Airplane Systems Modifications for Improved Cabin Smoke Evacuation

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16. Abstract

Two concepts for improved aircraft in-flight smoke evacuation were analyzed and tested. The concept definition and evaluation efforts involved an additional ventilation outflow valve on the aircraft underside along with either increased ventilation air volume from the engine compressors or a supplemental ram air supply. Subsequent test aircraft modification involved addition of a pressure controlling outflow valve on the top of the fuselage and upgraded engine bleed air volume flow for cabin air-conditioning. Ground and flight tests were conducted on a test B757 with buoyant and nonbuoyant theatrical smokes generated continuously in various places in the passenger cabin. Buoyant smoke could be localized only when generated in the vicinity of the upper lobe outflow valve. Nonbuoyant smoke could be localized only when generated in the vicinity of an outflow valve, whether the valve was on the top or bottom of the fuselage. The buoyant smoke was formulated to have the same type flow behavior as a plume from the visible flames of a burning surface. The nonbuoyant smoke might be more representative of a smoldering material.

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EXECUTIVE SUMMARY

As part of a comprehensive evaluation of aircraft in-flight cabin smoke evacuation capabilities, potential modifications to aircraft mechanical systems were analyzed and tested. The modifications under consideration were increased ventilation flows to the cabin through an upgraded environmental control system, a supplemental installation to draw external air into the fuselage, and use of an additional outflow valve to vent the aircraft.

The potential benefits of these modifications were estimated with a simplified aircraft cabin smoke spread model. The costs of installing these modifications on the entire domestic transport fleet was also estimated. The resultant findings were evaluated in conjunction with concurrent fire test experiments to select a modification scheme for aircraft ground and flight testing. A Boeing owned experimental B757 was selected for testing as it is reasonably representative of the current fleet. A B737 production outflow valve was installed on the top of the fuselage near the forward end of the passenger cabin. The system that supplies air to the cabin was modified to provide fresh air delivery rates at 215 percent of the rate normally provided in operation.

Ten ground tests and nine flight tests were performed with these modifications. All tests involved continuous generation of theatrical smoke at some point in the passenger cabin. Six of the ground tests employed an air-helium mixing device to give the smoke buoyant properties that were more representative of a fire plume.

The major finding of the testing was that smoke could be localized in the cabin only when it was generated in the vicinity of an outflow valve. Buoyant smoke could be localized only when generated near the outflow valve on the top of the fuselage.

INTRODUCTION

PURPOSE.

A 4-year program was undertaken by the Federal Aviation Administration (FAA) in order to determine whether improvements in airplane cabin in-flight smoke evacuation capabilities were feasible and warranted. The effort was mandated by a Congressional commitment made in testimony by FAA Administrator Engen in August 1984. This commitment involved an evaluation of both airplane emergency procedures and systems with a completion date of November 1988.

BACKGROUND.

In past aircraft accidents resulting from in-flight fires, smoke has spread throughout the aircraft cabin while the aircraft was still in flight (references 1 and 2). In addition to the potential deleterious effects on passengers and crew from exposure to smoke, the reduced visibility hampers passenger evacuation when the aircraft is landed successfully. Improvements in this area could involve either better ventilation control capability to localize smoke near the smoke source or ability to significantly dilute or remove the smoke.

The overall FAA smoke evacuation program included four major thrusts. The first involved characterizing the ventilation system design and performance of all the transport category aircraft in the civil fleet (reference 3). Included in this effort was a listing of the emergency procedures for smoke evacuation for these airplanes. The product of this effort served as a baseline of existing procedures and systems against which improvements could be evaluated.

The second thrust involved fire tests in enclosures that were one-quarter and one-half scale of transport cabins (references 4 and 5). These tests involved variations of fire size and enclosure ventilation rates to determine their effects on smoke and temperature buildup and distribution. The ventilation mode was from ceiling to floor as is universal in large transport passenger cabins. Among the numerous findings from these mockup tests was the observation that the buoyant smoke plume moved up to and along the ceiling in spite of the overall ceiling-to-floor ventilation pattern. The ventilation air did cause dispersion of the smoke and heat downwards, but the smoke concentration remained highest at the top of the enclosures. These buoyant effects motivated subsequent FAA development of a device that generated a strongly buoyant theatrical smoke.

A third effort involved FAA participation in a United States Air Force Military Airlift Command (MAC) program on flight tests of smoke and fume elimination procedures. The MAC program was motivated by loss of a C141 transport due to an in-flight fire and was directed at determining the effect of current and modified emergency procedures on smoke removal. Over 100 flight test hours were accrued on tests of approximately a dozen aircraft models including the B707, B727, and DC-9. The MAC cabin smoke elimination tests involved filling the entire cabin with dense theatrical smoke and observing the time taken for the smoke to clear. This scenario represents a situation where a fire has been extinguished prior to onset of smoke removal procedures. The FAA role was providing and operating the smoke generators, the light transmissometers, and the data acquisition system. The MAC tests uncovered no generic improved procedures. However, the tests did validate an earlier theoretical model on smoke clearing for this type scenario (reference 6).

The final major thrust to be initiated involved evaluation of potential aircraft systems changes for more effective smoke control or removal. The inability to develop improved procedures put additional emphasis on these systems evaluations.

OBJECTIVE.

The objective of the airplane systems evaluation was to develop and analyze potential improvements for enhanced emergency smoke evacuation and subject such modifications to airplane ground and flight tests.

IMPROVEMENT CONCEPTS

CONCEPT DEVELOPMENT.

