Federal Aviation
Administration

2014 Fire Safety Highlights

Contents

Effectiveness of Cargo Compartment Fire Resistant Containers and Fire Containment Covers against Large Lithium Battery Fires.

Almost all cargo transported in freighters is loaded on pallets that are covered and in cargo containers. A number of activities have resulted in the development of fire resistant covers and fire hardened containers to protect aircraft against cargo fires originating within the loaded enclosures. Previous testing of Fire Containment Covers (FCCs) and Fire Resistant Containers (FRCs) both with and without built in fire suppression systems showed promising results when tested with fire loads comprised of ordinary combustible materials. The test fires were either suppressed through oxygen starvation or, in the case of FRC's with built in suppression systems, completely extinguished. Testing of these potential fire mitigation strategies continued with fire loads that included large quantities of commonly manufactured rechargeable lithium-ion and non-rechargeable lithium metal batteries.

The configuration for the FCC/FRC battery testing consisted of approximately 5000 batteries added to the same fire load of ordinary combustible materials used in the initial testing.
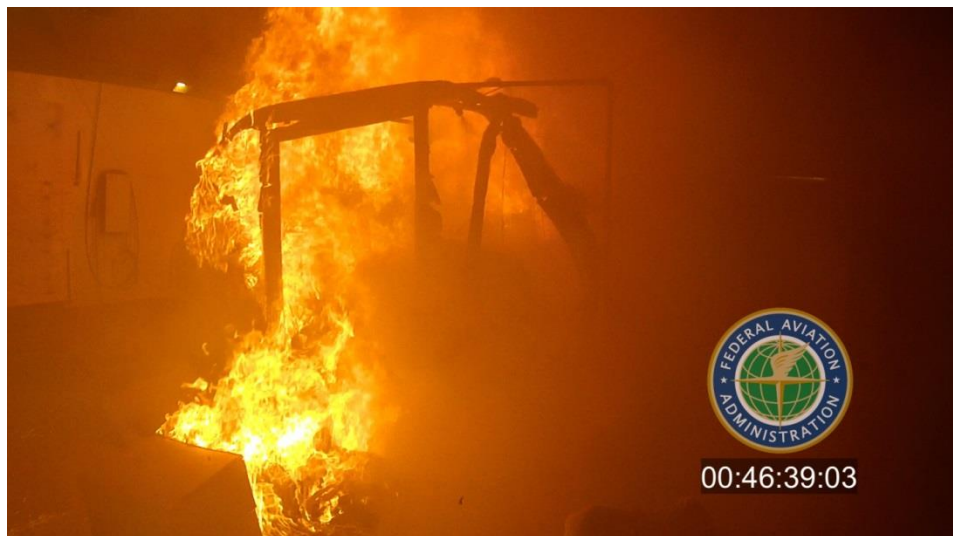
In the first FCC test involving lithium-ion batteries, the test fire was contained under the FCC for the four hour duration test. When lithium metal batteries were tested under the same conditions, the fire was not contained and the test was terminated after 16 minutes.

The FRC battery tests all included a built in fire suppression system consisting of a dry powder type of suppression agent that was pyrotechnically discharged. Two FRC tests were conducted with lithium-ion batteries. An explosion occurred inside the FRC during

both tests. The overpressure and subsequent fire destroyed the FRC s in both of these tests. During the first test, the conditions required for the automatic discharge of suppression agent were not reached prior to the occurrence of the explosion. The alarm algorithm was changed for the second test and detection and discharge of the suppression system did occur prior to the explosion but did not prevent it. The cause of these explosions was the ignition of flammable gases that were vented by the batteries in thermal runaway that had collected within the FRC. One additional test was conducted under these same conditions with lithium metal batteries. This test did not result in an explosion, but the FRC and suppression system were not effective in containing the fire, which burned through the FRC within three minutes. Additional research is underway to better characterize the composition of the gases vented from lithium-ion and lithium metal batteries during thermal runaway.

POC: Dave Blake

Fire-Safety of E-Tablets used as In-Flight Entertainment

The usage of electronic-tablets (e-tablets) as a replacement for the conventional in-flight entertainment system has gained in popularity among airlines globally. Innovative methods of storing and charging e-tablets in galley carts have been suggested or are already in service with some airlines.

The danger of thermal runaway in the lithium-ion-polymer batteries that are used in these e-tablets is well known, but the potential fire hazard resulting from e-tablets being stored and charged in galley carts or a similar enclosure has not been established. To examine this potential fire hazard, the Civil Aviation Authority of Singapore (CAAS) and the FAA carried out a series of tests to investigate the behavior of stored e-tablet fires.

The tests were conducted within a galley cart in a fully-operational but non-flyable 737 test aircraft. Thermal-runaway of the e-tablet lithium-ion-polymer battery was initiated by either a heat plate or an external alcohol fire. The arrangement of e-tablets inside the galley cart followed the typical methods of storage proposed by airlines and airframe manufacturers. The objective of the tests was to determine a suitable storage configuration for the e-tablets that would prevent the propagation of thermal runaway and to determine the effect that thermal runaway would have on a typical galley cart.

