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Cargo Fire Suppression by Depressurization

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Final Report

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16. Abstract The effectiveness of aircraft depressurization (reduced pressure) on the burning behavior of stacked cargo, batteries, fuel, and materials was measured in a 381-cubic-foot (10.8-cubic-meter) pressure vessel, modified to conduct fire tests at a specific reduced pressure or programmed to vary the pressure to simulate aircraft depressurization to control a cargo fire and subsequent emergency descent to sea level. It was determined that depressurization did not prevent flashover during cargo fires consisting of stacked cargo boxes filled with shredded paper, although the burning behavior of individual fuels and materials was reduced at lower pressures. The discharge of Halon 1301 prevented flashover during the cargo fires and also significantly reduced the air temperature. In addition, thermal runaway of lithium batteries overheated under controlled fire-exposure conditions was not prevented over a range of pressures from sea level to an elevation of 26,000 ft (7.9 km).					
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LIST OF ACRONYMS

PMMA Polymethyl methacrylate

EXECUTIVE SUMMARY

The purpose of the series of fire tests described in this report was to examine the effectiveness of depressurization (reduced aircraft pressure) on the burning behavior of cargo, batteries, and fuels. Aircraft depressurization is an approved method of fire protection in freighter (all cargo) aircraft.

The tests were conducted in a 381 ft³ (10.8 m³) pressure vessel modified to control the internal pressure to a specific value or programmed to simulate a depressurization profile to suppress a fire and an emergency descent to sea level. Instrumentation measured and recorded temperature, pressure, heat flux, mass loss of burning materials, oxygen concentration, and Halon 1301 (fire-extinguishing agent) concentration. Video cameras observed and recorded the tests.

During tests conducted with stacked cargo comprised of cardboard boxes loaded with shredded paper, flashover was not prevented when depressurization was initiated by the detection of a fire. Moreover, a second flashover occurred when the pressure increased during a simulated emergency descent. However, the discharge of Halon 1301, an extinguishing agent used in passenger airplane cargo compartments, prevented flashover and reduced the vessel air temperature to below 200°F (93°C). The temperature within the deep-seated cargo fire exceeded 600°F (316°C), which could cause lithium batteries to experience thermal runaway.

During tests conducted with lithium-ion (rechargeable) batteries exposed to a controlled fire condition, thermal runaway was not prevented over a range of pressures corresponding to sea level and an elevation of 26,000 ft (7.9 km). The time to thermal runaway increased with reduced pressure when exposed to a controlled flame but was invariant when exposed to radiant heat alone.

During tests conducted with propanol and Jet-A fuel fires in a pan, the mass loss burning rate decreased in a linear manner by approximately a factor of two from sea level to 26,000 ft (7.9 km). A similar reduction was observed for the flame spread rate of acrylic sheet.

In summary, these experiments demonstrated that depressurization did not prevent flashover during cargo fires, although the burning behavior of materials is reduced at lower pressures. In addition, depressurization will not prevent thermal runaway in lithium batteries overheated in a fire.

1. INTRODUCTION

The tests described in this report were conducted to evaluate the effectiveness of depressurization as a method to control in-flight cargo fires in freighter aircraft. Ventilation shutoff in the main-deck cargo compartment and aircraft depressurization is an approved method of suppressing a freighter cargo fire until the aircraft can be safely landed. Several scenarios with different fire sources were tested at varying pressures (altitudes) to observe the affect different altitudes had on each fire source's burning behavior. Depending on the scenario and fire source, the effect of altitude on the mass weight loss rate, flame spread, or enclosure temperature and oxygen concentration were examined.

2. TEST DESIGN

2.1 TEST CELL (PRESSURE VESSEL)

The evaluation of fire suppression by depressurization was conducted in the Pressure Fire Modeling Facility at the FAA William J. Hughes Technical Center, Atlantic City International Airport, New Jersey. The pressure vessel has a volume of 381 ft³ (10.8 m³) and a maximum working pressuring rating of 600 psig. The vessel's internal pressure can be reduced and controlled to a value corresponding to a flight altitude or a prescribed flight profile, and the air-exchange rate can be controlled to account for aircraft ventilation and leakage.

2.2 INSTRUMENTATION

Multiple sensors were installed inside the pressure vessel during these tests, including Type-K thermocouples, heat flux transducers, oxygen and Halon 1301 concentration analyzers, pressure transducers, flow meters, a scale, and a video camera. Simulating both altitude (pressure) and air exchange encountered during flight was accomplished using a vacuum pump in conjunction with throttle valve controllers. One of these control valves would control the pressure within the chamber while the other would control the flow through the chamber. The sensors were connected to a data-acquisition system programmed to record data at a rate of one sample per second. Variations in both altitude/pressure and airflow were controlled using algorithms that electronically controlled set point configurations for each of the throttle valve controllers during each test scenario.

3. TEST PROCEDURE

The test procedure is outlined below:

1. Data-acquisition hardware, analyzers, and transducers were turned on and given the proper amount of warmup time, as specified (4 hours minimum).
2. Materials being tested were loaded into the pressure vessel, and instrumentation was adjusted as necessary.
3. The pressure vessel door was hydraulically locked and its vent closed.
4. Set point information for a given flight profile was entered in the software as psia corresponding to altitude (i.e., 10.92 psia for 8,000 ft).

5. Once the pressure vessel had stabilized at the targeted pressure/altitude, the data-acquisition system and video recorder were started.
6. Thirty seconds after starting the data-acquisition system and video recorder, the fire source was ignited.
7. The test concluded when the objective was satisfied, which depended on what type test or scenario was being conducted.

4. TEST SCENARIOS

4.1 FIRE PAN TESTS

A series of pan fire tests was conducted with propanol and Jet-A fuel. A circular 5.25-inch (133 mm) diameter, 1-inch (25 mm) deep fire pan was loaded with 1.7-ounces (50 ml) of fuel to provide a relatively low-intensity fire with a surface area of 20.6-in² (133 cm²). The fire pan was centered on a scale. A set of direct current arc igniters served as a remote ignition source.

During these tests, the mass loss burn rate (grams/minute) was measured at different pressures. The relationship between the pressure and altitude depicted in the data presentation throughout this report is shown in table 1.

Table 1. Altitude (ft) vs. Pressure (psia)

ALTITUDE	PSIA
Sea Level	14.69
2,000	13.66
4,000	12.69
6,000	11.77
8,000	10.92
10,000	10.11
12,000	9.35
14,000	8.63
18,000	7.34
20,000	6.76
24,000	5.70
30,000	4.37

4.1.1 PROPANOL

This series of tests used 1.7-ounces (50 ml) of propanol as the fuel source. Each data point represents the average burn rate resulting from three tests at each altitude (pressure). During these tests, an increase in altitude (reduction in pressure) resulted in a linear decrease in burn rate, as

shown in figure 1. For example, the burn rate decreased by approximately a factor of two between sea level and 26,000 ft (7.9 km).