Under contract to the FAA, the Boeing Commercial Airplane Group developed two design concepts for improving smoke evacuation capability for aircraft (reference 7). Figures 1 and 2 show schematics of the two concepts along with graphical renditions of how they would be operated in flight. Concept A involves reworking the aircraft ventilation system so that the air packs can supply a larger amount of air to the cabin. Concept B involves addition of a duct and fan system that could provide the cabin ventilation ducts with ram air. Both concepts involved the installation of an additional outflow valve on the fuselage lower lobe in the forward part of the airplane. In Concept A the flow enhancement possibilities varied from model to model with a 50 percent increase possible in the B737 and no practical increase possible in the B767. Similarly, the ram air that could practically be provided under Concept B varied widely with models due to the particular design constraints of each. The concept development also included a cost estimation component. The cost of installing Concept A on the entire domestic fleet plus on all Boeing, Douglas, and Airbus production through 1992 was estimated at $380 million. The cost of applying Concept B to the same airplanes was estimated at $590 million.

CONCEPT ANALYSIS.

A simple steady-state theoretical smoke model was developed to predict the comparative effectiveness of the two concepts. The model was based on conservation equations, cabin ventilation airflow balancing, and empirical experience from past flight tests using theatrical smoke. The primary output of the model was the percentage of the cabin length that remained smoke free assuming that the continuously generated smoke cloud would stabilize at some location in the cabin. Figure 3 shows comparison of the length smoke free (LSF) for current procedures versus Concept A for the B757 at 35,000 feet for the smoke generation at forward, middle, and aft cabin. According to the model, Concept A would maintain an additional three to nine percent of the cabin smoke free. Application of the model to the entire fleet resulted in the prediction that neither concept offered much improvement over current procedures while an airplane remains in the air. However, during passenger evacuation with engines off, Concept A is predicted to leave none of the cabin length free of smoke while Concept B maintains an LSF comparable to that found in flight.

PARTS PRODUCTION.

The FAA contract had an optional clause for the design and production of modification parts for whichever concept came through the analysis study as the more promising. Since the analysis was done with a nonbuoyant model and concurrent mockup studies did show the strong effects of buoyancy on smoke movement, the FAA requested Boeing to submit a parts production proposal with the additional outflow valve on the fuselage upper -- rather than lower -- lobe. This parts production effort targeted the B757-200 and involved rescheduling the air pack flow control valve to operate at the normal 100 percent capacity, the available 165 percent, and an additional 215 percent high flow mode. The effort further involved structural design and fabrication of parts so that a B737 production outflow valve could be installed in the upper lobe of the aircraft. Because the selected area is a high stress area, the structural design and valve mounting/reinforcement fabrication were the major focus of the overall parts production effort. While Boeing produced the parts, the FAA developed a buoyant theatrical smoke source (reference 8) that involved mixing air, helium, and theatrical smoke to form a 200-cubic-foot-per-minute plume with the buoyant properties of air heated to 475 degrees Fahrenheit. Figure 4 shows this buoyant plume rising to the ceiling in a nonventilated B707 test fuselage. At the time of the photograph, the ceiling smoke layer had spread from the rear to the front of the passenger cabin.

AIRPLANE TESTS

AIRPLANE MODIFICATIONS.

An experimental Boeing owned B757 was selected for modification. Figure 5 shows a schematic of the test airplane as configured for the ground and flight tests. Use of either the existing aft or added upper lobe outflow valve could be selected from the flight deck. The added valve had its own controller so that each valve was entirely independent of the other. The modified pack control settings were also operable from the flight deck. Figure 6 shows an exterior view of the added outflow valve in the fully closed position. Figure 7 shows the valve from the airplane interior in the fully opened position.

Cabin ventilation flow rates were derived from pressure readings taken from the environmental control system mix manifold. The FAA was responsible for providing and operating the smoke generation equipment, transmissometers, and data acquisition. There were ten transmissometers placed at five locations approximately evenly spaced down the fuselage length. Boeing Commercial Airplanes was responsible for operating the aircraft, for test direction and for video coverage. The video coverage involved a camera at each end of the cabin with a view down the cabin length and an additional mobile camera with a view of the smoke generation area. Boeing was also responsible for a report documenting the airplane modifications and test conditions (reference 9).

GROUND TESTS.

Ten ground tests were performed and their results have previously been analyzed in detail (reference 9). The first four of these tests were checkout tests to verify the independent operation of the two outflow valves and the mix manifold pressures for normal operation and the high flow mode of 215 percent. In these four tests, nonbuoyant theatrical smoke was continuously generated in the middle of the aircraft cabin. Since theatrical smoke tends to move with local ventilation flows, these checkout tests also served to characterize gross cabin ventilation patterns when the forward outflow valve was used instead of the aft valve.

The remaining six ground tests employed the previously discussed buoyant theatrical smoke. Two tests were performed with smoke generation at each of the following locations: forward cabin, middle cabin, and aft cabin. One of the two tests was with pack flow set at 165 percent, while the other had pack flow set at 215 percent. Only when the smoke was generated at the forward location and the forward upper lobe valve used did the smoke remain localized to the generation area. In this case the smoke flowed upwards and out of the valve. In all cases where the lower lobe valve was used, the smoke spread throughout the length of the cabin -- regardless of the smoke generator location. Thus, while figure 3 predicts between 60 and 90 percent of the cabin length should be smoke free, use of buoyant smoke results in ZERO percent being smoke free. These tests demonstrated the effectiveness of an upper lobe outflow valve in removing buoyant smoke.

FLIGHT TESTS.

