas. Thus, from Table 1, tubes of 1 inch and smaller diameters should be tested, although the proposed G-3A standard addresses tubes down to 0.5 inch (23 mm) diameter. Whereas tubes of smaller diameters are sometimes found in aircraft fuel tanks, they are rarely used for fuel vent applications (where the interiors would contain vapors and not liquid fuel). Thus, the tube sizes shown in Table 2 are recommended for these round robin tests.

Table 2. Tubes for test

Coupling Dash Size	Tube Size Inches	Tube Wall Thickness
-08	0.500	0.028
-12	0.750	0.028
-16	1.000	0.028
-20	1.250	0.035
-24	1.500	0.035

The length of all tube specimens can be 15.43 inches (390 mm) so that by positioning the wire at 4 inches (100 mm) and again at 7.43 inches (190 mm) from an open tube end, both of the ignition conditions described above can be evaluated in the same specimen. It is not expected that tube wall thickness will influence the round robin test results, however, it is advisable to use the thicknesses listed in Table 2 since they are standard thicknesses, and most likely to be available.

Other items. The tests should be conducted under laboratory ambient atmospheric conditions similar to the conditions in which the couplings will be tested in accordance with the G-3A proposed standard.

Tube test procedures. Tests should begin with the largest diameter tube specimen listed in Table 2, and continued with tests of smaller diameter tubes until it is no longer possible for flames ignited inside the tube to ignite the chamber gas.

The standard proposed by G-3A calls for three tests to be applied to each coupling specimen with test current in each direction for a total of six tests. Thus, it is necessary that ignition sources inside the tubes produce flames that will reach the chamber gas in six out of six ignitions.

The round robin tests should demonstrate this result by applying six sparks within each of the tested tubes. No tube current, of course, is needed for these tube tests.

The procedures for preparing the chamber and flammable gas are to be as described in Section 7.7.2 of SAE ARP5416/EUROCAE ED-105 [iii] and will not be repeated here.

The tests should begin with the wire end 4 inches (100 mm) from an open end of the tube. An effort should be made to have the interior end of the wire insulation in contact with the tube, so that there will be a ~1 mm gap between the copper wire and the tube surface.

The tests will be conducted by raising the voltage on the energy storage capacitor until a spark is formed between the end of the wire and the internal surface of the tube. If the wire insulation is touching the tube interior surface, the insulation will spark at about 5 kV. If the wire is not touching the tube surface, higher voltage will be required. The voltages at which sparks occur should be recorded.

Note that no effort should be spent attempting to create a 0.2 mJ spark inside the tube. This would be a formidable task given the influence of stray capacitance and spark length on this standard.

If all of the 4-inch (100 mm) tests have been completed successfully, the test series should be repeated with the wire end 7.43 inches (190 mm) from one end of the tube.

The coupling tests are similar to the tube tests, but provide a more realistic ignition source, this being an electric **arc** (sometimes called a 'thermal spark') instead of a **spark** (sometimes called a 'voltage spark'). Arcs are produced by current across inadequate electrode contacts, whereas sparks are produced by voltages that ionize air between electrodes not in contact. Since the standard proposed by SAE G-3A applies to couplings that have greater potential for arcs than for sparks, it is important to try the proposed coupling tests with more realistic ignition sources.

Since couplings may also produce arcs at exterior surfaces, round robin tests only of tubes with couplings would probably be inconclusive.

The major difference between the tube tests and the coupling tests is that the ignition sources are to be produced in non-lightning rated couplings by injection of current through the coupling. A wire to the interior of the specimen with voltage applied will not be used.

Other aspects of the tests are the same as for the tube tests. Further details are as follows:

Test specimens: Type AS1650 couplers [vi] that do not have internal electrical bonding provisions or lightning current carrying capability ratings should be tested. The arrangement of Figure 2b of the proposed SAE G-3A standard [i], wherein two couplings are tested in series, in the same center and end tubes should not be used since this will produce confusing results. Instead, a single coupling between two
11.43 inch (290 mm) tube ends should be tested. This arrangement is as shown in Figure 6. The tube ends are supported by one or two clamps made of non-conducting material, as necessary, to position the tube ends and coupling to obtain the desired point contact of the ferrules.