Ten tests were conducted, and the conclusions associated with these tests are listed as follows:

1) The risk of lithium battery thermal runaway propagation was minimized by arranging the e-tablets in a vertical orientation and providing sufficient spacing between them.
2) Thermal runaway may cause the accumulation of flammable gasses in the galley cart and the risk of an explosion. An explosion can forcefully open a latched galley cart door.

3) The uncontained fire or explosion created within the galley cart due to thermal runaway had the potential to emerge out of the galley cart and spread to the adjacent structure and materials of the aircraft cabin (see figure 1).
4) As a result of the uncontained fire, there was a heavy accumulation of smoke in the cabin that had the potential to interfere with firefighting efforts.

The results of these tests provided evidence of the potential fire hazards associated with bulk storage of e-tablets in a galley cart or similar enclosure in the event of thermal runaway in a single lithium battery. Additional work was recommended to determine the desirable features of galley carts to contain a lithium battery fire and prevent the danger associated with fire, smoke intensity, and explosion.

POC: Tom Maloney

Figure 1. Flames emitted from e-tablets within a closed galley cart

Measuring Stored Chemical Energy in Lithium Ion Batteries Using a Bomb Calorimeter

Rechargeable lithium ion batteries are being used at an increasing rate since their introduction in the early 1990's. This is due to their high energy density and excellent charging and discharging characteristics. Lithium ion batteries are continuously being researched and developed to produce higher capacities. The high energy density of lithium ion batteries (LIB) makes safe shipment of this commodity as cargo on commercial aircraft a concern due to its potential to initiate a fire by thermal runaway, contributing to a fire by burning of the organic electrolytes and other combustible components. The ignition risk can be mitigated by shipping lithium ion batteries at a reduced state-of-charge (SOC). To demonstrate the safety benefit, work was conducted to determine the relationship between the state-of-charge of the LIB or its rated capacity, and the release of stored chemical energy during thermal runaway. This work focused on quantifying the release of stored chemical energy during thermal runaway using a bomb calorimeter purged with nitrogen to preclude any combustion of the battery contents. Data was obtained for the release of stored chemical energy during thermal runaway as a function of state-of-charge and rated capacity, and the combustible gases produced were analyzed using gravimetry, gas chromatography (GC), and Fourier transform infrared spectroscopy (FT-IR).

A bomb calorimeter (Parr Instruments Model 1341 Plain Jacket Oxygen Bomb Calorimeter) was modified to accommodate a single 18650 lithium ion battery along with other components required to heat the battery until thermal runaway occurred. Prior to heating the bomb was purged with nitrogen to inert the environment and prevent combustion. The battery was heated with a nichrome wire which produced thermal runaway usually in about 10 minutes. The temperature of the system was monitored until thermal equilibrium was reached. After the battery test the system was cooled and the same heating program was applied to generate a baseline.   The difference between the initial and maximum temperature of the baseline is subtracted from the difference between the initial and maximum temperature of the battery run to get the temperature rise of the system from the battery only. The temperature rise from the battery exothermic reaction is multiplied by an energy equivalent for the bomb

calorimeter to yield a net chemical energy release. Temperature measurements of batteries during thermal runaway show that the energy released can be enough to raise the temperature of 1 battery over 800°C in 2 seconds without any combustion. Figure 1 shows the relationship between energy release and battery charge for 4 types of 18650 batteries. Clearly, at low battery charge the risk of ignition by thermal runaway can be reduced significantly.

