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Evaluation of Large Class B Cargo Compartment's Fire Protection

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16. Abstract Twenty-six tests were conducted to evaluate the effectiveness of current fire safety requirements for large Class B cargo compartments as well as proposed improvements to the requirements. The major findings were that the current requirements are not effective on the types of fires tested and that there are several alternatives that could be implemented to better enable a large Class B compartment to withstand the types of fires tested.			
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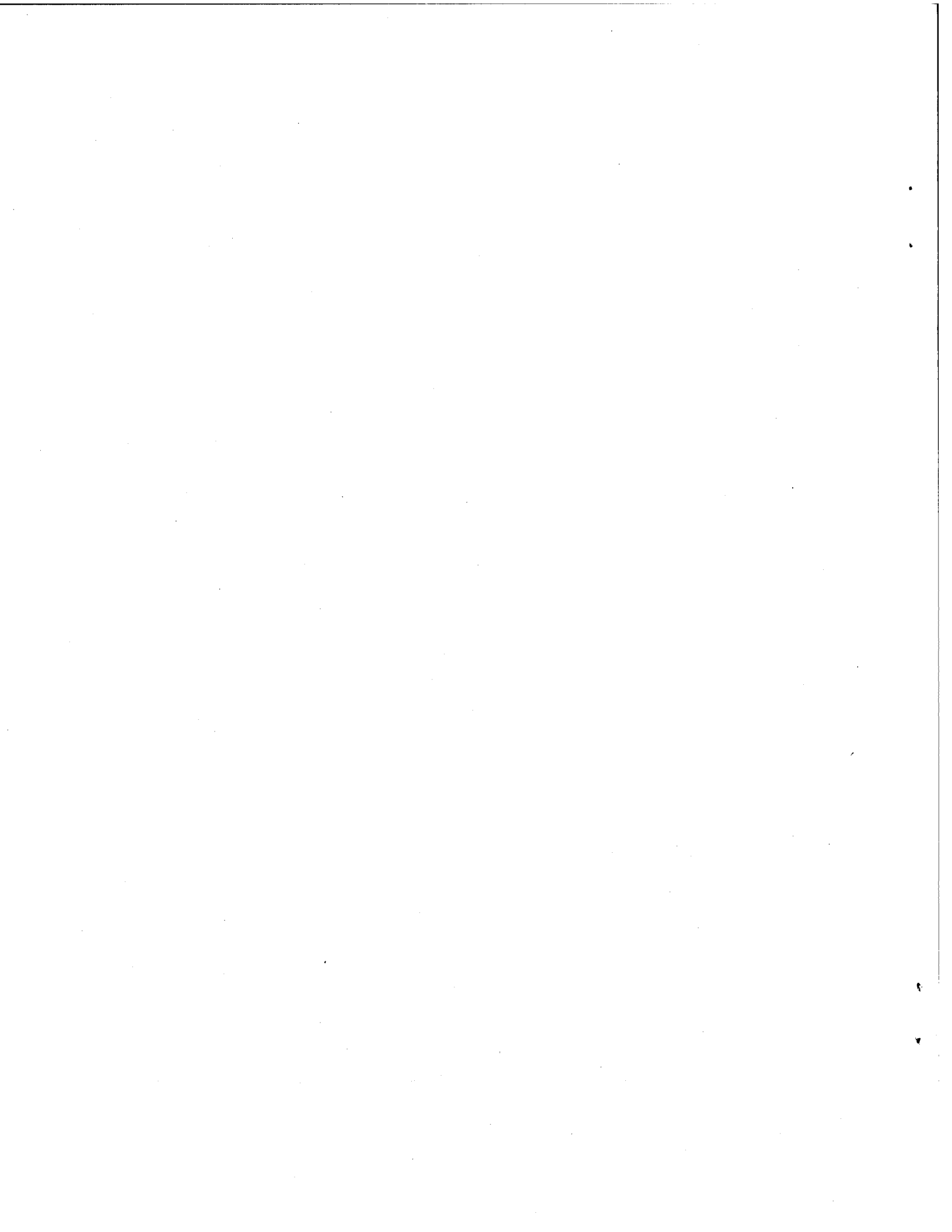


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EXECUTIVE SUMMARY

The purpose of this project was to evaluate the effectiveness of current fire safety requirements for large Class B cargo compartments and test the effectiveness of proposed improvements. This work was undertaken following the loss of a South African Airlines B747 "combi" (passengers and cargo compartment share the main deck) that crashed into the Indian Ocean. A cargo fire had occurred in the main deck Class B cargo compartment of this airplane and was the cause of the crash. The ignition source of the fire was not determined. At the time of the accident, Class B cargo compartments were required to have a smoke detection system that alarms in the cockpit and to have sufficient access inside the compartment to allow a crew member to effectively reach any part of the compartment with the contents of a hand held fire extinguisher. Testing was conducted to determine the temperature and visibility conditions in the compartment that would be required for a crewmember to locate and fight a fire. Further testing evaluated the effectiveness of fire containment covers over individual pallets, fire resistant cargo containers, a Halon 1301 suppression system, and a comparison of smoke detector versus infrared detector alarm response. One of the conclusions was that a crew member would not have sufficient visibility or extinguishing agent to control these types of fires. In addition, fire containment covers, fire resistant cargo containers, and a halon suppression system were all effective at controlling these fires. The infrared detectors responded faster than smoke detectors in the majority of the tests; however, the smoke detectors alarmed before there was sufficient heat to damage any structure or system within the cargo compartment.

INTRODUCTION

PURPOSE.

The purpose of this project was to determine the hazards generated by cargo fires in large Class B cargo compartments and to determine the effectiveness of various detection, extinguishment, and containment alternatives.

BACKGROUND.

This study was undertaken following the loss of a South African Airways B747-244B that crashed into the Indian Ocean. The aircraft was being operated as a "combi", which is a combination of passengers and cargo separated by a partition, on the main deck of the aircraft. A fire occurred in the cargo portion of the main deck which eventually caused the loss of control of the aircraft and the subsequent crash. Approximately 20 minutes elapsed between the cargo compartment smoke detector alarm and the crash. The fire was determined to have started in the forward right pallet although the ignition source was never determined. No evidence of explosives, hazardous materials, or sabotage was found [1]. This cargo compartment was certified as a Class B compartment. A Class B compartment is defined as one in which (a) there is sufficient access in flight to enable a crew member to effectively reach any part of the compartment with the contents of a hand held fire extinguisher; (b) when the access provisions are being used, no hazardous quantity of smoke, flame, or extinguishing agent will enter any compartment occupied by the crew and passengers; and (c) there is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station. Class B cargo compartments are found on aircraft ranging from wide-body transport category aircraft down to commuters. Transport category aircraft often use Class B compartments on combi operations where the volume of the main deck compartment can be varied depending on the mix of passengers and freight. Commuter aircraft generally have Class B compartments of a fixed size. Appendix A contains the classifications for cargo compartments.

DISCUSSION

The testing for this project was conducted in a B707 fuselage, a DC10 fuselage, and on pallets outside of the fuselages at the Full-Scale Fire Test Facility. Both fuselages (test articles) were mocked up as combis with a simulated passenger section and a cargo compartment on the main deck. These two sections were separated by a metal partition wall that extended from the cabin floor to the top of the airplane. The entire inside surface of the test articles that was above the floor was insulated with fiberglass batts and then covered with galvanized steel. This allowed the fuselages to withstand the test fires without any structural damage.

B707 TEST ARTICLE.

The cargo compartment in the B707 had a volume of approximately 1800 cubic feet. A large fan was used to supply ventilation air to the cargo compartment and to the passenger section through ten-inch-diameter perforated ducts mounted in the crown area. The ventilation system was calibrated to provide one change of air approximately every four minutes in both the cargo

compartment and passenger cabin sections. Figure 1 shows the test article and ventilation system.

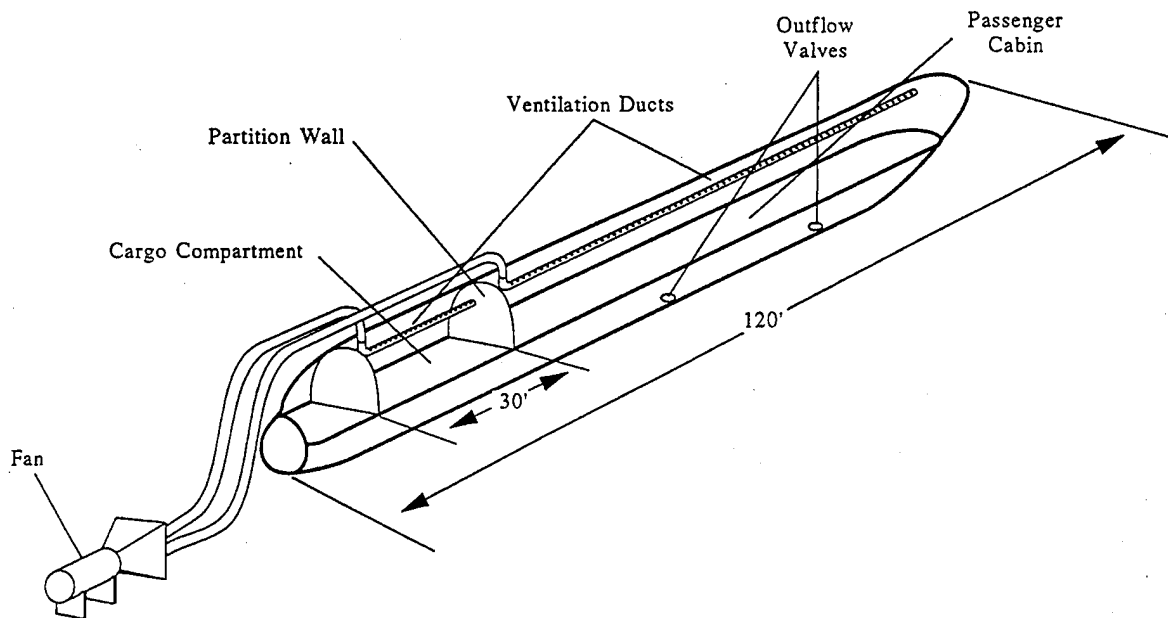


FIGURE 1. B707 TEST ARTICLE VENTILATION SYSTEM

The test article was extensively instrumented with Type K Chromel/Alumel thermocouples. Sixteen thermocouples, 21 inches apart, were mounted in the crown area of the cargo compartment along the airplane centerline. These thermocouples extended the entire length of the cargo compartment. Two thermocouple trees consisting of seven thermocouples spaced at one-foot intervals starting one foot above the floor and extending to seven feet above the floor were installed in the airplane; one thermocouple tree was in the cargo compartment and the other in the cabin section. Sixteen more thermocouples were arranged in a grid measuring 18 by 18 inches that was placed on top of the stack of boxes to be ignited. Four thermocouples were placed on the bottom of the pallet that contained the fire load and four more thermocouples were placed on the cargo compartment floor under the pallet. The pallet was approximately four inches above the floor. Four additional thermocouples were placed inside the stack of boxes to be ignited and were used to monitor the progress of the fire. A detailed description of the fire load is in a later section.

Two sets of smoke meters were installed in the test article, one in the cargo section and one in the cabin section. A set consisted of three smoke meters placed at heights of 2, 4, and 6 feet above the floor. Each smoke meter consisted of a collimated light beam and a photocell and measured the percent light transmission over a distance of one foot.

Gas sampling lines were installed at the same location as the three smoke meters in the cargo section of the fuselage and at the four-foot-height smoke meter in the cabin section. The gas that was drawn from these four locations was routed to four racks of gas analyzers. Each rack

continuously measured the concentration of carbon monoxide (CO), carbon dioxide (CO₂), and oxygen.

The millivolt signals from the thermocouples, smoke meters, and gas analyzers were routed to an analog-to-digital converter, processed by a computer, and converted into engineering units and stored. Data from each instrument was recorded at a rate of one data point every five seconds for the duration of the test.

Two video cameras in insulated boxes monitored and recorded a forward looking and aft looking view of the cargo compartment. Figure 2 shows the location of the B707 instrumentation.

