DOT/FAA/CT-90/9

FAA Technical Center
Atlantic City International Airport
N.J. 08405

Generation of a Buoyant Plume of Artificial Smoke for Airplane Tests

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September 1990

Final Report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/CT-90/9	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle GENERATION OF BUOYANT PLUME OF ARTIFICIAL SMOKE FOR AIRPLANE TESTS		5. Report Date September 1990
		6. Performing Organization Code
7. Author(s) Thor I. Eklund		8. Performing Organization Report No. DOT/FAA/CT-90/9
9. Performing Organization Name and Address Federal Aviation Administration Technical Center Atlantic City International Airport, NJ 08405		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
		13. Type of Report and Period Covered Final Report
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Technical Center Atlantic City International Airport, NJ 08405		14. Sponsoring Agency Code ACD-240
15. Supplementary Notes		

16. Abstract

A buoyant artificial smoke generator was developed for airplane test applications. In the device, theatrical smoke is mixed with a mixture of helium and air. The total gas flow, the helium to air ratio, and the theatrical smoke particulate generation rate can all be varied in the device. A gas mixture of 50 percent each of helium and air has the buoyancy properties of air, alone, heated to 475 degrees Fahrenheit. The device was used in cabin smoke evacuation tests in a modified Boeing 757 aircraft. Generation of the buoyant smoke in an aircraft resulted in dramatically different behavior from that previously observed with nonbuoyant theatrical smoke. The buoyant smoke spread further through the aircraft in a manner that was not predicted by an analytical model on cabin smoke spread. Besides being used to assess airplane cabin smoke evacuation capability, the buoyant smoke generator has been used to evaluate smoke detector performance and optimal location in Air Force jet aircraft.

17. Key Words Smoke, Fire Smoke Evacuation In-Flight Fire Helium Buoyant		18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 24	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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EXECUTIVE SUMMARY

Smoke evacuation and penetration tests aboard aircraft typically involve artificial smokes with minimal buoyant properties. The smoke source is often a theatrical smoke machine that projects a jet of fine aerosol droplets into the surrounding air. Because the cumulative volume displaced by all the individual aerosol drops is small, these artificial smokes do not simulate the gaseous volumetric expansion processes that occur during actual fires.

In order to provide a smoke with more realistic behavior for airplane tests, a device was developed that mixes helium, air and theatrical smoke to generate a rising plume that behaves similarly to a fire plume. The helium and air can be mixed in various proportions to yield mixtures that have a range of densities that can simulate the densities of hot combustion products. The total mixture delivery rate can be varied to simulate different fire sizes. The addition of helium not only provides for buoyancy but also provides the simulation of gaseous expansion. The theatrical smoke content of the mixture allows for observation of smoke movement behavior. The aerosol content further allows this buoyant smoke generator to be used for realistic tests of smoke detector installations.

The buoyant smoke generator was tested aboard a Boeing 757-200 aircraft. This aircraft was specially modified to provide for varying cabin ventilation flow rates. A provision was also incorporated in this aircraft for exhausting cabin ventilation air out of the top of the fuselage as an alternate to the standard outflow valve on the bottom of the aircraft.

The tests with buoyant artificial smoke showed smoke movement behavior entirely different from what had been seen in past testing. Under normal airplane ventilation conditions, the buoyant smoke will rise to the ceiling, move down the length of the cabin, and gradually mix with ventilation flow so that smoke fills the height of the cabin. Test results were compared with earlier analytical predictions of smoke movement. The predictions were demonstrated as incorrect when applied to the behavior of a buoyant smoke source.

INTRODUCTION

PURPOSE.

Theatrical smoke is commonly used to test smoke detectors and smoke control design features in aircraft. In contrast to hot smoke plumes from burning materials, theatrical smoke generators provide smoke plumes at relatively low temperatures which means they are not very buoyant. Furthermore, theatrical smoke plumes of themselves cannot simulate the volumetric gas expansion effects associated with combustion. In order to overcome these shortcomings, a device was developed to generate a buoyant mixture of helium and air as a carrier gas for the theatrical smoke.

BACKGROUND.

In some past aircraft accidents resulting from in-flight fires, smoke has spread throughout the aircraft cabin (references 1 and 2). These accidents indicate that current procedures and present aircraft cabin ventilation systems may not be able to prevent or eliminate this widespread smoke transport unless the fire is first extinguished. Even in that instance, the smoke is removed by gradual dilution as fresh air is pumped into the cabin. Since fresh air exchange rates are once every 3 to 5 minutes, the dilution process can be expected to take 10 to 15 minutes for substantial smoke clearing.

Smoke control to a great extent is determined by the aircraft ventilation system. Compressor bleed air from the engines is passed through heat exchangers and air cycle machines to the right conditions for cabin pressurization and ventilation. The air enters the cabin from overhead and/or sidewall distribution ducts through various nozzles that are designed to project the air into the cabin dynamically for passenger comfort. The air exits the cabin through grills at the base of the cabin sidewalls. The air exits the fuselage hull principally through an outflow valve to the rear of the aircraft and below the cabin floor. The overall air flow in the cabin is from ceiling to floor and tends to flow rearward in the cabin.

Two conceptual approaches were evaluated for improving smoke evacuation capability through ventilation system changes (reference 3). One approach added a capability for pumping ram air into the cabin, and the other involved upgrading the existing bleed air system to accommodate more airflow. Both involved an additional lower lobe outflow valve in the forward part of the aircraft. The motivation for the additional outflow valve was the potential for localizing smoke at the source by using the nearest outflow valve to the fire source. To evaluate the relative effectiveness of the two smoke evacuation approaches, a simplified cabin smoke spread model was developed. This model indicated that neither approach offered any significant improvement over current aircraft ventilation systems.

Initial expectations were that one of the two system changes would result in a definable improvement over current systems. Had this been so, a prototype of the best system would have been installed in an aircraft to experimentally verify the predicted improvement. The experiments would involve continuous theatrical smoke generation at various points in the aircraft cabin during level cruise flight. The predictions of the smoke spread model did not justify selection of either approach for flight testing.

The smoke spread model did not include buoyancy effects. With the assumption that a buoyant smoke source could be developed, the airplane modification approach was reworked so that the additional outflow valve would be installed on the upper lobe of the aircraft rather than the lower lobe. Prototype system installations were designed, fabricated, and tested on an experimental B757 (reference 4). The development criteria for the buoyant smoke source were based on the systems evaluation study scenarios (reference 3) and findings from related fire test work (references 5 and 6).

OBJECTIVE.

The objective was to design, fabricate, and evaluate a generator of buoyant theatrical smoke for use in aircraft testing of cabin smoke evacuation capability. A secondary objective was to determine the suitability for testing aircraft onboard smoke detectors.

GENERATOR DEVELOPMENT

DESIGN REQUIREMENTS.

One of the theatrical smoke generators extensively used for aircraft smoke tests is the Rosco Smoke Machine (Model PRO 1500). The planned approach for imparting buoyancy to the theatrical smoke was to devise a way of mixing the smoke with helium. The low atomic weight of helium makes it much less dense than air at equivalent temperatures and pressures. Thus, a plume of pure helium could be expected to rise and flow somewhat like the low density, hot gases from a fire plume.

The amount of gas to be generated was based on the scenarios in the systems evaluation study. These scenarios assumed a smoke source that produced 200 cubic feet per minute (cfm) of particulate laden gas. In a fire, air is entrained into the combustion zone, and the air's oxygen content reacts with fuel to release energy. This energy heats the combustion products along with inert components to form a gas mixture that is less dense but makes up more volume than the entrained air. Furthermore, the mass ratio of air to fuel will be around 10 so that the mass addition of fuel can be ignored to first approximation. Thus, the volumetric expansion effects of fire can be simplified and treated as heating of air that passes through the combustion zone. When the hot gas plume flows against walls and ceilings, some heat will be lost and the gas will correspondingly contract somewhat. The density of this partially cooled gas will give the volumetric smoke addition if the mass flow of air into the fire plume is known. The target density for the buoyant theatrical smoke was density derived from partially cooled ceiling layers in related fire tests.

