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Effects of Cargo Loading and Active Containers on Aircraft Cargo Compartment Smoke Detection Times

David Blake

December 2009

Final Report

October 2014 Revised

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16. Abstract

The purpose of this project was to evaluate how smoke detection times are affected when the same quantity of smoke is released in either an empty or fully loaded cargo compartment. It also evaluated the effect on smoke detection times from active cargo containers that produce additional airflow patterns. Active containers are equipped with climate control systems that maintain the container's temperature and humidity for the duration of the flight. Tests were conducted in the main deck cargo compartment of a Boeing 727 and in the aft, below-floor cargo compartment of a B-747SP.

Although there was some variability in the test results, in general, the smoke detectors alarmed quicker in loaded compartments than in empty compartments. In addition, the operation of the active cargo containers did not have a consistent influence on smoke detection times for the airflow conditions tested.

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LIST OF ACRONYMS

APU	Auxiliary Power Unit
FAA	Federal Aviation Administration
NTSB	National Transportation Safety Board
psi	Pounds per square inch

EXECUTIVE SUMMARY

The purpose of this test project was to evaluate how smoke detection times are affected when the same quantity of smoke is released in either an empty or fully loaded cargo compartment. This was in response to a National Transportation Safety Board recommendation to the Federal Aviation Administration over concern regarding the time that smoke detection occurred in a United Parcel Service DC-8 aircraft that experienced an in-flight cargo fire on February 7, 2006. The test project also evaluated the effect on smoke detection times from active cargo containers that produce additional airflow patterns. Active containers are equipped with climate control systems that maintain the container's temperature and humidity for the duration of the flight. A total of 206 tests were conducted in the main deck cargo compartment of a Boeing 727 aircraft to document the change in detection times between empty and fully loaded compartments of this configuration. Smoke was generated at three locations within each cargo container position in the compartment. An additional 215 tests were conducted in the aft, below-floor cargo compartment of a B-747SP to document not only the difference in detection times between empty and fully loaded compartments but also the effect of active containers on detection times. Smoke was generated in the center of each cargo container position in the compartment. Both aircraft were equipped with aspirated photoelectric smoke detection systems. A theatrical smoke generator was used to simulate smoke for all tests. The cargo containers were modified with vertical, open-ended ducts to allow the same plume of smoke to be released into either the empty or fully loaded cargo compartments.

Although there was some variability in the test results for some configurations, in general, the smoke detectors alarmed faster in fully loaded compartments than in the empty ones. In addition, the operation of the active cargo containers did not have a consistent influence on smoke detection times for the airflow conditions tested.

1. INTRODUCTION.

In response to a National Transportation Safety Board (NTSB) recommendation to the Federal Aviation Administration (FAA) regarding smoke detection, tests were conducted using two test articles: the main deck cargo compartments of a Boeing 727 and the aft, below-floor cargo compartment of a B-747SP. This report describes that test project.

1.1 PURPOSE.

The purpose of this test project was to evaluate how aircraft cargo compartment smoke detection alarm times change when the same quantity of smoke is released in either an empty or fully loaded cargo compartment. It also evaluated the impact of active cargo containers that produce additional airflow patterns on smoke detection alarm times.

1.2 BACKGROUND.

The requirements for the certification of cargo compartment fire detection systems are contained in Title 14 Code of Federal Regulations (CFR) 25.858, which reads as follows [1]:

> "§ 25.858 Cargo or baggage compartment smoke or fire detection systems.
> If certification with cargo or baggage compartment smoke or fire detection provisions is requested, the following must be met for each cargo or baggage compartment with those provisions:
> (a) The detection system must provide a visual indication to the flight crew within one minute after the start of a fire.
> (b) The system must be capable of detecting a fire at a temperature significantly below that at which the structural integrity of the airplane is substantially decreased.
> (c) There must be means to allow the crew to check in flight, the functioning of each fire detector circuit.
> (d) The effectiveness of the detection system must be shown for all approved operating configurations and conditions."

Prior to the introduction of this regulation in 1980, the FAA considered detection within 5 minutes after the start of a fire acceptable. Compliance with this regulation has traditionally been shown by performing flight tests with a variety of actual or artificial smoke generation methods in empty cargo compartments.

On February 7, 2006, a United Parcel Service DC-8 aircraft experienced an in-flight main deck cargo fire. The aircraft landed safely in Philadelphia and the flight crew evacuated. The aircraft was subsequently destroyed by the internal fire. The cockpit voice recorder on the accident aircraft revealed that the flight crew discussed a burning wood odor for approximately

20 minutes before the main deck smoke detection system alarmed. Following the investigation of this incident, the NTSB issued several recommendations [2]. One of the recommendations, A-07-98, was addressed to the FAA and reads as follows:

> "Ensure the performance requirements for smoke and fire detection systems on cargo airplanes account for the effects of cargo containers on airflow around the detection sensors and on the containment of smoke from a fire inside a container, and establish standardized methods of demonstrating compliance with those requirements."

This test project was an attempt to address the aspect of this recommendation that dealt with the effects of cargo containers. Additionally, the use of active cargo containers has become more prevalent. Active containers are equipped with climate control systems that maintain a specified range of temperature and humidity inside the containers for the duration of the flight. These containers typically recirculate cargo compartment air during operation. The effect of this independent airflow pattern on smoke detection times was another objective of this test project.

2. TEST DESCRIPTION.

2.1 B-727 TEST ARTICLE.

The B-727 test article was configured as an all-cargo aircraft. Cargo liners were installed on the ceiling and sidewall of the entire main deck compartment.