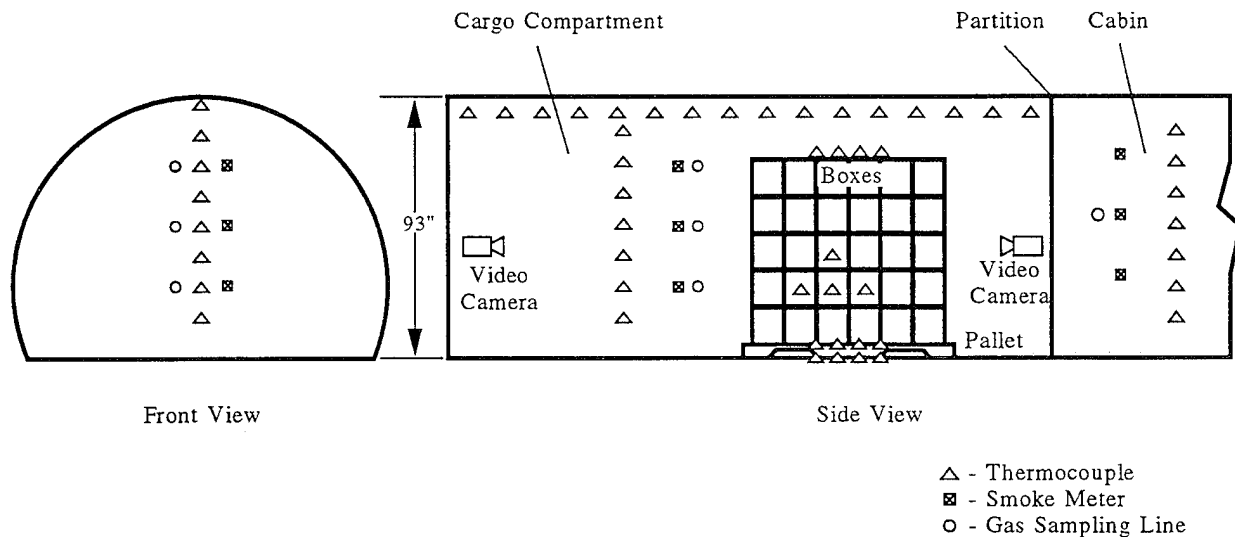


FIGURE 2. B707 TEST ARTICLE INSTRUMENTATION

An air sampling type of smoke detection system, similar to an in-service design, was installed in the main deck cargo compartment. It consisted of a manifold with ten ports equally spaced along the length of the cargo compartment and mounted in the crown area. A vacuum system was used to draw cargo compartment air through these ports into two parallel mounted photoelectric smoke detectors. The size of the ports was varied so that all the ports were drawing the same amount of air. Each port drew approximately 0.2 cubic feet per minute (CFM) of compartment air. The smoke detectors were calibrated to alarm at $92 \pm$ one percent light transmission per foot. The operation of the smoke detection system was verified using the William J Hughes Technical Center developed buoyant smoke generator [2]. This device uses a mixture of helium and air to which theatrical smoke is added. This produces a plume of smoke with similar buoyancy properties as the smoke plume from a small fire. Figure 3 shows the plume of smoke produced by the generator. Generating smoke for as little as 15 seconds with this device caused the smoke detectors to alarm in less than one minute for all the locations tested. Figure 4 shows the B707 smoke detection system.

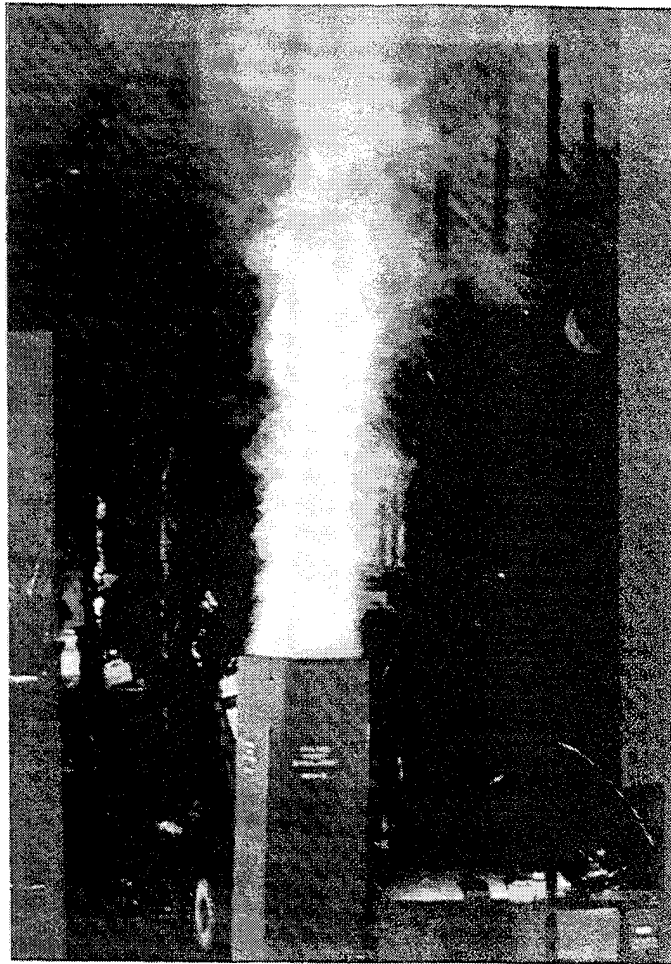


FIGURE 3. FEDERAL AVIATION ADMINISTRATION BUOYANT THEATRICAL SMOKE GENERATOR

Infrared detectors were mounted in the cargo compartment for some of the B707 tests. The location and operation of these detectors will be discussed in a later section.

A total-flood CO₂ system and a water spray system were both installed in the test article to suppress and control the fires at the completion of the tests.

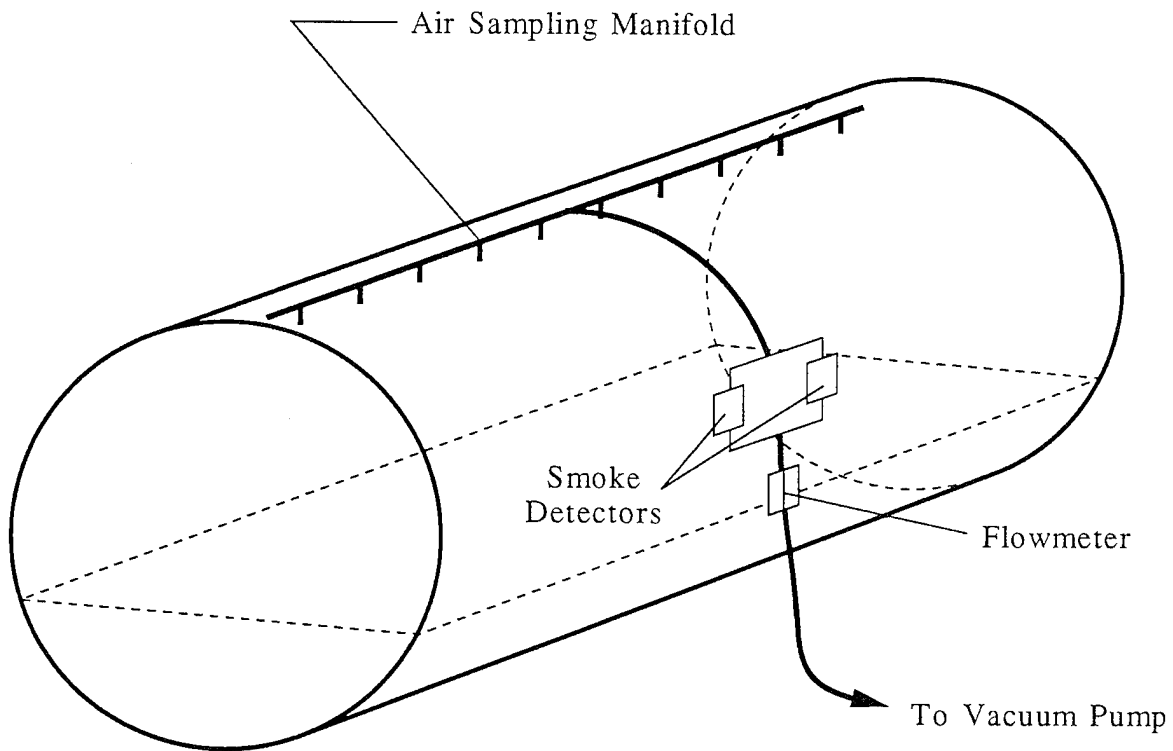


FIGURE 4. B707 CARGO COMPARTMENT SMOKE DETECTION SYSTEM

DC10 TEST ARTICLE.

The cargo compartment in the DC10 had a volume of approximately 9000 cubic feet. A large fan was used to supply ventilation air to the cargo compartment through ten-inch-diameter perforated ducts mounted on the upper sidewall. The system was calibrated to provide one change of cargo compartment air approximately every 5.5 minutes. The fan did not have sufficient capacity to provide ventilation air into the passenger cabin section. Figure 5 shows the DC10 test article and ventilation system.

A total of 32 chromel/alumel thermocouples were installed in the DC10 test article. Sixteen thermocouples, three feet apart, were installed in the crown area above the cargo compartment. A thermocouple tree consisting of eight thermocouples spaced one foot apart, starting from one foot above the floor and extending to eight feet above the floor was installed adjacent to the fire load in the cargo compartment. Four thermocouples were placed among the boxes that made up the fire load. The final four thermocouples were placed on top of the fire load.

Two Gardon gauge total heat flux calorimeters were used in the final DC10 test. They were installed through the top of the airplane along the centerline with the faces of the calorimeter flush with the top of the airplane. One calorimeter was centered over the fire load and the other over the aft edge of the fire load.

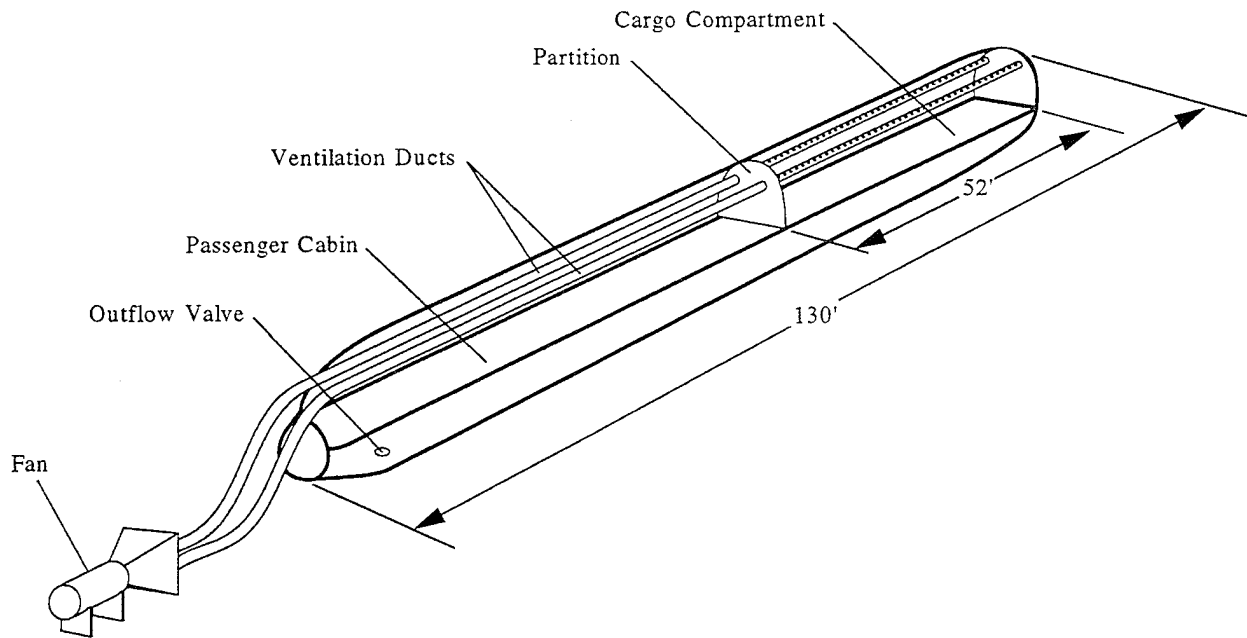


FIGURE 5. DC10 TEST ARTICLE VENTILATION SYSTEM

Two sets of smoke meters were installed in the cargo compartment, one set forward of the fire load and one set aft. A set consisted of three smoke meters placed at heights of 2, 4, and 6 feet above the floor. The smoke meters were the same as those used in the B707 test article and measured the percent light transmission over one foot.

A gas sampling station was installed in the cargo compartment aft of the fire load. Air was drawn from the compartment at heights of 19, 38, 57, and 76 inches above the floor. The gas from these four locations was routed to four racks of continuous gas analyzers. These analyzers measured the concentration of CO, CO₂, oxygen, and Halon 1301 (bromotrifluoromethane).

