



Federal Aviation
Administration

2015 Fire Safety Highlights



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Analysis of the Gasses Vented From Lithium Batteries and Their Effect on Aircraft Fire Protection

Lithium-ion and lithium-metal cells are known to undergo a process called thermal runaway during failure conditions. Thermal runaway results in a rapid increase in temperature of the battery cells accompanied by the release of flammable gas. These flammable gasses will often times be ignited by the high temperature of the battery and result in a fire. In addition to the combustion of these gasses as they vent, however, under certain conditions they may vent unburned, and their accumulation and potential explosion is of concern.

Thermal runaway events of lithium-metal and lithium-ion cells have resulted in numerous fires. Some of the notable fire events within the aircraft environment include an aircraft APU battery, an aircraft main battery and one aircraft ELT battery. In addition to lithium batteries installed on the aircraft, hundreds of millions of them are shipped every year as cargo. A Class-C cargo compartment is equipped to have an initial concentration of 5% Halon 1301 fire suppressing agent followed by a residual concentration of 3% for the remainder of a flight. These halon concentrations are effective at mitigating fires involving typical cargo materials: however, there is concern of whether these concentrations are sufficient to suppress a cargo fire involving lithium batteries and to mitigate the risks of a potential explosion of the accumulated vented battery gasses.

A series of tests were conducted to (1) analyze the various gasses that were vented from lithium cells in thermal runaway and (2) evaluate the risk of the build-up and ignition of lithium battery gasses within an aircraft cargo environment.

Small scale tests were carried out in a 21.7 liter combustion sphere where a gas chromatograph, NDIR (non-dispersive infrared) analyzer, paramagnetic analyzer and pressure transducer were used to quantify the individual gasses released from lithium batteries. Once the gas constituents were quantified, tests were performed to measure the pressure increase from combustion. Later, large scale tests were conducted in a 10.8m³ combustion chamber, a volume comparable to the volume of a relatively small loaded cargo compartment, to validate the small scale tests and evaluate the effect of halon 1301 on combustion of the battery vent gas.

Results of the small scale tests showed that the volume of gas emitted from cells increased with state-of-charge (SOC) as shown in figure 1. The gasses measured were carbon monoxide (CO), hydrogen (H₂) and total hydrocarbons (THC). Combustion of the gasses showed a lower flammability limit of 10% and an upper flammability limit

that varied from about 35% to 45% depending on SOC. The combustion tests also showed a maximum pressure rise of over 70 psia at a pressure corresponding to cruise altitude..

As shown in figure 2, tests conducted at approximately 5% halon concentration, which is the design concentration for aircraft cargo compartments, resulted in little change to the resulting pressure rise. Tests at approximately 10% concentration were required in order to inert the cargo compartment such that the battery gases were unable to be ignited.

In summary, the results of these tests showed that the lithium battery SOC affected gas volume substantially and that ignition of the flammable gases could result in an explosion that would compromise the safety of an aircraft. The Halon 1301 fire suppression system showed minimal effectiveness against battery gases at the current design concentration of 5%.

