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Smoke and Extinguisher Agent Dissipation in a Small Pressurized Fuselage

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November 1990

Final Report

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16. Abstract A test study was conducted using Halon 1211 and Halon 1301 fire extinguishing agents and aerosol smoke to study their behavior in a pressurized Cessna C-421B aircraft. Halon fire extinguishers were discharged and monitored at various locations to determine the concentrations of neat halon gases present, their dissipation rates and any resultant toxic threat to the occupants. Artificial smoke was also generated at various locations and was measured at three fixed locations in the aircraft, thereby providing localized visibility information as well as ventilation data. Peak halon concentrations were considered adequate to extinguish most fires. Halon dosages for the pilot and copilot were low or zero and those for the passengers were also low in relation to the toxic limits recommended. The high ventilation rates in the cockpit area contributed to clearing smoke from the cockpit quickly. It also prevented the smoke from entering the cockpit when it was released in the passenger cabin.			
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EXECUTIVE SUMMARY

This project complements prior studies in the use of hand held fire extinguishers in small aircraft and cabin smoke elimination studies in large and small aircraft. Measurements were made of halon extinguisher agent concentration and smoke obscuration levels in the cabin of a small pressurized fuselage. The aircraft used was a Cessna Model 421B, a small pressurized aircraft capable of seating 10 people, including the crew, and reaching altitudes of 30,000 feet. The aircraft was tested on the ground and was pressurized with compressed air from a shop facility instead of the engines' turbocompressors.

The Halon 1211 and Halon 1301 fire extinguishers were tested alternately at 10 locations in the aircraft. The neat halon gas concentrations were measured on a time resolved basis. Peak halon concentrations at the point of discharge were in excess of that required to extinguish most common fires. The maximum nose level dosages of Halon 1211 were less than a third of the four percent-minute allowance. Maximum dosages for Halon 1301 were about a fifth of the ten percent-minute allowance.

Three aerosol smoke meters were also installed and artificial smoke was generated at three locations in the aircraft. The use of the smoke meters provided data to determine local as well as total air change rate through the aircraft and provided visibility data for the three sections of the aircraft. A video camcorder was also used to record the pilots vision of the instrument panel. The calculated aircraft air change time for the cockpit, midcabin, and aftcabin was 32, 59, and 58 seconds, respectively. The higher air change rate in the cockpit was responsible for faster smoke clearing from that area and prevented smoke generated in the aft section from entering the cockpit and obscuring the pilot's vision. Data from the forward smoke meter, video camera, and calculations using a perfect mixer theory indicated that the copilot's vision of the non-illuminated instrument panel was restored from near zero visibility in about 75 seconds from the time the smoke source was eliminated. Both smoke data and calculated data indicated that it would take 110 seconds to view non-illuminated emergency signs in the cabin at a distance of 0.86 meters after the smoke source was eliminated.

INTRODUCTION

PURPOSE.

The primary purpose of this project was to evaluate the cabin environment in a small pressurized aircraft when halon hand fire extinguishers are discharged. A secondary purpose was to evaluate the effectiveness of the aircraft's forced ventilation system in removing smoke.

BACKGROUND.

In 1984 a study in the use of hand held halon fire extinguishers in small ventilated general aviation aircraft (reference 1) was undertaken by the Federal Aviation Administration (FAA) Technical Center. This work was completed on a Cessna C-210, a nonpressurized general aviation aircraft seating up to six people. These tests were conducted with the aircraft mounted in a wind tunnel, with both engine speed and air flow over the aircraft set for cruise conditions. Thus, realistic operating conditions were produced for these tests, including cabin ventilation. It was concluded that ventilation and stratification of the halon extinguishing gases produced safe conditions at the pilot's nose height while being of sufficient concentration to extinguish a fire at its source.

In 1986 a study was conducted on halon extinguishment of small aircraft instrument panel fires (reference 2). The objective was to evaluate the effectiveness of halon on fires involving electrical wire insulation and hydraulic fluid beneath the instrument panel in a small plane. In those tests a preburn time of 1 minute led to very smokey conditions and loss of visibility. It was concluded that once the fire was extinguished, immediate ventilation or dissipation of the smoke would be a high priority item.

In order to develop additional information on small pressurized aircraft typified by some commuter aircraft, a Cessna C-421B was obtained and instrumented. The first series of tests conducted was to determine the halon concentrations resulting from the discharge of hand held extinguishers in the aircraft. The second series of tests were conducted to monitor smoke elimination from the pressurized aircraft using only the aircraft's existing ventilation system.

DISCUSSION

AIRCRAFT CONDITIONS.

The aircraft used throughout the test series was a Cessna C-421B. This is a low wing pressurized aircraft with retractable tricycle type landing gear. It is capable of flights at altitudes of up to 30,000 feet (with supplemental oxygen). The aircraft maintains a constant 8,000-foot cabin pressure from 8,000 to 23,000 feet. The cabin pressure differential is gradually increased from 0 pounds per square inch gauge (psig) at 8,000 feet to 5 psig or 10.2 inches of Mercury at 23,000-foot altitude and is maintained at this differential above 23,000 feet. An engine driven turbocharger provides compressed air for cabin pressurization. Total air flow through the flow control venturis leading from the engines to the heat exchanger is 8 and 16 pounds per minute (lbs/min) above 35 percent engine

speed for single and dual engine output, respectively, according to information provided by the Cessna Aircraft Company.

The cabin is approximately 15 feet long and is about 4 feet 9 inches wide at the midcabin passenger compartment, and it tapers to 3 feet at the rear bulkhead. The internal height varies from 3 feet 11 inches at the cockpit, while most of the passenger cabin is 4 feet 2 inches and tapers to 3 feet 10 inches at the rear bulkhead. The volume of the cabin is 216.6 cubic feet, according to the Cessna Aircraft Company.

The cabin seats were not present during any of the tests.

AIRCRAFT PRESSURIZATION.

The aircraft was pressurized using compressed shop. The air delivery rate was regulated with a Foxboro 43AP Pneumatic controller via a Foxboro Stabilflo VI series control valve. The regulated compressed air fed both venturis that led to the aircraft's pressurization system. Thus, the compressed air entering the aircraft followed the same path as the air coming from the engines turbocompressor (figure 1). The regulator was adjusted to maintain a supply pressure of 35 pounds per square inch absolute (psia) to both sonic venturis. With this system the aircraft was pressurized within a short time of 45 seconds or less. At this time, the outflow valve and the safety relief valve opened and maintained the cabin pressure at 5.6 psig (figure 2).

AIRCRAFT VENTILATION.

Unlike large commercial aircraft that use a counter-flow (top/down) ventilation design, this aircraft has both high- and low-level cabin air supply vents and a single exhaust in the aft area of the passenger cabin. This helps to improve air circulation and is ideally suited to applications involving perfect stirrer theories.

Determination of the ventilation rate and time for an aircraft air change (τ) was calculated using the following rational:

The Cessna C-421B cabin air supply system consists of twin converging diverging nozzles (figure 3), one for each engine air source. Because of the flow behavior in the type nozzle used in this aircraft, the flow in the nozzle throat would be sonic even at fairly low ratios of upstream pressure to aircraft cabin pressures. Since the total cabin pressure was approximately 20 psia, the flow could be sonic with source pressure as low as 23 psia. This behavior was confirmed through measurements of supply pressure versus throat pressure for supply pressures between 23 and 50 psia. These measurements provide the basis for the use of Fliegner's Formula (reference 3) to calculate the air supply to the cabin as follows:

$$W = .532 p_0 A^* / \sqrt{T_0} \quad (1)$$

where W is in lb/sec, A^* is the throat area in ft^2 , p_0 is the supply pressure in lb/ft^2 , and T_0 is absolute temperature in degrees Rankine. The values used are as follows:

$$\begin{aligned} A^* &= .002 \text{ ft}^2 \text{ for diameter of 0.6 in.} \\ T_0 &= 520 \text{ degrees Rankine} \\ p_0 &= 5040 \text{ lb}/\text{ft}^2 \text{ for 35 psia supply.} \end{aligned}$$

Fliegner's Formula yields a flow rate of 0.46 lb/sec for the two venturis combined. Because the cabin was pressurized to 5.6 psig, the density of air in the cabin has to be corrected to 0.10 lb/ft^3 . The volumetric air delivery to the cabin is the flow rate divided by the density or 4.6 $\text{ft}^3/\text{second}$. The nominal time for a cabin air change is the cabin volume (216 ft^3) divided by the volumetric air delivery or 47 seconds.

One application involving a perfect stirrer theory is that relating visibility to ventilation (reference 4) to determine τ . The visibility at a given point in time during the smoke evacuation period is represented by the following equation:

$$-\ln(I/I_0) = 1s_p\sigma[\exp(-t/\tau)]/v \quad (2)$$

Where $-\ln(I/I_0)$ is the logarithm of the transmission ratio, l is the transmission length, s_p is the number of smoke particles present, σ is some particulate cross-section that absorbs light, t is the point in time of interest, τ is time for an air change, and v is the volume of the enclosure.

By selecting two points during this period and solving the two simultaneous equations, we arrive at the following relationship:

$$\frac{-\ln(I/I_0)_1}{-\ln(I/I_0)_2} = \exp((-t_1+t_2)/\tau) \quad (3)$$

Solving for τ yields the following equation:

$$\tau = \frac{(t_2-t_1)}{\ln \frac{\ln(I/I_0)_1}{\ln(I/I_0)_2}} \quad (4)$$

We can then select the two points in time and solve for τ .

HALON MEASUREMENT.

Three Beckman Model 865 infrared gas analyzers were factory field modified to measure Halon 1211 and Halon 1301 concentrations in the cabin. Sampling lines were run from the selected locations in the cabin to the remotely housed gas sampling system (figure 4). The instruments were calibrated prior to each test. Calibration gas concentrations for Halon 1211 were 3, 6.35, and 7.98 percent, and for Halon 1301 the calibration gas concentrations were 1.96, 4, and 8.06 percent. The maximum concentrations measured by the gas analyzers were limited to 11-12 percent. A remote electrically actuated fire extinguisher holder was constructed to house and fire the extinguishers. The three measurement locations were as follows:

1. Test area, fire extinguisher discharge location.
2. Knee area, corresponding to 20 inches above the floor at the area of discharge. The discharge area for the pilot's and copilot's seat test was at knee level where the seat cushion meets the seat back. Therefore the knee level location was measured at the front of the seat.
3. Nose area, corresponding to 37 inches above the floor at the area of discharge.

To determine the actual amount of extinguishing agent discharged, the extinguishers were weighed before and after the test.

SMOKE GENERATION.

The Rosco Model 1500 Fog Machine was used to generate the smoke for the smoke elimination tests. This smoke generator produces smoke by injecting smoke fluid into its heat exchanger where it is atomized at high temperatures; the resulting smoke is then blown out the discharge nozzle. The smoke production can be adjusted from levels of one to ten and was controlled from a remote location outside the aircraft. Fog fluid was available from the manufacturer and consisted of nonpetroleum products that had no unpleasant odors and were considered safe to inhale.

SMOKE MEASUREMENT.

Three aerosol smoke meters were used to measure light transmission in the aircraft cabin. The aerosol smoke meter consisted of a tube with a photocell on one end and a light source at the other end (figure 5). The smoke meter was 27 inches long. The light source was an adjustable beam flashlight, featuring a light path of ten centimeters before entering the tube and photocell. The flashlight used a regulated power supply to eliminate the use of batteries and the error associated with their discharge. Due to the short duration of the test, any error due to lightbulb output decay was considered insignificant.

All smoke measurements were made at eye level, corresponding to a height of 38 inches above the passenger/cockpit cabin floor.

INSTRUMENTATION.

Two Iron Constantan (type J) thermocouples were used to monitor temperature, one at the point of discharge and the other at nose level directly above the point of discharge. These thermocouples monitored ambient cabin temperatures and indicated the temperature change in those areas once the extinguisher was triggered. A Sensotec model TJE/717-02 pressure transducer was installed in the cabin to monitor the cabin pressure. Figure 6 shows the location of all instrumentation in the aircraft.

Cabin pressure, temperature, smoke visibility, and halon gas concentrations data were collected, processed, and graphed using a digital computer with data acquisition hardware and software. A video camcorder was used to monitor the obscuration that the pilot and the copilot would encounter during the smoke elimination tests. It viewed the entire instrument panel and was located at eye level, equidistant between the pilot and the copilot. It was also used to view

the halon hand-held fire extinguisher tests and gave an indication of the discharge time for each bottle where possible.

TEST SERIES, RESULTS, AND SUMMARY

HALON TEST SERIES.

Halon 1211 (2 1/2 pound) and Halon 1301 (3 pound) hand-held fire extinguishers were used during these tests. All of the gas analyzers were turned on at least 24 hours prior to calibration. At least 1 hour prior to calibration, the analyzers were set in the test mode and the computer was turned on. The extinguisher bottle was weighed and placed in the aircraft. The analyzers were calibrated, the video recorder was turned on, the computer was started and the aircraft was pressurized to 5.6 psig at which time the outflow valve and the safety relief valve opened. Once the pressure stabilized, the fire extinguisher was remotely triggered and data were collected for 90 seconds (10-second pre-trigger data also gave ambient readings).

The halon testing consisted of 20 tests taken at 10 different locations (figure 7), using both Halon 1211 and Halon 1301 at each location.

The locations were:

1. Under the instrument panel copilot's side
2. Under the instrument panel pilot's side
3. Circuit breaker panel pilot's side
4. Pilot's seat
5. Copilot's seat
6. Grill under copilot's seat facing passenger compartment
7. Second cabin vent left side
8. Control panel on left side before cabin door
9. Last cabin floor vent right side
10. Rear passenger seat/baggage area/110-Volt Outlet

HALON TEST RESULTS.

It is recommended that exposure to neat halon gases (reference 5) be limited to 4 percent-minutes (e.g., 4 percent for 1 minute or 1 percent for 4 minutes) for Halon 1211 and limited to 10 percent-minutes (e.g., 10 percent for 1 minute or 1 percent for 10 minutes) for Halon 1301. Assuming an instantaneous discharge of the fire extinguisher, the exposure to neat halon gases may be calculated with the following relationship (reference 5):

$$d = C_0 \tau \quad (5)$$

where d is the dose in percent-minutes, C_0 is the peak halon level in percent, and τ is the time required for the halon concentration to decay from the peak level to 37 percent of peak. However, since the extinguisher discharge time is not instantaneous, additional calculations are required to determine the exposure from the start of discharge to the peak level. A series of rectangles and triangles were fitted to the pre-peak portion of the curves (figures 9 through

28) to determine the pre-peak dose exposure on a test-by-test basis. Therefore, the total dose exposure is

$$d = C_0T + a_1 + a_2 \dots \quad (6)$$

where a_1 etc. is the pre-peak dose exposure.

Halon agent concentrations of 5 to 6 percent by volume are adequate to extinguish fires of most combustible materials (reference 6). Data from the halon test series are tabulated in table 1 and indicate peak halon concentrations at the sampling locations and the weight of the halon discharged. Calculations for dose in percent-minutes for the nose level locations are listed in table 2.

TEMPERATURE. Initial analysis of the temperature data indicated that during the 10 seconds prior to the discharge of the extinguisher, the temperature seen by the two thermocouples increased. This temperature rise was caused by the use of a high output incandescent light to illuminate the test area for enhanced video coverage.

Table 1 also contains the temperature at the discharge area for ambient conditions as well as the temperature change after the extinguisher was discharged. Maximum temperature changes were 40 °F for Halon 1211 and 68 °F for Halon 1301 (figure 8). On the average the temperature decrease for Halon 1211 was 16 °F and 32 °F for Halon 1301.

DISCHARGE UNDER THE INSTRUMENT PANEL. A number of electronic units or sets are located under the instrumentation panel in the cockpit. An electrical short in the units could result in a fire. Testing under the instrument panel consisted of four extinguisher discharges. One discharge each of Halon 1211 and Halon 1301 was directed under the instrument panel on the copilot's side, and identical tests were completed under the instrument panel on the pilot's side. The halon measurements were recorded every second and were plotted against time as shown in figures 9, 10, 11, and 12. Peak levels of 8 percent Halon 1211 and 11 percent Halon 1301 were recorded for the copilot's side, and peak levels of 9 percent Halon 1211 and 8.2 percent Halon 1301 were recorded for the pilot's side. Significant findings concern the short length of time before the halons were at very low levels. The measurements of figures 9, 10, and 12 were at low levels after 25 to 30 seconds while figure number 11 decreased in approximately 40 seconds. The pilot and copilot dose exposure to the halons was calculated from the concentration data to be zero.

DISCHARGE TO THE CIRCUIT BREAKER PANEL. This circuit breaker panel was located to the pilot's immediate left. The breaker panel was configured into a console and incorporated the switches and relays to the aircraft electrical wiring to all electric or electronic components. Two fire extinguishers were directed to the circuit breaker panel, one each of Halon 1211 and Halon 1301. The plots of the data are shown in figures 13 and 14. The Halon 1211 concentrations reached 10 percent maximum and were at low levels after approximately 30 seconds. The Halon 1301 results approached 11 percent maximum and reduced to low levels after approximately 45 seconds. The calculated doses of halon for the pilot and copilot were zero for these tests.