Data from each instrument were recorded at a rate of one data point every five seconds and stored on computer.

Two video cameras in insulated boxes provided a forward and aft looking view of the cargo compartment interior. These video signals were recorded for all tests. Figure 6 shows the DC10 instrumentation.

An air sampling smoke detection system similar to the one used in the B707 was also installed in the DC10 cargo compartment. It consisted of a manifold with nine ports spaced every 29 inches along the crown area above the section of the cargo compartment containing the fire load. A vacuum system was used to draw cargo compartment air through these ports into two parallel

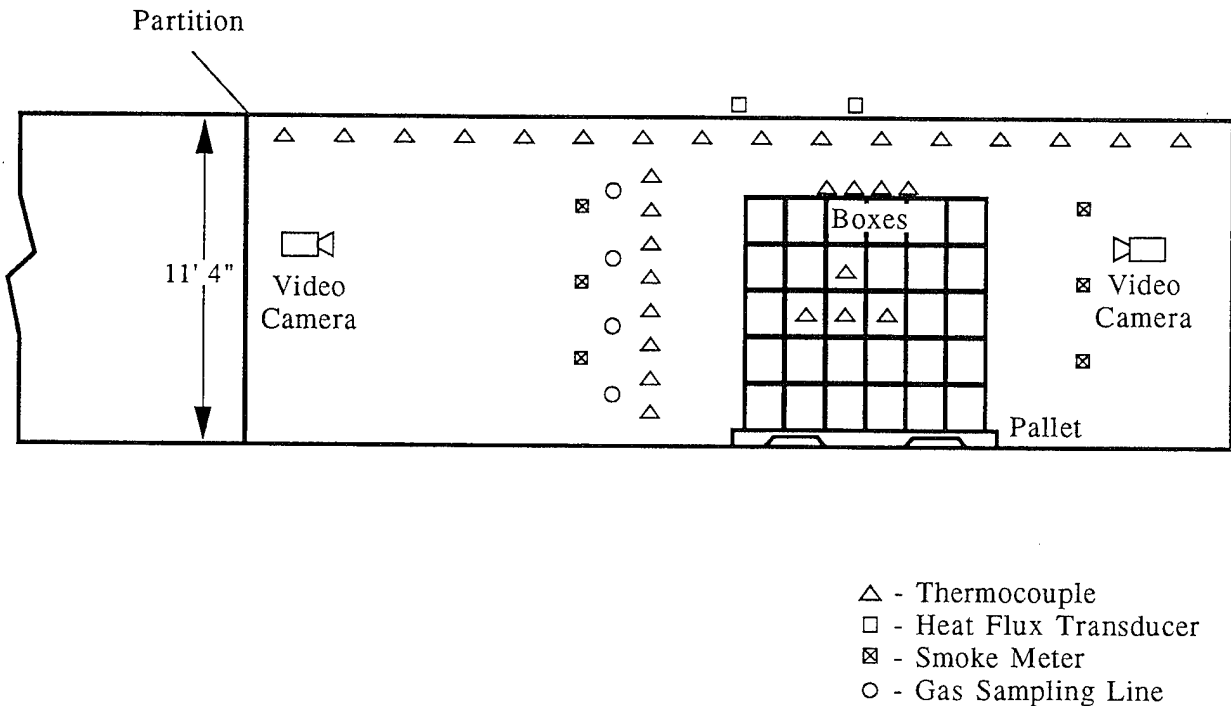


FIGURE 6. DC10 CARGO COMPARTMENT INSTRUMENTATION

mounted photoelectric smoke detectors. The size of the openings in the ports was varied so that each port would draw approximately 0.2 CFM of air. The smoke detector alarm point was 92 ± 1 percent light transmission over one foot. The operation of the smoke detection system was verified using the buoyant smoke generator that was used to verify the smoke detection system in the B707 test article. The alarm times were similar to those achieved in the B707 and in all cases were less than one minute. Figure 7 shows the DC10 smoke detection system.

Two Halon 1301 discharge systems were installed. The first system provided the initial extinguishing agent concentration of five percent and the second system metered agent to maintain the concentration above three percent to prevent open flaming reignition. The initial discharge system used 16 discharge nozzles spaced three feet apart and mounted in the crown area. Two hundred pounds of halon provided an initial concentration of just over five percent in the empty 9000 cubic foot compartment. Due to the compartment leakage, the average halon concentration from the initial discharge, as measured by the four gas probes, remained above three percent for 7.5 minutes. The metered system consisted of a one-ton Halon 1301 tank, a metering valve and two 1/4-inch copper distribution lines.

Halon was discharged at a rate of eight pounds per minute through the metering system. Seven minutes after the initial discharge of 200 lbs. of agent, the metering system was started and was able to maintain a three percent halon concentration in the area surrounding the fire load for the duration of the test. Figure 8 shows the halon suppression system in the DC10. A total-flood CO₂ system and a water spray system were also installed in the test article to suppress and control the fires at the completion of the tests.

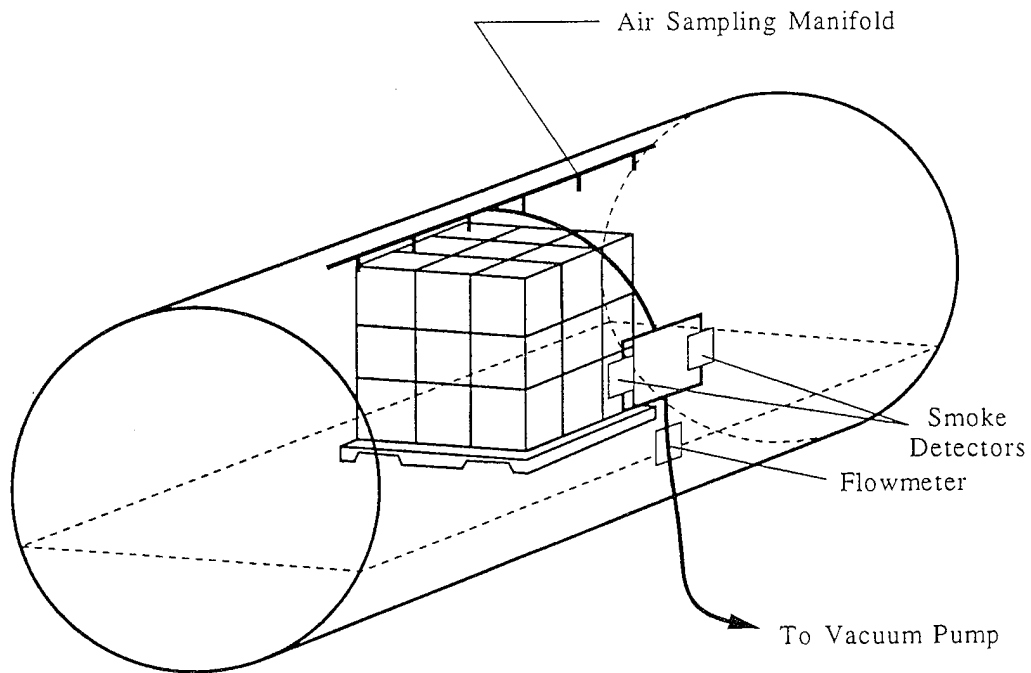


FIGURE 7. DC10 CARGO COMPARTMENT SMOKE DETECTION SYSTEM

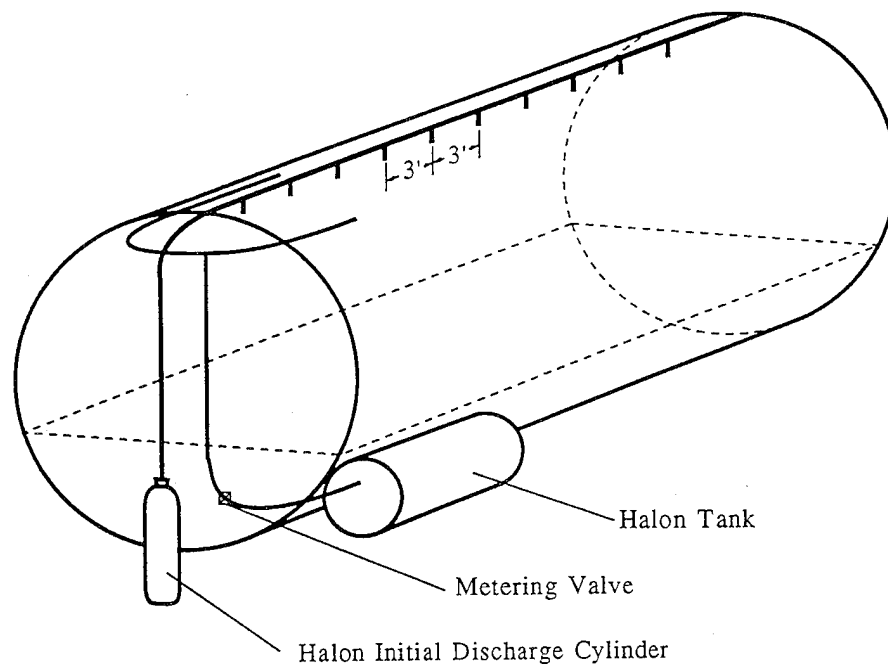


FIGURE 8. DC10 HALON DISCHARGE SYSTEM

TEST DESCRIPTION AND RESULTS

A total of 26 tests were conducted during this study. Table 1 gives a brief description of the 26 tests.

TABLE 1. SUMMARY OF TESTS

Test	Test Article	Detectors Used	Table 1 Fire Load Conditions
1	B707	Smoke	Fiberglass/Silicone FCC*
2	B707	Smoke and IR	Fiberglass/Silicone FCC
3	B707	Smoke	Fiberglass/Silicone FCC
4	B707	Smoke and IR	Fiberglass/Silicone FCC
5	B707	Smoke and IR	Fiberglass/Silicone FCC
6	B707	Smoke	Fiberglass/Silicone FCC
7	B707	Smoke	Polyethylene
8	B707	Smoke and IR	Aluminum Container
9	Building	None	Fiberglass/Silicone FCC
10	DC10	None	Cargo Net
11	Building	None	Fiberglass/Silicone FCC
12	Building	None	Polyethylene
13	DC10	Smoke and IR	Polyethylene
14	DC10	Smoke and IR	Polyethylene
15	DC10	Smoke and IR	Polyethylene
16	DC10	Smoke	Polyethylene
17	Building	None	Fiberglass Container w/Fiberglass Door
18	Building	None	Fiberglass Container w/Fiberglass Door
19	Building	None	Fiberglass Container w/Treated Vinyl/Nylon Door
20	Building	None	Fiberglass Container w/Treated Vinyl/Nylon Door
21	Building	None	Fiberglass Container w/Kevlar Door
22	Building	None	Kevlar/Silicone FCC
23	Building	None	Kevlar/Silicone FCC
24	Building	None	Kevlar/Silicone FCC
25	Building	None	Kevlar/Silicone FCC
26	Building	None	Kevlar/Silicone FCC

* Fire Containment Cover

EFFECTIVENESS OF CURRENT CLASS B CARGO COMPARTMENT REQUIREMENTS.

The tests that addressed the effectiveness of Class B cargo compartment fire protection design in use before the implementation of rule changes were tests 7, 8, 10, and 12. These tests were baseline tests of burning packaging material without the added protection of fire containment covers or a total-flood suppression system required in the Airworthiness Directive dealing with

Class B cargo compartments [3]. The fire load for tests 7, 8, and 10 was cardboard boxes filled with shredded newspaper. The density of this fire load was approximately 2.5 pounds per cubic foot. This fire load was used for all but one test because of its ease of preparation and because it consistently produced a deep seated fire. The fire load for test 12 was cardboard boxes filled with miscellaneous electronic hardware, computer tapes, and polystyrene packaging material. The density of this load was approximately eight pounds per cubic foot. That density is representative of the industry average. Ignition in all tests was achieved by energizing a coil of nichrome wire inside one of the boxes.

TEST 7. The boxes were stacked on a 88- by 108-inch aluminum pallet to a height of approximately six feet. The cargo loaded pallet was then covered with a sheet of 6-mil clear polyethylene (typical weatherproofing). The ignitor was placed in the bottom center box. The smoke detectors alarmed seven minutes six seconds after the nichrome wire was energized. This was at the same time that visible flames were observed and the polyethylene cover started to burn away. The fire grew quickly after that point with ceiling temperatures above the pallet at 1500°F 30 seconds later. Successful fire fighting by a crew member with a hand held fire extinguisher would have been virtually impossible at this point. The fire burned with enough intensity to reduce the oxygen concentration in the cargo compartment at the six foot level to approximately two percent despite the fact that ventilation air continued to be supplied to the compartment. The test was terminated at 14 minutes. At that time the conditions in the simulated cabin section at the six foot level were an oxygen concentration of 19.5 percent, carbon dioxide at 1 percent, carbon monoxide at 2000 part per million (ppm), light transmission at 82 percent, and a temperature of 125°F.

