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Aircraft Seat Fire Blocking Layers: Effectiveness and Benefits Under Various Scenarios

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Final Report

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16. Abstract

Full-scale tests were conducted utilizing the C133 test article located in the Full-Scale Fire Test Facility to determine the benefits that could be derived from fire blocking aircraft passenger seats. Various fire scenarios were selected and tests conducted to evaluate the effectiveness of various blocking materials. The scenarios selected fell into three broad classifications, (1) post-crash, (2) in-flight, and (3) ramp type fires. Test results indicate that the use of a fire-blocking material could increase survivable evacuation time during a post-crash fire that enters a fuselage through a break in the cabin, by as much as 50 percent. Tests also indicate that in-flight and ramp type fires that could destroy the aircraft with present seating materials, could be controlled with the use of a fire-blocking material.

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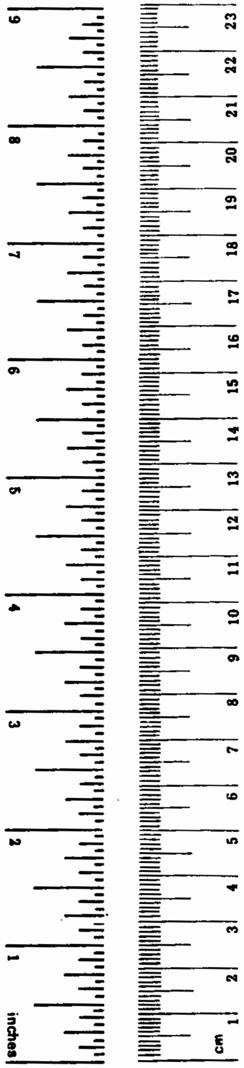
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

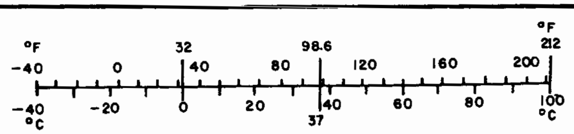
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

This report presents an indepth study, utilizing the C133 test article located in the Full-Scale Fire Test Facility, of the effectiveness and benefits that could be derived from the utilization of various blocking-layer materials. Tests were conducted in three basic categories, (1) post-crash, (2) in-flight, and (3) ramp type fires. The post-crash scenario, being the most severe, was used to evaluate the effectiveness of various blocking materials. Post-crash test series range from a single seat in a rupture opening to a full mockup of all interior aircraft materials in a 20-foot section of the aircraft. In-flight and ramp type fires were conducted to determine the benefits from utilizing the most promising blocking materials in the post-crash tests.

The results of fire-blocking tests indicate that the use of a blocking material could increase survivable evacuation time by 50 percent for post-crash, in-flight, and ramp fires (it could stop a fire before nonsurvivable conditions are reached). Other results obtained during this study were: (1) carry-on baggage located under a seat or in an overhead bin, contributed little to the decrease in survivability in a cabin during a post-crash fire, and (2) non-fire retardant urethane foam performed as well as the fire retarded type when incapsulated by a fire-blocking material.

INTRODUCTION

OBJECTIVES.

The main objectives of the test program were as follows:

(1) Determine the benefits of fire blocked urethane seats for various aircraft fire scenarios; (2) Study the effectiveness of various seat cushion fire-blocking materials; and (3) Determine the characteristics of aircraft cabin fires ignited by: (a) post-crash external fuel fire adjacent to a fuselage opening, (b) carry-on bag under a seat, in-flight, and (c) trash bag adjacent to a seat in a closed-up, unoccupied aircraft.

BACKGROUND.

Aircraft accident investigations, in most instances, do not furnish the detailed information required to identify the primary physical factors contributing to those fatalities resulting from fire. This lack of information is due, in part, to the infrequent occurrence of aircraft accidents and the usual destruction of evidence by the fire, but, more importantly, to the complex nature of the fire dynamics and hazards ultimately responsible for preventing escape by passengers and crewmembers. Therefore, although the outcome of an accident investigation may suggest the existence of a design deficiency leading to fire fatalities in a particular case, some form of controlled and well-instrumented experimentation is needed to validate the conclusions reached and the benefits of proposed improvements. The type of testing which is most convincing is that which most closely replicates the actual fire environment and aircraft geometry configuration; i.e., what has been termed a full-scale test. The utilization of full-scale tests is a major and integral aspect of the aircraft fire safety program conducted by the United States (U.S.) Federal Aviation Administration (FAA) (reference 1).

