Intrinsically Safe Current Limit Study for Aircraft Fuel Tank Electronics

October 2005

DOT/FAA/AR-TN05/37

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U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No.
DOT/FAA/AR-TN05/37

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
INTRINSICALLY SAFE CURRENT LIMIT STUDY FOR AIRCRAFT FUEL TANK ELECTRONICS

5. Report Date
October 2005

6. Performing Organization Code
ATO-P

7. Author(s)
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8. Performing Organization Report No.
DOT/FAA/AR-TN05/37

9. Performing Organization Name and Address

Federal Aviation Administration
William J. Hughes Technical Center
Airport and Aircraft Safety
Research and Development Division
Fire Safety Branch
Atlantic City International Airport, NJ 08405

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address

U.S. Department of Transportation
Federal Aviation Administration
Office of Aviation Research and Development
Washington, D.C. 20591

13. Type of Report and Period Covered
Technical Note

14. Sponsoring Agency Code
ANM-112

15. Supplementary Notes

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16. Abstract

This technical note describes research performed to determine the ignition hazard presented by small fragments of superfine steel wool that contact energized direct current wires in aircraft fuel tanks. Several different methods of shorting a circuit with steel wool were explored. An ignitable mixture of hydrogen, oxygen, and argon, calibrated to have a minimum ignition energy of 200 micro Joules, was used as an ignition detection technique. The electrical currents at the ignition threshold were recorded to determine safe maximum allowable current limits for fuel tank electronics. The lowest current found to ignite the flammable mixture was 99 milliamps (mA); the lowest current found to ignite a steel wool wad in air only was 45 mA.

17. Key Words
Jet A, Steel wool, Current limits, Fuel tank, Flammability, Minimum ignition energy

18. Distribution Statement
This document is available to the public through the National Technical Information Service (NTIS), Springfield, Virginia 22161

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
20

22. Price
N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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LIST OF ACRONYMS

μJ	Micro Joules
AC	Advisory Circular
Ar	Argon
dc	Direct current
FAA	Federal Aviation Administration
FQIS	Fuel Quantity Indication System
H	Hydrogen
mA	Milliamps
NEA	Nitrogen-enriched air
O	Oxygen
SVSIS	Standard voltage spark ignition source

EXECUTIVE SUMMARY

This technical note describes experimentation performed to determine the ignition hazard presented by small fragments of steel wool making contact with energized electrical circuits in flammable environments that could be present in aircraft fuel tanks. Superfine (0000) steel wool was used as the test material in this study, as was aluminum wool (00), bronze wool (00), and fuel quantity indication system wiring. A 28-volt direct current (dc) power supply was used to simulate energized aircraft electrical wiring, and the electrical current was limited using thin-film noninductive resistors. An ignition detection technique developed by Lightning Technologies, Inc., was used to determine if the sparking or burning event could cause an ignition of a gaseous mixture with a known minimum ignition energy of 200 micro Joules (μJ), the accepted minimum ignition energy of hydrocarbon fuel vapor.

The ignition detection technique employed a 36-liter cubic aluminum chamber with a blowout hole on top and a clear acrylic front panel with thermocouple and lever mechanism pass-throughs. Hydrogen, oxygen, and argon gases were proportioned with mass flow controllers and mixed in a canister, then introduced into the chamber. A standard voltage spark ignition source (SVSIS) was used to calibrate the mixture with a 200-μJ voltage spark. The gas mixture and the SVSIS were checked daily to ensure there was no day-to-day drift in the precision of the spark energy and the gas mixture. Voltage and current traces were recorded for each test with voltage and current probes connected to a digital oscilloscope. Temperature rise was measured with a K-type thermocouple connected to a LabView data acquisition system. A thin sheet of aluminum foil was used to seal the chamber blowout hole. Ignition was said to have occurred if a visual overpressure and inflation or rupture of the aluminum foil sheet was witnessed. The electrical current at which ignition occurred was recorded, and when the tests were completed, the results were compared to determine the minimum ignition current.

The tests showed that the lowest current causing ignition of the gas mixture was 99 milliamps (mA), with a wad of superfine steel wool contacting the open circuit. It was observed that the burning of the steel wool wad caused the ignition of the gas mixture; therefore, further investigation was concentrated on igniting a wad of steel wool. Experiments were performed with only air in the chamber to determine the lowest current that could ignite a wad of steel wool, which was about 45 mA, although the ignition characteristics were found to depend on each particular wad of steel wool. Based on these tests, it was concluded that the maximum allowable steady-state current limit of 10 mA root mean square, specified by the Federal Aviation Administration in draft Advisory Circular 25.981-1C, can be considered sufficient to preclude an ignition source.