Weight measurements were made to examine how much of the batteries contents were released as gases. The composition of the gases released is a mixture of flammable and non-flammable components. The flammable gases, as verified by infrared spectroscopy, consisted of methane and carbon monoxide. Gas chromatography identified hydrogen as a major component as well as a collection of low molecular weight hydrocarbon fuels. The non-combustible gas released was carbon dioxide as determined by the FT-IR and GC methods. It was found that the weight of combustible gases released was also directly proportional to the charged capacity of the battery. This data may be used to determine the number of batteries in thermal runaway that could cause an explosion in an enclosure of given volume.
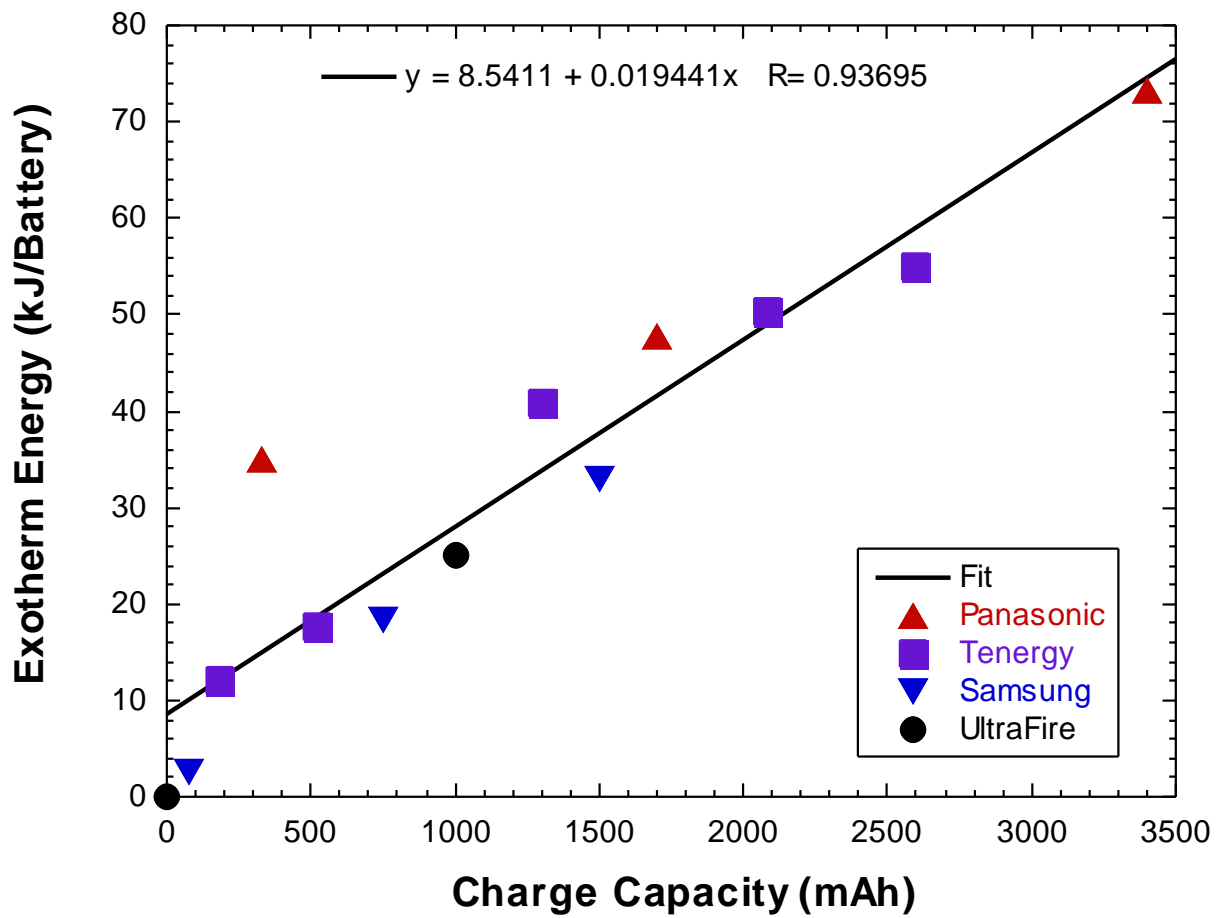

POC: Richard Walters

Figure 1. Relationship between energy release and battery charge for 4 types of 18650 batteries

Flammability of Hydrogen at Sub-Atmospheric Pressures and Reduced Oxygen Concentrations

There is increasing pressure on the aviation industry to improve fuel efficiency and reduce harmful emissions. One method being considered is to replace the auxiliary power unit (APU) with hydrogen fuel cells to supply electrical power to the aircraft. Hydrogen fuel cells produce electricity directly from the conversion of hydrogen and oxygen into water vapor, which is the only emission produced. The concern with using hydrogen as a fuel is fire safety, since hydrogen is easily ignited and produces powerful explosions over a very wide range of concentrations. Therefore, hydrogen's combustion properties were investigated and quantified for the conditions that could be experienced by an aircraft in-flight or on the ground.

Hydrogen's flammability was tested in air at pressures corresponding to sea level, 15,000, 30,000, and 40,000 feet of altitude. At these conditions, the lower and upper flammability limits, maximum explosion pressures, flammability properties in oxygen-depleted air, and limiting oxygen concentrations were measured. All testing was done in a 20 liter stainless steel chamber, based on the Bureau of Mines design for determining the explosion characteristics of dusts and gases. The chamber was evacuated, and refilled with the desired test concentration of hydrogen, nitrogen, and air, as measured by partial pressures. An ignited mixture was considered flammable if the pressure increased by 3% or more above the initial pressure.

Several tests near the lower flammability limit (LFL) were completed at each altitude. The limit was found to be 4.70% hydrogen at sea level and decreased as the altitude increased. At 40,000 feet, the LFL was 3.89% hydrogen. The graph of the LFL as a function of altitude is shown in figure 1. Similar tests were conducted for the upper flammability limit (UFL) as well. The UFL was 78.18% hydrogen at sea level, peaked at 78.87% at 15,000 feet, and then decreased to 76.87% at 40,000 feet. Based on previous studies and additional data collected in this testing it was found that the UFL decreased above this altitude because of the low spark energy used during these experiments. Thus, in these results the UFL at 30,000 and 40,000 feet was actually limited by the spark energy and not the rich limit of hydrogen. This low spark energy was not a factor in the other test conditions.