2.1.1 Ventilation System.

Ventilation was supplied to the compartment through a continuous air inlet mounted on the ceiling centerline. The source of the ventilation air was the output of one of the air-conditioning packs supplied with bleed air from the auxiliary power unit (APU). The ventilation rate was approximately 1050 cubic feet per minute, or one air change every 5.1 minutes. To better simulate in-flight airflow patterns, the outflow valves were fully opened and the electronics bay exhaust duct was disconnected inside the electronics bay. This forced all ventilation air out the outflow valves and produced a front-to-rear airflow through the fuselage. The electronics bay duct was disconnected downstream of the venturi tube that provided suction for the smoke detection system.

2.1.2 Smoke Detection System.

The B-727 main deck was equipped with an aspirated photoelectric smoke detection system consisting of four Systron Donner® detectors and eight sampling ports. The sample ports protruded through the sidewall cargo liners at a height of 66″ above the floor. Vacuum was provided by airflow through an equipment cooling duct in the electronics compartment and used to draw cargo compartment air through each sampling port. That air was then ducted to the flow-through smoke detectors located in the electronics compartment and then exhausted overboard. Each detector was fed by a pair of sampling ports. Photoelectric smoke detectors consist of a light beam and a photocell inside a chamber. The light beam and photocell are positioned so that the photocell is not normally exposed to the light beam. When smoke particles enter the chamber, the light beam is reflected off the particles and some light strikes the photocell and triggers an alarm. The detectors were calibrated to alarm at a smoke level between 94% and 96% light transmission per foot. The system was required to alarm within 1 minute of the start of a fire. Figure 1 shows the main deck smoke detection system.

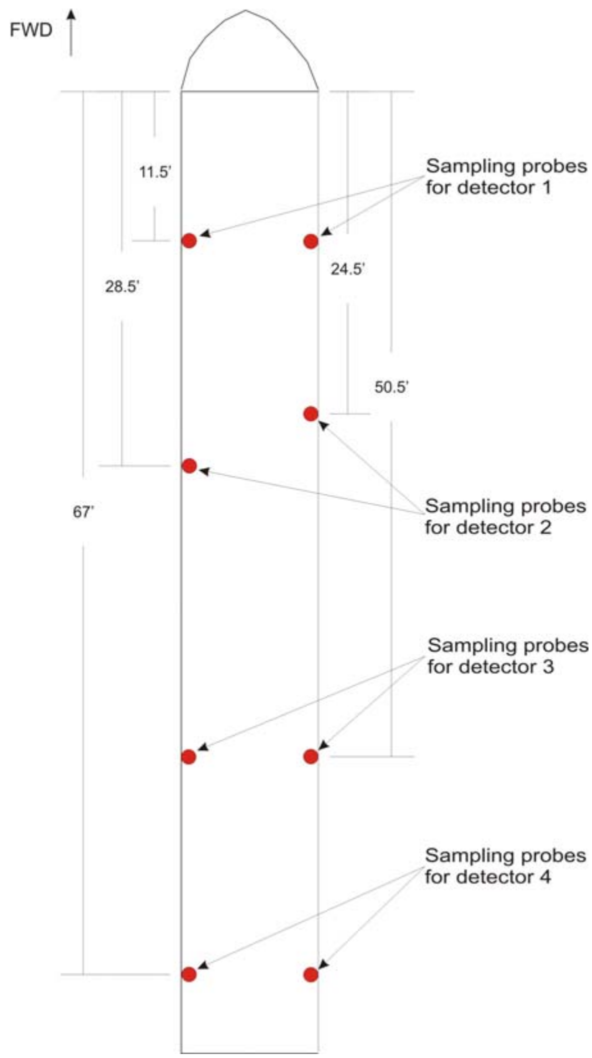

Figure 1. B-727 Main Deck Smoke Detection System

2.1.3 Cargo Containers and Positions.

The main deck was configured to hold eight 125″ wide by 88″ deep AAY cargo containers with an additional space, 125″ wide by 62″ deep, in the most forward position for smaller containers. AAY and AKE refer to the International Air Transport Association classification system that describes the container base size and contour. Smoke was generated at the edge of each container position for the tests conducted with the main deck cargo compartment empty. Figure 2 shows the cargo container positions and the smoke generator locations.

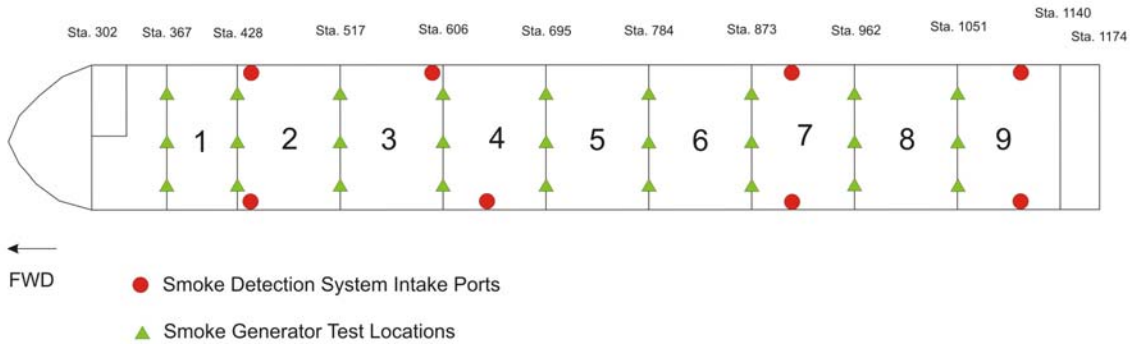

Figure 2. B-727 Cargo Container Positions and Smoke Generator Test Locations

One of the AAY containers was modified for the tests conducted with the cargo compartment fully loaded with containers. Three 14″ diameter ducts were installed vertically along the front edge of this container in the center, right, and left sides. The aluminum container skin was removed where these ducts intersected the container roof. The smoke generator was placed inside the container under each of the ducts for the fully loaded smoke tests and allowed the smoke plume to exit the container into the cargo compartment. The two unused ducts for each test were plugged with urethane foam. Figure 3 shows the modified smoke generator container.