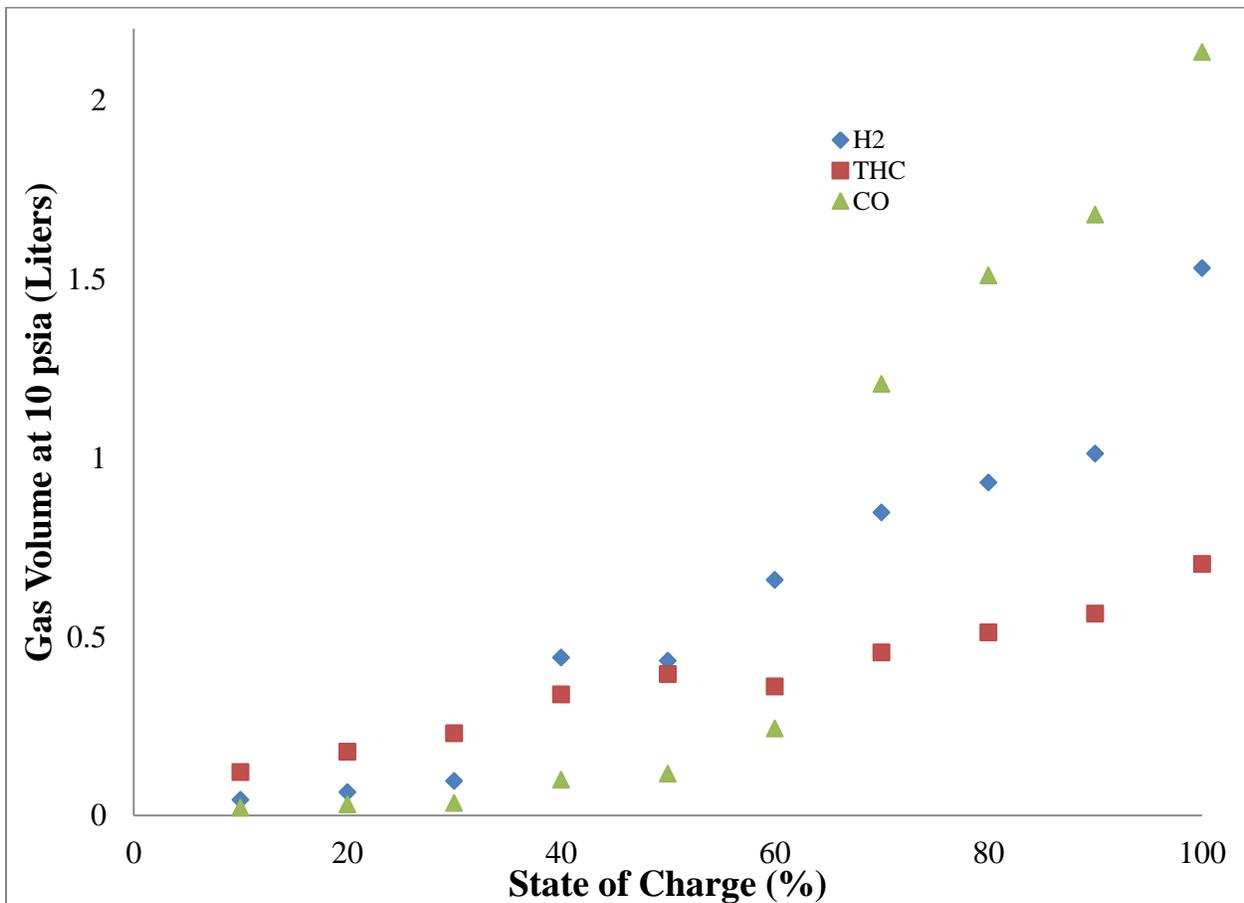


Figure 1: Variation of Flammable Gasses with SOC

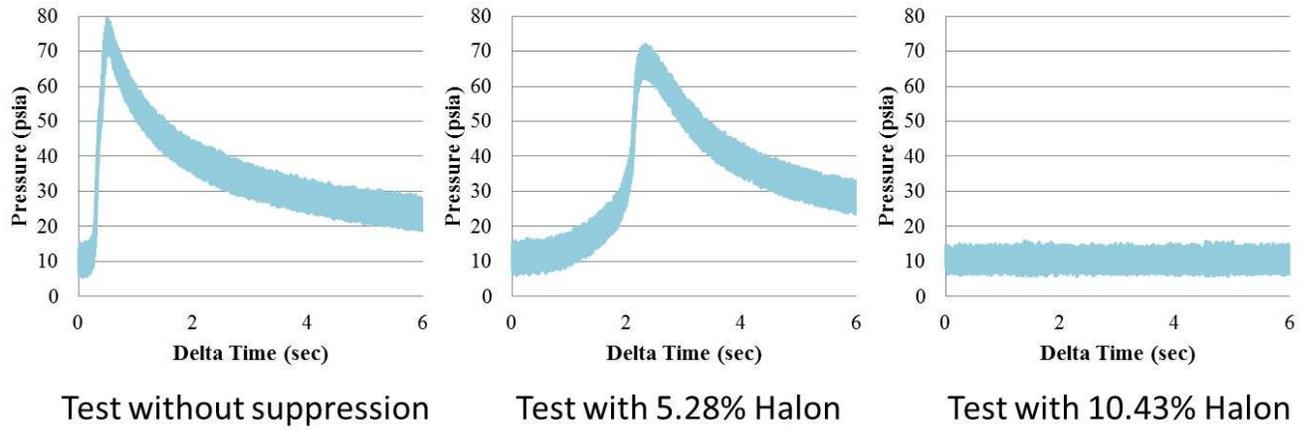


Figure 2: Combustion of Lithium Battery Vent Gasses with Various Quantities of Halon 1301

Energetics of Lithium Ion Battery Failure

Thermal runaway is an auto-accelerating, exothermic (heat generating) process caused by an internal short circuit in an electrochemical cell/battery. Thermal runaway can be initiated by a contaminant, manufacturing defect, mechanical insult, overcharging, or by the heat of a fire. Cell failure results in rapid internal heat generation with ejection of the cell components, including combustible electrolytes that can burn or explode in a baggage compartment, causing an accident. Failure of a single cell is a low probability event ($\approx 10^{-7}$), but the large number of cells shipped as cargo and the severe impact of an event on the survivability of the aircraft make the risk to passengers a safety concern. The present study addresses how rechargeable 18-mm diameter by 65-mm long cylindrical (18650) rechargeable lithium ion cells/batteries (LIBs) impact fire safety when these energy storage devices are carried on airplanes in passenger electronics or shipped as cargo. To this end, a thermal capacitance calorimeter [1], a bomb calorimeter [2,3] and a fire calorimeter [1] were used to measure the heat generated inside the cell during thermal runaway and the heat generated outside the cell by combustion of the cell contents of commercial 18650 cells/batteries having different cathode chemistries and charged to various degrees. Electrical resistance (Joule) heating of the cells was used to induce failure in the thermal capacitance and bomb calorimeters, while radiant heat was used to initiate thermal runaway in the fire calorimeter. In each case, internal heat generation began at about 150°C and thermal runaway commenced in earnest at about 200-250°C. Figure 1 is a high-speed thermal image of an 18650 lithium ion battery during the early stages of thermal runaway [4]. Temperatures are color-coded and range from room temperature 25°C (blue) to 250°C (white). Localized heating and venting of combustible electrolytes as liquid and gaseous jets are observed early in the failure history (Figure 1A). Thermal runaway is auto-acceleratory and complete within seconds of reaching 250°C [1], with total failure of the cell as shown in Figure 1B [4].

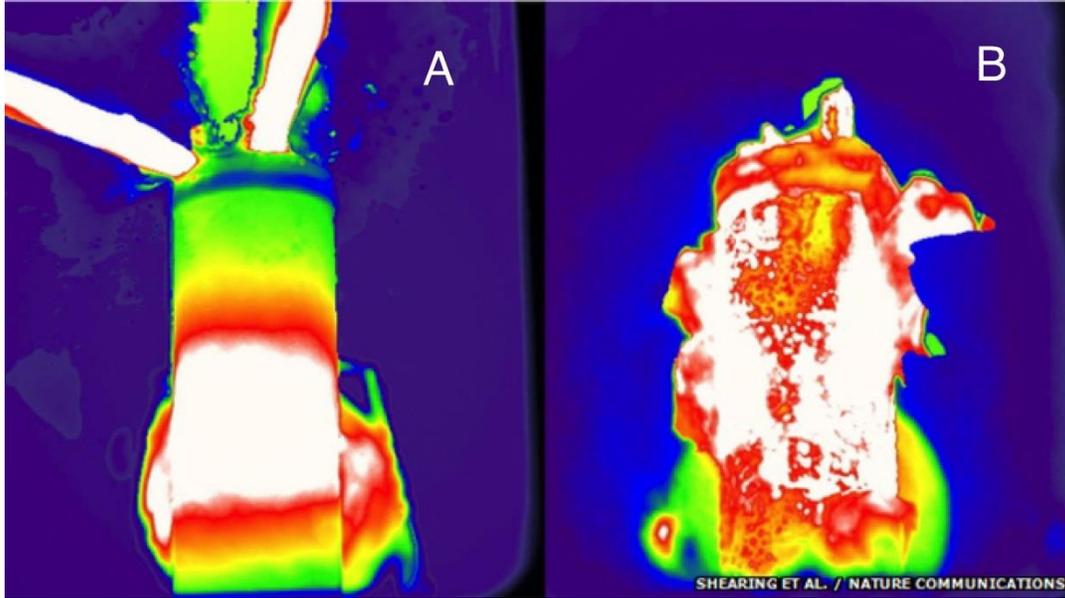


Figure 1. High-Speed Thermal Image Of 18650 Lithium Ion Battery In Thermal Runaway [1].

During thermal runaway the rate of heat generation inside the cell greatly exceeds the heat losses to the outside from the surface so the increase in the cell temperature at failure, ΔT_f , is equal to the amount of heat liberated at failure, ΔH_f , divided by the thermal capacity of the cell, which is the initial mass of the cell m_0 (kg) times its specific heat c_p (J/kg-K),

$$\Delta T_f = \frac{\Delta H_f}{m_0 c_p} \quad (1)$$

The temperature rise ΔT_f of the cell measured in the thermal capacitance calorimeter increased with the amount of stored electrical energy, $E = \varepsilon Q$, where ε is the cell potential in Volts (V) and Q is the charge on the cell in Coulombs (A-s) [2]. Equation 1 predicts a fully charged lithium cobalt oxide (LiCoO_2) 18650 cell with $m_0 = 0.044$ kg and $c_p = 1000$ kJ/kg will reach an internal temperature at failure, $T_f \approx 1200^\circ\text{C}$ (2200°F) for the measured ΔH_f in Figure 2, which is consistent with the presence of molten copper

electrode in the ejected cell contents [1,4] and is sufficiently high to ignite the combustible electrolytes ejected at cell failure [1-3]. The total heat released at cell failure ΔH_f was measured in a bomb calorimeter and was assumed to be equal to the stored electrical energy E plus the chemical energy of mixing, reaction, and thermal decomposition of the cell components, ΔU_{rxn} ,

$$\Delta H_f = E + \Delta U_{rxn} \quad (2)$$

Figure 2 shows measured values for the stored electrical energy E , the total heat liberated at failure ΔH_f , and the energy of the chemical/decomposition reactions ΔU_{rxn} (obtained by difference), versus the fractional charge on the cell, $Z = Q/Q_{max}$, where Q_{max} is the maximum/rated capacity of the cell in Coulombs. Figure 2 shows that E and ΔU_{rxn} contribute roughly equal amounts to ΔH_f , but their magnitudes are highly dependent on the type of cell (cathode chemistry), varying by as much as a factor of 3 between these cells. Figure 2A shows that the total heat release at battery failure ΔH_f is well correlated by the stored electrical energy, E , independent of cathode chemistry. In contrast, Figure 2B shows that ΔH_f has a strong dependence on cathode chemistry when fractional charge Z is used as the predictor (x -axis) variable.

