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FIRE SAFETY EVALUATION OF AIRCRAFT LAVATORY AND CARGO COMPARTMENTS

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16. Abstract

Large-scale aircraft lavatory and cargo compartment fire tests are described. Tests were conducted to evaluate the effectiveness of these compartments to contain fire and smoke. Two tests were conducted and are detailed. Test 1 involved a production Boeing 747 lavatory of the latest design installed in an enclosure outside the aircraft, to collect gases and expose animals to these gases. Results indicate that the interior of the lavatory was completely burned, evolving smoke and combustion products in the enclosure. Test 2 involved a simulated Douglas DC-10 cargo compartment retro-fitted with standard fiberglass liner. The fire caused excessive damage to the liner and burned through the ceiling in two areas. Test objectives, methods, materials and results are presented and discussed.

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SUMMARY

A program of experimental fires has been carried out to evaluate containment of fire in aircraft interior spaces such as lavatories and cargo compartments of wide-body jets. The objective of the program was to assess fire containment and other fire hazards by evaluation of ignition time, burn-through time, fire spread rate, smoke density, evolution of selected combustible and toxic gases, heat flux, and detector response. This information would establish a baseline data upon which improvements in fire safety for aircraft interiors could be designed. Two tests were conducted: one involving a standard Boeing 747 lavatory and one involving a simulated DC-10 cargo compartment.

A production lavatory module was furnished with conventional materials and was installed in an enclosure. The lavatory and enclosure were instrumented for temperature, heat flux, gas sampling, animal toxicity exposure, TV and photographic coverage. The ignition load was four polyethylene bags containing paper and plastic waste materials representative of a maximum flight cabin waste load. Standard aircraft ventilation conditions were utilized and the lavatory door was closed during the test. Lavatory wall and ceiling panels contained the fire spread during the 30-minute test. Smoke was driven into the enclosure primary through the ventilation grille in the door and through the gaps between the bifold door and the jam where the door distorted from the heat earlier in the test. The interior of the lavatory was almost completely destroyed by the fire.

A cargo compartment facility was utilized for the cargo test. Instrumentation was essentially similar to that of the lavatory with the addition of smoke detectors. No animals were utilized for evaluation of toxicity hazards in this test. The compartment was lined with the state-of-the-art fiberglass sheet used in aircraft cargo compartments.

Ventilation was similar to that of an operating aircraft. The ignition load was made up of a typical cargo consisting of filled cardboard cartons occupying 50% of the compartment volume. The fire was extinguished after 13½

minutes when the steel structure reached approximately 320°C (608°F). Two holes burned through the ceiling liner and the liner was extensively delaminated at other locations.

INTRODUCTION

Accidental fires in the lavatory and cargo compartments of modern wide-body jet aircraft may present a potential threat to aircraft integrity and to the safety of the crew and occupants of the passenger compartments (refs. 1-7). While such fires are generally rare and successfully controlled, efforts continue to minimize the possibility of a serious incident. Lavatory fires are more directly related to passenger safety because the lavatories adjoin the occupied passenger compartments, and are exposed to ignition sources and combustibles introduced by the passengers. The frequency of lavatory fires is shown in Table 1 (ref. 8).

Cargo compartment fires bear on passenger safety to the extent of damage to aircraft structural integrity and escape of pyrolysis products in the passenger cabin. The frequency of cargo compartment fires is shown in Table 2 (ref. 8).

Research efforts supported by the National Aeronautics and Space Administration include programs to evaluate and improve the fire safety of aircraft interiors and to maximize the fire containment capability of lavatory and cargo compartments. Research work described in this report on lavatory modules was performed at the Boeing Commercial Airplane Company at Renton, Washington, and work on cargo compartments was performed at the McDonnell-Douglas Corporation at Sacramento, California.

EXPERIMENTAL PROGRAM

Part I. FIRE SAFETY EVALUATION OF LAVATORY MODULES

Lavatories constitute intermittently occupied unattended spaces of passenger aircraft. As such, they present distinctive problems. Privacy requirements prevent supervision of passenger behavior in the main passenger compartment, as well as regular lavatory checks. The potential fire load in a lavatory varies with the passenger load, length of flight, and individual passenger behavior. Cigarette butts have been found in the waste containers despite posted prohibitions and flight attendant's spoken instructions against smoking in lavatories.

The number of lavatories in jet passenger aircraft varies with the aircraft. As shown in Table 3, the number ranges from 1 on a Boeing 737 to 16 on a 365-passenger wide-body Boeing 747.

Test Lavatory

The test lavatory was a production 747 wide-body airplane lavatory module (fig. 1) of the latest design (insofar as details which might affect fire containment capability). The lavatory construction materials are shown in Table 4 (ref. 9). This lavatory is also representative of lavatories on DC-10 and L-1011 wide-body aircraft. The lavatory contained production cabinets, toilet, toilet shroud and lighting. The amenity cabinet dispensers were supplied with the appropriate items.

In the corner of the lavatory ceiling above the amenities cabinet is a small access hole covered by an aluminum slide. In the test this access hole was backed with a panel of the same material and thickness as the rest of the ceiling. This modification eliminated the remote possibility that this area (hidden by the amenities cabinet) might burn-through first, preventing complete evaluation of wall and ceiling materials. This patch was made such that smoke, which might pass the slide in the production configuration, would be allowed to pass during the test; thus the integrity of the slide was evaluated.

Two lavatories are normally served by a single toilet tank sitting under the toilet shrouds of two adjoining lavatories. The tank did not play a part in this test and was not installed. Baffling and venting were installed under the shroud of the test lavatory for proper ventilation flow in the toilet region.

Two glass windows were installed in the bifold lavatory door at a convenient viewing height; one window was installed in the side opposite the cabinets. Windows were sized and positioned for good camera coverage and test observation. All three observation windows were well-sealed.

Test Enclosure

To collect gases and products of combustion emitted from the module, a sealed chamber of plywood lined with asbestos-fabric was built around the lavatory module with 0.9 m (3 feet) clearance on the top and 2 sides (fig. 2). A 10 cm × 10 cm (4 in. × 4 in.) pressure relief vent (with a "flapper" valve) was installed on the back side of the enclosure within 5.08 cm (2 in.) of the floor.

An aluminum chute was installed between the lavatory door grill and the enclosure door. The flapper valves (aluminum with elastomer seals) were sized such that: (1) ventilating air could be drawn into the lavatory through the grill with a minimum of additional pressure drop and (2) when rapid fuel burning occurred in the lavatory, the ventilating valve was closed. The smoke, forced out the door grill, was vented into the test enclosure through the flapper valve in the top of the chute.

Four transparent observation windows were installed in the test enclosure. One was located on the back wall of the enclosure near the top to view the ceiling and back upper corners of the lavatory, i.e., the areas expected to receive the maximum fire exposure in the test. Two transparent windows were installed on the side of the test enclosure adjacent to the non-cabinet side of the test lavatory. One of these windows was positioned for viewing of the undersink cabinet and the back lavatory wall, ceiling, and toilet shroud. The other window was positioned for viewing the animal exposure test system cage. One transparent observation window was placed at a convenient viewing height in the back of the enclosure. All four observation windows were sealed, and sized and positioned for camera coverage and test observation. Three 16-mm cameras provided photographic instrumentation during the test; one viewing the lavatory interior, two viewing inside the enclosure. Three television cameras provided additional coverage. Two CO_2 fire extinguisher nozzles were installed in the test setup; one projecting into the test enclosure, the other into the lavatory module. A CO_2 supply sufficient to inert the associated volume was plumbed to each nozzle. Manually operated valves to release the CO_2 into the test setup were also provided.

An animal exposure test system (AETS) (ref. 10) was installed within the test enclosure to assess the toxicity of the pyrolysis and combustion gases evolved from the lavatory. The cage (AETS) was placed within the 0.9 m (3 ft) space at a point 1.2 m (4 ft) above the floor (fig. 3). The cage was supported by its own stand and was not in direct contact with the lavatory wall. A camera viewing port was provided for coverage of the animals. Quick-connect type connectors were utilized to connect the rat wiring harness to the external cables. The connectors were installed in an access door on the enclosure adjacent to the animal cage. Cabling external to the enclosure connected the system to an FM tape recorder. One rat and six mice were used as subjects. The rat was instrumented for electrocardiograph (ECG) and respiration and was thus partly restrained whereas the mice were free to use an exercise wheel, providing an easier activity monitor. The use of both types of animals also provided additional information as to their relative toxic susceptibilities, which in this case proved to be quite similar.

Instrumentation was also installed to measure atmosphere ventilation rates, temperature, heat flux and to collect gas samples. Two instrumented venturies were installed to establish ventilation rate. Temperatures were recorded at 15-second intervals by 30 thermocouples located within and outside the lavatory module. Heat flux levels were recorded continuously from 4 calorimeters. Location of thermocouples and calorimeters is shown in fig. 4. In addition, temperature was monitored adjacent to the AETS. Gases were sampled within the lavatory at a place near the ceiling and within the test enclosure near the AETS. Three types of sampling were used: (1) captured samples were taken for later gas chromatographic analysis of CO_2, O_2, CO, and N_2 content,

(2) gas analysis tubes were used during the test to estimate HCN and HF concentration, and (3) gas samples were drawn through wash solutions to be later analyzed for HCN, HF, and HCL. The entire test system indicating location of test article and instrumentation is shown in figure 5.

Fire Source Location

Drawings and specifications for the 747 lavatories were reviewed to identify possible ignition and fire sources. In addition to the possibilities of fires starting in a waste compartment or in waste stored in a lavatory module, the following possible fire sources were also found: Light wiring, speaker transformer and terminal, fluorescent light ballast and relay, water cooler, water heater, flushing motor.

Examination of incident records (ref. 8) indicates that the largest percentage of lavatory fires started in the waste compartment from a match or cigarette. There were occasions when electrical malfunctions of the items listed above created smoke and overheating. Fires did not progress rapidly because of the lack of easily ignited fuel. A fire in the waste compartment and a fire in a large quantity of easily-ignited waste in the toilet shroud area represent respectively the most likely, and the maximum fires.

From this data, it is concluded that there are two possible locations for a waste fire. The first and most likely location is in the undersink waste compartment. The second location is in waste piled in the lavatory by flight attendants after cleaning galley areas, etc., near the end of the flight. Sometimes one lavatory is used for storage of such waste. The second fire source situation was selected for the test.

Ignition Load

The waste loads for the test were determined by collecting waste from several wide-body jets after long commercial flights and by preliminary Boeing tests in a simulated lavatory. Two trips were made to Seattle-Tacoma airport to collect the contents of lavatory waste compartments on wide-body airplanes for analysis and to determine contents of excess waste stowed in lavatory modules. The results of these trips are shown in table 5.

Of the flights examined, the London-Seattle flight (Pan American Flight 125) of August 8, 1974 had the greatest collection of waxed cups, paper towels, and other cellulose products. The waste compartments averaged about one-half full; the aft corner lavatory containers and upper deck containers were nearly empty and the main deck center lavatory containers nearly full. If the airplane passenger load had been greater, the less-used lavatories probably would have been used more and the waste load more evenly distributed. The highest average load per container proportioned upward to 100% passenger load factor was established as the test load derived from Flight 125.

In order to calculate a representative waste load, the following data was used:

PAA 125 cellulose load 8-8-74 = (12.67 lb)
Number of PAA 125 lavatories = 13
Estimate 747 avg. capacity = 365
PAA 125 passengers 8-8-74 = 187
PAA 125 waxed cups 8-8-74 = (.57 lb)
NW 7 plastic load 8-8-74 = (0.69 lb)
NW 7 passengers 8-8-74 = 109

For cellulose material the test load was:

(1) Paper Towels

$$\frac{12.67}{13} \times \frac{365}{187} = 0.86 \text{ kg } (1.9 \text{ lb}) \text{ use } 0.90 \text{ kg } (2.0 \text{ lb})$$

(2) Waxed Cups

$$\frac{0.87}{13} \times \frac{365}{187} = 0.06 \text{ kg } (0.13 \text{ lb}) \text{ use } 0.07 \text{ kg } (0.15 \text{ lb})$$

Following the same rationale, using Northwest Flight 7 as the maximum plastic load the test load contained:

$$\frac{0.69}{13} \times \frac{354}{109} = 0.08 \text{ kg } (0.17 \text{ lb});$$

however, since plastic was considered an undesirable waste because of its burning characteristics (smoky, long burning) the test load contents were arbitrarily doubled to 0.15 kg (0.35 lb) of polystyrene plastic cups.

There was no excess waste found stowed in any lavatory on airplanes checked. Approximately 20 flight attendants and airplane cabin cleaning personnel were questioned about the frequency, amount and type of excess galley or cabin waste which was stored in lavatories. All agreed that such storage was very infrequent on the wide-body airplanes; and in fact, of those questioned, none could specifically recall such storage on wide-body airplanes. (However, it must happen sometimes on wide-body airplanes since the attendants indicated that on standard-body airplanes it was not uncommon.) The excess waste in such situations was mostly comprised of napkins, polystyrene glasses, glass bottles, beer cans and soft drink cans from a beverage service after the meal. A galley service survey conducted by Boeing indicated that roughly 5% of the passengers accepted a beverage after a meal.

Based on this, the maximum waste load consists of 100 polystyrene cups (1.7 kg, 3.65 lb), 100 paper towels simulating napkins (0.45 kg, 1.01 lb), 24 tin soft drink cans and 3 aluminum beer cans, simulating drink service to 25% of 747 or 40% of DC-10 passenger loads. To be assured that a maximum condition was tested, a load four times the size of the waste compartment load was used in testing to simulate galley waste overflow.

The waste load (fuel source) for the undersink waste compartment was selected as 0.9 kg (2 lb) of paper towels, 0.07 kg (0.15 lb) of cold drink "waxed" paper cups, and 0.16 kg (0.35 lb) of polystyrene glasses, with paper material crumpled. The load for the galley waste overflow was selected as four polyethylene waste bags, each containing the same type of materials as those used in the waste compartment. Therefore, the total fuel load was comprised of these four bags containing 3.5 kg (8.0 lb) of paper towels, 0.27 kg (0.60 lb) of paper cups, and 0.6 kg (1.4 lb) of polystyrene glasses and the full load in the undersink waste compartment. The four bags were arranged for the test (fig. 6), two sitting upon the toilet shroud and two upon the lavatory floor. The igniter was placed in the upper portion of a lower bag as shown, and the hole through which the igniter leads entered were sealed with aluminum tape. The igniter was a resistance wire which was electrically heated to achieve ignition.

Test Results

The lavatory prior to fire testing is shown in figure 7.

After ignition occurred near the top of the lower bag next to the cabinet, the fire burned across to the other lower bag on the surface of the waste. From there it burned toward the bottom of the bag on the floor just inside the door. Approximately six minutes into the test, the fire stopped spreading on the waste surface and burned in a concentrated area next to the door on the floor pan and floor mat. Approximately 12 minutes after ignition, fire climbed up the waste and burned at the back wall. At this time all visibility in the lavatory was obscured.

Throughout the 30 minute test there was no flame penetration of walls or ceiling. A small amount of smoke escaped through the passenger service access hole in the ceiling over the amenities cabinet; a larger amount of smoke and a few small flames escaped past the door hinge when the fire burned on the floor, distorting the door and leaving a gap in the jamb.

The test was terminated 30 minutes after ignition by discharging CO_2 into the lavatory and the test enclosure. Approximately one hour after ignition the door was opened and two fires still burning were extinguished with water fog. These deep-seated fires were located in the undersink waste compartment and in the waste still burning on the shroud in the cabinet and backwall corner.

Temperature and Heat Flux Data

Figure 8 presents the readings of some of the thermocouples on the test lavatory. Thermocouples inside the lavatory were 2.54 cm (1 in.) away from the surface to obtain the environment temperature. The thermocouples inside the lavatory were numbers 4, 11, 24 and 25. The other thermocouples were bonded to various lavatory surfaces.

After the initial increase in temperature during the first six minutes, the ceiling temperature stabilized at 343-399°C (650-750°F). This shows that the rate of burning in the module was fairly constant as it was controlled by the ventilation rate. The thermocouples show how the fire developed during the late stages in the waste burning against the waste compartment, the shroud and the corner between the cabinet and back wall.

The maximum total heat flux was measured by the two calorimeters whose output is graphed in figure 9. The only air temperature recorded in the test enclosure was that near the AETS cage (fig. 10).

Combustion Products Analysis

Samples of the atmosphere from the lavatory interior were continuously pumped out through two stainless steel probes, whose inlets were located 10.16 cm (4 in.) below the ceiling. Aliquots were collected periodically in evacuated containers for analysis of O_2, N_2, CO, and CO_2. Simultaneously, known volumes of gas were bubbled through absorbing solutions to quantitatively scrub out HF, HCN, and HCl. Gas samples were taken in a similar manner from the test enclosure, through two probes whose inlets were located adjacent to the AETS cage.

The fixed gases were analyzed by gas chromatography. Fluoride and chloride ion concentrations in the scrubbing solutions were determined by specific ion electrode analysis. Cyanide ion concentrations in the scrubbing solutions were measured calorimetrically (pyrazolone method). Measurements were made on samples collected at 0, 6, 9, 12, 18, 24, and 30 minutes after ignition. Concentrations of HF, HCN, HCl, and CO were also checked during the test using gas analysis tubes.

Maximum levels of all four toxic gases (HF, HCN, HCl, and CO) were reached in the lavatory, as shown below:

Toxicant	Maximum Level Observed Ppm	Duration to Reach Maximum Level Min
HF	2,760	18
HCl	12,800	18
HCN	690	24
CO	70,000	12

These observed maximum values for HCN and HF may actually be too low. The very large amount of HCl generated overwhelmed the buffering capacity of the absorbing solutions, which then became acidic. This may have decreased the scrubbing efficiency for HF and HCN.

Graphs of the concentrations of the atmospheric gases and toxicants in the lavatory and test enclosure against time are shown in figures 11 - 17. Two episodes of toxicant production are indicated. Large amounts of HF, HCl, and CO, and severe oxygen depletion were observed at the beginning of the fire during the first episode. Very little HCN was produced. Probably during this period rapid burning of the waste fuel was occurring, with HCl and HF forming respectively through pyrolysis of the polyvinyl chloride floor mat and the polyvinyl fluoride surface of the lavatory interior.

The second episode, occurring between 12 and 18 minutes after ignition, produced greatly increased amounts of HF and HCl, generation of HCN, and even greater oxygen depletion. During this period it is probable that the lavatory interior was burning, including fire penetration of the epoxy inner panel skins to involve the polyamide core, thus forming HCN.

Lower concentrations of toxic gases were recorded in the test enclosure. Their build-up lagged considerably behind their formation in the lavatory, and their concentrations were still increasing at the end of the test.