Figure 3. Modified Smoke Generator Main Deck Container

2.2 B-747SP TEST ARTICLE.

The aft, below-floor cargo compartment in the B-747SP test article is a combination of containerized load and bulk load compartments. A barrier curtain separates the two sections but allows some airflow exchange between them. Only the forward containerized section of this compartment was used in these tests.

2.2.1 Ventilation System.

Ventilation air was supplied through three air inlets located along the ceiling centerline of the compartment. The source of the ventilation air was two air-conditioning packs supplied with bleed air from the APU. The airflow rate was approximately 286 cubic feet per minute, or one air change approximately every 6 minutes.

2.2.2 Smoke Detection System.

The aft cargo compartment was equipped with an aspirated photoelectric smoke detection system consisting of two Autronics® smoke detectors and ten sampling ports. The sampling ports protruded through the compartment ceiling liners with one port located above each of the ten cargo container positions. A venturi ejector provided suction to draw cargo compartment air through the ceiling sampling ports to the flow through detectors mounted above the cargo compartment ceiling liner. The cargo compartment air from all ten sampling ports was combined into a single sample line, which was then split into two lines that connected to each detector. The alarm point of the detectors was 90.6 ±1% light transmission per foot. At the time this system was certified, detection within 5 minutes of the start of a fire was considered acceptable by the FAA.

2.2.3 Cargo Containers and Positions.

The aft cargo compartment held ten AKE cargo containers. The containers could not be loaded in the forward 24 inches of the compartment because of two potable water tanks in that location. Smoke was generated in the center of each container position for the test conducted with the compartment empty. One aluminum container was modified for the fully loaded compartment tests. A 14″ diameter duct was installed vertically in the center of the container. The aluminum container skin was removed where the duct intersected the container roof. The smoke generator was placed inside the container under the duct and allowed the smoke plume to exit the container into the cargo compartment. Six additional containers were modified to simulate refrigerated or active cargo containers. A vertical section of 8″ diameter duct with 90° elbows attached to the top and bottom was attached to the interior sidewall of the container. The two elbow sections penetrated the container sidewall near the top and bottom. An inline duct fan was installed in the vertical duct section. These ducts and fan were used to draw air from the cargo compartment into the duct and exhaust the air back into the cargo compartment. This simulated the airflow induced in the cargo compartment by the refrigeration units installed in active containers. Test were conducted with the fans configured to either draw air into the top and out the bottom or into the bottom and out the top. Figure 4 shows the aft cargo compartment container positions, air inlets, and smoke detection sampling ports. Figure 5 shows the modified, smoke generator AKE cargo container. Figure 6 shows the simulated active AKE cargo container.

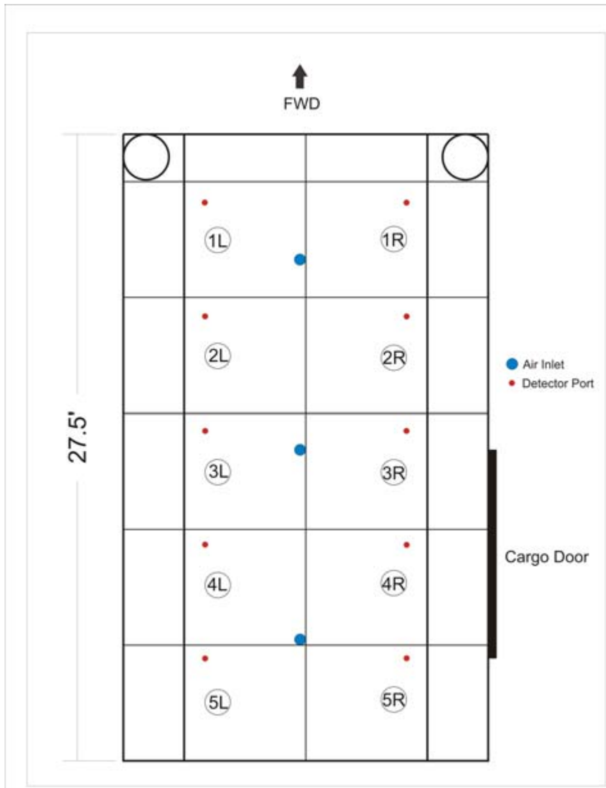

Figure 4. B-747SP Aft Cargo Compartment

Figure 5. Modified Smoke Generator AKE Cargo Container

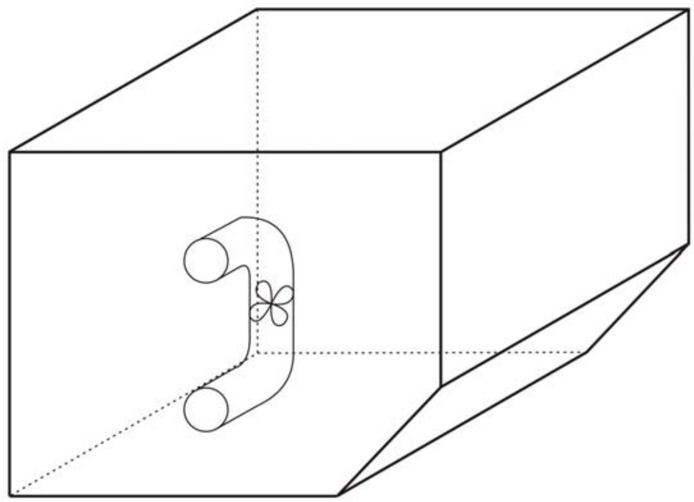

Figure 6. Simulated Active AKE Cargo Container

2.3 SMOKE GENERATOR.

Simulated smoke was generated with a Corona Vicount Aviator 55 SDT smoke generator. The generator vaporizes a mineral oil-based fluid, which condenses after release and produces 0.2- to 0.3-micron-diameter liquid droplets. Carbon dioxide (CO_2) is used as the propellant to force the fluid through the generator. Adjusting the regulator pressure of the CO_2 controls the smoke output of the generator. Four heating rods in the output chimney section of the generator were used to control the buoyancy of the smoke plume. The smoke generator was allowed to warm up for at least 30 minutes and then generated smoke for several minutes before starting the tests each day.

