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Preliminary Investigation of the Fire Hazard Inherent in Micro Fuel Cell Cartridges

Harry Webster

May 2010

Final Report

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16. Abstract

Micro fuel cells are an alternative to batteries as a portable source of electricity. Unlike a battery, which stores electricity, a fuel cell chemically reacts a base fuel with oxygen from the air to generate electricity. A fuel cell is recharged by simply replacing the fuel. The potential flammability of the base fuels is a concern when carried onboard an aircraft.

A series of tests were performed to evaluate the flammability hazard associated with fuel cell fuel cartridges. Tests were conducted with various fuel chemistries including methanol, formic acid, butane, hydrogen gas, and borohydrides. The response of each fuel cartridge to an external alcohol fire was evaluated.

Most of the fuels tested were flammable. The cartridge containing formic acid did not ignite under the test conditions. Butane produced the most vigorous fire. Heating hydrogen gas stored in a metal matrix caused breaching of the enclosure allowing the gas to escape and ignite. Borohydrides were difficult to ignite but gave off a flammable fume when heated and were capable of deep-seated exothermic reaction. It was found that the cartridge material can have a significant effect on flammability. Metal cartridges protected the fuel from an external fire better than plastic cartridges. Halon 1211 was effective against all but the deep-seated borohydride exothermic reaction.

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EXECUTIVE SUMMARY

Portable electrical power is a necessity in the modern world. The uses for portable electrical power range from electronic devices such as cell phones and laptop computers to electric automobiles. Most often this takes the form of single use or rechargeable batteries. The trade off in any portable electrical power source is always capacity versus weight and volume. Batteries have limitations in the amount of electric energy that can be stored, though the battery industry continues to push these limits, allowing more and more capacity in a given weight and volume. Rechargeable batteries must be connected to an external source of electricity for recharging. Because charge times vary, rapid recharge is the goal of research.

Micro fuel cells provide an alternative to batteries as a portable source of electricity. A fuel cell is an electrochemical device that converts fuel and oxygen into electricity. The fuel is supplied in removable or refillable cartridges and can be of several different chemistries. The fuel cell extracts hydrogen gas from the base fuel. The hydrogen gas then reacted with oxygen from ambient air to produce electricity. The reacted hydrogen and oxygen resulted in water or water vapor as a byproduct.

In this research, a series of tests were conducted to evaluate the flammability hazard of selected base fuels, which were packaged in the original equipment as manufactured for consumer use where possible. The base fuels included gaseous hydrogen, liquid alcohols and acids, and granular borohydride compounds and mixtures. If the cartridges were not available, the fuel was tested in bulk form. The tests measured the response of the cartridge and fuel to an external, low-level fire source.

Most of the fuels tested were flammable. It was found that the cartridge material can have a significant effect on flammability. Metal cartridges protected the fuel from an external fire better than plastic cartridges. The cartridge containing formic acid did not ignite under test conditions. Butane produced the most vigorous fire. Hydrogen gas stored in a metal matrix is under low pressure and breaching of the enclosure allows the gas to escape and ignite. Borohydrides are difficult to ignite, but emitted a flammable fume when heated and were capable of deep-seated exothermic reaction. Halon 1211 was effective against all but the deep-seated borohydride exothermic reaction.

This is a preliminary report that tests single fuel cells. This is not representative of large fuel cells or a determination of the outcome for a large quantity of fuel cells packaged for transportation as cargo. This initial testing was to look at passenger quantities of the type and size that may be allowed to be carried by passenger and crew for use in consumer devices. Further testing may be done at a later date should a need, new data, or information concerning fuel cell transportation and their use become known.

1. INTRODUCTION.

Portable electrical power is a necessity in the modern world. The uses for portable electrical power range from electronic devices such as cell phones and laptop computers to electric automobiles. Most often this takes the form of single use or rechargeable batteries. The trade off in any portable electrical power source is always capacity versus weight and volume. Batteries have limitations in the amount of electric energy that can be stored, though the battery industry continues to push these limits, allowing more and more capacity in a given weight and volume. Rechargeable batteries must be connected to an external source of electricity for recharging. Because charge times vary, rapid recharge is the goal of research.

A competing mode of portable electrical energy production is the micro fuel cell. Fuel cells are an alternate power source used in lieu of or in conjunction with batteries to power electronic equipment. A fuel cell is an electrochemical device that reacts hydrogen from the fuel and oxygen from the air to produce electricity with water as a byproduct. The chemical reaction continues as long as available hydrogen can be extracted from the base fuel. The amount of electricity produced is limited by the amount of available fuel. The oxygen is drawn from the atmosphere.

Recharging a fuel cell is accomplished by replenishing the spent base fuel. This can take the form of draining the spent fuel and refilling with fresh fuel, or can be as simple as removing a cartridge and replacing it with a fresh one.

Energy storage is often accompanied by flammability issues. Previous work has focused on the flammability of lithium, single-use batteries and lithium-ion rechargeable batteries [1 and 2]. These batteries can be ignited from both internal shorts and from external fire sources. Single-use lithium batteries have the additional characteristic of not being extinguishable with the normal fire-extinguishing agents carried onboard a commercial aircraft. This has led to the banning of bulk shipment onboard commercial, passenger-carrying transport aircraft.

The focus of the tests described in this report is a preliminary investigation into the flammability hazards associated with the base fuels currently being considered for fuel cells. Wherever possible, the fuel as tested was stored in original equipment manufacturer cartridges. This is preferable since the cartridge can mitigate or enhance the flammability characteristics. Due to the new nature of this industry, production cartridges were not always available. In these instances, bulk fuel was tested. These tests included only relatively small fuel cartridges with limited amounts of base fuel. The results should not be extrapolated to apply to large fuel cells, such as currently being considered as aircraft auxiliary power unit replacements.

Several types of base fuels were evaluated. These included gaseous hydrogen, stored in either pressurized containers or in metal hydrides; liquid methanol/water mixtures; granular sodium borohydrides; and liquid formic acid. Analysis included a literature search of chemical and physical properties of the base fuel. Tests consisted of exposing the cartridges to a low-intensity alcohol external fire.

Aviation micro fuel cell concerns include:

- In-flight operation and refilling
- Transportation in carry-on and checked luggage
- Bulk shipment as cargo

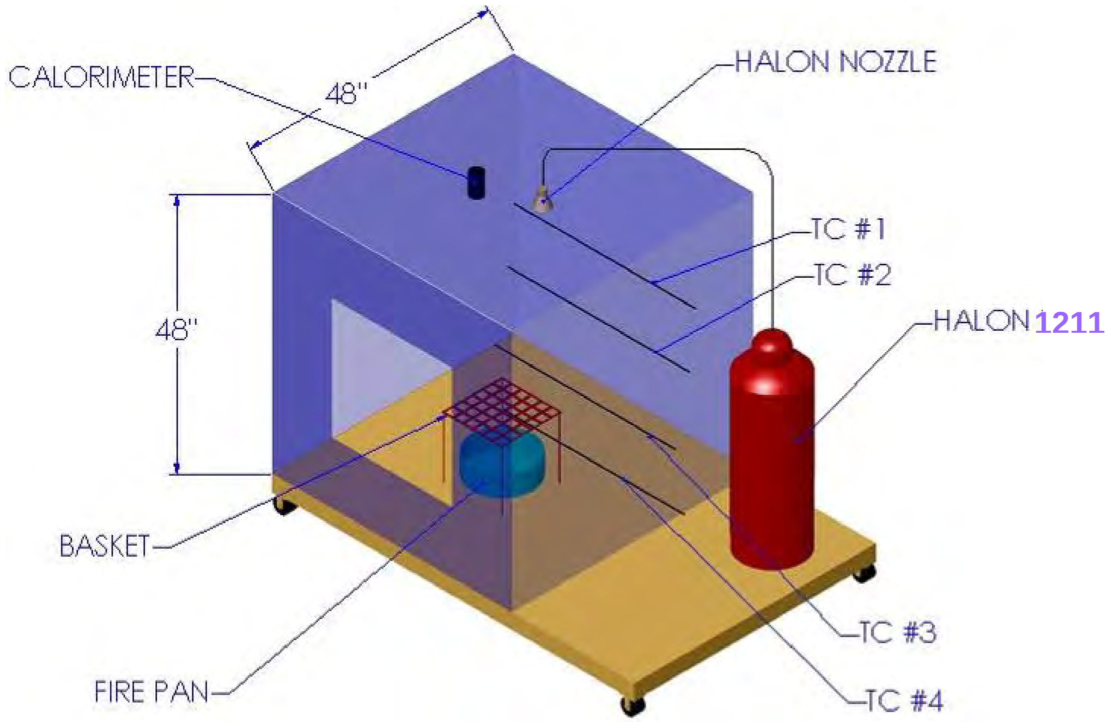
2. TEST DESIGN.