TABLE 1. HALON SERIES TEST DATA

FIGURE	TEST LOCATION	AGENT	TIME SEC	MAX HALON TEST LOC	CONCENTRATION (%) KNEE	NOSE	WEIGHT LBS	TEMP DEG F	TEMP DEG F
9	UNDER INSTR. PANEL COPILOT'S SIDE	1211	10	8	0.1	0	2.9	78	15
10	UNDER INSTR. PANEL COPILOT'S SIDE	1301	11	11	0.1	0	3.0	76	22
11	UNDER INSTR. PANEL PILOT'S SIDE	1211	13	9	1.4	0	2.7	77	9
12	UNDER INSTR. PANEL PILOT'S SIDE	1301	--	8.2	1.3	0	3.1	76	14
13	CIRCUIT BREAKER PANEL	1211	13	10	1.3	0	2.7	79	23
14	CIRCUIT BREAKER PANEL	1301	11	11	4.2	0.3	2.7	78	68
15	PILOT'S SEAT	1211	13	6.3	2.1	1.1	2.4	76	9
16	PILOT'S SEAT	1301	--	10.5	5.9	2.8	3.0	76	51
17	COPLOT'S SEAT	1211	10	5.9	2.6	4.3	2.7	74	7
18	COPLOT'S SEAT	1301	--	8.6	4.4	1.9	3.0	76	22
19	GRILL UNDER COPILOT'S SEAT FACING CABIN	1211	14	4.9	11.2	3.3	2.9	79	25
20	GRILL UNDER COPILOT'S SEAT FACING CABIN	1301	10	6.9	5.7	4.1	3.1	78	34
21	SECOND CABIN VENT LEFT SIDE	1211	--	2.9	4.4	2.3	2.6	89	4
22	SECOND CABIN VENT LEFT SIDE	1301	--	3.2	4.2	3.7	3.1	88	23
23	CABIN VENT BEFORE DOOR LEFT SIDE	1211	--	7.2	11.2	3.5	2.8	80	14
24	CABIN VENT BEFORE DOOR LEFT SIDE	1301	--	9.2	6.2	0.9	3.1	81	36
25	LAST CABIN VENT RIGHT SIDE	1211	--	7.2	11.2	3.1	2.8	78	15
26	LAST CABIN VENT RIGHT SIDE	1301	12	7.4	5.9	3.0	3.1	77	20
27	REAR OF CABIN AT 110 VOLT OUTLET	1211	--	5.7	3.3	1.1	1.9	97	40
28	REAR OF CABIN AT 110 VOLT OUTLET	1301	13	7.2	4.2	2.8	3.1	95	32

TABLE 2. CALCULATED NEAT HALON DOSE EXPOSURES

AGENT	TEST LOCATION	Halon Dose Percent Minutes
1211	UNDER INSTR. PANEL COPILOT'S SIDE	0
1301	UNDER INSTR. PANEL COPILOT'S SIDE	0
1211	UNDER INSTR. PANEL PILOT'S SIDE	0
1301	UNDER INSTR. PANEL PILOT'S SIDE	0
1211	CIRCUIT BREAKER PANEL	0
1301	CIRCUIT BREAKER PANEL	0
1211	PILOT'S SEAT	0.1
1301	PILOT'S SEAT	0.2
1211	COPILOT'S SEAT	1.2
1301	COPILOT'S SEAT	1.3
1211	GRILL UNDER COPILOT'S SEAT FACING CABIN	0.7
1301	GRILL UNDER COPILOT'S SEAT FACING CABIN	1.1
1211	SECOND CABIN VENT LEFT SIDE	1.3
1301	SECOND CABIN VENT LEFT SIDE	2.1
1211	CABIN VENT BEFORE DOOR LEFT SIDE	0.8
1301	CABIN VENT BEFORE DOOR LEFT SIDE	0.6
1211	LAST CABIN VENT RIGHT SIDE	1.4
1301	LAST CABIN VENT RIGHT SIDE	1.1
1211	REAR OF CABIN AT 110 VOLT OUTLET	0.2
1301	REAR OF CABIN AT 110 VOLT OUTLET	0.8

DISCHARGE TO THE PILOT'S AND COPILOT'S SEATS. Halon 1211 and Halon 1301 were discharged to the pilot's and copilot's seats. The plots of the data are shown in figures 15, 16, 17, and 18. The peak halon levels measured at the pilot's seat were 6.3 percent for Halon 1211 and 10.5 percent for Halon 1301. The peak halon levels measured at the copilot's seat were 5.9 for Halon 1211 and 8.6 for Halon 1301. The halons concentrations went to low levels in 45 to 55 seconds. The seats may be areas of low ventilation. The pilot's and copilot's dose of halons were 0.1 and 1.2 percent-minutes for Halon 1211 and 0.2 and 1.3 percent-minutes of Halon 1301, respectively.

DISCHARGE TO THE GRILL UNDER THE COPILOT'S SEAT. The grill at the base of the copilot's seat, facing the passenger cabin, was selected as an area of concern due to its inaccessibility in the event of a fire. Halon 1211 and Halon 1301 fire extinguishers were discharged to the grill. The results are plotted on figures 19 and 20. The maximum levels were 11.2 and 6.9 percent for Halon 1211 and 1301, respectively. The Halon 1211 went to low levels in 45 seconds and the Halon 1301 gases went to low levels in about 50 seconds. The calculated dose at nose level was 0.7 and 1.1 percent-minutes, respectively.

DISCHARGE TO THE SECOND CABIN VENT LEFT SIDE. The extinguishers were discharged to the second cabin vent on the left or pilot's side. Low levels of halons were measured at this location. A maximum of 4.4 percent was measured for Halon 1211, and 4.2 percent for Halon 1301. The results are shown in figures 21 and 22. The halon gases at the nose height accumulated after a noticeable delay. In the case of Halon 1211, gases at the passengers nose level were initially detected 18 seconds after detection at the test location and at the knee. In the case of Halon 1301, the agents at the passengers nose were initially detected 5 to 6 seconds after detection at the test location and the knee levels. The halon dose at nose level was 1.3 and 2.1 percent-minutes for Halon 1211 and Halon 1301, respectively.

DISCHARGE TO THE CABIN VENT BEFORE THE DOOR. This vent was the last cabin vent on the floor on the left side of the aircraft. It was located directly below a small control panel just before the door. Peak halon levels measured were 11.2 and 9.2 percent for Halon 1211 and Halon 1301, respectively (figures 23 and 24). The presence of extinguishing agents at nose level was delayed 7 seconds in the case of Halon 1211 and 5 seconds in the case of Halon 1301. The dose at nose level was 0.6 percent-minutes for Halon 1211 and 0.8 percent-minutes for Halon 1301.

DISCHARGE TO THE LAST VENT RIGHT SIDE. The last cabin vent near the floor on the right side was selected as the next target. It was also located directly opposite the cabin door. The results are presented in figures 25 and 26. Peak values were 11.2 and 7.4 percent for Halon 1211 and Halon 1301, respectively. The agent levels at the passengers nose were delayed 4 to 7 seconds compared with the other measurements. The nose level dose of neat halons was 1.4 percent-minutes and 1.1 percent-minutes for Halon 1211 and 1301, respectively.

DISCHARGE TO THE CABIN REAR SEAT CENTER. The fire extinguishers were directed to a 110-volt outlet located on a raised area in the aft section of the cabin. The results are shown in figures 27 and 28. The peak values were 5.7 percent for Halon 1211 and 7.2 percent for Halon 1301. The nose level dose was 0.8 and 0.2 percent-minutes for Halon 1211 and 1301, respectively.

SUMMARY OF EXTINGUISHER AGENT RESULTS.

Hand held fire extinguishers charged with 2.5 pounds Halon 1211 and 3 pounds of Halon 1301 were discharged in a pressurized Cessna Model 421B aircraft. The aircraft was pressurized to 5.6 psig on the ground with compressed air. The agent concentration was measured at the discharge area, at the knee level, and at the nose level. Aircraft locations of extinguisher discharge were at the following locations: under the instrument panel, the circuit breaker panel, the pilot and copilot seats, the grill under the copilot's seat, the second vent on the pilot's side, the vent before the door, the last vent on the right side or copilot's side, and the rear passenger seat/baggage area/110-volt outlet area. This last location was near the outflow and safety relief valves.

Extinguisher concentration near the location of discharge peaked over 11 percent in three cases. The lowest value recorded was 4.2 percent. The high concentrations dissipated to low levels in the cockpit in 30 seconds and up to 50 seconds in the cabin. The crew and passengers dose exposure to the neat halons was calculated and found to be low in relation to the amount that can be safely tolerated.

SMOKE ELIMINATION TEST SERIES.

For the smoke elimination testing, both the aerosol smoke meters and the computer were turned on 1 hour prior to calibration. The smoke generator was turned on, set to a smoke output of nine, and allowed sufficient time to warm up; during this time the calibration was performed on the smoke meters. The aircraft was pressurized to 5.6 psig at which time the outflow and pressure relief valves opened. When the pressure stabilized, the smoke generator was remotely turned on. After 1 minute and 20 seconds the smoke generator cycled off for 30 seconds and then cycled on again for approximately 40 seconds. It was then turned off. This cycling phenomenon was an inherent characteristic of the smoke generator. When the smoke generator is first powered on, an internal heater block must reach a preset temperature before the unit is operational. Once the generator is turned on, the smoke fluid is pumped through the heater block, atomized, and discharged out the nozzle. At smoke settings above 2 1/2, the block will drop below the minimum operating temperature despite the fact that the heater is always on. This causes the smoke generator to cycle off, allowing the heater block to reach operating temperature. Once the operating temperature is reached, the generator cycles back on for another 1 minute and 20 seconds and then the cycle is repeated. No cycling occurred when the smoke generator was set to a valve of 2 or less. In the tests conducted, this cycling phenomenon merely simulated a fire being detected, extinguished, restarted, and finally being permanently extinguished.

The smoke elimination tests consisted of 6 tests at three locations (figure 29), each test being repeated twice. The three smoke generator locations were as follows: (1) facing forward and equidistant between the pilot and the copilot seats, (2) facing forward, centered with the first passenger window and the sides of the aircraft and (3) facing the rear, centered with the fourth passenger window and the sides of the aircraft.

SMOKE ELIMINATION TEST RESULTS.

Since the smoke generator cycled on and then off for a short period of time and then on again, the time for an air change, τ , was calculated from smoke data for only the latter period of smoke elimination. Using equation 4 and the data found in figures 30 through 35 τ was calculated and shown in table 3.

TABLE 3. CALCULATED τ FROM SMOKE DATA

Figure	Cockpit τ	Midcabin τ	Aftcabin τ
30	29	70	73
31	32	66	58
32	29	64	67
33	38	76	72
34	--	37	33
35	--	42	44
	----	----	----
AVG	32	59	58

τ (seconds/aircraft air change)

The results indicate that the ventilation in the cockpit area was much higher than that of the rest of the cabin. This was visually confirmed by the following observations: (1) smoke generated in the rear of the passenger cabin approached but could not enter the cockpit area, and (2) the cockpit area was the first area to clear.

Since all exiting air must flow to the rear of the cabin and out the outflow valve and the emergency relief valve, it is reasonable to use the smoke density measured in this area in order to determine the total aircraft air change τ . The τ of 58 computed from the aft cabin smoke data compares favorably with the calculated τ of 47 from equation 1.

Of particular interest is at what point in time will the pilot again be capable of viewing his instruments. Three different techniques were employed to determine this value and the results are listed in table 4.

The first method was to review the video recordings made of the tests to determine the time necessary to see the instrument panel once the smoke generator was turned off.

The second method was to use the smoke data to determine the time necessary to reach a specified light transmission once the smoke generator was turned off. This would correspond to the minimum time required for the pilot to view the instrument panel at a distance of 0.86 meters from his eyes to the instrument panel.

For visibility of non-illuminated signs (under 25 foot-lamberts), Jin (reference 7) gives the following relationship:

$$K \times L = 3.0 \quad \text{for non-illuminated signs} \quad (7)$$

where K is an extinction coefficient with units in inverse meters and L is the obscurity threshold in meters. Thus at a distance of 0.86 meters, the viewer would lose sight of a non-illuminated sign once the extinction coefficient reached 3.5.

"The physical basis for light extinction measurements is Bouguer's law, which relates the intensity of the incident monochromatic light of wavelength, I_0 , and the intensity of the light, I , transmitted through a path length, L , of the smoke

$$I/I_0 = e^{-KL} \quad (8)$$

where K is the extinction coefficient." (Reference 8). Using equation 8 and solving for the corresponding light transmission at 0.86 meters with an extinction coefficient of 3.5 yields

$$\begin{aligned} I/I_0 &= e^{(-KL)} \\ &= e^{(-3.5 \times .86)} \\ &= .05 \end{aligned}$$

Since I/I_0 represents the light transmission at the panel to pilot distance of 0.86 meters, it is necessary to convert this into the corresponding light transmission that would be seen by the 10-centimeter sampling length of the smoke meter. The relationship between light transmission and distance is

$$I_1/I_0 = (I/I_0)(L_1/L) \quad (9)$$

where I_0 is the light transmission with no particles present, I and I_1 are the light transmissions at their respective path lengths of L (0.86 meters) and L_1 (0.1 meters). Substituting I/I_0 and the two path lengths into equation 10 would yield an equivalent light transmission in percent at the smoke meter of

$$\begin{aligned} (I_1/I_0)(\%) &= (I/I_0)(L_1/L) \times 100 \quad (10) \\ &= .05(.1m/.86m) \times 100 \\ &= .71 \times 100 \\ &= 71\% \end{aligned}$$

Therefore, once reaching and exceeding this value the pilot would be able to view the instrument panel. These times were obtained by using the cockpit data in figures 30 through 33.

The third method calculated a value based on the perfect stirrer theory used in reference 4. Which indicates the time necessary for an enclosure to go from 5 percent visibility to 71 percent visibility is 2.2τ . Thus the calculated time for the pilot to see his instrument panel is

$$\begin{aligned} \text{Time} &= 2.2(\text{average calculated } \tau \text{ of cockpit}) \\ \text{Time} &= 2.2(33 \text{ seconds}) \\ &= 73 \text{ seconds} \end{aligned}$$

Review of the results of the three methods (table 4) yields comparable values of 78, 70, and 73 seconds from near zero visibility until the pilots were able to view the instrument panel, once the smoke generator was turned off.

TABLE 4. TIME TO VIEW INSTRUMENT PANEL

Figure #	Video Measured Time Seconds	Graphed Measured Time Seconds	Calculated Time Seconds
30	105	67	--
31	65	74	--
32	53	56	--
33	90	84	--
	---	---	---
Avg Time	78	70	73

Methods two and three were also used to determine the time it would take to view a non-illuminated sign in the cabin at the same distance (table 5). In method two, the mid cabin and aft cabin data in figures 30 through 35 were used to obtain the measured times. In method three, since the light transmission in the mid and aft areas only reached 10 percent, a value of 1.9(τ) was used as the time required to reach 71 percent light transmission. Calculated time for the mid and aft areas to reach 71 percent light transmission are

$$\begin{aligned}\text{Time} &= (1.9)(59) \\ &= 112 \text{ seconds}\end{aligned}$$

$$\begin{aligned}\text{Time} &= (1.9)(58) \\ &= 110 \text{ seconds}\end{aligned}$$

and are shown in table 5.

Review of table 5 shows that the calculated times of 112 and 110 seconds compare quite favorable with the measured times of 109 and 105 seconds for the mid and aft cabin areas respectively.

TABLE 5. TIME TO VIEW EMERGENCY SIGNS

Figure #	Measured Time Mid Cabin Seconds	Measured Time Aft Cabin Seconds	Cal. Time Mid Cabin Seconds	Cal. Time Aft Cabin Seconds
30	152	133	---	---
31	---	105	---	---
32	115	125	---	---
33	132	129	---	---
34	67	66	---	---
35	79	73	---	---
	---	---	---	---
Avg Time	109	105	112	110

SUMMARY OF SMOKE ELIMINATION RESULTS.

Artificial smoke from a smoke generator was released at various locations in a Cessna 421B aircraft pressurized to 5.6 psig. The smoke concentration was measured in the cockpit and in the mid and aft cabin areas. A video camera was mounted at what would be the copilot's eye level to view the instrument panel.

Calculations from the smoke data indicated that the cockpit air change rate was higher than that of the cabin area. This was confirmed by visual observations.

Calculated values of air change times from the smoke data compared favorably with the values derived from the pressure/flow measurements.

The average time for the copilot to view the non-illuminated instrument panel once the smoke generator was turned off was found using three methods. The resulting times were in close agreement with each other.

Two methods were used to determine the average time for a person to view a non-illuminated sign in the cabin once the smoke generator was turned off. Comparable results were obtained from the measured data and the calculated values using the perfect stirrer theory.