1. INTRODUCTION.

A flammable mixture of fuel vapor and air can exist at times in a partially filled aircraft fuel tank containing jet fuel. Research has been done to develop methods to eliminate or reduce the risk of having an explosive condition in the fuel tank. There are a few different approaches to preventing fuel tank explosions. Explosions need three conditions to occur simultaneously: a flammable fuel source, sufficient oxygen to react with fuel molecules, and an ignition source to start the chemical chain reactions. Eliminating any one of these conditions will prevent a fuel tank explosion.

1.1 REDUCING OXYGEN CONCENTRATION.

Recently, attention has been focused on developing a low-cost, low weight, high-efficiency fuel tank inerting system for use in large transport airplanes [1]. This system uses high temperature bleed air from the engines to create nitrogen-enriched air (NEA) with as high as 98% nitrogen concentration. The NEA is plumbed into the ullage space above the liquid fuel in the fuel tank, forcing air out the vents and creating an atmosphere with a maximum oxygen concentration of 12%. This value has been shown to be the lowest oxygen concentration that will support ignition of jet fuel vapors [2]. This approach eliminates one of the key ingredients required to have a fuel tank explosion (sufficient oxygen).

1.2 REDUCING IGNITION PROBABILITY.

Ignition of fuel vapors can occur as a result of several different mechanisms. Voltage sparks, thermal sparks, and hot surfaces are the most probable ignition sources present in or around a fuel tank. Any of these ignition sources could occur due to lightning strikes, electrical faults in fuel tank electronics, or short circuits caused by cleaning debris, such as steel wool or other small conductive filaments that may have been inadvertently left within a fuel tank. Combined with fuel tank inerting, reduction or elimination of the likelihood of ignition sources could provide an additional safety factor to preclude virtually any fuel tank mishaps during the life of a transport aircraft.

Electrical spark has been the standard method of determining ignition energy required to ignite a flammable mixture. The generally accepted minimum ignition energy for a hydrocarbon/air mixture is around 200 micro Joules (μJ) for a specific mixture of fuel and air, usually at a stoichiometric mixture or slightly richer [3]. The 200-μJ energy in most experiments is the energy stored in a capacitor and discharged across an electrode gap as a voltage spark. It should be noted that the stored capacitor energy is not the exact amount of energy deposited into the spark, as there are always losses between the capacitor and the electrodes. Nevertheless, the capacitor energy is a very good approximation of the minimum ignition energy of a mixture and the relative ignition strength of a voltage spark.

Flammable mixtures can also be ignited by means of thermal or friction sparks. Thermal sparks are different from voltage sparks; they are very small burning particles of metal that radiate bright colors due to high temperature burning. Thermal sparks are produced either by two hard surfaces sliding against each other creating a shower of sparks or a wire or filament making or breaking contact in a circuit, creating small burning particles of wire or electrode material. The nature of thermal sparks makes it very difficult to produce a repeatable and quantifiable thermal spark event to use to measure the ignitability of a flammable mixture, as was found in reference 4.

Spontaneous ignition of flammable vapors can also occur due to heat transfer from a hot surface to fuel molecules. A standard test method has been developed to measure the autoignition temperature of a liquid fuel by dropping a small amount of fuel onto a flat, heated surface and noting the temperature at which a flame is observed [5]. It has been accepted that the autoignition temperature of jet fuel is around 450˚F [6], although this is not an exact figure. Many factors can affect the ignition of the fuel vapors and the propagation of a flame front from the hot spot. The design of the test apparatus will determine the type of combustion that will occur. Cool flames can develop and propagate through a flammable mixture without creating an explosion as long as the rate of heat generated is not much greater than the rate of heat lost; explosions can only occur if significantly more heat is generated than lost.