2.1 SCOPE.

These tests were designed to determine the flammability characteristics of fuel cell replaceable fuel cartridges and any associated hazard to transport aircraft when carried onboard or placed in carry-on luggage. The flammability parameters investigated included container integrity, ignition of the base fuel, intensity of resulting fire, and effectiveness of Halon 1211 in extinguishing the fire. The fuel cell cartridges tested differed markedly in size and base fuel type. Several manufacturers supplied the test specimens. Some were production cartridges, some were pre-production units, and one supplier supplied the base fuel only. Due to widely different types and sizes of cartridges, no direct comparison should be drawn regarding the flammability of each unit.

2.2 TEST FACILITY.

The same test chamber that was constructed to measure the flammability of lithium batteries was used for these tests. The chamber was constructed of 1/8″ noninsulated steel sheeting and measured 4′ by 4′ by 4′, producing a 64-cubic-foot test facility. The entire front side opened for easy access and was fitted with a Plexiglas windowpane located in the door to allow observation and recording of the fire test. The chamber was equipped with variable 3″ vent holes located on the centerline of the sidewalls, 2″ from the floor. Rectangular 3″ by 30″ horizontal slots were cut near the top of the sides and back wall. These slots were sealed with aluminum foil to act as blow-out panels to prevent an overpressure from damaging the structure. The facility was fitted with a Halon 1211 fire-extinguishing system. A steel angle frame supported a basket made from 0.5″ wire mesh, used to support the fuel cartridges over the fire pan. The frame positioned the test article 4″ above the 1-propanol fire. Figure 1 shows a diagram of the test chamber.



TC = Thermocouple

Figure 1. The 64-Cubic-Foot Test Chamber

2.2.1 Instrumentation.

The 64-cubic-foot test facility was fitted with four type C thermocouples located in the center of the chamber and spaced 12″, 24″, 36″, and 48″ from the floor. The thermocouples were numbered from the top, with the 48″ height assigned number 1 and the 12″ height assigned number 4. These thermocouples measured the temperature rise in the chamber. In addition, a calorimeter was installed in the center of the chamber ceiling and assigned channel 5. The calorimeter was used to measure the heat flux produced by the ignition source fire and the fuel cell fires.

A video camera was positioned outside the chamber and recorded the fire event through the Plexiglas.

2.2.2 Ignition Fire Source.

The chamber was fitted with a circular 4.5″ diameter, 2.0″ deep fire pan. This was loaded with 240 ml of 1-propanol to provide a low-intensity fire with a surface area of 15.9 square inches. The fire pan was centered on the chamber floor. The fire pan diameter was reduced from that used in the lithium battery tests and its depth was increased. The increased depth allowed for a longer-duration 1-propanol fire. The decreased diameter reduced the fire intensity, which was necessary to conduct longer-duration tests.

2.3 BASELINE TESTS.

The facility was calibrated with a series of baseline tests, using the 1-propanol ($C3H7OH$) fuel. The volume of 1-propanol determined the duration of the fire. The amount of 1-propanol was adjusted to ensure a 10-minute ignition fire. The 4.5″ pan required 240 ml of 1-propanol.

The calibration fire was run for a total of 10 minutes and was very stable for that time period. The temperatures ramped up very quickly to a peak temperature of 290°F, as measured 12″ above the fire pan. This temperature averaged 243°F for the duration of the test. The peak temperature at the ceiling of the test chamber was 255°F and averaged 215°F (figure 2). Heat flux readings climbed rapidly to 0.1 Btu/ft^2-sec and steadily increased during the test to peak at 0.2 Btu/ft^2-sec (figure 3).

The temperature and calorimeter results from the baseline tests were subtracted from the results of the fuel cartridge tests to determine the fire contribution of the fuel cartridge.