In efforts parallel to the airplane systems evaluation, fire tests were done on one-quarter and one-half scale aircraft cabin mockups (references 5 and 6). These tests involved ceiling-to-floor ventilation patterns with air change times comparable to those found in aircraft. Ventilation rates and fire sizes were varied to determine effects on the cabin interior environment. Because the fires of interest were those that would not be immediately destructive for an aircraft, all tests were done with fires small enough that ceiling layer temperatures did not reach 500 ^{o}F over a 10-minute test. A major finding from these tests was that approximately 80 percent of the heat released in the combustion zone was absorbed by the ceiling and upper cabin walls. Only 20 percent or less was exhausted at the floor grill location in the form of heated exhaust gas. In order to be able to relate the artificial smoke generation to these fire tests, the density of the artificial smoke was targeted to be equivalent to air heated to between 400 and 500 °F. To get this density, it was evident that helium would have to be diluted with air.

This 200-cfm smoke production rate from a fire that loses 80 percent of its heat to the enclosure linings can be used to estimate the fire source that is represented. Using the simplified view of the fire as heating of entrained air, the equivalent fire heat release rate for this smoke source can be defined as follows:

$$Q = 5V_2 d_1 (T_1/T_2) C_p (T_2 - T_1) \qquad (1)$$

In this equation, Q is the fire's energy release rate, V is the volumetric production of gas, d is density, C_p is heat capacity, T is absolute temperature, and subscripts 1 and 2 refer to ambient and plume thermal conditions, respectively. The factor of 5 in the equation compensates for an assumed 80 percent of plume heat being lost to the enclosure lining materials. Using values of 475 °F for the heated gas and 72 °F for ambient, the 200-cfm smoke source is representative of a fire heat release rate of 246,000 Btu/hr. For comparison, the 2-gallon-per-hour oil burner used in cargo compartment liner tests (reference 7) theoretically has a heat output of 250,000 Btu/hr. This indicates that a 200-cfm buoyant smoke source represents a significant fire source.

The final question associated with gas mixture requirements involves the ratio of helium to air that is needed to simulate heated air at a specific temperature. This can be derived from use of the perfect gas law with mixtures.

$$(1-x)d_A + (x)d_H = d_2 \qquad (2)$$

The subscripts A and H refer to air and helium at ambient temperature and x is the mole fraction of helium in the mixture. Equation 2 can be restated as

$$p_A/R_A T_1 + p_H/R_H T_1 = p_1/R_A T_2 \qquad (3)$$

where R refers to the gas constants for air and helium respectively. This can be rearranged to form

$$p_H/p_1 = (R_H/R_A)(T_1/T_2 - p_A/p_1) \qquad (4)$$

The latter pressure ratio can be substituted by the following form of the law of partial pressures:

$$p_A/p_1 = 1 - p_H/p_1 \qquad (5)$$

Equation 4 can then be manipulated to form

$$p_H/p_1 = (1 - T_1/T_2)R_H/(R_H - R_A) \qquad (6)$$

The ratio of the partial pressure of helium to the ambient pressure is identical to the ratio of the volume of helium to the volume of the helium air mixture. Using degrees Rankine (^{o}R) as the temperature unit, equation 6 can be written as follows:

$$V_H/V = 1.16(1 - T_1/T_2) \qquad (7)$$

Figure 1 shows a plot of volume fraction of helium mixtures that would have the same density at 72 ^{o}F that heated air would over a range of temperatures. A mixture of 50 percent helium by volume in air has the same density as air heated to 475 ^{o}F (935 ^{o}R).

DEVICE DESCRIPTION.

Figure 2 shows a schematic of the device in its original configuration (Patent Application Serial No. 371,883, filed June 27, 1989). Air is supplied through two horizontal ducts running into the base of the mixing chamber (chimney). These ducts are each 5 inches square. The left duct is 1 foot in length while the right is 3 feet long. The two muffin fans are powered through a speed control transformer so that air delivery rate can be adjusted. Theatrical smoke is injected into the longer duct to allow adequate mixing with air so that the jet of aerosol from the smoke generator will not impinge and collect on the mixing chamber walls. Detail A of figure 2 shows the 8-inch-diameter ring that distributes the helium to the mixing chamber. The ring is mounted horizontally in the mixing chamber (i.e., the axis through the ring is vertical), and the inner circumference of the ring has 12 holes drilled with a 5/32-inch bit. The regulator pressure from helium supply bottles is adjusted to get the desired helium flow rate. Earlier attempts to place the ring drill holes on the upper or lower faces of the delivery ring were unsuccessful due to jet pump effects in the mixing chamber resulting from that configuration. The mixing chamber itself is 1 foot square and 3 feet high. At the outlet on the top is a 1.5-inch-thick piece of reticulated foam (Type I polyester safety foam manufactured by Scott Paper Company). This foam causes a small pressure drop from the mixing chamber to the outside such that the smoke mixture is uniform across the exit plane. Tests without the foam evidenced exit flows that were highly asymmetrical.

To get a mixture that was 50 percent each of helium and air, the following procedure was used: A hand-held velometer was placed at the chamber exit, and the air flow was adjusted until a velocity of 100 feet per minute was attained. This was done with the helium supply turned off. Once this setting was achieved, the fan speed controller was left at the set position, and the helium supply was turned on. The helium bottle regulator pressure was increased until a hand-held oxygen analyzer at the mixing chamber exit indicated an oxygen content of approximately 10.5 percent. In routine use, the same mixture and flow rate could be attained by setting the speed control and the helium pressure at the gage on the chamber face to the calibration values.

Figure 3 shows the device in operation in a B707 test fuselage. The view is from the aft end of the aircraft cabin looking forward along the center aisle. The buoyant theatrical smoke is shown flowing out of the top of the mixing device. At the lower right is the Rosco smoke machine. Also to the right are five ganged helium bottles which provide about 10 minutes operation at the 200-cfm total delivery rate. At the time the photograph was taken, the smoke had spread above hatrack level all the way to the cockpit. This is evidenced by the scattered light halo around each of two floodlights located above the hatrack level. Each light is located just forward of each of the two individuals stationed along the aisle.

For the tests reported here, the Rosco Pro 1500 smoke machine was operated at a setting of two. This setting resulted in adequate smoke for smoke movement observations, and it was low enough that the machine did not cycle on and off as it characteristically does at higher settings (reference 8).

AIRPLANE TESTS

TEST PLAN.

The B757 smoke evacuation test plan included ten ground tests and nine flight tests (reference 4). Four of the ground tests employed the Rosco Pro 1500 without the use of helium. These tests were primarily directed at testing aircraft and data collection systems, but they do offer a basis for comparison with buoyant smoke. Six of the ground tests employed the helium mixing device, and those tests are the major focus of the test discussion of this report. Figure 4 shows a schematic of the test aircraft and shows design changes and aircraft station numbers. There were two design changes: The flow control valves that regulate the cabin air supply from the engine compressors were both modified and rescheduled to provide three flow settings. They were (1) the 100 percent that is used normally when cabin air recirculation fans are in operation, (2) the available 165 percent for use when recirculation fans are out of operation, and (3) the 215 percent setting that is not available on production aircraft. The other design change was the installation of a B737 production pressure-controlling outflow valve on the starboard side of the B757 at station 490 at roughly the 2 o'clock position looking forward.

The three flow settings have to be put in perspective with regard to actual aircraft operations. In a normal takeoff configuration, the air pack settings will be 100 percent and both recirculation fans will be on. The combined fresh and recirculated air amount to a delivery rate of 300 pounds per minute. Emergency procedures for cabin smoke evacuation in the B757 call for shutting off both recirculation fans. At the 100 percent pack setting, this would result in the delivery rate dropping to 142 pounds per minute. However, when the recirculation fans are turned off, as per emergency procedures, the packs automatically go to 165 percent. At sea level takeoff conditions, the 165 percent setting gives 234 pounds per minute air supply. The 215 percent pack setting provides 307 pounds per minute, which is virtually the same as the total fresh and recirculated flow under normal airplane operations. The test pack settings of 165 and 215 percent provide a capability of determining whether increased airflow affects smoke removal.