Animal Exposure Test Results

Data from the instrumented rat was recorded on 2.54 cm (1 in.) magnetic tape. Electrocardiograph and respiration data were observed simultaneously on a dual-beam oscilloscope at the test enclosure observation window, and also on individual scopes outside the test enclosure at the recording station. The tape was pen-recorded on an 8-channel strip chart. The ECG was examined for cardiac arrhythmias (skipped beats), the respiration was examined for changes in pattern and integrated respiratory volume, and the AETS cage temperature profile was recorded.

The temperature recorded adjacent to the AETS cage is shown in figure 10. The mice died approximately 18 minutes after test initiation.

An analysis of the recorded information from the instrumented rat indicated that the first cardiac arrhythmia appeared at 7 minutes, 40 seconds. Arrhythmias numbered approximately fourteen (14) during the next minute after which they seemed to disappear until nearly seventeen minutes into the test. Coincident with the frequent arrhythmias mentioned above and for the previous 30 seconds, the R wave of the ECG diminished in amplitude by nearly 50%.

A summary of the ECG/Respiration history of the exposed rat is as follows:

ECG/Respiration	Time into Test min	sec
First arrhythmia (skipped beat)	7	40
Fourteen arrhythmias	8	40
ECG amplitude diminished	15	
Bradycardia and respiratory arrest	17	
Cardiac arrhythmias, marked bradycardia, sporadic arrest for 2-7 seconds	17	25
Permanent cardiac arrest (death).	18	

During the burn test, it was observed that the rat's ECG signal reflected physical activity of the subject; this is easily recognizable in the ECG channel on the strip chart. Therefore, it appears that the ECG record would serve as an indicator of physical activity of the instrumented subject, obviating the necessity for cinematic or TV coverage except for visual documentation of the test. Data recorded on the strip chart recorder is shown in figures 18-20. Data includes:

- Raw respiration pattern.
- Filtered respiration pattern. The respiratory sensor is sufficiently sensitive to pick up the heart beat; this is filtered out.
- Integrated respiratory volume. An arbitrary respiratory volume is selected electronically and when a series of single breath volumes are summed to achieve this volume, the integrator starts over adding up the next aliquot. Time per aliquot is the significant factor in determining this volume of respiration. For example, respiratory integration time varied from 10-12 seconds in the first test minute to 50 seconds in the 14th test minute.
- Electrocardiogram (ECG).

Damage Assessment

Figure 21 is an overall view of the lavatory after the test. All the interior cabinet sandwich panels were charred and delaminated. None of the lavatory walls nor the ceiling were penetrated by flames. The wall opposite the cabinet was distorted and bowed outward. A small area of resin on the outside wall of the waste compartment was scorched. The bifold lavatory door suffered the most damage, delaminating and distorting. It cannot be determined how the observation windows cut in this door may have affected the extent of the damage.

The door lintel, shown in figure 21 hanging from the CO_2 extinguisher plumbing, was in place until the rapid CO_2 discharge at test termination wrenched it from the lavatory.

Part II. FIRE SAFETY EVALUATION OF CARGO COMPARTMENTS

Aircraft cargo compartments, because of their under-the-floor location in proximity to passengers, need protection against fire hazards. Fire prevention for small compartments relies on containment and self-induced smothering. This involves air leakage control, which is impractical in larger compartments with large loading doors. Another means of fire control is by smoke and fire detection and subsequent quenching or extinguishment of the fire by an active fire extinguishing system. The main fire-control objective for all compartments is to confine fire within the walls of the cargo compartment until a landing can be effected, the cargo pulled out and large-scale ground fire-fighting equipment be brought to bear. The threat level of fires occurring in cargo compartments has not been fully defined; neither has the degree of "hardening" required to safely contain or extinguish the fire.

The objective of this test was to establish the degree of damage and fire containment imposed by a fire produced by a typical cargo load. The potential load in a cargo compartment varies in composition, occupied volume and weight depending on the aircraft type (passenger or freight) and length of flight. Studies conducted by the FAA and aircraft industry indicated that a representative cargo load would occupy 50% of the cargo compartment volume. A similar cargo load was utilized in this test.

Test Cargo Compartment

The simulated cargo and baggage test compartment utilized in this test was representative of cargo compartments of various jet aircraft (Boeing 707, 727; Lockheed L-1011; McDonnell-Douglas DC-9, DC-10). The cargo configuration and cargo load utilized is shown in table 6. The cargo test arrangement showing the relationship of equipment, cargo load and ventilation is shown in figure 22. A blower external to the test compartment produces air flow in the tunnel external to the compartment which simulates the cabin air-conditioning air flow. The air inlet adjacent to the ceiling and the outlet on the left slant side simulates the compartment vent valve and cargo door respectively. The total ventilation rate through the cargo compartment was 74.04 m^3/min (2614.38 cfm). The compartment was lined with state-of-the-art fiberglass sheets and sealed per production standards. The corrugated steel floor was sealed with a silicone potting material. The loading gate was equipped with a continuous end seal which completely sealed the compartment during the test, except for the ventilation indicated above.

The arrangement of the instrumentation is shown in figure 23. Pyrotector smoke detectors were located on the ceiling centerline. Four thermocouples were located 2.54 cm (1 in.) below the ceiling to record air temperature, two on the ceiling to record liner temperature and two above the ceiling to record the structure temperature. Two calorimeters were bonded on the surface at the ceiling to record heat flux. One pressure transducer, 0-3447 N/m^2 (0-0.5 psi), was installed in the sidewall. Gas sampling tubes were installed on the sidewall to collect gas samples of hydrocarbons, O_2, CO_2 and CO. Two 16-mm motion picture cameras and a TV camera were utilized for observing the fire. Two orifice plate flow meters were installed to monitor the ventilation and air flow through the tunnel. CO_2 fire extinguishing nozzles were located on the ceiling centerline.

Test Results

The electrical ignitor was placed in the cardboard boxes at the location shown in figure 23. The cardboard boxes were arranged in the compartment as shown in figure 24. At time 0 power was applied to the ignitor. At 1 min 6 sec the center smoke detector responded and at 1 min 8 sec the forward smoke detector responded. At 1 min 10 sec flames erupted in the vicinity of the ignitor. At 1 min 16 sec the aft smoke detector responded. At 2 min 10 sec smoke obscured visual and televised observation of the fire. The pressure transducer recorded no change in compartment pressure during the first 9 minutes of the test. At that time the sensing line was damaged by heat and no further data was taken. The time/air temperature history adjacent to the ceiling is shown in figure 25. The structure and liner time-temperature history is shown in figure 26. As shown, the fiberglass liner temperature reached maximum at approximately 8 minutes. The heat flux rate in the ceiling at locations B and D (fig. 23), is shown in figure 27. As shown, maximum heat flux was reached within 2 minutes after ignition at location B which is directly above the area where ignition occurred. Data from instrumentation and movie coverage indicated that the fire progressed from the ignition source at point B (fig. 23) toward the vent inlet. Flames were observed through the inlet hole during most of the test. No flash fire occurred. The air temperature plots (fig. 25) show an initial temperature peak at the time the flames were first visible through the windows. The air temperature then decayed for about 1½ minutes before climbing again. Each location exhibited the same general temperature profile in a different time sequence, depending on the distance from the ignition source. The liner temperature plots (fig. 26) closely follow the shape of their respective air temperature plots, but at a lower level and with less fluctuation. The heat flux plot (fig. 27), follows the same profile as the respective temperature plots. More heat was released during the initial ignition than at any other point in test.

Figures 28 and 29 relate the concentrations of oxygen, carbon dioxide, carbon monoxide, total hydrocarbons and methane as a function of time. Oxygen and total hydrocarbons were essentially monitored continuously while the values for the other three constitutents were derived from the eight grab samples. The test was terminated at approximately 13½ minutes by shutting off ventilation and discharging the CO_2 firex system. The criterion for terminating the test was the structure temperature reaching approximately 320°C (608°F). The bulk of the cargo was then pulled from the compartment and extinguished with water. The last half pallet of cargo was damaged by the fire and did not pull out of the compartment. As a result, a fire hose had to be directed into the compartment to quence this last portion of the burning cargo.

Post-test examination revealed two holes burned through the ceiling liner adjacent to the vent inlet. The holes were approximately 55.8 cm × 55.8 cm (22 in. × 22 in.) and 25.4 cm × 50.8 cm (10 in. × 20 in.) as shown in figure 23. Though extensive areas of the ceiling and sidewall liner were delaminated and baked free of resin, no other burn-throughs occurred. Burn-through of the liner constitutes failure of the cargo compartment. Fire damage caused to the cargo liner is shown in figure 30.

SUMMARY OF RESULTS

In the case of the lavatory test it may be concluded that:

- Fire spread was contained in the lavatory module for the 30 minute test period, but distortion of the bifold door permitted escape of some flames, smoke and gases after approximately 6 minutes. This fire behavior may be representative of lavatories in actual service when ventilation is limited such as when the door remains closed.
- Maximum temperatures were recorded at the lavatory ceiling within 15 minutes.
- Heat flux levels did not exceed 1.58 W/cm^2 (1.4 Btu/ft^2 sec) possibly due to a fuel rich condition which produced a smoldering situation.
- The type of fire encountered in this lavatory test was severely limited by ventilation. During the initial period the fire spread rapidly, and the rate of O_2 consumption exceeded the amount of O_2 being drawn into the lavatory and the resulting O_2 depletion decreased the speed of the burning. Accumulated heat caused pyrolysis to continue at a rapid rate while the burning subsided to a smoldering condition. This cyclic unsteady-state burning and pyrolysis cycle is typical of an enclosure fire in which the ventilation is limited.
- Air temperatures in the plywood test enclosure did not exceed 90°C (194°F) indicating that air temperatures in the actual passenger compartment would be significantly less.
- HCL and HF reached lethal levels in the test enclosure at the conclusion of the test but O_2 depletion was not serious. It is tentatively concluded that the animals in the AETS cage in the test enclosure expired primarily from the combined hypoxic effects of HCl and HF gases and high temperature with minor contribution to hypoxia being made by CO and possibly other unknown gases.

In the case of the cargo compartment test it may be concluded that:

- Fire spread was contained in the cargo compartment for a period of 13.5 minutes under operating ventilation conditions, indicating that an aircraft experiencing a cargo compartment fire should be either landed within this time period or initiate effective fire suppression procedures.
- Failure of the epoxy-fiberglass cargo liner at the ceiling was the cause of failure to contain the fire and combustion gases.
- Air and structural temperatures exhibited the most rapid rise within the first 5 minutes. Temperatures stabilized after 5

minutes near the ignition source, and after 9 minutes at remote locations. Structural temperatures climbed steadily until the CO_2 was released.

- Smoke detector response was observed within 66 seconds after ignition which provides early warning of an incipient fire.
- Heat flux levels reached 5 W/cm^2 (4.405 Btu/ft^2 sec) at the ceiling in the vicinity of the ignition point, indicating that this heat flux level may be the maximum to be expected in a cargo compartment fire.
- The CO_2 fire extinguishing system was ineffective in extinguishing the fire at the conclusion of the test.

ACKNOWLEDGMENT

The authors wish to thank Donald Williams, California State University, Chico for compilation and reduction of some of the data.

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Table 1.—Lavatory incidents, U.S. air carriers.

AIRCRAFT INVOLVED	NUMBER OF INCIDENTS	FLIGHT PHASE	NUMBER OF INCIDENTS
DC8	5	CRUISE	18
727	6	INSP./MAINT.	3
747	3	CLIMB	2
707	3	APPROACH	1
737	2	DESCENT	1
DC10	2	TAXI/GROUND HANDLING	1
DC9	3	TOTAL	26*
1011	1		
188A	1		
TOTAL	26*		

*11 FLAME AND SMOKE PRESENT
15 SMOKE PRESENT

Table 2.—Cargo fires, U.S. air carriers.

DATE	TYPE OF FIRE	AIRCRAFT INVOLVED	FLIGHT PHASE
05-30-63	CARGO	CV990	STATIC
07-09-64	BAGGAGE	V745D	IN FLIGHT
03-25-65	MAIL BAG	CV440	TAXI
04-17-66	BAGGAGE	L188	IN FLIGHT
07-31-67	LUGGAGE	V745D	IN FLIGHT
05-23-72	CHEMICAL	707-331C	STATIC
11-03-73	HNO_3 CARGO	707	LANDING

Table 3.—Number of lavatories in jet aircraft.

NUMBER OF LAVATORIES IN JET AIRCRAFT	
AIRCRAFT TYPE	NO. OF LAVATORIES
707	3 — 6
720	4 — 5
727	2 — 4
737	1 — 3
DC8	4
DC9	3
747	7 — 16
DC10	8 — 10
L-1011	5 — 7

Table 4.—Baseline lavatory materials.

PANEL	MATERIALS DESCRIPTION
CEILING	1. 0.005 cm (0.002 in.) PVF (TiO_2) 2. TYPE 181 GLASS-EPOXY 3. TYPE 120 GLASS-EPOXY 4. 1.2 cm (0.48 in.) THICK 0.3 cm (0.12 in.) CELL POLYAMIDE CORE 5. 120 GLASS-EPOXY 6. 181 DECORATIVE LAMINATE WITH ITEM 1 SURFACE (CANVAS)
BACK & SIDE WALLS	1. 181 DECORATIVE LAMINATE WITH SILK SCREENED PVF SURFACE (CANVAS) 2. 120 GLASS-EPOXY 3. 2.4 cm (0.96 in.) THICK 0.3 cm (0.12 in.) CELL 48 kg/m^3 (2.9 lb/ft^3) POLYAMIDE CORE 4. TYPE 120 GLASS-EPOXY 5. 181 DECORATIVE LAMINATE WITH SILK SCREENED PVF SURFACE (CANVAS)
BACK WALL (ACOUSTIC WALL PANEL)	SAME AS ITEMS 1-4 ABOVE PLUS 5. DACRON FABRIC PERFORATED POLYAMIDE DECORATIVE LAMINATE WITH SILK SCREENED PVF SURFACE
SHROUD	1. 2.4 cm (0.96 in.) THICK USING 181 GLASS CLOTH AND F.R. POLYESTER RESIN
CABINETS	1. TYPE 120 GLASS-EPOXY 2. 0.63 cm (0.25 in.) THICK 0.3 cm (0.12 in.) CELL 48 kg/m^3 (2.9 lb/ft^3) POLYAMIDE CORE 3. TYPE 120 GLASS-EPOXY 4. 181 DECORATIVE SURFACE LAMINATE WITH 0.005 cm PVF (TiO_2) (CANVAS)
FLOOR PAN	0.3 cm THICK PHE. OXIDE WITH A FLOOR MAT OF GLASS REINFORCED PVC
TOILET SEAT	MODIF PHENYLENE OXIDE

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Table 5.—Lavatory combustible waste survey.

DATE: AIRLINE: TYPE AIRLINE:	FLIGHT TO: FROM / TO / ELAPSED TIME	LOCAL TIME: / LOCAL TIME: / HRS:	PASSENGERS: TOTAL – FIRST CLASS / TOURIST	TOTAL LAVS: LAVS CHECKED	WASTE COMPARTMENT, Kg (lb)				COMMENTS ODDS AND ENDS
					CELLULOSE MATERIALS	WAXED CUPS	PLASTIC PRODUCTS	CIGARETTES & MATCHES	
6-11-74 NORTHWEST 747	#7 NEW YORK SEATTLE 5.5	10:00 A 12:27 P	74 20 54	12 10	1.1 (2.5)	.06 (0.15)	P. STYR. .2 (.4)	1 SOAKED 1 IN CUP OF H_2O	12 SMALL BARS OF SOAP
6-11-74 PAN AMERICAN 747	#125 LONDON SEATTLE 9.5	2:30 P 4:00 P	127 – –	13 13	3.5 (7.5)	.23 (0.50)	P. STYR. 80% P. ETHYL. 20% .05 (.1)	2- 1 SOAKED 1 UNLIT	2 TOMATO JUICE CANS 1 SOFT DRINK CAN
6-11-74 UNITED 747	#286 LOS ANGELES SEATTLE 2.5	5:00 P 7:22 P	114 16 98	11 11	0.7 ([illegible])	.05 (0.10)	P. STYR. .1 (.2)	--- ---	10 LIQUOR MINIATURES 1 BABY FOOD JAR
6-11-74 NORTHWEST DC-10	#27 CHICAGO SEATTLE 4.25	5:20 P 7:30 P	70 20 50	7 7	1.8 (3.9)	.02 (0.05)	P. STYR. .05 (.1)	--- ---	1 MINIATURE BREATH SPRAY (AEROSOL)
6-11-74 UNITED 747	#157 CHICAGO SEATTLE 4.25	6:20 P 8:35 P	275 34 241	11 11	2.1 (4.7)	.18 (0.40)	P. STYR. 70% P. ETHYL. 30% .05 (.1)	1-SOAKED WITH H_2O	
8-8-74 NORTHWEST 747	#7 NEW YORK SEATTLE 5.5	10:00 A 12:27 P	109 –	13 13	1.6 (3.47)	.12 (0.26)	.3 (.7) *	2 ALL IN 2 HEAVY P. STYRENE CUPS	7 LIQUOR MINIATURES
8-8-74 PAN AMERICAN 747	#125 LONDON SEATTLE 9.5	2:30 P 4:00 P	187 –	13 13	5.8 (12.57)	.40 (0.87)	.09 (.2) *	1-SOAKED ---	16 SMALL BARS OF SOAP 1 BEER CAN (TIN)
8-8-74 UNITED 747	#286 LOS ANGELES SEATTLE 2.5	5:00 P 7:22 P	134 12 122	11 11	0.8 (1.78)	.08 (0.19)	.02 (.05) *	--- ---	1 GLASS JUICE BOTTLE (LARGE)
8-8-74 NORTHWEST DC-10	#27 CHICAGO SEATTLE 4.25	5:20 P 7:30 A	71 – –	7 7	1.7 (3.85)	.08 (0.18)	.03 (.07) *	--- ---	2 PULL-TAB (OFF BEER CANS)
8-8-74 UNITED DC-10	#157 CHICAGO SEATTLE 4.25	6:20 P 8:35 P	90 – –	7 7	1.5 (3.30)	.05 (0.10)	.005 (.01) *	---	

* 95% P. STYRENE
5% P. ETHYL.

Table 6.—Cargo compartment configuration.