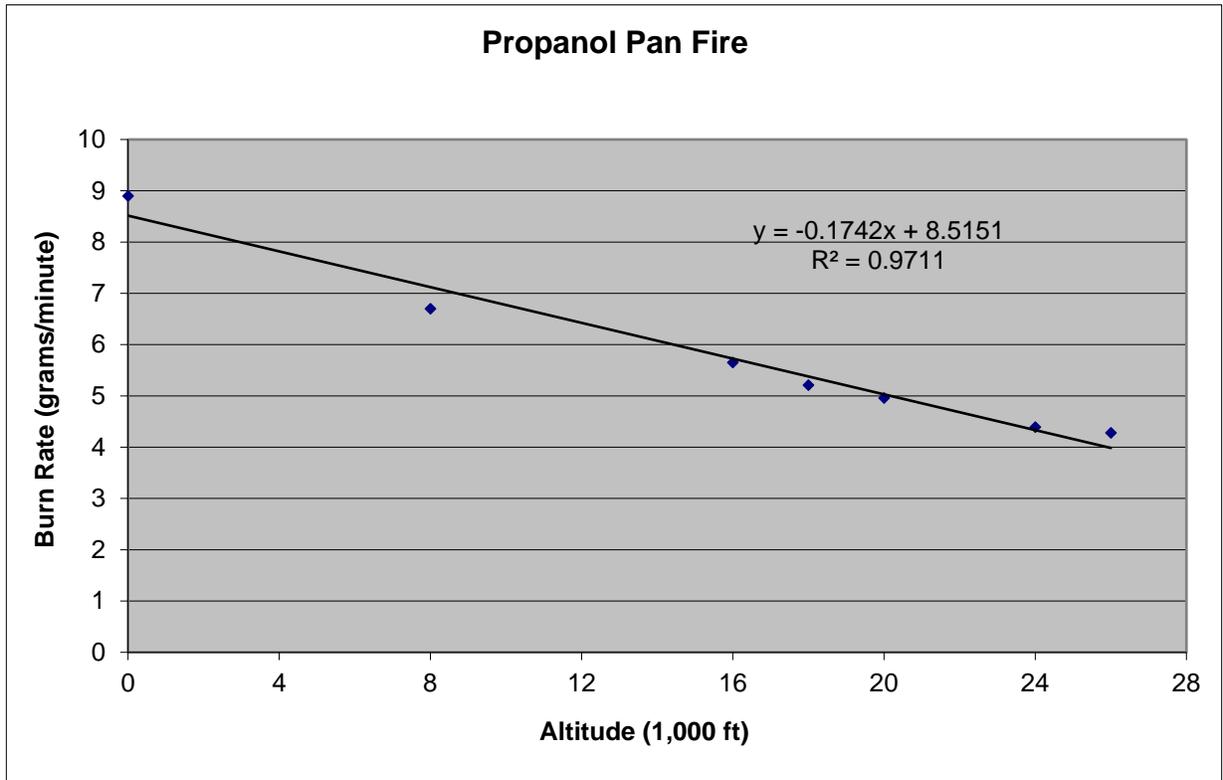


Figure 1. Propanol pan fire

4.1.2 JET-A

This series of tests used 1.4-ounces (40 ml) of Jet-A as the fuel source with 0.3-ounces (10 ml) of hexane to aid in the ignition of the Jet-A, which has a minimum flash point of 100°F (38°C). Each data point represents the average burn rate resulting from three tests at each altitude. As shown in figure 2, during these tests, a linear decrease in burn rate with altitude also occurred with Jet-A with a similar but slightly smaller slope than calculated for propanol.

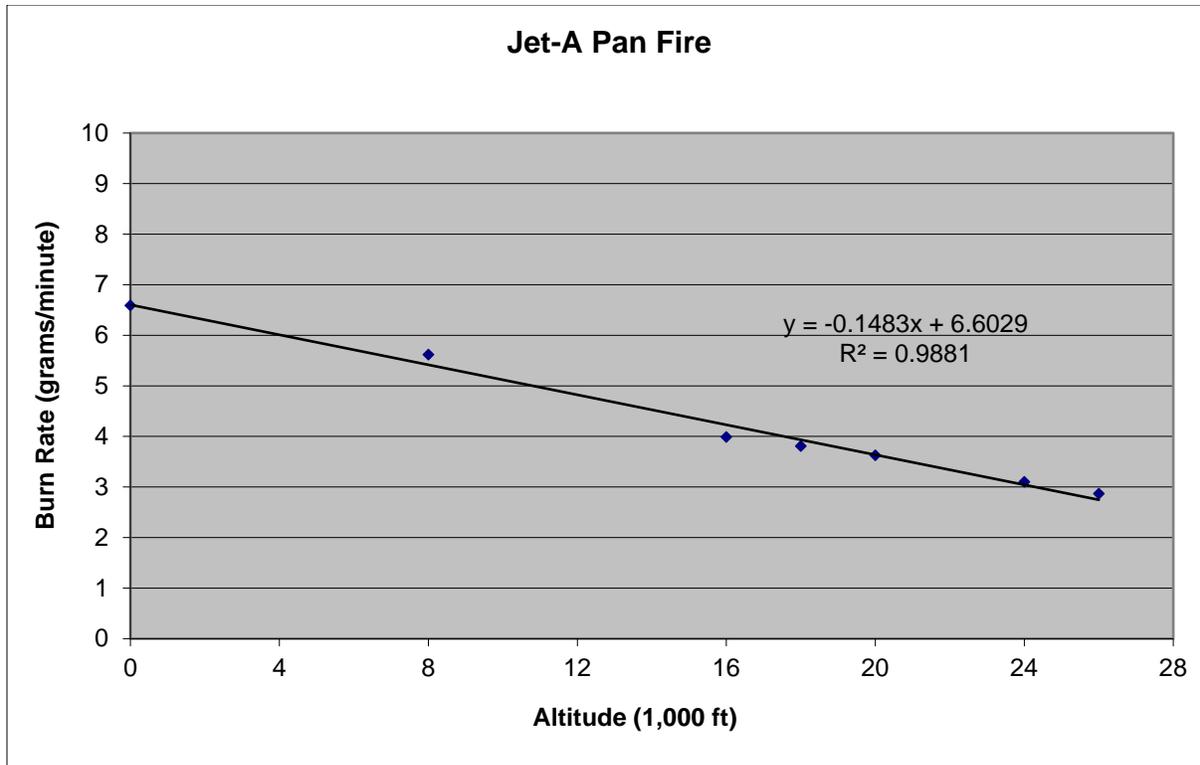


Figure 2. Jet-A pan fire

4.2 POLYMETHYL METHACRYLATE

For this scenario, the flame spread rate of horizontal samples of polymethyl methacrylate (PMMA) sheeting was measured as a function of altitude. The ignition source was a Bunsen burner flowing 98 in³/min (1.6 L/min) of propane. Samples measuring 3-inch (76 mm) wide, 8-inch (203 mm) long, and 0.125-inch (3.2 mm) thick were supported horizontally with the burner flame impinging on the center of the 3-inch (76 mm) edge. Each sample was scribed with two lines 2.4-inch (6 cm) apart, and a stop watch was used to record the amount of time it took the flame to travel between the two lines. Heat flux was measured from left to right as the flame traveled between the two lines. Each data point represents the average flame spread rate resulting from three tests at each altitude. These tests also demonstrated a linear decrease in flame-spread rate with increasing altitude, as shown in figure 3. Unlike propanol and Jet-A, the PMMA samples would not always ignite at the higher altitudes. To adjust for this, testing at higher altitudes was done by igniting the PMMA at a lower altitude (8,000 ft) before proceeding to the higher altitude.