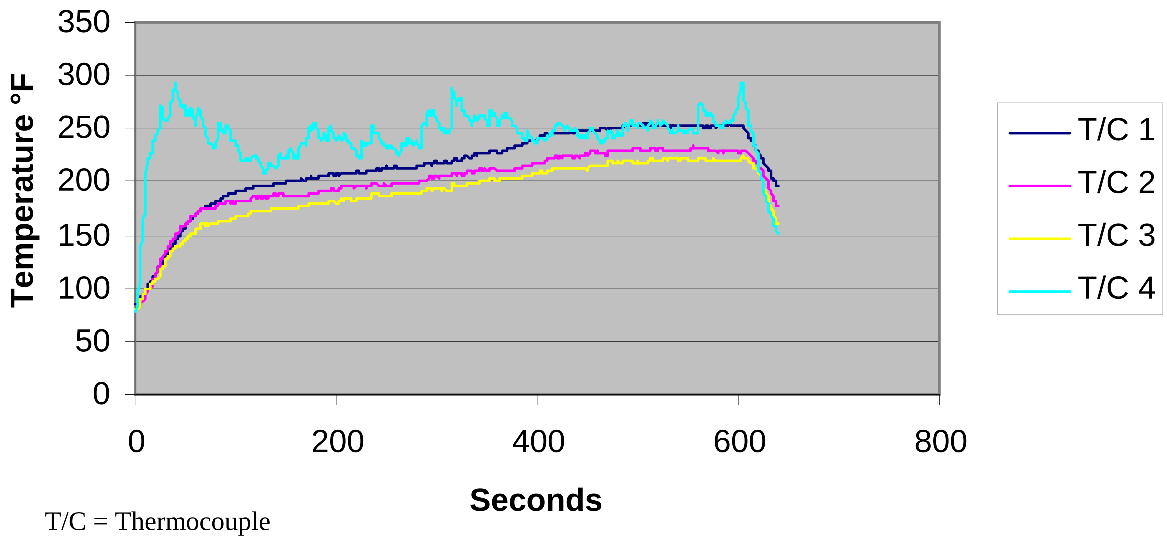


Figure 2. Baseline Temperature

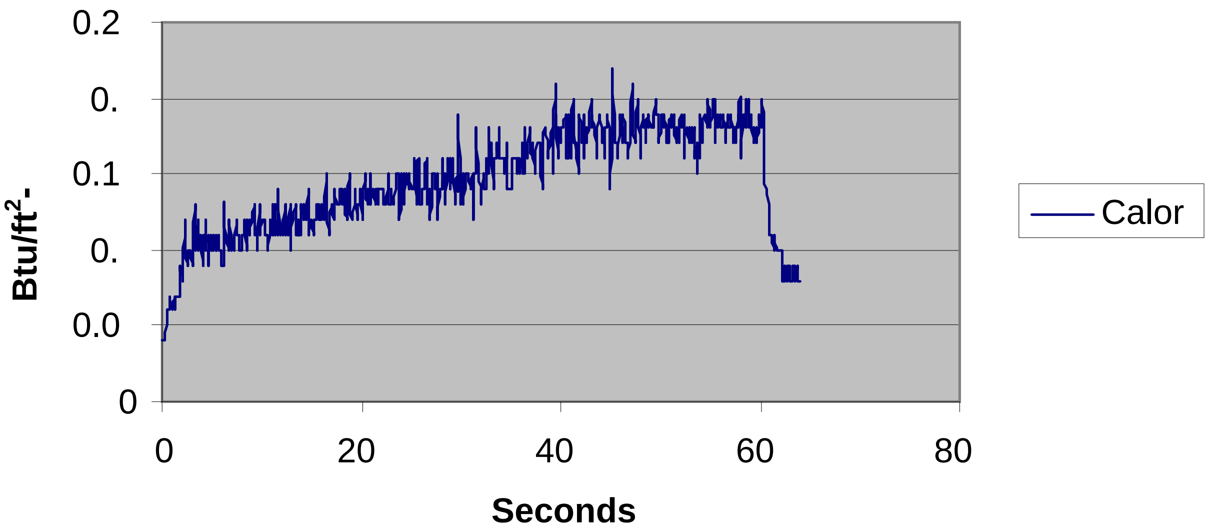


Figure 3. Baseline Heat Flux

3. MICRO FUEL CELL FUEL TYPES.

All fuel cells operate by reacting hydrogen with oxygen. Some cells use pure hydrogen as the fuel, others extract the hydrogen from a hydrocarbon base fuel. The base fuels range from highly flammable to relatively inert. Information for these fuels was obtained from their Material Safety Data Sheets (MSDS). The fuels tested and their physical properties are as follows:

- Methanol
  - Methanol is a flammable liquid that has a flash point of 53.6°F.
  - The auto ignition temperature of methanol is 851.0°F.
  - Vapors may form an explosive mixture with air.
  - Vapors may be heavier than air.
  - Explosion limits: lower, 6% by volume, upper, 31% by volume.
  - Methanol is oxidized directly in a Direct Methanol Fuel Cell system.
  - Reformed methanol fuel cells produce hydrogen “on demand” and consume the hydrogen immediately.

- Formic acid
  - Formic acid is a flammable, corrosive liquid that has a flash point of 156.2°F.
  - The auto ignition temperature of formic acid is 1002.2°F.
  - Explosion limits: lower, 18%, upper, 57% by volume.
  - Formic acid is oxidized directly in a Formic Acid Fuel Cell.

- Sodium borohydride

    - Sodium borohydride is a flammable, corrosive solid that is not easily ignited.
    - Reacts violently with water giving off flammable hydrogen gas.
    - Indirect borohydride fuel cells produce hydrogen "on demand" and consume the hydrogen immediately within the fuel cell.

- Butane

    - Butane is a highly flammable colorless liquid that has a flash point of -76°F.
    - The auto ignition temperature of butane is 860°F.
    - Explosion limits: lower, 1.6%, upper 8.4% by volume.
    - Vapors may be heavier than air.
    - A butane or a butane/propane mix is oxidized directly by a solid oxide fuel cell system.

- Hydrogen

    - Hydrogen is a flammable gas.
    - The auto ignition temperature of hydrogen is 1058°F.
    - Explosion limits, lower, 4%, upper, 74.5% by volume.
    - The gas is lighter than air.
    - Pressurized hydrogen fuel cells oxidize the fuel directly.
    - Hydrogen stored in a metal hydride: hydrogen is produced on demand and consumed immediately with the fuel cell.

4. FUEL CELL CARTRIDGE FLAMMABILITY TESTS.

4.1 METHANOL.

Methanol fuel cell cartridges were supplied by two manufacturers. These cartridges differed in size, shape, and methanol volume. Each cartridge was exposed to the 1-propanol fire with the results as follows.

4.1.1 Direct Methanol Corporation Fuel Cell.

The Direct Methanol Corporation (DMC) provided model 101-208 fuel cell cartridge. The unit has a capacity of 50 ml of methanol in a water solution. The cartridge is shown in figure 4.

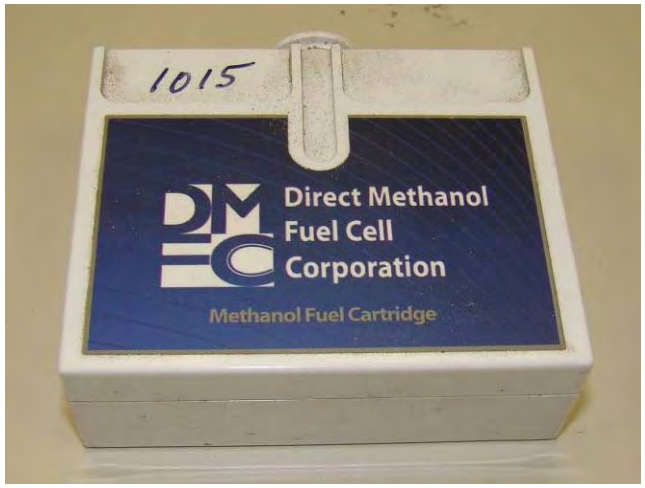


Figure 4. The DMC Model 101-208

4.1.2 Fire Exposure Results for the DMC Fuel Cartridge.

The DMC model 101-208 was exposed to the baseline 1-propanol fire. The following timeline represents significant events:

- 0:00 1-propanol fire ignited
- 0:45 Cartridge integrity breached, contents of cartridge released
- 6:32 Extinguished with Halon 1211

The plastic case material deformed rapidly when exposed to the 1-propanol fire. The plastic case supported combustion and was self-sustaining. The 50 ml of methanol/water did not add significantly to the 1-propanol fire. The temperature results are shown in figure 5. The peak temperature, measured 12″ above the fire pan, was 254.4°F and averaged 201.3°F. The peak temperature, measured at the ceiling, was 280.1°F and averaged 237°F. The 12″ readings were slightly lower than the baseline test results. The ceiling temperatures were slightly higher than the baseline results. The flammable plastic case and methanol/water mixture were easily extinguished with Halon 1211. The cartridge, after the test, is shown in figure 6.