Nine separate flight tests were conducted with the B757. These tests involved initiation of continuous generation of nonbuoyant smoke while cruising at 20,000 feet. After a period of approximately 2 minutes had elapsed, a rapid descent was initiated. As quickly as possible within airplane performance and air traffic control restraints, the airplane was landed and brought to a stop. Doors were then opened for a simulated passenger evacuation period while smoke generation continued. In total elapsed time, these tests were similar to previously reported accidents (references 1 and 2). Figure 8 shows the type smoke buildup that occurred in these tests.

The first three flight tests involved smoke generation in the forward cabin and simulation of current procedures, Concept A, and Concept B in that order. Even though the airplane was modified only for a Concept A design (with the outflow valve on the top rather than bottom), Concept B was simulated by depressurizing the aircraft when it had descended to 10,000 feet and also increasing cabin ventilation from 165 to 215 percent at this time. Additionally, the ventilation was left on for an additional 2 minutes after the airplane stopped and doors were opened.

When the aft outflow valve was used as per current procedures and smoke generation was at the forward location, smoke filled the entire cabin length during the aircraft descent. However, since the smoke was nonbuoyant, it hugged the floor at the rear of the cabin. In the second and third flight tests where the forward upper lobe outflow valve was used, the smoke flowed up to and out of the outflow valve and was concentrated in the cabin cross section between the smoke generator and the valve. Figure 9 shows the type behavior evidenced in these two tests. An interesting comparison between Concept A and Concept B from these two tests was the smoke behavior when the airplane came to a stop and the aft two doors were opened. In the Concept A test, the cabin ventilation was turned off and the generated smoke remained in the forward cabin. In the Concept B test, the ventilation remained on when the doors were opened and this ventilation air carried the smoke through the cabin length to the rear doors. Figure 10 shows a comparison of the LSF predicted versus actual for these tests.

In two flight tests with the smoke generated in the aft cabin, the LSF for current procedures and Concept A were 77 and 84 percent, respectively. These are comparable to the model predictions of 84 and 88. The other four flight tests involved smoke generation in the mid cabin area. Two used the lower lobe outflow valve, and two used the upper outflow valve. In all four cases the smoke flowed through the cabin filling whichever end had the open outflow valve.

CONCLUSIONS

An upper lobe outflow valve can effectively contain and remove both buoyant and nonbuoyant smoke when the smoke source is in the vicinity of the valve.

A lower lobe valve can effectively contain and remove nonbuoyant smoke when the smoke source is in the vicinity of the valve.

Confined nonbuoyant smoke will migrate through the cabin toward open doors when ventilation air is not turned off.

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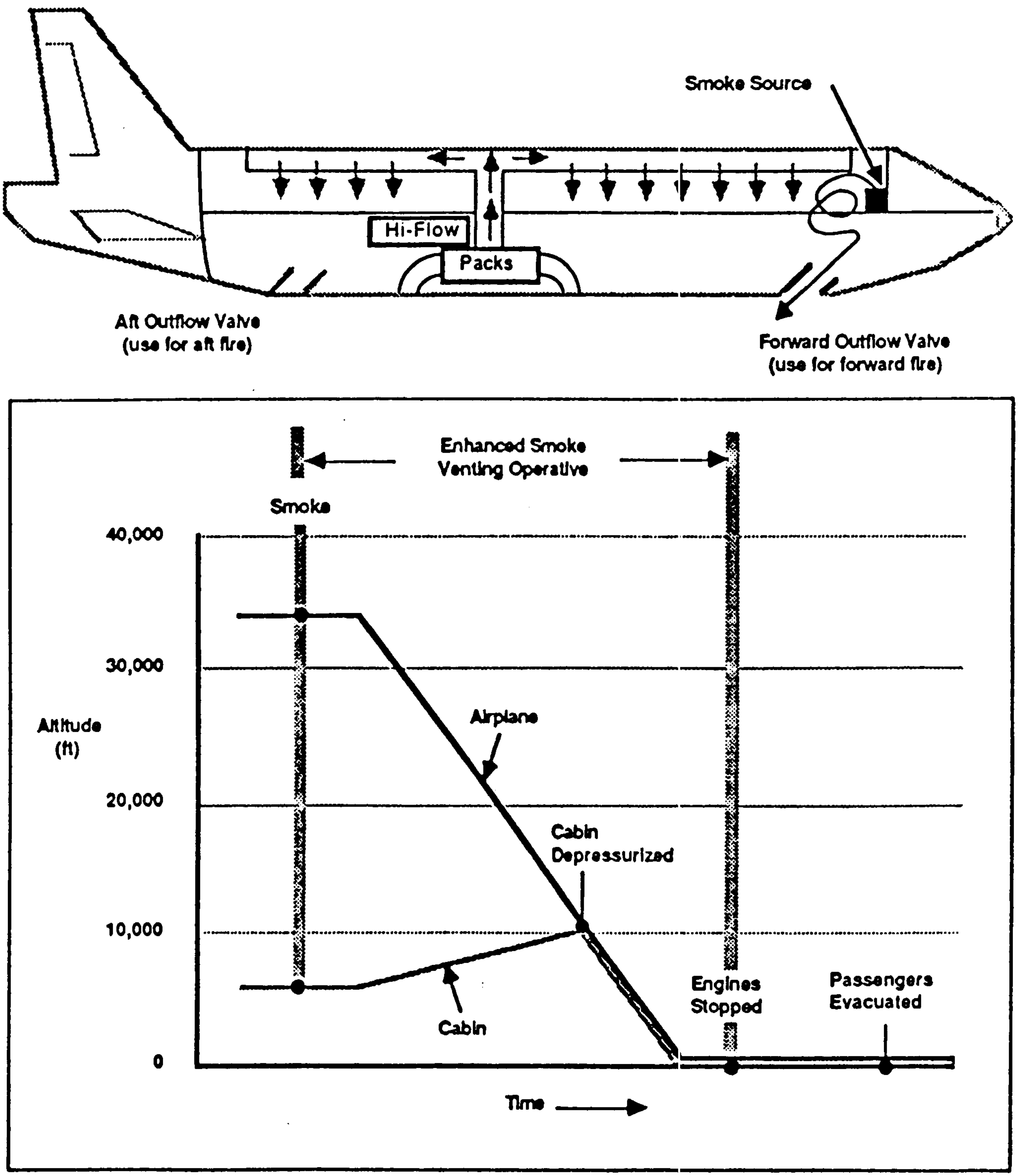