TEST 8. An aluminum cargo container with a volume of approximately 375 cubic feet was constructed and placed on the 88- by 108-inch pallet for this test. The container was not tightly sealed and had air gaps along several edges. The ignitor was again placed in the bottom center box. The smoke detector system alarmed at 13:47. The ceiling temperature above the container increased slowly until about 19 minutes at which time there was a rapid increase to about 1300°F. The test was terminated at 24 minutes with ceiling temperatures still over 1200°F. The aluminum sidewalls of the container were burned through in several places but the roof was intact. The lowest oxygen concentration in the cargo compartment at the six foot height was 12 percent. The conditions in the cabin section at the six foot level when the test was terminated were an oxygen concentration of 20 percent, CO₂ at less than 1 percent, CO at 2000 ppm, and a temperature of 100°F (temperature was 80°F at the start of the test). Figures 9 and 10 show the temperature and smoke conditions in the cargo compartment at six feet above the floor that a firefighter would be exposed to after smoke detection for the polyethylene covered fire load (Test 7) and the containerized fire load (Test 8). The distance at which a back lighted sign is visible is related to light transmission by the following formula [4]:

$$V = 3.5/\log(1/T)$$

Where:

V = Visibility in feet

T = Fraction of light transmitted over one foot.

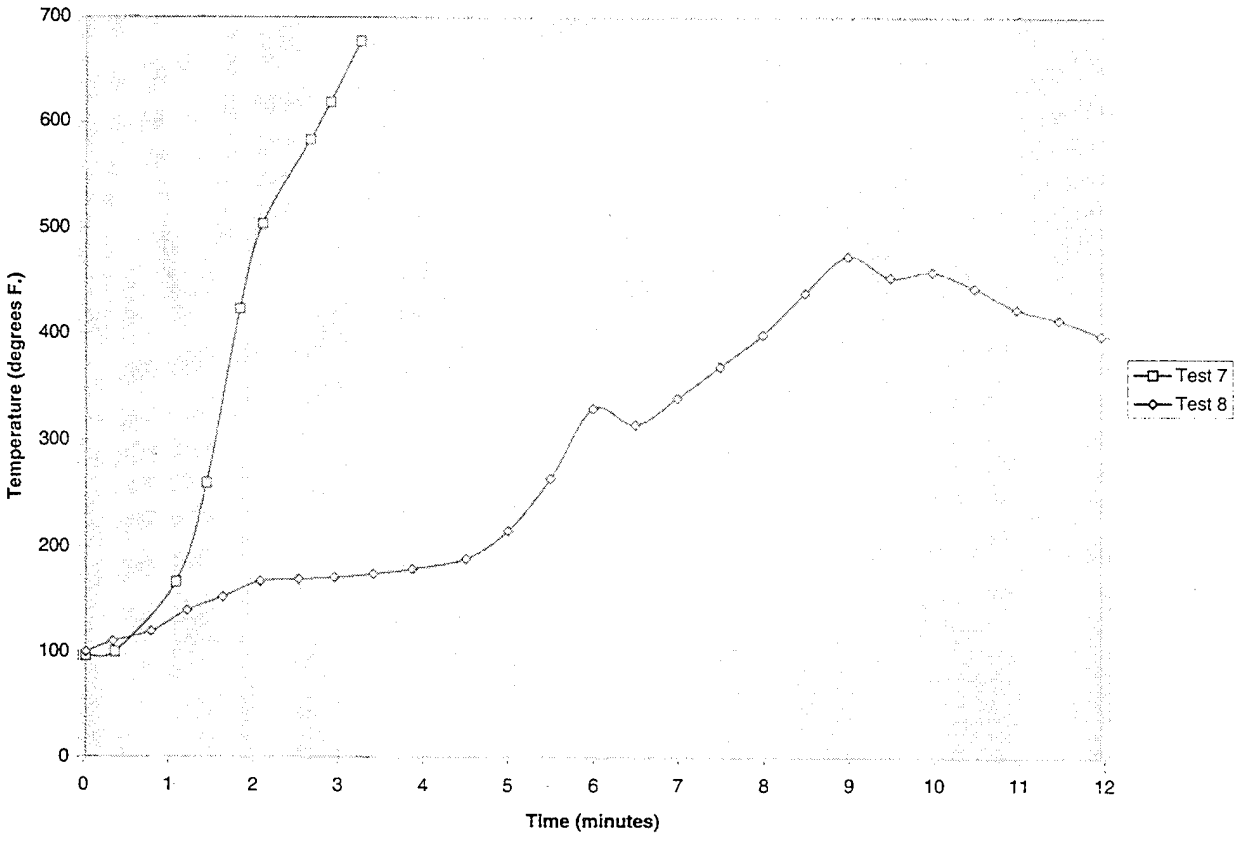


FIGURE 9. CARGO COMPARTMENT TEMPERATURES AFTER SMOKE DETECTION FOR TESTS 7 AND 8

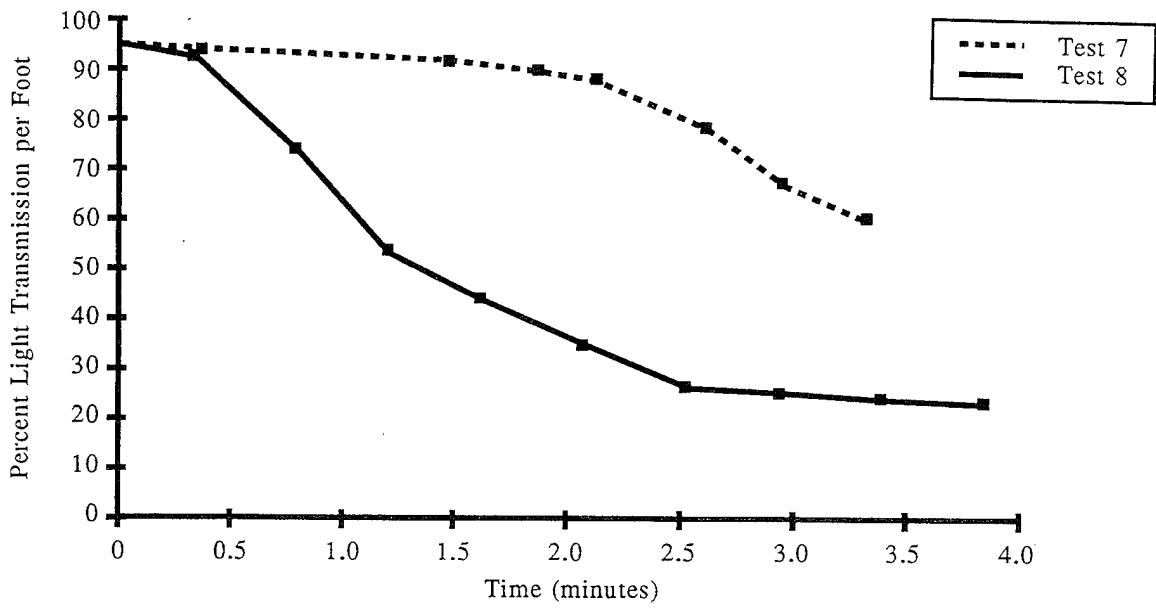


FIGURE 10. CARGO COMPARTMENT SMOKE LEVELS AFTER SMOKE DETECTION FOR TESTS 7 AND 8

As an example of how visibility is effected by smoke, figure 11 is a plot of visibility versus time for these two tests using the light transmission data from figure 10 and the above formula. In figures 9 through 11, time zero is the time of smoke detector alarm for each test. The relatively rapid loss in visibility and untenable temperatures, particularly during the palletized cargo test, demonstrates that it would be impossible for a crew member to attempt to extinguish a fire under these hazardous conditions.

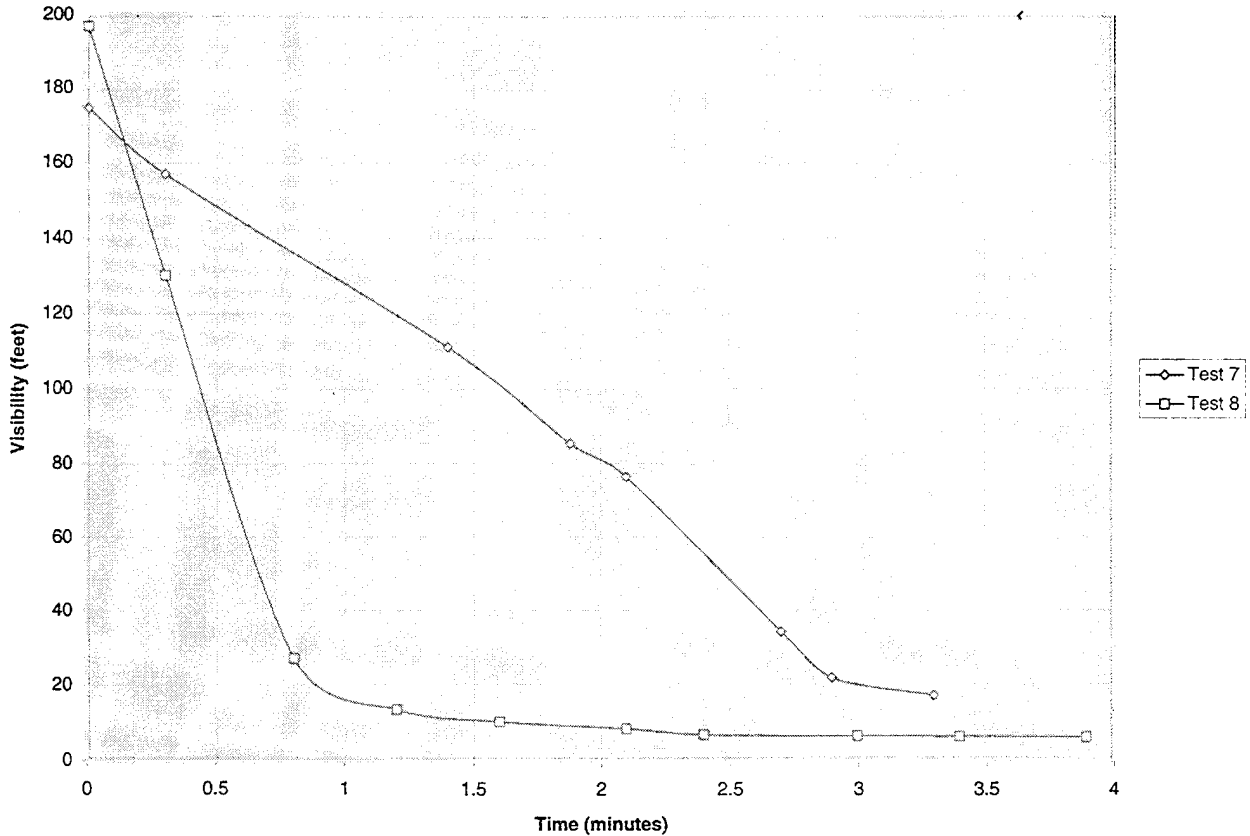


FIGURE 11. CARGO COMPARTMENT VISIBILITY FOR TESTS 7 AND 8

TEST 10. In this test, a fully trained Atlantic City Airport firefighter attempted to extinguish a pallet fire. The test was conducted inside the DC10 fuselage on a 88- by 125-inch aluminum pallet. Cardboard boxes filled with shredded newspaper were stacked on the pallet to a height of eight feet. The boxes were then covered with a cargo net. The ignitor was placed in the bottom center box. The smoke detection system had not yet been installed in the test article. Flames were visible at the top of the pallet at 7:15. The CO₂ system was discharged briefly at 7:45 and again at 8:45 to knock down the fire. The firefighter entered the compartment at 10:15 wearing fully protective clothing and self-contained breathing equipment. The firefighter had access to two 17-pound Halon 1211 and two 2.5-gallon water extinguishers. The firefighter was instructed to only attempt to fight the fire from two sides of the pallet. This was to simulate the access that would be available in a fully loaded main deck cargo compartment. For whatever reason, the firefighter attempted to fight the fire from all four sides of the pallet. He fully discharged one of the Halon 1211 extinguishers and had used 1/2 of the other when he was ordered out of the

compartment by the fire chief because conditions in the compartment had deteriorated to the point where the fire chief felt it was no longer safe. The boxes were burning intensely at that point and the test was terminated.