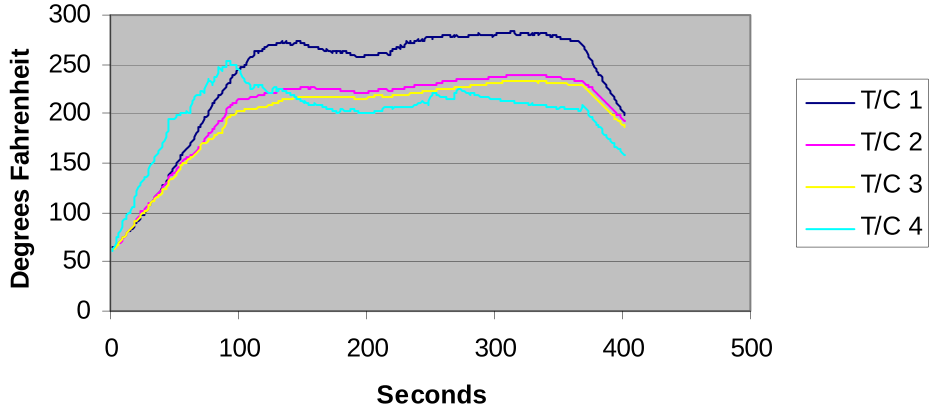


Figure 5. The DMC Temperature Results

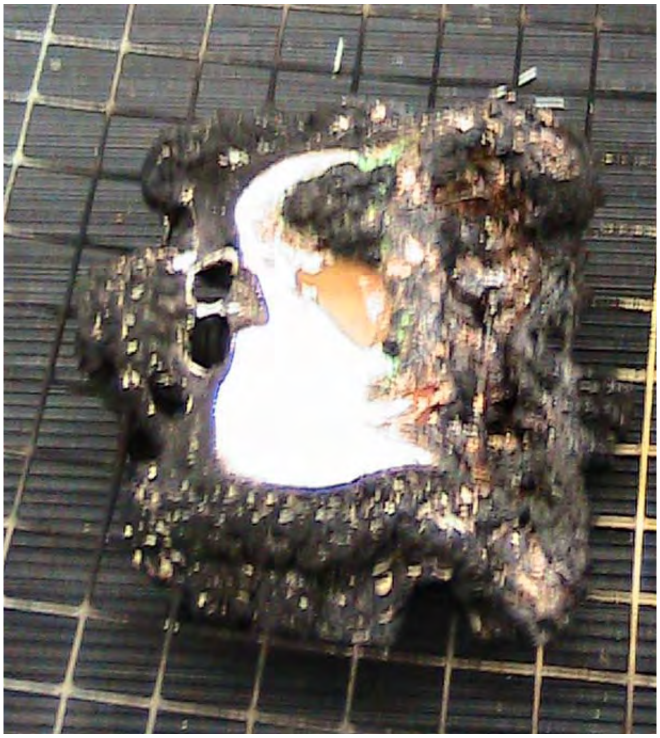


Figure 6. The DMC Fuel Cartridge, Posttest

4.1.3 UltraCell.

The fuel cartridge provided by UltraCell consisted of a metal cylinder with plastic end caps and fittings. One side of the unit had electrical contacts. The capacity of the fuel cartridge was 250 cc of a mixture of 67% methanol and 33% water. The cartridge is shown in figure 7.

Figure 7. UltraCell Fuel Cartridge

4.1.4 Fire Exposure Results for the UltraCell Fuel Cartridge.

The UltraCell fuel cartridge was exposed to the 1-propanol baseline fire. The following timeline represents significant events.

- 0:00 1-propanol fire ignited
- 3:30 The contents vented through an end fitting
- 12:00 Extinguished with Halon 1211

The plastic material that forms the mount and end caps deformed and supported combustion when exposed to the 1-propanol fire. The metal cylinder was unaffected until 3.5 minutes into the test. At that point, the content of the cylinder was vented through an end fitting. The 250-cc methanol/water mixture was flammable and burned with a reddish flame, adding significantly to the size and appearance of the baseline fire. The peak temperature, measured 12″ above the fire pan, was 409.8°F and averaged 214.8°F. This was 120°F higher and 28°F lower than the baseline 12″ peak and average, respectively. The temperatures measured at the ceiling peaked at 497.8°F and averaged 290.1°F. This is 243°F and 75°F higher than the baseline ceiling peak and average, respectively. The flammable plastic fittings and the methanol/water mixture were easily extinguished with Halon 1211. The temperature results are shown in figure 8. The cartridge, after the test, is shown in figure 9.

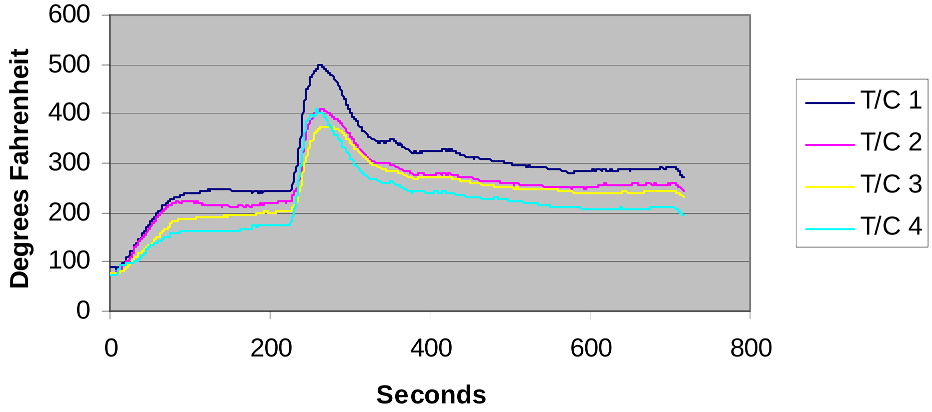


Figure 8. UltraCell Temperature Results

Figure 9. UltraCell Fuel Cartridge, Posttest

4.2 FORMIC ACID.

Tekion Incorporated supplied a fuel cartridge containing formic acid.

4.2.1 The Tekion Incorporated Fuel Cartridge.

The Tekion fuel cartridge consisted of a plastic enclosure similar to a printer ink cartridge. The enclosure had a fitting on the top. The volume of formic acid was unknown, but was estimated to be approximately 50 cc. The cartridge is shown in figure 10.

Figure 10. Tekion Fuel Cartridge

4.2.2 Fire Exposure Results for the Tekion Fuel Cartridge.

The Tekion cartridge was exposed to the 1-propanol baseline fire. The following timeline represents significant events.

- 0:00 1-propanol fire ignited
- 1:02 Liquid formic acid sprayed in a 2′ to 3′ stream from the fitting on top.
- 11:30 Extinguished with Halon 1211

The plastic enclosure deformed, but did not support combustion. The enclosure maintained its integrity except at the fitting. The liquid formic acid did not ignite. Peak and average temperatures at the 12″ height and at the ceiling were within tolerance for the baseline fire. The cartridge, after the test, is shown in figure 11.

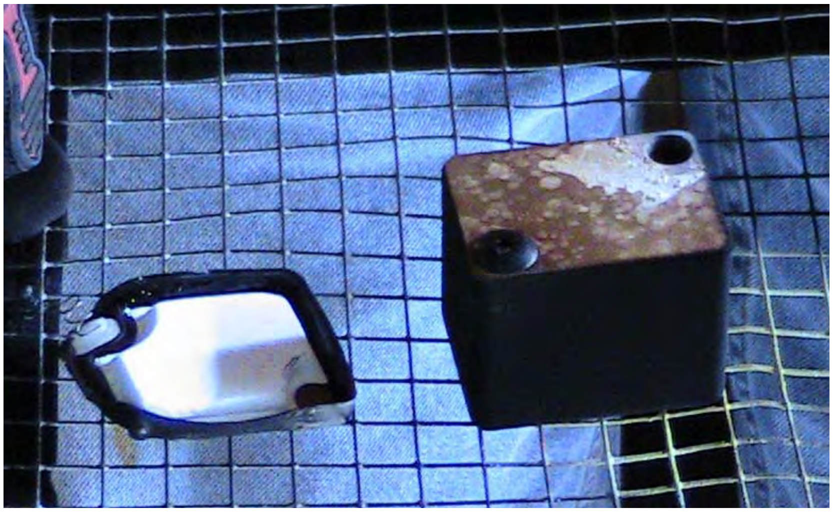


Figure 11. Tekion Fuel Cartridge, Posttest

4.3 BUTANE.

Lilliputian Systems supplied a fuel cartridge containing butane.

4.3.1 The Lilliputian Systems Fuel Cartridge.

The Lilliputian Systems fuel cartridge consisted of a plastic cylinder with a metal fitting at one end. The volume of liquid butane is unknown, but estimated to be 50 cc or less. The fuel cartridge is shown in figure 12.

Figure 12. Lilliputian Systems Fuel Cartridge

4.3.2 Fire Exposure Results for the Lilliputian Systems Fuel Cartridge.

The Lilliputian Systems cartridge was exposed to the 1-propanol baseline fire. The following timeline represents significant events.