A number of organizations, including the National Transportation Safety Board (NTSB), which has the responsibility for investigating civil aviation accidents in the United States, have analyzed the incidence of aircraft accidents accompanied by fire. A study by NTSB for the period 1965 to 1974, estimated that 15 percent of all fatalities in U.S. air carrier accidents were attributable to the effects of fire (reference 2).

Aircraft cabin fires may be categorized as follows: ramp, in-flight, and post-crash. The characteristics of each are sufficiently distinct to require separate analysis. Ramp fires occur when an aircraft is parked at the ramp, usually in an unattended condition, but less frequently during servicing. Past ramp fire experience has resulted in loss of property, but not loss of life. For example, a B727 was extensively damaged as a result of a fire originating from discarded smoking material placed inside a plastic disposal bag located adjacent to a passenger seat (reference 3). The loss was estimated at $3,200,000. The elapsed time before discovery of the fire, approximately 50 minutes, is consistent with the ability of polyurethane foam to support smoldering combustion for long periods of time before transitioning to open flaming. Most in-flight fires occur in accessible areas, such as a galley, and are detected and extinguished promptly. On rare occasions, in-flight fires become uncontrollable, leading to large loss of life. A most recent example was an L1011 in-flight cargo compartment fire over Saudi Arabia, eventually claiming all 301 occupants onboard the airplane (reference 4). The fire became life threatening when flames penetrated through the cabin floor, involving seats and other interior materials. In the United States, all fatalities attributable to fire occur in post-crash fire accidents (reference 2). Most post-crash cabin fires are accompanied by a large fuel-spill fire. Burning interior materials may affect the survivability of cabin occupants in those accidents with a predominantly intact fuselage and a fuel fire adjacent to a fuselage opening, such as a rupture or door opening (references 5 and 6). Under these conditions, seats near a fuselage rupture or door opening will be subjected to intense thermal radiation and/or flames from the fuel fire.

It is difficult, if not impossible, to assess the role of a particular interior material, or materials, in general, on the number of fatalities in crash accidents accompanied by fire. Numerous factors are known to affect the behavior of a material in a fire (reference 7), although the present status of fire technology does not allow for the prediction of the combined effect of each factor on the overall threat to cabin occupants under a given fire condition. Nevertheless, there does exist both direct and indirect data of the importance of interior materials on survivability during a post-crash cabin fire. Of a direct nature is the measurement of high levels of blood cyanide in some accident victims (reference 8). These measurements have been incorporated into U.S. accident investigations since 1970. However, the relationship between cyanide levels in blood samples taken from accident victims to the concentration of cyanide to which the victim was exposed to during the fire has been questioned (reference 9).

Another form of direct data is the fact that although most crash accidents are accompanied by fuel spillage, several fatal accidents have occurred with insignificant or no fuel release. For example, at Salt Lake City in 1965, a B727 crashed and caught fire as the result of a severed fuel line beneath the cabin floor. The initial fire, consisting of a relatively small quantity of spilled fuel, was probably not life threatening in itself, but was of sufficient intensity to ignite the cabin interior, which resulted in 43 fatalities (reference 10). More recently, a B747 crashed in Seoul, Korea in 1980, without any fuel spillage, yet the ensuing fire killed 15 people. More of an indirect nature of data is the recognition that an aircraft cabin is an enclosure with limited egress, high loading of plastic and synthetic interior materials, and high occupancy density. Past large-scale tests conducted in the United States on simulated cabin interiors or mockups (references 11, 12, and 13) have demonstrated that hazardous and fatal conditions will arise from ignition of interior materials with the development of a self-sustaining fire. In the laboratory, a wide range of heat, smoke, and toxic gas levels have been measured during testing of in-service materials subjected to intense fire exposure (reference 14). These test data gathered under specific and, perhaps, not completely realistic conditions indicate the potential dangers of burning interior materials.

Complexity of cabin design is one of the many factors that make it difficult to determine the importance of interior materials on post-crash cabin fire survivability. The cabin interior is completely lined with multi-layered materials and furnished with hundreds of seats. Each component is selected with due consideration given to fire safety, functionality, durability, processability, cleanability, economics, and, of increasing importance, weight. Current FAA regulations specify that all major components "self-extinguish" after a prescribed exposure to a small flame (reference 15).