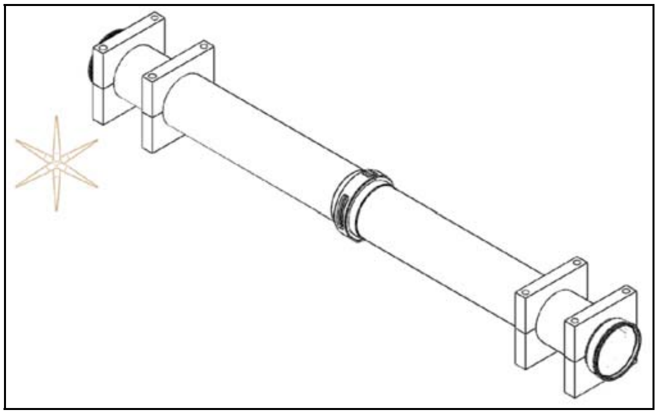

Figure 6. Coupling test arrangement
(This is the same arrangement as for Sinusoidal Resonance Survey and Dwell Vibration tests in [i])

Couplings commensurate with the tube sizes in Table 2 should be tested. Only one coupling in one set of tube ends need be tested, unless the tests produce welding or other damage that prevents internal arcing. As recommended in the standard proposed by SAEG-3A [i], the tube ends should be positioned 3.5 degrees apart, as necessary to produce a point contact between ferrules on the interior of the coupling.

Test current: The test current should have the waveform of Current Component B as defined in SAE ARP 5412/EUROCAE ED-84 [ix] as recommended in the proposed standard [i] and Section 7.3.3 of SAE ARP5416 [ii]. This waveform is typical of lightning currents that re-distribute to metal conductors within both metal and CFC fuel tanks.

The Current Component B waveform also represents the longer duration components of the external lightning environment that couple most efficiently to conductors inside of fuel tanks and other aircraft structures without apertures through which external magnetic fields may penetrate. The Current Component B waveform is shown in Figure 7.

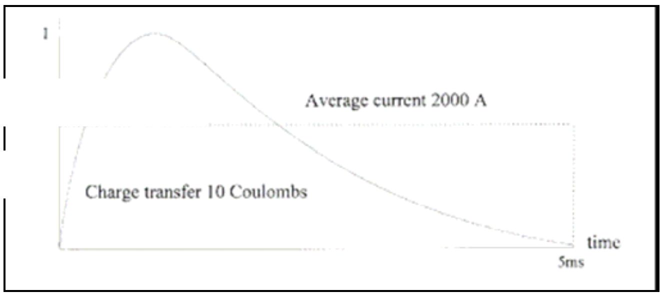

Figure 7. Current Component B Waveform [ix]

From experience, it has been shown that current amplitudes of 500 A have produced internal arcing capable of reliably igniting flammable gasses within the tubes.

Currents in fuel tubes have been reported [x] to range between 10s and 100s of amperes in most installations. Some tubes that are installed within fuel tanks made of CFC, or attached to pumps installed in exterior skins within lightning strike zones, have experienced 1000s of amperes of current.

Photography: The Hydrogen gas does not emit visible light during the burn which allows the simultaneous use of photography and flammable gas to detect arc or spark ignition sources. For the coupling tests, it is recommended that photography be used together with the hydrogen gas mixture so that arc or spark ignition sources on the exterior of the coupling specimen can be detected. Flames ignited by exterior ignition sources should be recorded, but these do not contribute to the desired test results. If ignition sources appear on the exterior of the coupling, the coupling should be rearranged to eliminate those sources. Only ignitions originating inside the tube are to be counted for this round robin test series.

Ability of flames, once ignited, to propagate through tubes is not related closely to the energy dissipated by the ignition source. An exception to this is when there are several, simultaneously-occurring ignition sources within the same tube, in which event flames may quickly become explosions and propagate with sonic velocities. This is why only one coupling should be included in the tube test specimen shown in Figure 6.

A successful test result is one in which the ignition within the tube has ignited the chamber gas.

The six tests described above should be applied to each tube and coupling diameter specimen listed in Table 2 until flames ignited inside the tube no longer ignite the chamber gas. Six tests are proposed since that is the number included in the standard proposed by SAE G-3A. In that proposal, three tests are to be applied with the test current ‘positive’ (i.e. in one direction), and the other three tests are to be applied with ‘negative’ (i.e. the current in the other direction). Since the possible contacting surfaces within the coupling are the same on both sides, the direction of current should have no influence on test results. Thus, the plan to apply six tests is simply to remain numerically consistent with the G-3A proposal.

Documentation: The round robin reports should provide details of all test specimens, test conditions and test results in sufficient detail that they can be combined with results of tests at other laboratories for presentation to the EUROCAE and SAE lightning committees who will review the results and provide recommendations to the SAE G-3A committee for inclusion in the final lightning capable coupling standard.

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