FIGURE 1. CONCEPT A -- PACK HI-FLOW VENTILATION

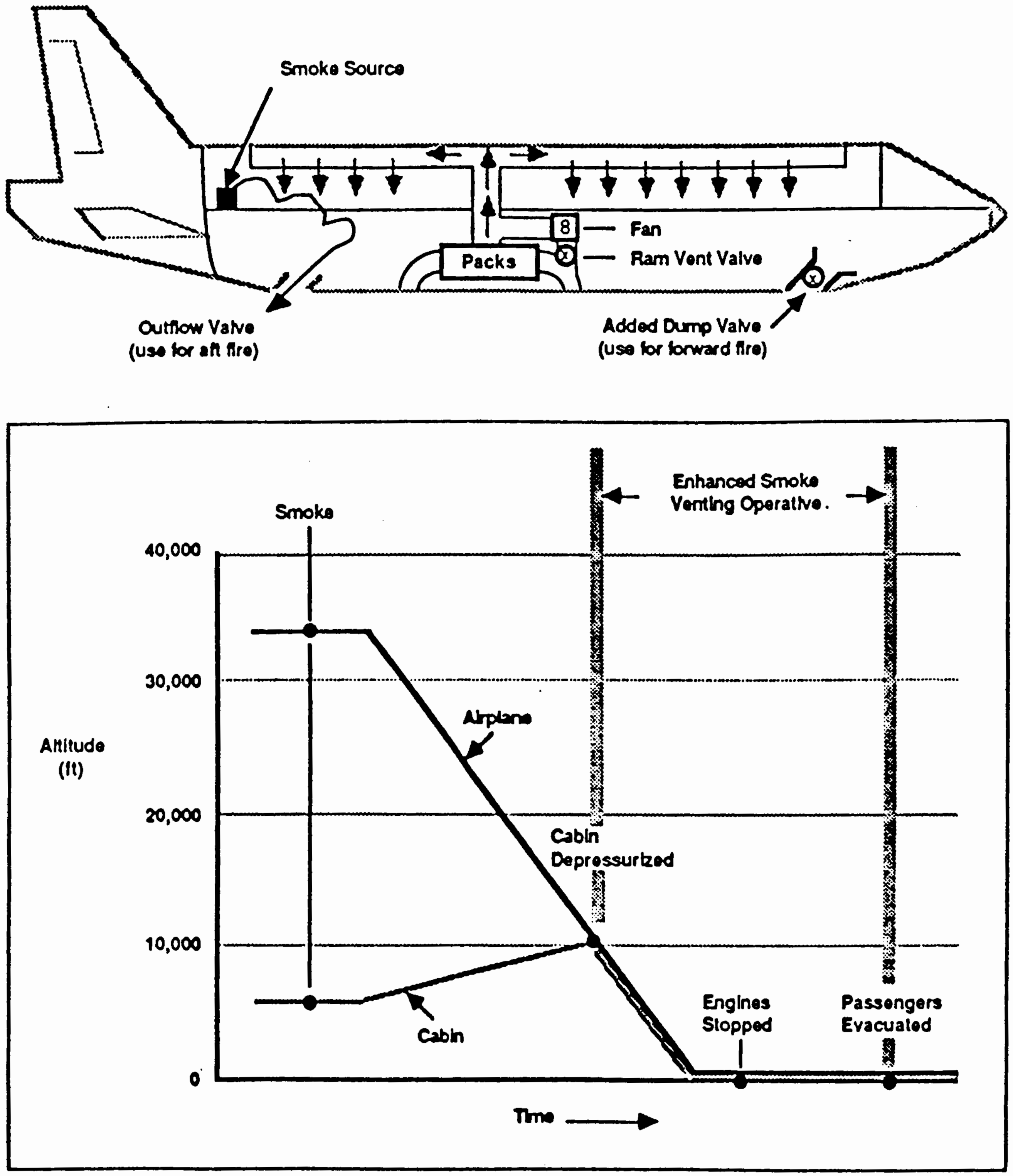

FIGURE 2. CONCEPT B -- RAM VENTILATION