Moreover, at their own initiative, the airframe manufacturers strive to select materials with low-smoke emissions and low-flame spread rate. One manufacturer also screens materials for emission of specified toxic gases. Despite apparent differences in design goals and philosophy, the cabin materials used by the three major U.S. airframe manufacturers are very similar. The composite panels which constitute the bulk of the sidewalls, stowage bins, ceilings, and partitions are basically composed of a Nomex™ (aramid) honeycomb core with fiberglass facings impregnated with epoxy or phenolic resin and a decorative laminate composed of Tedlar™ (polyvinyl fluoride) layers or Tedlar and polyvinyl chloride layers. A greater variety of materials are used for floor coverings and seat cushions, which are selected by the airlines, but are typically wool pile carpet and cushioning composed of flame retardant (FR) urethane with a wool (90 percent)/nylon (10 percent) upholstery cover. A full-scale test configuration should include, at least, the major cabin usage categories; i.e., carpet, seats, sidewall panels, storage bins, and ceiling panels.

From a practical necessity, aircraft materials are and should be selected based on the results of small-scale fire tests. However, it is generally recognized that small-scale test results do not reflect the behavior of a material in its end use application under realistic fire conditions. Therefore, until more realistic and meaningful small-scale tests are developed, the FAA, as well as many other organizations engaged in fire testing, are relying more heavily on large-scale tests and, to a much lesser degree, full-scale tests for materials evaluation. Full-scale tests are usually performed for more far-reaching reasons; namely, to define the nature of a perceived fire problem, to identify governing parameters, to bracket fire conditions, to examine the relevency of small-scale test results, and to demonstrate the benefit of improved material or fire management systems.

In the past, the number of fire tests consisting of exposure of a realistically-furnished cabin test article to a fuel-fire have been small in number (references 11, 13, and 16). Each of these test programs were deficient in one or more of the following manners:

1. Instrumentation was incomplete or improper (e.g., absence of smoke measurements or test animals, improper sampling of reactive acid gases);

2. The test article was not fully protected to allow for multiple tests, causing the results to be inconclusive or unconvincing;

3. The fuel-fire was unrealistic in terms of size (too small) and position (placement was inside the fuselage). The effect was to exaggerate the contribution of fuel-fire smoke to the cabin environment and to subject the interior materials to unrepresentative low levels of radiant heat;

4. Precautions taken to negate the effect of random ambient wind, which has a pronounced, and sometimes dominant affect on external fuel fire penetration through a fuselage opening (references 17, 18, and 19), were ineffective. Therefore, the effect of the fuel-fire with regard to heat exposure of the interior and its contribution to cabin hazard levels was not identical from test to test.

5. Protection of the test article interior with sheet metal probably created higher wall heat losses than would have been encountered with a real interior. Thus, the wall losses could have far exceeded the levels measured in enclosure fires; i.e., 50 to 95 percent of the total energy released by the fire (reference 20). None of the test articles simulated a wide-body cabin. In the development of the cabin fire test article described subsequently in this report, an attempt has been made to rectify the problems, enumerated above, that were encountered by earlier investigators.

The FAA convened the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee to "examine the factors effecting the ability of aircraft cabin occupants to survive in the post-crash environment and the range of solutions available" (reference 11). The committee approved the objectives set forth by the FAA in its program plan (reference 1) for full-scale cabin fire testing. After examination of the contemporary makeup of aircraft cabin interiors, the committee concluded that a near-term solution was available to protect or replace the FR urethane used in seat cushions, which was believed to be the most flammable of all the interior materials used in large quantities.

DISCUSSION

BLOCKING LAYER MATERIAL.

Over the past 20 years or more, the aircraft industry has constructed aircraft seat cushions from urethane foam which posseses low weight and excellent comfort, resiliency, and durability. In appplications where weight is not a consideration, Neoprene™ foam is a viable replacement for urethane foam when improved fire performance becomes a requirement (reference 21). However, Neoprene foam is approximately 3 or 4 times as dense as urethane foam, and would create a prohibitive weight penalty in aircraft seating. A thin, lightweight blocking-layer material, encapsulating the urethane foam to prevent or retard fire involvement of the urethane, is an attractive protective measure for aircraft seating. The blocking-layer material is an interliner between the upholstery cover and foam cushion. In some cases it can also function as a ticking.

Table 1 is a list of candidate blocking-layer materials for aircraft seating evaluated in this report. There are two basic types of blocking layer materials; (1) foams and (2) aluminized fabrics. The foam-blocking layers are neoprene (polychloroprene), which are glued to the urethane foam. Upon exposure to heat or flame, neoprene foam-blocking layers produce a relatively stable char, which acts as an insulator and reduces the rate of heat transfer to the urethane foam. Of the two foams listed, only Vonar™ is marketed as a blocking layer; LS-200 is normally used as a full cushion. The lightest Vonar blocking layer has a cotton scrim and weighs 23.5 oz/square yard.