LENGTH:	812.80 cm (26 ft., 8 in.)
HEIGHT:	170.18 cm (5 ft., 7 in.)
WIDTH:	414.02 cm (13 ft., 7 in.)
VOLUME:	56.64 m^3 (2000 $ft.^3$)
VENTILATION:	0.28 changes/min = 15.86 m^3/min (0.28 changes/min = 560 cfm)
TUNNEL FLOW:	74.04 m^3/min (2614.38 cfm)
CO_2 FIREX BACKUP SYSTEM, 99.77 kg (200 lbs)	
IGNITION SOURCE:	GAS SOAKED RAG AND HOT WIRE
CARGO LOAD:	50% GROSS COMPARTMENT VOLUME
CARGO COMPOSITION:	45.72 cm x 45.72 cm x 45.72 cm (18 in. x 18 in. x 18 in.) CARDBOARD CARTONS LOOSELY FILLED WITH CURRENT COMMERCIAL TYPE PACKING MATERIAL (e.g., RUBBERIZED HAIR, POLYETHYLENE, POLYURETHANE, CELLULAR FILM, FIBER BOARD, AND KIM PAC)

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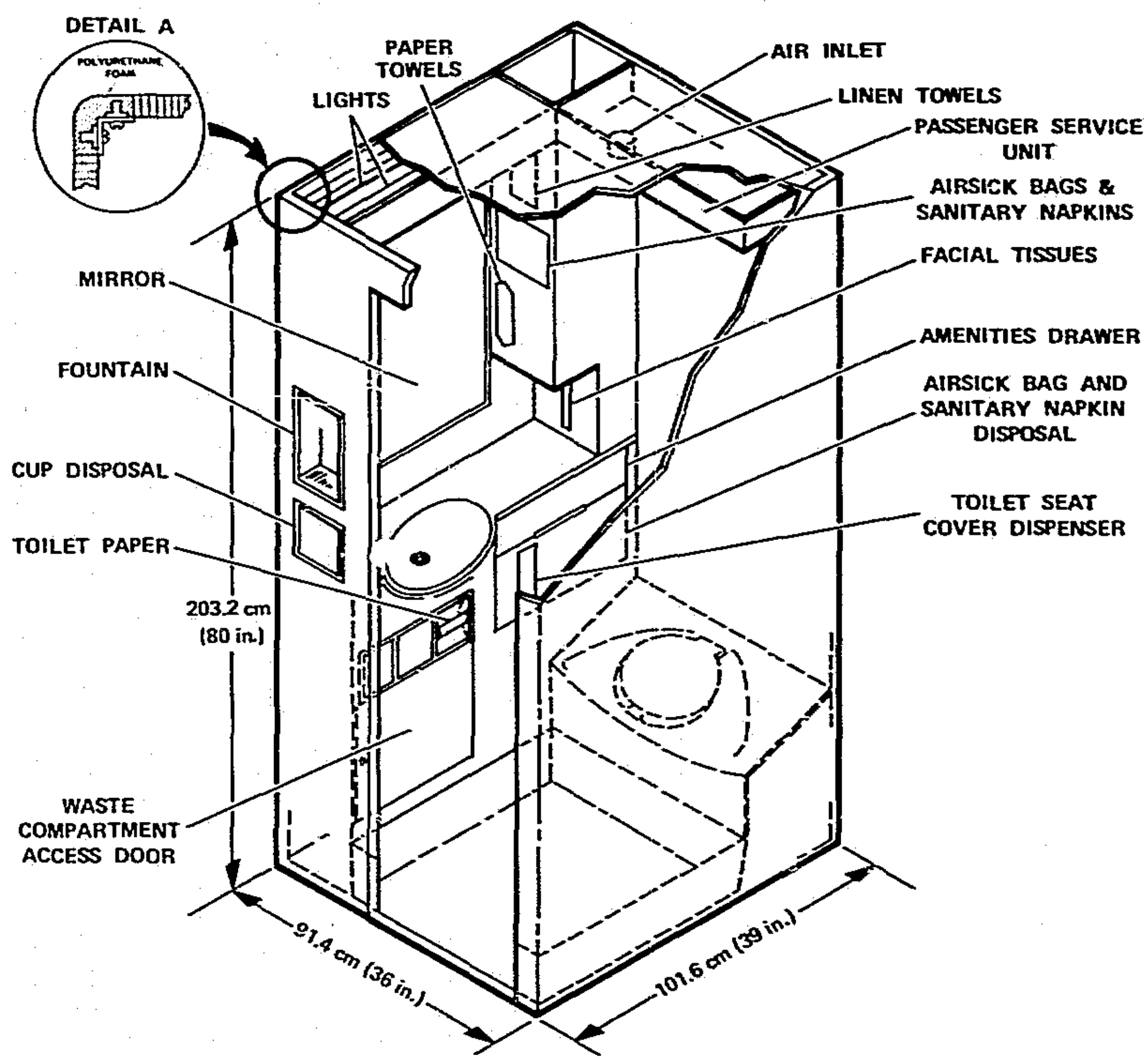


Figure 1.—Boeing 747 aircraft lavatory.

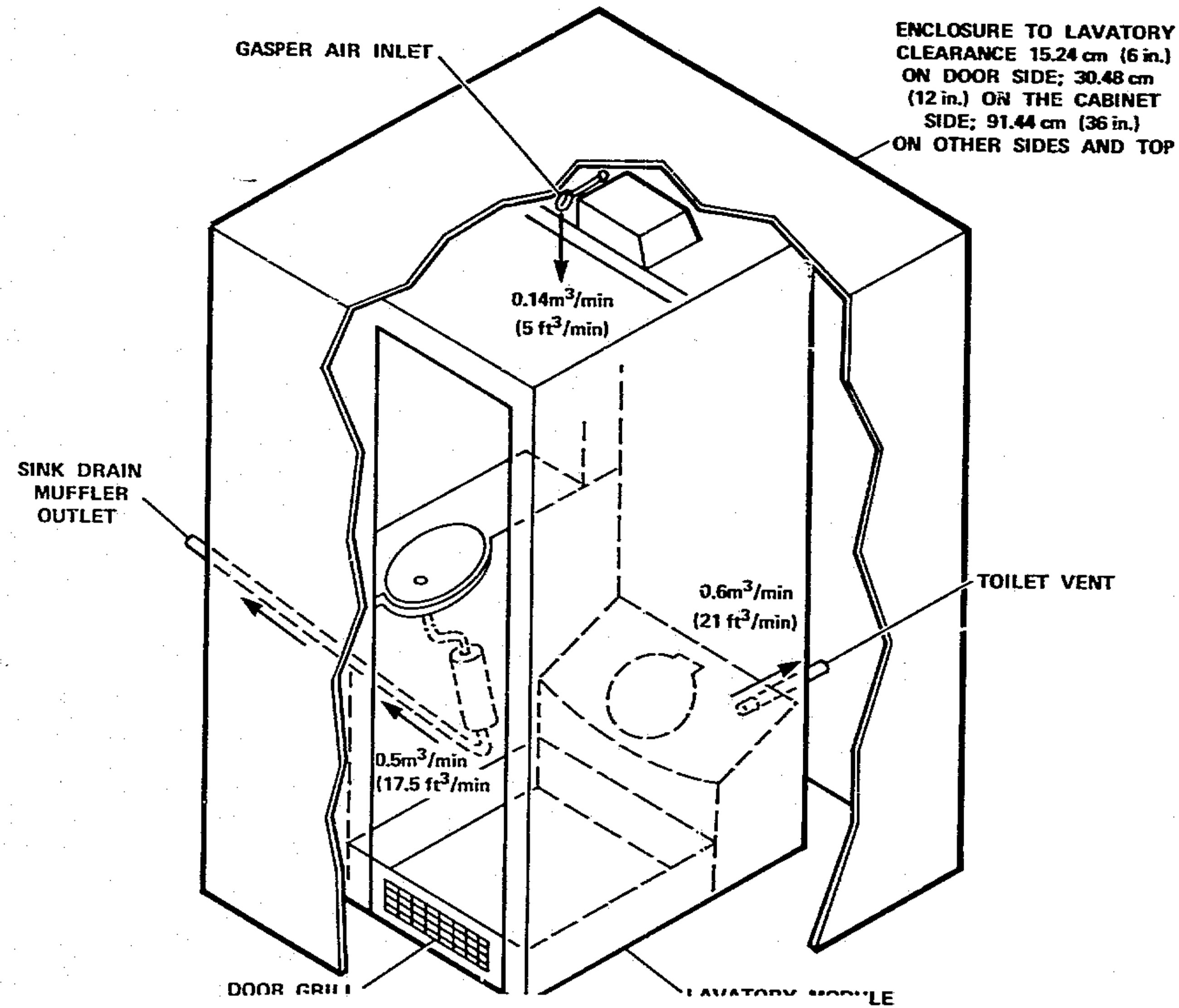


Figure 2.—Test enclosure.

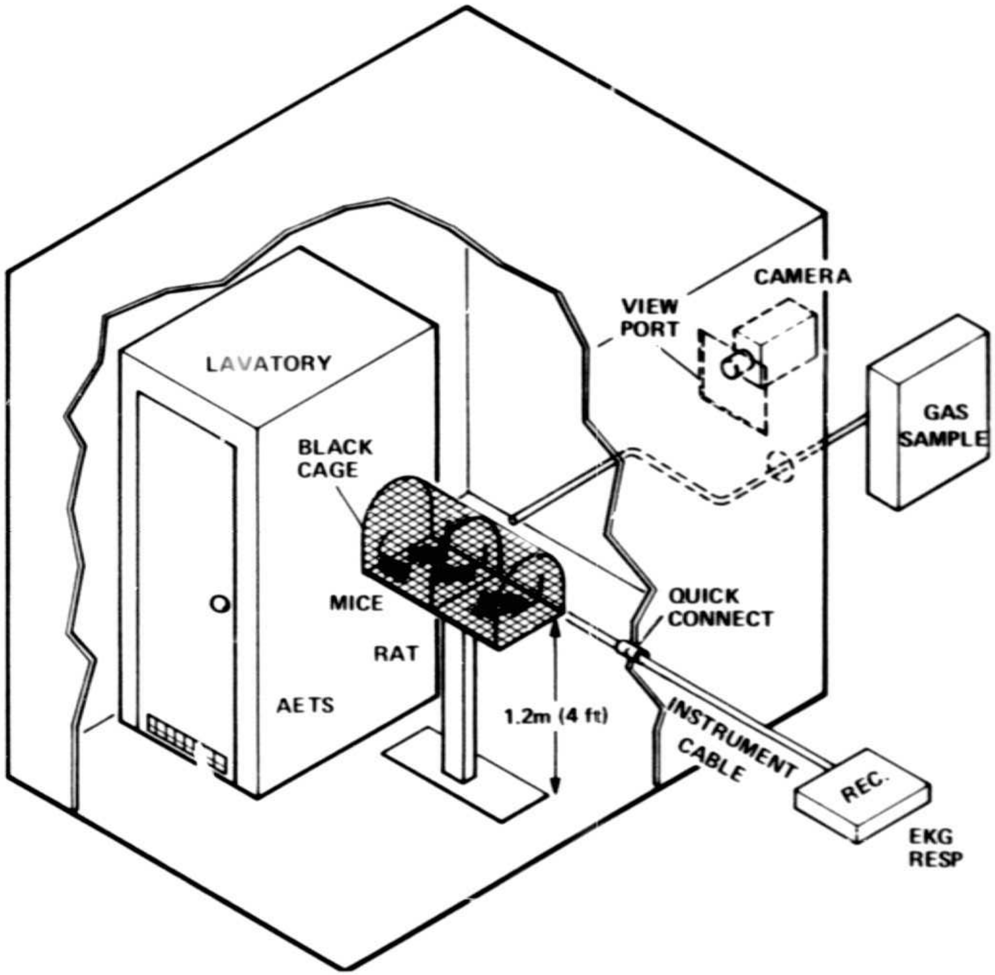


Figure 3.—Animal exposure test system.

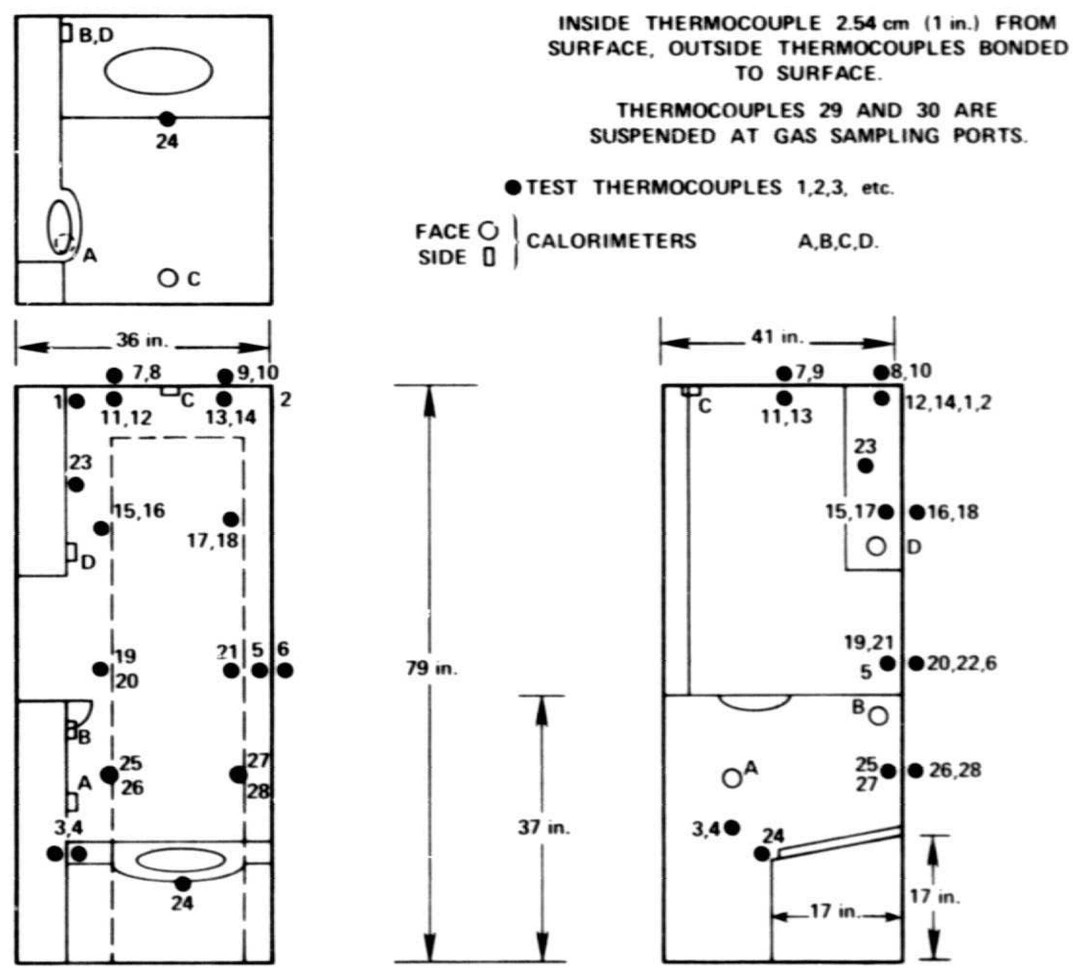


Figure 4.—Thermocouple and calorimeter location.

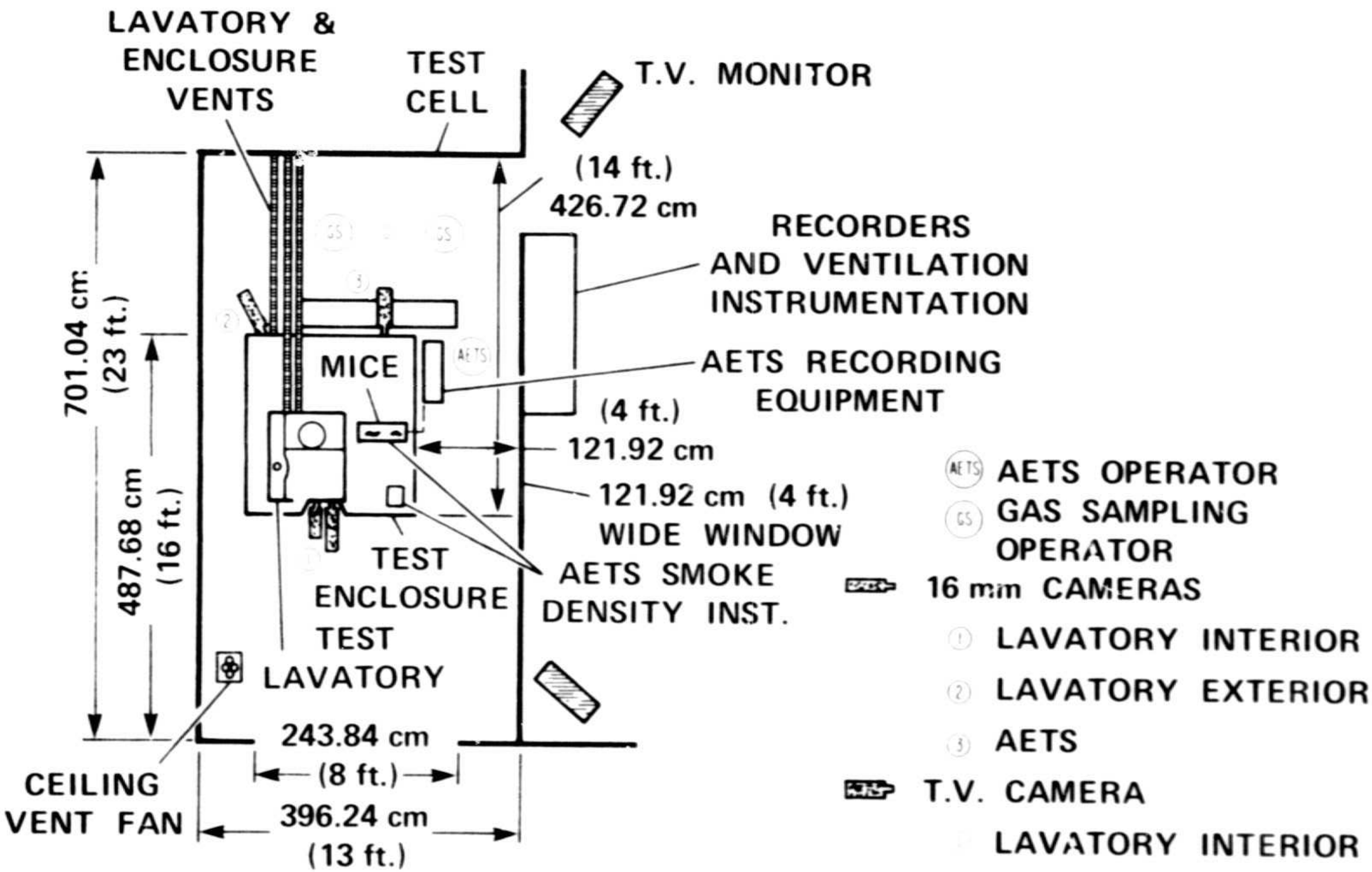


Figure 5.—Lavatory module test set-up.