CONCLUSIONS

1. Hand held Halon 1211 fire extinguishers of 2.5-pound capacity and Halon 1301 of 3 pound capacity are safe for use in pressurized aircraft similar in size to the Cessna Model 421B.
2. Ventilation of the pressurized aircraft was a major factor in producing safe conditions at the pilot or passengers' nose level. Calculation of exposure to the neat halons in terms of dose for the pilot and passengers was low.
3. Halon gases dissipated rapidly in the pressurized aircraft.
4. Once the smoke source was eliminated, the higher cockpit air change rate helped to clear smoke in the cockpit faster than in any other area in the aircraft.
5. The higher air change rates in the cockpit were responsible for keeping smoke not originating directly in that area from obstructing the crew's view of the instrumentation.
6. The application of perfect stirrer theory to small, well ventilated aircraft produces comparable results with actual tests.
7. Once the smoke source is eliminated, the crew's view of the instrument panel at a distance of 0.86 meters will be restored from near zero visibility in 75 seconds.
8. Once the smoke source is eliminated, it will take approximately 110 seconds to view a non-illuminated emergency sign in the cabin at a distance of 0.86 meters.

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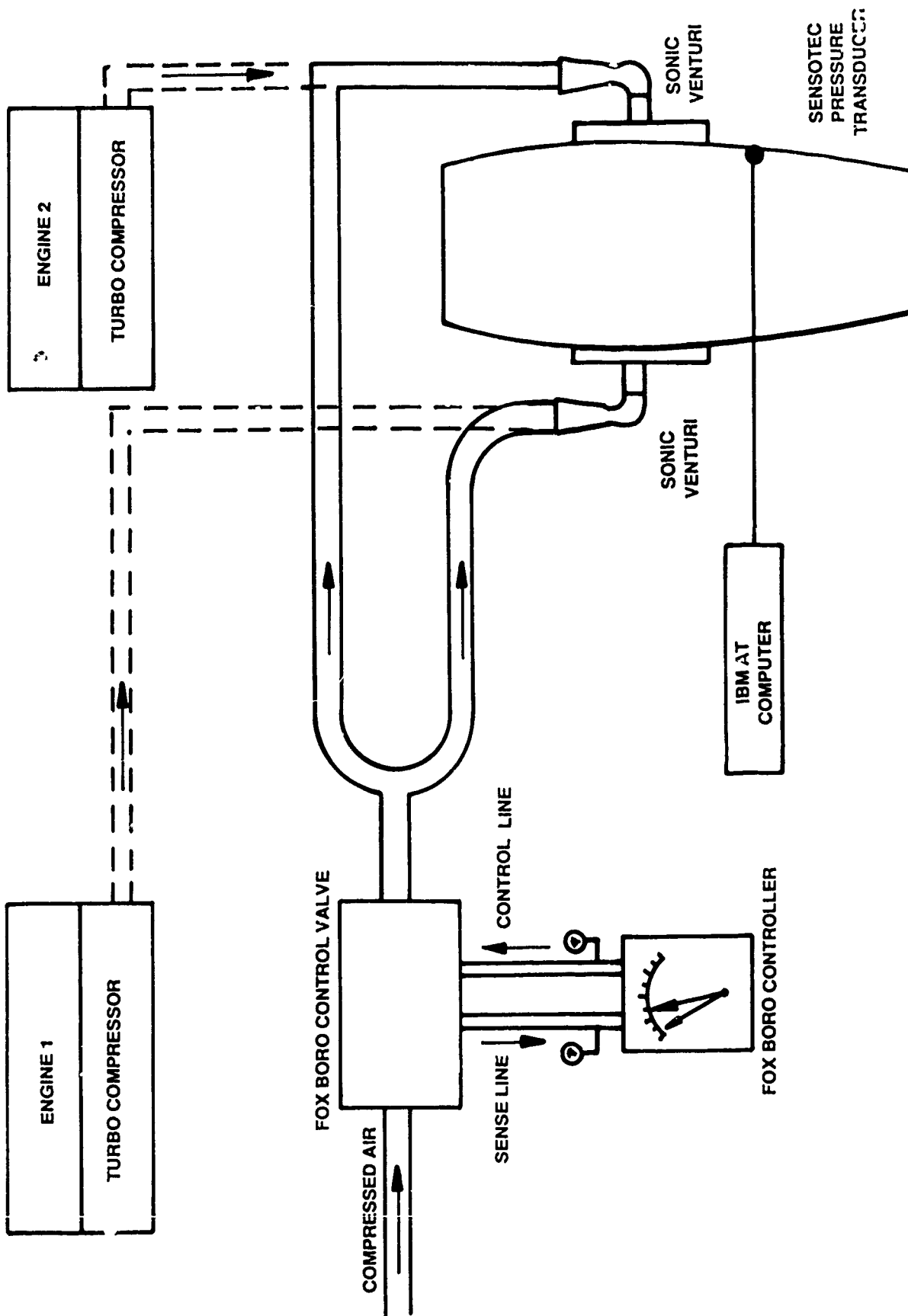


FIGURE 1. AIR PRESSURIZATION SYSTEM

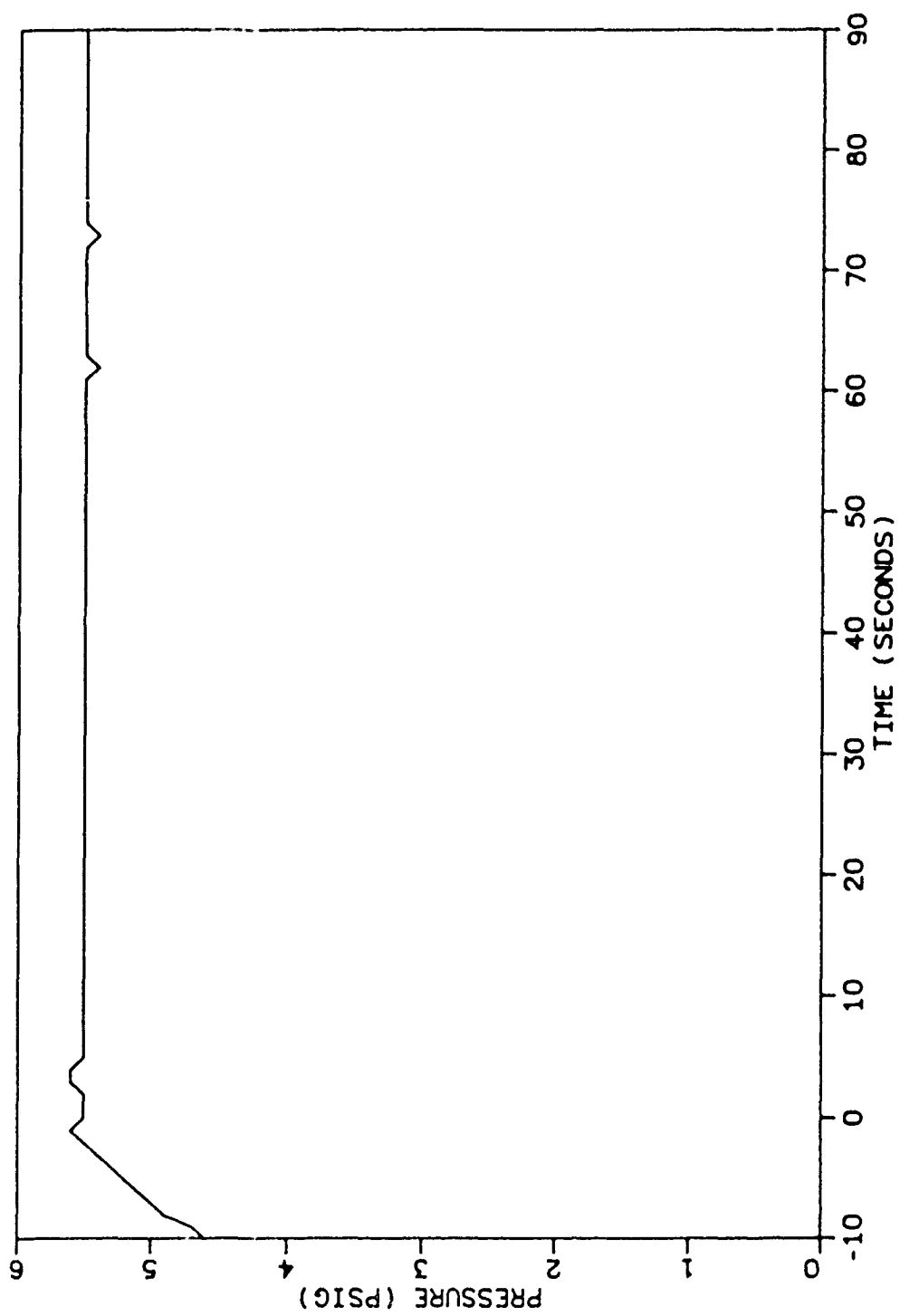


FIGURE 2. CABIN PRESSURE

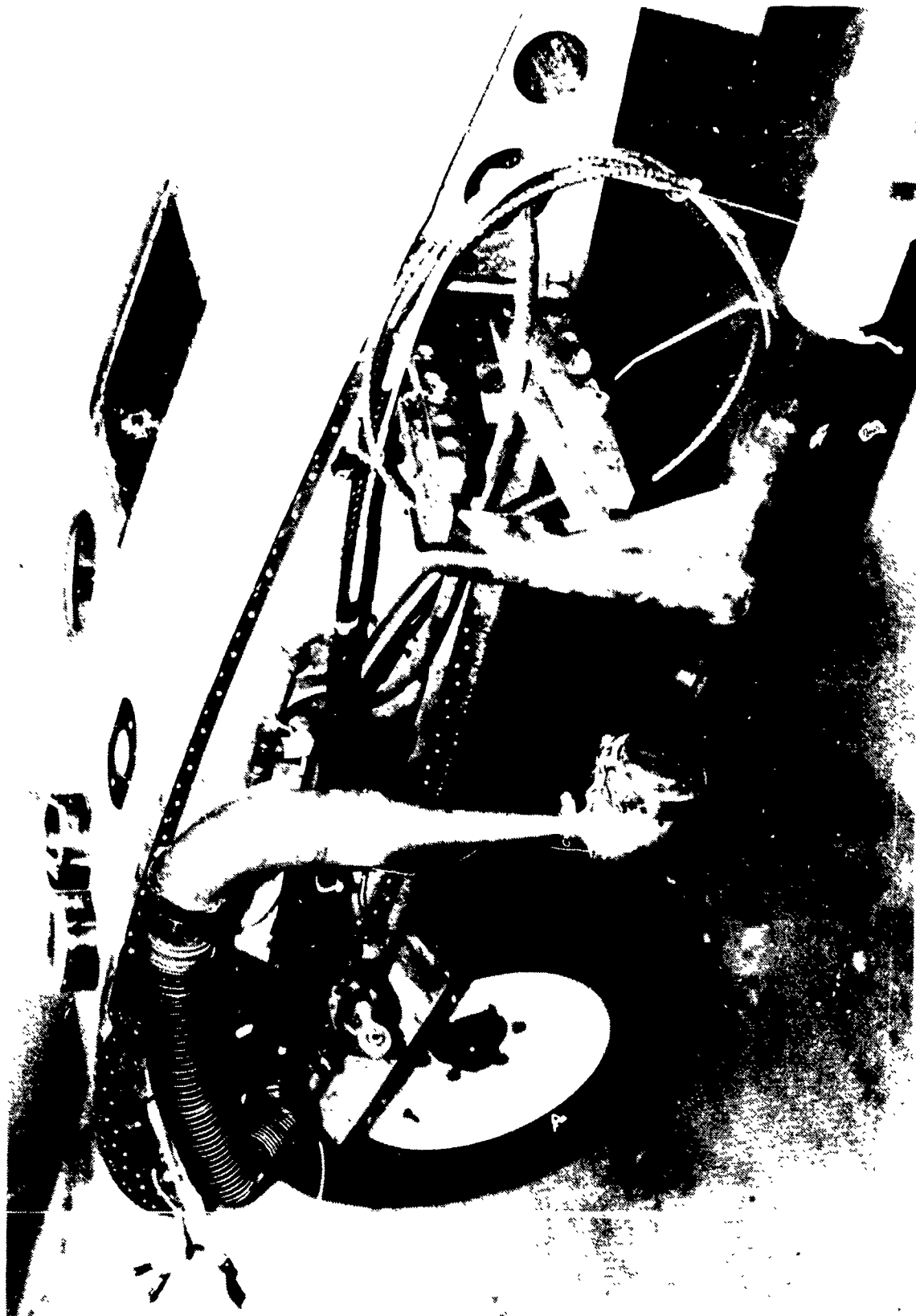


FIGURE 3. SONIC VENTURI

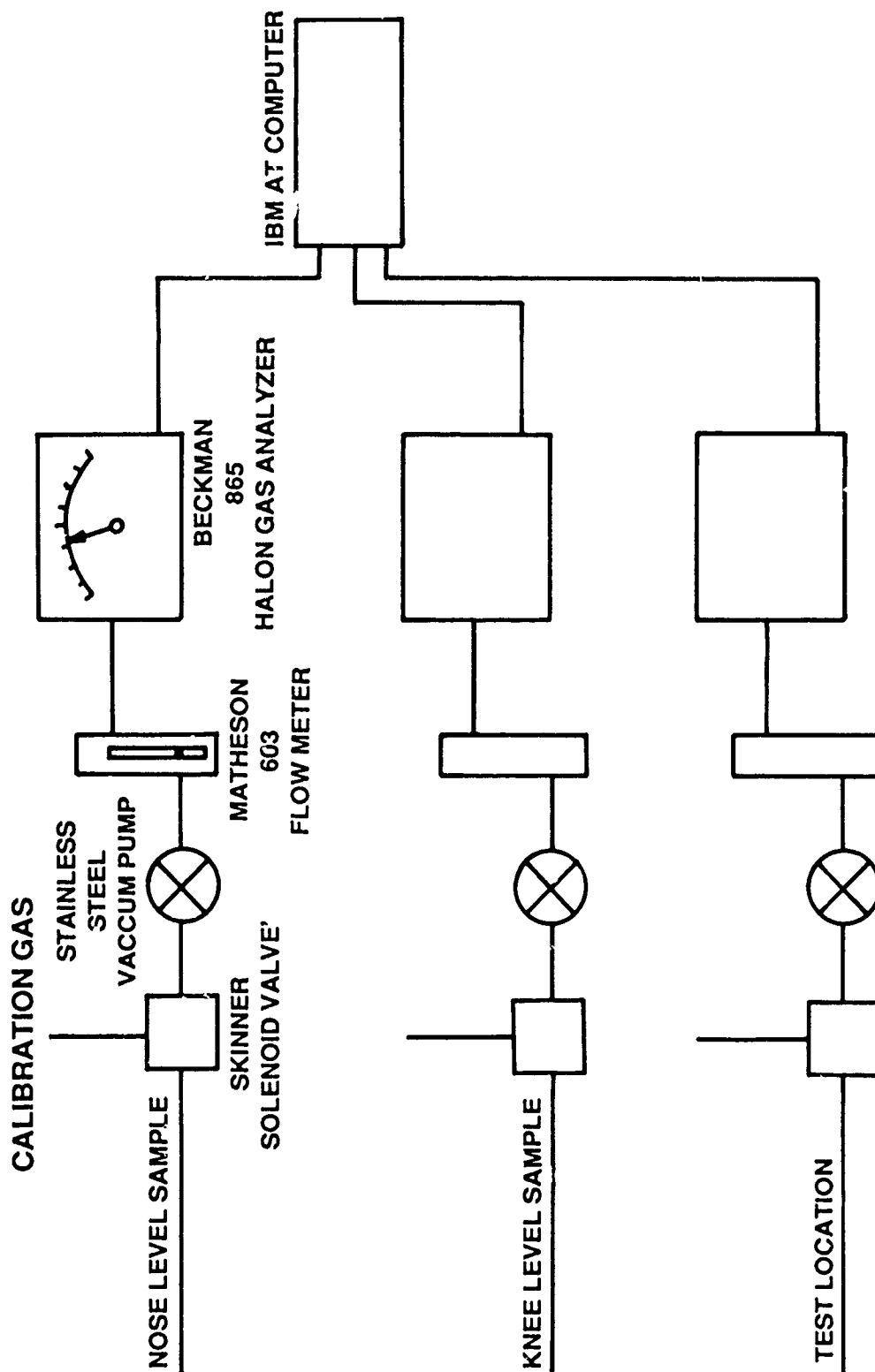
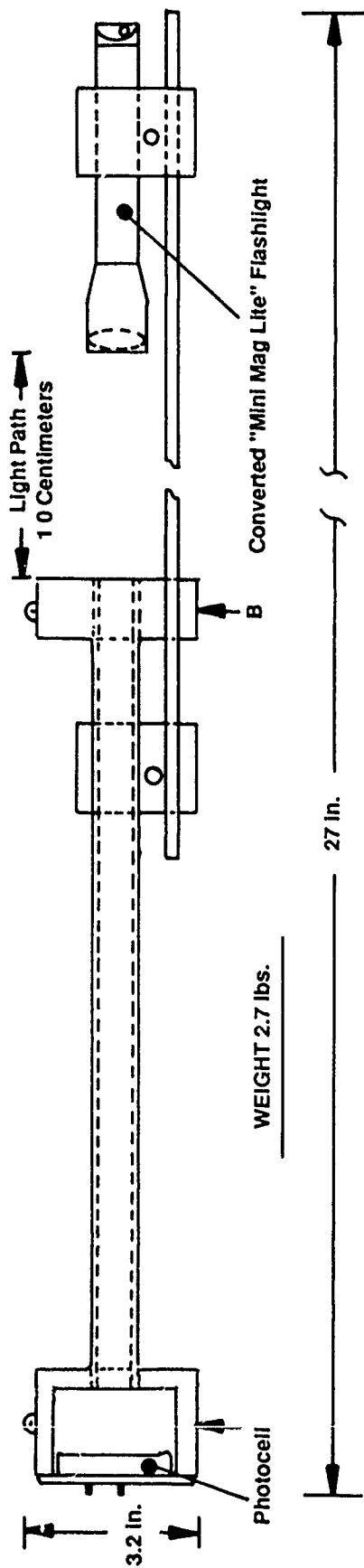