3. TEST RESULTS.

3.1 B-727 TEST RESULTS.

A series of preliminary tests were conducted to select an appropriate setting for the smoke generator. It was desired to use a similar quantity of smoke for these tests as was used for the initial aircraft smoke detection system certification tests. Those certification tests required that the detection system alarm within 1 minute of the start of smoke generation. The certification tests were conducted in an empty cargo compartment. Several smoke generator locations were initially tested in the empty B-727 cargo compartment and seemed to indicate that the aft most container position produced the longest detection times. The smoke generator output was adjusted to produce detection times at that location that were close to, but did not exceed, 1 minute. The generator settings that achieved this target were 18 pounds per square inch (psi) of CO_2 pressure and the use of two of the heater probes in the exhaust chimney. After the actual test series had started, it was discovered that some of the other container positions produced alarm times that exceeded 1 minute.

A minimum of three tests were conducted on the right side, center, and left side at each container position with the cargo compartment both completely empty and fully loaded with empty main deck AAY cargo containers. Tests were repeated more than three times at some locations that produced a wider than normal scatter in detection times. There were a total of 206 tests conducted at 27 different locations in the B-727. The average detection time and the standard deviation of the range of detection times for every test position and loading configuration were computed. Figure 7 shows the average detection times for all the positions tested. The error bars in figure 7 represent plus and minus one standard deviation of the range of detection times for each location.

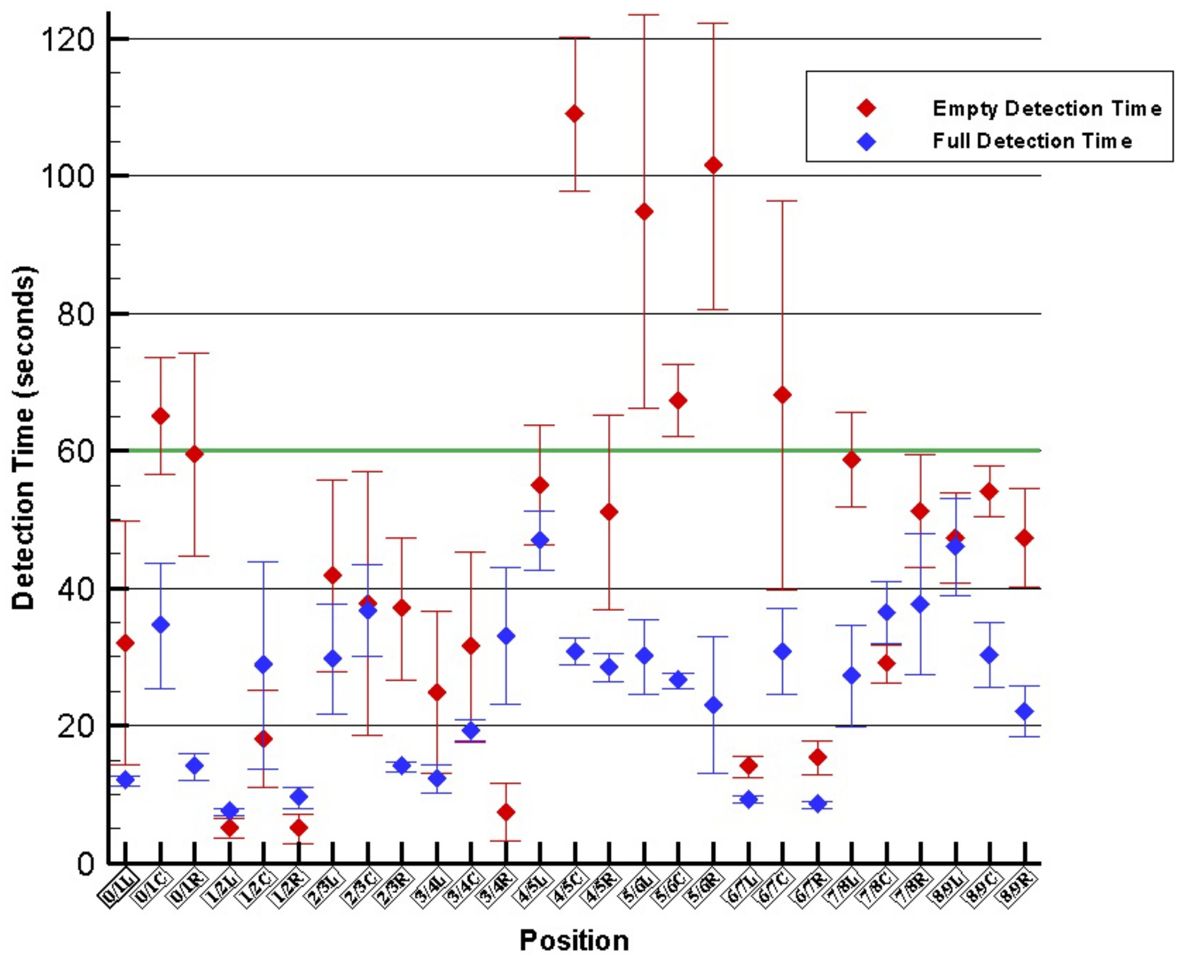

Figure 7. B-727 Empty and Full Test Results

Figure 8 shows the B-727 test results in a different format. For each position tested, the average time for detection in the fully loaded cargo compartment is subtracted from the average time for detection in the empty compartment. A positive detection time difference indicates the detectors alarmed faster in a full compartment than in an empty compartment for a given smoke generator location. A negative value indicates detection occurred faster in an empty compartment. Detection occurred faster in the empty compartment in only 5 of the 27 test locations. In four of those five positions, the difference in detection times was not significant at 11 seconds or less.