TEST 12. This test was conducted on a 88- by 125-inch pallet on the floor of the Fire Test Facility. Cardboard boxes filled with computer tapes and various electronic components such as electric typewriters, computer terminals, etc., and packed in polystyrene was used as the fire load. The eight pounds per cubic foot average density of this fire load is representative of the industry average cargo density. The boxes were stacked on the pallet to a height of eight feet and covered with a clear sheet of 6-mil polyethylene. One of the lower outside boxes of the stack was filled with shredded newspaper and a nichrome wire ignitor. The fire burned through the polyethylene adjacent to the ignited box 40 seconds after ignition. By 1.5 minutes into the test, the pallet was fully involved with flames approximately five feet above the top of the stacked boxes. The test was terminated at 3.5 minutes with more than 50 percent of the boxes consumed by the fire. Figure 12 shows the loaded pallet and figure 13 shows the fire approximately 1.5 minutes after ignition. This test demonstrated that the standard fire load employed by the Federal Aviation Administration (FAA), consisting of shredded paper in cardboard boxes at a density of 2.5 pounds per cubic foot, is no worse a fire load (more severe fire condition) than the representative cargo load employed during this test.

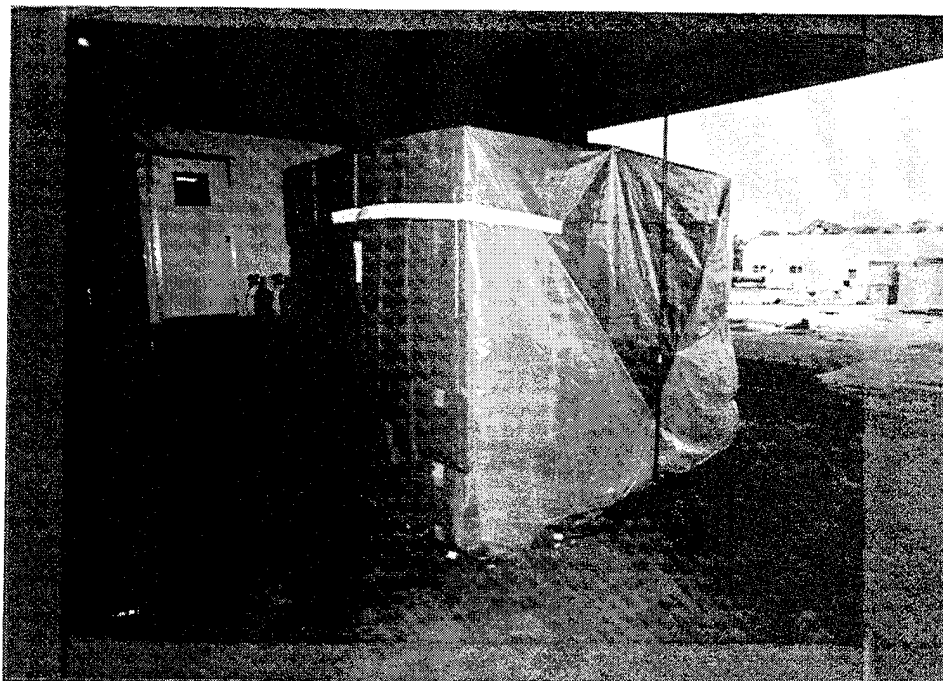


FIGURE 12. PALLET LOADED WITH HIGHER-DENSITY FIRE LOAD BEFORE IGNITION

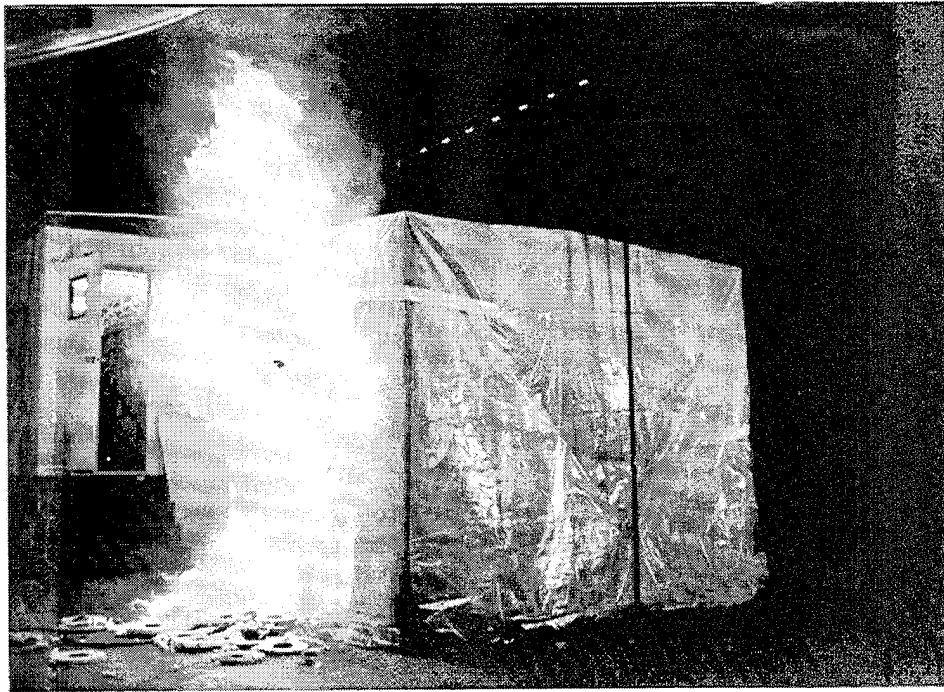


FIGURE 13. BURNING BOXES APPROXIMATELY 1.5 MINUTES AFTER IGNITION

EFFECTIVENESS OF FIRE CONTAINMENT COVERS (FCC'S).

One of the options for increased fire protection in Class B compartments is through the use of Fire Containment Covers (FCC's). These are flexible, fire resistant covers sized to fit over pallets and containers. The covers used in this project were supplied by a number of manufacturers and were constructed of coated, woven fiberglass cloth and coated, woven Kevlar cloth. The woven fiberglass-based covers will pass the oil burner test (FAR Part 25, Appendix F, Part III) required for cargo compartment liners but the Kevlar-based materials will not. The oil burner test exposes the materials to much higher temperatures than the full scale tests but only for a five-minute duration. Thirteen tests were conducted using these FCC's with the test variables including ignition location, volatiles added to the fire load, and simulated in-service damage to the FCC's. The tests using FCC's were test number 1 through 6, 9, 11, and 22 through 26.

TESTS 1 THROUGH 6. These tests were conducted in the B707 test article using cardboard boxes filled with shredded newspaper as the fire load. They were stacked six feet high onto an 88- by 108-inch aluminum pallet.

Test 1. For test 1, the ignitor was placed in the bottom center box. A new, undamaged FCC constructed of woven fiberglass cloth with a silicone coating was used for this test and it contained the fire for the entire 90-minute planned test duration. The highest ceiling temperature measured above the pallet was 160°F at 35 minutes and the densest smoke level was 70 percent light transmission at 90 minutes. At the conclusion of the test, the CO₂ system was discharged

and several minutes later, firefighters entered the compartment to extinguish the still smoldering fire. Shortly after the FCC was removed the boxes burst into flames, visibility quickly decreased to near zero and the instrumentation in the cargo compartment was extensively damaged. The firefighters were unable to control the fire. The fire was eventually brought under control by closing the compartment doors and discharging CO₂ several more times. The FCC used in this test was destroyed during the fire-fighting effort. Figure 14 shows the covered pallet before the start of the test. This test also served to illustrate that it may be dangerous to have crew members attempt to extinguish a deep-seated cargo fire. Even professional firefighters, in full protection gear, were unable to extinguish the long smoldering, deep-seated fire employed during this test.

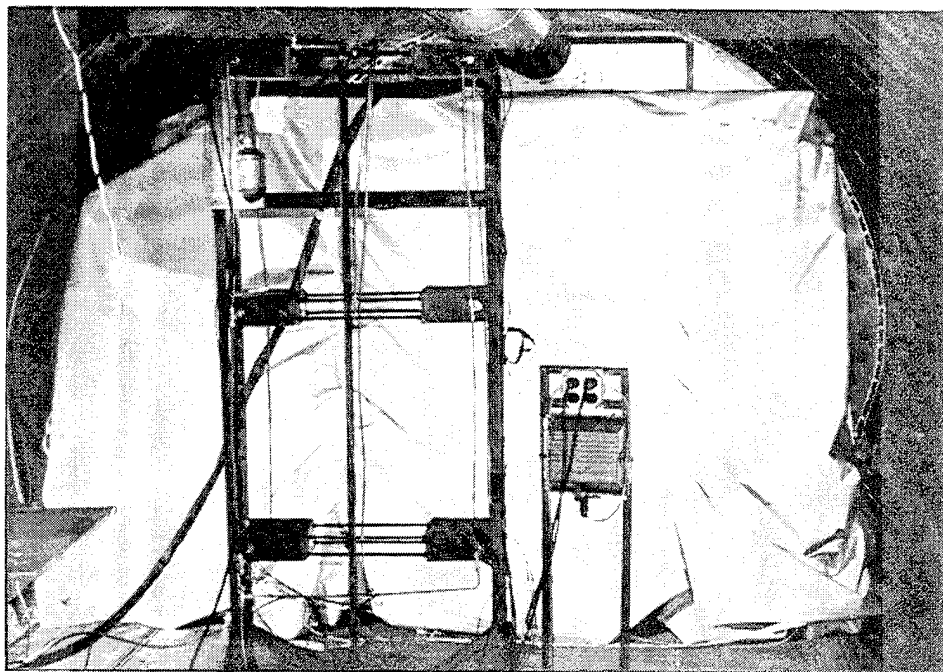


FIGURE 14. PALLET OF CARDBOARD BOXES COVERED WITH FCC

Test 2. For test 2, all conditions were the same as test 1 except that the ignitor was placed in the top center box. A new, undamaged FCC of the same construction was used and the fire was again contained for the entire 90-minute test.

Test 3. Tests 3 through 6 used the same FCC that was used in test 2. Because of this, the FCC was in a progressively worse condition, with more areas without the silicone coating and more and larger rips and holes for each subsequent test.

Test 3 used the same configuration as test 1 with the ignitor in the bottom center box. However, for this test, two aerosol cans of hair spray with a net weight of 9 ounces each were placed in the cardboard box containing the ignitor. The propellant used in these cans, and almost all other aerosol cans manufactured today, is a mixture of propane, isobutane, and butane. There was sufficient visibility in the compartment to observe the cans bursting at 8:40 and 14:05. The oxygen concentration under the FCC was low enough when the cans burst to prevent the released propellant from igniting. The fire was contained for the entire 90-minute test.

Test 4. Test 4 used the same conditions as test 2 with the ignitor placed in the top center box. Two 9-ounce aerosol cans were again placed in the box with the ignitor for this test. There was more smoke in the compartment during this test due to the deteriorating condition of the FCC so the time the cans burst was not visible. However, the low oxygen concentration under the FCC again prevented the released propellant from igniting. The fire was again contained for the 90-minute test.

Tests 5 and 6. Tests 5 and 6 were surface burning fires on the outside surface of a box on the outer edge of the pallet. The fire in test 5 was ignited on a box on the bottom row of the pallet and the fire for test 6 was on a box on the top row. The fires were ignited by pouring one pint of methyl alcohol onto the outside of the box in the area at which the nichrome wire ignitor was attached. The outside of the FCC ignited and burned briefly at the beginning of both tests and then self-extinguished. The maximum ceiling temperatures during test 5 never exceeded 200°F and the compartment was almost completely clear of smoke when the test was terminated at 90 minutes. During test 6 the smoke was much heavier and ceiling temperatures were also significantly higher. This was due to the fact that the FCC had become badly deteriorated after being used for the fifth consecutive test. The test was terminated after 75 minutes when the ceiling temperature exceeded 500°F.

TESTS 9, 11 AND 22 THROUGH 25. These tests were conducted on the floor of the Fire Test Facility on a 125- by 88-inch aluminum pallet. The pallet was stacked to a height of eight feet with cardboard boxes filled with shredded newspaper. Ignition was achieved by energizing a coil of nichrome wire located in one of the boxes. In all of these tests, the smoldering fires immediately reignited when the covers were removed at the end of the tests.

Test 9. In test 9, the boxes were covered with an unused silicone coated woven fiberglass FCC. The fire was ignited in a box on the bottom row in the center of the stack. After ignition, the fire continued to smolder for the three-hour duration of the test but was entirely contained within the FCC.