- 0:00 1-propanol fire ignited
- 0:45 Plastic enclosure breached, butane released and ignited
- 1:05 Butane fuel consumed
- 2:30 Extinguished with Halon 1211

The plastic enclosure melted, thereby releasing the butane fuel. The fuel ignited, filling the 64-cubic-foot chamber with fire. The butane fuel was consumed in approximately 20 seconds. The plastic enclosure did not support combustion. The temperature results are shown in figure 13. The peak temperature, measured 12″ above the fire pan, was 993.4°F, 703°F above the baseline 1-propanol fire. The peak temperature at the ceiling was 941.1°F, 686°F above the baseline 1-propanol fire. The butane ignition was rapid, almost explosive. The butane cartridge was the only fuel to register a significant heat flux reading. The heat flux peaked at 2.07 Btu/ft^2-sec, 1.8 Btu/ft^2-sec above the baseline 1-propanol fire. The heat flux results are shown in figure 14. The cartridge, after the test, is shown in figure 15.

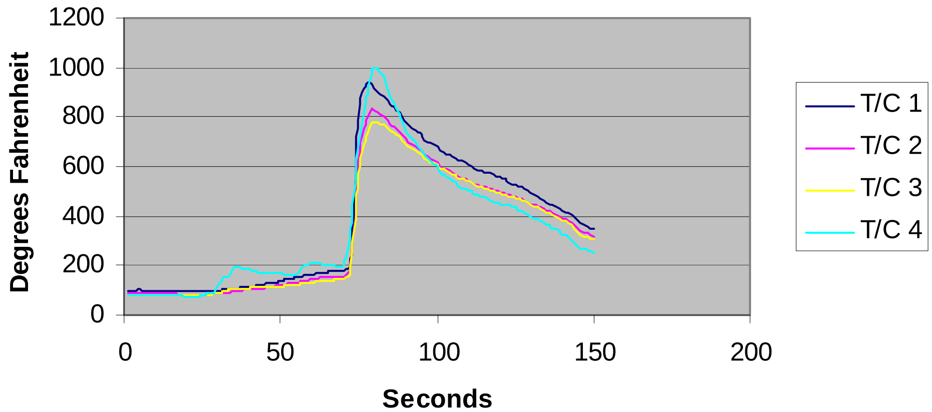


Figure 13. Lilliputian Temperature Results, Butane

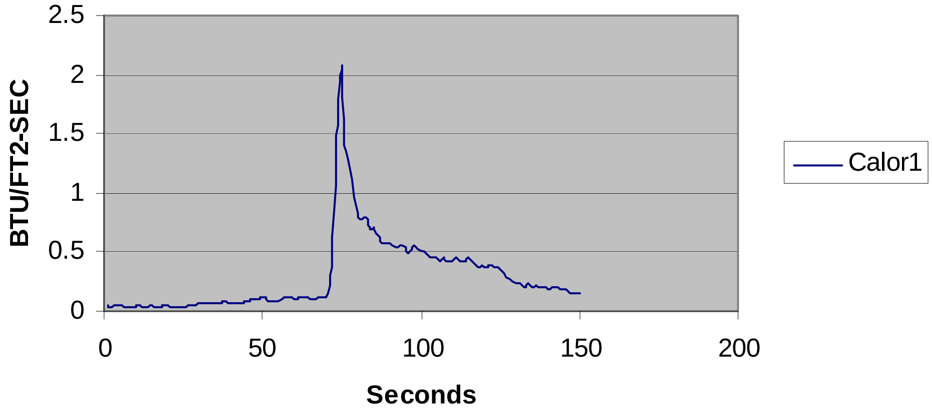


Figure 14. Lilliputian Heat Flux Results, Butane

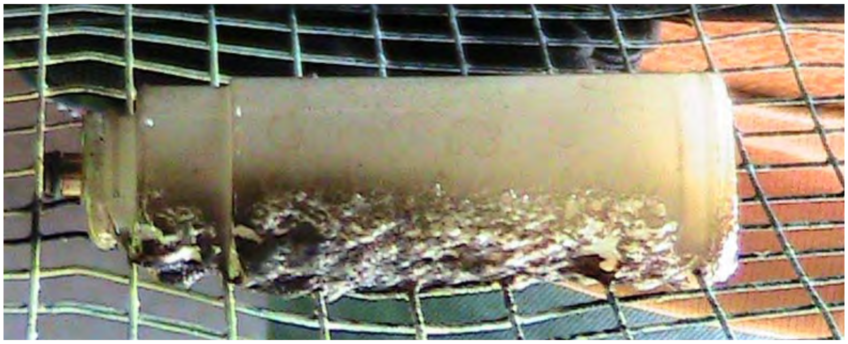


Figure 15. Lilliputian Fuel Cartridge, Posttest

4.4 GASEOUS HYDROGEN FUEL CELL CARTRIDGES.

JADOO Power Systems and ANGSTROM Technology supplied fuel cell fuel cartridges that stored gaseous hydrogen. The two units differed in size and hydrogen capacity.

4.4.1 JADOO Power Systems.

The unit supplied by JADOO Power Systems was a relatively large robust metal cylinder, designated Type C5. There was a plastic end cap on one end, and a metal fitting on the other. The hydrogen gas was stored in a metal hydride under low pressure. The fuel cartridge is shown in figure 16.

Figure 16. JADOO Power Systems Fuel Cartridge

4.4.2 Fire Exposure Results for the JADOO Power Systems Fuel Cartridge.

The JADOO Power Systems fuel cartridge was exposed to the 1-propanol baseline fire. The following timeline represents significant events.

- 0:00 1-propanol fire ignited
- 9:30 Vented hydrogen gas from end cap fitting and ignited
- 15:00 Extinguished with Halon 1211

The JADOO fuel cartridge was initially unaffected by the 1-propanol fire. Very late in the test, the hydrogen was released through the end cap fitting and was ignited. The venting gas formed a torch-like fire that jetted out approximately 18″ from the fitting. The hydrogen fire was reddish in color. This torch gradually diminished in size, until it was only about 8 inches long when the test was terminated by discharging Halon 1211 at the 15-minute mark. The temperature results are shown in figure 17. The peak temperature, measured 12″ above the fire pan, was 338.7°F, 48.7°F above the baseline fire. The peak temperature, measured at the ceiling, was 412.1°F, 157.1°F above the baseline fire. The heat flux was also up slightly, measuring 0.33 Btu/ft^2-sec, 0.12 Btu/ft^2-sec above the baseline 1-propanol fire. The remaining hydrogen fire was easily extinguished Halon 1211. The heat flux results are shown in figure 18.

