Ground Tests of Aircraft Flight Deck Smoke Penetration Resistance

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16. Abstract

This report documents a series of tests to determine the amount of positive pressure differential between the flight deck and surrounding areas necessary to prevent smoke from penetrating into the flight deck. The testing also explored methods to demonstrate the effectiveness of those ventilation conditions. The tests were conducted on the ground in a Boeing 727-100 freighter and a 747SP aircraft. A thin plastic sheet covering the flight deck door opening and a theatrical smoke generator were successfully used to demonstrate a positive pressure differential that was effective at preventing the penetration of theatrical smoke into the flight deck of the B-727. The 747SP ventilation system was not capable of preventing smoke penetration during these ground tests.

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EXECUTIVE SUMMARY

This testing was performed in support of the Aviation Rulemaking Advisory Committee harmonization working group. The group was tasked with developing draft regulations and advisory material to implement an International Civil Aviation Organization standard to include security considerations into the type certification of new aircraft. One of the new requirements of this agreement was to include specific design features to prevent smoke and gases from entering the flight deck following the activation of an explosive or incendiary device anywhere in the aircraft except the flight deck itself. The threat from this scenario would be the smoke and gases from an ensuing fire after the activation of the device. Ground tests were conducted in a Boeing 727-100 and 747SP aircraft in an attempt to either measure or demonstrate the positive pressure differential between the flight deck and surrounding areas needed to prevent smoke penetration into the flight deck. A thin sheet of plastic covering the flight deck door opening and a theatrical smoke generator placed in the cabin area were used to demonstrate that a positive pressure differential existed at a particular ventilation setting in the B-727 aircraft and that the pressure was sufficient to prevent smoke penetration into the flight deck. The actual pressure differential was not directly measurable. The ventilation system on the 747SP aircraft was not capable of preventing smoke penetration into the flight deck during these ground tests.

PURPOSE

The purpose of this project was to determine the ventilation conditions necessary to prevent smoke penetration into aircraft flight decks.

BACKGROUND

The testing was conducted in support of the Aviation Rulemaking Advisory Committee harmonization working group comprised of aviation industry representatives and regulators. The group was tasked with developing draft regulations and advisory material to implement an International Civil Aviation Organization standard to include security considerations into the type certification of aircraft. Most of the security design requirements became effective as international requirements on March 12, 2000, and are included in Annex 8 of the Convention on International Civil Aviation. One of the new requirements was to include specific design features to prevent smoke and gases from entering the flight deck following the activation of an explosive or incendiary device anywhere in the aircraft except the flight deck itself. The threat from this scenario would be the smoke and gases from an ensuing fire after the activation of the device. Current regulatory requirements do not address the ingress of smoke, other than from a cargo compartment. It is assumed that the fire is subsequently extinguished with either hand-held extinguishers or fixed systems. Smoke control procedures used when an in-flight fire is still burning could be detrimental in some circumstances. One of the considerations in the development of the draft regulations was the need to demonstrate compliance. Flight tests have historically been required to demonstrate compliance with many regulations. A well-defined method of showing compliance with the draft regulation in the form of a draft advisory circular was a desired product from the harmonization working group. It was readily apparent to the working group that a positive pressure differential between the flight deck and the surrounding spaces would be necessary to prevent smoke penetration into the flight deck. The testing described in this report was focused on determining how much of a pressure differential was needed and how it could best be measured and/or demonstrated.

TEST ARTICLES

A Boeing 727-100 freighter and a 747SP passenger aircraft were used in this project. All of the tests were conducted on the ground with the aircraft unpressurized.

The ventilation system on the B-727 consists of two air conditioning packs fed by bleed air from either the aircraft engines or the auxiliary power unit (APU). Only the APU was used as the source for bleed air in these tests. The aircraft operations manual limits the ventilation system to one pack when the APU alone is used as the bleed air source. Inlet ventilation air was supplied to the flight deck through a left and right ceiling vent and a left and right floor vent. In addition, five gasper outlets were present in the flight deck and were located at the captains, first officer, flight engineer, forward observer, and aft observer seats. Each vent and gasper could be opened and closed individually. Air was available through the vents and gaspers whenever a pack was running. The quantity of air to the gaspers could be increased by turning on a gasper fan switch on the flight engineer's panel. A cabin airflow control handle mounted on the back wall of the flight deck could be used to vary the ratio of conditioned air directed into either the flight deck or the main deck cargo compartment. In the full upright position, labeled as 10, airflow into the main deck cargo compartment was maximized. This is the normal in-flight handle position. In the full downward position, labeled as shutoff, airflow into the main deck was minimized and airflow into the flight deck was noticeably increased. The volume of the B-727 flight deck was 338 cubic feet.