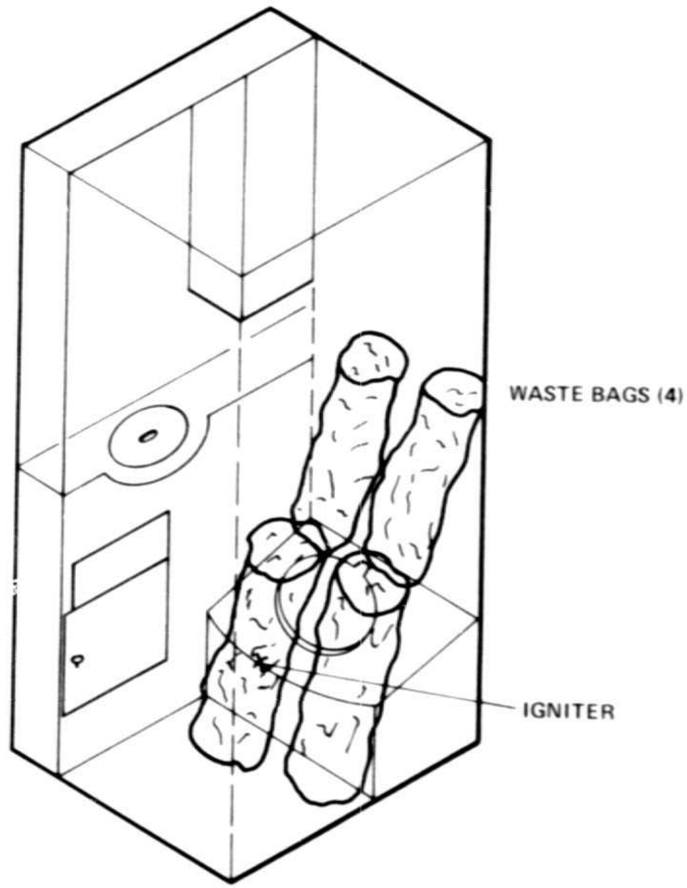


Figure 6.—Fire load arrangement.

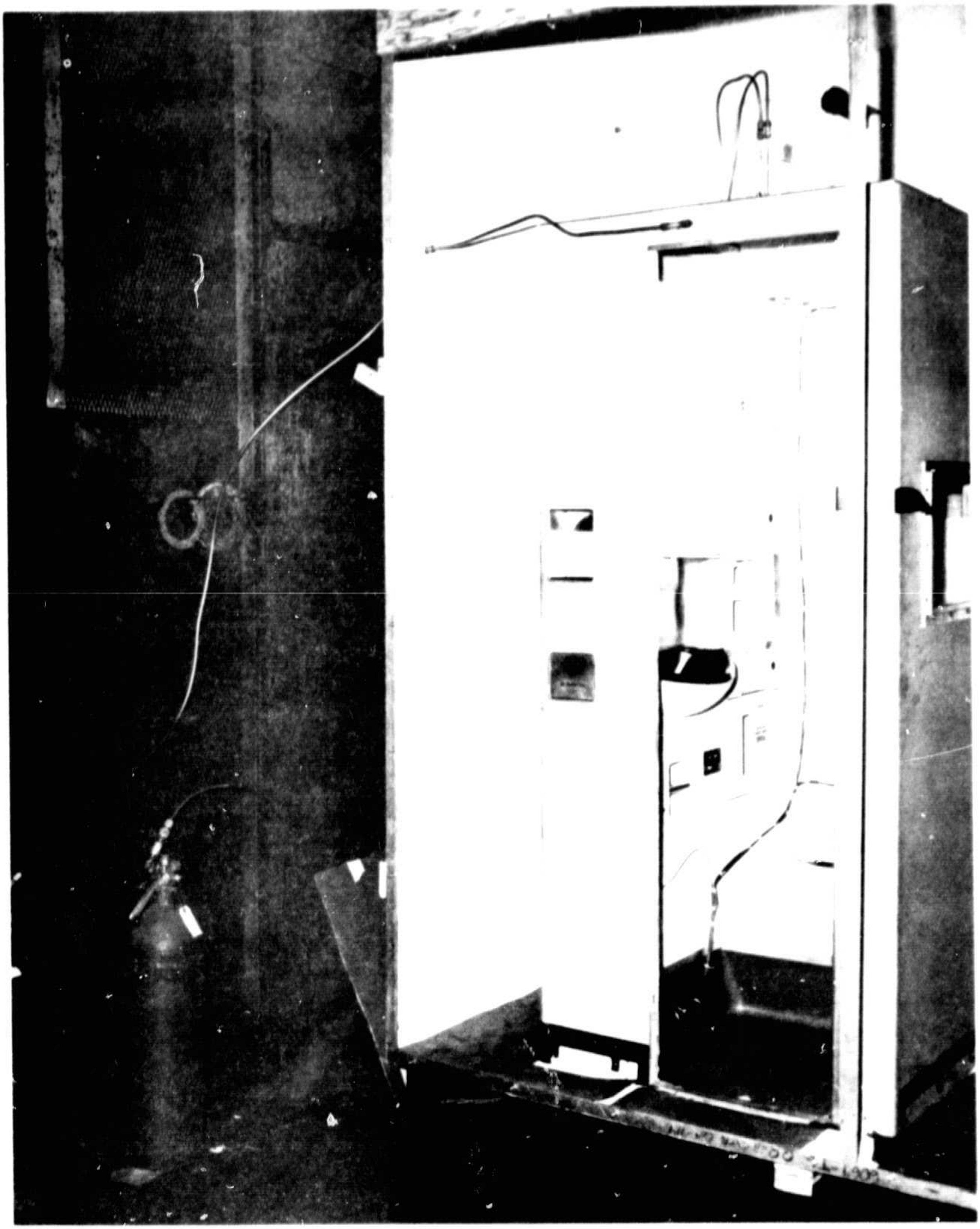


Figure 7.—Lavatory prior to the test.

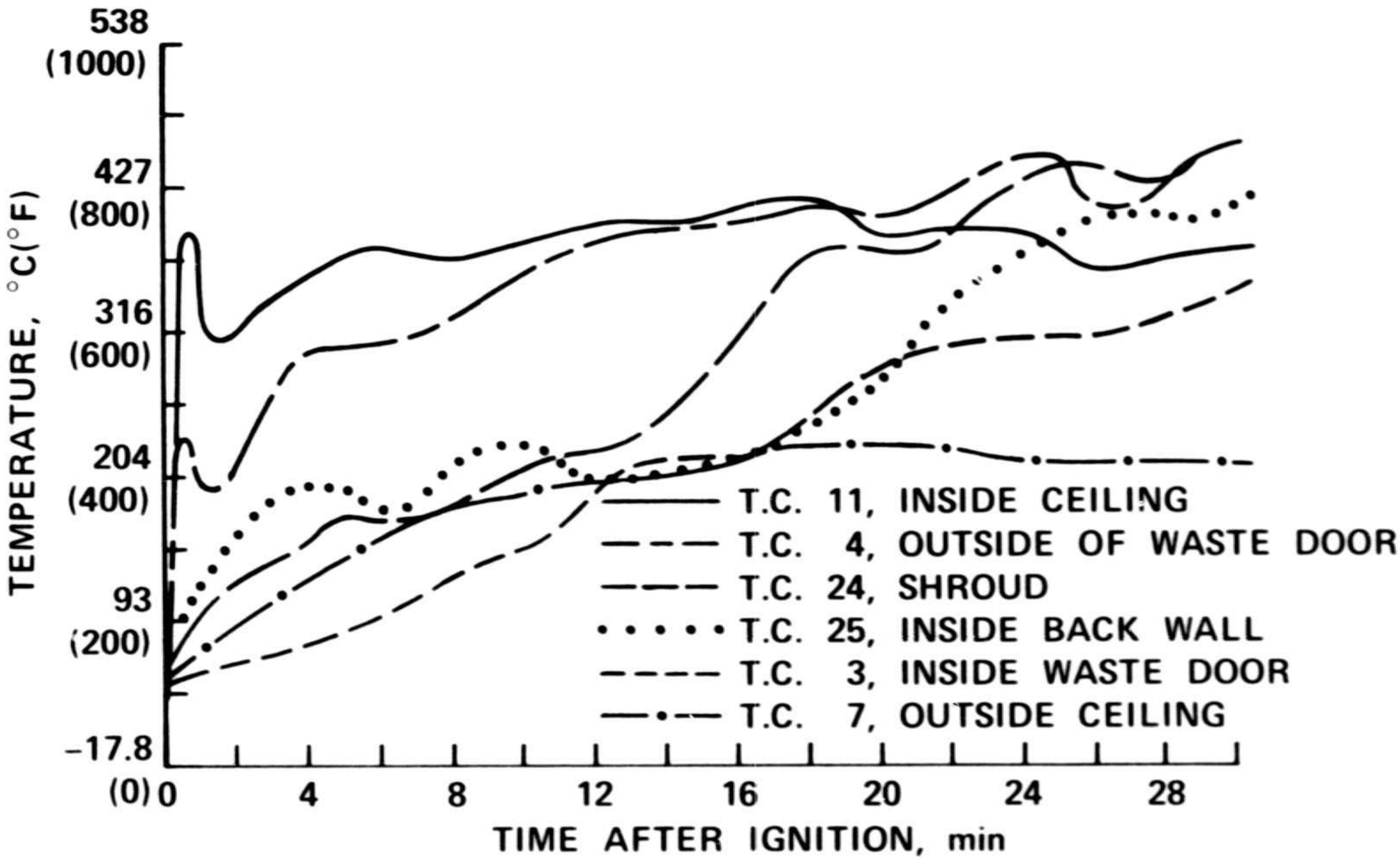


Figure 8.—Surface temperature in lavatory.

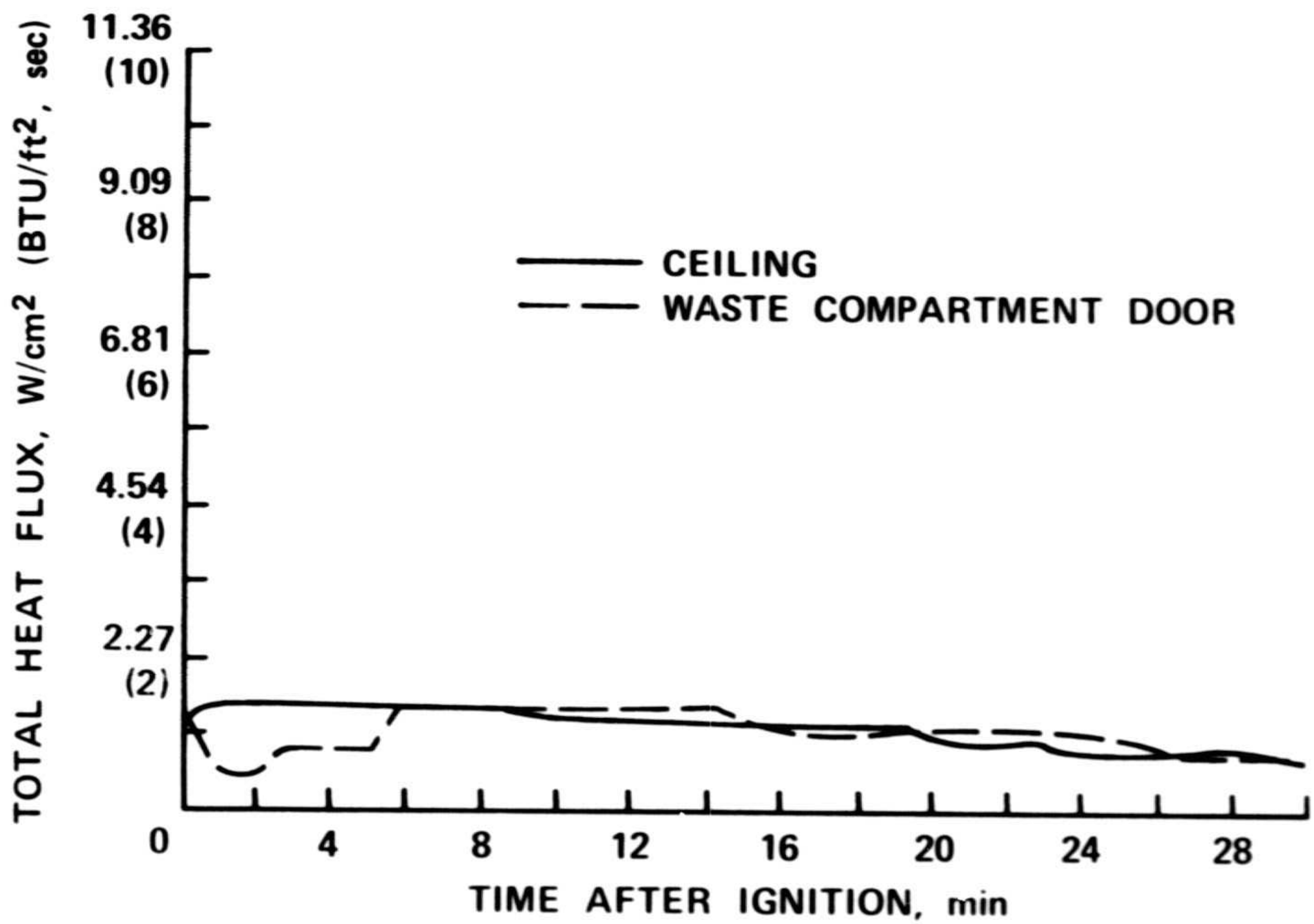


Figure 9.—Heat flux rate in lavatory.

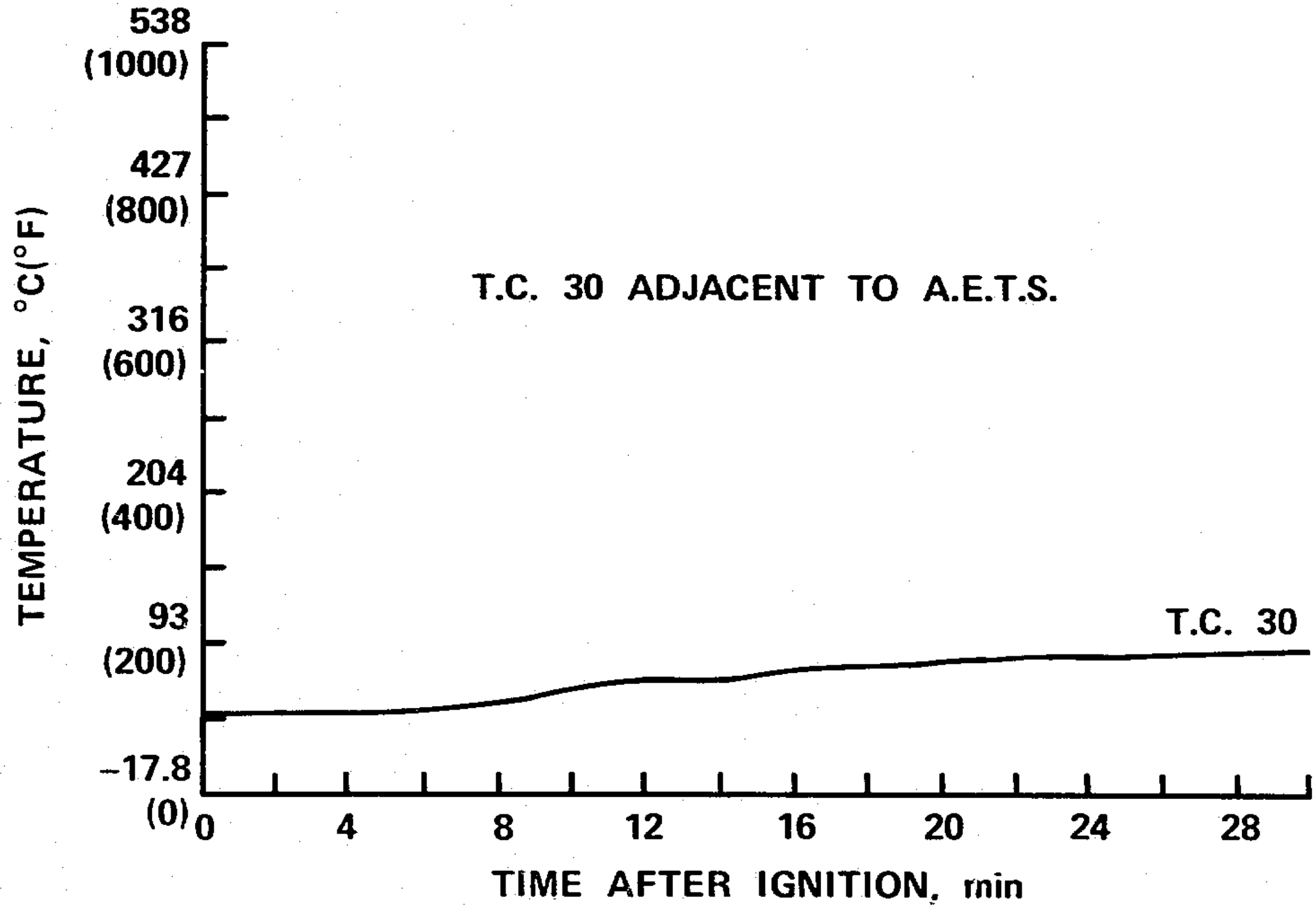


Figure 10.—Air temperature in enclosure.

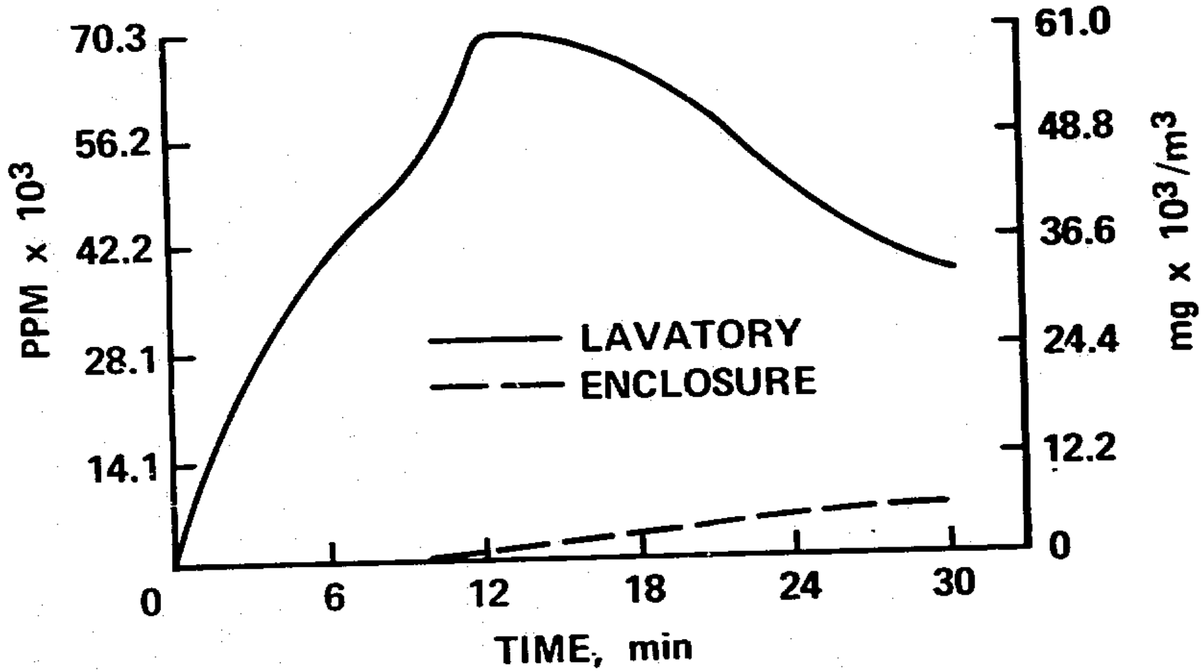


Figure 11.—Concentration of CO.