The three smoke generation locations for these tests were adjacent to the port sidewall at stations 465, 1030, and 1664. These stations are at the forward, middle, and aft locations in the passenger cabin. Two smokemeters were mounted at each of five stations along the fuselage. The station positions were 560, 800, 1030, 1270, and 1530. Thus, the smokemeter stands were spaced at approximately 20-foot intervals along the cabin length. The top smokemeter was

66 inches above the floor, and the bottom meter was 43 inches above the floor. Figure 5 shows a schematic of the type smokemeter used in these tests. The smokemeter signals were processed in an ACRO 900 data acquisition system and stored on a Zenith 181 lap-top computer. Besides manual notes recorded by test participants, further documentation was gathered in the form of video coverage from three video cameras. A camera was mounted at each end of the cabin with a view down the length of the fuselage. The third camera was on a tripod which was moved with the smoke generator to get coverage of smoke behavior at the generation location.

The air delivery rate to the cabin was monitored through observation of the pressure in the aircraft mix manifold. Air from the left and right packs along with recirculated air from two fans are brought together in this manifold before flowing to the cabin distribution ducts.

Table 1 shows the test conditions for the ten ground tests. In tests 1 through 4, the test duration was planned to last until the smoke spatially stabilized but no longer than 10 minutes each. Tests 14, 16, and 18 were to be conducted with air packs in operation until smoke spatial stabilization or 10 minutes. At that time the packs would be turned off and two aircraft doors opened. Smoke generation would then continue for 2 more minutes. These three tests would have aspects of a smoke-filled aircraft landing using current procedures and systems. The 2 minutes of added smoke generation with doors open are somewhat representative of a period for passenger evacuation. These three tests (14, 16, and 18) employed helium for buoyancy, had the 165 percent pack flow setting, used the lower lobe rear outflow valve, and had recirculation fans turned off.

Tests 15, 17, and 19 were planned to include aspects of the two design change concepts and also to include helium for buoyancy. The air pack flow setting was 215 percent, the recirculation fans were off, and the outflow valve nearest the smoke source was open while the other was closed. These tests were to be conducted with air packs in operation until smoke stabilization or 10 minutes. At that time two doors would be opened, but the packs would be left on and smoke generation would continue. After 2 minutes in the doors open and pack on mode, the packs would be turned off, but smoke generation would continue for another 2 minutes. These tests might show if continued cabin ventilation during passenger evacuation was of any benefit.

The smoke movement observations in these ground tests could change in flight due to one major factor. In the ground tests the pressure differential across the fuselage hull was too negligible to cause significant leakage. Thus, all the airflow leaves the airplane through the outflow valves. For example, use of the rear outflow valve in the 165 percent pack setting mode with recirculation fans off would result in all air distributed to the front half of the cabin moving axially in the fuselage from front to rear. This same condition in pressurized flight would have a smaller axial velocity component because air would leave the fuselage not only through the outflow valve but also by means of numerous leakage points such as door seals on the main deck and in the cargo compartments.

TABLE 1. TEST CONDITIONS

	AIRPLANE VENTILATION			SMOKE GENERATION		
TEST NO.	OUTFLOW VALVE	RECIRC FANS	PACK FLOW (%)	STATION LOCATION	BUOYANT	CABIN DOORS USED
1	AFT	ON	100	1030	NO	NONE
2	FWD	ON	100	1030	NO	NONE
3	AFT	OFF	215	1030	NO	NONE
4	FWD	OFF	215	1030	NO	NONE
14	AFT	OFF	165	465	YES	4L,4R
15	FWD	OFF	215	465	YES	4L,4R
16	AFT	OFF	165	1664	YES	1L,1R
17	AFT	OFF	215	1664	YES	1L,1R
18	AFT	OFF	165	1030	YES	1L,1R
19	AFT	OFF	215	1030	YES	1L,1R

NONBUOYANT TEST RESULTS.

In tests 1 through 4, smoke was generated without helium with the smoke machine located at station 1030 for all four tests. In all these tests, the smoke moved with the flow of ventilation air in the cabin. Test 1 had the air pack flow setting at 100 percent and both recirculation fans on. Since recirculated air makes up approximately half of the cabin air delivered, roughly half the air outflow from the cabin went to the recirculation fans in the front while the rest went to the lower lobe outflow valve in the rear. The net effect was a negligible cabin axial flow at the smoke generation point with the result that the smoke produced remained confined to the area between stations 850 and 1300.

In test 2, the pack setting was at 100 percent and both recirculation fans were on. However, the upper lobe outflow valve was used instead of the lower lobe valve. Since all cabin airflow sinks were in the front half of the aircraft, all the smoke flowed to the front of the aircraft where it could exit through the outflow valve or through the floor grills. No smoke flowed in the aft direction.

For tests 3 and 4, the recirculation fans were turned off and the pack setting was 215 percent. In test 3, the rear outflow valve was used with the result that the smoke spread rapidly to the rear of the aircraft. The axial flow was strong enough to tilt the smoke plume from the smoke machine rearward. No smoke flowed forward.

In test 4, the forward upper lobe outflow was used with the result that the smoke spread to the forward cabin and exited through the outflow valve. No smoke moved rearward in this test.

Because the theatrical smoke flowed with the ventilation air, strong three-dimensional effects were observed in these tests due to the placement of the smoke generator against the port cabin wall. The most dramatic example was in test 3 where the ceiling ventilation jets blocked the theatrical smoke from moving across the cabin to the starboard side. The effects of the ventilation jets coupled with the axial flow in the cabin caused the smoke to move rearward in a spiral fashion along the port side.

The results of these tests can be compared with the predictions from the non-buoyant model developed earlier (reference 3). That model predicted the smoke would remain localized at the center of the cabin with current procedures and also with the 215 percent air pack setting; and in both cases, between 62 and 65 percent of the cabin length would be free of smoke. In tests 3 and 4, the smoke moved from the midpoint to either the back or front end of the fuselage; and in both cases, 50 percent of the fuselage remained smoke free. In test 1 where the smoke did remain localized, the smoke free fraction of the fuselage was 68 percent. However, because the recirculation fans were on in test 1, the test cannot be considered representative of current procedures.

BUOYANT TEST RESULTS.

Tests 14, 16, and 18 employed the 200-cfm buoyant smoke and were identical except for smoke generator location (forward, aft, and mid fuselage, respectively. Because the recirculation fans were off and the aft outflow valve was used, the average rearward fuselage axial flow at the 165 percent pack setting would be approximately 15 feet per minute or 0.25 feet per second. This would range from near zero at the front of the cabin to nearly 0.5 feet per second at the back.

Unlike the results of tests 1 through 4 where the smoke followed the ventilation air, the buoyant smoke in tests 14, 16, and 18 travelled along the fuselage at speeds and directions relatively unaffected by the axial ventilation flow velocities. Also in contrast was the two-dimensional behavior of the buoyant smoke. Even though the buoyant smoke generator was adjacent to the port cabin wall, the rising smoke plume quickly spread laterally across the cabin. At a given time, the overall cabin smoke pattern or density varied longitudinally along the cabin length and vertically--but not laterally--across the cabin.

These three tests involved generating smoke with the airplane ventilation system turned on for 5 minutes, 20 seconds; 6 minutes, 18 seconds; and 6 minutes, 15 seconds, respectively. At that time the ventilation was turned off in each test, and two doors were opened for an additional 2 minutes of continued smoke generation (simulated passenger evacuation period). For all three tests, the following observations applied:

1. The smoke remained stratified in the vicinity of the smoke generator.

2. As the smoke moved along the ceiling, the ceiling ventilation jets caused mixing, so that the smoke became more homogenous from floor to ceiling as the distance from the smoke generation point increased.

3. By about 5 minutes, floor levels throughout the aircraft were hazy.

4. Conditions in the cabin stayed the same or became slightly worse during the 2-minute period when the ventilation was turned off.