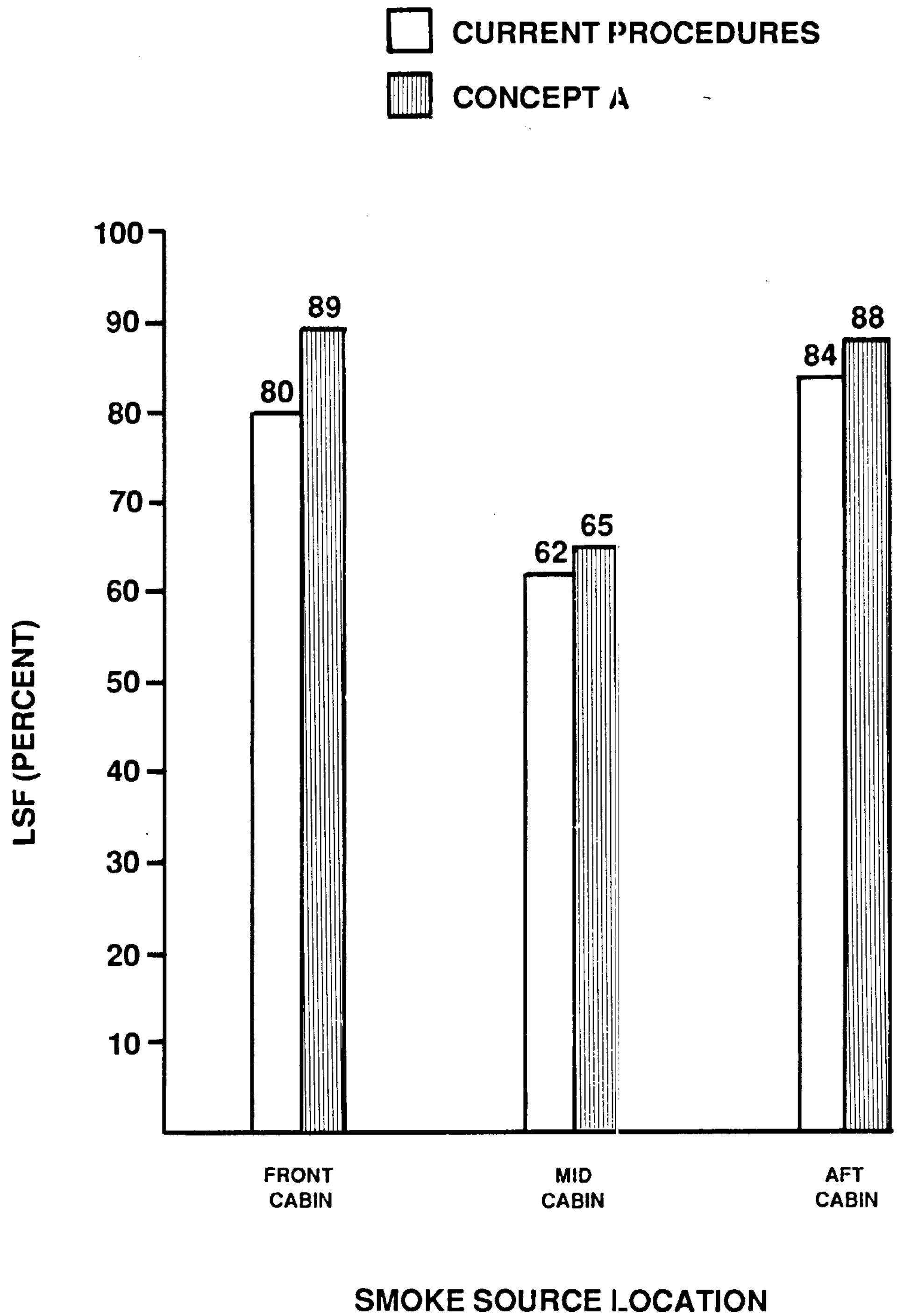

FIGURE 3. PREDICTED LENGTH SMOKE FREE

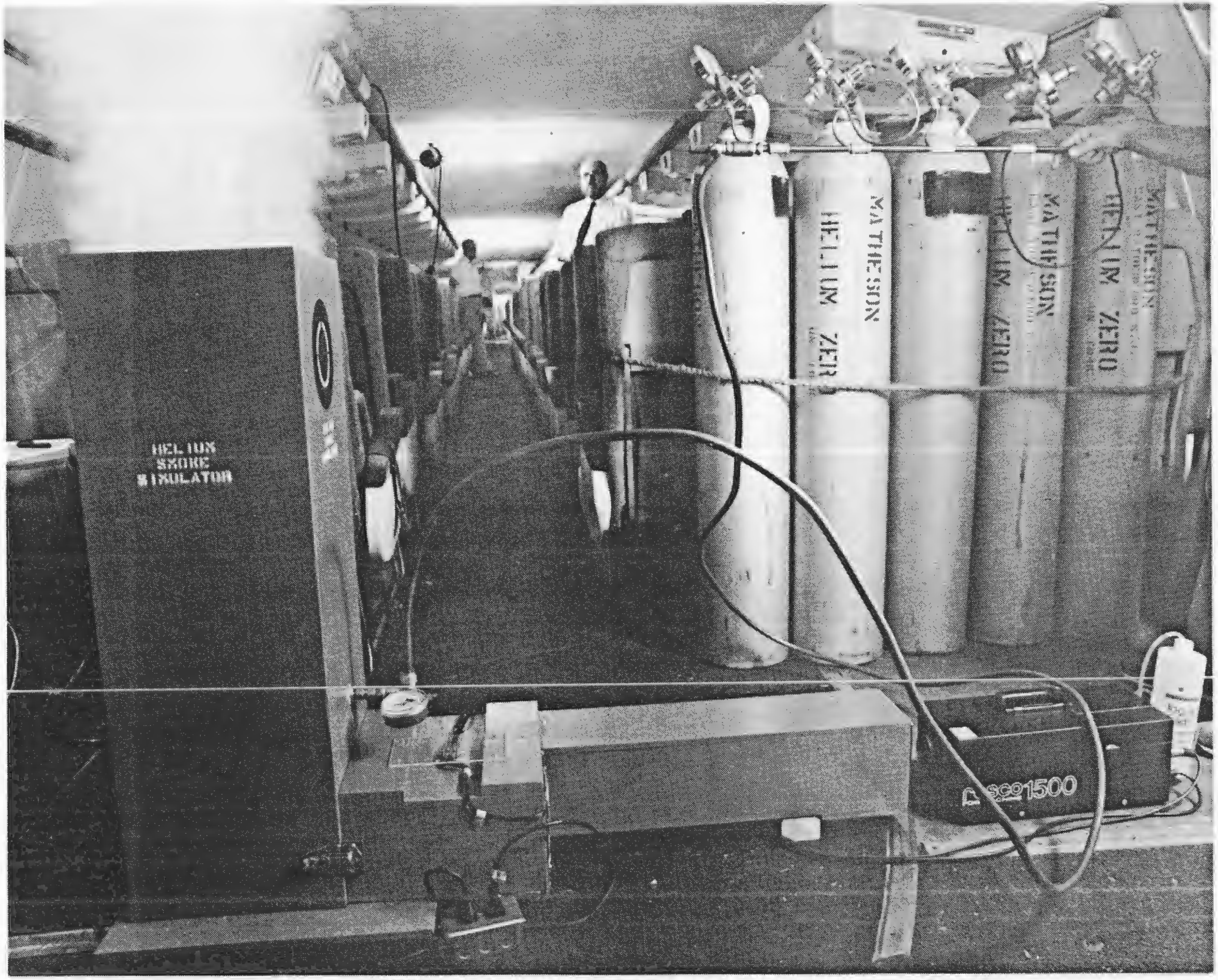

FIGURE 4. BUOYANT SMOKE GENERATOR