The flammability of hydrogen was also tested in air with varying concentrations of nitrogen added. The full range of hydrogen concentrations were tested with pure air, and 20%, 40%, and 60% nitrogen added at each altitude. At high altitudes, the gas mixtures remained flammable across a wider range of hydrogen concentrations, but the lower altitude tests produced much higher peak pressures due to the increased density of hydrogen and oxygen present. As expected, the highest pressure measured of all the tests performed was at a stoichiometric hydrogen and air concentration at sea level. The pressure increased to 100.8 psi above the initial pressure and reached that peak 12 ms after the spark was triggered. This corresponded to a pressure rise of almost seven times the initial pressure. Very powerful explosions also occurred in any tests conducted away from the flammability limits, which further highlighted aircraft safety concerns.

Enough nitrogen was added in to reach the limiting oxygen concentration (LOC) for hydrogen at all altitudes as well. This is the minimum amount of oxygen required for hydrogen to be flammable. This was achieved by reducing the amount of oxygen in the air by adding nitrogen, then adding hydrogen to make a stoichiometric ratio with the corresponding amount of oxygen. For example, a test run with a 4% oxygen concentration had 8% hydrogen and 88% nitrogen. The LOC was 4.21% oxygen at sea level and decreased as the altitude increased to 3.49% oxygen at 40,000 feet (Figure 2).

Overall, it was found that at high altitudes the gas mixtures remained flammable across a wider range of hydrogen concentrations, but at low altitudes the tests produced much higher peak pressures due to the increased density of hydrogen and oxygen. Also, a lower concentration of oxygen is needed to ignite hydrogen at high altitudes, which would require more nitrogen to inert the environment.
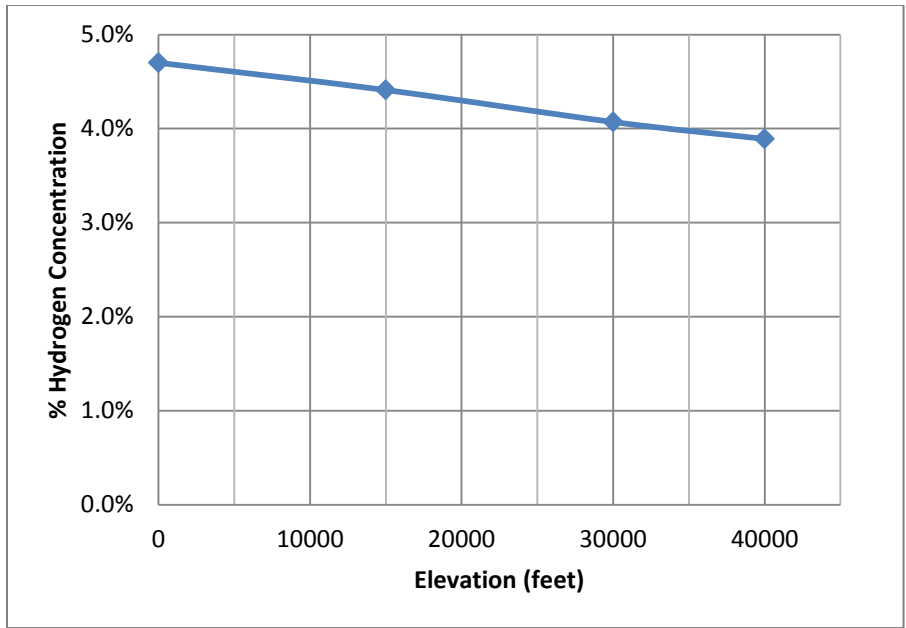

POC: Steven Rehn

Figure 2. Lower flammability limit of hydrogen in air as a function of altitude
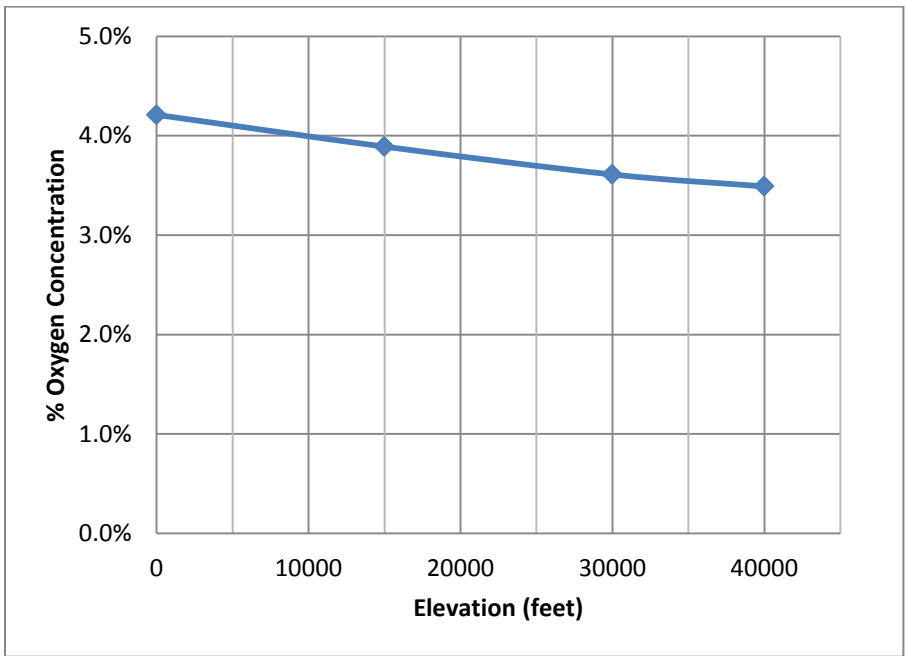