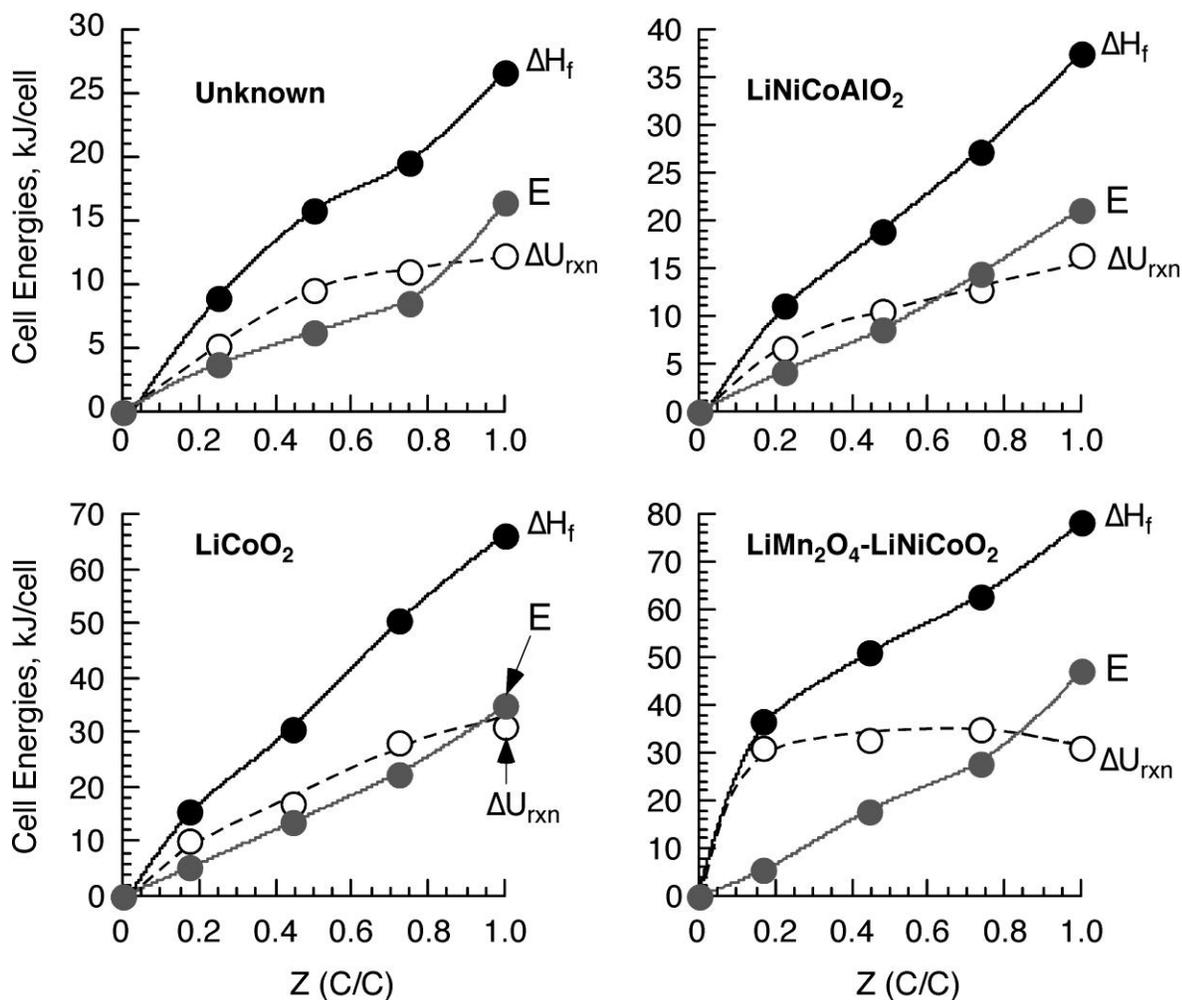


Figure 2. Stored Electrical Energy E , Chemical Reaction Energy ΔU_{rxn} , and Total Heat Released at Cell Failure, $\Delta H_f = E + \Delta U_{\text{rxn}}$, Versus the Fractional Charge, Z for Four Different 18650 Lithium Ion Batteries.

Figure 3 is a plot of the total heat released at cell failure measured in the bomb calorimeter ΔH_f versus- A) the stored electrical energy E and, B) the fractional charge, Z for each of the 4 lithium ion cells of Figure 2. Figure 3A shows that ΔH_f is well correlated by E regardless of the cell cathode chemistry, while a strong dependence on cell chemistry is observed when Z is the predictor (x-axis) variable.