FIGURE 4. GAS SAMPLING SYSTEM



Federal Aviation Administration Aerosol Meter (FAAAM)

A&B 1/4" X 20 THREADED HOLES

FIGURE 5. FEDERAL AVIATION ADMINISTRATION AEROSOL SMOKE METER

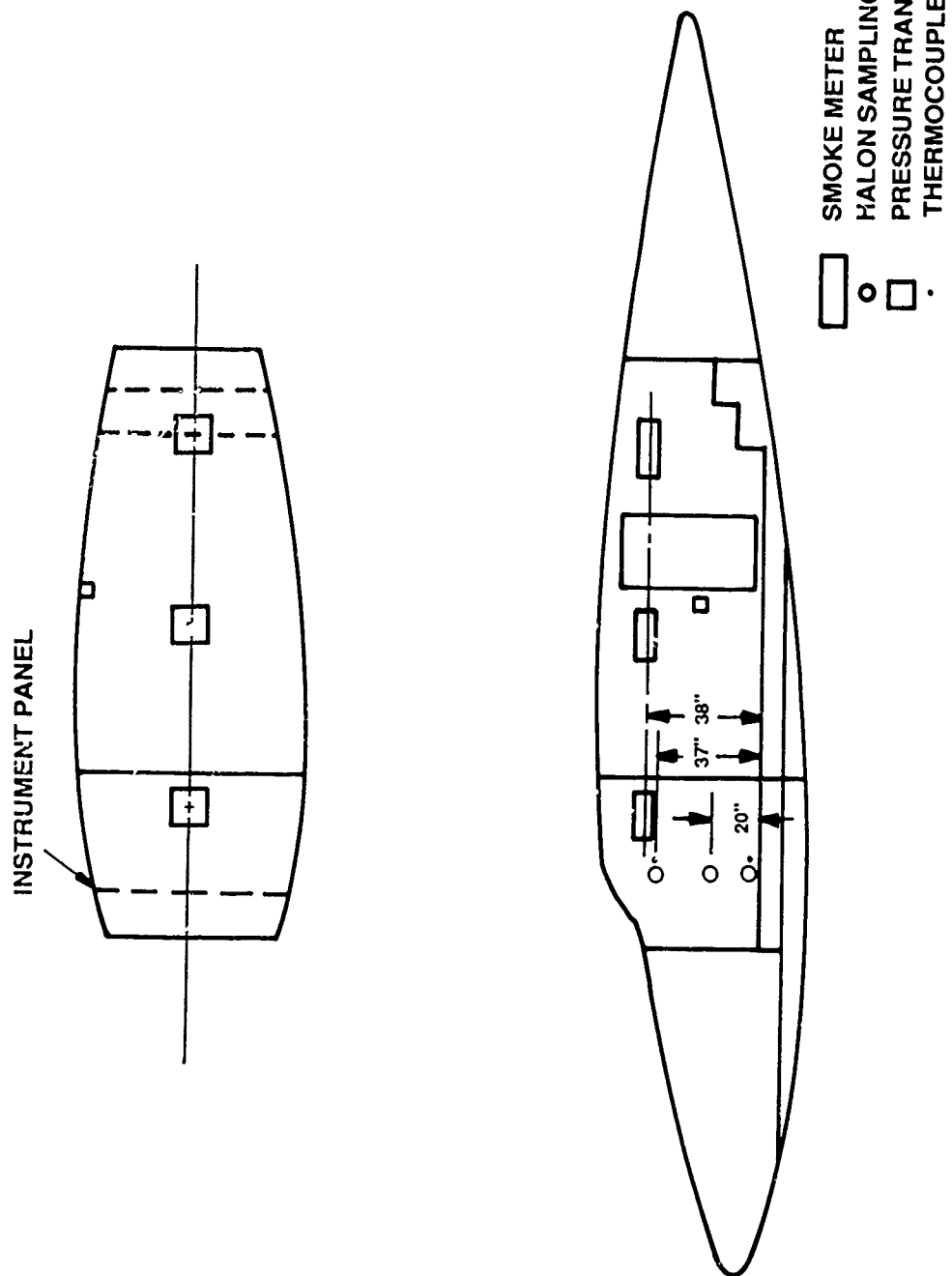


FIGURE 6. INSTRUMENTATION

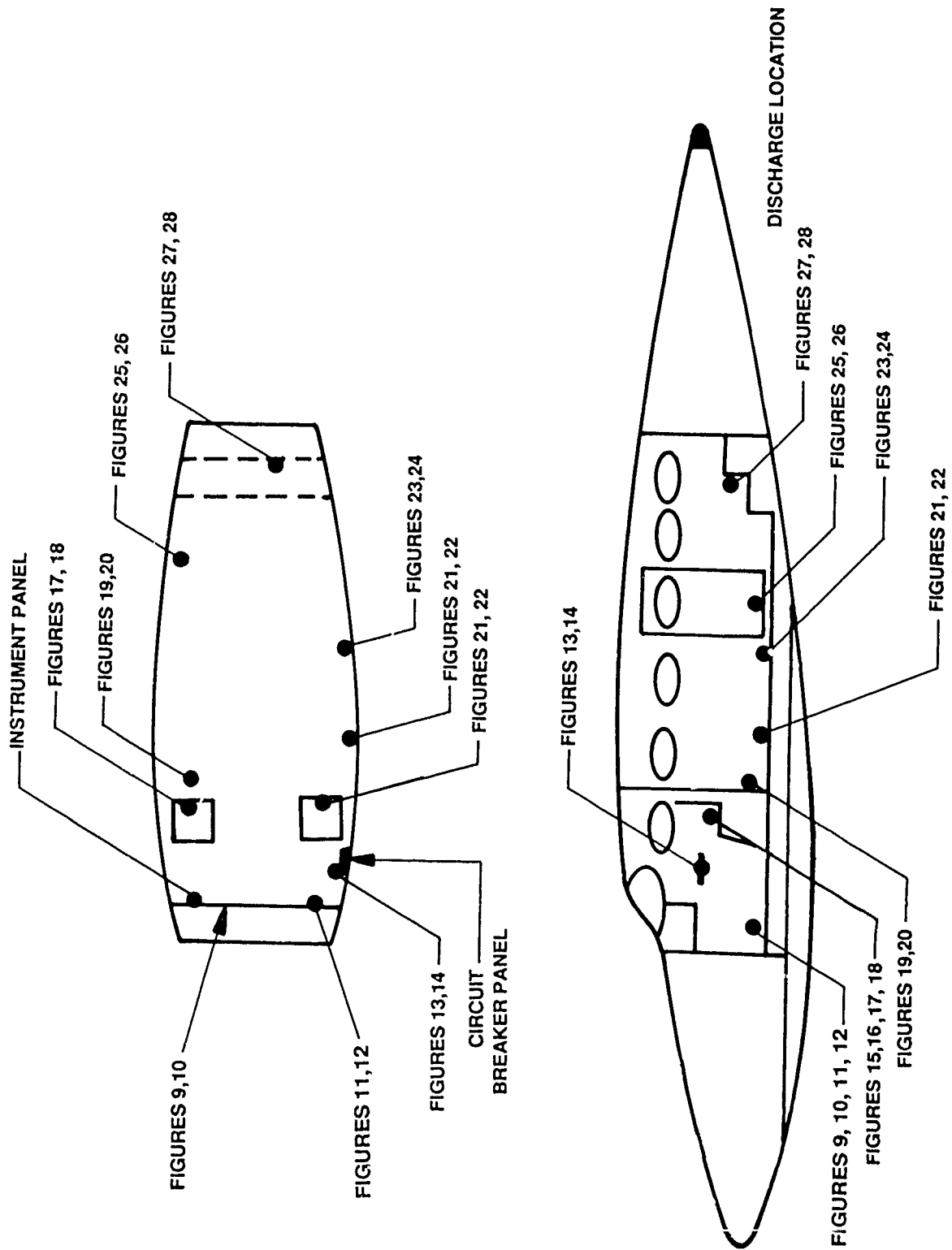


FIGURE 7. HALON TEST LOCATIONS

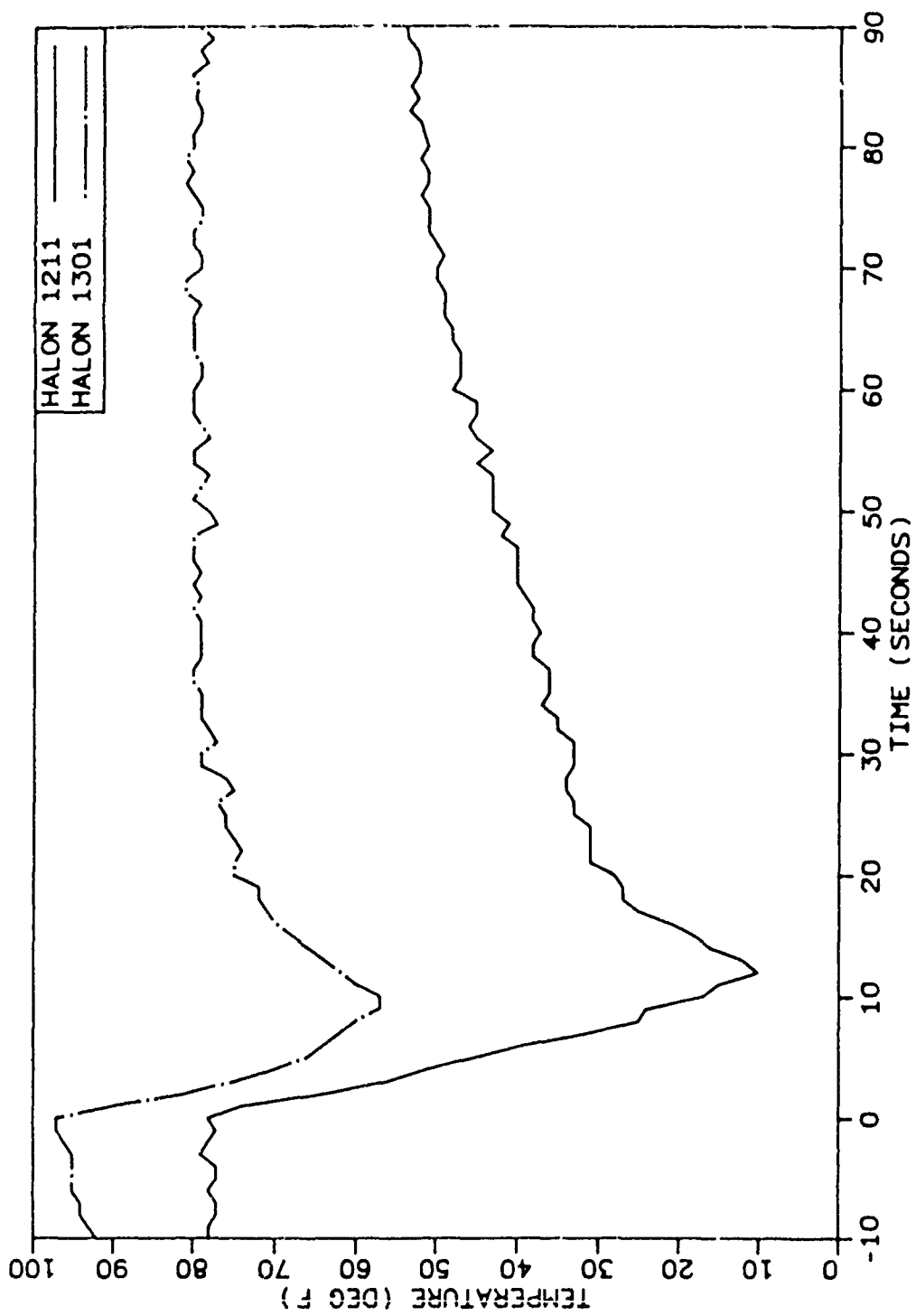


FIGURE 8. MAXIMUM DISCHARGE TEMPERATURE DIFFERENTIALS

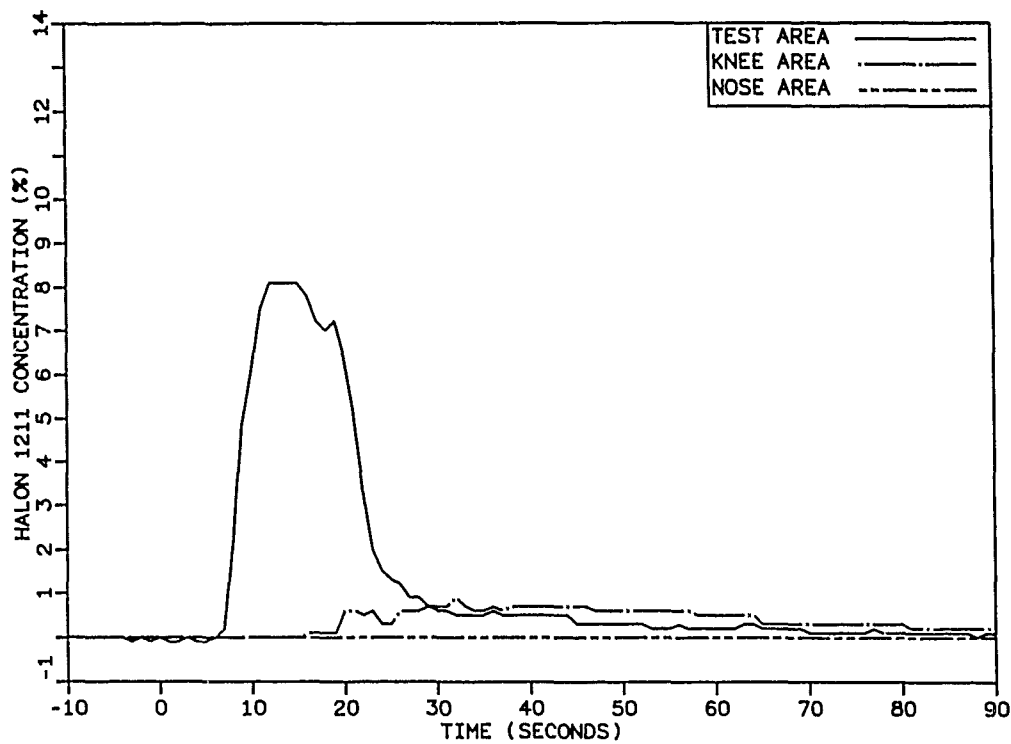


FIGURE 9. HALON 1211 CONCENTRATIONS UNDER THE INSTRUMENT PANEL
COPILOT'S SIDE

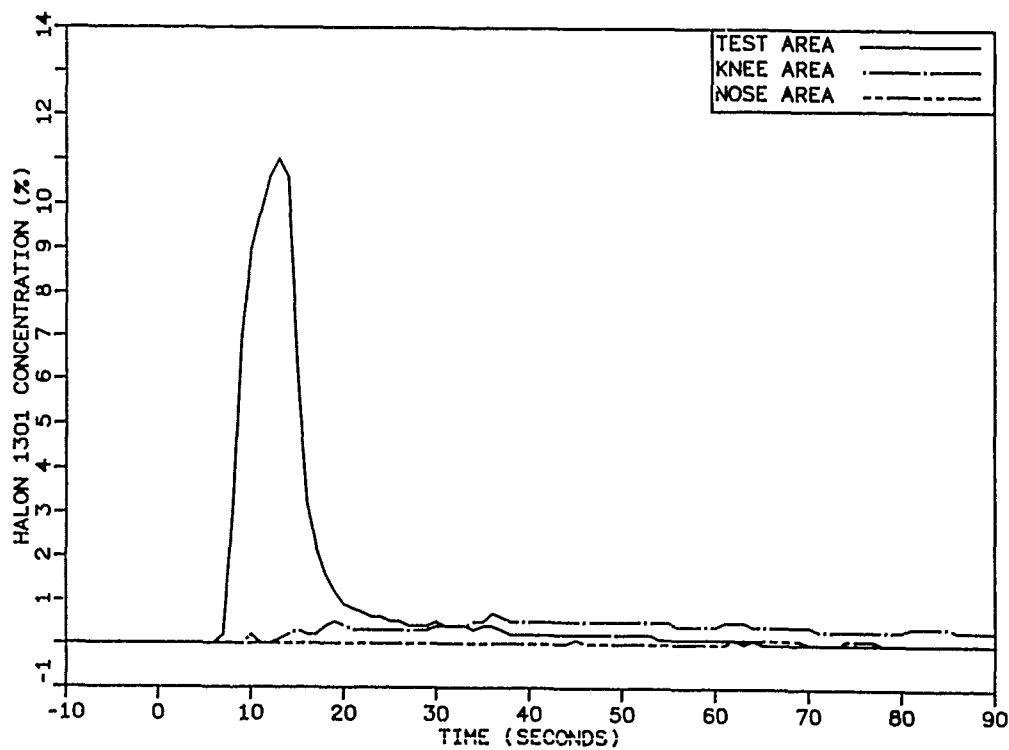


FIGURE 10. HALON 1301 CONCENTRATIONS UNDER THE INSTRUMENT PANEL
COPILOT'S SIDE

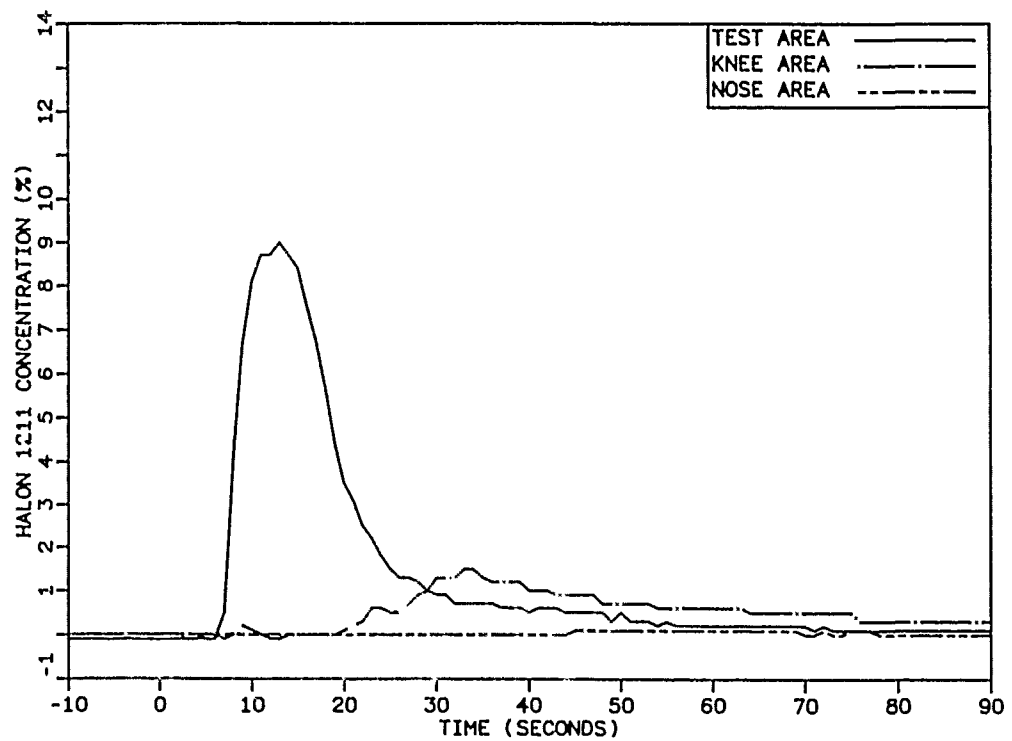