Currently, the Federal Aviation Administration (FAA), guidance for electrical systems that introduce electrical energy into fuel tanks, such as fuel quantity indication systems (FQIS), provided in draft Advisory Circular (AC) 25.981-1C, states a maximum steady-state current of 10 milliamps (mA) root mean square (rms) is considered an intrinsically safe design limit for FQIS. It also states that current levels above 10 mA rms, particularly for failures and transient conditions, could also be considered acceptable, provided that proper substantiation by test and/or analysis justifies them as intrinsically safe. As an example, the AC states that for transient conditions, it is acceptable to limit the transient current to 150 mA rms, and failures that result in steady-state currents above 10 mA rms should be improbable and not result in steady-state currents greater than 30 mA rms. These values were determined after a considerable factor of safety was applied to the lowest values found from previous tests using Jet A vapors and steel wool filaments as the ignition source. The experimentation presented in this work was performed using a calibrated gas mixture with a predetermined minimum ignition energy to solidify the confidence in the electrical current guidance in draft AC 25.981-1C.

1.3 PREVIOUS WORK.

Some unpublished research was performed to determine if the small thermal sparks caused by combustion of steel wool could ignite fuel vapors. An open-cup flashpoint tester was used to create Jet A vapors, and electrodes were placed above the open cup. Wads of superfine steel wool were dropped onto the electrodes and small thermal sparks and burning of the steel wool sample was noticed. However, it was observed that the burning of the sample did not ignite the Jet A vapors. The experiment was not fully controlled, as the composition of the mixture of fuel and air above the open cup was unknown, as well as the minimum energy required to ignite the mixture. The researchers recommended that tests should be performed in a mixture that is known to be ignitable at a certain minimum energy and can be easily repeated.

Controllable mixtures of various hydrocarbons, such as propane, ethylene, or acetylene, could be used and would suffice as a substitute for Jet A. These gases, however, usually have significant pressure and temperature increases upon combustion and require heavy duty or vented combustion vessels, which would produce flames several feet high in the laboratory. Hydrogen gas was chosen as a possible ignition detection technique for the current research for its ease of mixing, lower temperatures and pressures upon combustion, and sensitivity to lower ignition energies [4].

1.4 SCOPE.

The purpose of this study was to determine the lowest electrical current required to ignite a flammable fuel vapor mixture. It was proposed to determine if the burning/thermal sparking created by steel wool is significant enough to cause an explosion in a flammable mixture, and what currents would be required to cause steel wool to ignite the mixture. Several different methods of creating a short circuit with steel wool were used to explore various fault possibilities. Also, various materials were used for comparison to the steel wool, such as aluminum wool, bronze wool, and wire from FQIS probes.

The current study employed a mixture of hydrogen (H), oxygen (O), and argon (Ar) that allows for repeatable ignition and can be calibrated with a standard voltage spark at a low energy. Tests were performed in a small chamber that was filled with the ignitable mixture. Experimentation was performed per a test matrix, and voltages and currents were recorded to determine the lowest currents that will cause ignition of the hydrogen mixture.

2. EQUIPMENT AND PROCEDURES.

2.1 APPARATUS.

All experimentation was performed in the Fuels Research Facility at the FAA William J. Hughes Technical Center, Atlantic City International Airport, New Jersey. The test setup consisted of an Agilent (model 6554A) microprocessor-controlled direct current (dc) power supply, which was used to supply voltage and current for the events to be tested. The power supply could be operated in either a constant voltage or constant current mode by determining the resistance in the circuit and calculating a voltage for a desired current or vice versa. Unfortunately, for the purpose of this testing, the calculation time of the microprocessor gave large overcurrent transient pulses at the initiation of a short circuit. This was resolved by using in-line, thin-film noninductive resistors to minimize transient current pulses. Constant current could be assured by using a constant voltage (28 Vdc) and a calculated resistance to give the desired current, using Ohm’s law. The voltage and current traces were measured with a Tektronix P5205 high-voltage probe and a Tektronix TCP202 current probe. These probes were connected into a Tektronix TDS3014B digital oscilloscope that captured and recorded the events.

The minimum ignition energy apparatus was designed by Lightning Technologies, Inc., of Pittsfield, MA. It uses a mixture of hydrogen, oxygen, and argon that can be easily ignited at low energy levels using the standard voltage spark ignition source (SVSIS). The amount of gas mixture flowing into the chamber is regulated by two mass flow controllers, which can be programmed to deliver specific proportions of each gas. The SVSIS is a high-voltage dc power supply feeding into a variable vacuum capacitor and through an adjustable spark gap. A corona source is used to initiate spark breakdown. The chamber is a 13″ cube made of 1/8″ aluminum metal on all sides. A foil covering for the top surface relieved the overpressure after combustion. A 1/4″ clear heavy-duty acrylic sheet was fabricated to replace one side of the chamber, in order to see into the chamber. Four holes were drilled and tapped in the acrylic panel to allow for electrode and thermocouple penetrations, as well as for the mechanism to be used to short out the circuit from outside the chamber. Temperatures were measured using a precision K-type thermocouple and recorded using LabView software.