The ventilation system on the 747SP consists of three air conditioning packs fed by bleed air from the engines or APU. Again, only the APU was used as the bleed air source in the 747SP tests. One, two, or all three packs could be used with bleed air from only the APU. Inlet ventilation air was supplied to the flight deck through a ceiling vent in the aft ceiling, a flight engineer floor vent, upper and lower crew rest bunk vents, a forward observer seat knee vent, and an aft observer seat floor vent. The captain and first officer each had individually controlled foot and windshield vents. Five gasper vents were also located in the flight deck: one at each of the captains, first officer, flight engineer, and forward and aft observer seats. Each gasper could be opened and closed individually. Airflow through the inlet vents could be increased by turning on a flight deck fan switch mounted on the flight engineer's panel. An additional switch on the flight engineer's panel could change the equipment cooling mode from normal to smoke. In normal mode, air is drawn out of the flight deck and past avionics racks under the flight deck floor and then exhausted under the forward cargo compartment. When smoke mode is selected, the air is still drawn out of the flight deck with the same fan and passes over the avionic racks but is then exhausted overboard. Main deck recirculation air could also be turned on or off from the flight engineer's panel. The volume of the 747SP flight deck, including the crew rest area, was 920 cubic feet.

TEST SERIES

Initial testing attempted to measure a differential pressure between the flight deck and the surrounding areas. Bulkhead compression fittings were installed in the flight deck door and through the flight deck floor and ceiling in both the B-727 and 747SP. A Magnehelic differential pressure gauge with a range of 0 to 0.25 inches of water (0 to 0.009 psi) was attached to the compression fittings. The smallest increment on the differential pressure gauge was 0.005 inches of water (0.00018 psi). Each compression fitting was checked at every possible combination of ventilation system settings that affected flight deck airflow. A consistent, measurable pressure differential was not observed on the differential pressure gauge for any of the ventilation settings.

The next phase of testing used a theatrical smoke generator. The purpose of testing with a smoke generator was to determine if there was some combination of ventilation system settings that could prevent smoke from penetrating from the cabin area into the flight deck even though a pressure differential was not directly measurable. The smoke generator vaporizes a glycol-based fluid, which condenses in air, giving the appearance of smoke or fog. The smoke generator was placed on the floor of the B-727 in the main deck cargo compartment. The outlet of the smoke generator was pointed directly at the closed flight deck door, approximately 8 feet away.

The initial test minimized airflow into the flight deck by closing all four inlet vents and all five gaspers, turning the gasper fan off, and placing the cabin airflow control handle in the 10 position. The smoke generator was then turned on at its maximum setting. Smoke penetrated into the flight deck along the bottom and lower sides of the flight deck door. The smoke generator produced a sufficient quantity of smoke to completely fill the forward section of the main deck cargo compartment. The fuselage was cleared of all smoke after the completion of this and all subsequent tests.

The second test was conducted with the inlet vents and gaspers fully opened, the gasper fan off, and the cabin airflow valve in the 10 position. Again, smoke penetrated into the flight deck shortly after the smoke generator was turned on. The smoke only entered under the bottom of the flight deck door and not along the lower sides.

In the third test, the inlet vents and gaspers were fully open and the gasper fan was turned on. The cabin airflow valve was in the 10 position. Smoke penetrated into the flight deck under the bottom of the flight deck door.

In the fourth test, airflow into the flight deck was maximized. The inlet vents and gaspers were fully open and the gasper fan was on. The cabin airflow valve was moved to the shutoff position. Smoke did not penetrate into the flight deck even after several minutes of smoke generation. At the completion of this test, visibility in the main deck cargo compartment was essentially nonexistent due to the quantity of theatrical smoke. Tests two through four were repeated at a later date with the same results.