Test 11. In test 11, another new FCC of the same construction was used but was deliberately damaged in an attempt to simulate possible in service damage. Three "L" shaped slits, with each leg of the "L" approximately four inches long, were cut into three sides of the FCC at a height of five feet above the floor. The ignition location was the same as test 9. The fire again smoldered for the three-hour test but was contained within the FCC. The slits led to a chimney effect with heavy smoke exiting the slits and higher temperatures under the FCC than in test 9. Figure 15 shows the smoke escaping from the slits during this test.

Test 22. Test 22 used a silicone coated woven Kevlar FCC. The ignition location was a box on the bottom row on the outside edge of the stack of boxes. The test duration was 2.5 hours and the fire was contained under the cover the entire time.

Test 23. Test 23 used the same Kevlar FCC used in test 22. In this test the ignition location was a box on the top row on the outside edge of the stack. The fire was again contained for the 2.5 hour test.

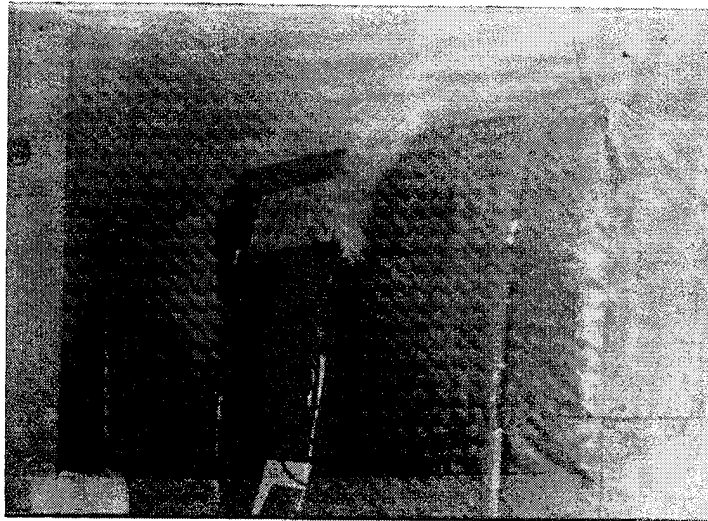


FIGURE 15. SMOKE ESCAPING FROM SLITS IN FCC

Tests 24 and 25. Tests 24 and 25 used a flat sheet of neoprene coated woven fiberglass cloth with an intumescent coating on one side. The sheet was draped over the stack of boxes with the intumescent coating on the inside and the covered pallet was wrapped with safety wire several times to gather in the excess material. Test 24 was conducted for one hour and completely contained the fire. For test 25, the blanket was deliberately damaged to determine the damage tolerance that would be acceptable in actual use. Five "L" shaped slits, with each leg of the "L" four inches long were cut into the blanket. One on each vertical side approximately five feet above the floor and one cut into the horizontal top surface of the cover. This test was conducted for three hours and contained the fire. Large quantities of smoke were continually generated for the entire test duration.

Test 26. Test 26 was a test of a slightly different concept than the previous FCC tests. There was a suggestion to attach a FCC to the walls and ceiling of an existing Class B cargo compartment as a somewhat permanent part of the aircraft. This concept was envisioned to be used on Class B compartments on smaller commuter airplanes where the volume of the compartment cannot be varied. A angle iron framework was constructed over which a silicone coated Kevlar based FCC was draped. The volume under the cover was approximately 425 cubic feet. Previous testing with this material showed that it could contain fires in fully loaded pallets. The purpose of this test was to determine if it could contain a fire in a partially loaded compartment with more oxygen available initially. Therefore slightly less than half of the 425 cubic feet was filled with cardboard boxes filled with shredded newspaper. The fire was ignited in a box on the top row. The test duration was one hour and the fire was contained. Figure 16 shows the partially loaded pallet before the cover was fully lowered.

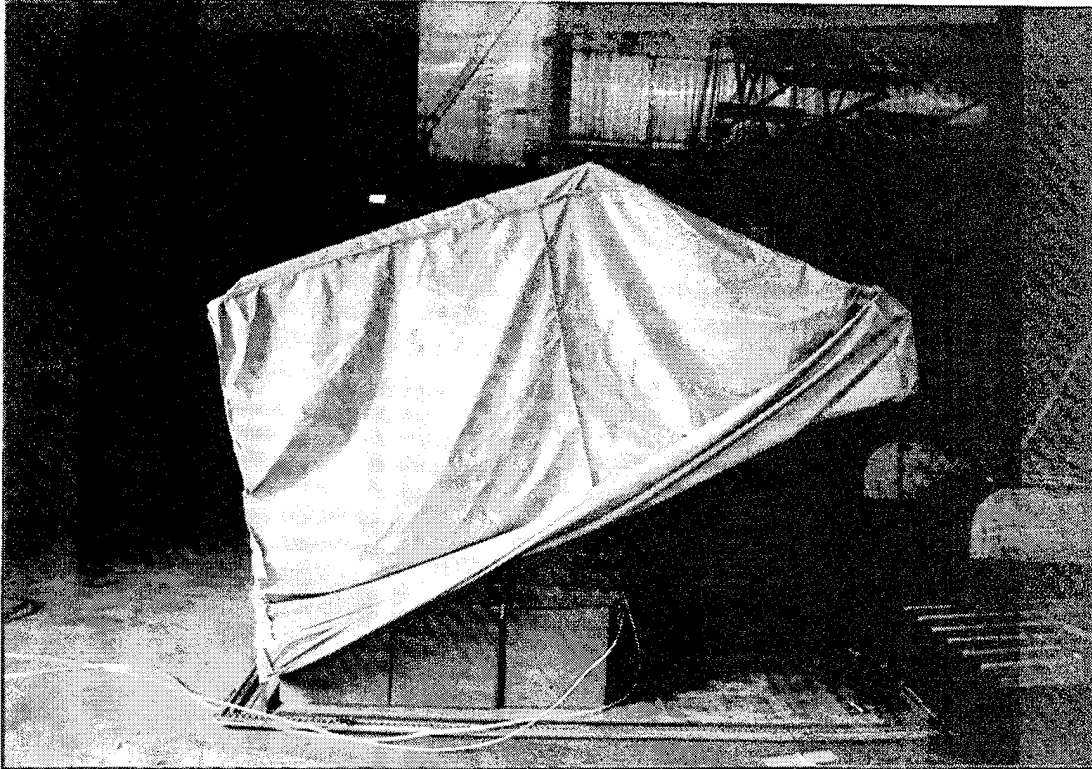


FIGURE 16. PARTIALLY LOADED PALLET COVERED WITH FCC

EFFECTIVENESS OF FIRE RESISTANT CONTAINERS.

Another passive method for improving the fire protection of Class B cargo compartments is through the use of fire-resistant cargo containers. Some operators prefer to use containers, when possible, rather than pallets because of the better security and protection from the weather provided by containers. These containers are generally constructed of aluminum or fiberglass and are fairly fire resistant provided they are well sealed. However, previous testing has shown that the vinyl/nylon and similar materials commonly used as a door covering can burn through rapidly if the fire is in the area of the door covering. Tests 17 through 21 tested several types of materials as door coverings on a Type A rigid fiberglass main deck container. Figure 17 shows the shape and dimensions of this container. The container was filled with cardboard boxes filled with shredded newspaper. The ignition location for all tests was on the bottom row adjacent to the door covering material.

TESTS 17 AND 18. A neoprene coated woven fiberglass cloth was used as a door covering for these tests. The covering had a vertical zipper sewn into it extending the full height of the door opening. This was the configuration and method of construction that the manufacturer proposed for certification. Test 17 was conducted for 30 minutes and contained the fire. The duration for test 18 was 90 minutes and again completely contained the smoldering fire.

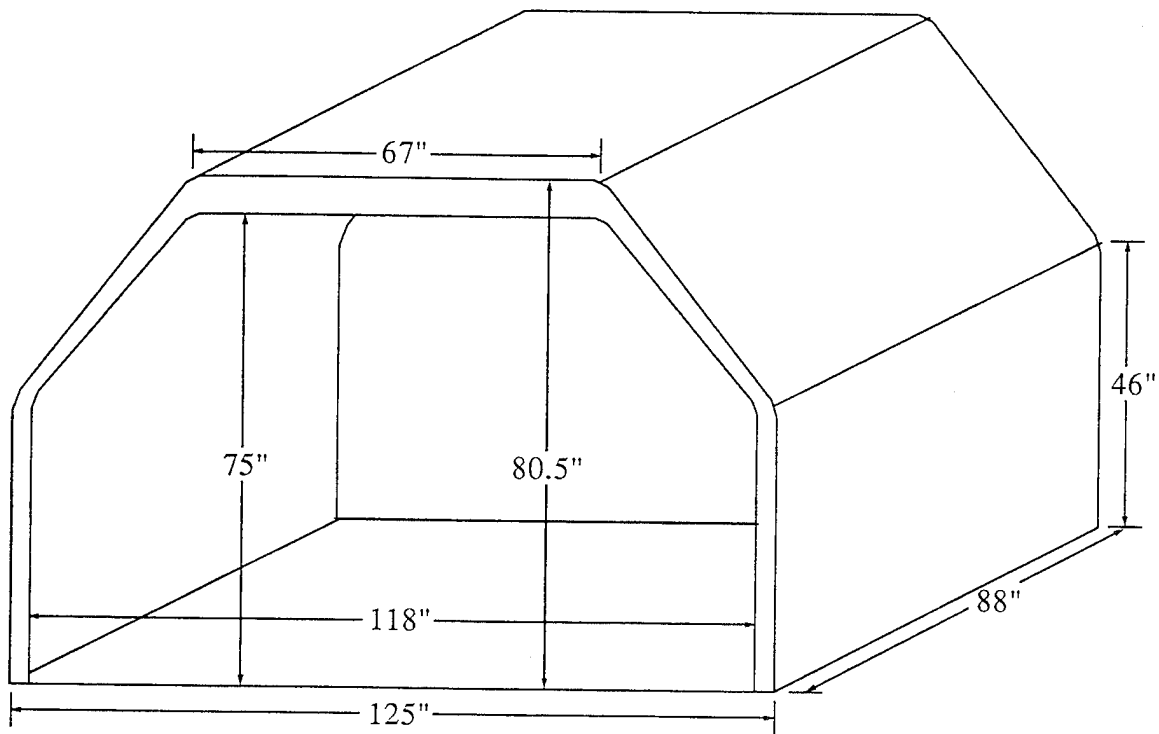


FIGURE 17. TYPE A MAIN DECK CARGO CONTAINER

TESTS 19 AND 20. These two tests used a vinyl/nylon material similar to what is currently used on some containers but with the addition of a fire retardant coating on the inside surface. One piece of the material was attached to the container all along the edge of the door opening with no consideration for how it would be opened and closed in actual use. In test 19, the fire penetrated the door covering three minutes after ignition and rapidly grew out of control. In test 20, the fire was contained for the one-hour test duration but the heat of the fire caused the covering to shrink in places and it appeared to be very close to mechanical failure because it was so taut from shrinking.

TEST 21. This test used a silicone coated woven Kevlar cloth as the door covering. A single piece of the fabric was again used in this test without any provisions for opening and closing the door covering. The test was conducted for one hour and the fire was completely contained.

EFFECTIVENESS OF HALON 1301 SUPPRESSION SYSTEM.

An active method for increased fire protection in Class B cargo compartments is a total-flood suppression system. Four tests (13, 14, 15, and 16) were conducted to determine the effectiveness of a Halon 1301 system in the 9000 cubic foot DC10 cargo compartment. The fire load for these tests was cardboard boxes filled with shredded newspaper, stacked eight feet high on a 125- by 88-inch aluminum pallet. The boxes were then covered with a sheet of clear, 6-mil

polyethylene. Figure 18 shows the loaded pallet before the start of the test. For test 16, additional boxes covered with polyethylene were stacked around the pallet to simulate the adjacent pallets that would be present in a fully loaded compartment. A coil of nichrome wire inside one of the boxes was again used as the ignition source. The test variables were ignition location and the delay time between smoke detection and suppression system activation. The test procedure was to energize the nichrome wire, wait for smoke detection, shut off the ventilation system and discharge the initial Halon bottle after a predetermined delay, start the metered Halon system seven minutes after the initial discharge, run the metered system for 30 minutes, and then terminate the test. The test durations varied considerably because they were dependent on the initial smoke detector activation times.