The gas mixture used in the device consisted of hydrogen, oxygen, and the inert gas argon. Research has shown that the lower-flammability limit for this mixture is about 5% H_2, 5% O_2, and 90% inert gas (% by volume) [3]. The oxygen concentration can be increased to 12%, and the hydrogen concentration can be slightly increased to give a gas mixture with a desired minimum ignition energy and ignition probability. Increasing the oxygen and hydrogen concentrations further results in overpressures higher than the maximum pressures recommended for the explosion chamber [4]. It should be noted that although ignitions can be achieved at oxygen concentrations below 12% with hydrogen gas as the fuel, this oxygen concentration is insufficient to sustain flame propagation in a hydrocarbon/air mixture such as Jet A, as the lower-flammability limit for hydrocarbon fuels has been experimentally determined to be near 12% O_2 [2 and 3].

2.2 TEST PROCEDURES.

2.2.1 Hydrogen Ignition Chamber Calibration.

The procedures listed in the literature from Lightning Technologies, Inc., were followed to setup the system in such a way that a specific mixture would exist in the chamber that can be reliably ignited at a minimum ignition energy of 200 μJ. The spark gap was set for 2 mm, and the chamber was filled with a nonignitable mixture of 4% H_2, 12% O_2, and 84% Ar. After the chamber was filled, the spark source was turned on and the breakdown voltage was recorded for ten spark events using the same chamber fill. The mean and standard deviation of the ten sparks was calculated, and a voltage was selected that is one standard deviation below the mean. Using the corona source, it was verified that this selected voltage would reliably breakdown the gap. The results of these calculations are shown in table 1.

TABLE 1. BREAKDOWN VOLTAGES AND CALCULATED CAPACITANCE

Mean Breakdown (kV)	Standard Deviation (kV)	Mean - Std. Dev. (kV)	Capacitance (pF)
4.54	0.53	4.01	24.9

The capacitance of the variable vacuum capacitor was checked with a digital LCR (inductance/capacitance/resistance) meter and adjusted to 24.9 pF to give a capacitor discharge energy of 200 μJ. It was determined that the spark will occur reliably in a mixture of hydrogen, oxygen, and argon at 4 kV, which would deliver a capacitor energy of 200 μJ. The manual stated that a mixture is desired that will just cause ignition at the given spark energy so that the minimum energy that will ignite this mixture will be no less than 200 μJ. The manufacturer indicated that filling the tank with five volumetric tank exchanges would give 99.3% concentration of the desired mixture. This mixture was found by starting with an initial composition of 5% H_2, 12% O_2, and 83% Ar and testing for ignition. Ignition was not achieved after two separate tank fills with four ignition attempts each, so the mixture was adjusted to 5.25% H_2, 82.75% Ar, and 12% O_2, and ignition was attempted again. It was desired to have an 85% to 95% probability of ignition, which was achieved by attempting ten ignitions, with one not resulting in ignition, thus giving a 90% probability of ignition. It was not necessary to calibrate the apparatus before every test, as long as the gap setting was not moved and the capacitance was not adjusted. It was sufficient to do two ignition tests, one every 4 hours of testing in a day, to check the ignitability of the mixture.

2.2.2 Test Procedure.

At the beginning of every test day, the spark gap was checked with a standard 2-mm-thick gauge, and the electrodes and the glass insulators of the SVSIS were cleaned with isopropyl alcohol wipes to eliminate any current leakage to ground. An electric space heater was placed underneath the chamber to eliminate any water vapor in the area of the spark gap, capacitor, and insulators to prevent current leakage. The mass flow controllers were also turned on at the beginning of the day to allow time for them to warmup and operate properly. An ignition test was performed at the beginning of the day and in the afternoon to check the ignitability of the chosen test mixture at 200 μJ. A chamber fill time of 5 minutes was allowed to give 99% mixture purity. The fill and vent valves were then closed off, and the gas inside the chamber was allowed to settle for a few minutes. The SVSIS was turned on and the capacitor began to charge. When the electrostatic voltmeter approached 4 kV, the corona source was switched on and the capacitor energy would discharge into the spark gap. If the spark did not ignite the mixture, it was necessary to wait 2 minutes before the next attempt. Usually, if the mixture did not ignite within four to five ignition attempts, the chamber was purged and a new mixture was introduced, and ignition would be attempted again. This process was repeated until ignition was achieved, at which time the work on the test matrix could begin. It was determined that with a total of 21 ignition tests there were 18 ignitions and 3 nonignitions, giving an 86% ignition probability, consistent with the manufacturer's recommendation of 85% to 95% probability of ignition.