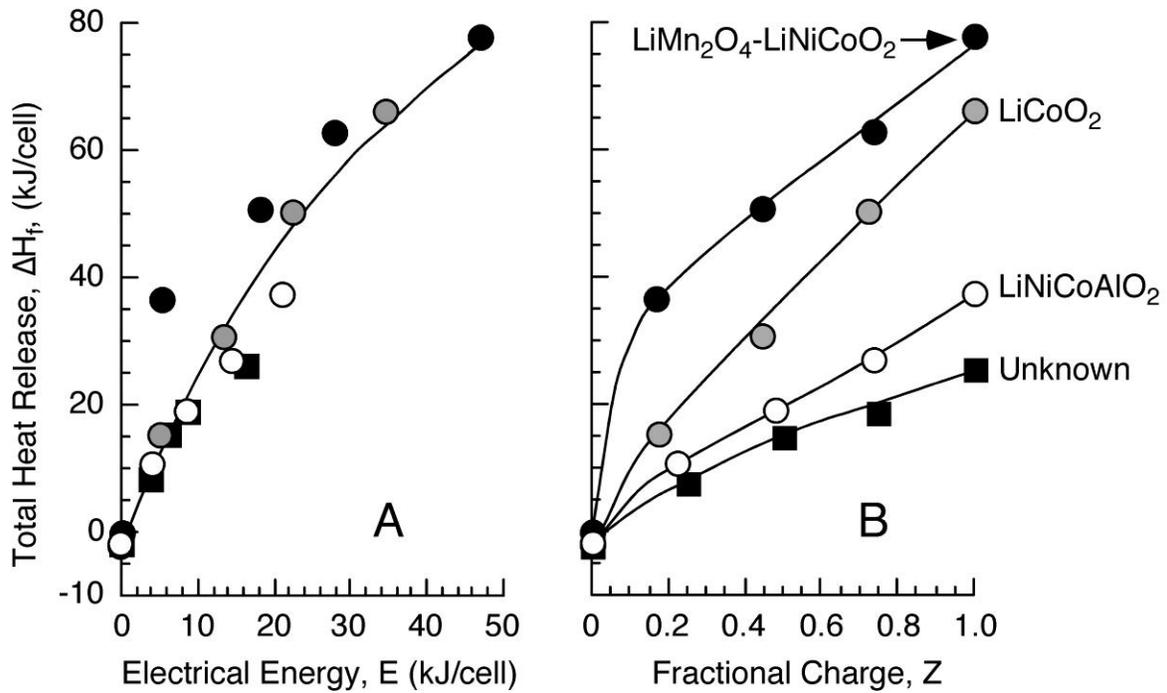


Figure 3. Total Heat Release, ΔH_f , at Cell Failure Versus: A) Stored Electrical Energy E , and B) Fractional Charge, Z for the Four 18650 Lithium Ion Cells/Batteries of Figure 2.

The heat generated by flaming combustion of the electrolytes released at cell failure was estimated by multiplying the mass of volatiles measured in the inert (nitrogen) environment of the bomb calorimeter m_f (kg) by the average effective heat of combustion EHOc (J/kg) of the ejected cell contents in air measured in the fire (cone) calorimeter, i.e.,

$$\Delta H_c = m_f \times EHOc \quad (3)$$

Figure 4 compares the heat released inside the cell during failure, ΔH_f from Figure 2 to the heat released outside the cell by flaming combustion of the volatile organic electrolytes in a fire calorimeter, ΔH_c for the 4 cells/batteries of Figure 2. Figure 4A shows that the heat released inside the cell at failure ΔH_f is comparable to the heat released outside the cell by the burning electrolytes ΔH_c , and that the data are

reasonably well correlated using the stored electrical energy E as the predictor variable (x -axis). Figure 4B shows that these same data are poorly correlated when the fractional charge Z is used as the predictor variable.

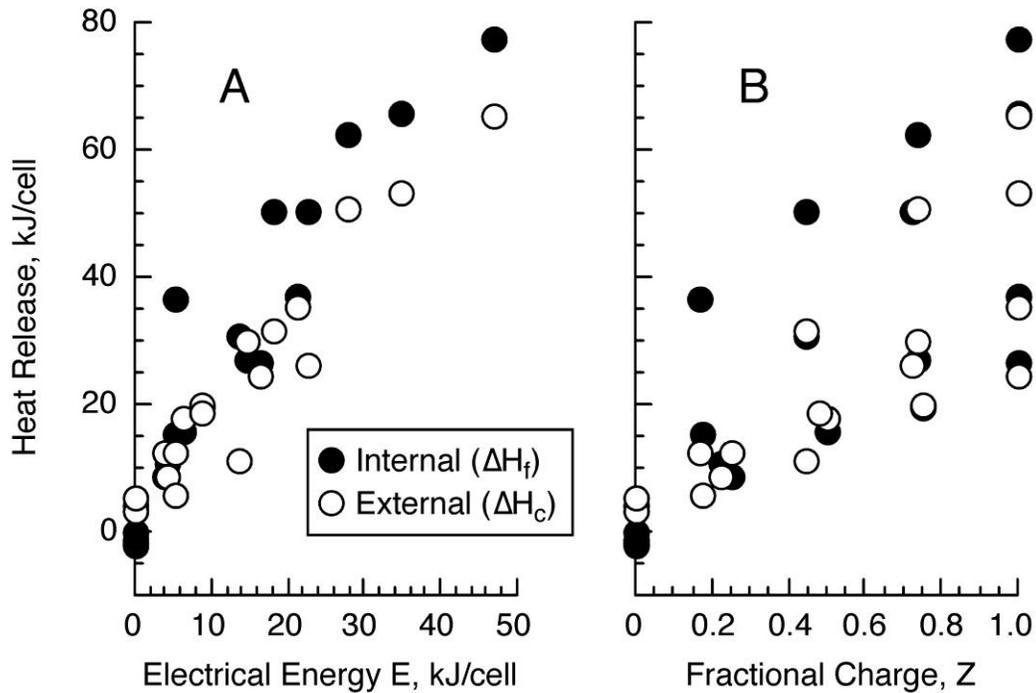


Figure 4. Heat Released Inside Cell at Failure, ΔH_f , and Heat Released Outside the Cell by Burning of the Electrolytes ΔH_c , Versus: A) Stored Electrical Energy E and; B) Fractional Charge, Z for the Four 18650 Lithium Ion Cells/Batteries of Figure 2.

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1. J.G. Quintiere, R.N. Walters, S. Crowley and R.E. Lyon, Fire Hazards of Lithium Batteries, Technical Note DOT/FAA/TC-TN15/17, Federal Aviation Administration, February 2016.

2. R.N. Walters and R.E. Lyon, Measuring Energy Release of Lithium Ion Battery Failure Using a Bomb Calorimeter, Technical Note DOT/FAA/TC-TN15/40, Federal Aviation Administration, March 2016.
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4. D.P. Finegan, M. Scheel, J.B. Robinson, B. Tjaden, I. Hunt, T.J. Mason, J. Millichamp, M. Di Michiel, G.J. Offer, G. Hinds, D.J.L. Brett, and P.R. Shearing, In-Operando High-Speed Tomography Of Lithium-Ion Batteries During Thermal Runaway, *Nature Communications*, 6924, April 28, 2015.

Evaluating a Novel Halon-Replacement Fire Extinguishing Agent in an Engine Nacelle Fire Simulator

Testing occurred during August 2014 through February 2015 to evaluate a blended fire extinguishing agent intended to replace halon 1301, as might be used in the fire zones of a large transport aircraft's engine nacelle and auxiliary power unit (APU) compartments. The testing was completed consistent with the 4TH revision of the "Minimum Performance Standards for Halon 1301 Replacement in the Fire Extinguishing Agents/Systems of Civil Aircraft Engine and Auxiliary Power Unit Compartments" (MPSHRe). The testing occurred in the nacelle fire simulator (NFS) belonging to and operated by the Fire Safety Branch within the U.S. Federal Aviation Administration (FAA), located at the FAA's WJ Hughes Technical Center (FAATC). Personnel supporting this testing activity were from an aviation industry team, the FAA, FAATC contract support staff, and the European Aviation Safety Agency (EASA). Additional supporting activities were completed locally which preceded and interlaced with the indicated testing dates.

The MPSHRe test process, providing one means to replace halon 1301 in this civil aviation application, exists as a working document, which has been publically available throughout. Developing the MPSHRe guidance began in 1995 and currently exists in its 4TH revision. This process represents the effort of the civil aviation community for this issue, as promulgated by a task group within the International Aircraft Systems Fire Protection Working Group. Tangible work has been previously completed at the FAATC, within its NFS.