An important number to derive from these tests is the rate the ceiling smoke layer moved along the aircraft. Figure 6 shows the signal traces at the top smokemeters at stations 1530 and 800 during test 16. Since the smoke took 62 seconds to travel 61 feet, the smoke movement rate from rear to front between the two stations was 0.98 feet per second. Visual observation during the same test showed the smoke reaching station 800 at 85 seconds after smoke generation started at station 1664. This indicates a movement rate of 0.85 feet per second. In test 18, manual notes indicate that the smoke reached station 700 at 30 seconds after the start of smoke generation at station 1030. This indicates a movement of 0.92 feet per second. Thus, the forward smoke layer progression speed in these tests can be approximated at 0.9 feet per second.

Data like that on figure 6 can be analyzed for the rearward smoke movement in test 14. The data indicate that the smoke traveled from the smokemeters at station 800 to those at 1530 in 52 seconds. This gives a movement rate of 1.2 feet per second when the smoke is moving with the axial flow rather than against it. Doing the analysis at station 1030 instead of 800 leads to an indicated movement rate of 2 feet per second. Thus, the rearward smoke movement is somewhere in the vicinity of 1.5 feet per second.

If the average rearward ventilation velocity were 0.3 feet per second, a smoke movement velocity of 1.2 feet per second in still air would become 0.9 feet per second in the forward direction or 1.5 feet per second in the rearward direction. The relative sizes of these numbers are significant in identifying the type axial velocities needed for smoke control. It is further important to note that a more buoyant (or hotter) smoke would have a higher velocity in still air than the smoke that is the object of this discussion.

Tests 15, 17, and 19 all had the ventilation setting of 215 percent and therefore should have had axial cabin flow 30 percent higher than the tests at the 165 percent setting. Test 15 had buoyant smoke production in the forward part of the cabin and employed the forward upper lobe outflow valve. In this test the smoke was confined to the cabin front and exited the outflow valve without spreading throughout the cabin length. However, when the ventilation was left on and the aft cabin doors opened, the smoke moved from the front to the aft cabin with smoke throughout within a 2-minute period. The ventilation was then turned off and smoke generation continued for 2 more minutes. There was no substantive change in cabin conditions in this latter period.

Test 17 involved smoke generation in the aft cabin and used the lower lobe outflow valve. Although the smoke did spread throughout the cabin in this test, the smoke in the forward cabin remained extremely thin until the forward passenger doors were opened at 6 minutes into the test. At that point the smoke from the rear of the cabin moved forward and substantially lowered visibility at all points in the cabin ahead of station 800. When the ventilation was shut off 2 minutes later and smoke generation continued, visibility conditions in the forward cabin continued to remain poor.

Figures 7 and 8 compare the light transmission at the smokemeter location closest to the smoke source for tests 15 and 17. The period of smoke generation prior to opening the cabin doors was 3 minutes and 2 seconds for test 15 and 6 minutes for test 17. In test 15, the continuous venting through the upper lobe outflow valve resulted in very little smoke obscuration in that area of the cabin. The upper and lower smokemeters at station 560 were averaging 94 and 97 percent transmission, respectively. At 3 minutes into test 17, the upper and lower smokemeters at station 1530 were averaging 77 and 93 percent transmission, respectively. In test 17 the buoyant smoke could not exit at the ceiling. Thus, the smoke could move only longitudinally along the fuselage ceiling or downward as it was mixed by the ceiling ventilation jets.

Test 19 involved smoke generation in the mid cabin and use of the aft outflow valve. The results of this test were very similar to test 17 with smoke flowing forward when the forward doors were opened and visibility remaining poor during the 2-minute period following ventilation shutoff. However, the smoke spread faster and with more obscuration into the front of the cabin in the early part of this test as compared to test 17.

The buoyant smoke test results can be compared with the nonbuoyant model predictions (reference 3). For the various operational configurations, the model predicts 62 to 65 percent of the cabin length will remain smoke free when smoke is generated in the mid-cabin area. When smoke is generated in the aft cabin, the model predicts that 84 to 88 percent of the cabin length will be smoke free. When smoke is generated in the front of the cabin, the model predicts that 79 to 91 percent of the cabin length will be smoke free. Except for test 15, the tests with buoyant smoke generated at these locations resulted in ZERO percent of the cabin length being smoke free. Test 15, which had smoke generated in the forward cabin and had the forward upperlobe outflow valve in operation, resulted in approximately 72 percent of the cabin length remaining smoke free.

ADDITIONAL APPLICATIONS

The buoyant smoke generator developed for the airplane smoke evacuation program has been used in subsequent applications in the commercial and military airplane sectors. Copies of the original prototype have been loaned to Boeing and Douglas who tried the devices in B747-400 and MD-11 applications respectively. The USAF Military Airlift Center used the device in flight tests of the C-5B to test the effectiveness of the airplane smoke detectors and to find more effective locations for their placement. The 4950th Test Wing of the USAF Aeronautical Systems Division used the device to test the effectiveness of the cabin smoke detectors and their installation housings in the VC-25A airplane.

SUMMARY

A buoyant theatrical smoke generator was developed and tested for airplane applications. The device simulates a hot air plume with a production rate of 200 cubic feet per minute at 475 °F. This is a source that is comparable with the output of a 2-gallon-per-hour oil burner and is achieved by mixing 100 cubic feet per minute each of air and helium. Theatrical smoke is entrained into this mixture for either tracing smoke plume movement or testing smoke detectors.

Airplane tests to date have shown that test results from such a buoyant smoke source are radically different from those that are found when a commercial theatrical smoke generator is used by itself. With nonbuoyant smoke, cabin air flow management in some cases can result in confinement of smoke to the generation area. For instance, when a theatrical smoke generator is placed in the rear of the passenger cabin, the smoke will often remain localized there when aircraft recirculation fans in the front of the aircraft are turned off. Turning the fans off results in a fore to aft cabin flow that blocks a nonbuoyant smoke from spreading forward. In contrast, a buoyant smoke can overcome this axial flow and spread against it all the way to the front of the cabin.

Nonbuoyant theatrical smoke moves through the cabin in a manner that is a telltale for overall cabin ventilation flows. For instance, when smoke is generated in the front of the cabin with aft lower lobe outflow valve open and recirculation fans off, the smoke will very gradually move from the front of the aircraft to some point in the aft half of the cabin. The smoke in the aft part of the cabin will hug the floor. This is demonstrating that the ventilation air distributed in the front half of the aircraft is axially carrying all the generated smoke rearward. None can leave through the forward floor grilles because the recirculation fans are off. Once the smoke is carried past the wing root area, then air and smoke can exit floor grills and flow to the aft outflow valve. Thus, when the rearward moving smoke and air gets to the aft half of the aircraft, the air from the front combined with air delivered through the distribution ducts in the rear results in a downward flow of air that keeps the smoke near the floor in the aft half of the aircraft.

Under the identical airplane configuration (recirculation fans off and aft outflow valve open), buoyant theatrical smoke generated in the front of the cabin results in relatively quick spread of smoke to the rear of the aircraft cabin. Near the smoke generation point, the smoke remains relatively stratified near the ceiling. However, as the buoyant smoke moves aft, it is continually mixed by downward directed ceiling ventilation jets. Thus, the smoke at the rear of the cabin is relatively homogenous in density from floor to ceiling. In a matter of minutes a buoyant smoke plume at one end of the cabin will lead to poor visibility conditions throughout the cabin.

Airplane testing has shown that the buoyant smoke can be localized in the cabin when axial flows are aided by a ventilation air outflow valve at the ceiling of the aircraft in the vicinity of the smoke origination point. In the specific test that demonstrated this smoke containment capability, the buoyant plume was located in the forward part of the cabin ahead of a pair of first class dividers, and the ventilation flow was at the 215 percent setting. Recorded manual notes show that the ceiling smoke layer spread back to these dividers. Since all cabin air was flowing forward to the forward ceiling mounted outflow valve, these

dividers provided a flow constriction that accelerated the axial flow even more at that location. This flow forward between the dividers was adequate to prevent the ceiling smoke layer from moving any further aft in the cabin. The general effectiveness of venting the cabin from the ceiling could be determined only by further systematic study with variation of the following parameters: smoke generation point, ceiling vent location, ventilation air supply rate, and location of cabin dividers. It can be further noted that ceiling venting does not necessarily mean penetration of the fuselage hull in the upper lobe. Alternatively, a vent located in the ceiling could be routed through ducting to an outflow location below the main deck.