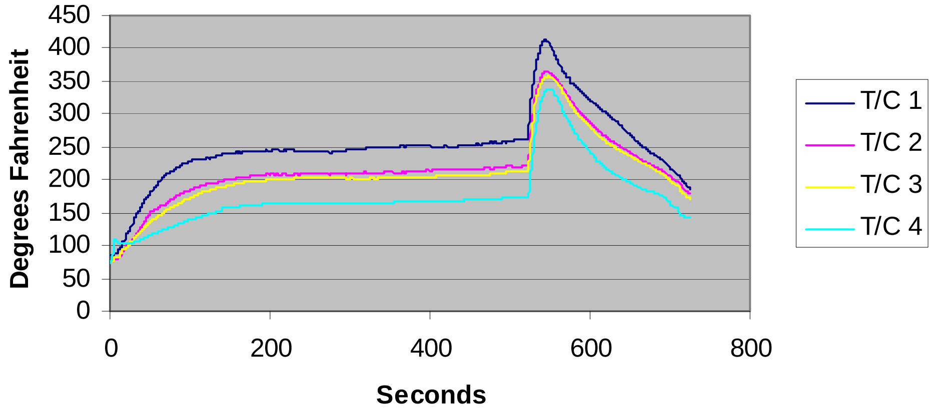


Figure 17. JADOO Power Systems Temperature Results, Hydrogen

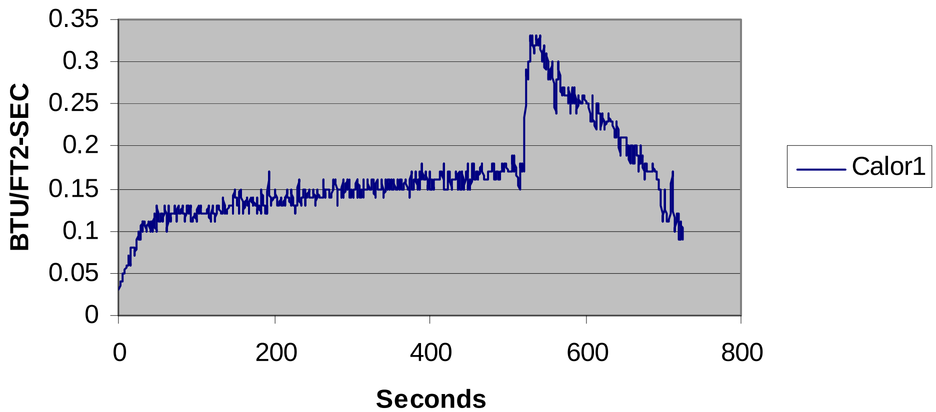


Figure 18. JADOO Power Systems Heat Flux Results, Hydrogen

4.4.3 ANGSTROM Technology.

The unit supplied by ANGSTROM was a small, flat fuel cell designed to power a cell phone. This unit stores hydrogen in a metal hydride under low pressure in a plastic enclosure. The fuel cartridge is shown in figure 19.

Figure 19. ANGSTROM Fuel Cartridge

4.4.4 Fire Exposure Results for the ANGSTROM Fuel Cartridge.

The ANGSTROM fuel cartridge was exposed to the 1-propanol baseline fire. The following timeline represents significant events.

- 0:00 1-propanol fire ignited
- 1:30 Edges of the plastic enclosure glowed red
- 5:30 Red glow ceased
- 11:30 Extinguished with Halon 1211

The ANSTROM fuel cartridge gradually released its hydrogen in a slow, controlled manner. The plastic enclosure charred but did not support combustion. The released hydrogen did not add any measurable intensity to the baseline 1-propanol fire. Peak temperatures were within experimental tolerance of the baseline fire. The cartridge, after the test, is shown in figure 20.

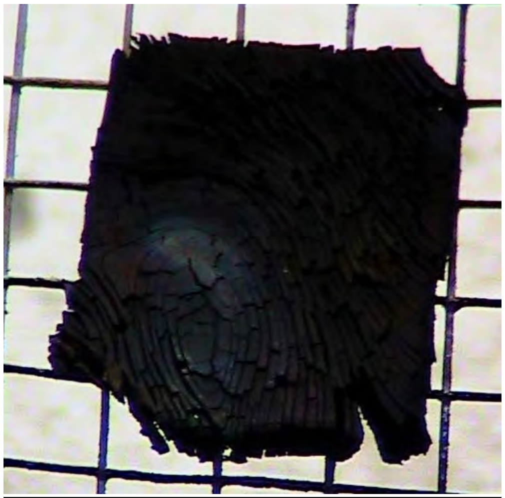


Figure 20. ANGSTROM Fuel Cartridge, Posttest

4.5 SODIUM BOROHYDRIDE.

Several manufacturers supplied fuel cell cartridges that contained sodium borohydride.

4.5.1 Medis Technologies, Ltd.

The unit supplied by Medis Technologies Ltd. was the only complete fuel cell tested. This unit is a one-time-use fuel cell and is not designed to be recharged or have replaceable fuel cartridges. The fuel cell is encased in a plastic enclosure and has parallel vent openings on the top. The fuel type is a mixture of 35 ml of sodium/potassium borohydride solution, 25 ml of potassium hydride solution, and 25 ml of water. The fuel cell is shown in figure 21.

Figure 21. Medis Technologies, Ltd. Fuel Cell

4.5.2 Fire Exposure Results for the Medis Technologies, Ltd. Fuel Cell.

The Medis Technologies, Ltd. fuel cell was exposed to the 1-propanol baseline fire. The following timeline represents significant events.

- 0:00 1-propanol fire ignited
- 1:30 Some venting occurred, increased fire intensity
- 3:20 Venting ceased
- 12:00 Extinguished with Halon 1211

The plastic enclosure deformed when exposed to the 1-propanol fire and supported combustion. This allowed some fuel material to vent into the fire and visually increased the baseline fire by a small amount. There was no rapid burning or forceful venting. The peak temperature, measured 12″ the fire pan, was 230.0°F, 60°F below the baseline. The peak temperature, measured at the ceiling, was 307.3°F, 52.3°F above the baseline. The temperature results are shown in figure 22. The cartridge, after the test, is shown in figure 23.

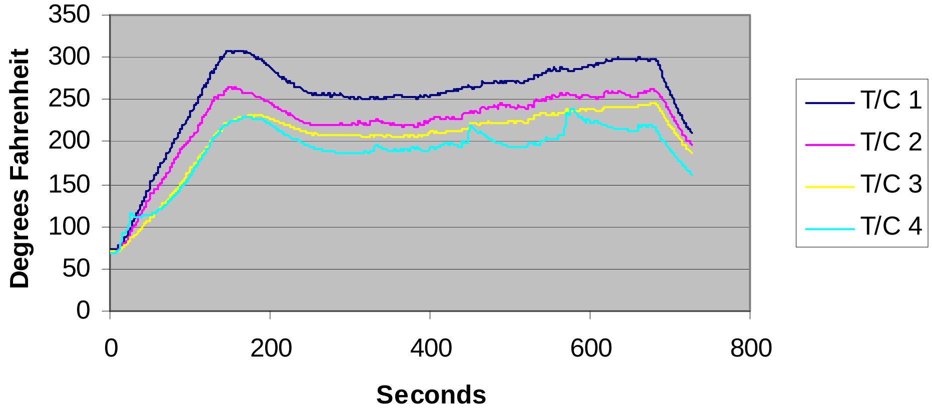


Figure 22. Medis Technologies, Ltd. Temperature Results, Sodium/Potassium Borohydride Solution

Figure 23. Medis Technologies, Ltd. Fuel Cell, Posttest

4.5.3 PROTONEX.

The fuel cartridge supplied by PROTONEX, designated model C720, consisted of a plastic cylindrical enclosure, flattened on the sides with a threaded plug in one end. The fuel type is a mixture of sodium borohydride and sodium hydroxide. The fuel cartridge is shown in figure 24.

Figure 24. PROTONEX Fuel Cartridge

4.5.4 Fire Exposure Results for the PROTONEX Fuel Cartridge.

The PROTONEX fuel cartridge was exposed to the 1-propanol baseline fire. The following timeline represents significant events.

- 0:00 1-propanol fire ignited
- 0:58 Plastic enclosure penetrated
- 7:00 White paste oozes from penetration, small flame visible
- 11:00 Fume buildup in test chamber extinguishes alcohol fire
- 12:00 Small flame on side of fuel cartridge self-extinguishes

The plastic enclosure was penetrated early in the test. The fuel inside did not immediately exhibit any surface burning, however, fumes released by heating the fuel contributed to the baseline fire. Eventually, a white paste oozed from the side of the fuel cartridge and exhibited a small, self-supporting flame. The fume buildup in the chamber extinguished the 1-propanol fire near the end of the test, followed by the self-extinguishment of the small flame on the white paste. The peak temperature, measured 12″ above the fire pan, was 307.8°F, 18°F above the baseline. The peak temperature, measured at the ceiling, was 357.9°F, 102.9°F above the baseline. The temperature results are shown in figure 25. The heat flux also showed a small increase, peak heat flux was 0.29 Btu/ft^2-sec, an increase of 0.09 above the baseline. Heat flux results are shown in figure 26. The fuel cartridge, after the test, is shown in figure 27.