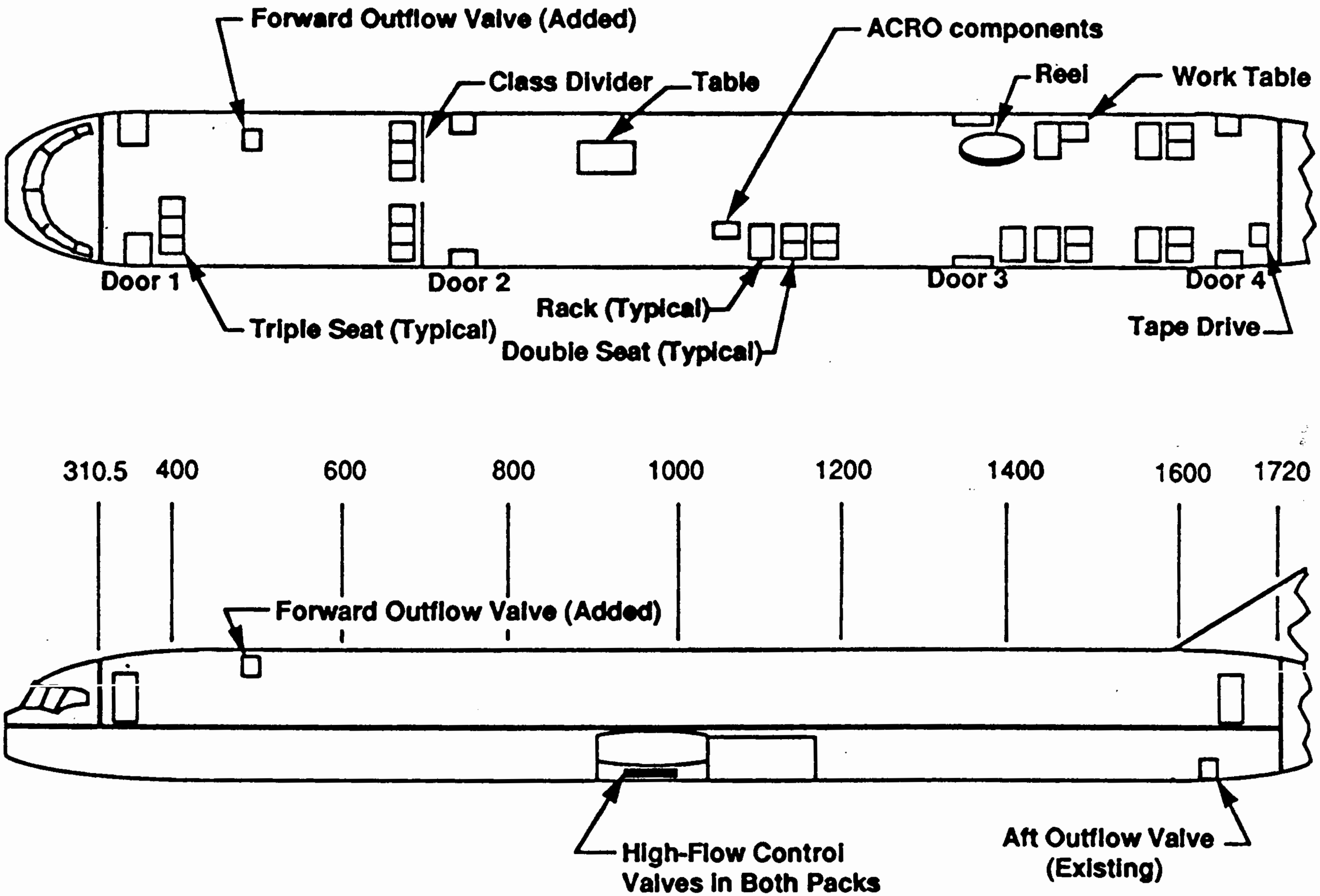

FIGURE 5. AIRPLANE MODIFICATIONS

FIGURE 6. UPPER LOBE OUTFLOW VALVE (EXTERIOR)