Mixing helium with air also allows partial simulation of the volumetric expansion effects associated with combustion. The expansion effect simulated by a 200-cubic-foot-per-minute buoyant source may not be too significant in a non-compartmentized passenger cabin where the overall ventilation flow may be from one to several thousand cubic feet per minute. However, the 200-cubic-foot-per-minute buoyant source is likely to have significant effects in confined compartments (like cockpits and lavatories) where the overall ventilation rates can be comparable to or significantly less than the 200 figure. For example, the B757 cockpit ventilation rate is approximately 280 cubic feet per minute. Airplane lavatory ventilation rates are generally 35 to 40 cubic feet per minute. Certification smoke tests involve placing a smoke generator in the lavatory and demonstrating that nothing more than wisps of smoke escape into the passenger cabin. What this essentially shows is that the air flow is managed such that cabin air can flow into the lavatory from the cabin during flight but not from the lavatory into the cabin. Use of the 200-cubic-foot-per-minute buoyant source might overwhelm the smoke containment or management capabilities of these type compartments.

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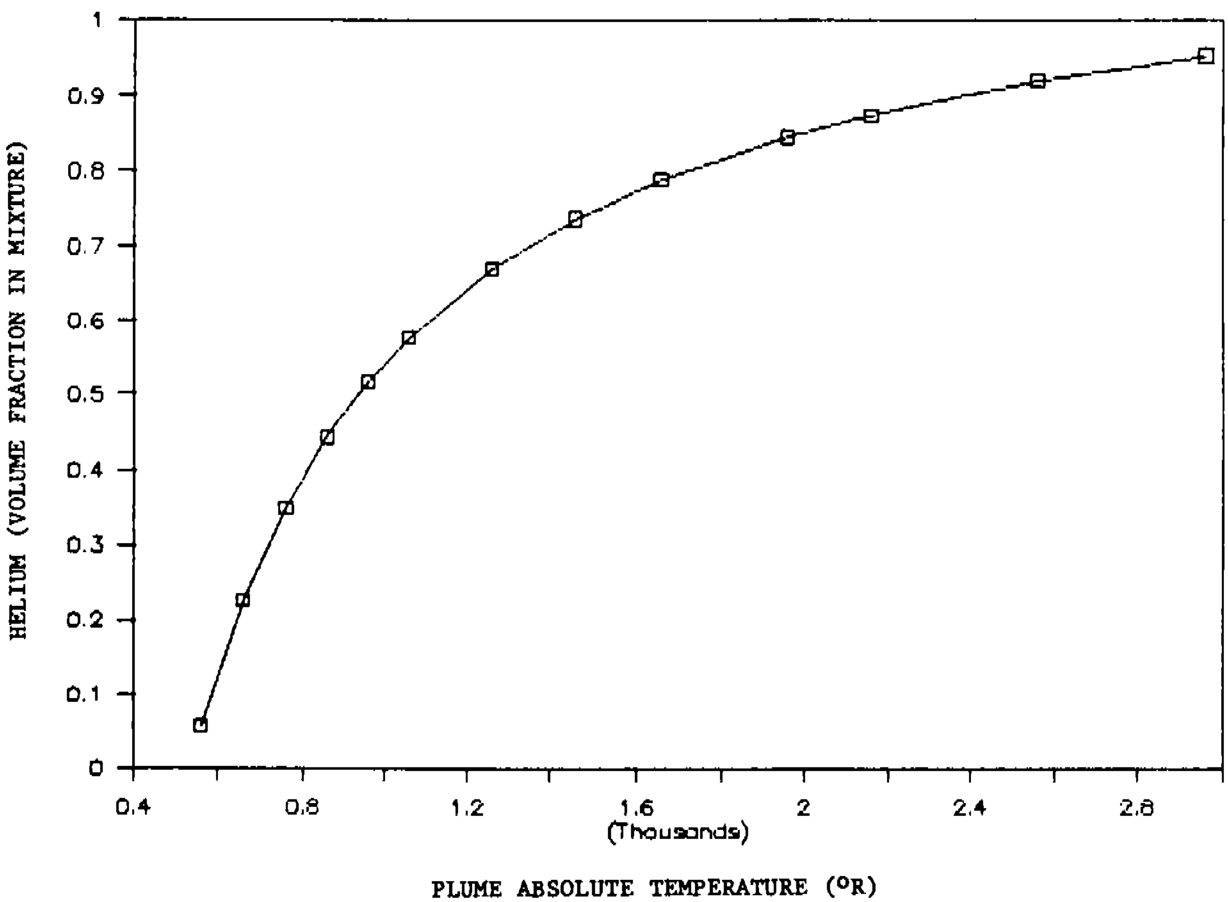