Figure 3. The limiting oxygen concentration of hydrogen as a function of altitude

Heat and mass transfer due to a small fire in an aircraft cargo compartment

An inflight fire may have grave consequences if not detected rapidly and before growing into an uncontrollable size. Early fire detection is not trivial, especially for the inaccessible areas of the aircraft such as cargo compartments, where a direct visual inspection is not possible during flight. For aircraft fire safety, it is particularly critical to identify the fire at the very early stages when it is still small and its spread is limited. Understanding the fire dynamics and more specifically the transport of induced smoke and hot gases as a result of a fire in an enclosure is fundamental in the selection and optimal location of fire/smoke detectors.

For the purpose of this study, a plume of hot-gas mixture generated by a small-fire placed on the floor near the center of an empty aircraft cargo compartment, was examined. A computational fluid dynamics (CFD) model was developed, and predictions were made of the temporal and spatial distribution of a chosen set of variables, such as gas temperatures, heat fluxes, and concentration levels of the main combustion products throughout a cargo compartment enclosure. The numerical modeling was carried out using the fire dynamics simulator (FDS) developed by the National Institute of Standards and Technology (NIST) [1]. The model results are compared with the available experimental data previously collected during the full-scale fire tests of a representative narrow-body aircraft cargo compartment [2, 3].

It was demonstrated through this study that the heat flux to the ceiling directly above the fire source constitutes the bulk of heat loss in the compartment. The study focused on this region since inaccurate predictions of the heat flux would yield poor model performance when compared to the experimental data.

Figure 1 compares heat flux predictions obtained by the model and measurements from the full-scale fire tests at two locations: directly above the fire source, and 1.5 m away. Although different model configurations were investigated, only a select few are shown (Run1 to Run10). Measurements from the full-scale tests are displayed with red symbols, while simulation results are shown with lines. As can be seen from the figure, the wall heat flux directly above the fire source (stagnation heat flux) is noticeably higher (almost ten times) than the heat flux 1.5 m away (far-field heat flux). Although the

model performs well in predicting the far-field heat flux, its accuracy for the stagnation heat flux is very sensitive to the model set-up used.

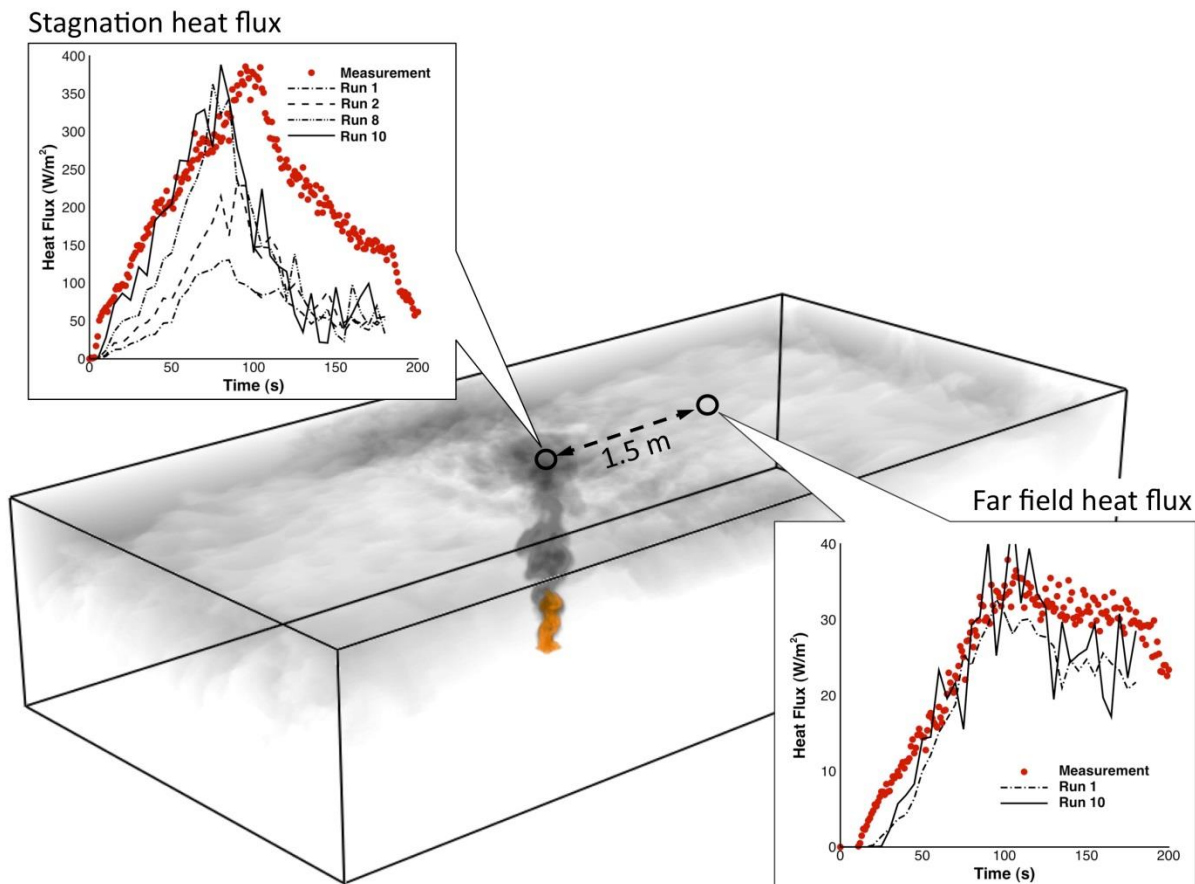Further details of this study can be found in reference [4].