The difference in detection time at position 3/4R was 26 seconds. At that location, the smoke generator chimney was almost directly below one of the smoke detection sidewall sample ports as shown in figure 2. When this location was tested with the compartment fully loaded, the plume of smoke exited the container duct at a point higher than the detector sample probe and had to fill the compartment ceiling space before descending to the probe. The average detection time difference for all 27 positions tested was 20 seconds faster for the fully loaded condition.

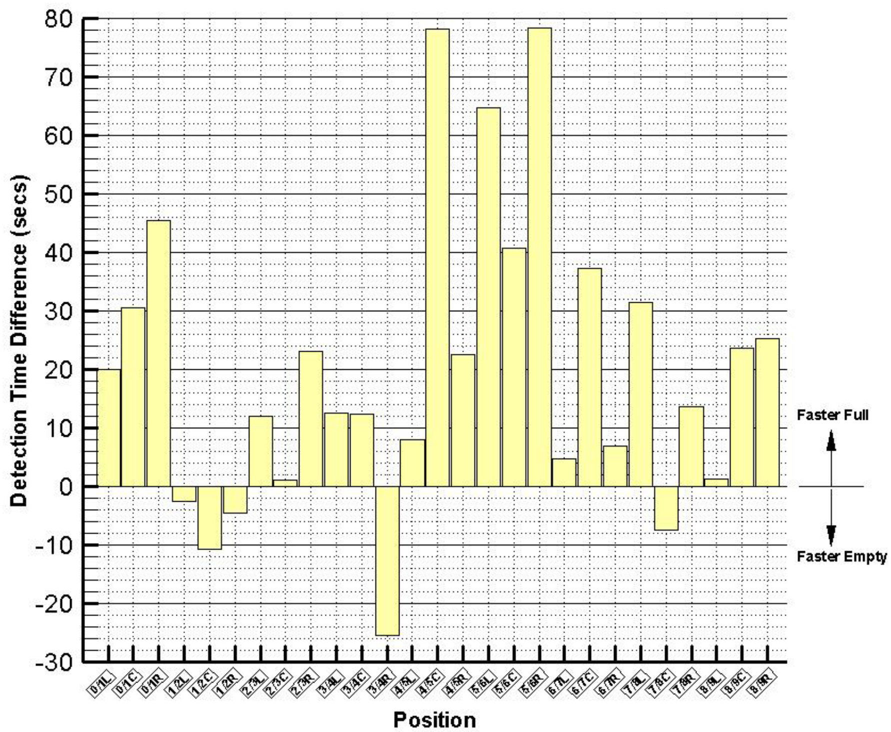

Figure 8. B-727 Detection Time Difference

3.2 B-747SP TEST RESULTS.

Preliminary tests were also conducted in the B-747SP to determine the appropriate settings for the smoke generator. The ventilation air was supplied to the compartment through three discreet inlets in the ceiling. Although the ventilation rate was slightly lower than the ventilation rate in the B-727 main deck compartment, the airflow was much more turbulent in the B-747SP because of the higher air velocity through the three inlets compared to the continuous inlet vent in the B-727. This resulted in a much more erratic response by the smoke detection system. Visual observation of the smoke generator output showed that a brief, relatively dense burst of smoke was emitted when the generator was initially turned on. Following this, the plume became much less dense, but variability in the smoke density would continue to occur. A variety of combinations of CO_2 pressure and chimney heater probes were tested in an attempt to achieve consistent and repeatable alarm times in the 1- to 2-minute range. A setting of 11 psi with two heaters on did not produce an alarm in most locations within 5 minutes. A setting of 13 psi with two heater probes produced an alarm in less than 10 seconds in most locations. A setting of 12 psi with two heater probes would generally produce an alarm within about 10 seconds that would only last for a few seconds, followed by occasional intermittent alarms, and then a steady alarm that would usually remain on for the duration of the test. Varying the amount of heater probes used did not produce better results. This was not the desired behavior of the detection system but it was the best that could be achieved given the amount of turbulence within the compartment and the behavior of the smoke generator. A CO_2 pressure of 12 psi and two heater probes were therefore used for the remaining tests. It appeared that the initial burst of smoke from the smoke generator was sufficient to be momentarily detected followed by the detectors going out of alarm as the smoke plume thinned. The detectors would go back into alarm after the smoke layer from the thinner plume built up on the ceiling of the compartment. The effect of the turbulence within the compartment also had a noticeable effect on the smoke plume. The plume would rarely be emitted straight up from the generator but instead, was pushed in different directions that varied with time as the generator was running.

A minimum of four tests were conducted at each of the ten locations with the cargo compartment empty and fully loaded with empty AKE containers. In many locations, significantly more tests were conducted due to the more erratic test results. For the fully loaded condition, additional tests were conducted with the fans used to simulate active cargo containers turned on in various combinations, locations, and airflow direction (drawn in at the top and exhausted at the bottom, or drawn in at the bottom and exhausted at the top). The average detection time and standard deviation of the range of detection times were computed for each location, loading, and airflow condition.

3.2.1 Empty Versus Fully Loaded Results.

One hundred nineteen tests were conducted to document the difference in detection times in the empty compartment compared to the fully loaded compartment. The fans used to simulate active containers were not used for these tests. Due to the erratic detection times during these tests, it was more difficult to draw definite conclusions. For the majority of tests in the empty compartment, the detectors would alarm relatively quickly but mostly for only a very brief time. The intermittent detections would sometimes only last for 1-2 seconds in some tests and 5-10 seconds in others. In some tests, the brief alarms would occur only once, while in others it occurred several times. In almost all tests, the detectors would eventually stay in alarm for an extended period at some point. This behavior was not observed in the majority of the tests conducted with the compartment fully loaded. In these tests, the early intermittent detector alarms generally did not occur. When the detectors alarmed, they generally stayed in alarm for an extended period.