The next phase of testing attempted to demonstrate when a positive flight deck pressure differential existed. A thin sheet of clear polyethylene plastic (approximately 0.0045 inches thick) was loosely attached to the flight deck door frame of the B-727. The entire perimeter of the plastic sheet was sealed against the floor and door frame with tape and the flight deck door was left fully open. The sheet was loose enough to allow it to deflect at least 6 inches or more either forward into the flight deck or aft into the cabin area. Airflow into the flight deck was initially minimized after the plastic sheet was put in place. The airflow was then incrementally increased by first opening the four inlet vents and all five gaspers in the flight deck, turning on the gasper fan, and finally moving the cabin airflow valve handle to its full downward shutoff position. Several minutes elapsed after each ventilation system change to allow equilibrium conditions to be reached. It was only after the last valve position was changed to the shutoff position that the plastic sheet started to deflect into the cabin area, indicating a positive pressure in the flight deck. It took approximately 15 seconds for the plastic sheet to deflect fully into the cabin area and take up all the slack that was available. The cabin/flight deck valve was then opened and closed several more times. When opened, the plastic sheet would collapse into a neutral position, and each time the valve was closed it would deflect into the cabin area.

The preceding tests established that a slight positive pressure could be achieved in the B-727 flight deck and that it was sufficient to prevent smoke penetration. The next series of tests attempted to quantify the airflow conditions that were successful. A 4-inch-diameter vane anemometer was used along with appropriate air collection attachments to measure the volumetric airflow entering the flight deck from the four inlet vents and five gaspers during each of the previously tested airflow conditions. The maximum airflow condition that did not prevent smoke penetration and the condition that did prevent penetration were each repeated three times. Table 1 lists the ventilation conditions and results for the B-727 tests. Table 2 lists the results of the airflow measurement tests in terms of both the total volumetric airflow into the flight deck and the air change rate in minutes per air change for the 338-cubic-foot flight deck.

TABLE 1. BOEING 727 TEST RESULTS

Test	Inlet Vents	Gaspers	Gasper Fan	Main Deck Airflow	Results
1	Closed	Closed	Off	Open-10	Smoke under flight deck door and along lower sides
2	Open	Open	Off	Open-10	Smoke under flight deck door and along lower sides
3	Open	Open	On	Open-10	Smoke under flight deck door
4	Open	Open	On	Closed	No smoke penetration
5	Open	Closed	Off	Open-10	No deflection of plastic sheet
6	Open	Open	Off	Open-10	No deflection of plastic sheet
7	Open	Open	On	Open-10	No deflection of plastic sheet
8	Open	Open	On	Closed	Plastic sheet deflected aft into cabin area
9	Open	Closed	Off	Open-10	Measured flight deck inlet air
10	Open	Open	Off	Open-10	Measured flight deck inlet air
11	Open	Open	On	Open-10	Measured flight deck inlet air
12	Open	Open	On	Closed	Measured flight deck inlet air
13	Open	Open	Off	Open-10	Smoke under flight deck door and along lower sides
14	Open	Open	On	Open-10	Smoke under flight deck door
15	Open	Open	On	Closed	No smoke penetration
16	Open	Open	On	Open-10	Measured flight deck inlet air
17	Open	Open	On	Closed	Measured flight deck inlet air
18	Open	Open	On	Open-10	Measured flight deck inlet air
19	Open	Open	On	Closed	Measured flight deck inlet air

TABLE 2. BOEING 727 FLIGHT DECK AIRFLOW

Test	Ventilation Conditions	Flight Deck Air (ft^3/min)	Air Change Time (min)	Smoke Penetration into Flight Deck
9	Vents open, gaspers closed, cabin valve-10	67.7	5.0	Yes
10	Vents open, gaspers open, gasper fan off, cabin valve-10	112.1	3.0	Yes
11	Vents open, gaspers open, gasper fan on, cabin valve-10	148.3	2.3	Yes
16	Vents open, gaspers open, gasper fan on, cabin valve-10	169.9	2.0	Yes
18	Vents open, gaspers open, gasper fan on, cabin valve-10	162.4	2.1	Yes
12	Vents open, gaspers open, gasper fan on, cabin valve-shutoff	231.6	1.5	No
17	Vents open, gaspers open, gasper fan on, cabin valve-shutoff	257.6	1.3	No
19	Vents open, gaspers open, gasper fan on, cabin valve-shutoff	236.9	1.4	No