The MPSHRe process is two-part, where (i) issues relating to the end-use of a halon-replacement candidate must be shown acceptable and (ii) the halon-replacement candidate is subject to testing to prove acceptable fire extinguishment capabilities. The testing component occurs in a full-scale test fixture capable of providing forced ventilation flows, fire threats, and fire extinguishing agent storage and delivery, which is wholly analogous to a fire and its extinguishment in an engine fire zone, although the article is not actually an aircraft engine. The FAATC NFS satisfies requirements of MPSHRe revision 4. Much detail and background exists pertaining to the MPSHRe-driven test process which is omitted because it is beyond the scope of this writing. A reader more curious about such detail is advised to obtain and review the MPSHRe to satisfy such curiosities.

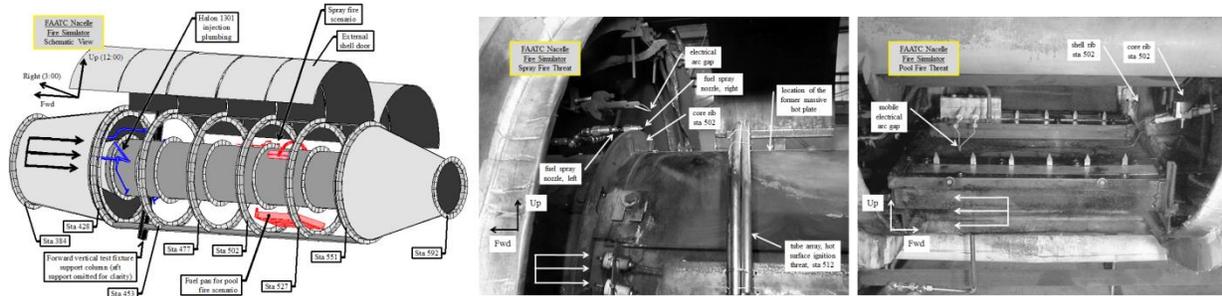


Figure 1. Detail Imagery of the FAATC NFS.

Evaluations to effect halon 1301 replacement occur in the FAATC NFS test section, which has an annular cross section of 0.88 m^2 , based on an inside diameter of 0.6 m and a 1.2 m exterior. The test section's annular volume is 2.83 m^3 , excluding the inlet and outlet transitions. The fixture is primarily made of 6.4 mm thick mild steel. The fire threats are located 1.8 m downstream from the front, constant cross-sectional plane of the test section. A spray fire threat resides at 12:00 and a pool at 06:00. Fire extinguishing agent is injected near the test section inlet. Its external delivery plumbing penetrates the inlet transition to permit internal injection.

Halon 1301 behavior is known for a "protected" volume of 0.53 m^3 inside the FAATC NFS, centered on the upstream end of the fire threats, and related to indications measured by a modified Statham-derivative gas analyzer at 12 points within this volume dispersed along 3 rings of 4 points. The halon 1301 delivered to the "protected" volume is described by (i) volume concentration and (ii) a resident duration of $\frac{1}{2}$ second, which is analogous in form to the FAA certification criteria for halon 1301 of 6%v/v halon 1301 for $\frac{1}{2}$ second.

The air-based ventilation flows internal to the FAATC NFS are approximately 1.2 kg/s at $T \approx 38^\circ\text{C}$ or 0.45 kg/s at $T \approx 127^\circ\text{C}$. The spray fire threat is based upon an aviation turbine fuel (JP-8), lubricating oil or hydraulic fluid. Two fuel nozzles each deliver a 60° hollow cone producing a total fuel flow rate of 0.95 liters/min. The spray fire is electrically ignited and interacts persistently with the electrical ignition source while simultaneously heating a collection of stainless steel tubes which poses an autoignition ("hot surface") threat by the time of agent interaction. Aviation turbine fuel fires the pool fire threat. The pool is 51 cm long x 27 cm wide x 1.27 cm deep. The pool fire is electrically ignited and interacts persistently with the electrical ignition source. The bulk fuel temperature is $63\text{-}68^\circ\text{C}$ when ignited for any fire extinguishment test.

Per the MPSHRe, evaluating a replacement candidate for halon 1301 parity requires testing in at least 4 conditions. These conditions result from combining 2 forced ventilation flows and 2 fire threats. The fire threat is either pool- or spray-based. When delivered satisfying FAA certification criteria, halon 1301 behavior for these conditions is characterized and monitored in the FAATC NFS over time.

A blended fire extinguishing agent was assessed per MPSHRe revision 4 during August 2014 through February 2015. During the completion of this project, more than 100 tests were completed to acceptably progress through the MPSHRe-indicated test process. The tests were accomplished either (i) to perform measurements of the replacement candidate's concentration field as it migrated through the NFS in the internal forced ventilation flow or (ii) to assess the candidate's ability to extinguish fire, as compared to halon 1301. See figure 2 for imagery representative of the progression through a pool fire extinguishment test.



Figure 2. Imagery Representative of the Progression Through a Pool Fire Extinguishment Test in the FAATC NFS.

Additional testing was completed to assess if the candidate would pose atypical challenges, given the candidate's atypical blended composition. The gas analyzer typically used for concentration measurement in aircraft engine and APU fire zones relies upon a differential pressure measurement signal and relates to a concentration analyzer originally manufactured by Statham Laboratories. Because multiple species in the candidate's blend are independently detectable by Statham-derivative gas analyzers, a smaller set of tests were accomplished with independent collection and analysis by alternate concentration measurement method, to affirm a substantiated belief the blended candidate would perform acceptably within an envelope of conditions, thus permitting the use of a Statham-derivative gas analyzer for candidate distribution analysis. The second method of concentration analysis utilized a non-dispersive infrared technique. The independent collection and concentration analysis affirmed the use of a

Stham-derivative analyzer for an envelope of conditions, and contributed to observing how the candidate behaved when outside the envelope of Stham-derivative analyzer use.

The project outcomes were (i) the recommendation of a concentration value for the candidate that can be considered equal to that of halon 1301 as specified for this application by the FAA, (ii) the affirmation that a Stham-derivative gas analyzer can be used to measure the distribution of the candidate in a forced ventilation flow within a given envelope of test conditions, and (iii) an extended duration of work that contributed additional experience and knowledge to better generally understand the candidate. The recommendation of the candidate's concentration for future certification action is in preliminary review at this time. As such, the value is not reported here, as that value may change during review.

The Development of a Flame Propagation Test Method for Composite Fuselage Structure

The increasing use of composite materials as primary and secondary structures in commercial airplanes presents unique certification challenges for the Federal Aviation Administration (FAA). Traditional metallic structures do not react with fires and, therefore, have not been required to meet any of the FAA's cabin interior fire test requirements, which have increased in severity in recent years to protect against fires in inaccessible areas after the fatal in-flight fire of Swissair 111 in September 1998. A composite airplane introduces large surface areas of composite materials into the inaccessible areas, as the inboard surface of the skin and all of the structures are located behind the cabin sidewalls and thermal/acoustic insulation, potentially introducing flammability hazards into an area where fire detection and extinguishment is difficult. By mandating that the composite structural materials must be resistant to propagating flames and self-extinguishing when exposed to a moderately sized fire, the FAA can ensure that a fire in an inaccessible area will be localized and short-lived, allowing for continued safe flight and landing of the airplane.