In tests conducted with both the empty and full compartments, significant variability in detection times was observed for tests conducted on different days under the same conditions. The tests were carried out over a period of several months. Ambient outside temperatures and wind speed and direction varied considerably in that duration. Prior to the start of the tests each day, the APU was started and two air-conditioning packs were operated for at least 1 hour to allow the cargo compartment temperature to stabilize before any tests were conducted. Outside air temperature and the air-conditioning pack duct temperature were recorded for all tests. Those data were analyzed to look for trends in detection times versus those parameters but no trends were evident. Despite that, it was assumed that ambient conditions had some effect on the detection time results due to the lack of any other explanation for the variability observed in test results under the same conditions conducted on different days.

The average detection time and standard deviation of the range of detection times were computed for each smoke generator position and loading configuration. Figure 9 shows the results of the empty and fully loaded compartment tests. The average detection times shown in figure 9 reflect the first detection alarm times, regardless of the alarm duration. Using these criteria, detection occurred faster at five positions with the compartment empty and faster in the other five positions with the compartment fully loaded.

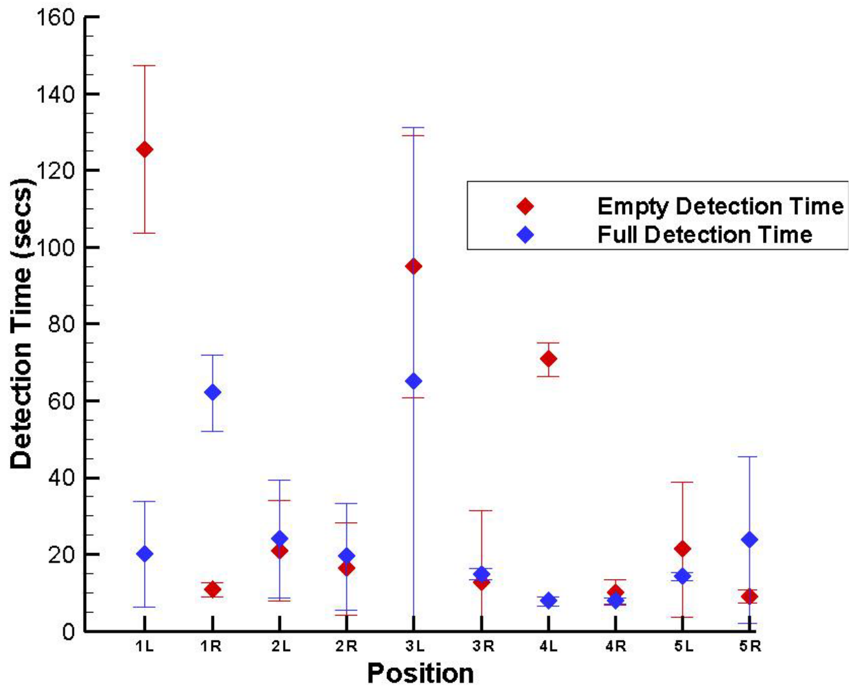

Figure 9. B-747SP Empty and Full Test Results

Figure 10 shows the B-747SP test result in a different format. For each position tested, the average time for first detection in the fully loaded compartment is subtracted from the average time for the first detection in the empty compartment. If the negligible difference in detection times at positions 2L, 2R, 3R, 4R, and 5L are ignored, detection occurred faster in the fully loaded compartment in three of the remaining five positions. The difference in the average detection times for all ten positions tested was 13 seconds faster in the fully loaded cargo compartment.

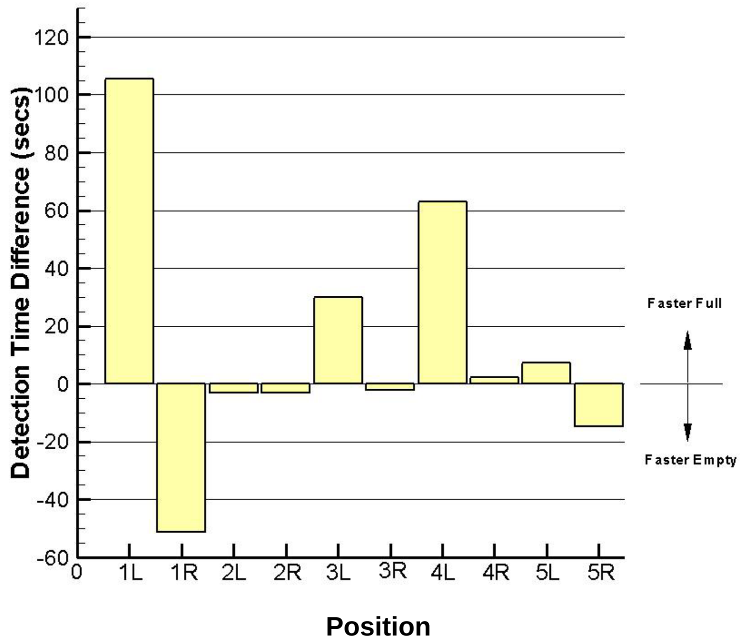

Figure 10. B-747SP Detection Time Difference

Another way to analyze the test results is to ignore the brief intermittent detector alarms that occurred more often in the empty compartment tests and only consider detection to have occurred when the detectors alarmed and stayed in alarm for the duration of the tests. In that case, the average detection times and standard deviation of the range of detection times would be those shown in figure 11. Using these criteria for detection, the average detection times in the loaded compartment were faster in nine out of the ten positions.