FIGURE 11. HALON 1211 CONCENTRATIONS UNDER THE INSTRUMENT PANEL PILOT'S SIDE

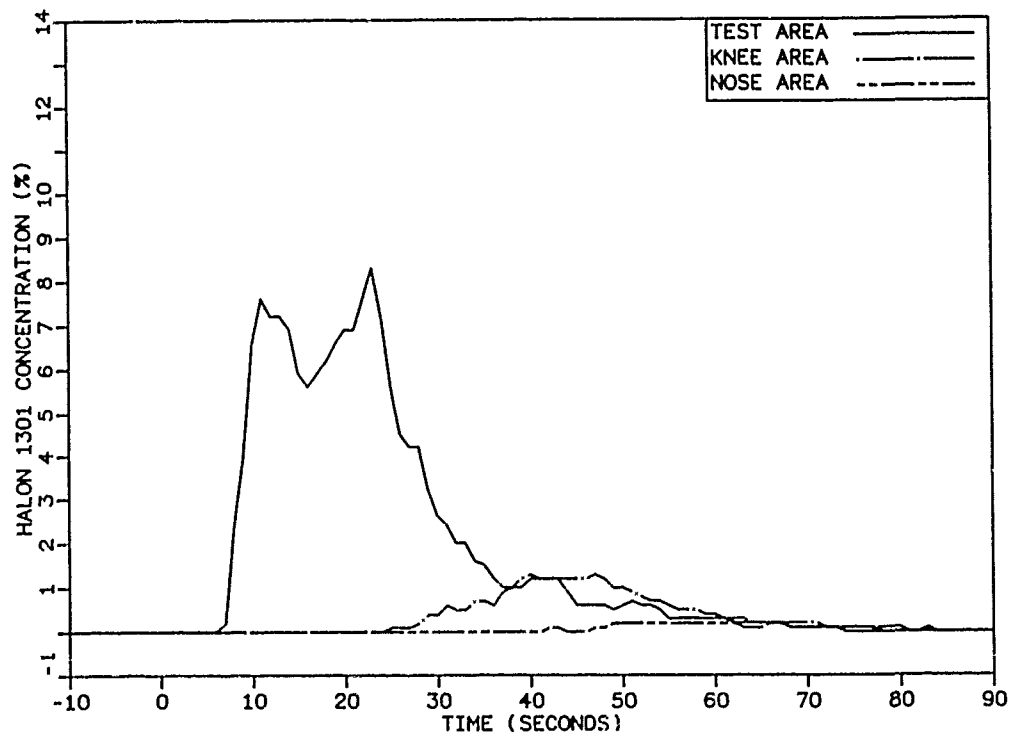


FIGURE 12. HALON 1301 CONCENTRATIONS UNDER THE INSTRUMENT PANEL PILOT'S SIDE

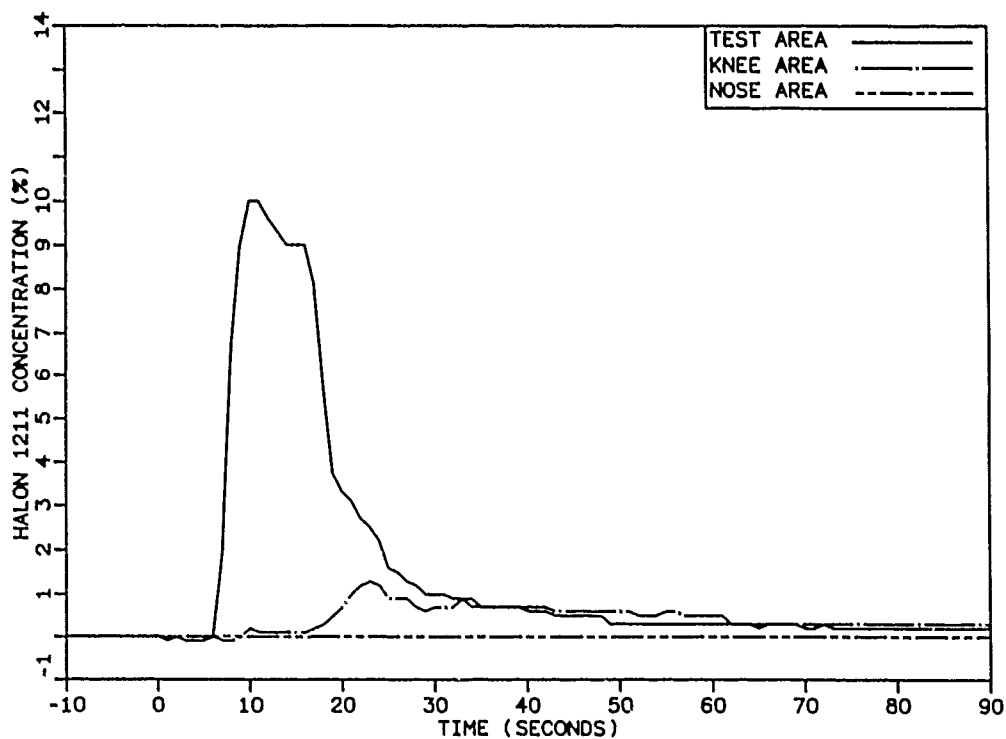


FIGURE 13. HALON 1211 CONCENTRATIONS CIRCUIT BREAKER PANEL PILOT'S SIDE

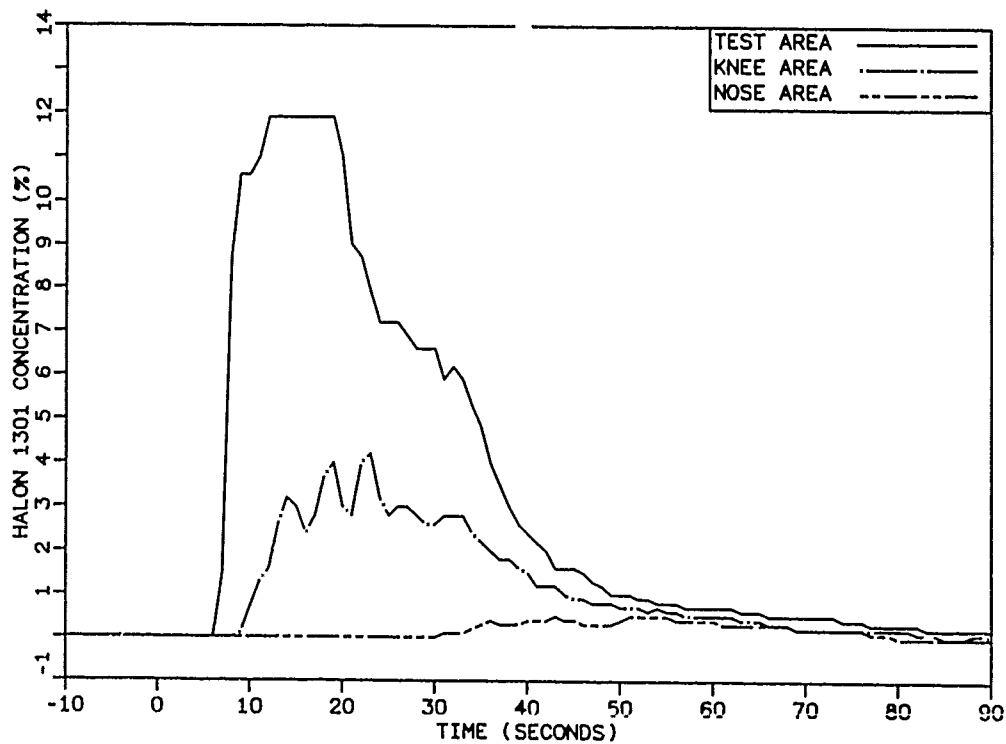


FIGURE 14. HALON 1301 CONCENTRATIONS CIRCUIT BREAKER PANEL PILOT'S SIDE

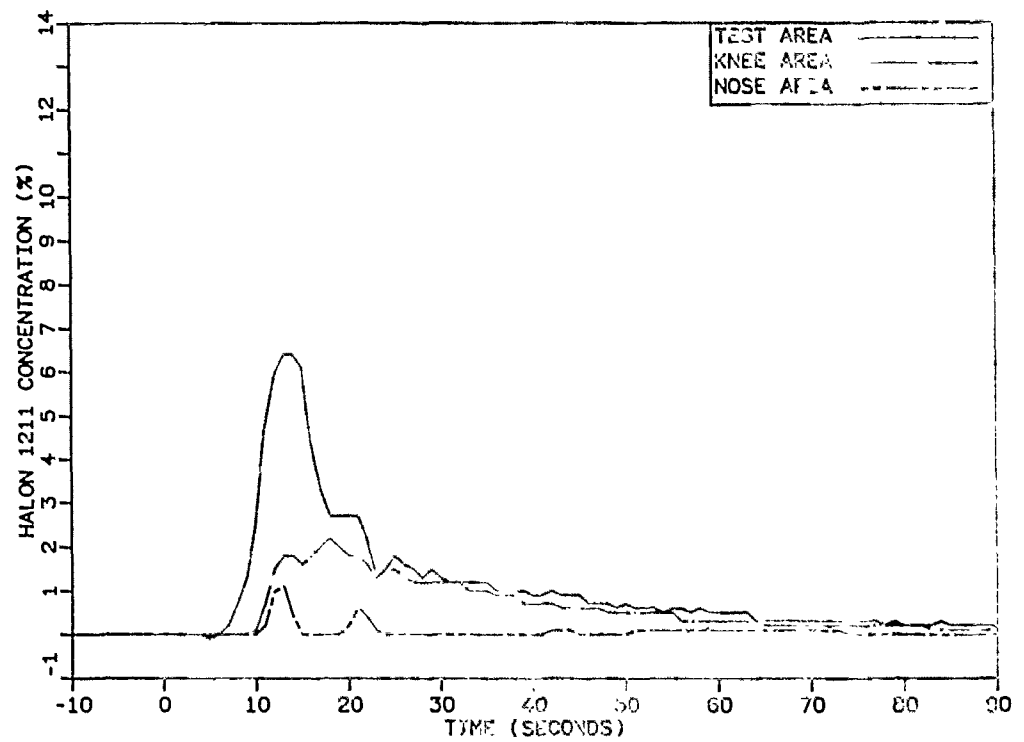


FIGURE 15. HALON 1211 CONCENTRATIONS PILOT'S SEAT

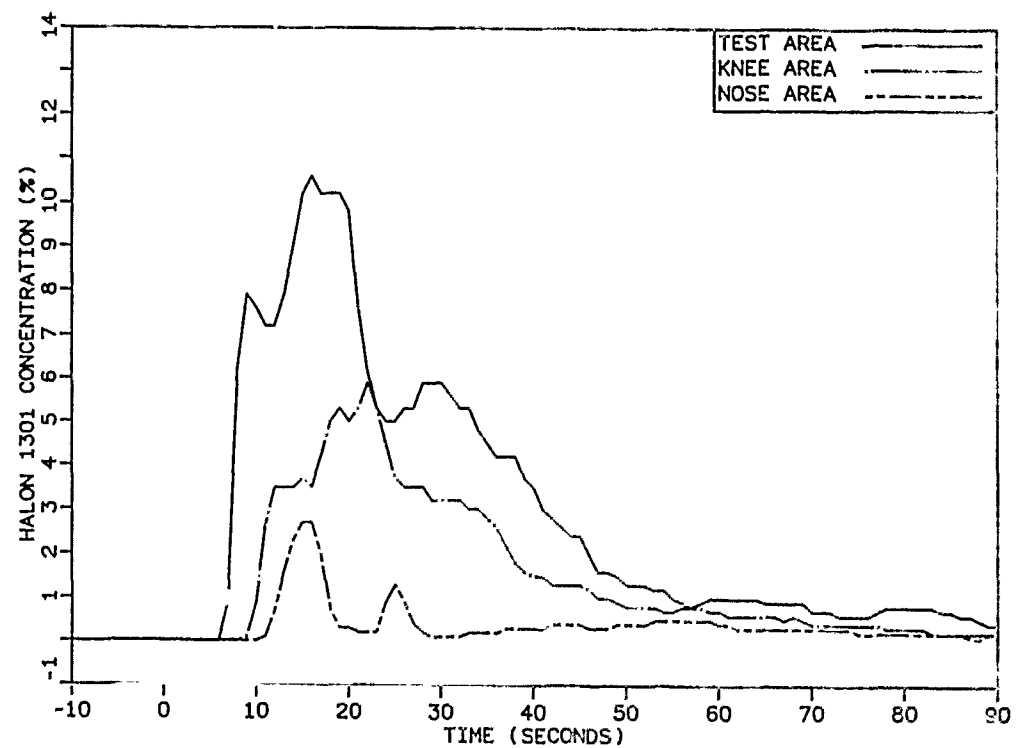


FIGURE 16. HALON 1301 CONCENTRATIONS PILOT'S SEAT

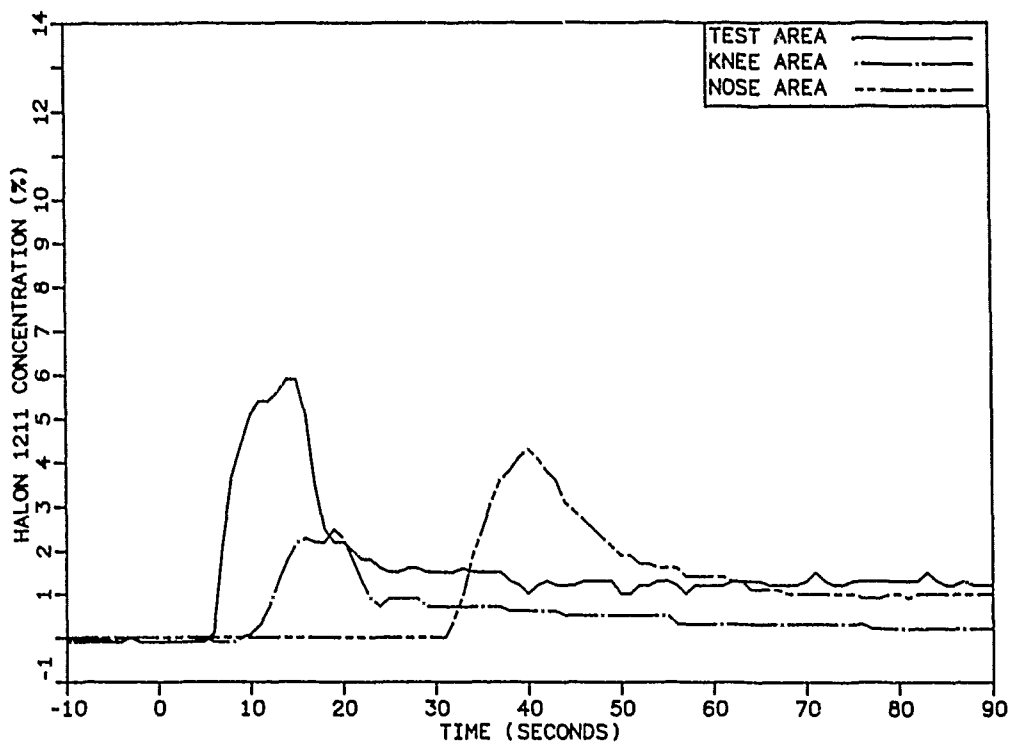


FIGURE 17. HALON 1211 CONCENTRATIONS COPILOT'S SEAT