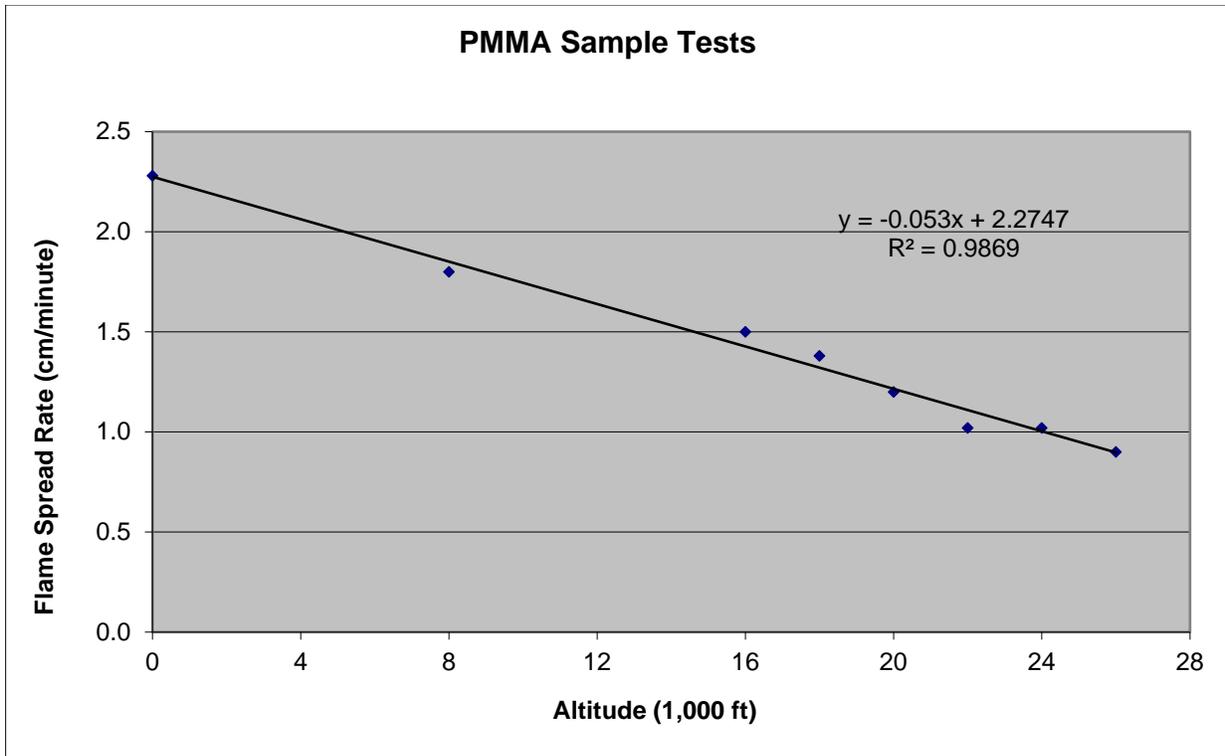


Figure 3. PMMA sample tests

4.3 LITHIUM-ION AND LITHIUM-METAL CELLS

A major concern in aviation is the safe shipment of lithium-ion (rechargeable) and lithium-metal (non-rechargeable) cells and batteries. If a lithium battery experiences, for example an internal short circuit, exothermic chemical reactions can occur within the cell that increase the cell temperature until a sudden and rapid spike in temperature (and pressure) occurs, releasing the contents of the cell through vent openings or by rupturing of the cell. This hazardous cell failure is called thermal runaway. During this overall process, in tests conducted by the FAA in recent years in which lithium cells were overheated, the thermal runaway event is preceded by a distinct release or venting of gases because of the higher temperature and pressure within the cell. The pattern of early venting preceding the thermal runaway event was consistently observed during these tests. This series of tests was done to determine the effect of varying altitude on this venting/thermal runaway pattern. Two different sources were used to overheat the cells: an open flame and a radiant heater.

This series of tests used rechargeable lithium-ion (lithium cobalt oxide; 50% nominal charge) and non-rechargeable lithium-metal (manganese dioxide; 100% nominal charge) cells and batteries. Test results demonstrated that altitude does not affect the series of cell events; however, altitude does affect the flame temperature during direct cell exposure and, therefore, the time it takes for the venting and ignition events to occur.

4.3.1 DIRECT FLAME EXPOSURE

For this scenario, the Bunsen burner flame impinged on the cell, which was placed on a wire mesh tray. A thermocouple was placed 2-inch (51 mm) above the mesh container, and a video camera focused on the battery during the test. A stopwatch was used to determine the time from ignition of the pilot flame to the onset of battery-cell venting. Time was also recorded for the thermal runaway event, as evidenced by the ignition of the vented flammable electrolyte.

Figures 4 and 5 show the time to each event versus altitude for lithium-ion and lithium-metal cells, respectively. It was determined that the reduced pressure at altitude did not prevent thermal runaway for either type cell. However, the time increment between initial venting and thermal runaway increased at the highest altitudes (lowest pressures) tested. This was attributed to the reduction in flame intensity and reduced battery heating with decreased pressure. In addition, the time to vent and to thermal runaway occurred much earlier for the smaller metal cells, which were heated faster.