Similar tests were next conducted in the 747SP aircraft. The flight deck door opening was covered with a thin sheet of polyethylene that was sealed around the perimeter. Air conditioning packs one and two were used. Airflow into the flight deck was initially minimized and then incrementally increased. The response of the plastic sheet was observed after each ventilation setting change. The ventilation settings that had the greatest potential for producing a positive pressure in the flight deck was with all flight deck gaspers opened, the flight deck fan on, foot and windshield vents open, and the cabin recirculation fans off. No obvious deflection of the polyethylene sheet was observed in either direction under this and all other ventilation settings.

The volumetric airflow into the 747SP flight deck was also measured using a 4-inch-diameter vane anemometer for three different ventilation system settings. The airflow out of the foot and windshield vents could not be easily measured so those valves were closed for these tests. A smoke penetration test was conducted following each ventilation measurement. The smoke generator was placed in the cabin approximately 8 feet from the closed flight deck door with the outlet pointing directly at the door. Smoke immediately penetrated into the flight deck during these three tests. The maximum measured airflow into the flight deck was less than that achievable in the B-727. The volume of the 747SP flight deck was almost three times as large as the B-727, therefore, the time for one air change was significantly longer in the 747SP. Following the ventilation measurement tests, three additional smoke penetration tests were conducted. During tests 12 and 13, the smoke generator remained in its original position pointing directly at the flight deck door. One pack was used for test 12, and three air conditioning packs were used for test 13. Smoke immediately penetrated into the flight deck during these two tests. In test 14, all three packs were again used and the other ventilation settings remained the same. This time, however, the smoke generator was turned 90 degrees so that the outlet faced the cabin sidewall. Smoke did not penetrate into the flight deck during this test even though the cabin was completely filled with theatrical smoke. The momentum of the theatrical smoke towards the small openings surrounding the flight deck door during tests 9 through 13 was sufficient to allow smoke penetration. This is further evidence of the lack of a positive pressure differential between the flight deck and cabin. Table 3 gives the ventilation settings and the results of the plastic sheet deflection and smoke penetration tests for the 747SP. Table 4 lists the measured flight deck inlet air in terms of both the total volumetric airflow and the air change rate in minutes per air change for the 920-cubic-foot flight deck during tests 9 through 11.

TABLE 3. BOEING 747SP TEST RESULTS

Test	Gaspers	Flight Deck Fan	Recirc Air	Foot Windshield Vents	Equip. Cooling	Packs Used	Results
1	Closed	Off	Off	Closed	Normal	1,2	No movement of plastic
2	Open	Off	Off	Closed	Normal	1,2	No movement of plastic
3	Open	On	Off	Closed	Normal	1,2	No movement of plastic
4	Open	On	On	Closed	Normal	1,2	No movement of plastic
5	Open	On	Off	Open	Normal	1,2	No movement of plastic
6	Open	On	Off	Open	Normal	1,2	No movement of plastic
7	Open	On	Off	Open	Smoke	1,2	No movement of plastic
8	Open	On	Off	Open	Smoke	1,2	No movement of plastic
9	Open	Off	Off	Closed	Normal	1,2	Immediate smoke penetration
10	Open	On	Off	Closed	Normal	1,2	Immediate smoke penetration
11	Open	On	Off	Closed	Smoke	1,2	Immediate smoke penetration
12	Open	On	Off	Closed	Normal	1	Immediate smoke penetration
13	Open	On	Off	Closed	Normal	1,2,3	Immediate smoke penetration
14	Open	On	Off	Closed	Normal	1,2,3	No smoke penetration

TABLE 4. BOEING 747SP FLIGHT DECK AIRFLOW

Test	Flight Deck Air (ft^3/min)	Air Change Time (min)	Smoke Penetration
9	141.7	6.5	Yes
10	205.9	4.5	Yes
11	205.9	4.5	Yes

TEST RESULTS

The initial approach to the testing attempted to directly measure a pressure differential between the flight deck and the surrounding spaces for a ventilation condition that prevented smoke penetration. If this could have been accomplished, it would have provided the simplest and most convenient method to demonstrate compliance with the requirement to prevent flight deck smoke penetration. Due to the design of the ventilation systems and the numerous openings between the flight deck and surrounding areas, this was not achieved on the two airplanes used in the testing.