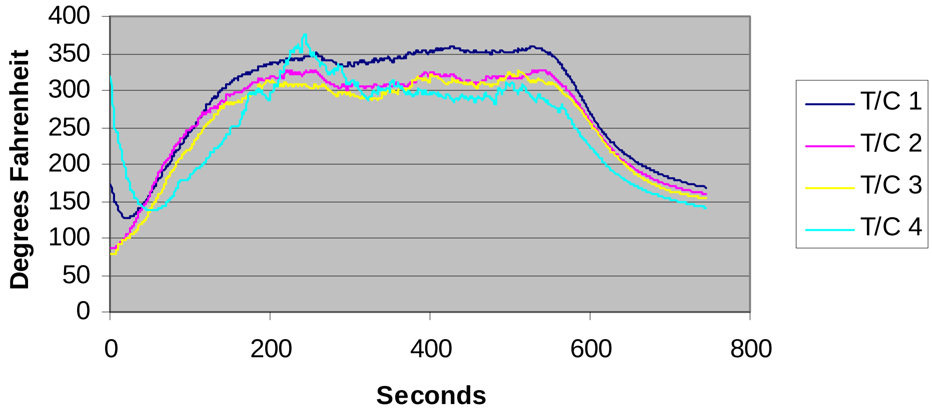


Figure 25. PROTONEX Temperature Results, Sodium Borohydride and Sodium Hydoxide

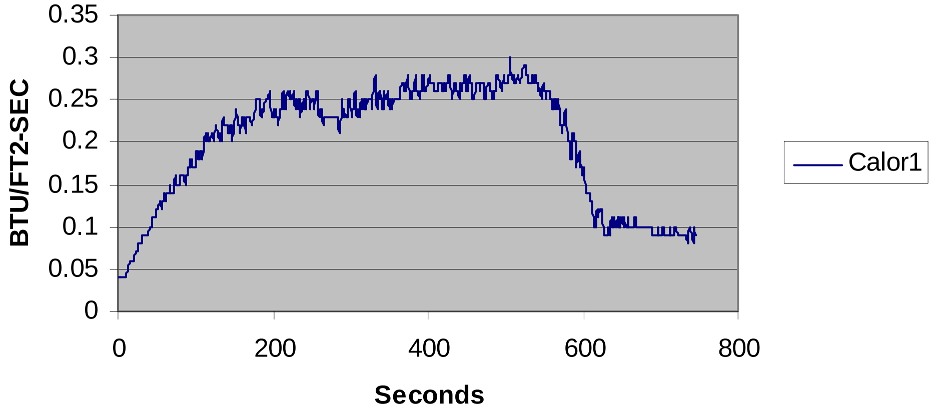


Figure 26. PROTONEX Heat Flux Results, Sodium Borohydride and Sodium Hydoxide

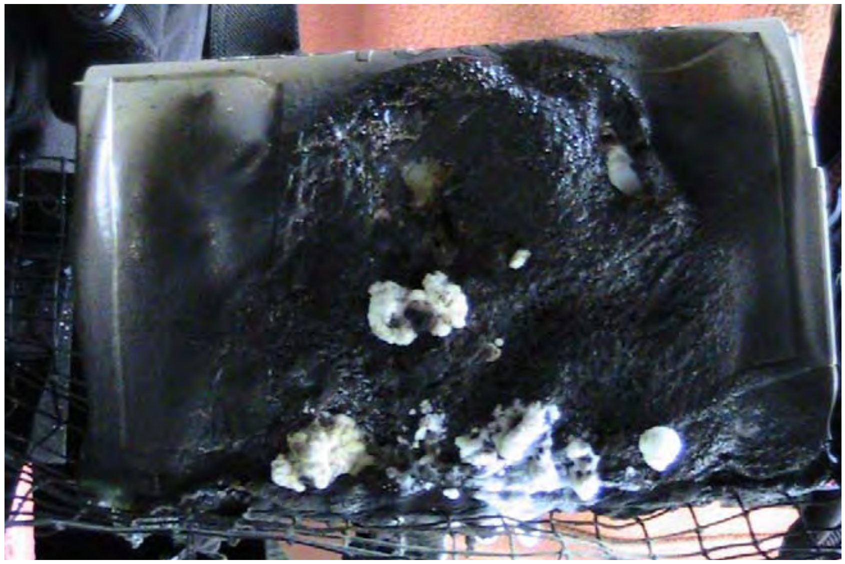


Figure 27. PROTONEX Fuel Cartridge, Posttest

4.5.5 TruLite.

The fuel cartridge supplied by TruLite, designated model KH4 HydroCell, consisted of a metal cylinder with a plastic end cap. The fuel type is listed as sodium borohydride. The fuel cartridge is shown in figure 28.

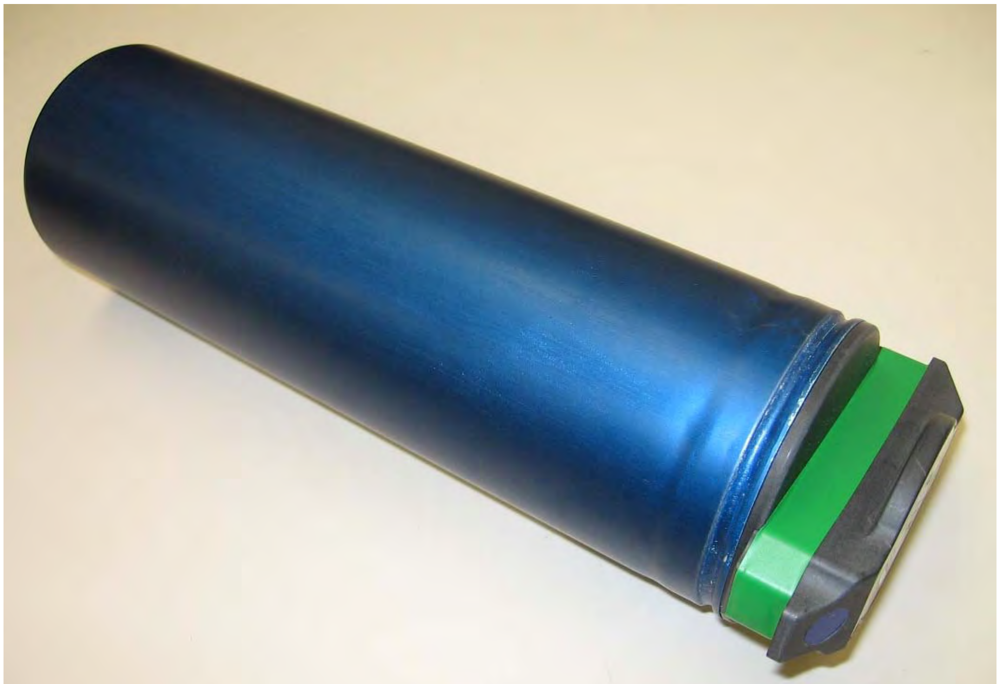


Figure 28. TruLite Fuel Cartridge

4.5.6 Fire Exposure Results for the TruLite Fuel Cartridge.

The TruLite fuel cartridge was exposed to the 1-propanol baseline fire. The following timeline represents significant events.