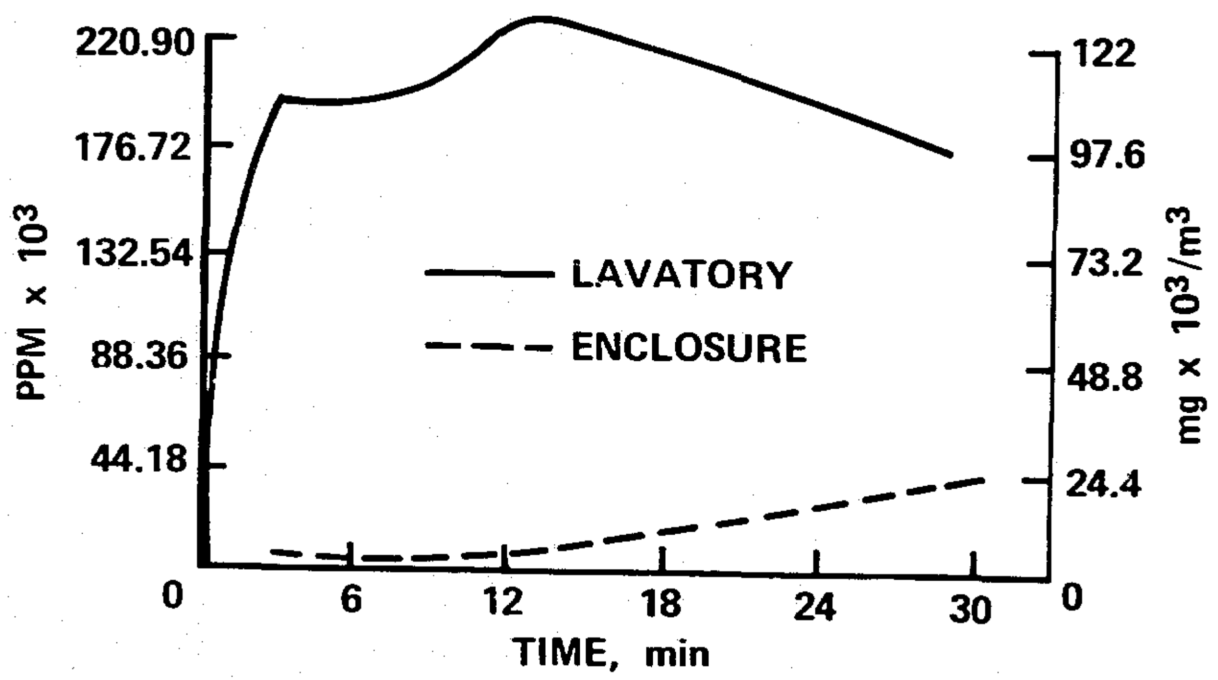


Figure 12.—Concentration of CO_2.

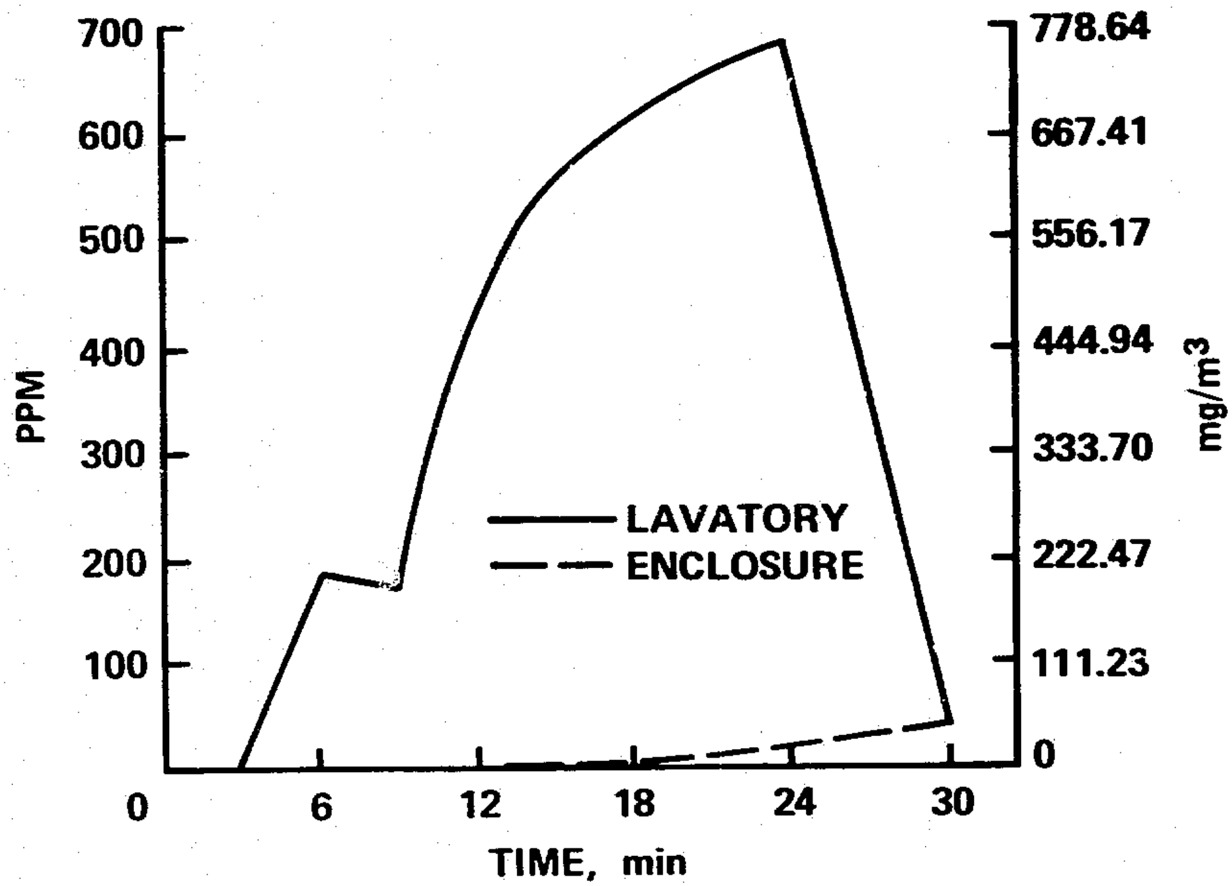


Figure 13.—Concentration of HCN.

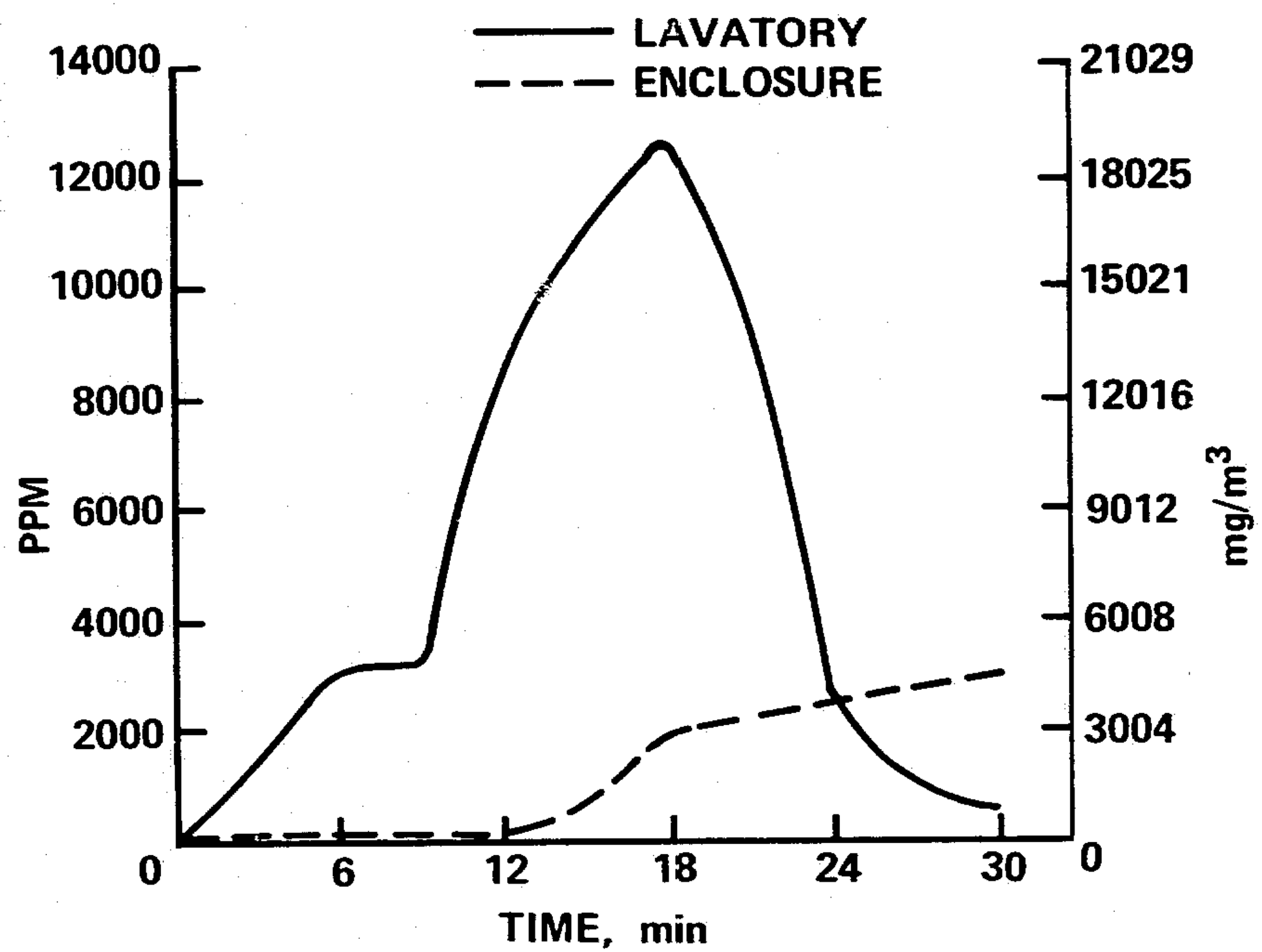


Figure 14.—Concentration of HCl.

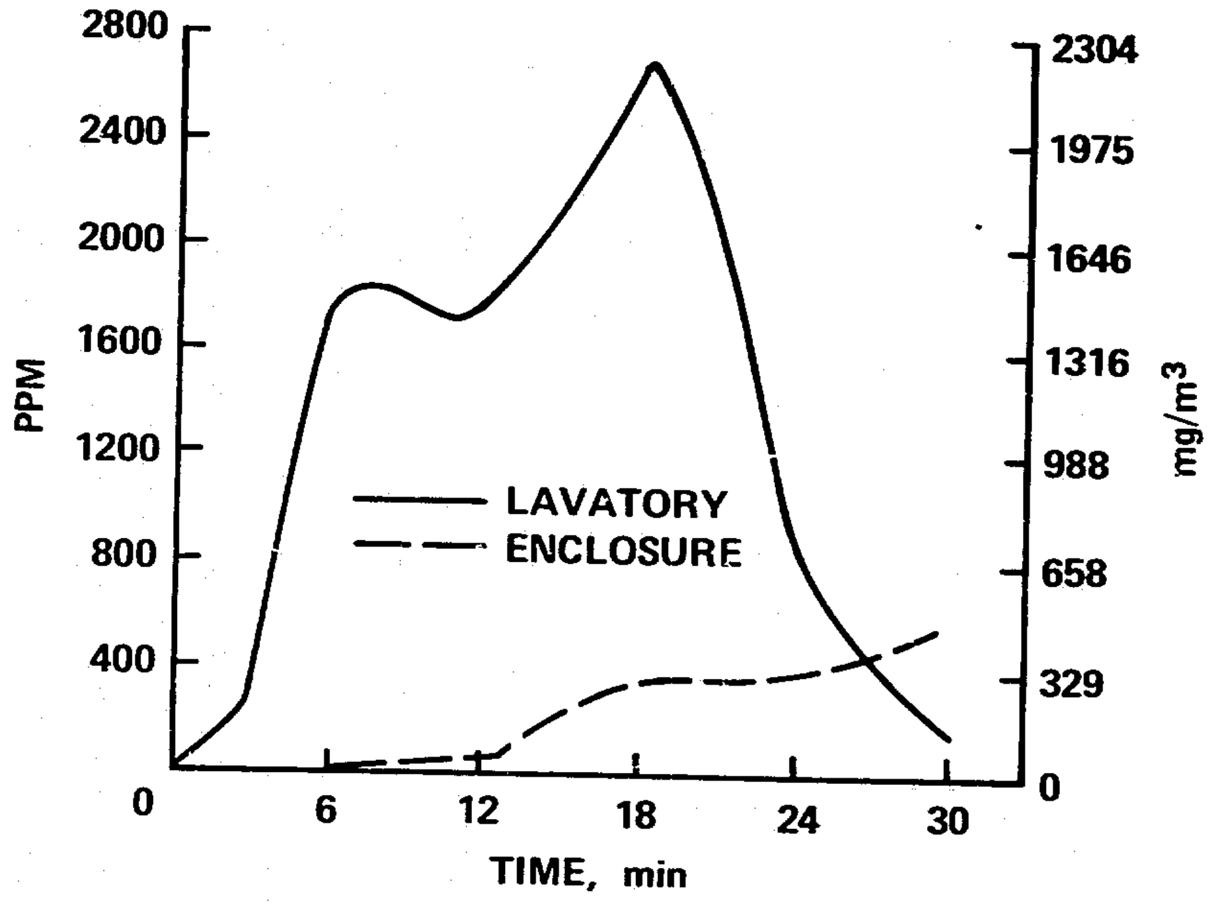


Figure 15.—Concentration of HF.

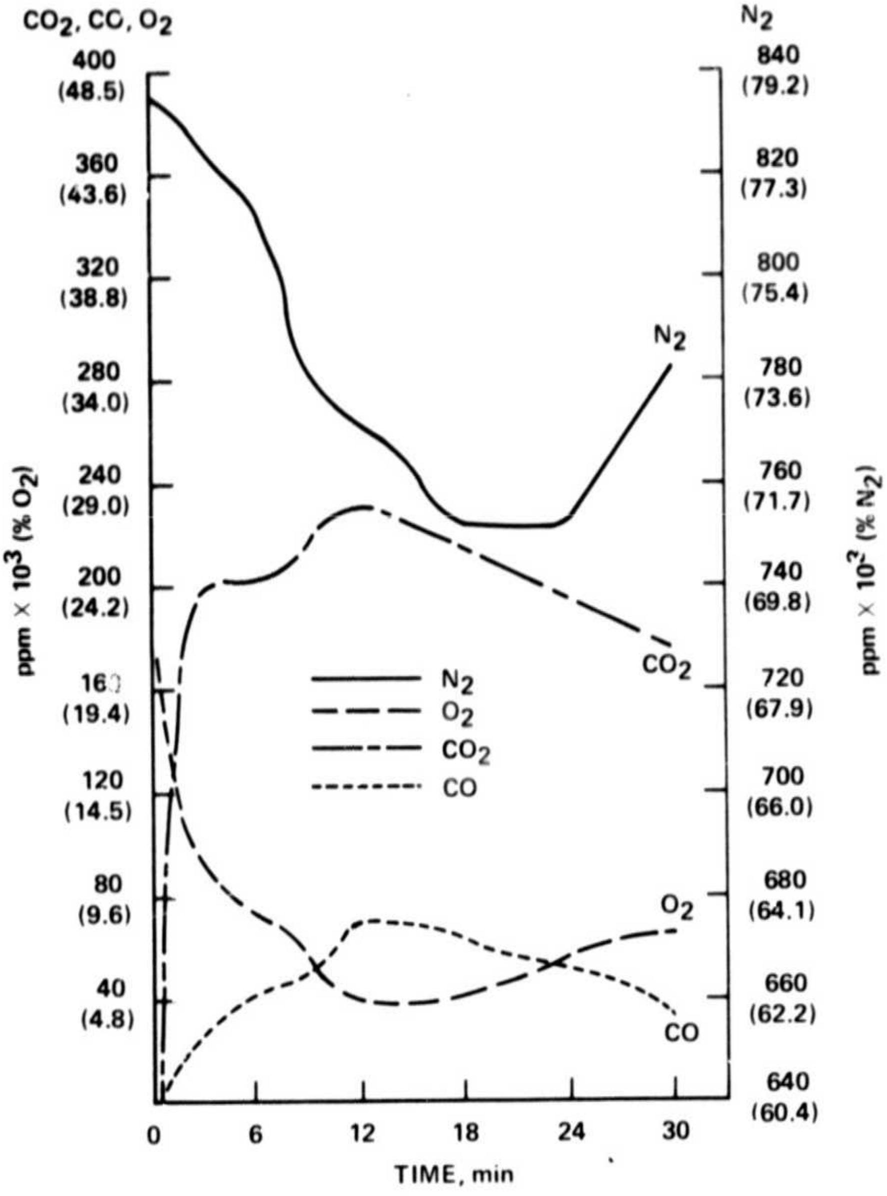


Figure 16.—Major gases in lavatory.