Subsequent tests, using a theatrical smoke generator and a sheet of thin plastic covering the flight deck door opening, identified one combination of ventilation settings in the B-727 that clearly demonstrated the existence of a positive pressure differential and also prevented smoke penetration. The flight deck door opening on the B-727 measures 19″ wide by 75″ high, which equates to an area of 1425 square inches. The smallest increment on the differential pressure gauge used to measure differential pressure directly was 0.005 inches of water (0.00018 psi). Assuming the actual pressure differential was somewhere in the vicinity of one-half of the smallest increment on the gauge, this would equate to a total force of approximately 0.13 pounds acting on the plastic sheet. Given that it took about 15 seconds to fully deflect the plastic sheet into the cabin area, this order of magnitude of the actual pressure differential that existed seems reasonable. If methods to accurately measure pressure differentials in this range exist, they could be useful to demonstrate conditions that can prevent smoke penetration. A positive pressure differential, using the plastic sheet as an indicator, was not achievable with the 747SP aircraft systems.

The successful ventilation condition in the B-727 had a flight deck air exchange rate of one change of air in an average time of 1.4 minutes. Air exchange rates alone are not good indicators for predicting smoke penetration. Air exchange rates of 1.4 to 2.3 are faster than typical cabin air exchange rates [1]. This would imply that a positive pressure would exist in the flight deck relative to the cabin at these exchange rates because more air per unit volume was forced into the flight deck than into the cabin. Testing showed that this was not necessarily the case as smoke penetrated into the flight deck or the plastic sheet did not deflect into the cabin at air exchange rates of 2 to 2.3 minutes. This occurred in B-727 tests 3, 7, and 14.

Although the use of a plastic sheet over the flight deck door opening and a theatrical smoke generator were successfully used to demonstrate the prevention of smoke penetration, drawbacks with these methods still exist. One potential area of uncertainty was illustrated in 747SP tests 13 and 14. The ventilation conditions were identical during these two tests and smoke penetration was only dependant on the orientation of the smoke generator. Smoke penetrated into the flight deck during test 13 when the smoke generator was pointed at the door but did not during test 14 when the smoke generator was pointed at the cabin sidewall. Smoke generator orientation, the type and output rate of the smoke generator, and the variations in flight deck and cabin layouts of future aircraft that would be required to demonstrate compliance with this requirement could be the deciding factors instead of the existence of a positive flight deck pressure differential. Another area of uncertainty that was observed in the early 747SP tests involved the movement of the plastic sheet covering the flight deck door opening. In some tests, there appeared to be some movement of certain areas of the plastic that was either too slight to be conclusive or could not be repeated in subsequent tests. For marginal designs, this could lead to subjective judgments that could vary between different individuals conducting the tests, especially in combination with the variability observed with the smoke generator orientation. An additional area of concern was that the condensed vapors from theatrical smoke generators are generally colder than smoke from actual fires so the buoyancy would be different, which could affect the smoke penetration behavior. The difference in the behavior of artificial smoke generators compared to actual smoke is a well established phenomenon, and its effect on test results is not unique to this application. However, artificial smoke is the only practical option, for safety reasons. The potential differences in behavior should be considered in all uses of artificial smoke.

CONCLUSIONS

1. A theatrical smoke generator and a plastic sheet covering the flight deck door opening were successfully used to demonstrate the prevention of smoke penetration from the cabin area into the flight deck.

2. Maximizing flight deck ventilation rates is an important, but not the only, factor for preventing smoke penetration into the flight deck caused by a cabin fire.

3. A completely objective method to demonstrate ventilation conditions that would prevent flight deck smoke penetration was not identified.

REFERENCES

1. Lorengo, D. and Porter, A. "Aircraft Ventilation Systems Study, Volume I," DOT/FAA/CT-TN86/41-1, 1986. This document is exempted from public availability and is a record subject to provisions of 14 CFR 191.1. Release of information contained herein is prohibited without the express written approval of the Director, Office of Airworthiness.