The test matrix is shown in table 2. The test procedure for each configuration started with loading the wire sample into the test-specific apparatus in the explosion chamber. Since steel wool filaments are less than one-thousandth of an inch thick, a magnifying glass was used to select a strand from the wad. The chamber was then sealed off with the foil blowout panel and filled with the ignitable mixture. A 100-ohm resistor was initially used to dampen out the transient current pulse. The current was controlled by step increasing the power supply voltage. The voltage step increments would vary depending on the wire. In later tests involving wads of superfine steel wool, the current was limited by the resistance, where for a constant 28 volts, the current could be regulated by changing the in-line resistance. The oscilloscope was used to measure the steady and transient voltage/current traces for each test. After each test, the data were downloaded from the oscilloscope and imported into Microsoft® Excel.

For the test configuration with a single filament between two electrodes, the voltage was step increased until filament failure. If a filament failed without ignition of the mixture, the standard spark source was used to check if the mixture was in fact ignitable. For the test configurations with transient pulses due to making and breaking contact with the electrodes, a maximum of ten ignition trials were attempted at each step. If ignition was not achieved, the current was increased, and ignition was attempted again. The mixture was routinely checked for ignitability during all tests. For tests that resulted in low-current ignition, which was the main concern in this study, several trials were run to zero in the lower-current limit that would cause ignition.

TABLE 2. TEST MATRIX

	Materials				
Test Configuration	0000 Steel Wool	00 Aluminum Wool	00 Bronze Wool	FQIS Wire	FQIS Shielding
1. Single filament or wire fixed between two electrodes	completed	completed	completed	N/A	completed
2. Single filament or wire with one end initiating contact with one copper electrode and the other end fixed to the other electrode	completed	completed	completed	N/A	completed
3. Single wire or filament with one end initiating contact with a flat aluminum electrode and the other end fixed to the other electrode	completed	completed	completed	N/A	completed
4. A chafed wire or wire shield initiating contact with an edge of an aluminum plate and the other end fixed to the other electrode	N/A	N/A	N/A	completed	N/A
5. A clump of steel or aluminum wool initiating contact with both electrodes	completed	completed	N/A	N/A	N/A

3. ANALYSIS.

The standard method for quantifying the energy contained in a voltage spark is to measure the amount of energy stored in the capacitor before discharge into the spark gap. Knowledge of the capacitance and the stored voltage can give the spark energy as

$$E = \frac{1}{2}CV^2 \tag{1}$$

Where E is the stored energy in Joules, C is the capacitance in farads, and V is the voltage in volts. To calculate the capacitance required for the standard voltage spark ignition source, the desired spark energy and the discharge voltage can be used to solve the above equation for the capacitance.

To calculate the electrical energy input into a wad of steel wool by an open circuit, measurements of the current and voltage as functions of time are required. The following equation gives the input energy:

$$E = \int_{t_0}^{t} VIdt \qquad (2)$$

Where E is the input energy in Joules, V is the voltage in volts, I is the current in amps, and t is time measured in seconds. An appropriate time domain, $t_0<t<t_f$, should be selected that best characterizes the moment of contact with the open circuit, where t_0 is the time at which contact is first made with the electrodes, and t_f is the time at which the current stabilizes.

4. RESULTS.

Table 3 shows the lowest currents that caused ignition for each test type. Although there were many tests performed, only the minimum currents are shown, since the objective here is to determine intrinsically safe current levels. It is apparent from the table that only tests using superfine steel wool resulted in low-current ignition (around 100-200 mA).

TABLE 3. MINIMUM IGNITION CURRENTS (AMPERES)

Test Configuration	Steel Wool	Aluminum Wool	Bronze Wool	Frayed FQIS	FQIS Shielding
1	0.114	0.628	0.672	---	---
2	0.230	0.808	0.840	---	1.73
3	0.128	0.696	0.608	---	1.29
4	---	---	---	1.29	---
5	0.099	0.400	---	---	---

4.1 TEST CONFIGURATION 1.

In test configuration 1, using single strands of steel wool, the heating of the filament was found insufficient to cause a hot surface ignition of the gas. However, if the current was increased to a certain point, the filament would fail (break) and the heat generated by the burning of the filament would cause ignition of the gas mixture. By observing the filament during failure and recording the event using a video camera, it could be seen that when the filament fails, it splits into two halves. At the point of failure on each half the filament tip glows bright orange and consumes itself by propagating a flame along its length toward the clamp. Eventually, the rate of heat lost becomes greater than the rate of heat generated, and the embers become extinguished.