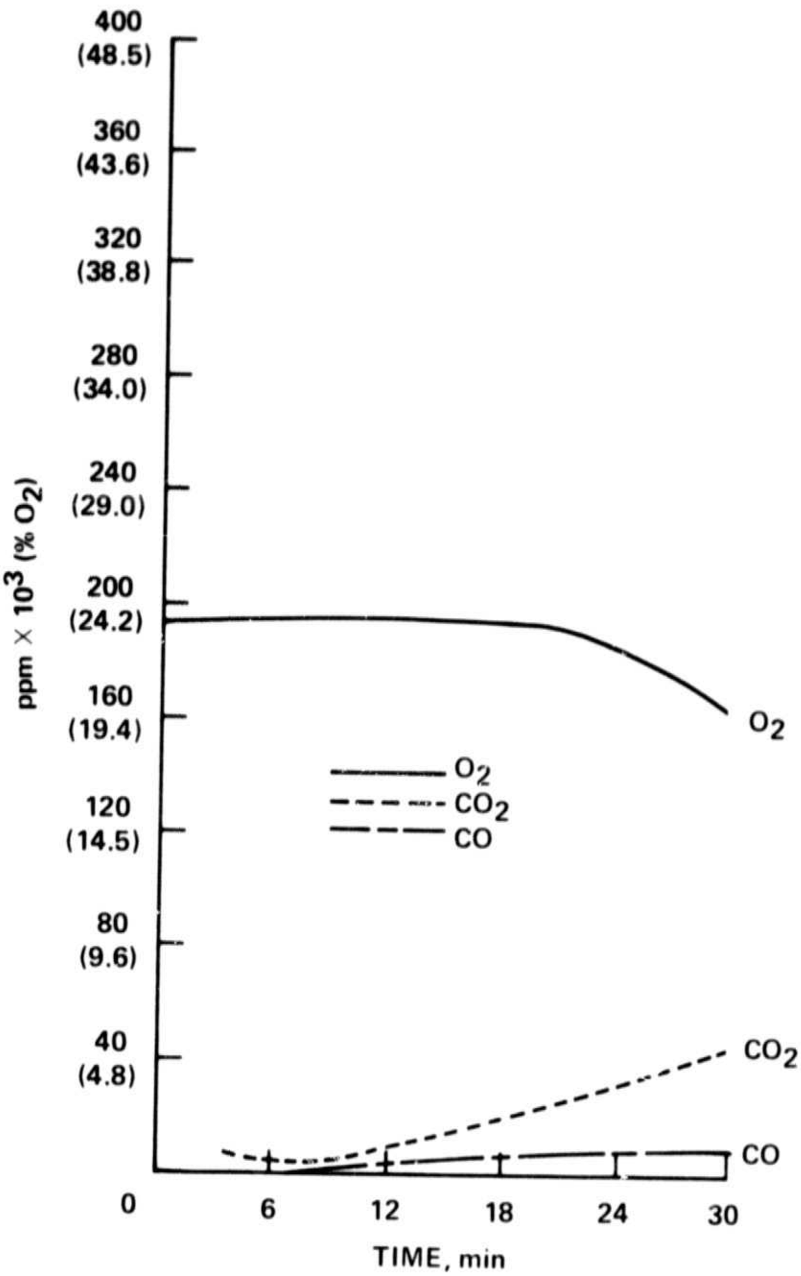


Figure 17.—Major gases in enclosure.

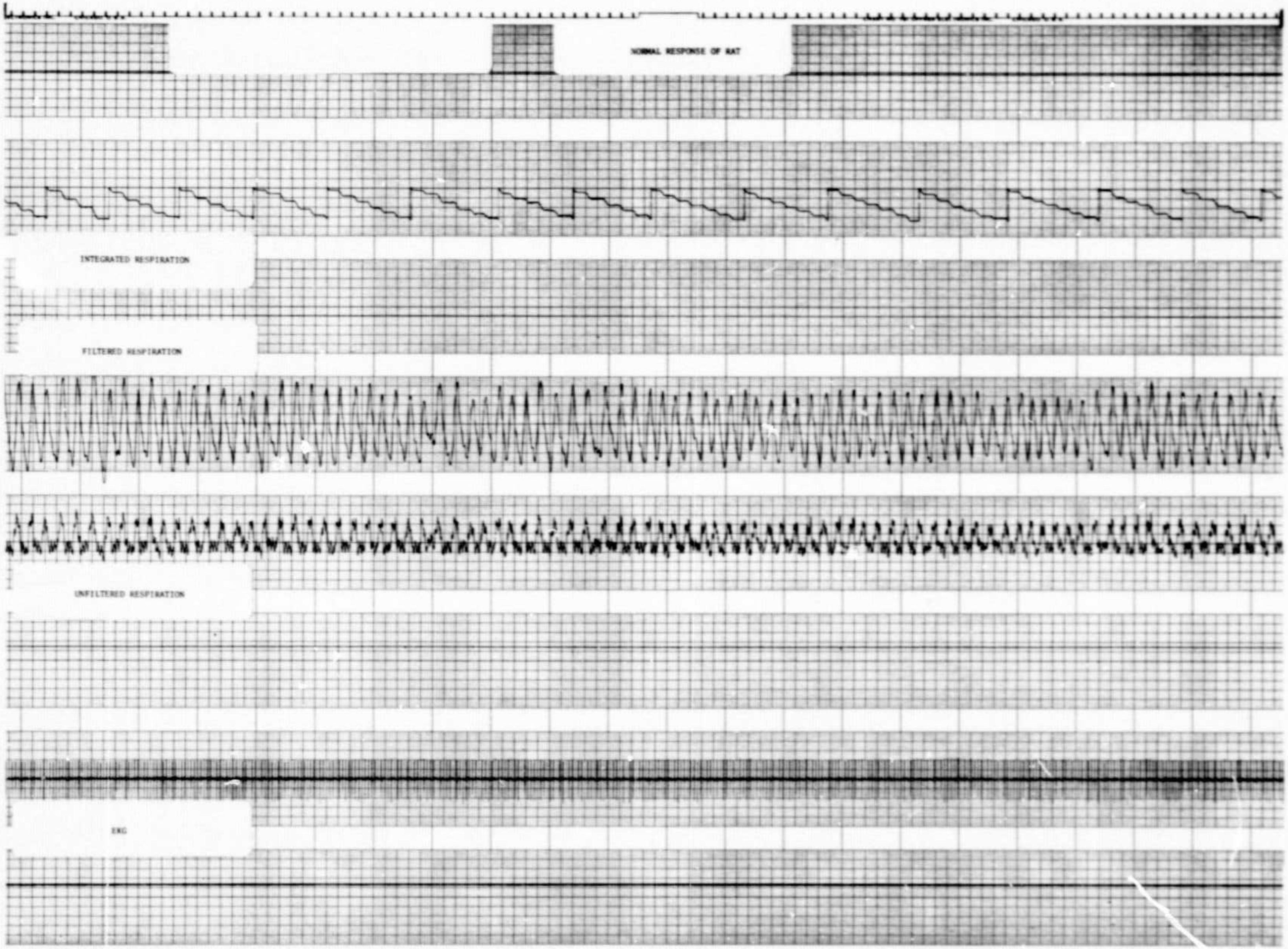


Figure 18.—Normal response of rat.

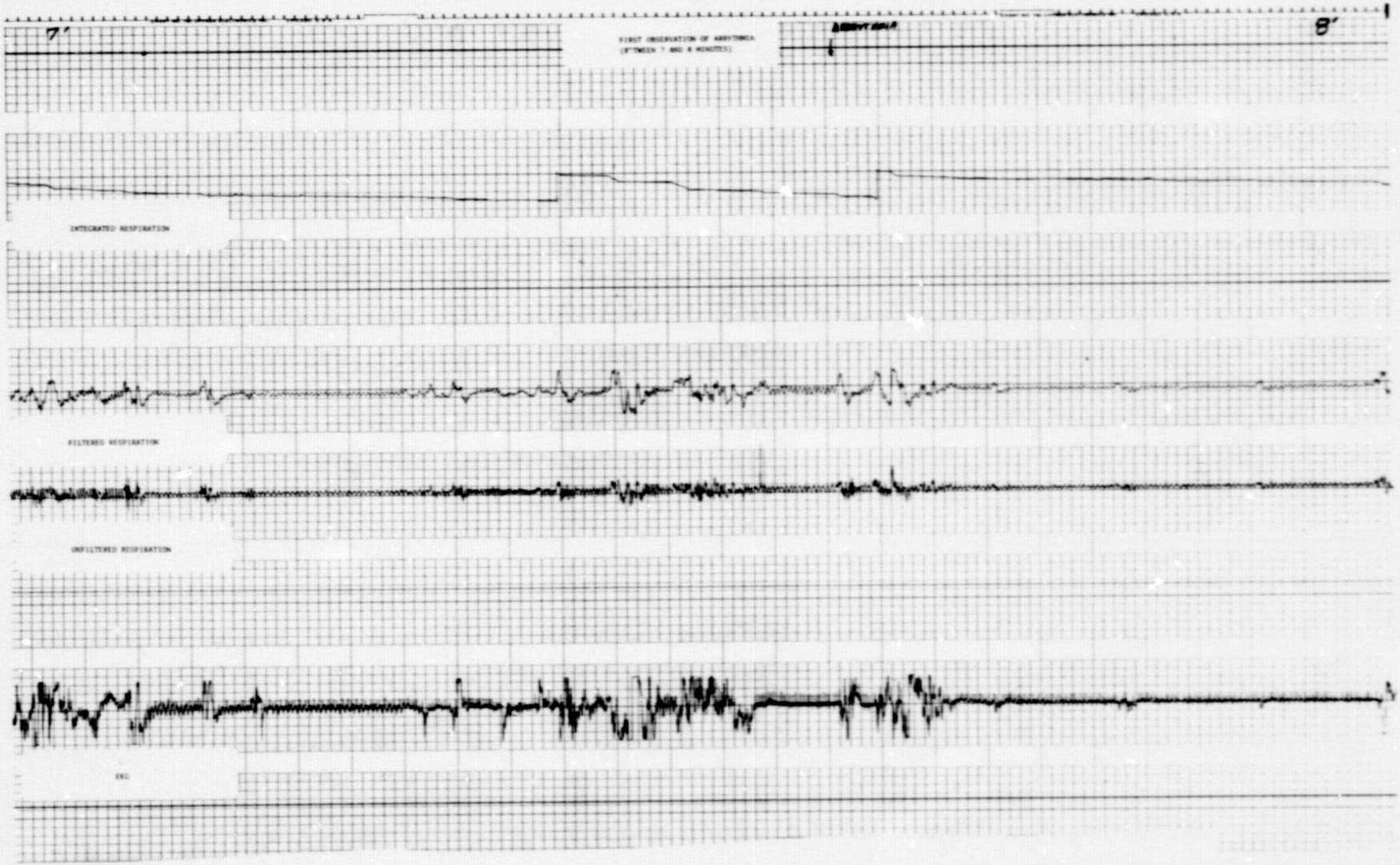


Figure 19.—First observation of arrythmia (between 7 and 8 min).

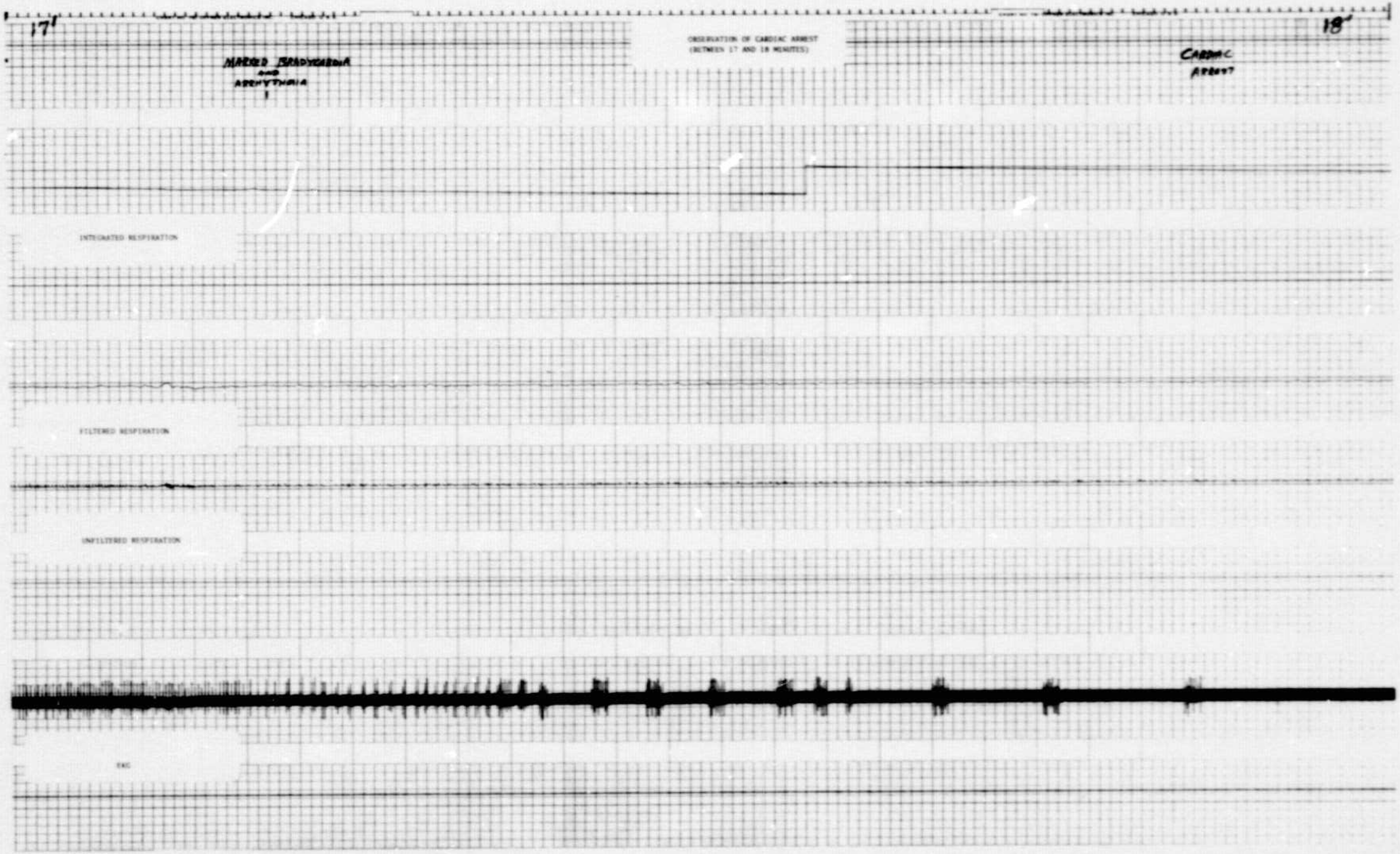


Figure 20.—Observation of cardiac arrest (between 17 and 18 min).

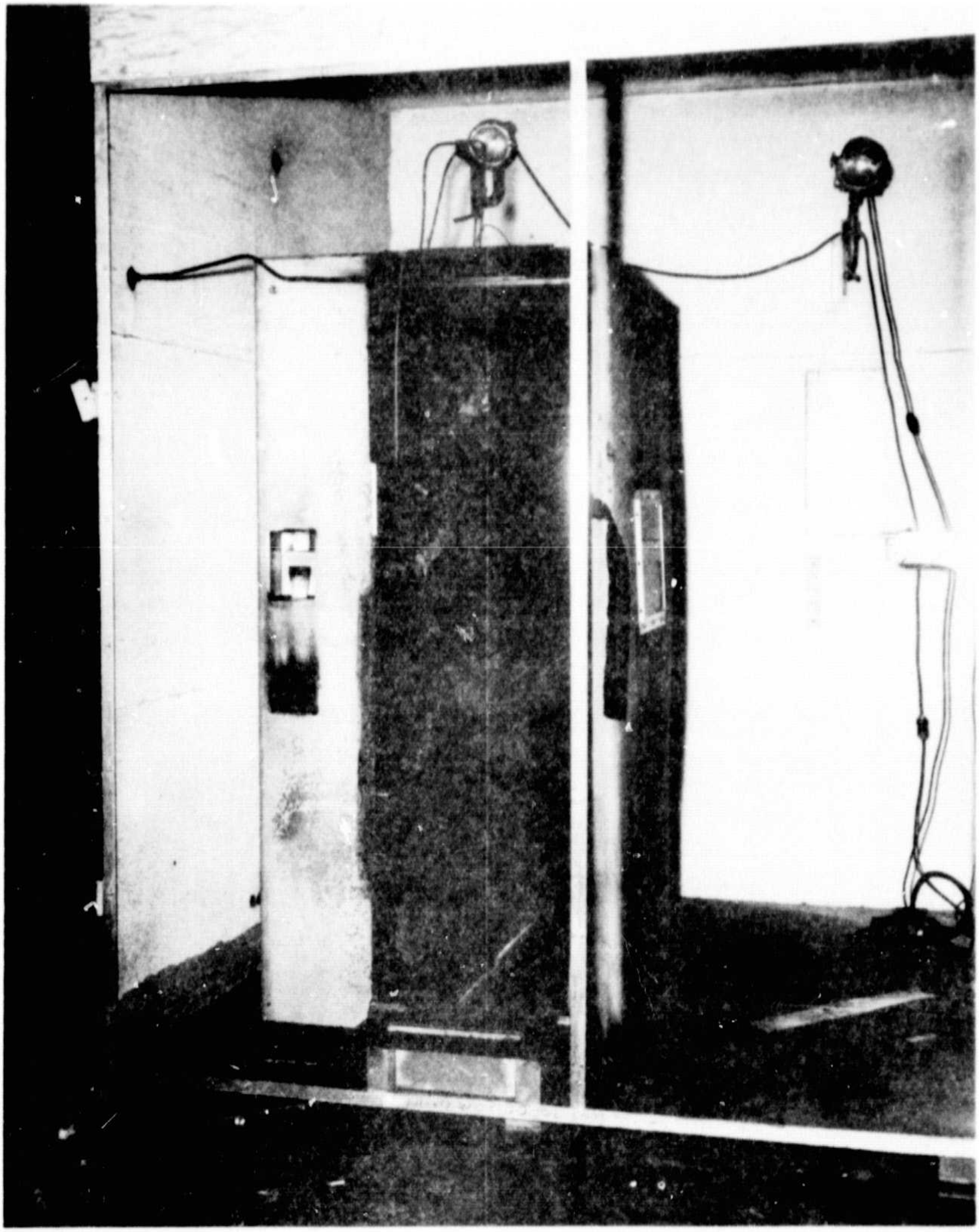


Figure 21.—Lavatory after the test.