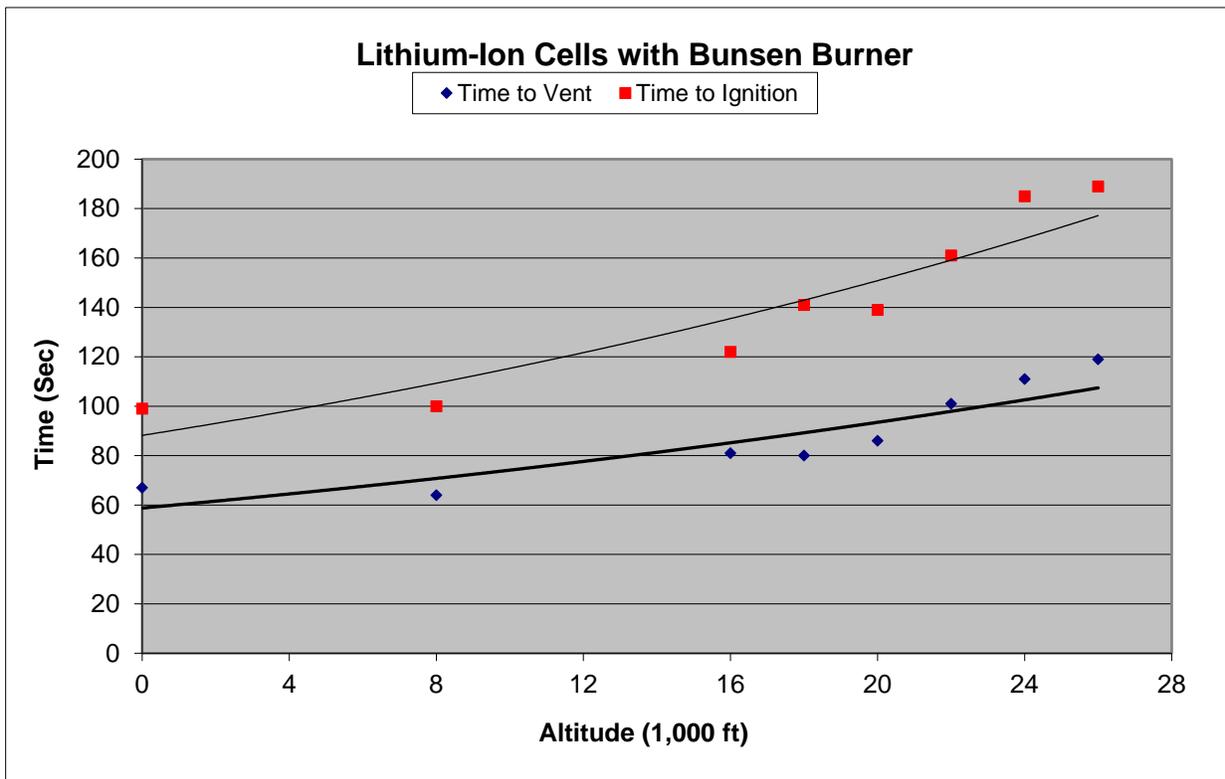


Figure 4. Lithium-ion cells using Bunsen burner

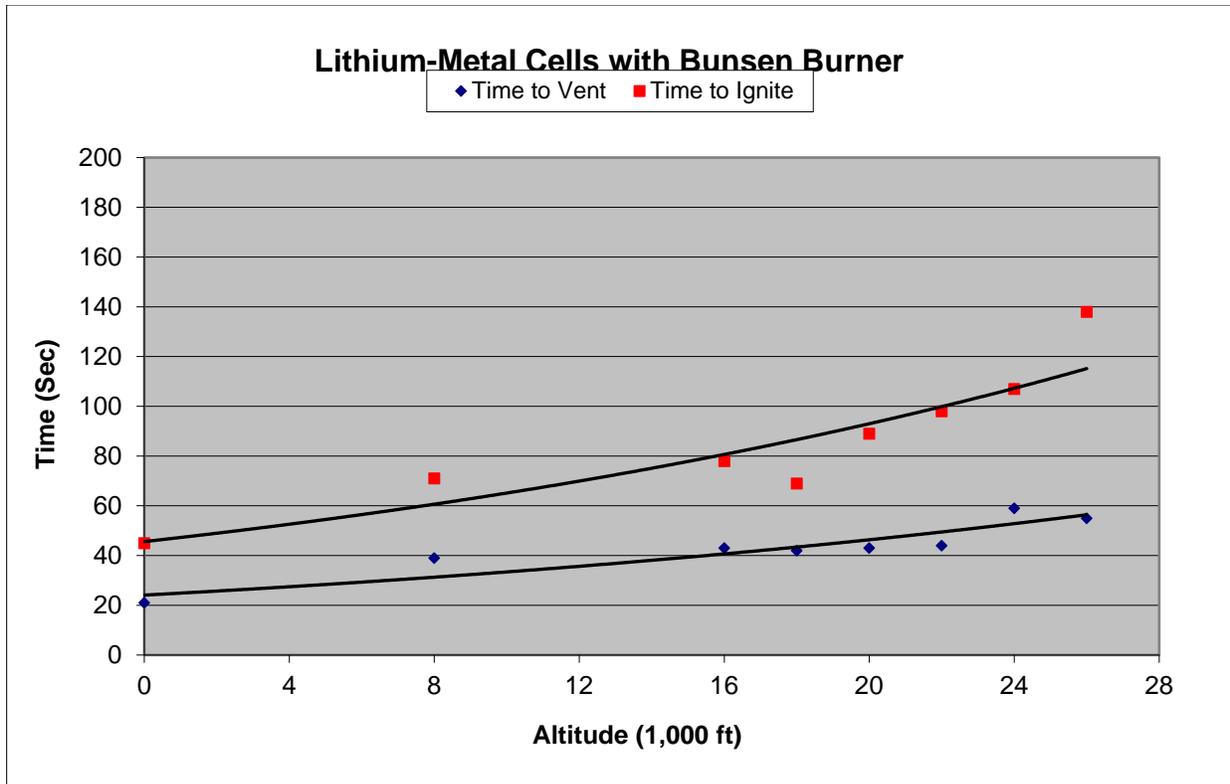


Figure 5. Lithium-metal cells with Bunsen burner

4.3.2 RADIANT HEAT EXPOSURE

The only significant change for this scenario was replacing the Bunsen burner with a 110 VAC Glow-Bar electric resistance type heater and the placement of the wire mesh tray on the heater's convection fins. As shown in figures 6 and 7, neither the lithium-ion cells nor the lithium-metal cells showed any effect of altitude with respect to the time for the venting and thermal runaway ignition events. Unlike the Bunsen burner diffusion flame, the radiant heat flux is independent of pressure, though the heating rate was significantly smaller. This lower heating rate may have been a factor in the lack of ignition of the vented electrolyte during thermal runaway in three of the lithium-metal cell tests (see figure 7).