Figure 1. Comparison of ceiling heat fluxes in the first three minutes of fire

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[3] D. Blake, J. Suo-Anttila, Aircraft cargo compartment fire detection and smoke transport modeling, Fire Safety J. 43 (2008) 576–582.

[4] E. S. Oztekin, Heat and mass transfer due to a small-fire in an aircraft cargo compartment, International Journal of Heat and Mass Transfer (2014) 562 – 573.

POC: Ezgi Oztekin

Adaptation of the NexGen Burner to the Aircraft Seat Cushion and Cargo Liner Flammability Tests

Past FAA research yielded the development of stringent test requirements for seat cushions and cargo liners that expose the material samples to a severe flame produced by an oil burner. The research was driven by full-scale fire tests that demonstrated a 40-60 second improvement in postcrash fire survivability through the use of seat cushions meeting the new criteria. Testing indicated the urethane foam used in the seat cushions was the primary fuel source involved in a cabin fire. Separate research focused on the ability of the protective cargo compartment liner system at preventing in-flight cargo fires from burning through the liner. A new stringent flammability test for cargo liner burnthrough resistance was developed to ensure that cargo fires would be confined within the cargo compartment until the aircraft could be safely landed.

During the development of both the seat cushion flammability test and the cargo liner burnthrough test, the Park DPL-3400 burner became the burner of choice as these tests were standardized and became regulation. Several hundred Park burners were manufactured for this application. However, during the more recent development of a new test for thermal acoustic insulation burnthrough resistance, production of the Park burner ceased, necessitating the need for a replacement burner. In addition, a new burner was required for laboratories intending to establish either the existing seat cushion or cargo liner flammability tests.

This need for the availability of a standard burner prompted the Fire Safety Branch to develop the next-generation, or "Nexgen", burner that could be built from readily-available components. Rather than using an electric motor to drive the blower fan and fuel pump, the Nexgen burner relies on a pressurized air source and a sonic orifice to meter in the precise amount of combustion air, which provides more consistent flame characteristics over a range of ambient laboratory conditions. Beyond the burner itself, internal components that impact the profile of air entering the combustion zone were also examined and evaluated. Ultimately, the Nexgen burner was modified with two new components known as the flame retention head and static plate in order to achieve an acceptable level of test reproducibility between different laboratories. This was

established based on an evaluation of test data on identical materials from a number of laboratories. The retention head/static plate has become the new standardized configuration of the Nexgen burner for both the cargo liner and seat cushion flammability test.

The adaptation of the Nexgen burner for both the seat cushion flammability test (figure 1) and the cargo liner burnthrough test (figure 2) fulfills the need for a suitable replacement burner for these tests. The existing flammability test methods detailed in the Fire Test Handbook are being revised to include a description of the Nexgen burner, so that new laboratories will have the opportunity to fabricate or purchase the appropriate burner equipment necessary to conduct these flammability tests.

POC: Tim Marker

Figure 1. Seat cushion flammability test

Figure 2. Cargo liner burnthrough test

Measuring Gas Phase Activity of Flame Retardant Compounds in Aircraft Plastics Using the FAA Microscale Combustion Calorimeter