After doing some research on steel wool and calling a steel wool manufacturer, it was learned that machining oil is an inherent part of the manufacturing process. Some steel wool brands have less of an oil coating than others, but for the most part, all brands have some amount of oil coating. It is believed that the oil either initiates the burning of the filament or acts as a fuel for the burning; nevertheless, it seems that the oil coating plays a role in the combustion process. Several different brands of steel wool were acquired and tested, but it became apparent that the brand of the steel wool had little effect on the failure and burning characteristics when compared to the effect of the length and thickness of the strand. The aluminum and bronze wool filaments would glow reddish-orange for the entire length of the filament without igniting the gas. Ignition would occur at filament failure for these samples as well, although the currents were much higher than those of steel wool. Ignition was not achieved using FQIS wire until the current was over 1 amp.

Focusing on the steel wool, the next step was to determine the effect of filament length and thickness on failure current. Using a magnifying glass to examine a strand of steel wool, it was seen that the thickness of the filament varies along the length; therefore, measuring the filament with a micrometer would not give an accurate assessment of the thickness. Measuring the resistance with an ohmmeter gave a good approximation of the relative thickness of a strand of steel wool when compared to other strands of the same length. Strands with lower resistances tended to fail at higher currents, and strands with higher resistances failed at lower currents. Changing the length would also affect the resistance, so lengths of 0.5″, 1.5″, 2.5″, and 3.0″ were tested to determine any effect that length would have on failure current. Many experiments were done with only air in the chamber to determine failure current trends for filaments of different sizes.

It was initially assumed that if a filament failed, the burning of the filament would definitely cause ignition of the gas. However, after testing some filaments in the gas that were known to fail at low currents in air, it was found that the filament would fail without resulting in an ignition, and the failure occurred with less burning of the filament. This may be caused by the difference in oxygen concentration between the gas mixture (12%) and air (20.9%), as the oxygen concentration in the gas mixture may not be sufficient for proper oxidation during the filament combustion process. The results from the steel wool filament tests in the ignitable mixture are shown in figure 1. Each length is represented by a shaped figure; ignitions are represented by solid figures, and nonignitions are represented by hollow figures. It should be noted that all points are filament failures that resulted in the steel wool burning.

It can be seen that the lowest ignition occurred around 115 mA, although some nonignitions occurred at higher currents, such as one at about 155 mA. It was found that very thin, short filaments with high resistance could not provide enough heat to ignite the mixture upon filament failure. Shorter filaments, it seems, do not have enough material for the embers to propagate, or the surface area to volume ratio is so large that quenching occurs rapidly, and little heat is generated before extinguishment. For filaments of the same resistance (~30 Ω), the figure shows that ignitions occur for the longer filaments (2.5″ and 3.0″) and not for shorter filaments (0.5″ and 1.5″), indicating that filament size does determine the current at which a filament fails, and consequently, the amount of heat generated during filament combustion.