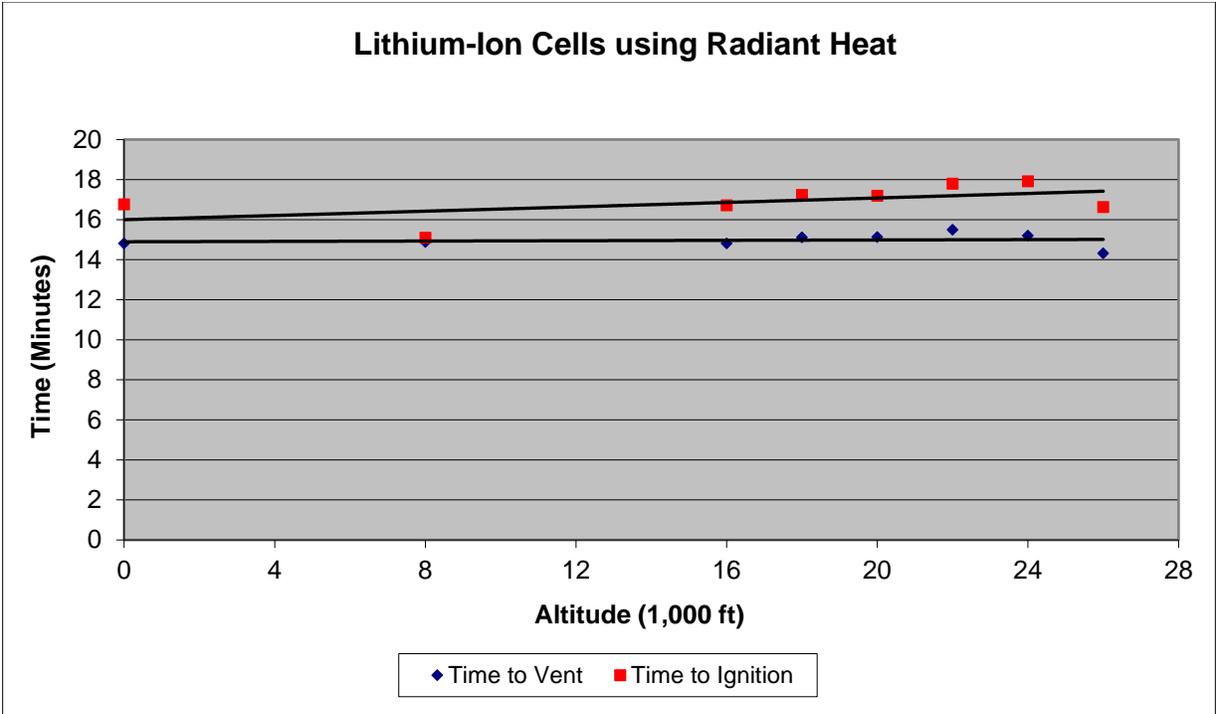


Figure 6. Lithium-ion cells using radiant heat

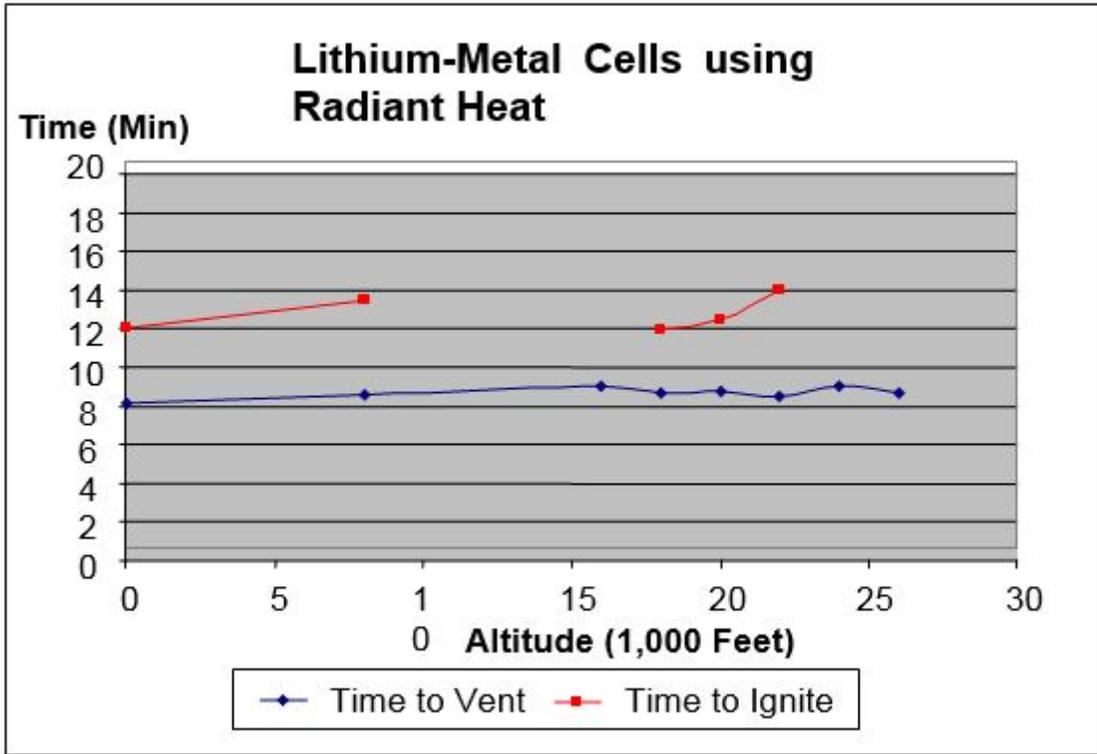


Figure 7. Lithium-metal cells using radiant heat

4.4 SIMULATED CARGO COMPARTMENT FIRE

This series of tests was conducted to determine the effect of varying altitudes and altitude profiles in suppressing a cargo compartment fire. The fire load was 12 cardboard boxes, each containing 2.5 lb (1.1 kg) of shredded paper. Cardboard boxes filled with shredded paper are a standardized fire load used by the FAA during cargo compartment fire-safety testing. One of the boxes contained an ignition source. It was configured with ten 1-inch (25 mm) diameter holes to ensure adequate oxygen to sustain the ignition source and contained an igniter made of nichrome wire wrapped around four paper towels (see figure 8). Energizing the nichrome wire ignited the paper towels, which served as an ignition source.

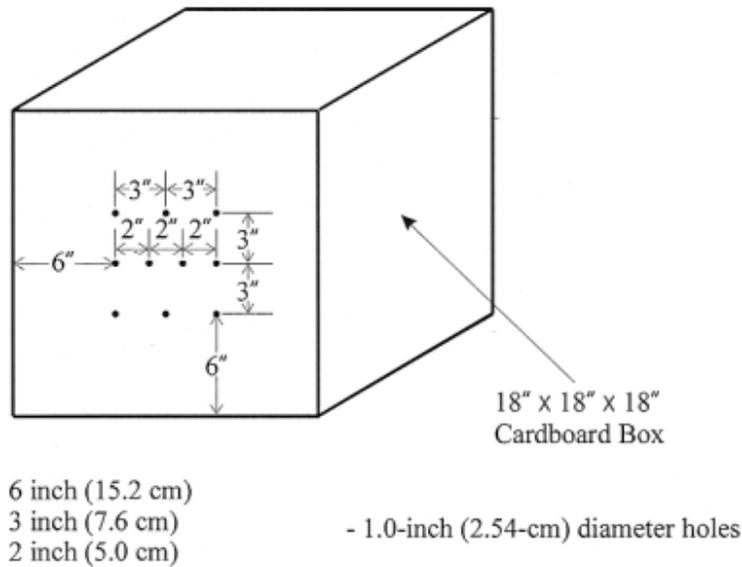


Figure 8. Ignition-box configuration

Figure 9 shows the arrangement in the pressure vessel for the cargo-compartment tests. Five thermocouples were placed in the vessel: three evenly spaced longitudinally above the center of the boxes, one in the rear of the pressure vessel, and one directly above the igniter box.