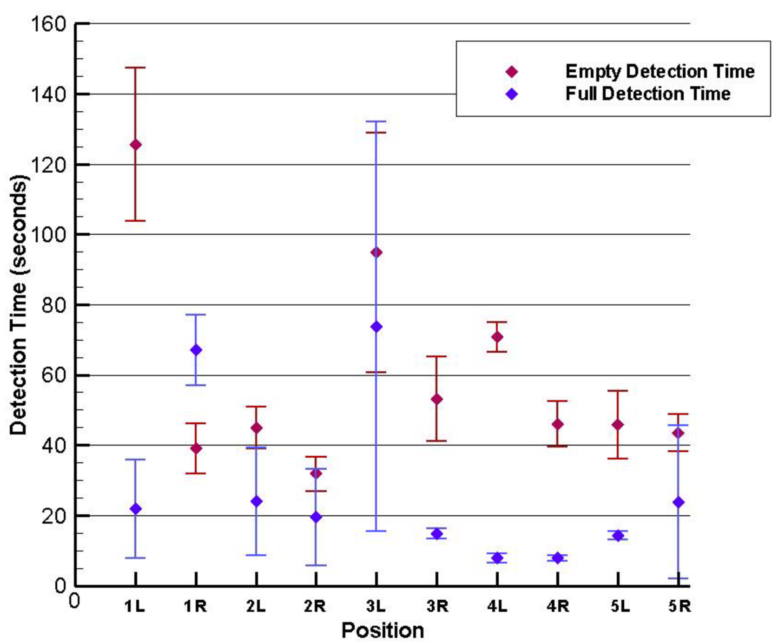

Figure 11. B-747SP Sustained Detection Empty and Full Test Results

3.2.2 Active Container Test Results.

An additional 96 tests were conducted to evaluate the effect of simulated active cargo containers on detection times in a fully loaded cargo compartment. Smoke was generated at four different positions and the fans in either two, four, or six of the simulated active containers were turned on. Two of the smoke generator positions were repeated with the active container airflow direction reversed. Table 1 shows the test conditions for this series.

Table 1. Active Container Test Series

Generator Position	Active Container Positions	Airflow Direction
1L	1R, 2R	Bottom to top
1L	2L, 3L	Bottom to top
1L	1R, 2R, 2L, 3L	Bottom to top
1L	1R, 2R	Top to bottom
1L	2L, 3L	Top to bottom
1L	1R, 2R, 2L, 3L	Top to bottom
3L	2R, 3R	Bottom to top
3L	2L, 4L	Bottom to top
3L	2R, 3R, 2L, 4L	Bottom to top
3L	2R, 3R	Top to bottom
3L	2L, 4L	Top to bottom
3L	2R, 3R, 2L, 4L	Top to bottom
4L	3L, 5L, 1R, 2R, 3R, 4R	Bottom to top
5L	3R, 4R	Bottom to top
5L	4L, 5L	Bottom to top
5L	3R, 4R, 4L, 5L	Bottom to top

The average smoke detection times and standard deviation of the range of detection times were computed for each test configuration. As shown in previous tests, some of the results of this test series varied considerably for tests conducted on different days under the same conditions. No discernible pattern of the active containers' effect on smoke detection times was observed for the container airflow and compartment ventilation conditions tested. Figures 12 through 15 show the average smoke detection times plus and minus one standard deviation for each test configuration in this series.