To date, the FAA has imposed Special Conditions to certify composite fuselage airplanes for flame propagation resistance. These Special Conditions are typically met by placing a moderately sized fire adjacent to a representative composite skin and structure test article, between the thermal acoustic insulation and the composite. The fire source is ignited, and allowed to burn to extinguishment. Once it is apparent that the fire burned completely, the test article is inspected for visible evidence of flame propagation along its surface, which is evidenced by regions of delamination and exposed carbon fibers. If the fire remained in a localized area and did not travel extensively along the composite, then the material is considered to be safe for use in inaccessible areas. Although the Special Conditions are an adequate safety determination means, a more standardized and universally-applicable evaluation method is desired to use for future composite fuselage certification applications. The Fire Safety Branch was tasked with developing a laboratory-scale test method that simulates the conditions of the tests used to comply with the Special Conditions certifications tests done so far.

Initially, a test rig was developed to perform multiple intermediate-scale composite flame propagation tests in a controlled environment. The rig, displayed in Figure 1, is a variable-angle composite panel holder that simulates the effects of a confined inaccessible area near a composite fuselage skin. The fire source was a 4-inch wide by 4-inch deep by 9-inch tall urethane foam block with 10 milliliters of heptane soaked in the bottom to provide uniform burning. A variety of aerospace and non-aerospace grade composite materials were acquired for evaluation in the test rig. All test samples

were assessed for post-test flame propagation length and width. The results from these initial tests were used to correlate a new laboratory-scale test to performance of the same materials in tests similar to the Special Conditions tests. These tests also confirmed the flame propagation resistance of typical aerospace-grade composites that was observed during testing for Special Conditions certification of composite airplanes.

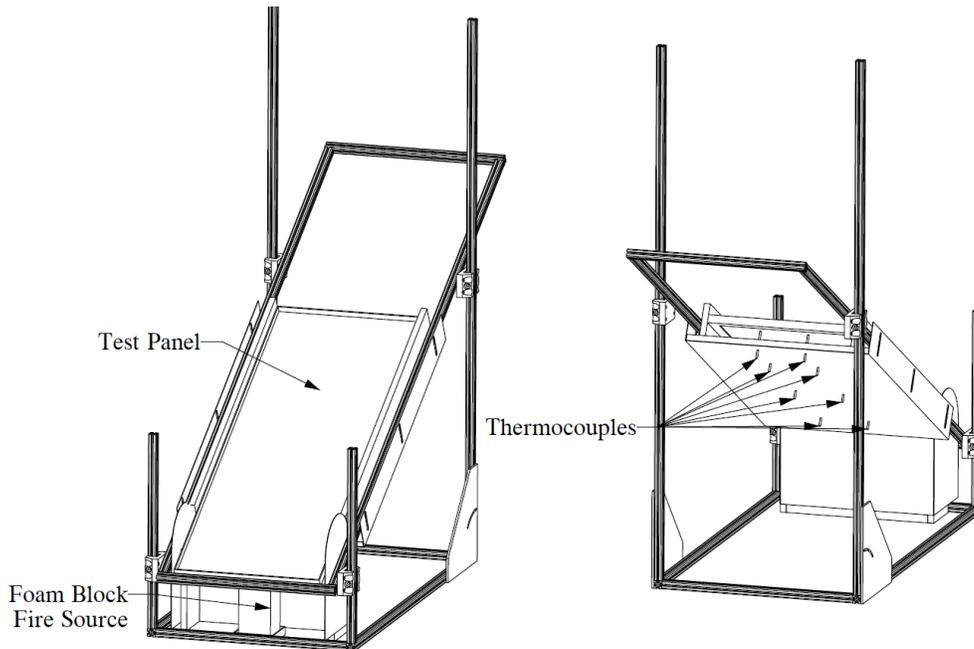


Figure 3. Intermediate Scale Test Apparatus, Front and Back View.

A laboratory-scale test method, known as the Vertical Flame Propagation (VFP) test apparatus, was developed for evaluating the flame propagation potential of composite materials in structural applications for aircraft fuselage skin and structure. The VFP, displayed in Figure 2, consists of a 710-watt, two and three quarter-inch diameter radiant coil furnace mounted vertically and opposite of a six-inch by twelve-inch composite test sample. A six-flamelet propane-air pilot burner impinges on the lower portion of the test sample for fifty seconds, at which point it is translated away. The sample is then allowed to burn while still exposed to the radiant heat flux emitted by the coil furnace. The burn time beyond pilot flame removal is recorded, as well as post-test measurements of burn length and burn width. Three test apparatuses were constructed and validated with a machine-to-machine comparative test series. Reproducibility was confirmed by testing all machines in different laboratories at the FAA Technical Center, as well as shipping one device each to Boeing and Airbus, repeating the same test series. Feasibility testing has also confirmed that the VFP can be used to assess flame

propagation on air ducting and wire insulation which are also located in the same inaccessible areas as composite structure and therefore should meet the same flammability requirements.