Flame retardant compounds are routinely added to cabin materials in order to pass stringent FAA fire performance requirements for ignitability, smoke generation and heat release rate. The most effective and widely used flame-retardants in aircraft interiors are bromine-containing compounds that slow down (inhibit) the heat-producing reactions of the fuel gases with oxygen in the flame of a burning plastic. These heat-producing reactions that occur in the combustion zone of the flame, shown in red on the left hand side of Figure 1, can be reproduced in the combustor of the FAA microscale combustion calorimeter, or MCC, shown on the right hand side of Figure 1. Slowing down these combustion reactions in the flame using gas-phase active flame-retardants reduces the heat release rate of the burning plastic and leads to passing results in FAA fire tests. Unfortunately, some of these compounds, called polybrominated diphenyl ethers, or PBDEs, are being phased out by the Environmental Protection Agency (EPA) because of health and environmental concerns and are no longer available for use as flame-retardants for aircraft interior plastics.
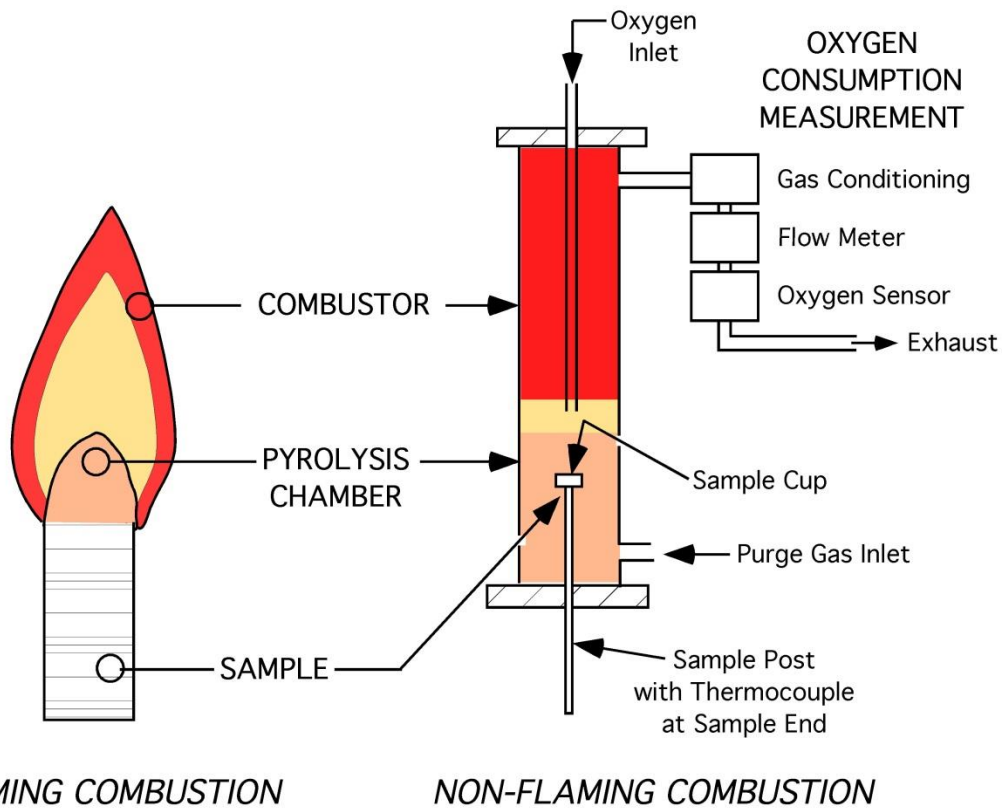
Oxygen
Inlet

OXYGEN
CONSUMPTION
MEASUREMENT

Gas Conditioning

Flow Meter

Oxygen Sensor

Exhaust

COMBUSTOR

Sample Cup

PYROLYSIS
CHAMBER

Purge Gas Inlet

SAMPLE

Sample Post
with Thermocouple
at Sample End

FLAMING COMBUSTION   NON-FLAMING COMBUSTION

Figure 1. Diagram Showing How the MCC Reproduces the Processes of Flaming Combustion in a Non-Flaming Laboratory Test

To accelerate the discovery of PBDE alternatives the Fire Safety Branch attempted to use the FAA microscale combustion calorimeter (MCC) to measure how much flame-retardants slow down the combustion reactions of polymers in flames and compare these results to fire performance to see if the MCC could be used to screen new compounds for flame inhibition in fire tests.   Under standard conditions [1] the MCC generates a gaseous fuel pulse of the flame retardant plastic by controlled pyrolysis of milligram-sized samples in nitrogen, and complete combustion of these fuel gases at 900°C in excess oxygen. The FAA's approach to screening flame-retardants for gas phase activity was to lower the combustor temperature to slow down the combustion reactions [2]. Measuring the amount of oxygen consumed by flame retardant plastics at each temperature in the MCC combustor allows for calculation of the speed of the heat-producing reactions in the flame and the effect of flame retardants on the heat release rate of the burning plastic.