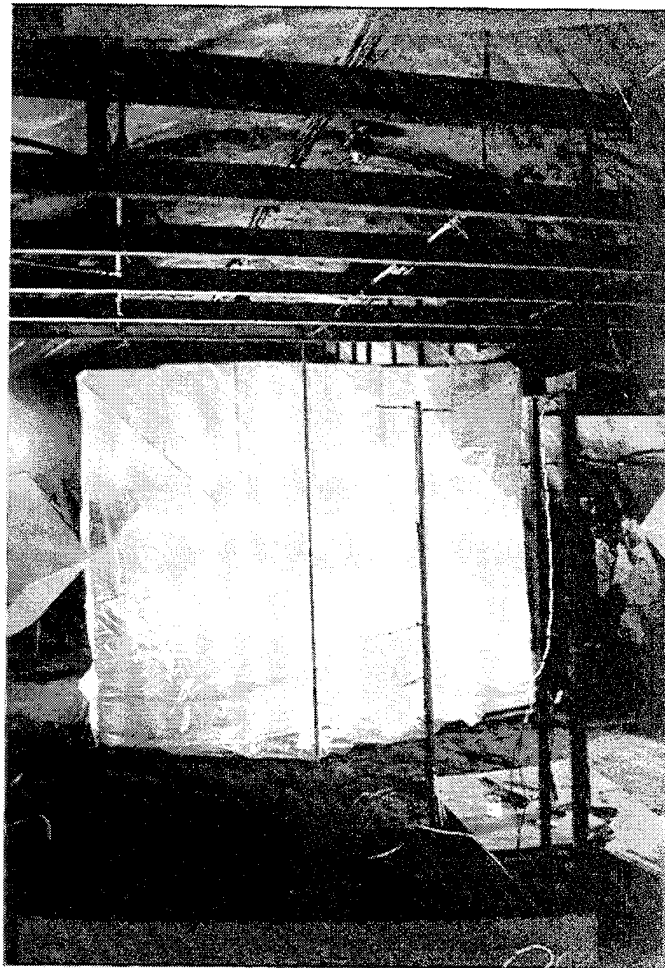


FIGURE 18. POLYETHYLENE COVERED BOXES ON PALLET

TEST 13. The nichrome wire was placed in the bottom center box for this test. There was a 30-second delay between smoke detection and the initial halon discharge. The fire was suppressed but not extinguished and continued to produce heat while the halon concentration was above three percent. The temperatures at the top of the compartment tended to stabilize during the last ten minutes of the test and were slightly below 500°F. Figure 19 shows the crown area temperatures above the pallet during this test.

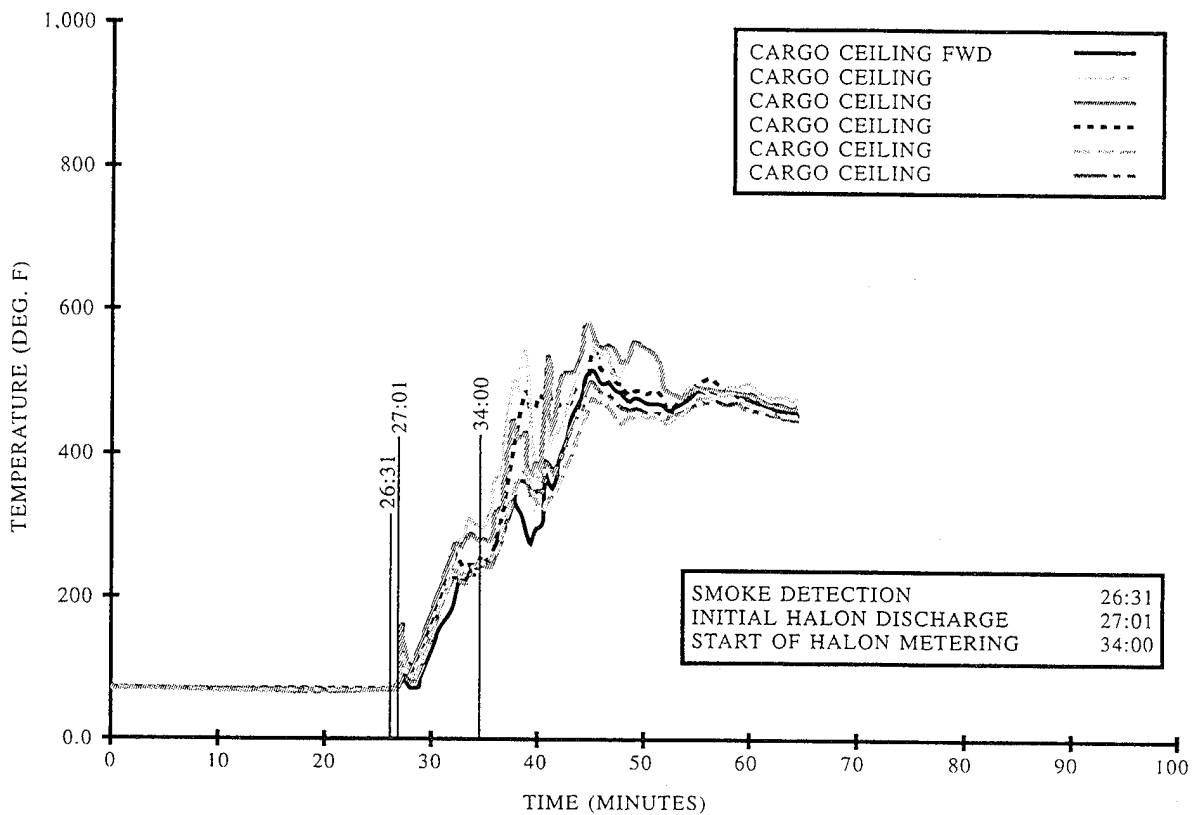


FIGURE 19. TEST 13 CROWN AREA TEMPERATURES ABOVE PALLET

TEST 14. The ignition location for this test was in the top center box. All other conditions were the same as test 13, including the 30-second delay in halon discharge. The fire burned through the polyethylene cover at the top of the pallet much sooner than in test 13. The initial discharge knocked down the flames but the fire reignited before the metering system was started. When that happened, ceiling temperatures above the pallet reached 1500°F and remained elevated for over one minute until the metered system became effective and reduced temperatures. The average halon concentration in the compartment from the initial 200-pound discharge remained above three percent for 7.5 minutes. It was decided to start the metered system after only seven minutes to be slightly conservative. Since Halon 1301 is approximately five times heavier than air, even though the average concentration is above three percent, the halon in the higher locations in the compartment settles very quickly and the concentration at those locations is below three percent much sooner than the average. Since the fire was ignited at the top of the pallet, the concentration at that location dropped below three percent and the fire reignited before the metered system was started. Once the metered system became effective the temperatures at the top of the compartment stabilized in the 400 to 500°F range as they did during test 13. Figure 20 shows the halon concentrations at four different heights during this test.

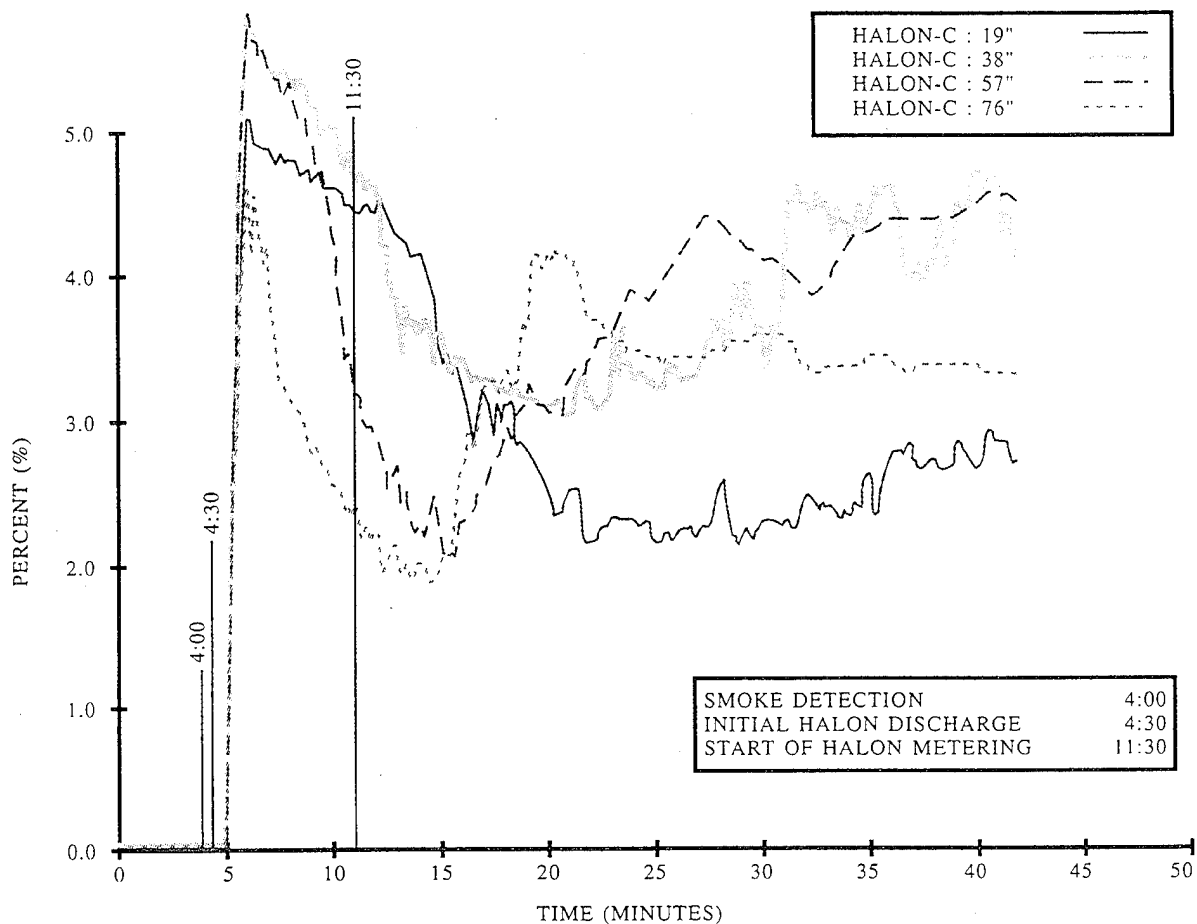


FIGURE 20. TEST 14 HALON CONCENTRATIONS

TEST 15. The ignition location for test 15 was in a box on the outside of the bottom row on the aft side of the pallet. All other conditions, including the 30-second delay in Halon discharge, were the same as in tests 13 and 14. During this test the fire burned through the polyethylene at the same time as smoke detection. The 30-second delay in Halon discharge allowed ceiling temperatures above the pallet to exceed 1000°F briefly until the Halon became effective and reduced temperatures. The temperatures along the compartment ceiling stabilized between 300 and 420°F during this test.

TEST 16. For this test, the nichrome wire was placed in the bottom center box. The delay between smoke detection and halon discharge was extended to 4.5 minutes. This was done to assess the implication of having a crew member physically verify the presence of smoke in the cargo compartment after the smoke detection system alarmed but before the suppression system was activated. It was estimated that 4.5 minutes was required for the flight deck to notify a cabin crew member of the detector alarm, have the crew member go to the compartment door, unlock it, remove the cargo restraint net, check for the presence of smoke, and report back to the flight deck. The previous tests used an assumed delay of 30 seconds between smoke detector alarm and

the discharge of the suppression system. During this test, the fire burned through the polyethylene cover before smoke detection. The top of the compartment was therefore exposed to temperatures above 1500°F initially and then decreasing to approximately 1100°F for approximately 4.6 minutes before the halon system was discharged. The reason for the temperature decrease was the oxygen concentration at all four measurement heights was reduced to 10 to 12 percent by the fire. This occurred even though the ventilation system was still operating during this time. Two calorimeters were mounted in the top of the compartment for this test. The peak heat flux measured during the five-minute uncontrolled initial fire was approximately 9 BTU/ft²-sec. After the Halon system became effective, the ceiling temperatures dropped down to between 400 and 550°F for the duration of the test. The temperatures and heat flux measured during this test at the top of the compartment were very similar to the exposure conditions required for the certification of cargo liner material, as described in FAR 25 Appendix F, Part III. Figures 21 and 22 show temperatures and heat flux measured during this test compared to the temperature and heat flux produced by the oil burner employed in the certification test.