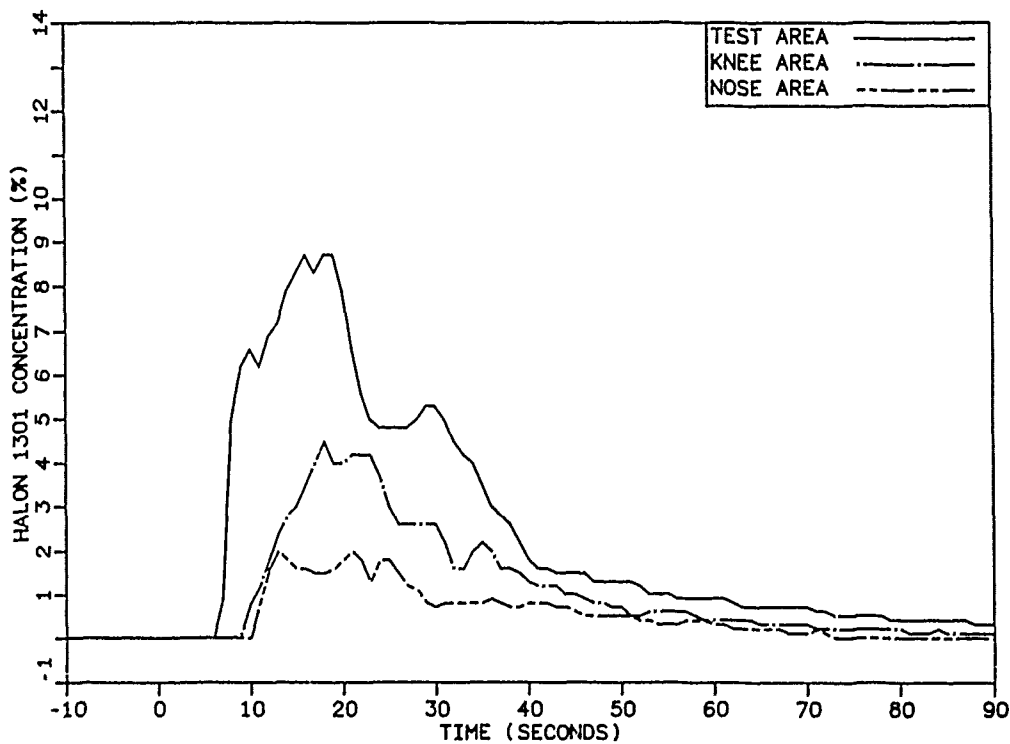


FIGURE 18. HALON 1301 CONCENTRATIONS COPILOT'S SEAT

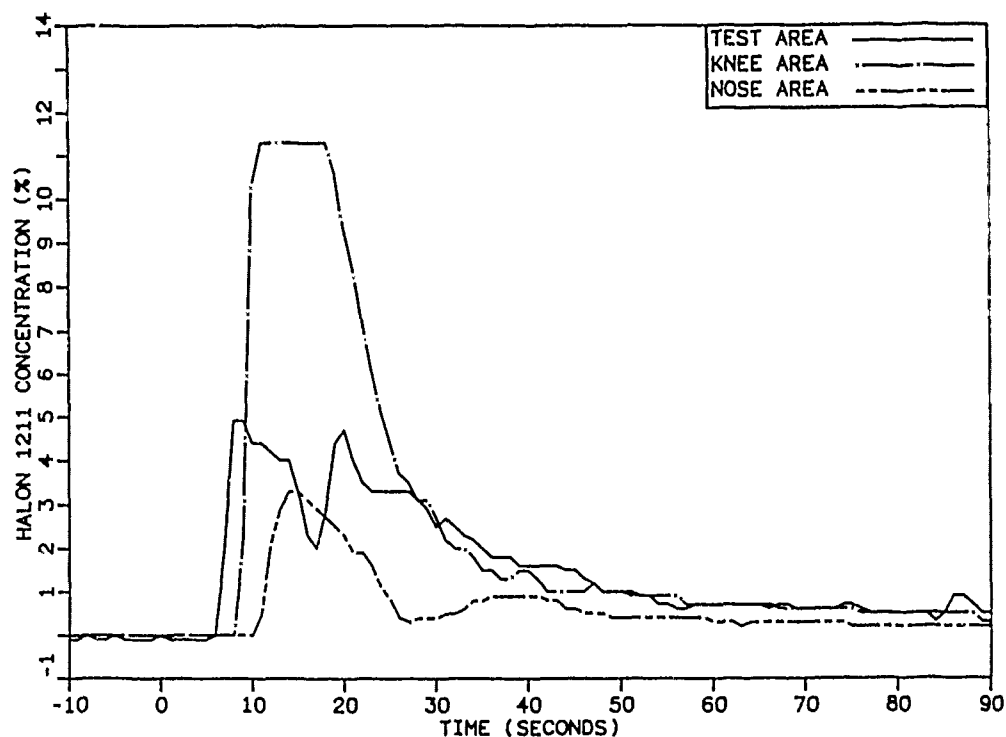


FIGURE 19. HALON 1211 CONCENTRATIONS CABIN SIDE OF GRILL UNDER COPILOT'S SEAT

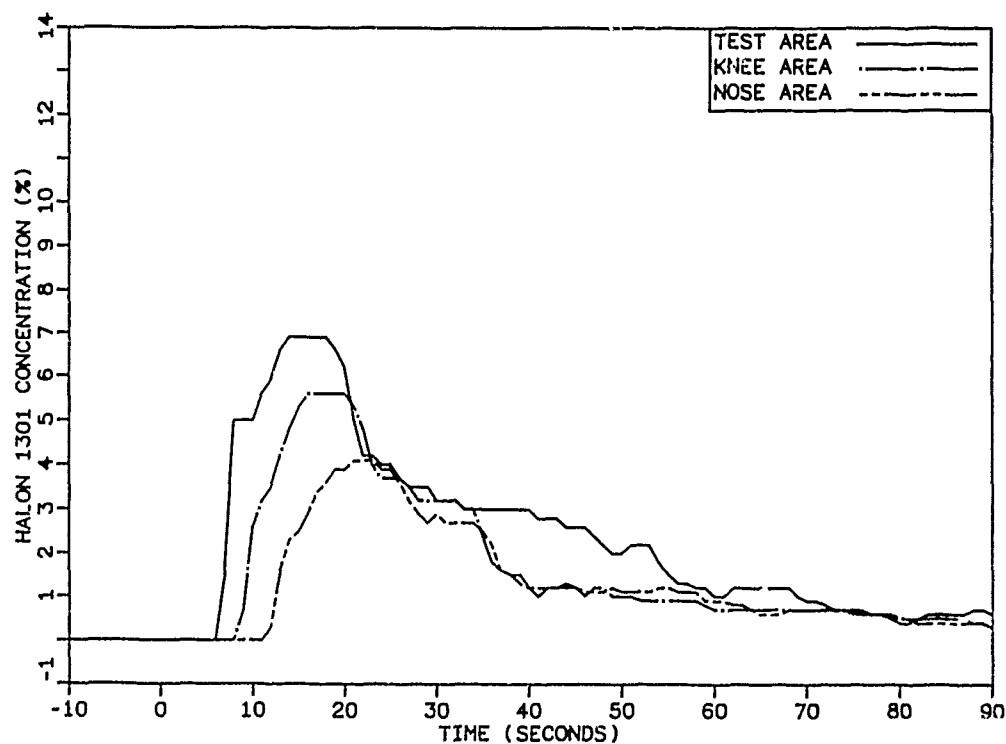


FIGURE 20. HALON 1301 CONCENTRATIONS CABIN SIDE OF GRILL UNDER COPILOT'S SEAT

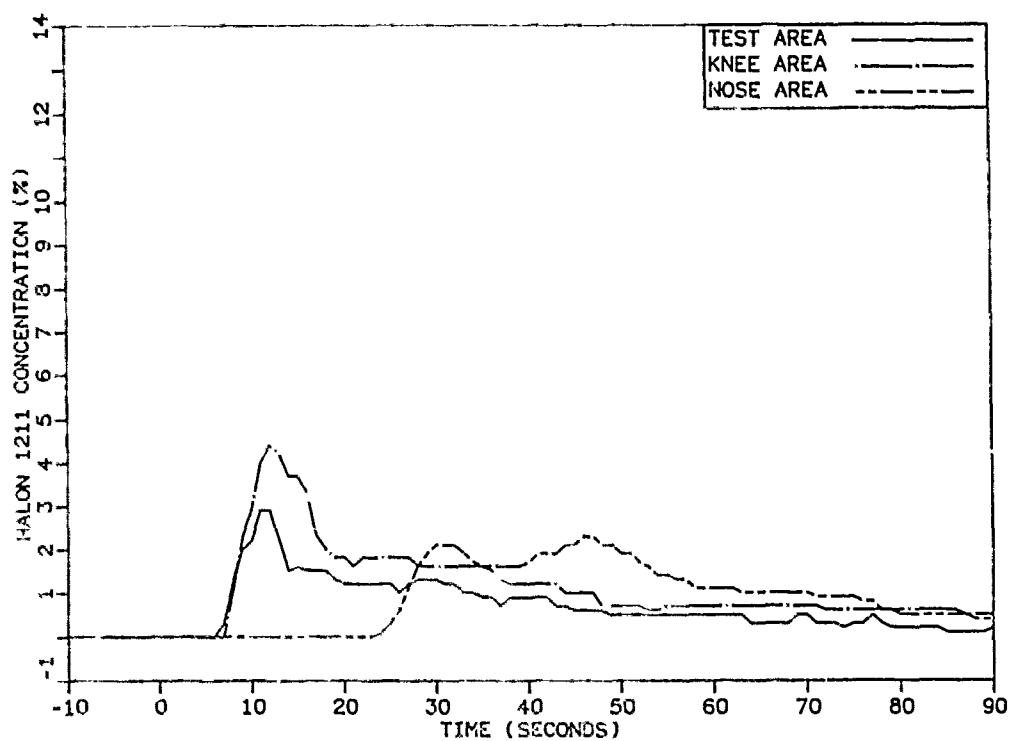


FIGURE 21. HALON 1211 CONCENTRATIONS CABIN AREA SECOND VENT NEAR FLOOR LEFT SIDE

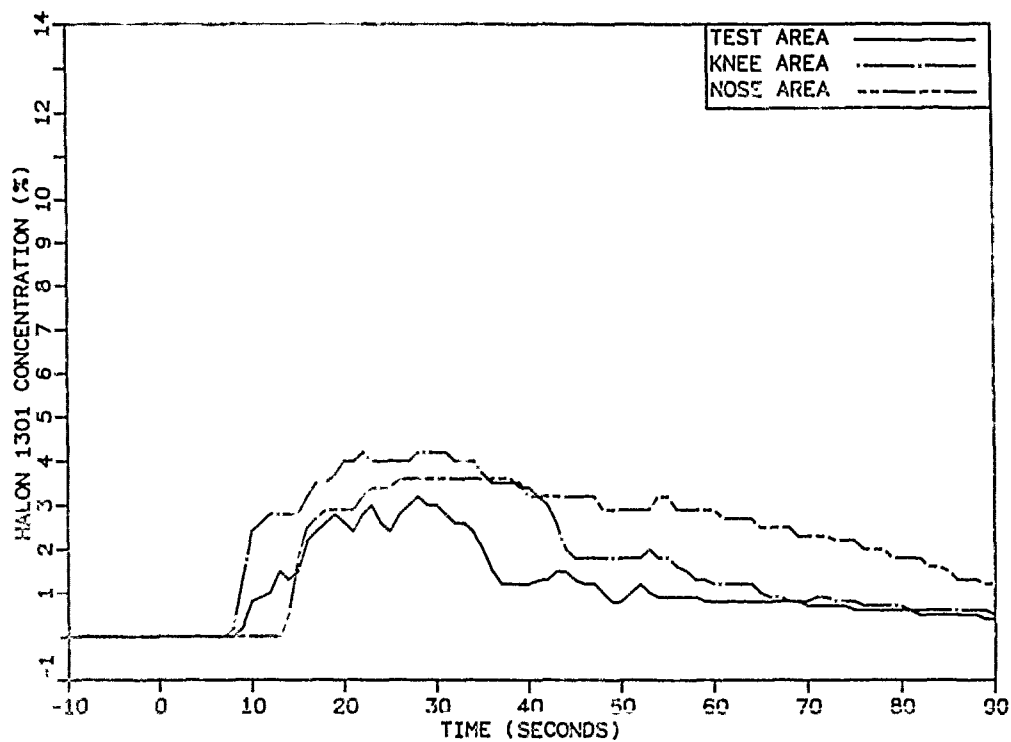


FIGURE 22. HALON 1301 CONCENTRATIONS CABIN AREA SECOND VENT NEAR FLOOR LEFT SIDE

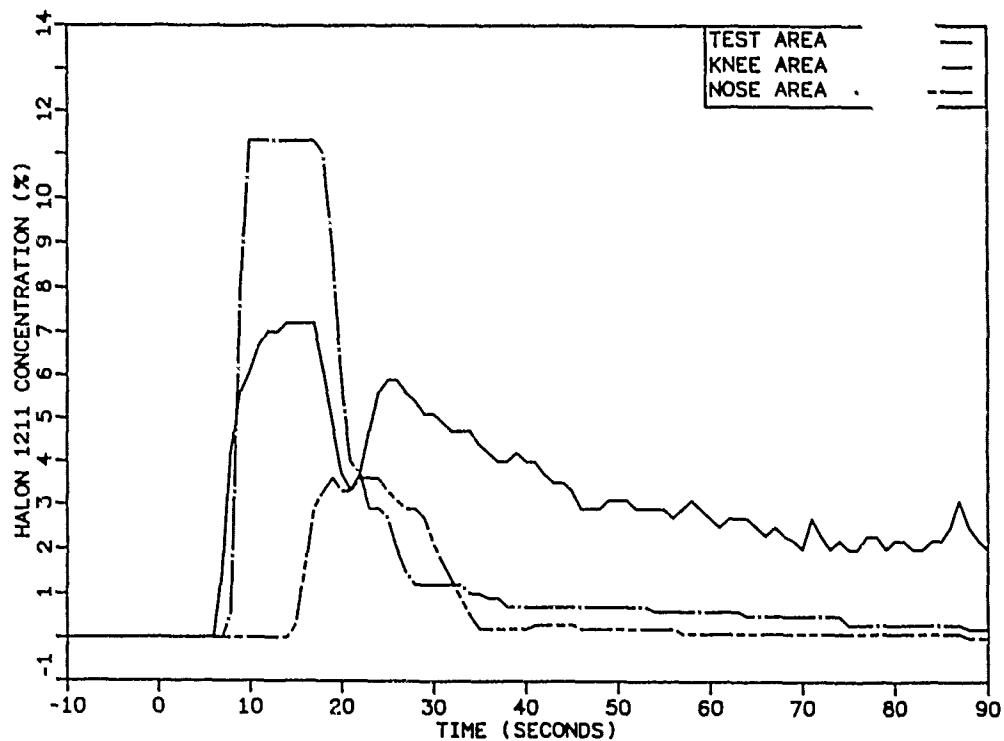


FIGURE 23. HALON 1211 CONCENTRATIONS CABIN AREA LAST VENT BEFORE DOOR LEFT SIDE

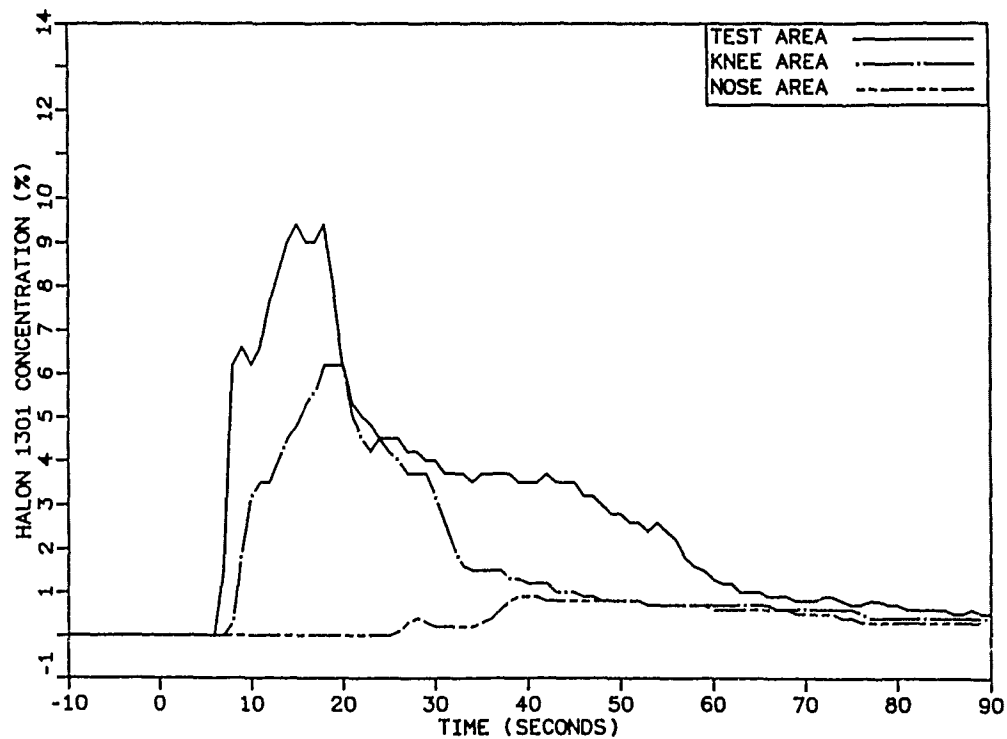