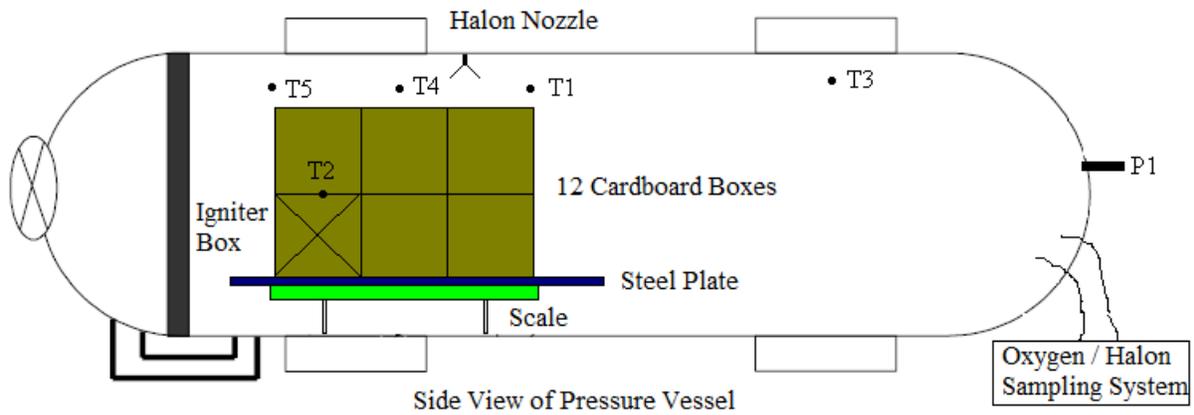


Figure 9. Cargo-compartment test arrangement in pressure vessel

A gas-concentration sampling system (see figure 10) was used to continuously monitor the vessel-space oxygen concentration during all tests and the Halon 1301 concentration during the 4th test when discharged.

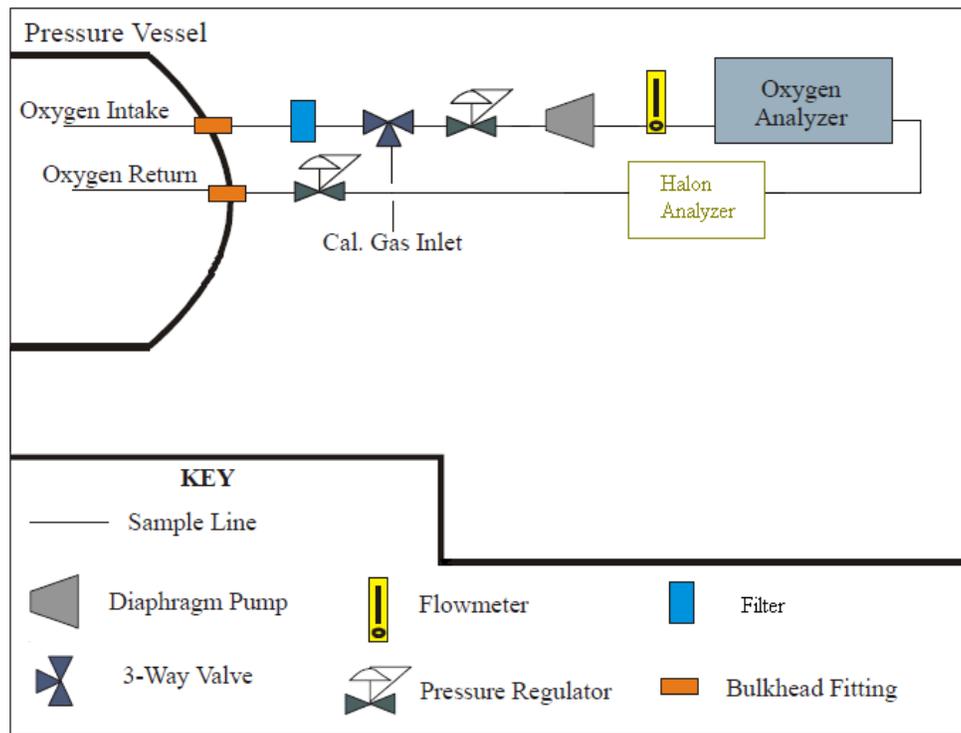


Figure 10. Gas analysis instrumentation for cargo-compartment tests

A flow meter linked to a control valve allowed for simulation of leakage and was set to 10 scfm (283 slpm). The 12 boxes were stacked on a steel plate that was set on a scale to record weight loss while burning.

The goal of this series of tests was to determine the effectiveness of various altitude profiles (depressurization) on controlling a cargo fire. Four flight scenarios or depressurization profiles were tested (see table 2). Each test began at a pressure corresponding to 8,000 ft (2.4 km), which is the normal pressure at cruise altitude. In scenario 1, the vessel pressure was maintained at 8,000 ft (2.4 km) until descent to sea level. In scenarios 2 and 3, the vessel was depressurized in 5 minutes to an equivalent altitude of 18,000 and 24,000 ft (5.5 and 7.3 km), respectively. In scenario 4, the effectiveness of Halon 1301 was evaluated at 8,000 ft (2.4 km) for comparison with scenario 1. Once a rapid temperature rise or ignition was observed by the igniter box thermocouple, the pressure was reduced to the equivalent altitude in scenarios 2 and 3, but maintained at 8,000 ft (2.4 km) in scenarios 1 and 4. This was followed by a 20-minute soak time at this altitude/pressure. After the soak time, the pressure vessel was brought back to a sea level condition.

Table 2. In-flight fire scenario depressurization profiles

Scenario	Altitude (pre fire)	Altitude (once fire observed)	Soak Time (minutes)	Descent Time to Sea Level (minutes)	Descent Rate (ft/min)
1	8,000 ft	8,000 ft	20	8	1,000
2	8,000 ft	18,000 ft	20	14	1,286
3	8,000 ft	24,000 ft	20	17	1,412
4	8,000 ft	8,000 ft	20	8	1,000

In scenario 4, Halon was discharged into the vessel when the fire was observed. The Halon bottle was located outside of the vessel and sat on a scale to monitor the agent discharge weight. The discharge nozzle was located directly above the center of the boxes (see figure 9). An initial discharge of 8 lb (3.6 kg) of Halon was used to extinguish the fire, and then a trickle flow of Halon was discharged to maintain a level above 3% Halon to prevent reignition of the deep-seated fire. The Halon discharge sequence and concentration profile follow the pattern of cargo compartment Halon 1301 fire-suppression systems in passenger transport aircraft.

4.4.1 Scenario 1: Cruising at 8,000 ft (~10.92 psia)

As in all scenarios, the igniter in scenario 1 was energized 60 seconds after the beginning of the test. Approximately 3 minutes later, a flashover occurred, as evidenced by the rapid increase in temperature, achieving a peak of 1400°F (760°C), and the corresponding decrease in oxygen (see figure 11). The air temperature was reduced to and maintained at 300°F (149°C) until descent was initiated following the 20-minute soak time, although the temperature near the box was considerably higher, peaking at 600°F (316°C). Approximately midway through the 8-minute descent, a second flashover occurred because of the higher pressure and incoming air.