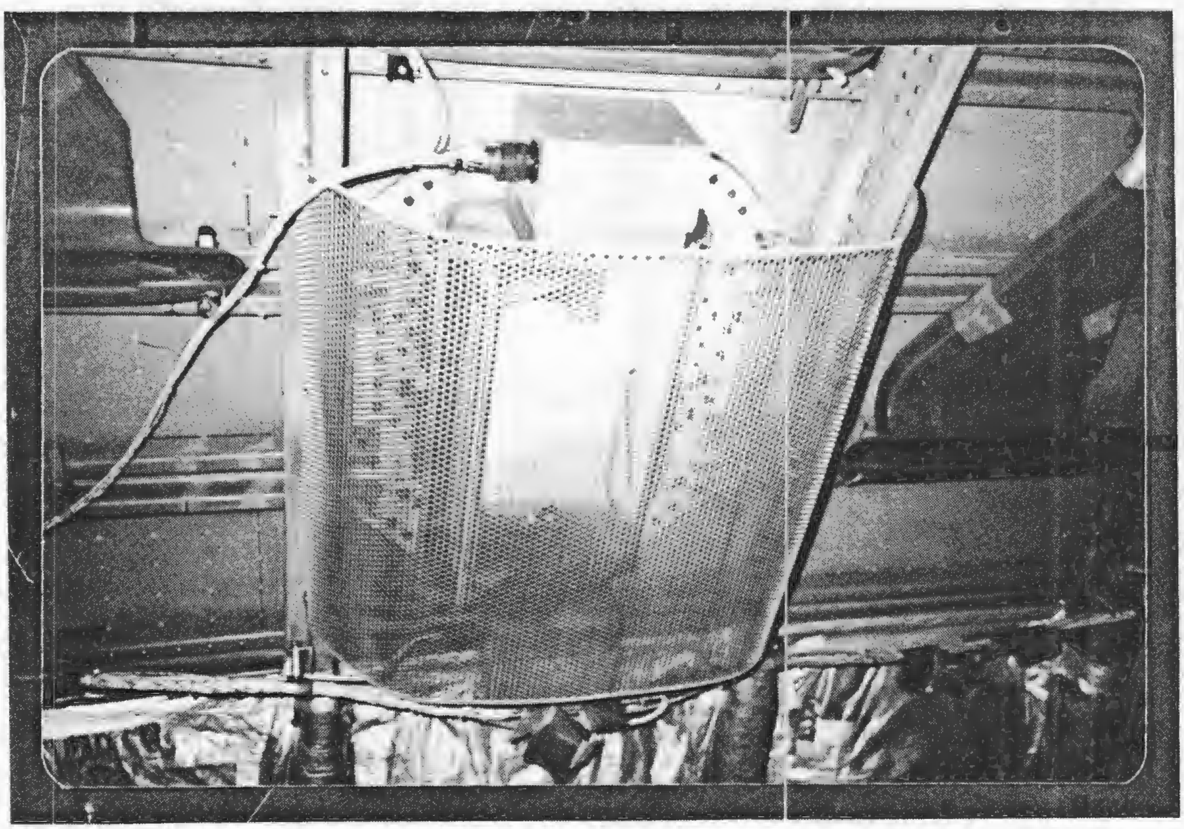

FIGURE 7. UPPER LOBE OUTFLOW VALVE (INTERIOR)