FIGURE 1. HELIUM FRACTION VERSUS EQUIVALENT AIR TEMPERATURE

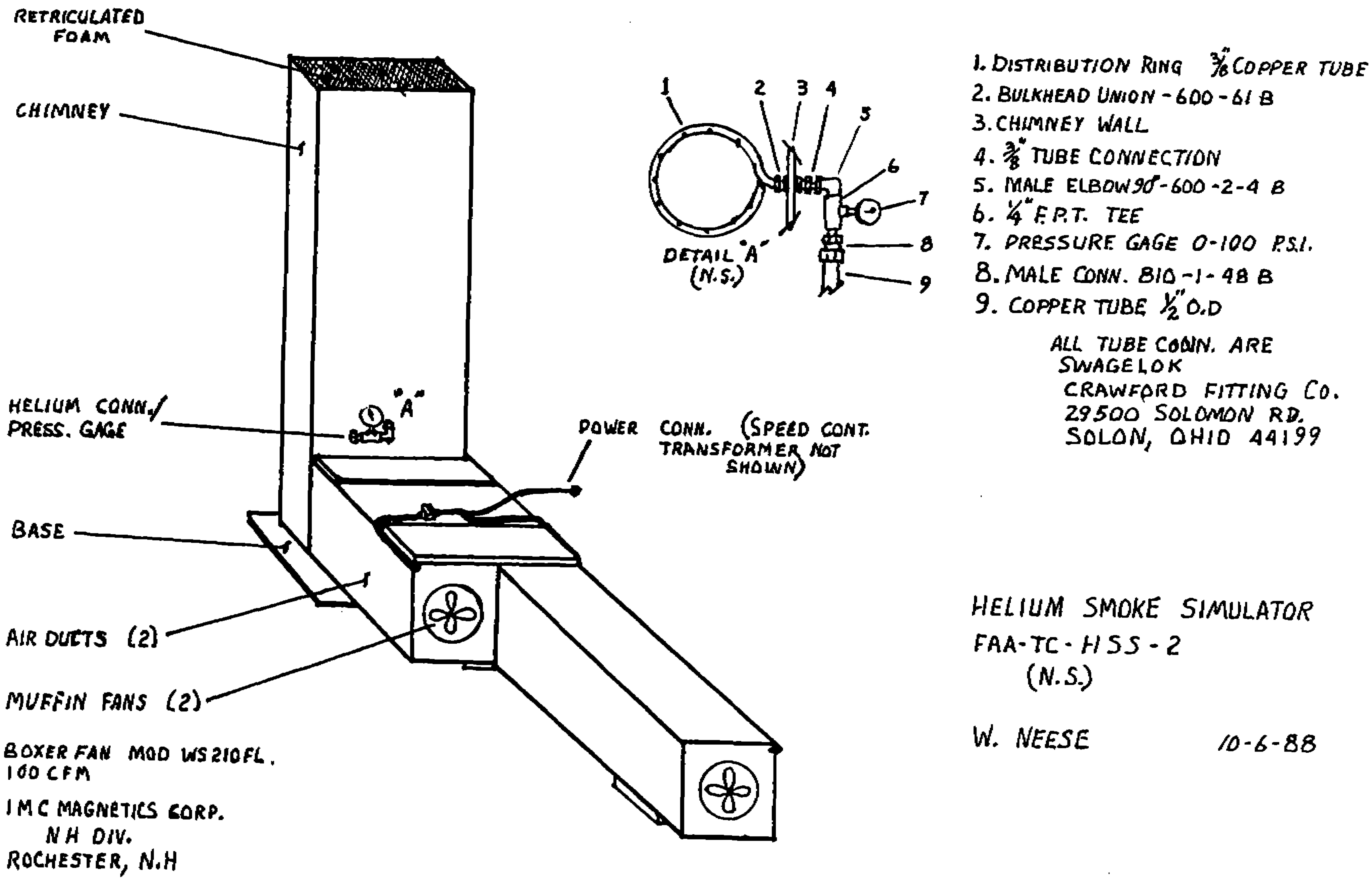

FIGURE 2. BUOYANT SMOKE GENERATOR SCHEMATIC

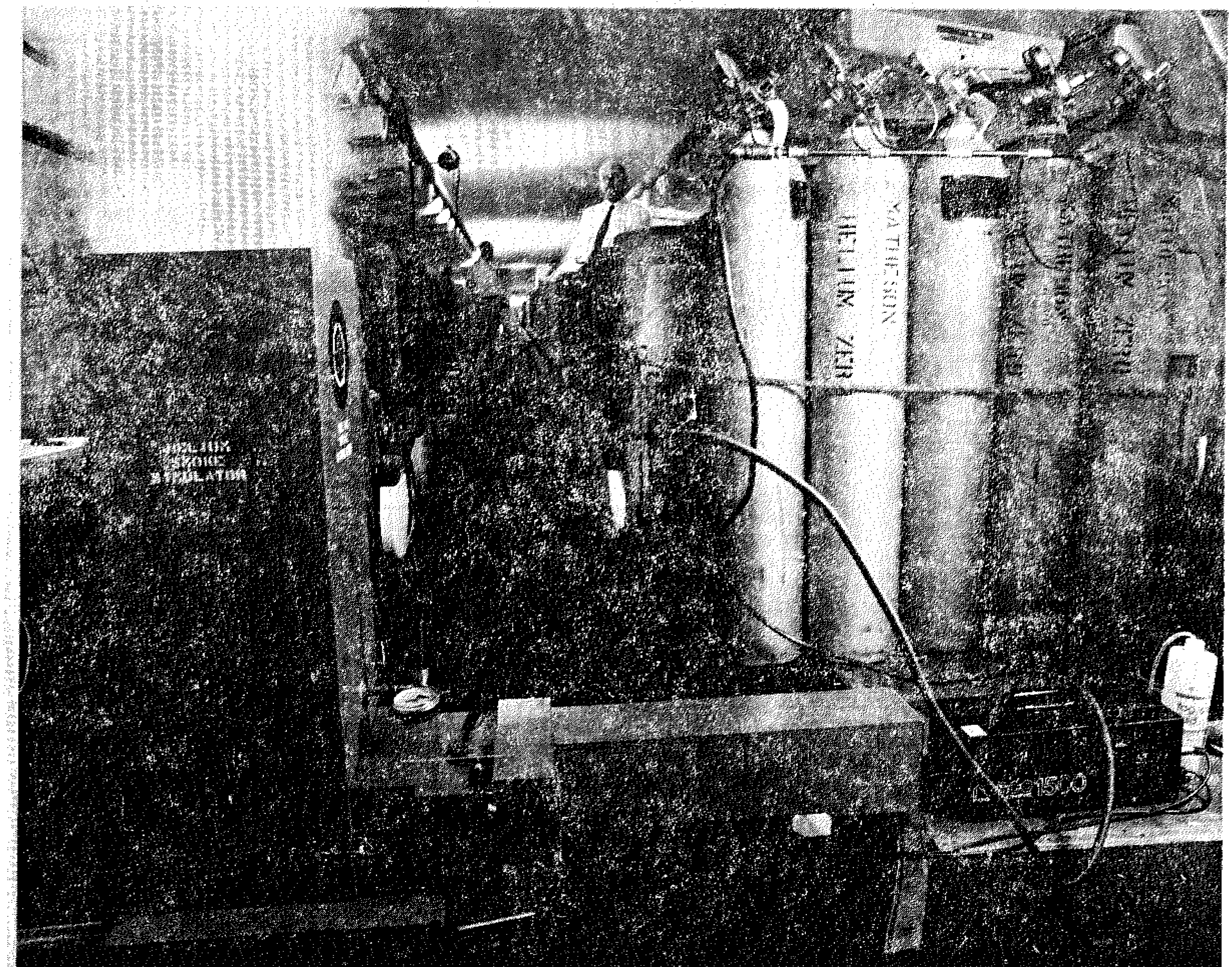

FIGURE 3. BUOYANT SMOKE GENERATOR IN OPERATION