FIGURE 24. HALON 1301 CONCENTRATIONS CABIN AREA LAST VENT BEFORE DOOR LEFT SIDE

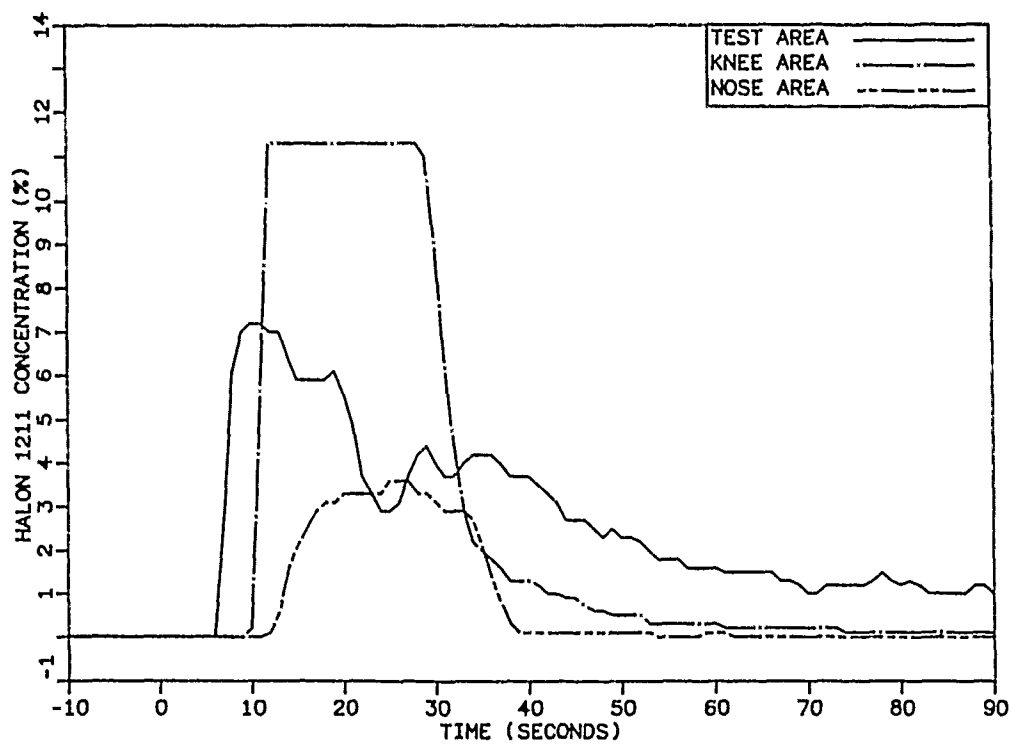


FIGURE 25. HALON 1211 CONCENTRATIONS CABIN AREA LAST VENT RIGHT SIDE

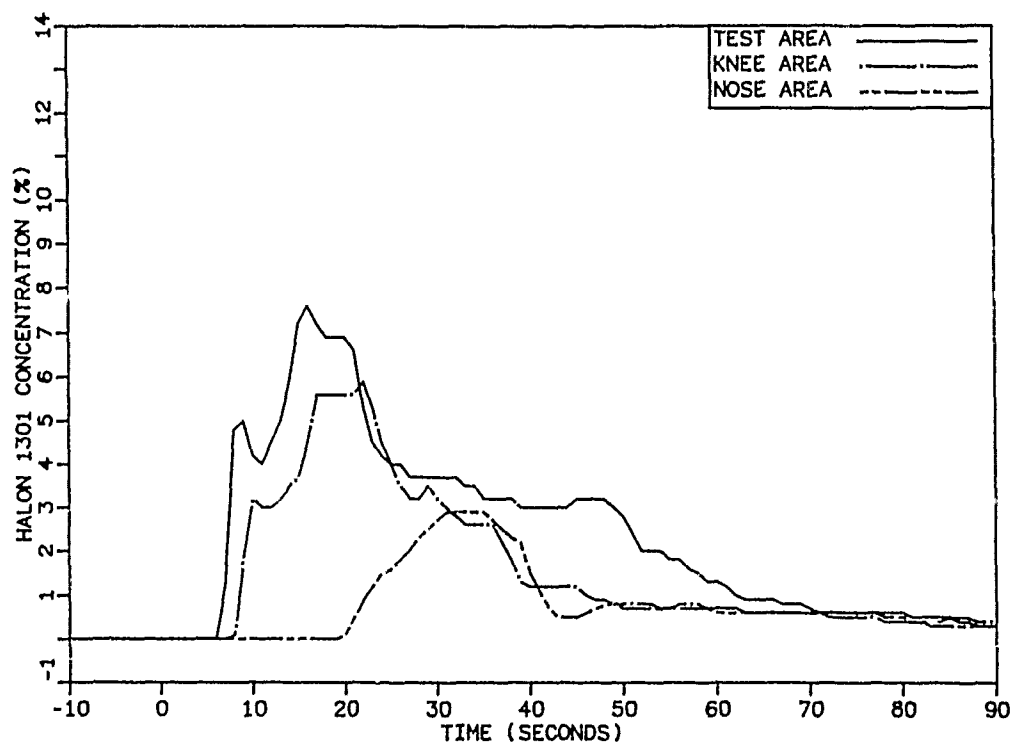


FIGURE 26. HALON 1301 CONCENTRATIONS CABIN AREA LAST VENT RIGHT SIDE

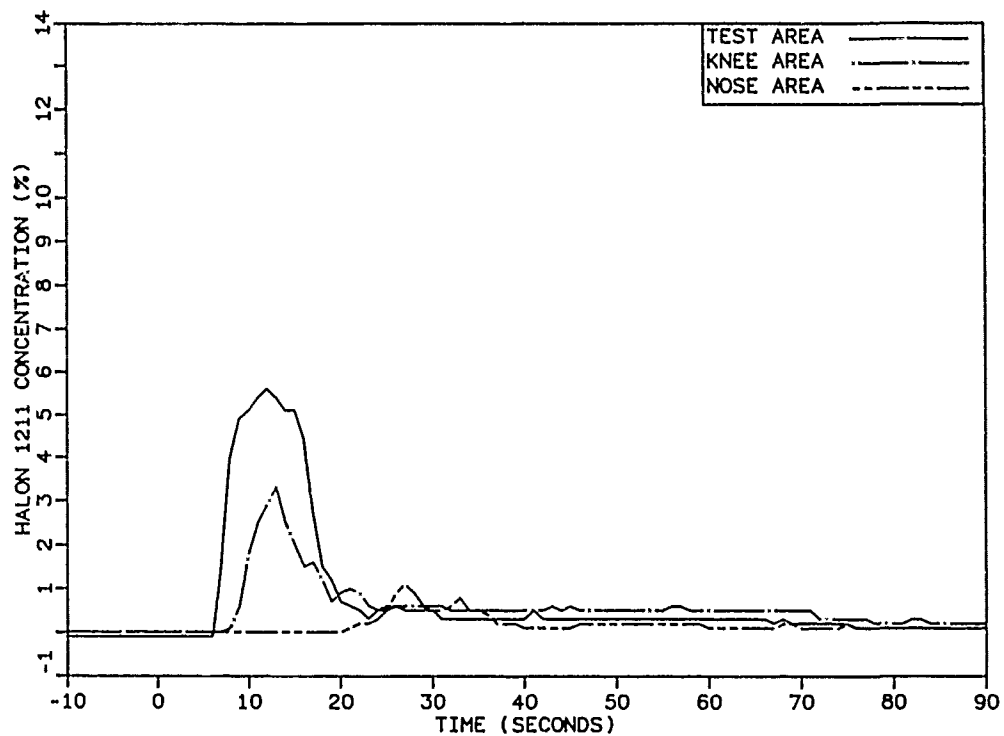


FIGURE 27. HALON 1211 CONCENTRATIONS IN REAR CABIN AT 110-VOLT OUTLET

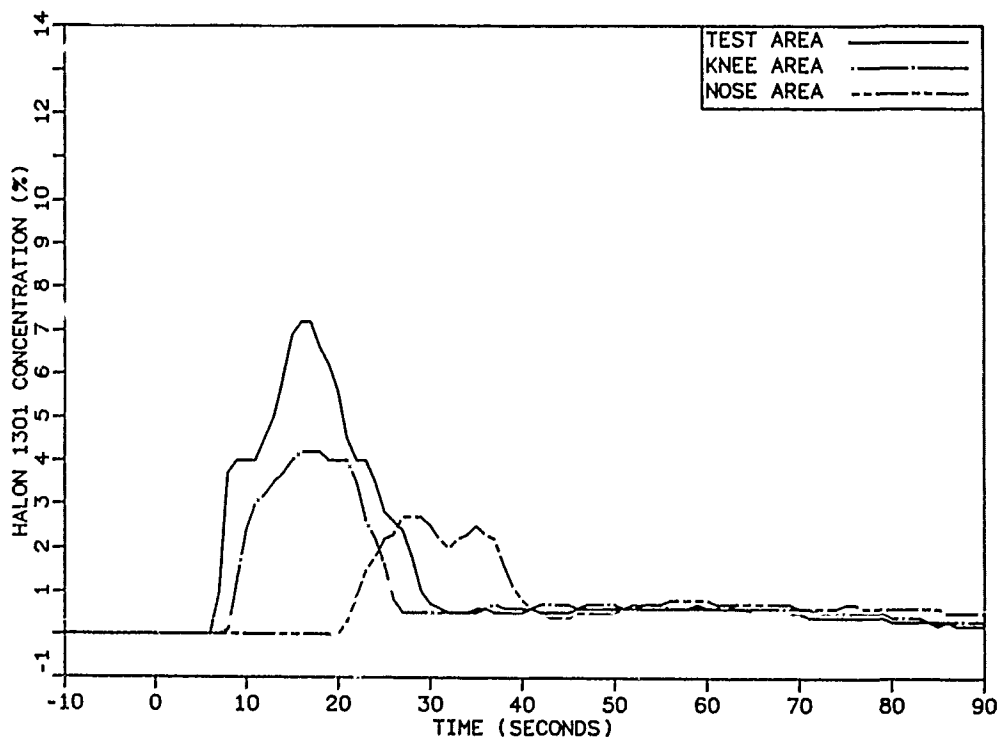


FIGURE 28. HALON 1301 CONCENTRATIONS IN REAR CABIN AT 110-VOLT OUTLET

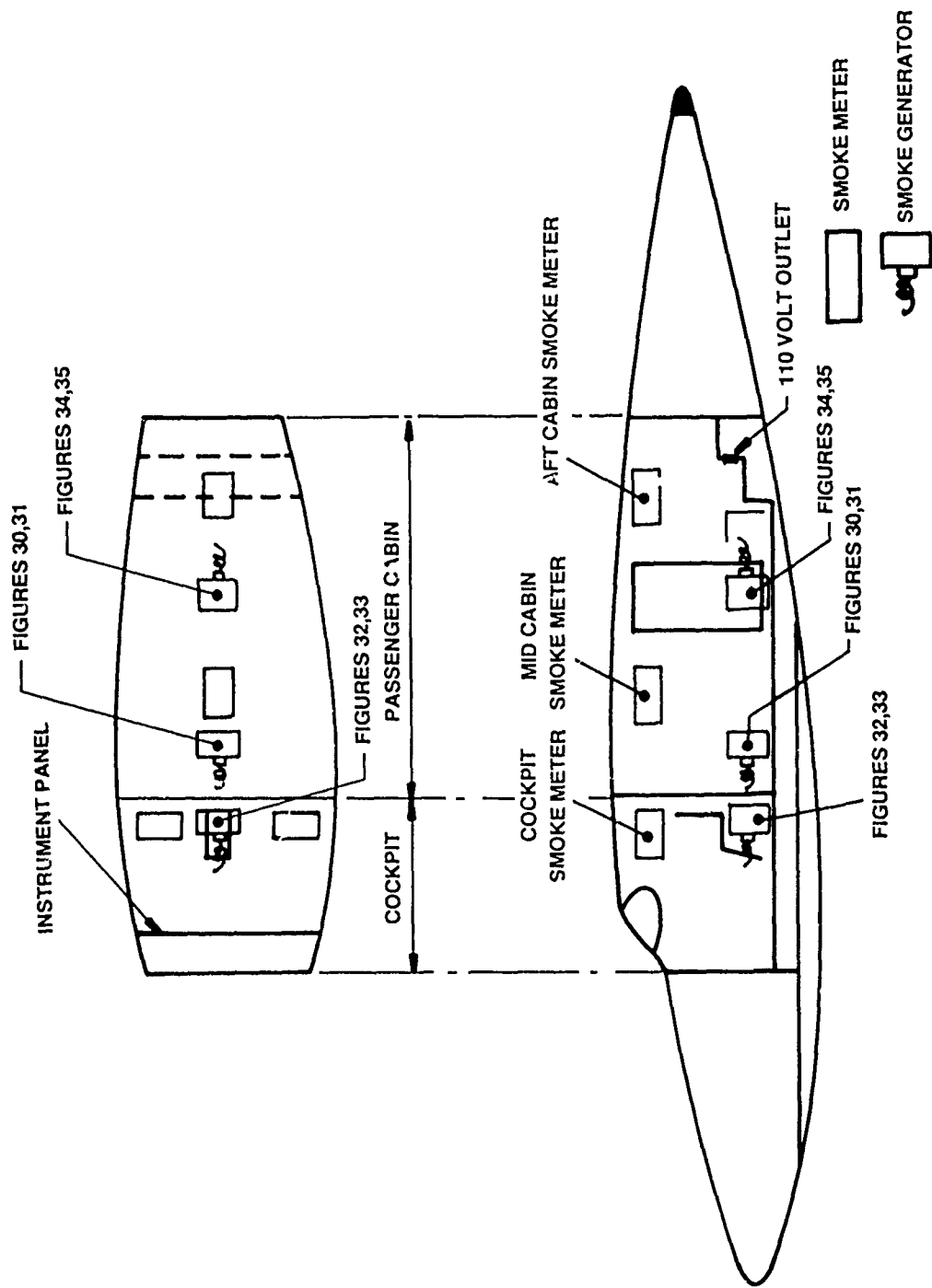


FIGURE 29. SMOKE METER/GENERATOR LOCATIONS

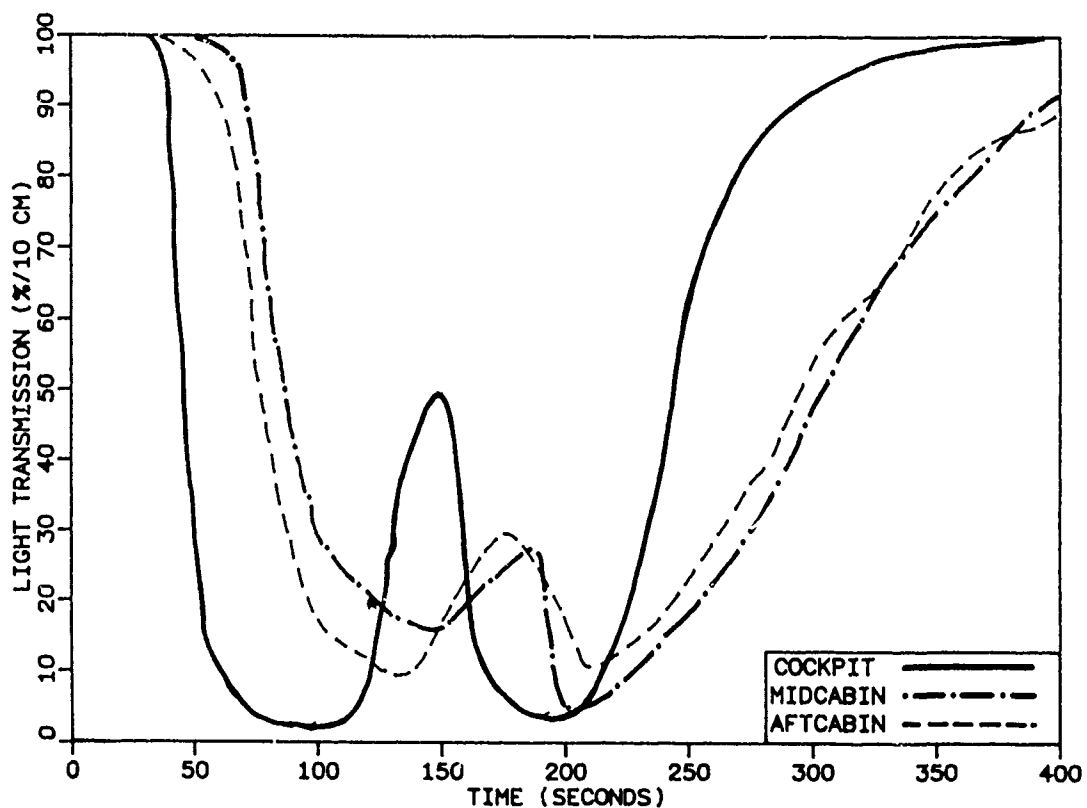