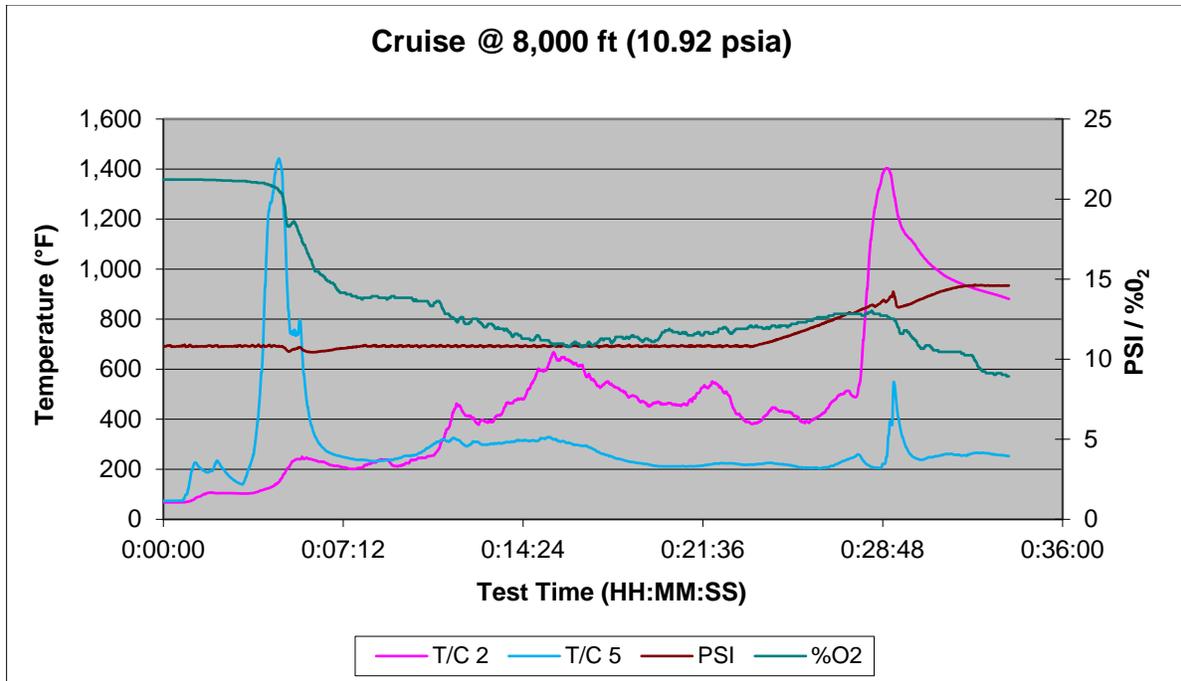


Figure 11. Cruising at 8,000 ft (~10.92 psia)

4.4.2 Scenario 2: Depressurizing to 18,000 ft (~7.34 psia)

Figure 12 shows the effectiveness of depressurization to a pressure equivalent to 18,000 ft (5.5 km).

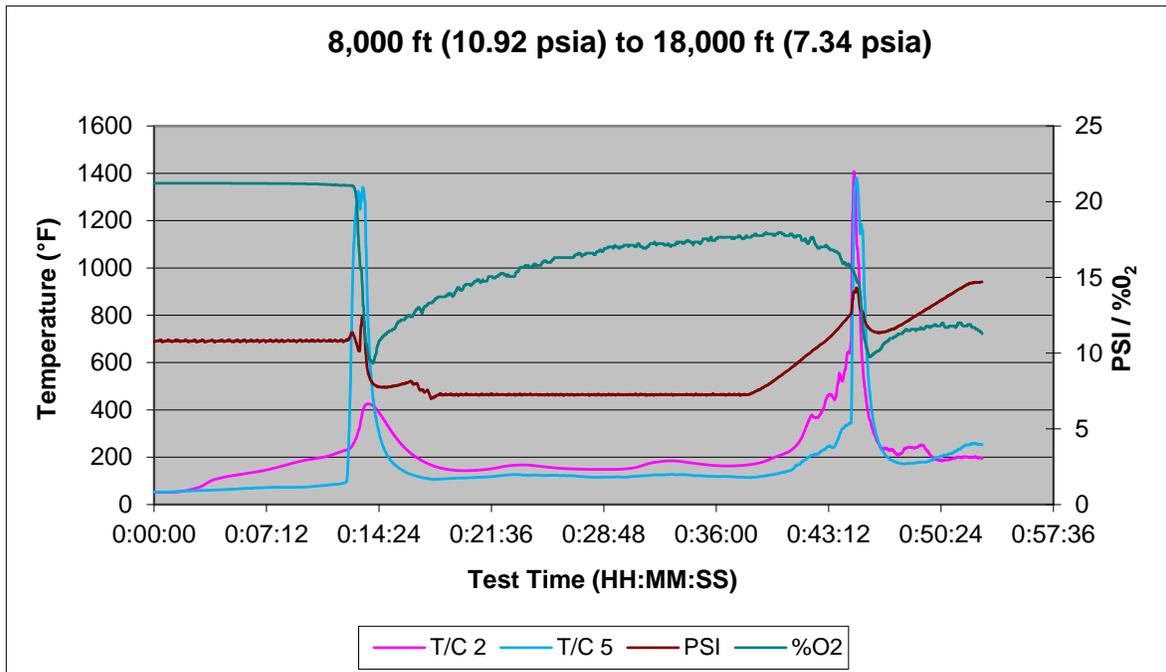


Figure 12. Depressurizing to 18,000 ft (~7.34 psia)

4.4.3 Scenario 3: Depressurizing to 24,000 ft (~5.7 psia)

Scenarios 2 and 3 compared the effectiveness of depressurization to a pressure equivalent of 18,000 and 24,000 ft (5.5 and 7.3 km) respectively (figures 12 and 13). In both tests, flashover occurred after ignition. Following depressurization, the temperatures in the vessel were maintained below 200°F (93°C), noticeably below the temperatures experienced when the altitude was maintained at 8,000 ft (scenario 1). The oxygen concentration increased because of leakage, but the low pressures prevented reignition. However, flashover occurred in both scenarios during descent.