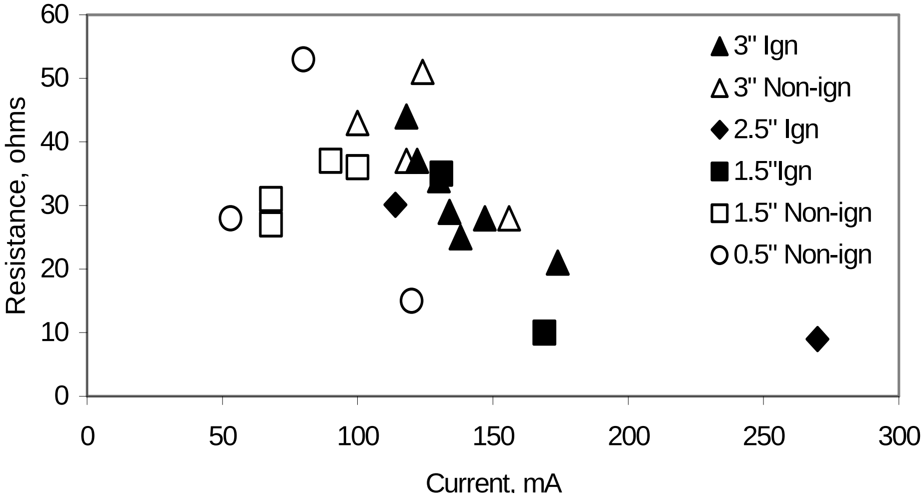

FIGURE 1. FAILURE CURRENTS FOR TEST CONFIGURATION 1

4.2 TEST CONFIGURATIONS 2, 3, AND 4.

For test configurations 2, 3, and 4, one end of a single strand of wire was connected to a positive electrode via alligator clamp, while the other end was connected to a lever mechanism that could remotely bring the wire into contact with a ground electrode. Test configuration 2 used a copper wire as ground, while test configuration 3 used a flat aluminum plate. In test configuration 4, the wire used was a frayed piece of FQIS wire, while the ground electrode used was an edge of the flat aluminum plate. It was noticed for all cases that small thermal/friction sparks could be observed while dragging the wire along the electrode. As before, the only material that caused low-current ignitions was the steel wool. For the low currents (under 200 mA) of interest in this study, none of the thermal sparks generated could ignite the mixture. Ignition of the mixture was achieved upon failure/combustion of the filament, as in the previous test configuration. The filament tip would glow orange locally at the point of contact with ground and would propagate along the filament until it burned out, causing ignition of the mixture. The lowest ignition current achievable with these test configurations was 128 mA using the aluminum plate as the ground electrode. A higher minimum current (230 mA) was found for the copper electrode. The frayed wire in test configuration 4 did not behave any differently than a single strand of FQIS wire, giving off small thermal sparks at currents as low as 500 mA but no ignitions until the current was over 1 ampere. The key finding from these tests was that the low-current thermal sparks were inadequate to cause ignition of the gas mixture, but it was the filament burning, as in test configuration 1, that caused ignition.

4.3 TEST CONFIGURATION 5.

Test configuration 5 involved introducing a small wad of steel wool between a pair of energized electrodes. Previous tests have shown that a wad of steel wool can be ignited by a dc power source at currents as low as 32 mA. Steel wool combustion is characterized by small thermal/friction sparks that can propagate through the steel wool sample, creating a glowing orange wad for about 5 seconds before extinguishment. This combustion is not exactly the same as was witnessed with single filaments; in that case, the steel itself would change phase and fuel the combustion. For a wad of steel wool, it seemed that only the oil coating and some of the core steel was burned, leaving behind a skeleton of some steel, which still conducted current. This combustion may not be as hot as in the single filament case, as there is no fusing or melting of the steel wool, although some small diffusion flames, like in a candle, were seen in rare cases. Burning the wad of steel wool provided sufficient heat, however, and has been proven to ignite the hydrogen mixture at a current as low as 99 mA. This current is not a minimum steel wool combustion current, as it was found that wads of steel wool could combust at currents as low as 45 mA in the chamber with only air. Again, the discrepancy of oxygen concentrations in the hydrogen mixture and air may be the likely determining factor between ignitions and nonignitions of the steel wool wad.

Figure 2 shows the voltage and current traces from a test in air that resulted in the steel wool wad burning at 45 mA. Choosing a time domain from the onset of the current spike until current stabilization, the calculated energy was approximately 0.02 µJ. This energy is not a spark energy; rather it can be thought of as an initiation energy or the energy required to create small burning embers in a wad of steel wool, which can then proceed to spread throughout the wad. Therefore, in a gaseous mixture calibrated with a 200-µJ minimum ignition energy, a wad of steel wool can ignite the mixture with only a minimal initiation energy input of approximately 0.02 µJ. Basically, this shows that only a very small amount of energy is required to start combustion of a steel wool wad, which may eventually have enough energy to ignite the hydrogen mixture.