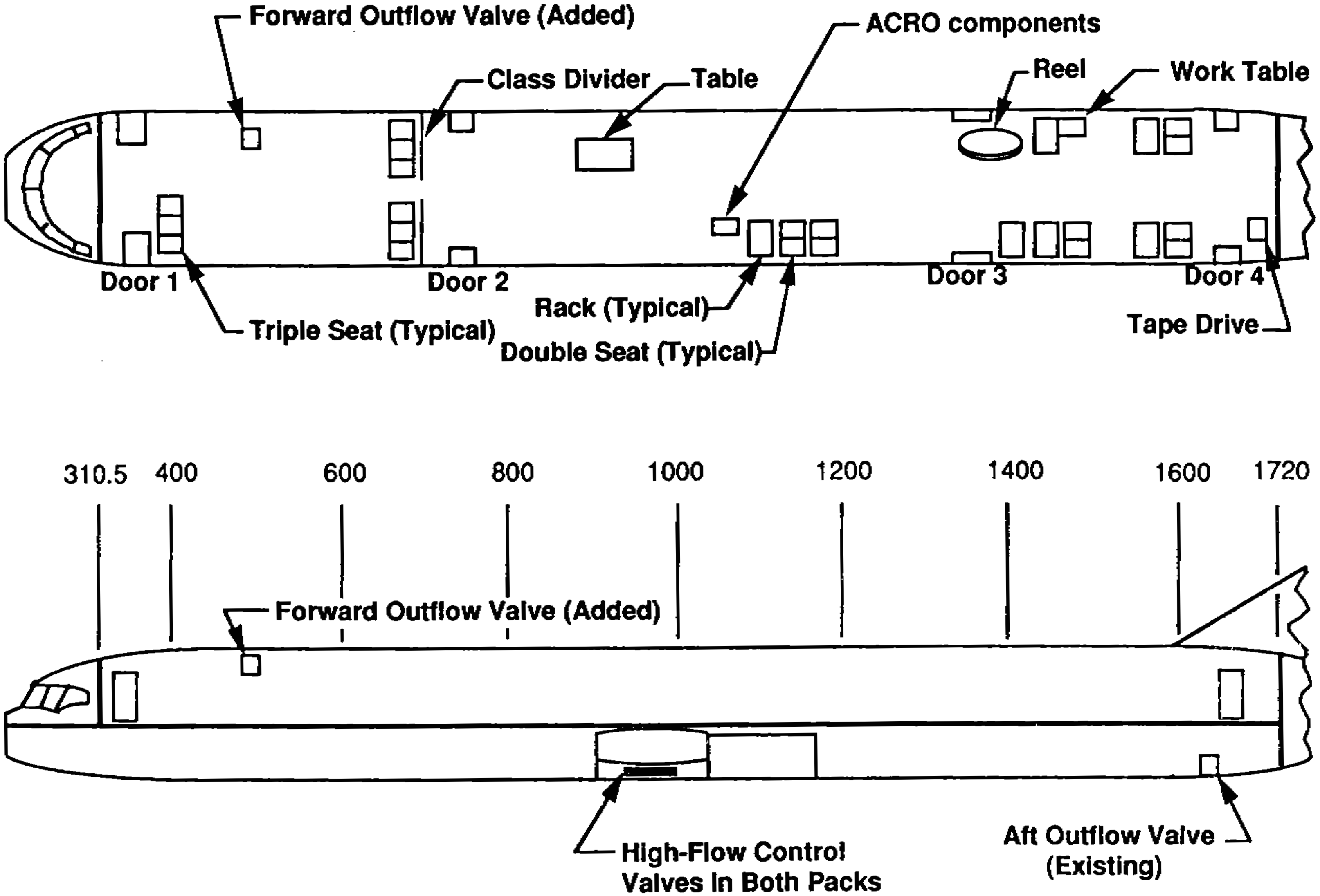

FIGURE 4. B757 TEST AIRPLANE SCHEMATIC

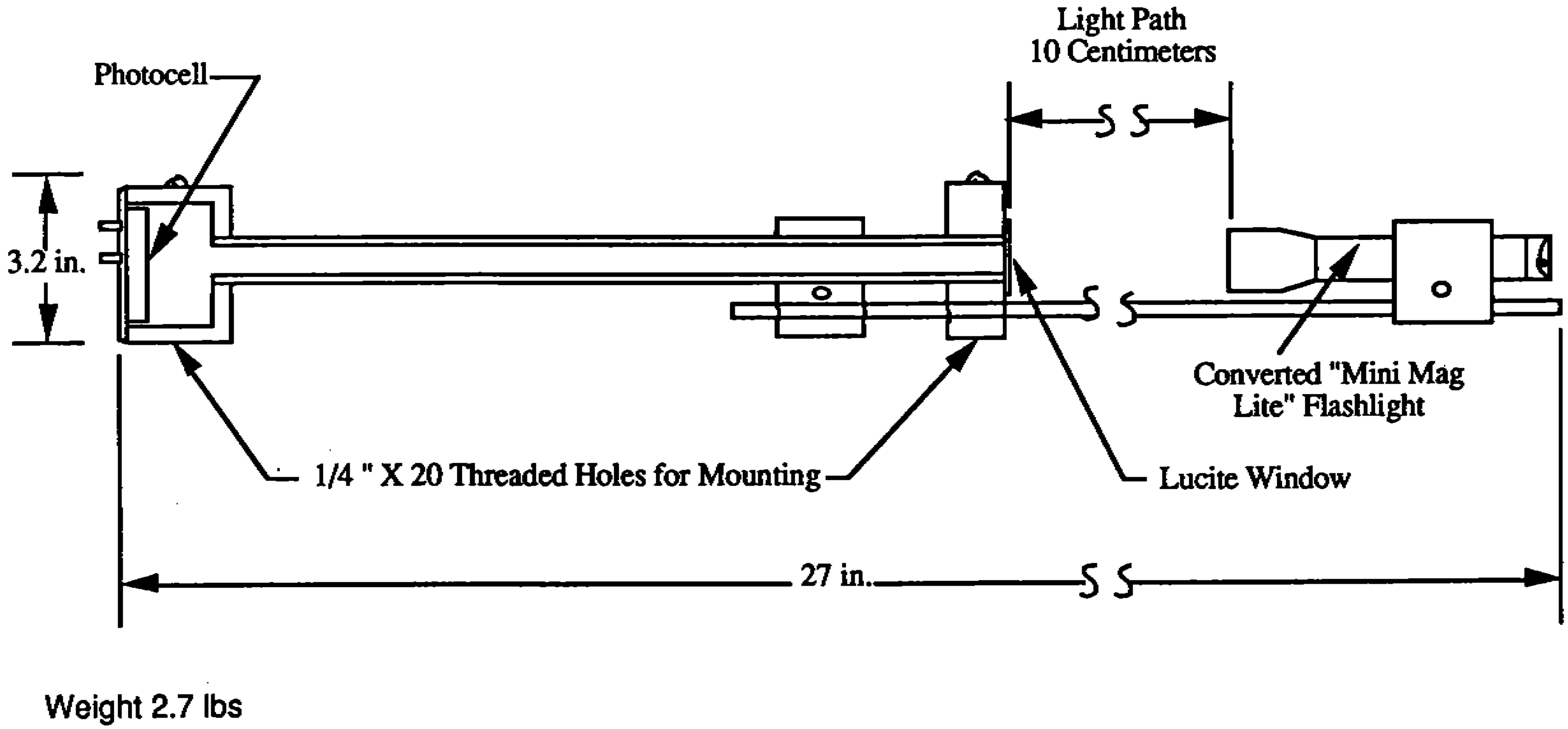

FIGURE 5. SMOKEMETER SCHEMATIC

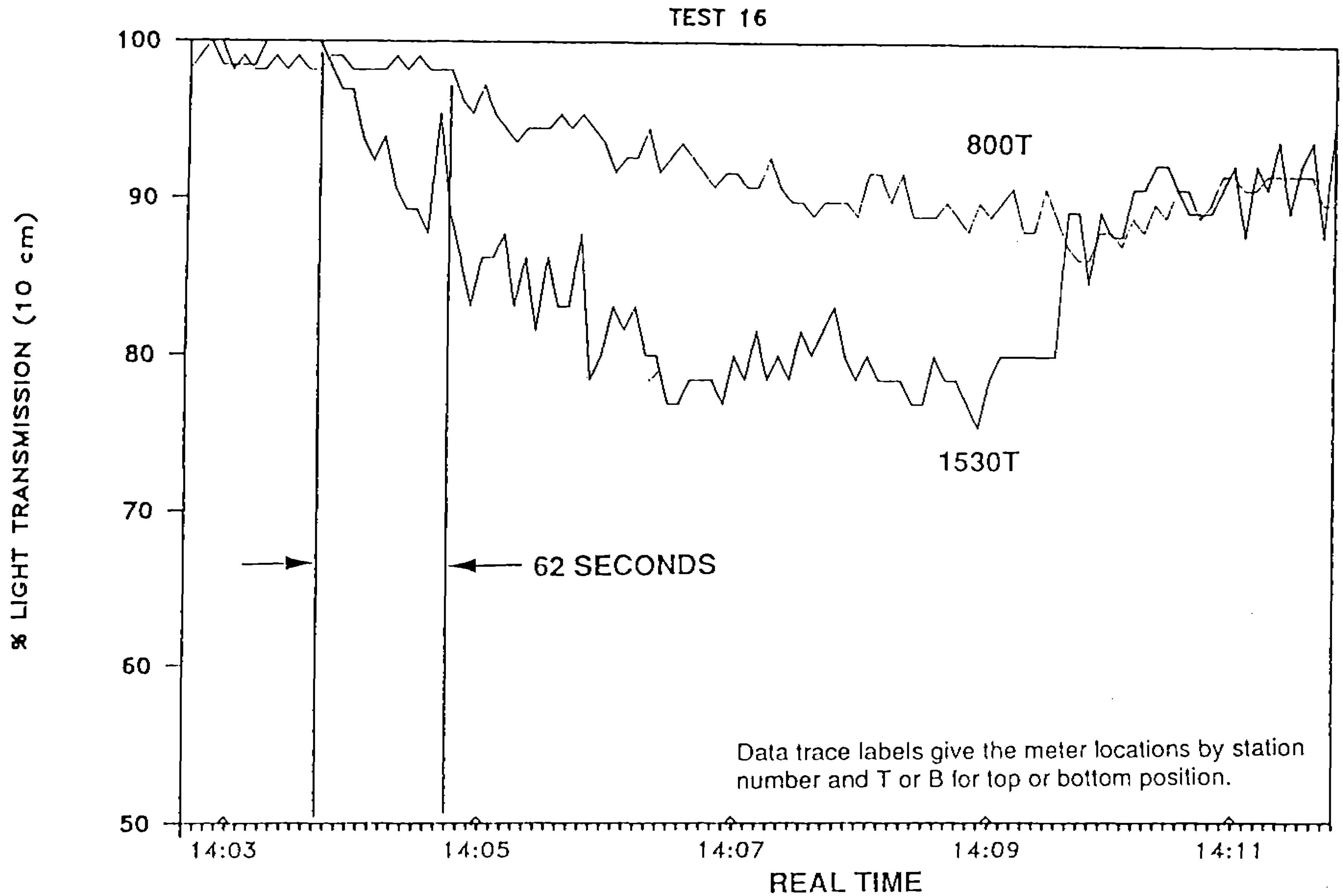

FIGURE 6. TIME FOR SMOKE LAYER TRAVEL