FIGURE 30. SMOKE ELIMINATION TEST NO. 1 - SMOKE GENERATOR AT SECOND CABIN WINDOW FACING FORWARD

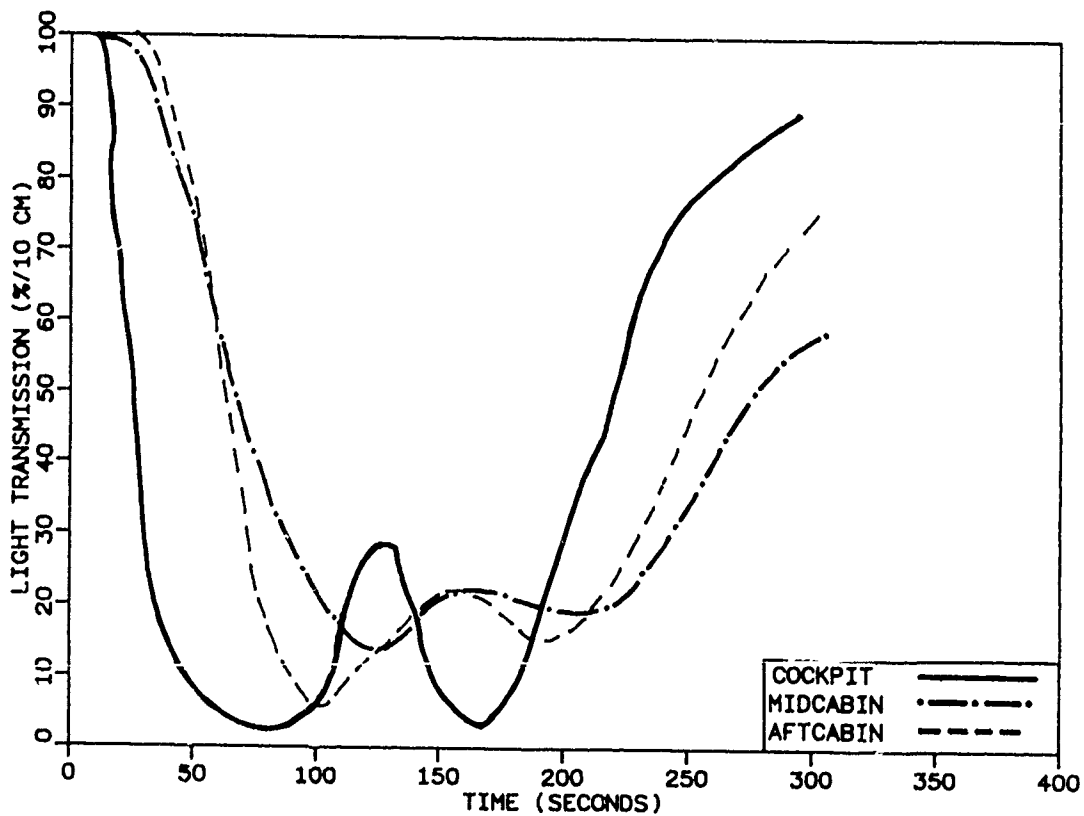


FIGURE 31. SMOKE ELIMINATION TEST NO. 2 - SMOKE GENERATOR AT SECOND CABIN WINDOW FACING FORWARD

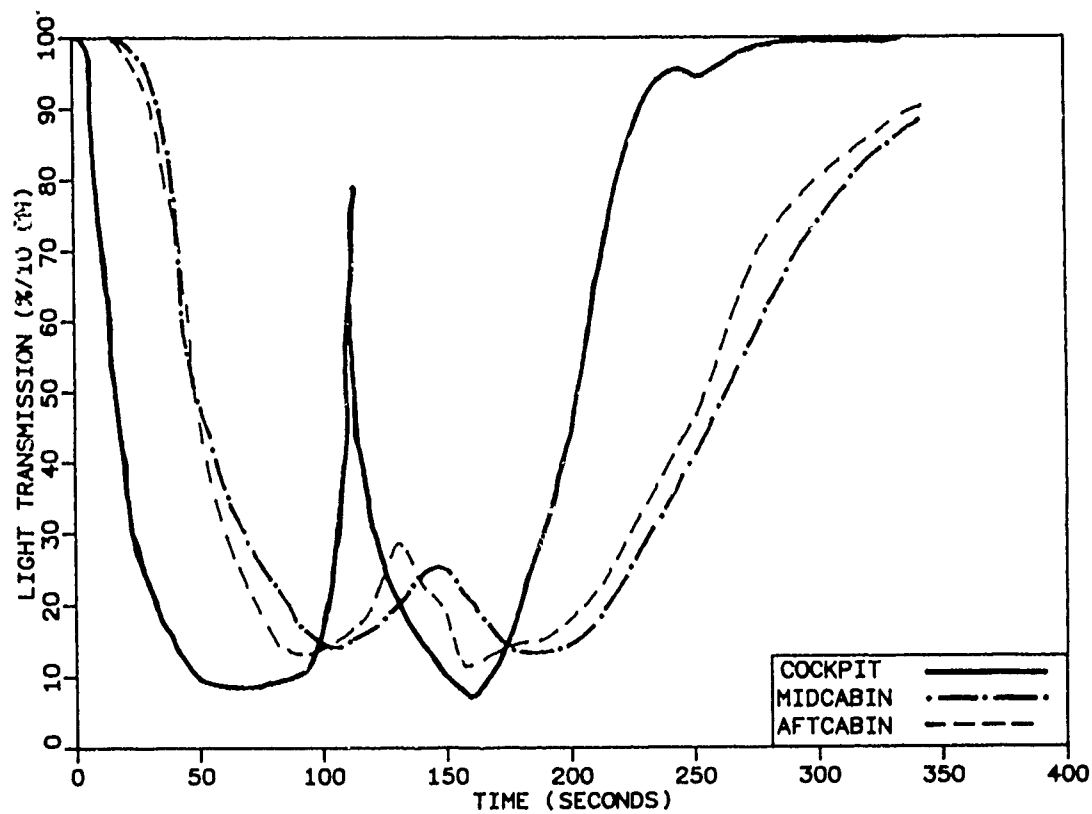


FIGURE 32. SMOKE ELIMINATION TEST NO. 1 - SMOKE GENERATOR IN COCKPIT FACING FORWARD

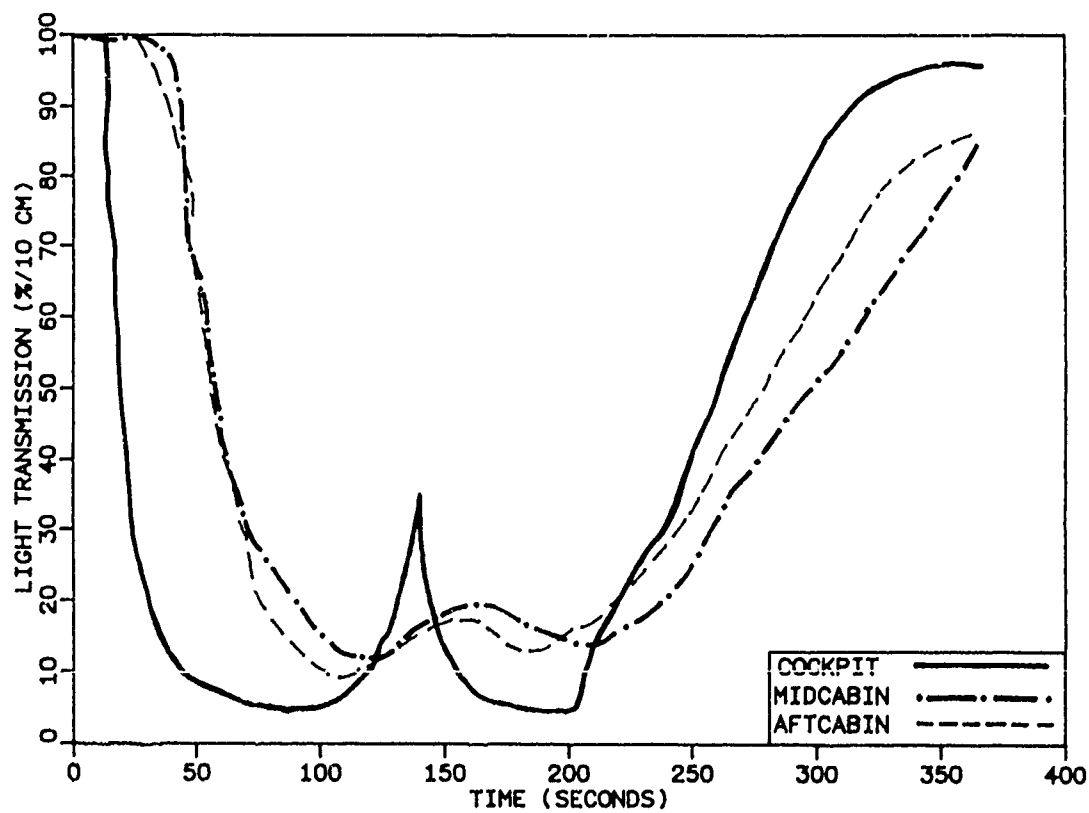


FIGURE 33. SMOKE ELIMINATION TEST NO. 2 - SMOKE GENERATOR IN COCKPIT FACING FORWARD

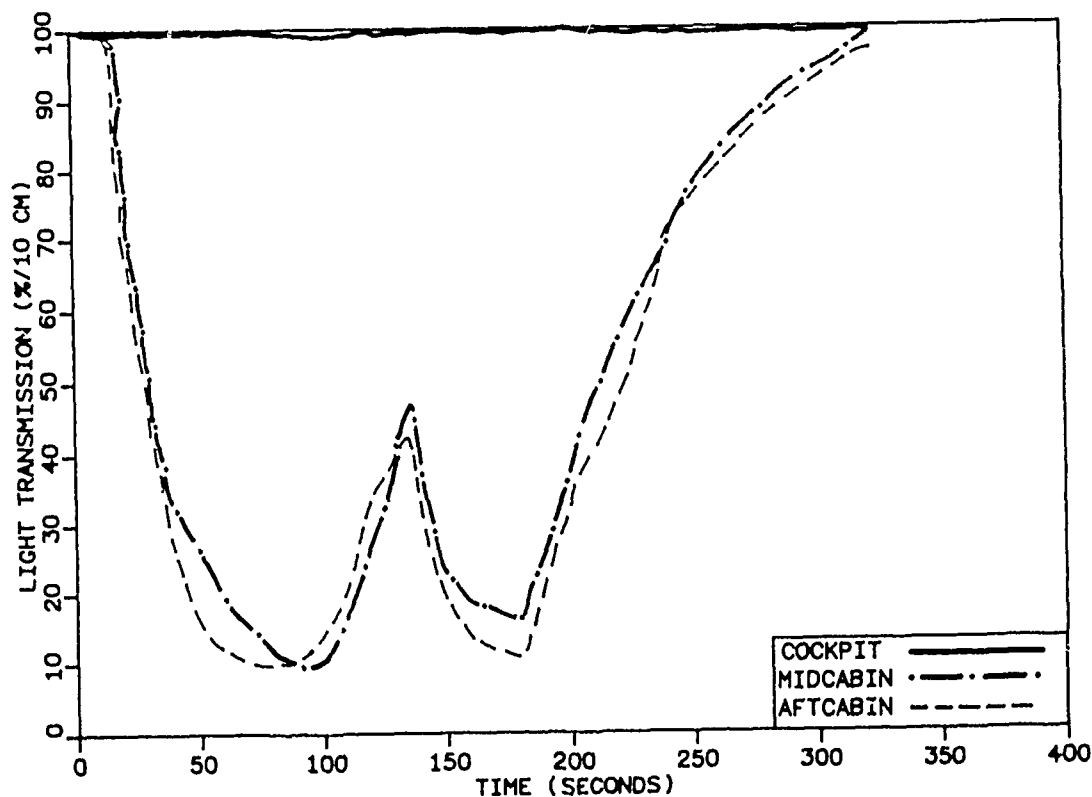


FIGURE 34. SMOKE ELIMINATION TEST NO. 1 - SMOKE GENERATOR AT FOURTH CABIN WINDOW FACING AFT

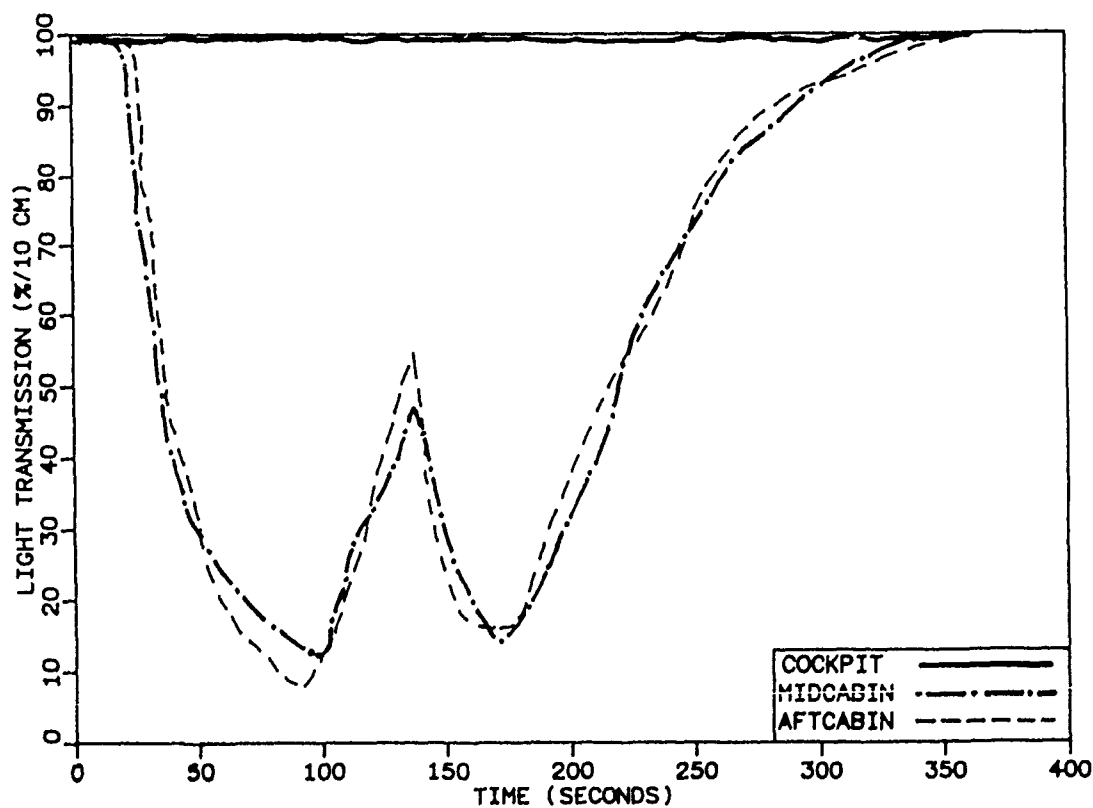


FIGURE 35. SMOKE ELIMINATION TEST NO. 2 - SMOKE GENERATOR AT FOURTH CABIN WINDOW FACING AFT