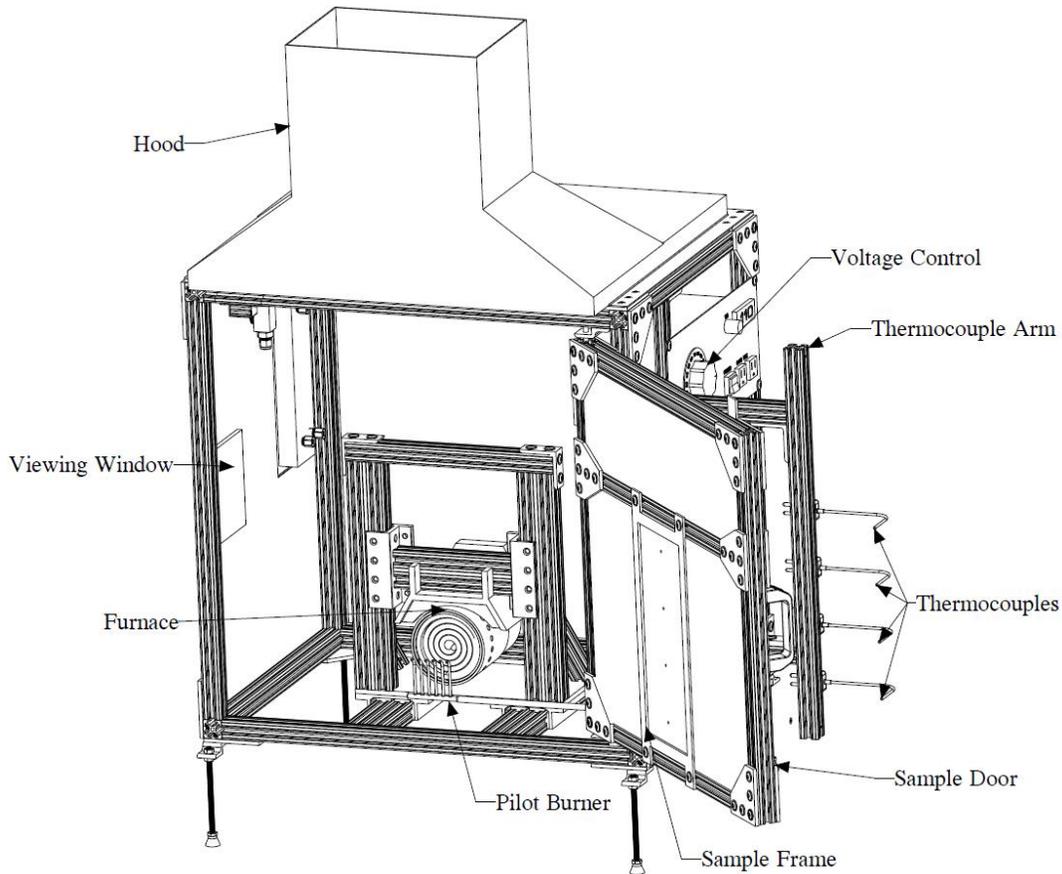


Figure 4. Schematic of the Vertical Flame Propagation (VFP) Test Apparatus.

Although the lab-scale test method has been developed and refined for use in certification, the intermediate-scale test rig is still useful to evaluate other factors that may influence the flame propagation of a composite structure while the aircraft is in-flight. A recent study, detailed in FAA report [DOT/FAA/TC-TN15/1](#), evaluated the effect of the composite panel thickness and external ambient conditions on inboard surface flame propagation. A variety of composite samples were evaluated, all produced from the same unidirectional carbon epoxy prepregs with toughened 350°F epoxy system, ranging in thickness from 0.044-inch to 0.3675-inch for the solid laminates and a honeycomb panel with 4 plies of carbon epoxy bonded to a 1-inch thick aramid honeycomb core. The results from this test series indicate that the relative flammability of a composite material is dependent on the rate of heat dissipation from the flame-

impinged surface. This varies depending on several factors, including the panel thickness and the heat dissipation rate at the outboard surface. As displayed in Figure 3, thin panels (0.04-inch to 0.1-inch thick) were found to propagate flames under static ambient conditions, and were also more heavily influenced by the heat transfer at the outboard surface. Thicker panels (0.13-inch to 0.37-inch thick) were found to have enough thermal mass between the flame-impinged surface and the outboard surface to not propagate flames under static ambient conditions, and were relatively unaffected by the heat transfer at the outboard surface. The sandwich panel was found to behave like a thin composite panel with an insulated outboard surface, and was entirely unaffected by the heat dissipation rate at the outboard surface.

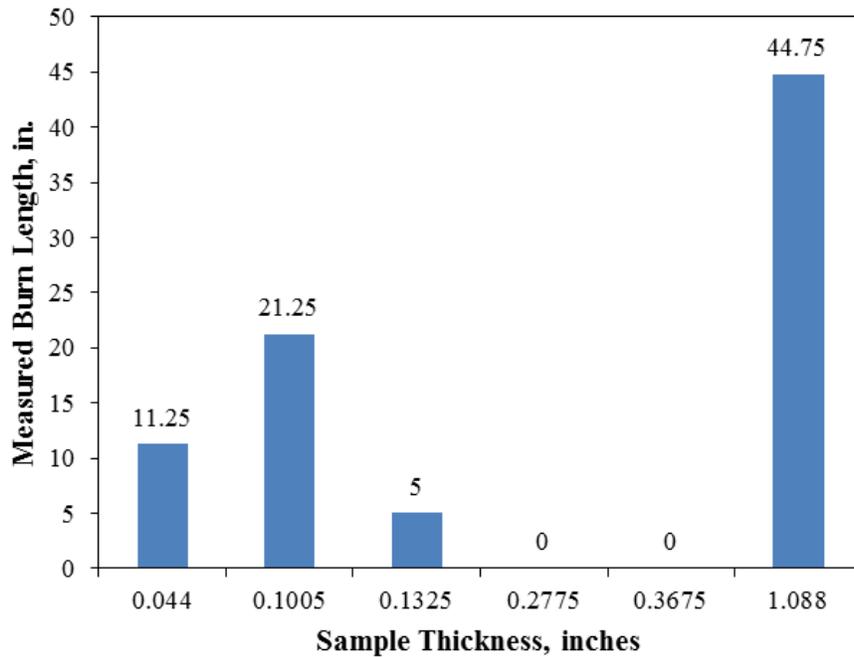


Figure 5. Measured Burn Length for Various Panel Thicknesses.

Controlled Fuel-Oxygen Ratios in the Microscale Combustion Calorimeter

The toxicity of smoke from polymeric materials when they burn is of great concern. The most toxic decomposition products are generated when fires are under-ventilated (fuel-rich) and there is not enough oxygen present to completely burn them. The problem is worsened when a fire occurs in a confined space, such as an aircraft cabin. Inherently fire-resistant materials and materials loaded with flame retardants inhibit the combustion process potentially creating smoke containing toxic combustion products including carbon monoxide. These products, in high enough concentrations, can cause incapacitation and death.

The FAA microscale combustion calorimeter (MCC) has been adapted to provide a way to measure the toxicity of burning plastics. The MCC method was modified to control a stoichiometric amount of oxygen with no knowledge of a samples chemical composition. This is done by running a preliminary test where the sample is degraded and its decomposition products completely reacted in an excess of oxygen. The exact amount of oxygen required to completely burn the products is calculated from this. Subsequent tests use this information and oxygen is controlled and normalized for sample weight to produce desired fuel to oxygen ratio during a materials decomposition. Carbon monoxide and carbon dioxide analyzers measure how much of each gas is generated during the combustion, providing a simple way to measure smoke toxicity. Fourier-transform infrared spectroscopy (FTIR) is also used to measure these gases as well as identify other hazardous components. In addition, the FTIR has been calibrated for several other toxic gases of interest to provide quantitative yields of those products (if present).

This research provides a new method of quickly evaluating materials toxic gas production under different ventilation scenarios. Ultimately, this method will help identify safer, non-halogenated flame retarded materials for use in passenger aircraft cabin interiors.