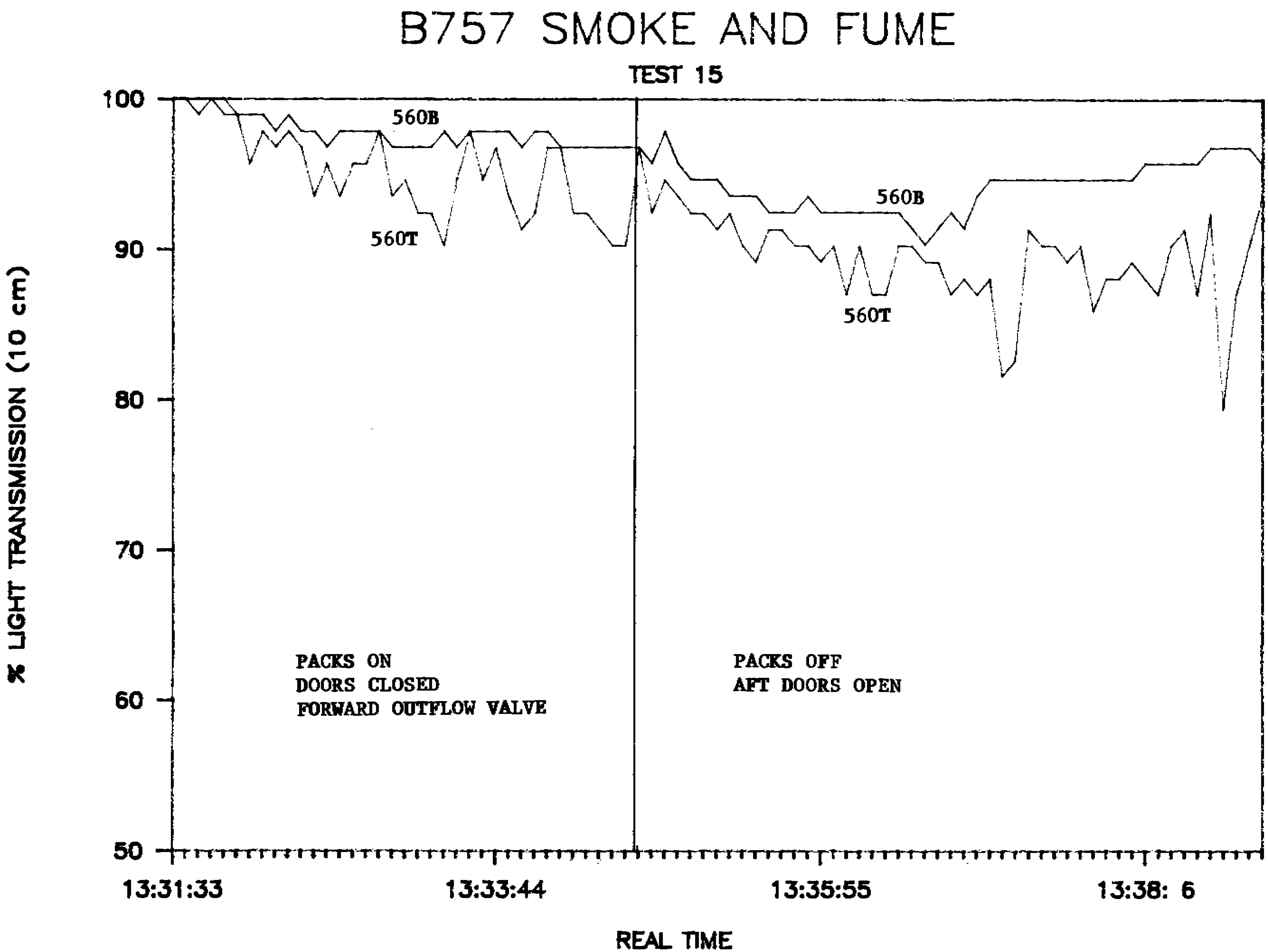

FIGURE 7. SMOKE PROFILES WITH FORWARD SMOKE GENERATION.

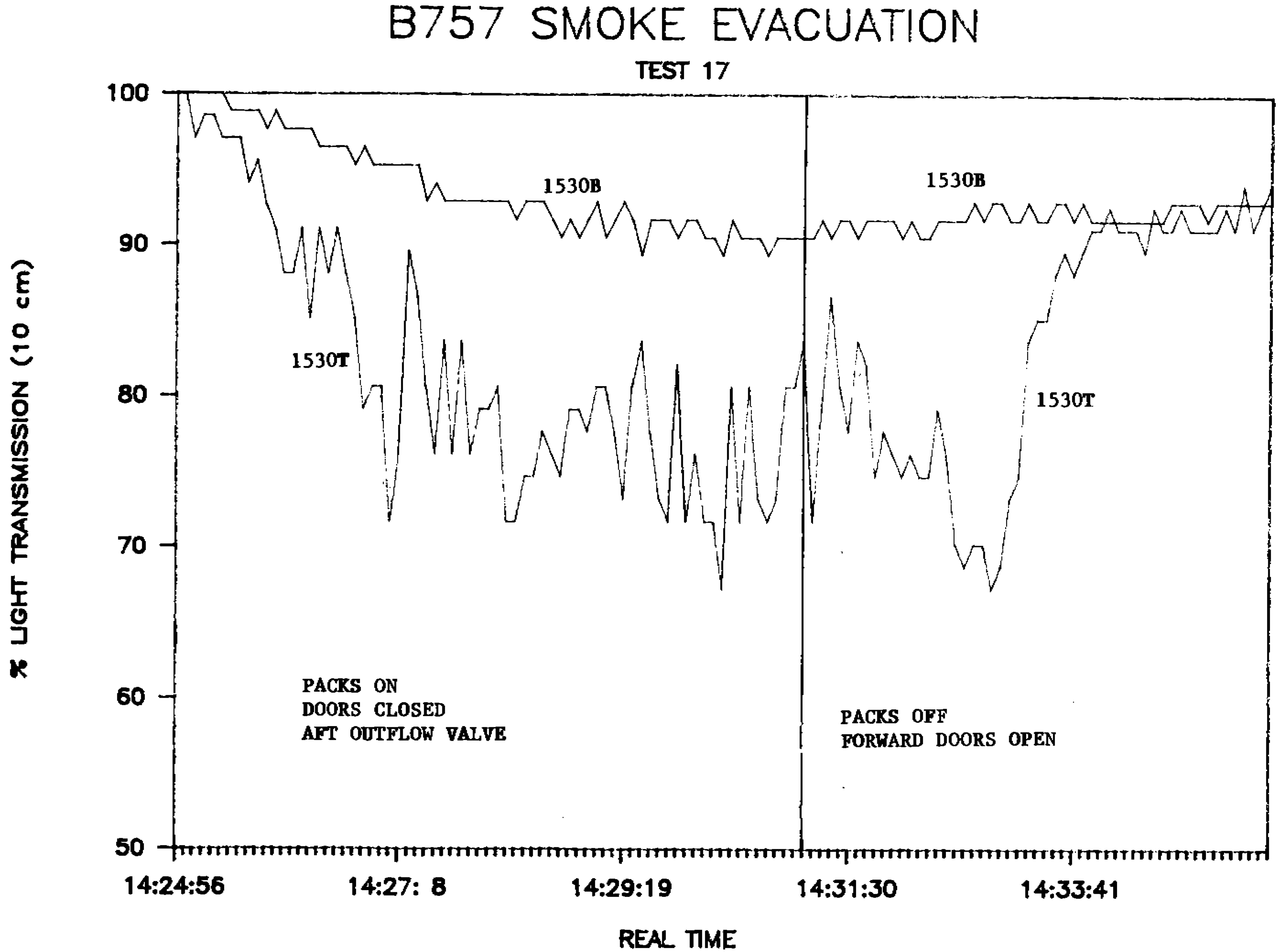

FIGURE 8. SMOKE PROFILES WITH AFT SMOKE GENERATION

*U.S. GOVERNMENT PRINTING OFFICE: 1990-504-061/20156