Figure 2 is a bar graph showing the results of these experiments and calculations for blends of brominated polystyrene with pure polystyrene, mixtures of tetrabromobisphenol-A epoxy with bisphenol-A epoxy, and compounds of red phosphorus flame retardant in nylon. Plotted on the ordinate (y-axis) of Figure 2 are the flame retardant/polymer system and the weight percent of the active flame retardant element (bromine or phosphorus) in the compound. The abscissa (x-axis) is the extent to which the flame retardant slows down the combustion reaction of the polymer in the flame, plotted on a logarithmic scale. Figure 2 shows that bromine slows down (inhibits) the combustion reactions in a polystyrene flame more than a thousand fold, while it slows down the rate of the epoxy combustion reactions by only a factor of ten or so. Flame inhibition of nylon by phosphorus is small compared to the bromine systems. This is consistent with the known mechanism of phosphorus activity, which is to increase char formation in the solid polymer to reduce the amount of combustible gases given off during burning. These results indicate that both the flame retardant and plastic fuel are important in determining the flame inhibiting activity of gas phase flame-retardants.
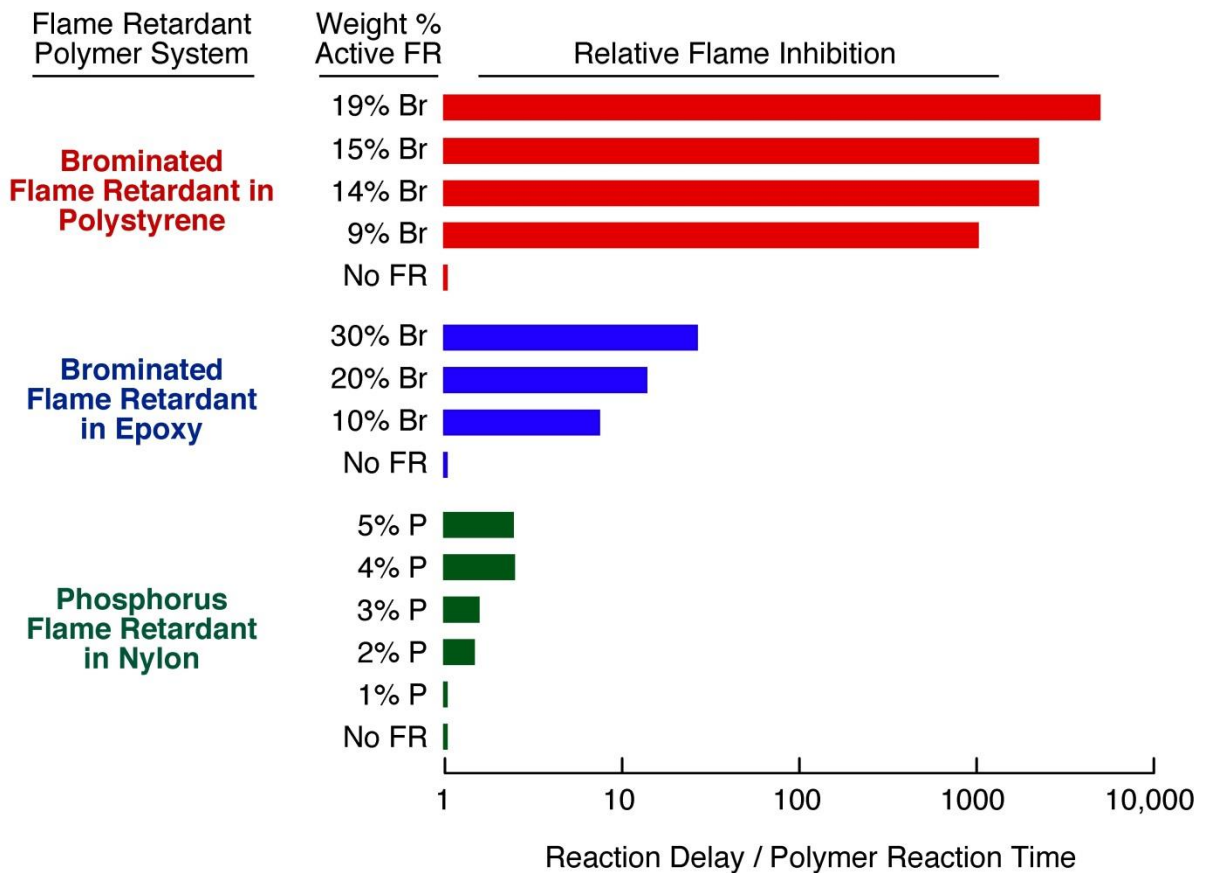

Figure 2. Relative Flame Inhibition of Bromine and Phosphorus Flame Retardants in Polymers

The relative flame inhibition of bromine and phosphorus in polystyrene, epoxy and nylon shown in Figure 2 is consistent with fire test results for these systems, which show an increase in fire performance with an increase in gas phase activity. Consequently, the research demonstrated a methodology using a standardized, lab-scale test (the MCC) that is useful for screening PBDE replacement flame-retardants for gas phase activity.

References

[1] ASTM Standard D7309-13a (2013), Test Method for Determining Flammability Characteristics of Plastics and Other Solid Material Using Microscale Combustion Calorimetry, ASTM International, West Conshohocken, Pennsylvania.

[2] R.N. Walters, N. Safronava and R.E. Lyon, A Microscale Combustion Calorimeter Study of Gas Phase Combustion of Polymers, *Combustion and Flame*, published on-line, September 2014.

POC: Rich Lyon