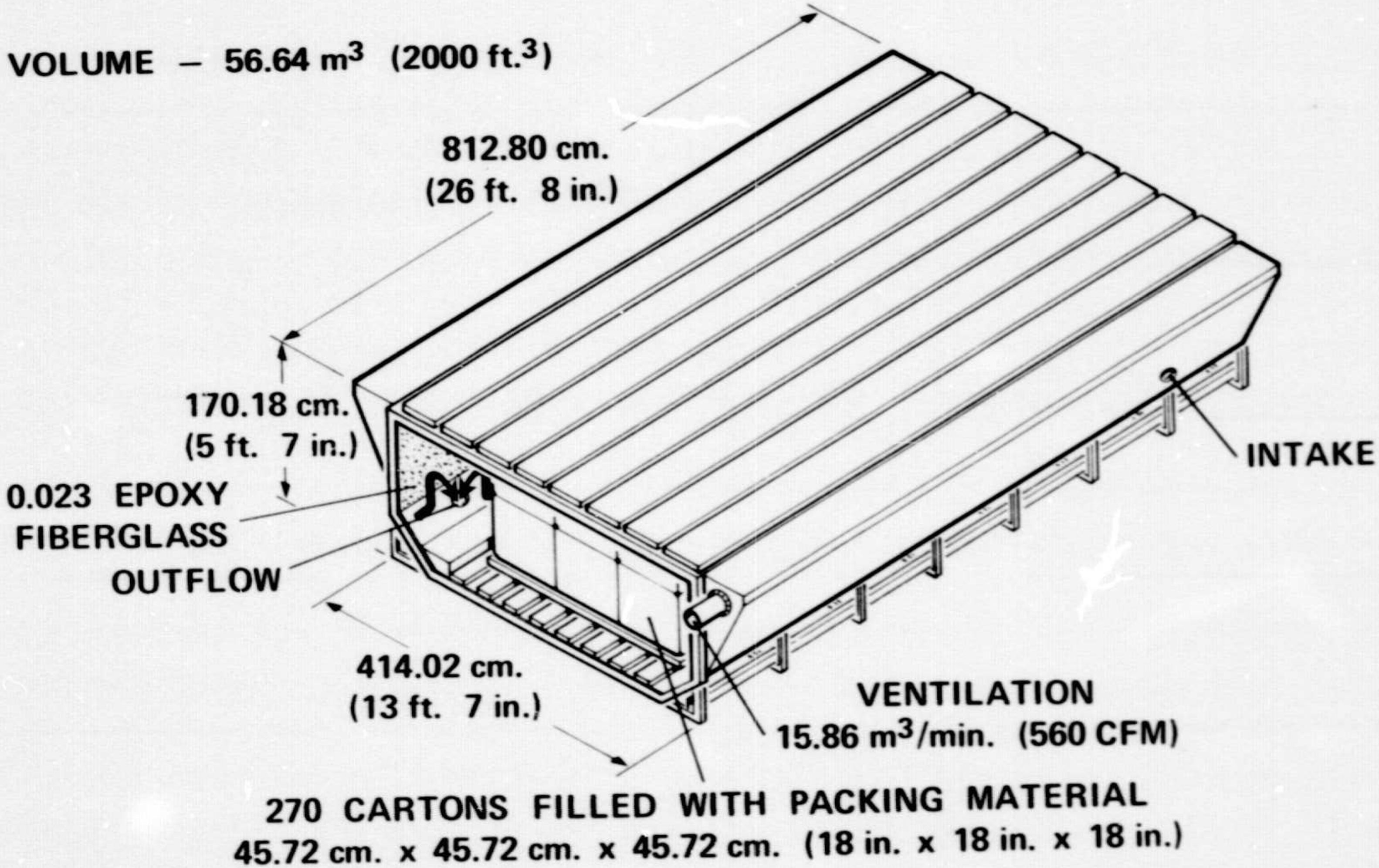
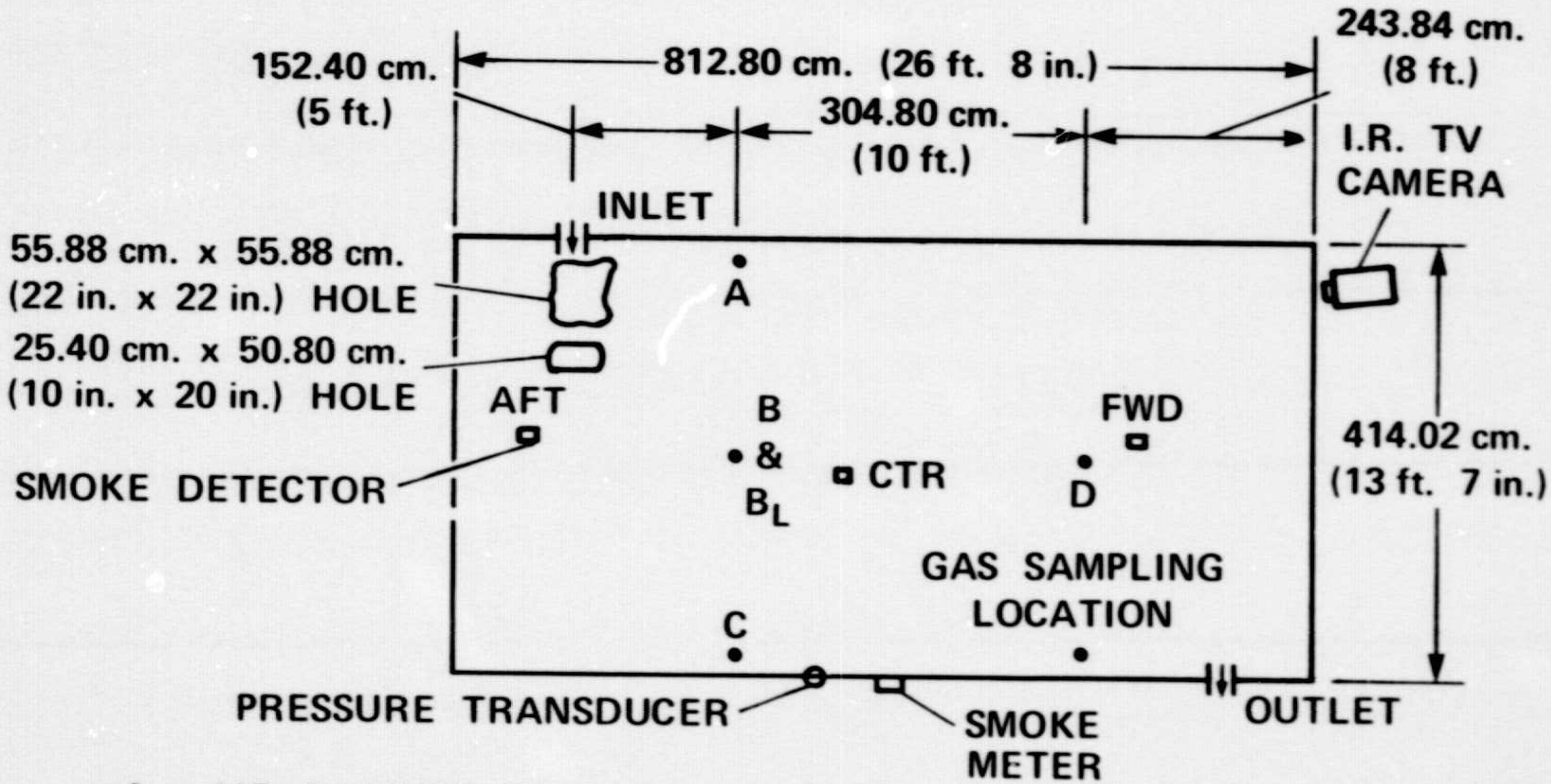


Figure 22.—Cargo test compartment.



A – AIR & LINER T.C.
B – AIR, LINER, & STRUCTURE T.C.; CALORIMETER; IGNITION
C – AIR & LINER T.C.
D – AIR & LINER T.C.; CALORIMETER

Figure 23.—Instrumentation location in compartment.

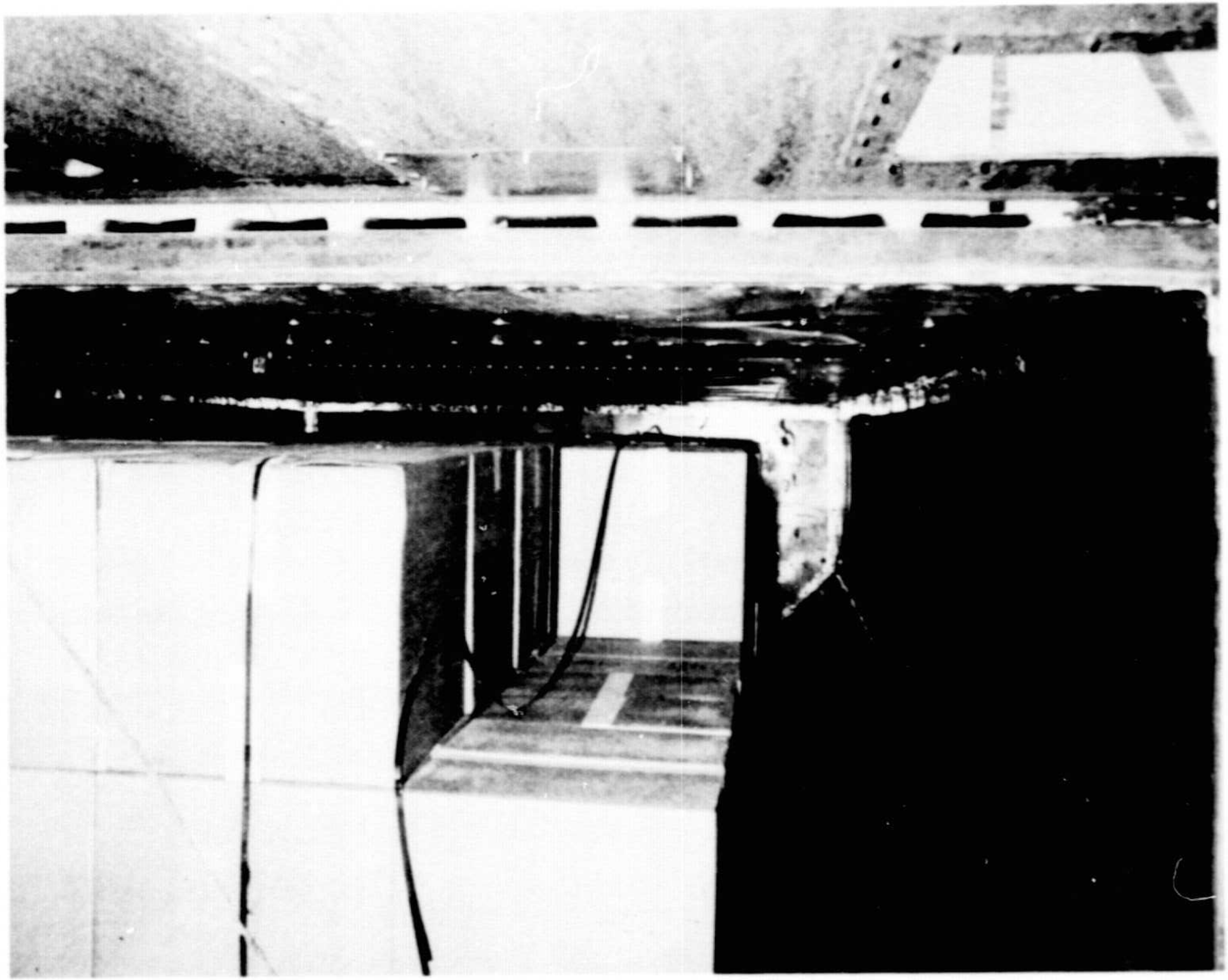


Figure 24.—Cargo compartment prior to the test.

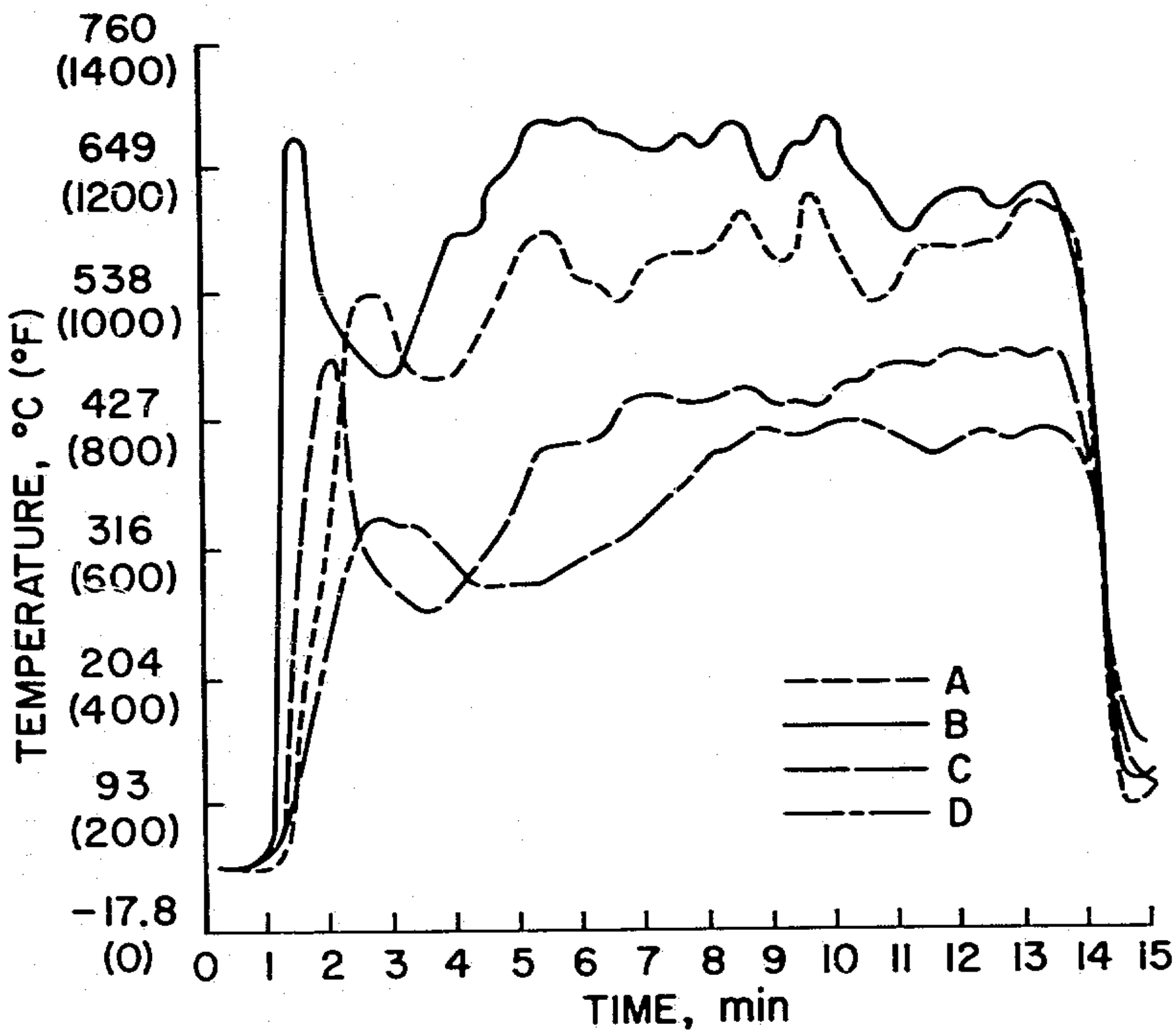


Figure 25.—Air temperature at ceiling.

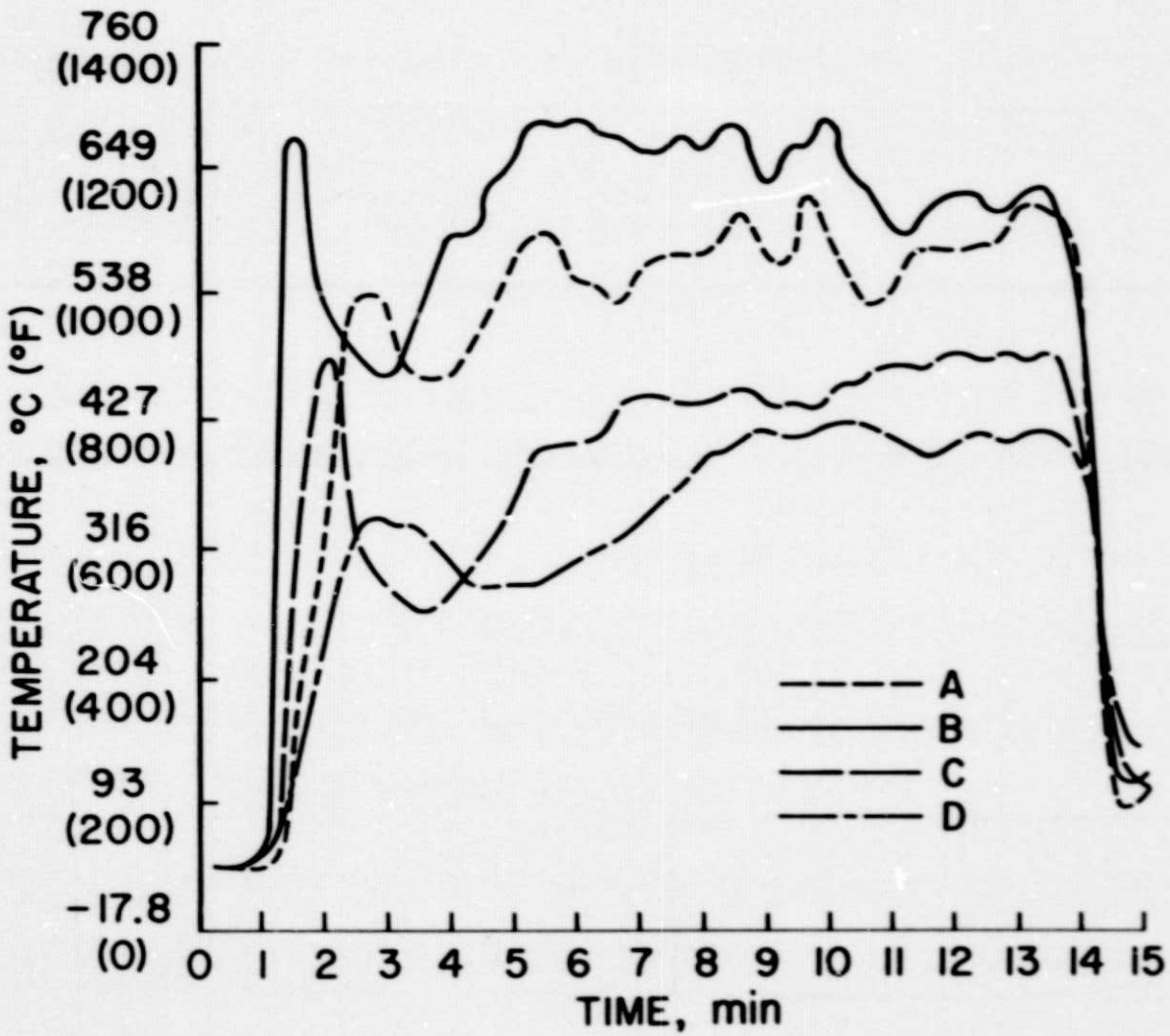


Figure 25.—Air temperature at ceiling.