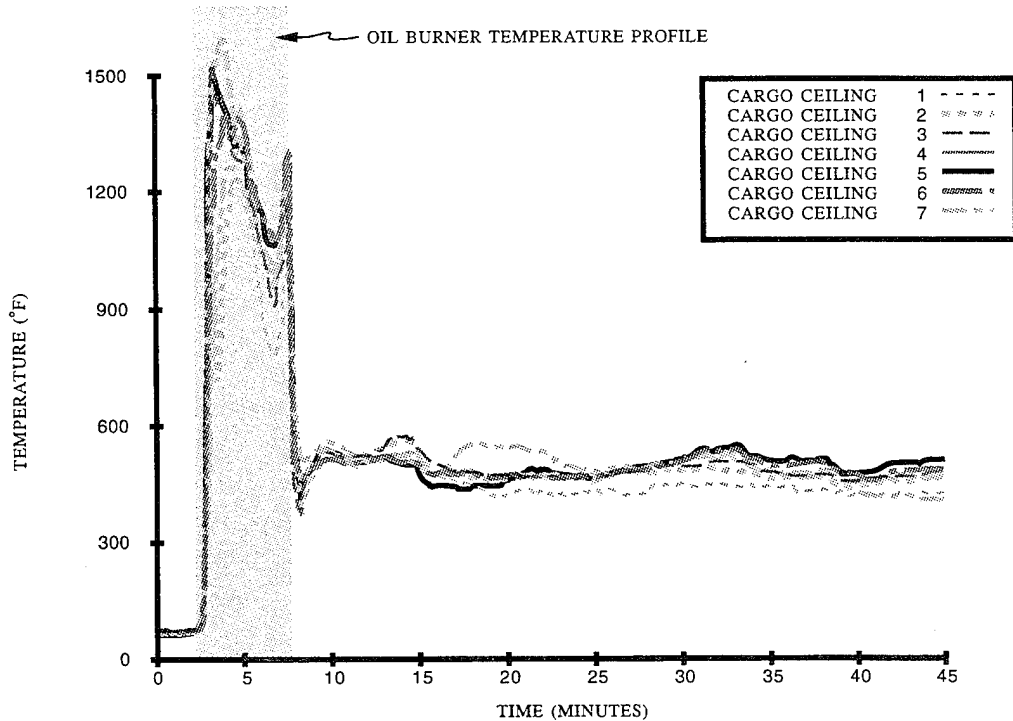


FIGURE 21. TEST 16 CROWN AREA TEMPERATURES AND OIL BURNER TEMPERATURE PROFILE

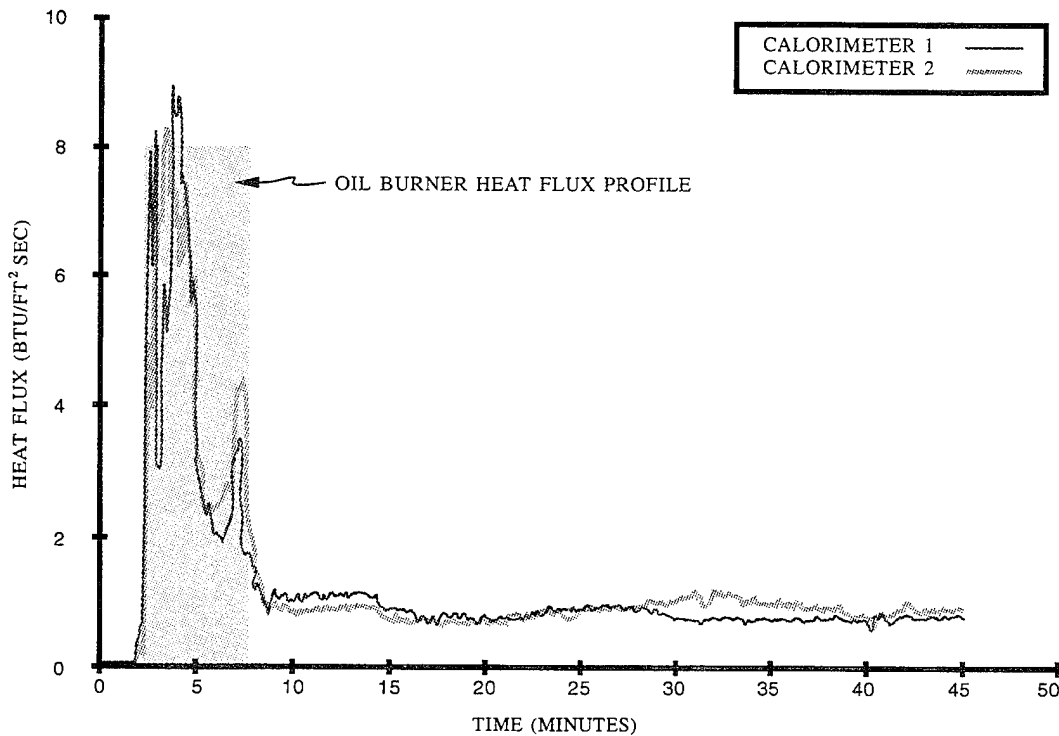


FIGURE 22. TEST 16 HEAT FLUX AND OIL BURNER HEAT FLUX PROFILE

EFFECTIVENESS OF SMOKE DETECTION SYSTEM.

All of the tests in the B707 and four of the DC10 tests were conducted with a smoke detection system as described earlier. The smoke detectors were either thoroughly cleaned or replaced between tests. The smoke detector alarm times varied widely among all the tests. Table 2 shows the smoke detector alarm times and the maximum temperature recorded by any of the ceiling thermocouples at the time of smoke detection. The maximum ceiling temperature at smoke detection did not exceed 165°F for any test except test 16. During test 16, very little smoke was generated before open flames were observed at the top of the pallet. The ceiling thermocouples were directly exposed to this open flaming for approximately 20 seconds before enough smoke accumulated to activate the smoke detectors.

TABLE 2. SMOKE DETECTION TIMES AND CORRESPONDING MAXIMUM CEILING TEMPERATURES

Test	Smoke Detection (Minutes:Seconds)	Maximum Temperature at Detection (Deg. F)
1	31:00	165
2	11:44	132
3	16:11	105
4	11:40	112
5	0:44	83
6	0:45	80
7	7:06	96
8	13:47	137
13	26:31	77
14	3:58	79
15	24:30	103
16	2:57	1490

COMPARISON BETWEEN SMOKE DETECTION AND INFRARED DETECTION.

Seven tests were conducted with both infrared (IR) and smoke detection systems installed. They were tests 2, 4, 5, 8, 13, 14, and 15. Table 3 shows the detection times for the smoke detectors and the IR detectors as well as the maximum ceiling temperatures at the times of detection. The IR detectors that were used were prototype units supplied by two different manufacturers. The alarm thresholds for the detectors were somewhat arbitrary because there was not a specific FAA criteria that the units were designed to meet. The units could have easily been made more or less sensitive. The smoke detectors can be adjusted to alarm between 84 and 96 percent light transmission per foot so they could be made more or less sensitive than their 92 percent light transmission alarm point also. The IR detectors were mounted in the crown area of the cargo compartment. Their field of view included the entire top surface of the loaded pallet or container and in most cases at least one side of the loaded pallet also. The test conditions for these seven tests included boxes covered with fire containment covers, boxes inside an aluminum cargo container, and boxes covered with a clear sheet of polyethylene. The ignition locations also varied and included boxes ignited in the bottom center, top, and side of the pallets. The IR detectors responded faster in five tests, the smoke detectors were faster in one test and both types of detectors activated simultaneously in one test. Test 2 had the most significant difference in alarm time at over four minutes and also the largest difference in ceiling temperatures at alarm. Despite the faster response by the IR detectors in most of these tests, the smoke detectors still alarmed before the fire was hot enough to do damage to structures or systems that might be in a cargo compartment.

TABLE 3. COMPARISON OF SMOKE AND INFRARED DETECTORS

Test	Smoke Detection Minutes:Seconds	IR Detection	Delta Time	Temp. at Smoke Det. Degrees F	Temp. at IR Det.	Delta Temp.
2	11:44	7:30	4:14	132	72	60
4	11:40	11:00	0:40	112	90	22
5	0:44	0:35	0:09	83	79	4
8	13:47	13:15	0:32	137	93	44
13	26:31	24:57	1:34	77	71	6
14	3:58	5:35*	(1:37)	79	79	0
15	24:30	24:30	0:00	103	103	0

* The halon system was activated at 4:28. IR detection may have occurred earlier than 5:35 if the halon had not been discharged.

CONCLUSIONS

1. The reliance on a crew member with hand held fire extinguishers to control the types of fires ignited in this study would not be effective and may be life threatening because of the smoke obscuration and elevated temperatures that occur very soon after smoke detector alarm.
2. Fiberglass- and Kevlar-based fire containment covers of the type tested are effective at containing the fires even with simulated in-service damage. The Kevlar-based material tested was able to contain the fires even though it would not pass the fire test requirement for cargo lining materials specified in FAR Part 25 Appendix F Part III.
3. Fiberglass and aluminum cargo containers can effectively contain the test fires provided that they have fire-resistant materials as door coverings and are reasonably well sealed.
4. A total-flood Halon 1301 suppression system can control the test fires. Even though the fires can be controlled, the structure and systems in the crown area of the cargo compartment can still be exposed to the short term temperature and heat flux levels similar to those produced by the oil burner test required for cargo liners and to longer term temperatures as high as approximately 500°F.
5. The smoke detection system did not always detect the test fires quickly although it did detect them in all cases but one when the air temperature in the crown area of the cargo compartment was well below the temperature that could damage structure or systems in that area. In the one case that the detectors did not activate the alarm before elevated temperatures were present, the detector alarmed approximately 20 seconds after flames broke out of the top of the pallet.
6. The infrared detectors that were tested alarmed faster than the smoke detectors in five of seven tests.

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3. Airworthiness Directives; Boeing Models 707, 727, 737, 747, 757 Series Airplanes; and McDonnell Douglas Models DC-8, DC-9, and DC-10 Series Airplanes. AD 93-07-15, Federal Register/Vol. 58, No. 74/ Tuesday, April 20, 1993.
4. Jin, T., "Visibility through Fire Smoke (Part 2. Visibility of Monochromatic Signs through Fire Smoke)," Report of Fire Research Institute of Japan, No. 33, 1971.

APPENDIX A

FAR section 25.857 Cargo compartment classification.

- (a) Class A. A Class A cargo or baggage compartment is one in which—
 - (1) The presence of a fire would be easily discovered by a crewmember while at his station; and
 - (2) Each part of the compartment is easily accessible in flight.

- (b) Class B. A Class B cargo or baggage compartment is one in which—
 - (1) There is sufficient access in flight to enable a crewmember to effectively reach any part of the compartment with the contents of a hand fire extinguisher;
 - (2) When the access provisions are being used, no hazardous quantity of smoke, flames, or extinguishing agent will enter any compartment occupied by the crew or passengers; and
 - (3) There is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station.

- (c) Class C. A Class C cargo or baggage compartment is one not meeting the requirements for either a Class A or B compartment but in which—
 - (1) There is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station;
 - (2) There is an approved built-in fire-extinguishing system controllable from the pilot or flight engineer stations;
 - (3) There are means to exclude hazardous quantities of smoke, flames, or extinguishing agent, from any compartment occupied by the crew or passengers;
 - (4) There are means to control ventilation and drafts within the compartment so that the extinguishing agent used can control any fire that may start within the compartment.

- (d) Class D. A Class D cargo or baggage compartment is one in which—
 - (1) A fire occurring in it will be completely confined without endangering the safety of the airplane or the occupants;
 - (2) There are means to exclude hazardous quantities of smoke, flames, or other noxious gases, from any compartment occupied by the crew or passengers;
 - (3) Ventilation and drafts are controlled within each compartment so that any fire likely to occur in the compartment will not progress beyond safe limits; and
 - (4) [Reserved]
 - (5) Consideration is given to the effect of heat within the compartment on adjacent critical parts of the airplane. For compartments of 500 cu. ft. or less, an airflow of 1500 cu. ft. per hour is acceptable.

- (6) The compartment volume does not exceed 1,000 cubic feet.
- (e) Class E. A Class E cargo compartment is one on airplanes used only for the carriage of cargo and in which—
- (1) [Reserved]
 - (2) There is a separate approved smoke or fire detector system to give warning at the pilot or flight engineer station;
 - (3) There are means to shut off the ventilating airflow to, or within, the compartment, and the controls for these means are accessible to the flight crew in the crew compartment;
 - (4) There are means to exclude hazardous quantities of smoke, flames, or noxious gases from the flight crew compartment; and
 - (5) The required crew emergency exits are accessible under any cargo loading condition.