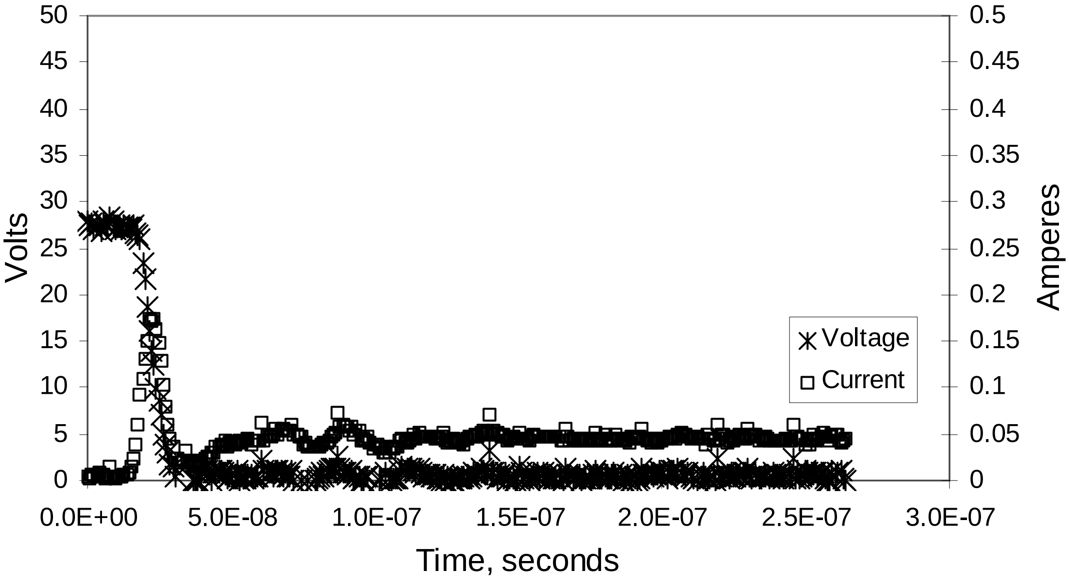

FIGURE 2. VOLTAGE AND CURRENT TRACES FROM STEEL WOOL WAD

It should be noted that the probability of a steel wool wad combusting was not very high and decreased as the test current decreased. For the 45 mA case, only two wads combusted in about 100 attempts, giving a combustion probability rate of about 2%. It was believed that each steel wool wad had different characteristics, some had more fine strands than others, and the ignition probability was believed to depend on the wad itself and which parts made contact with the electrodes. Tests for the steel wool wads was halted at 40 mA after six different samples on two different days with about 400 attempts without ignition. Although previous testing found 32 mA to be the minimum combustion current for a steel wool wad, the lowest current found in this test was 45 mA.

5. SUMMARY OF RESULTS.

This study was performed to determine the lowest current that is required to ignite a calibrated flammable gas mixture by several different methods. The following conclusions can be drawn from the results of the tests.

- Single filament heating (test configuration 1):
  - For all test materials, filament heating was found insufficient to cause hot surface, or autoignition, of the gas mixture.
  - Ignition of the gas mixture was achieved only after filament failure and combustion for steel, aluminum, and bronze wool. The thicker fuel quantity indication system wire was unable to cause any type of ignition at the current amplitudes used for these experiments.
  - Superfine (0000) steel wool was the only material that was able to cause ignition of the gas mixture from applied currents lower than 200 milliamps (mA).
  - The overall size of a single filament of superfine steel wool was characterized using the filament length and resistance and was found to affect the failure characteristics of the filament.
  - The lowest filament failure current was 53 mA for a 1/2″ long strand with a resistance of 28 ohms, but was unable to cause ignition of the gas mixture. Short filaments did not provide sufficient heat for gas ignition.
  - The lowest filament failure current to cause ignition of the gas was 114 mA from a 2.5″ long strand with a resistance of 30 ohms.
- Intermittent contact with ground (test configurations 2, 3, and 4):
  - For all test materials, the small thermal sparks created by making and breaking contact with ground were insufficient to cause low-current ignition of the gas mixture.
  - The lowest current found to cause ignition was 128 mA from a strand of steel wool; however, ignition of the gas mixture was achieved only after filament failure and filament combustion, not from thermal sparking or arcing.

- Steel wool wad contacting an open circuit (test configuration 5):
  - Ignition of the gas mixture was caused by the burning steel wool wads.
  - The lowest applied current that caused steel wool combustion and subsequent hydrogen gas mixture ignition was 99 mA.
  - The lowest applied current that caused steel wool combustion in air was 45 mA; however, when attempted in the gas mixture, the steel wool wad would not combust at this applied current.
  - Although 45 mA of applied current could not combust the steel wool wad in the gas mixture, it may be considered the lowest current that poses a significant threat of combusting a steel wool wad.
  - The probability of steel wool wad combustion was found to decrease as the applied current decreased. The probability is affected by the size, shape, and thickness of each particular steel wool wad.

6. REFERENCES.

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