- 0:00 1-propanol fire ignited
- 4:04 End cap deformed and pulled away from the cylinder
- 8:00 1-propanol fire extinguished by fumes

The metal cylinder contained the fuel for most of the test. The plastic end cap deformed and pulled away from the cylinder, exposing the interior contents. There was a metal screen located under the cap that prevented any fuel from spilling out. Some fumes were released as the cylinder was heated, which increased the intensity of the baseline fire. These same fumes eventually extinguished the 1-propanol baseline fire. There was no visible surface burning of the sodium borohydride and the cylinder cooled to room temperature in a normal amount of time, indicating that there was no deep-seated fuel fire within the cylinder. The peak temperature, measured 12″ above the fire pan, was 311.8°F, 21.8°F below the baseline. The peak temperature, measured at the ceiling, was 275.9°F, 20.9°F above the baseline. The temperature results are shown in figure 29. Figure 30 shows a posttest photograph of the TruLite fuel cartridge.

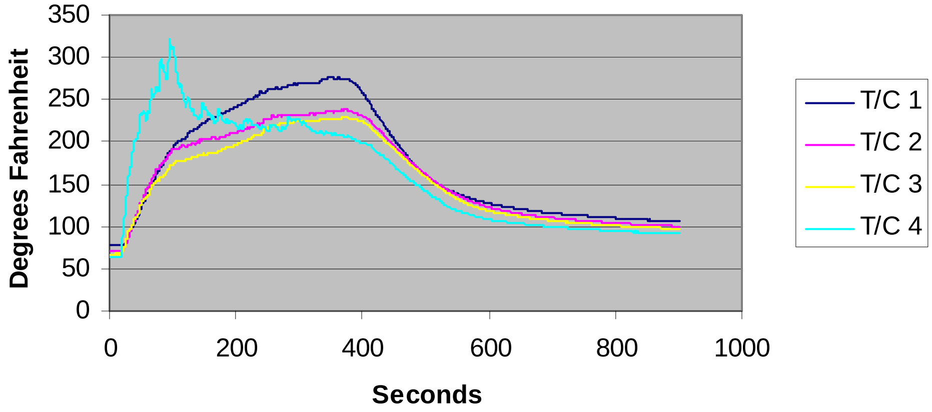


Figure 29. TruLite Temperature Results, Sodium Borohydride

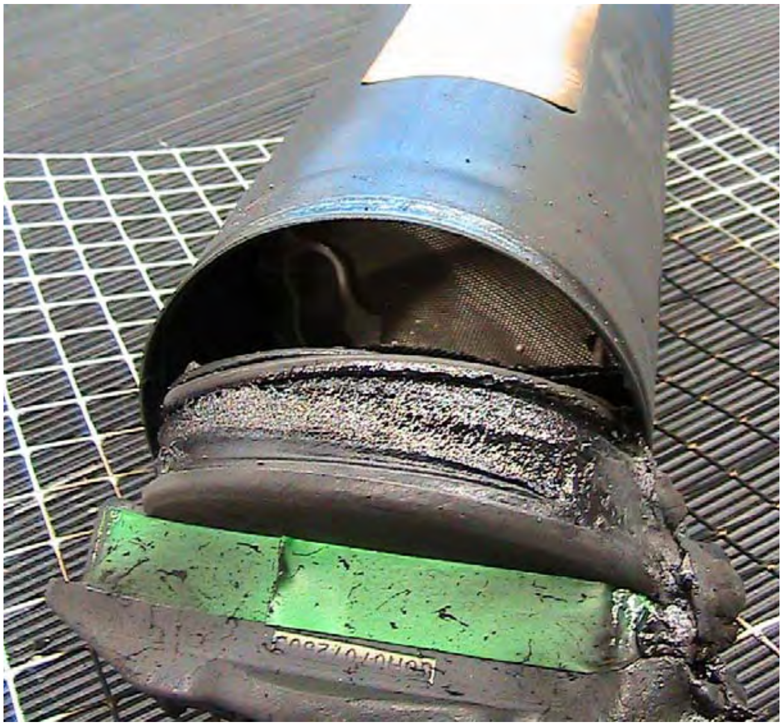


Figure 30. TruLite Fuel Cartridge, Posttest

4.5.7 Millennium Cell.

Millennium Cell provided only the fuel in a loose form, not enclosed in a cartridge. The fuel was a mixture of sodium hydroxide and sodium borohydride. This mixture was placed in a 2″ pipe cap, exposing the fuel on the top side to the baseline fire.

4.5.8 Fire Exposure Results for the Millennium Cell Fuel.

The Millennium Cell fuel was exposed to the 1-propanol baseline fire. The following timeline represents significant events.

- 0:00 1-propanol fire ignited
- 0:32 Fuel ignited with small surface flame
- 12:00 Flame was extinguished with Halon 1211; the 1-propanol fire extinguished at the same time.
- 15:00 Fuel reignited, pipe cap was hot

This fuel appears to be the same type use in the PROTONEX fuel cartridge. It exhibited the same surface burning. Under these test conditions, the fuel also developed a deep-seated exothermic chemical reaction that remained hot for 2 hours after the fire test. Halon 1211 had no effect on this deep-seated reaction. In the quantities tested here, the fuel did not have any effect on the baseline fire. Peak temperatures were within the experimental tolerance of the baseline fire.

5. DISCUSSION.

5.1 METHANOL.

Methanol proved flammable under test conditions, as expected. The size of the added fire was proportional to the volume of methanol in the cartridge. The metal enclosure resisted the external fire better than plastic, but each released the contents readily. Halon 1211 was effective in extinguishing a methanol fire.

5.2 FORMIC ACID.

Formic acid is listed as flammable in the MSDS. However, in these tests, it did not ignite. The acid squirted from the enclosure in a stream approximately 2′ to 3′ long. The corrosive nature of the fuel could pose a heath hazard under these conditions.

5.3 BUTANE.

Butane was the most flammable of the fuels tested. The cartridge provided the least amount of protection from an external fire. Once penetrated, the liquid butane burned rapidly, filling the test chamber with fire. The butane fire registered the highest temperature and heat flux measurements. Halon 1211 should be effective, but was not tested.

5.4 HYDROGEN GAS.

The volume of hydrogen gas as well as the storage method affected the flammability of the cartridges. The construction of the high-volume JADOO unit resisted the external fuel fire longer than any other unit. However, when it failed, it released the hydrogen gas from its metal hydride in a torch-like manner. The ANGSTROM unit, a much lower-volume cartridge, stored the hydrogen in a metal hydride that released the gas slowly. The hydrogen fires were extinguishable with Halon 1211.

5.5 BOROHYDRIDES.

The various borohydrides proved difficult to ignite. Heating the fuel seemed to produce a fume that added to the baseline fire. The same fume built-up in the chamber, eventually extinguishing the 1-propanol fire. Once exposed, the borohydride burned with a small surface flame. The test with the fuel only in a metal pipe cap showed that the fuel was capable of deep-seated exothermic chemical reaction that was unaffected by Halon 1211.

6. CONCLUSIONS.

The following conclusions were drawn as a result of the tests performed.

- The cartridge material and construction can have a significant effect on the fuel flammability. Metal cartridges resisted the external fire better than plastic cartridges. Some plastic material was flammable.
- Formic acid did not ignite under the test conditions, although it is listed as flammable in the Material Safety Data Sheet.
- Butane produced the most vigorous fire, registering the highest temperatures and heat flux readings.
- Hydrogen gas stored in a metal matrix is under low pressure. Breaching of the enclosure allows the gas to escape and ignite.
- Borohydrides were difficult to ignite, gave off a flammable fume when heated, and were capable of deep-seated exothermic reaction when heated.
- Halon 1211 is effective against all but the deep-seated borohydride exothermic reaction.

7. REFERENCES.

1. Webster, H., "Flammability Assessment of Bulk-Packed, Nonrechargeable Lithium Primary Batteries in Transport Category Aircraft," FAA report DOT/FAA/AR-04/26, June 2004.
2. Webster, H., "Flammability Assessment of Bulk-Packed, Rechargeable Lithium-Ion Cells in Transport Category Aircraft," FAA report DOT/FAA/AR-06/38, September 2006.