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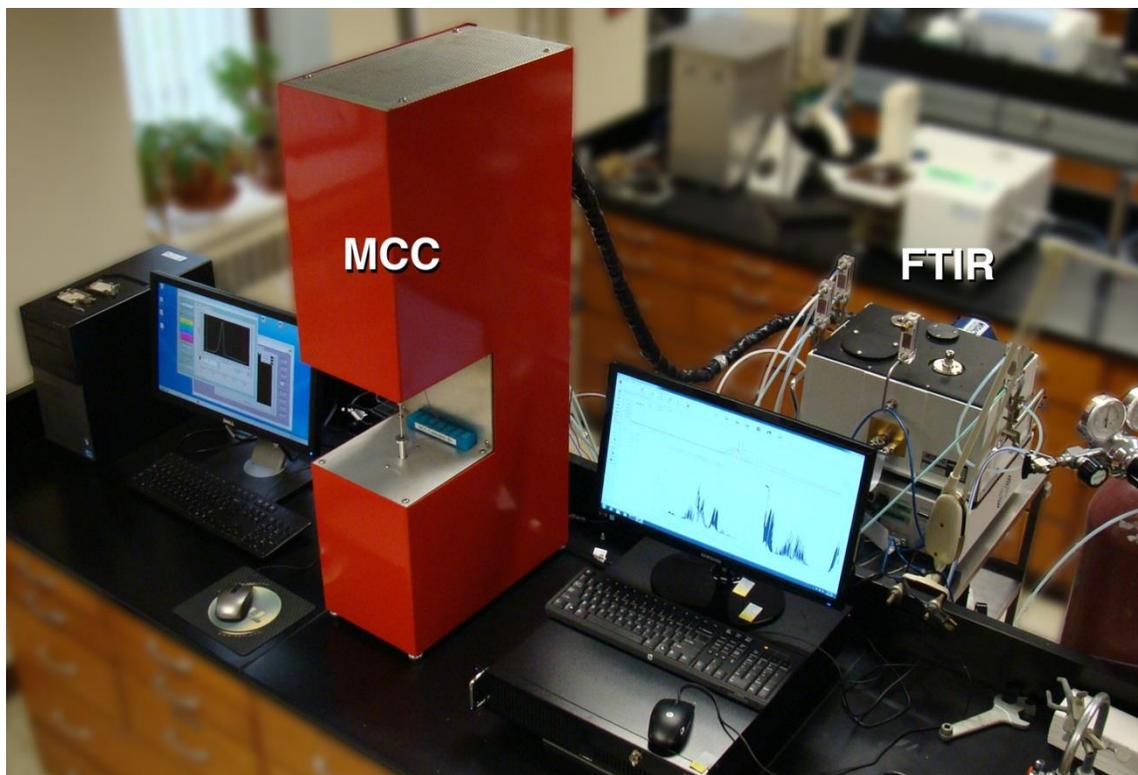


Figure 1: FAA microscale combustion calorimeter coupled with a Fourier transform infrared spectrometer used to measure the gaseous toxic decomposition products from burning plastics.

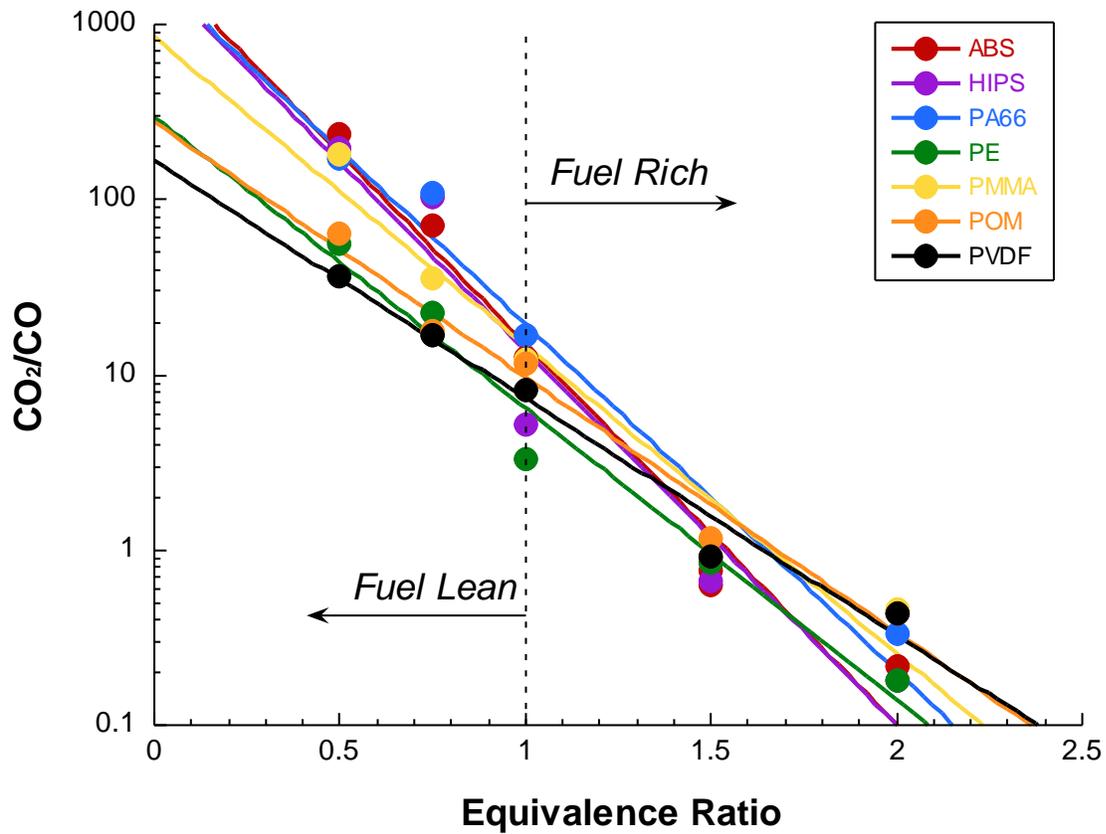


Figure 2: Data from unmodified plastics showing several orders of magnitude increase in carbon monoxide production as oxygen concentration is decreased during combustion.

Effect of Moisture on the Ignition Time of Polymers

Moisture has been shown to be an important factor on the ignitability of combustible solids. In case of wood, moisture *increases* the time to ignition. A previous study of high temperature engineering plastic Poly(arylether-ether-ketone) showed that moisture *decreases* the time to ignition of samples. Additional five engineering plastics: Polycarbonate, Polyoximethylene, Polymethylmethacrylate, Polyphenylsulfone and Polyhexamethyleneadipamide were studied to extent the previous work. It was determined that emersion polymers in water or exposure polymers to relative humidity of 50% caused the polymers to ignite earlier [1].

Prior the testing, polymer samples were conditioned at three different environments to obtain wet, 50% relative humidity and dry samples. Conditioned samples were subjected to the series of experiments with different external heat flux to measure the time to ignition of samples in a cone calorimeter. In some cases, times to ignition varied by a few hundred of seconds between wet and dry samples. Conditioned samples were also examined by Microscale combustion calorimetry to determine the effect of moisture on the thermal and decomposition properties. It was found the absorbed moisture did not change ignition or decomposition temperatures significantly, but was released as steam bubbles that changed the surface density and heating at the surface.



Figure 1. Photograph of surface of wet PA66 sample.

The experimental findings were confirmed by numerical pyrolysis modeling tool ThermaKin. The two phase solid-to-foam model qualitatively captured the premature ignition of moisture containing samples.

Based on the results of this study, standard conditioning procedures were highly recommended for standardized tests to ensure the reproducibility of the tests.

[1] N. Safronava, R.E. Lyon, S. Crowley, S.I. Stoliarov, "Effect of Moisture on Ignition Time of Polymers", Fire Technology, October 2014