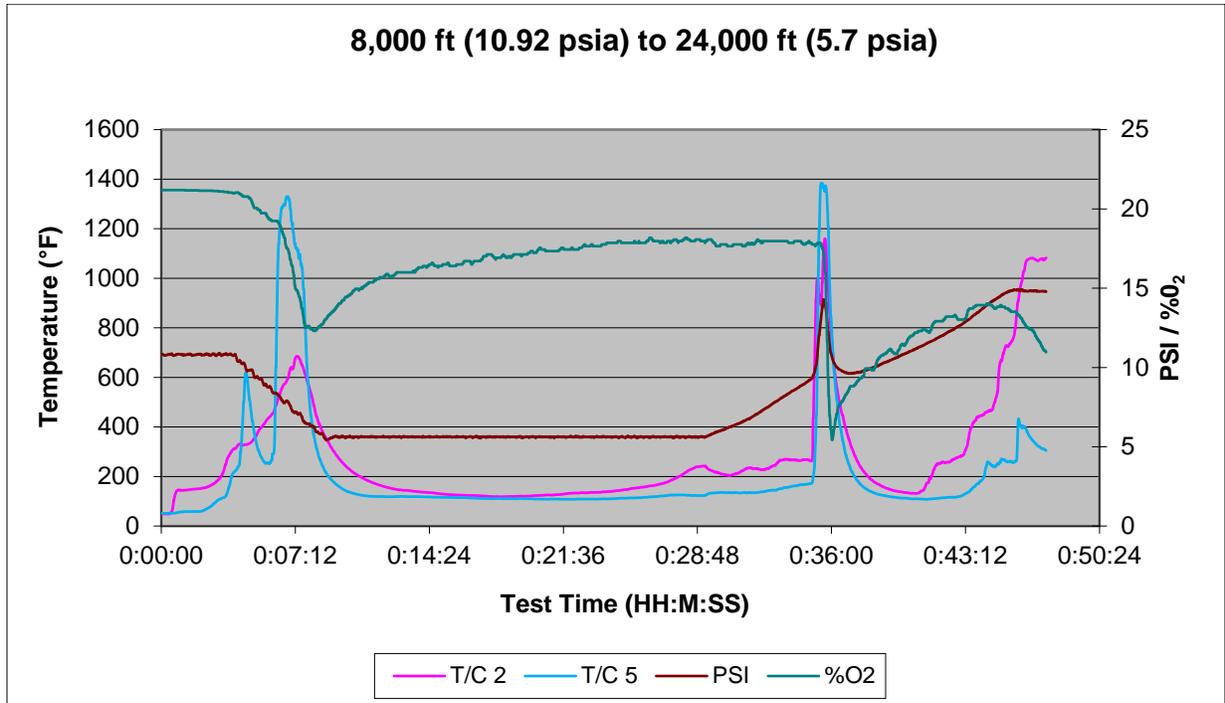


Figure 13. Depressurizing to 24,000 ft (~5.7 psia)

4.4.4 Scenario 4: Cruising at 8,000 ft (~10.92 psia) With Halon

The discharge of Halon 1301 (figure 14) was highly effective in that both flashovers experienced during scenarios 1–3, following ignition and during descent, were prevented. Interestingly, the ignition-box temperature rose during descent, apparently because the Halon did not penetrate effectively into or between the boxes, but the vessel air temperature never exceeded 300°F (149°C) throughout the descent, although it rose slightly during the deep-seated burning within the cargo boxes.

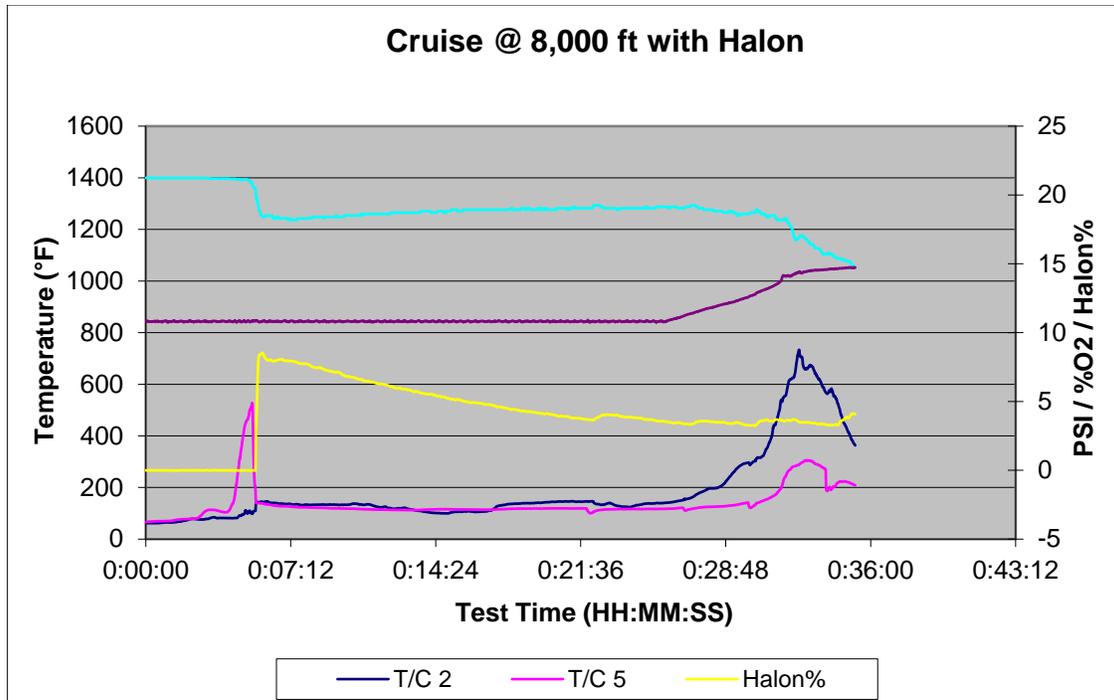


Figure 14. Cruising at 8,000 ft (~10.92 psia) with Halon

5. CONCLUSIONS

Based on a series of tests conducted in a pressure vessel modified to control the internal pressure to a specific value or programmed to simulate a depressurization profile to suppress a fire and an emergency descent to sea level, the following conclusions were made on the effect of reduced pressure on the burning behavior of materials, batteries, and stacked cargo:

- Flashover was not prevented when depressurization was initiated by the detection of a fire in a stacked loading of cargo consisting of cardboard boxes filled with shredded paper.
- Flashover occurred again when the pressure increased during a simulated emergency descent.
- The discharge of Halon 1301 and maintaining a minimal concentration of 3% prevented flashover and reduced the air temperature in the vessel to below 200°F (93°C).
- During the suppression of the fire with Halon 1301, the temperature measured within the deep-seated cargo fire exceeded 600°F (316°C).
- Thermal runaway in lithium-ion batteries caused by exposure to a controlled fire condition was not prevented over a range of pressures corresponding to sea level and an elevation of 26,000 ft (7.9 km).
- The time to thermal runaway in lithium batteries increased with reduced pressure when exposed to a controlled fire, but was invariant when exposed to radiant heat alone.
- The mass-loss burning rate of propanol and Jet-A fuel decreased in a linear manner by approximately a factor of 2 from sea level to 26,000 ft (7.9 km).
- The flame spread rate of polymethyl methacrylate (acrylic sheet) decreased in a linear manner by approximately a factor of 2 from sea level to 26,000 ft (7.9 km).