FIGURE 8. TYPICAL CABIN SMOKE

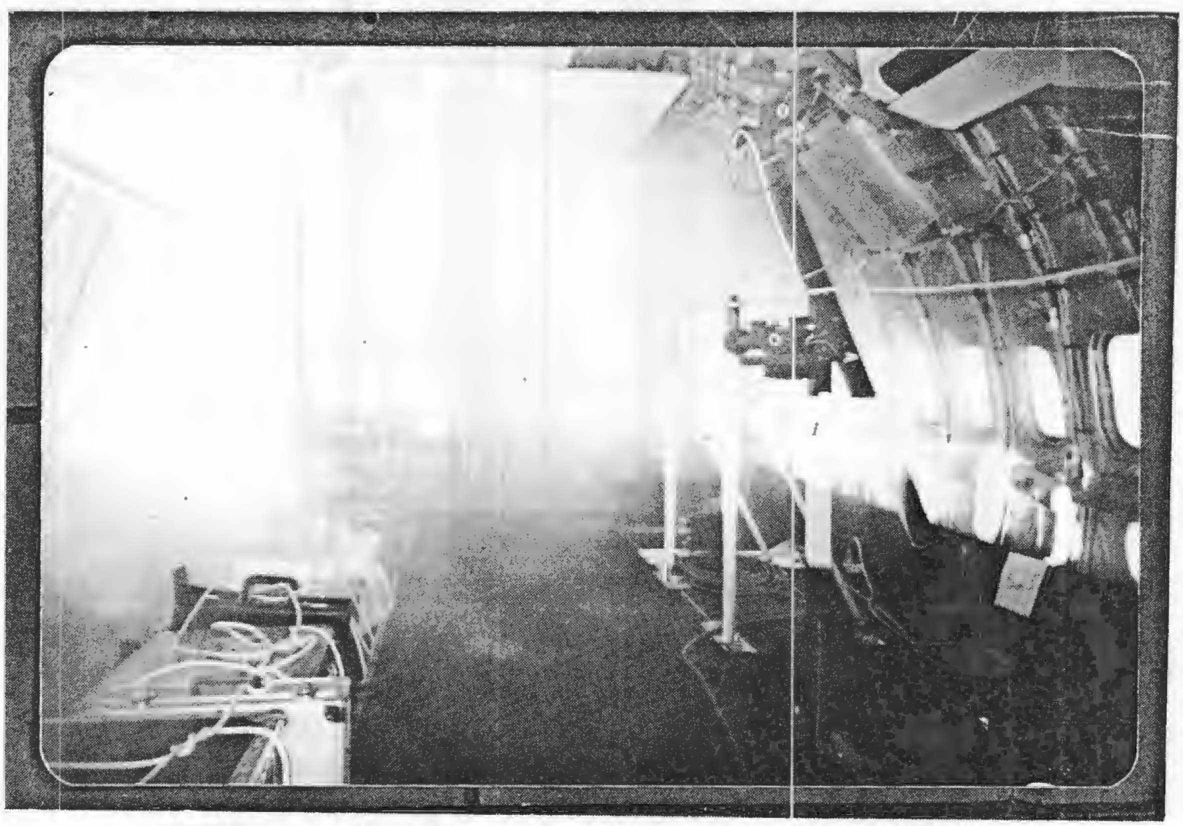

FIGURE 9. FORWARD SMOKE FLOWING TO OUTFLOW VALVE

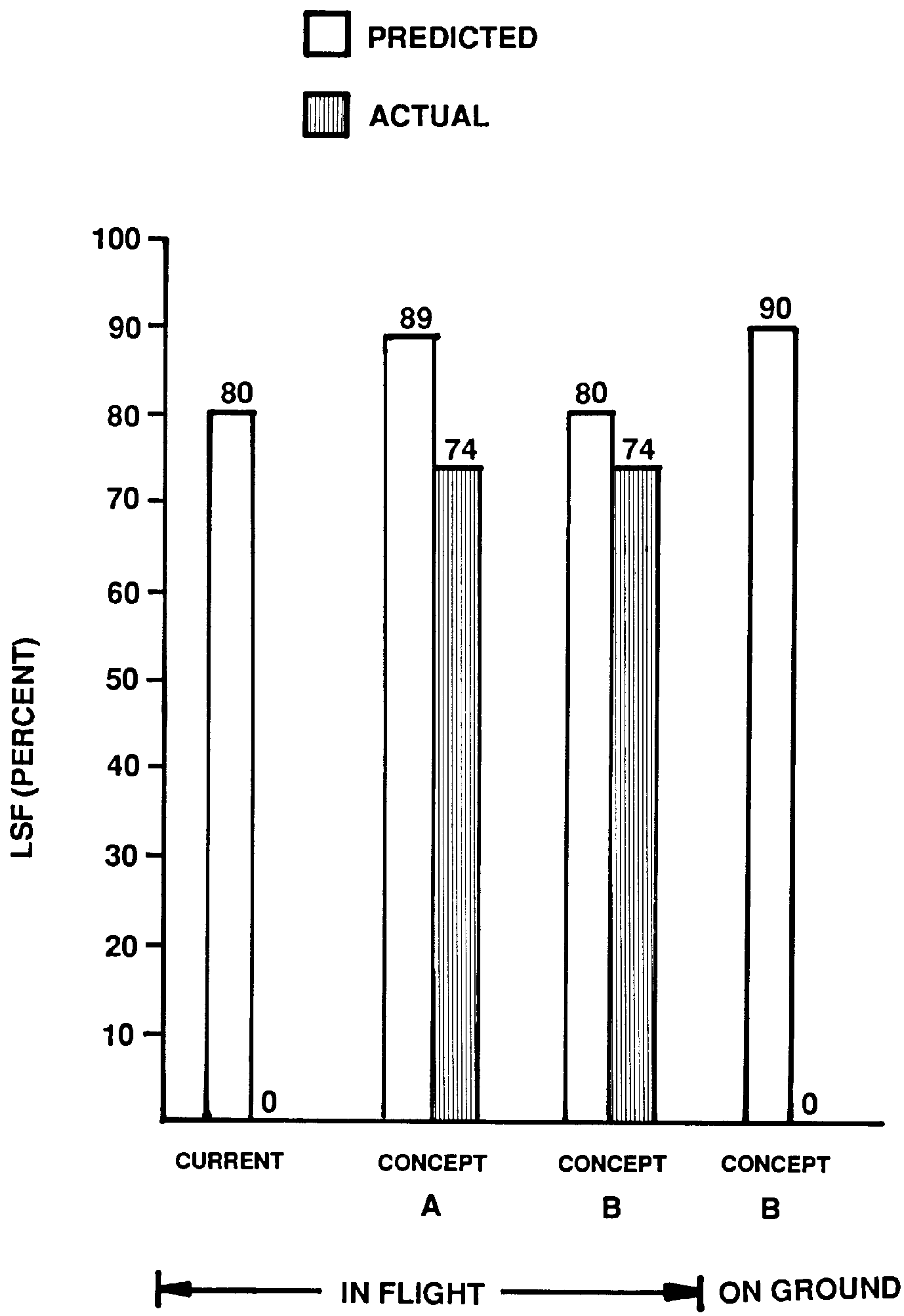

FIGURE 10. PREDICTED VERSUS ACTUAL LSF FOR FORWARD SMOKE GENERATION