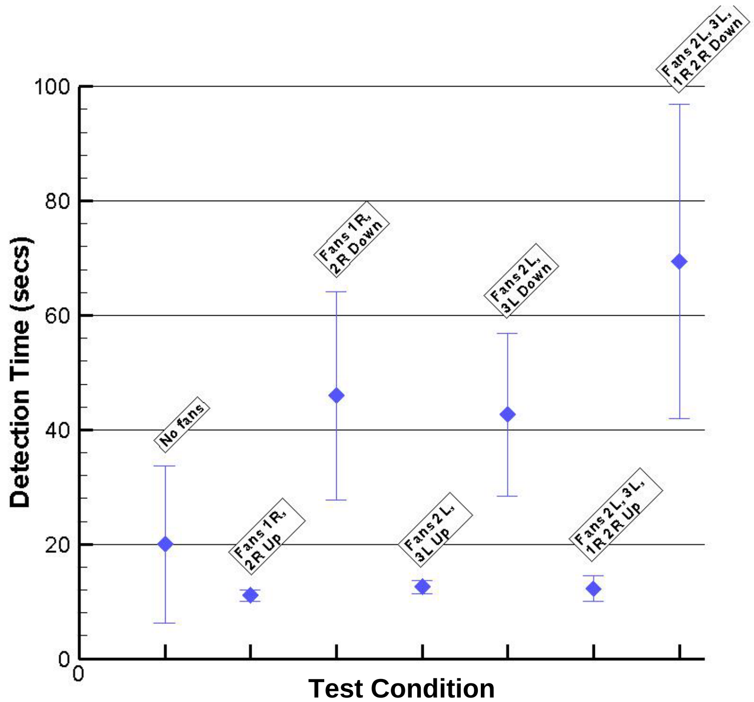

Figure 12. Active Container Test Series, Smoke Generator at Position 1L

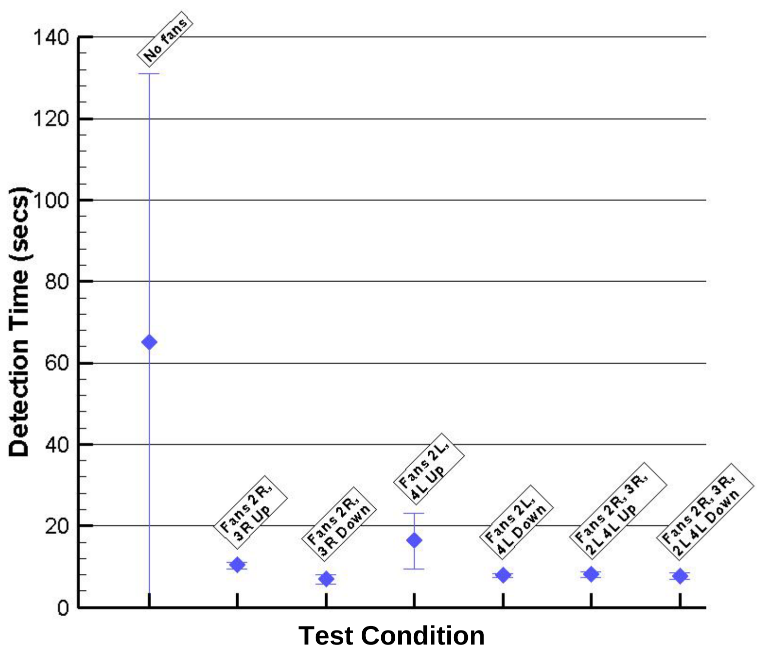

Figure 13. Active Container Test Series, Smoke Generator at Position 3L

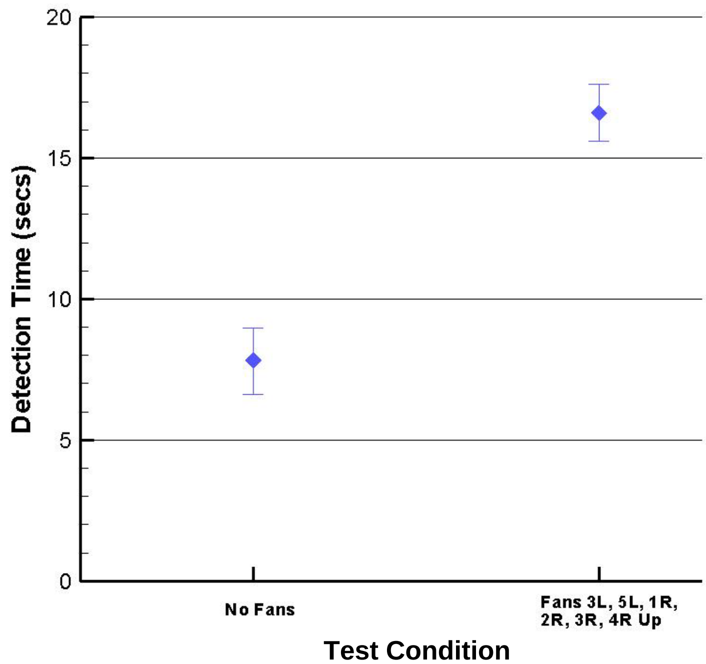

Figure 14. Active Container Test Series, Smoke Generator at Position 4L

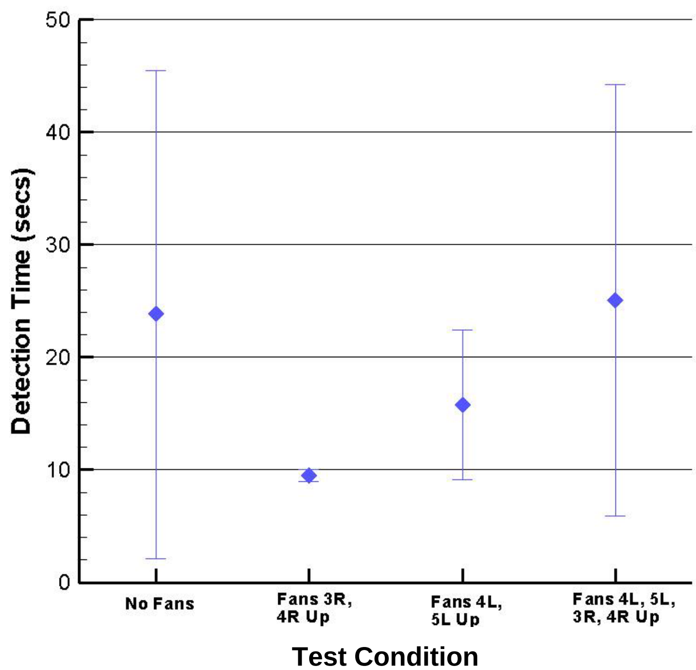

Figure 15. Active Container Test Series, Smoke Generator at Position 5R

4. CONCLUSIONS.

Smoke detection generally occurred faster in fully loaded cargo compartments than in empty compartments. This was observed consistently in the main deck B-727 results. The results from the B-747SP tests in the below-floor compartment were more erratic but the general trend was faster detection times when the compartment was full.

It was concluded that active containers did not have a consistent influence on smoke detection times under the airflow conditions tested. The tests results were so variable that no pattern in the change in detection times was observed between tests with the fans operating compared to the tests with the fans off.

5. REFERENCES.

1. Title 14 Code of Federal Regulations Part 25 Airworthiness Standards: Transport Category Airplanes.

2. "Aircraft Accident Report: In-Flight Fire United Parcel Service Company Flight 1307, McDonnell Douglas DC-8-71F, N748UP, Philadelphia, Pennsylvania, February 7, 2006," NTSB Report Number AAR-07-07, December 4, 2007.

ERRATA

Report No. DOT/FAA/AR-09-52	Effects of Cargo Loading and Active Containers on Aircraft Cargo Compartment Smoke Detection Times
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	Prepared for
	U.S. Department of Transportation Federal Aviation Administration William J. Hughes Technical Center Atlantic City International Airport, NJ 08405
Title Page	Changed Report number to reflect the revision number and added the revision date.
Technical Report Documentation Page	Changed Report number to reflect the revision number and added the revision date.
Page 16	Changed the word “empty” to “full.”