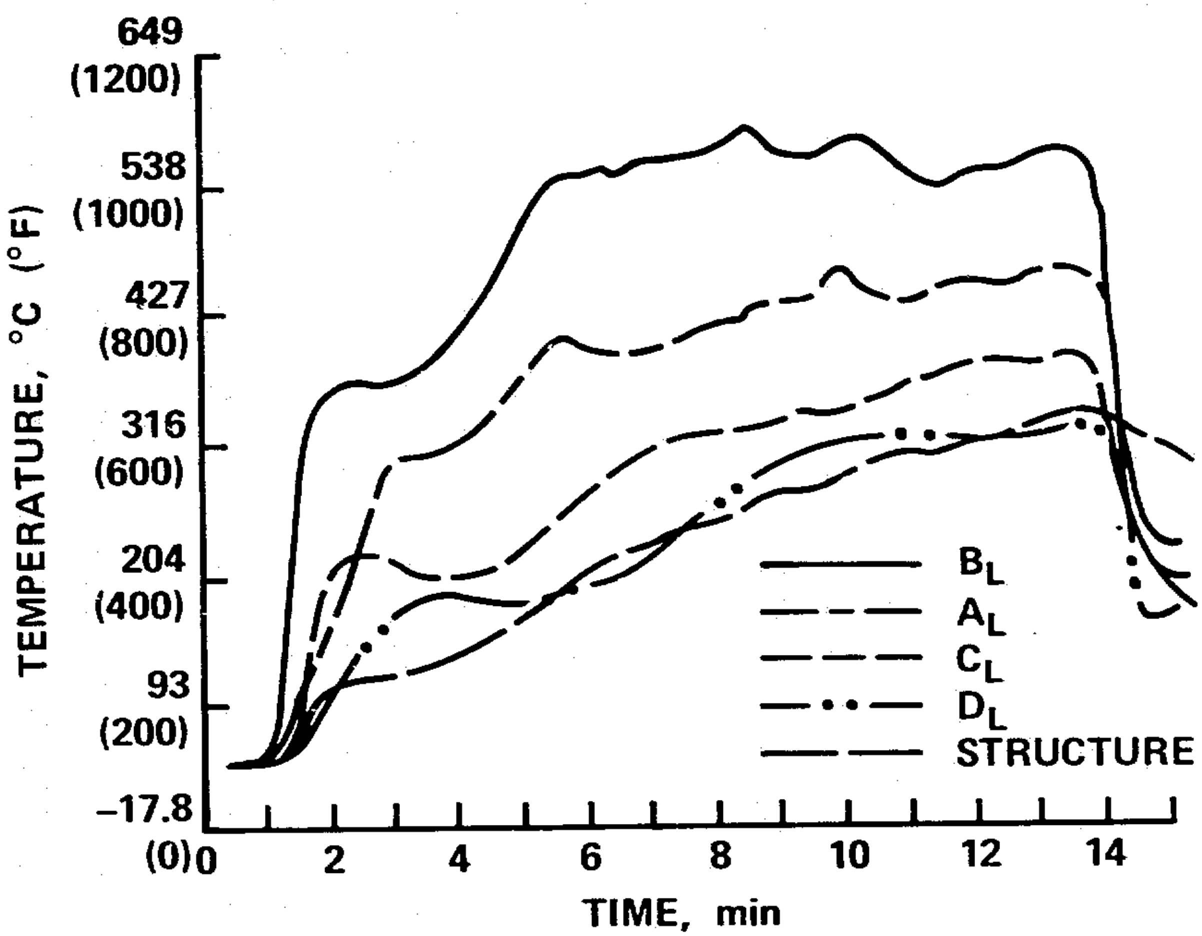


Figure 26.—Structure and liner temperature.

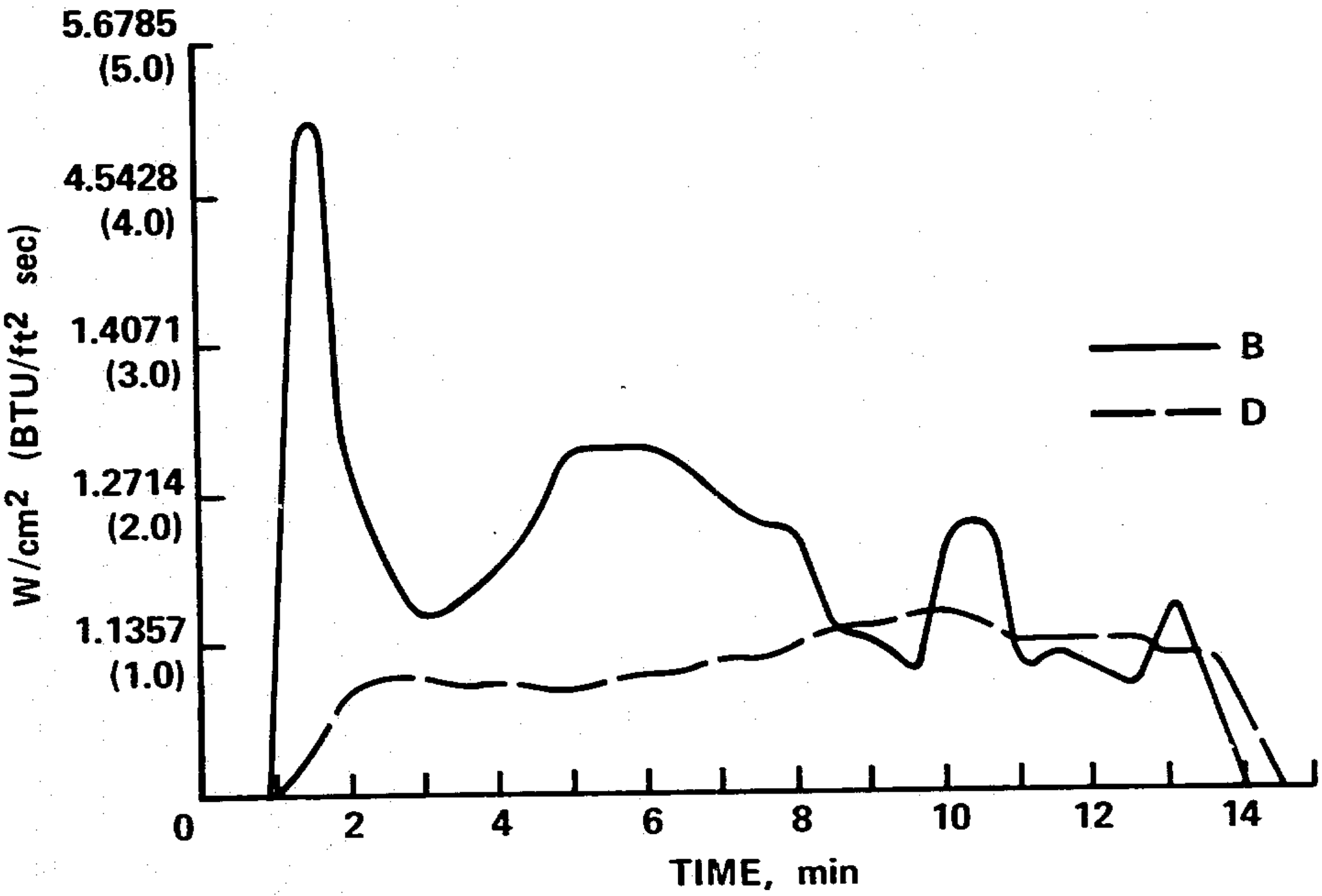


Figure 27.—Heat flux rate at ceiling.

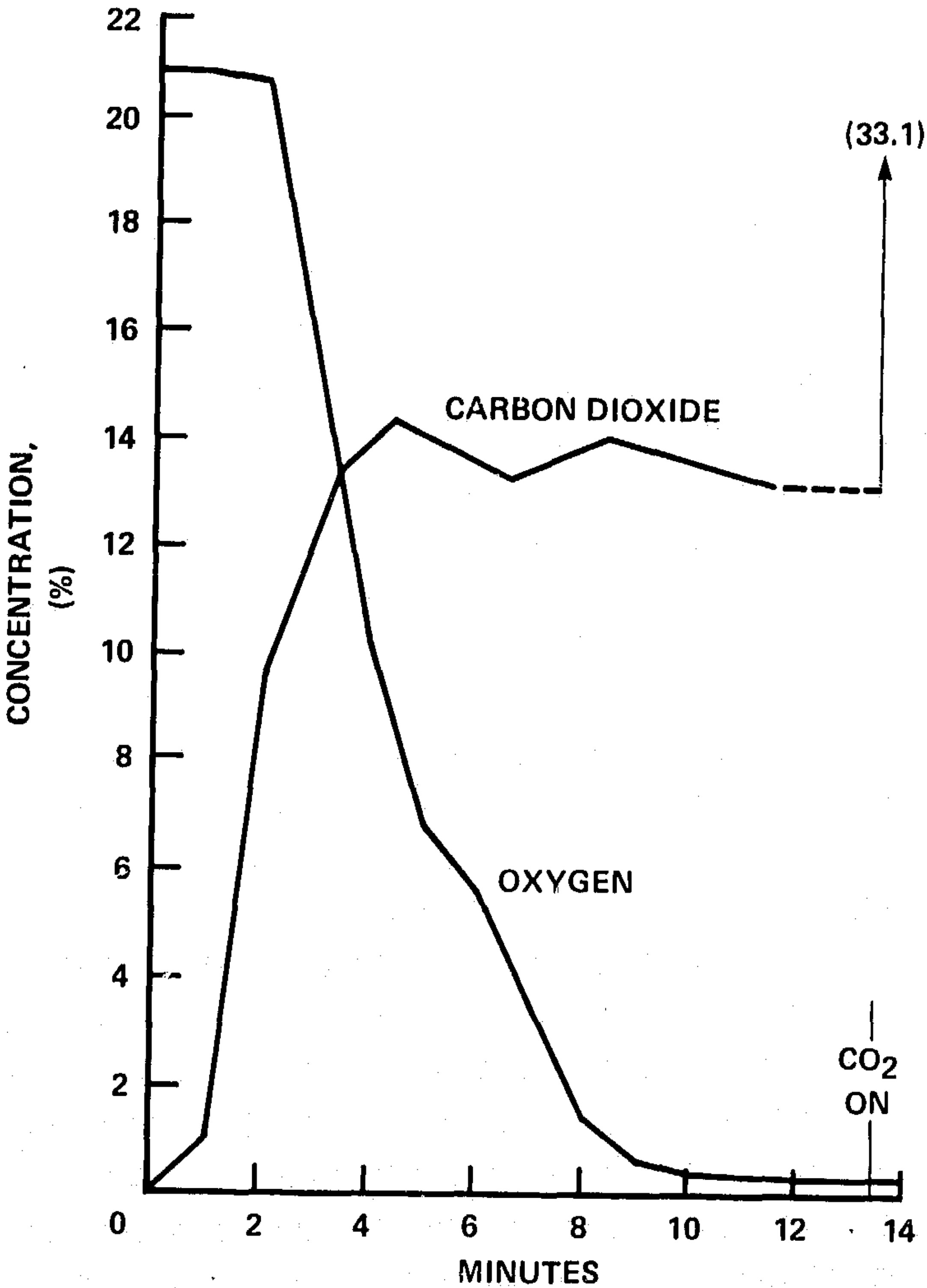


Figure 28.—Concentration of CO_2 and O_2.

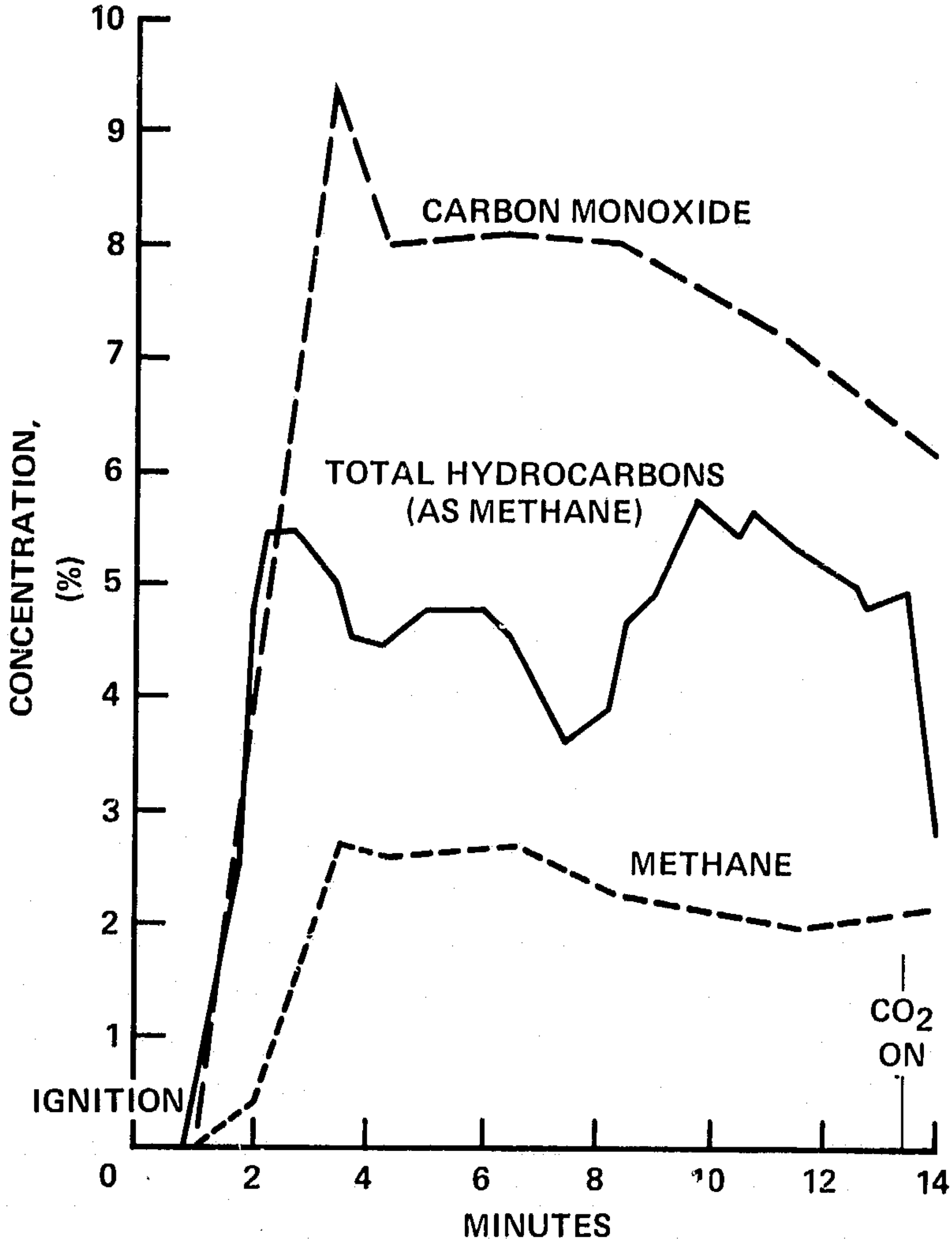


Figure 29.—Concentration of CO and CH_4.

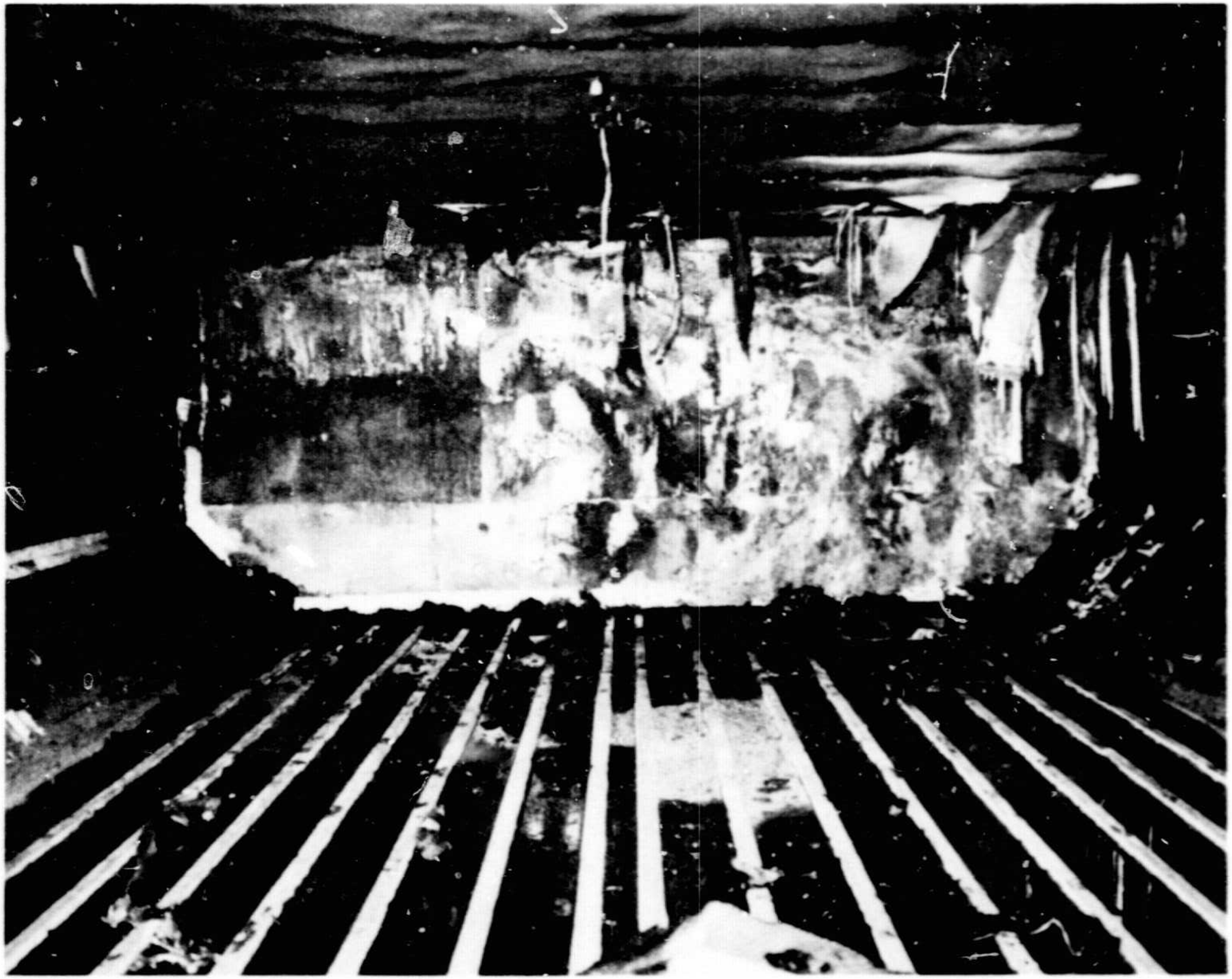


Figure 30.—Cargo compartment after the test.