A more recent blocking layer consideration is the aluminized fabrics, used primarily in protective clothing against heat or fire. These materials were identified by the National Aeronautics and Space Administration (NASA) as a possible alternate to a Vonar blocking layer at approximately 1/2 the weight (reference 22). Fabric blocking layers are designed to cover the urethane foam in the same manner as an upholstery cover, with the open end being sewn or fastened in some manner to completely cover the urethane. Fabric-blocking layers are composed of high-temperature synthetic fibers, and an aluminized outer coating to reflect heat. The aluminized coating may also impart some degree of protection by preventing or delaying the formation of urethane drippings on the floor which, if ignited, can contribute to the spread of fire (reference 23).

STANDARD INTERIOR MATERIALS.

For many of the tests, standard interior materials of actual aircraft were used. They included honeycomb composite ceiling panels, honeycomb composite overhead storage bins, honeycomb composite sidewall panels with window reveals, and wool/nylon pile carpets. Seats were standard aircraft type, with wool (90 percent)

TABLE 1. SEAT MATERIALS TESTED

MATERIAL NAME	MATERIAL TYPE	WEIGHT	SOURCE
LS-200	Foam	7.5 lb/ft^3	Toyad
Vonar-3PE	Foam on Polyester Cloth	$\approx$ 27 oz/yd^2	Dupont
Vonar-3FG	Foam on Fiberglas Cloth	$\approx$ 28 oz/yd^2	Dupont
Polyimide	Foam	1.05 lb/ft^3	Solar
Norfab 11 HT26	Aluminized Cloth	12.9 oz/yd^2	AMATEX
Celiox	Aluminized Cloth	10.9 oz/yd^2	GENTEX
PBI	Cloth	10.8 oz/yd^2	Celanese
#2043 Urethane Fire Retardant (RF)	Foam	2.0 lb/ft^3	North Carolina Foam
Urethane Non-Fire Retardant (NF)	Foam	1.4 lb/ft^3	Upjohn
R76423 Sun Eclipse Azure Blue	Cloth 90% Wool/10% Nylon	14 oz/yd^2	Collins & Aikman
Fabric 90% Wool/10% Nylon	Cloth	*	*
Fabric 50% Wool/50% PVC	Cloth	*	*

and nylon (10 percent) upholstery. A full list of materials and results of laboratory fire tests of the materials is shown in appendix A.

TEST ARTICLE.

The test article was a C133 aircraft, modified to resemble a wide-body cabin interior, as shown in figure 1 and in reference 17. The cross-sectional area is similar to, although slightly smaller than, a wide-body cabin. An interior volume of 13,200 ft^3 is representative of a wide-body jet.

All combustible materials installed in the original cargo aircraft were removed and the new floor, sidewall, and ceiling surfaces are composed of noncombustible materials. A CO_2 total flooding system allows for the selective termination of a test. These protective measures have resulted in a durable test article, which has withstood hundreds of tests with only minor damage. This allowed for the conduct of parametric studies with different materials or different fire test conditions.

The test article is located inside the Full-Scale Fire Test Facility at the FAA Technical Center. This facility is designed for the conduct of large test fires indoors, allowing for the control of ambient wind conditions. The indoor location also allows for greater ease of testing without the concern of environmental conditions, such as, rain, wind, and below freezing temperatures.

For all post-crash fire tests, an external fire was provided by 50 gallons of jet fuel (JP-4) in an 8-foot by 10-foot by 4-inch deep steel pan located outside and adjacent to a 42-inch by 76-inch opening in the test article (figure 2). When required, simulated ambient wind through the fuselage fire penetration opening was provided by a 36-inch diameter fan mounted adjacent to the test article. A transition duct was attached to the fan outlet to distribute the air uniformly through the opening. The velocity of the simulated wind was controllable by the insertion of orifice plates in the fan outlet duct. Fan operation could be either continuous or intermittent.

During the ramp and in-flight fire tests, all fuselage doors and windows were closed. Simulated environmental control system airflow was supplied (figure 3) during the in-flight tests. No airflow was supplied for the ramp fire tests.

The exact test article configuration varied from test series to test series, and will be described separately, later in this report. All station numbers are in inches, measured from the forward edge of the cabin floor (datum in figure 1).

INSTRUMENTATION.

The C133 test article was extensively instrumented to measure the major hazards produced by a cabin fire at various cabin locations as a function of time. The most extensive measurement was that of air temperature; a series of thermocouple poles on the fuselage centerline were located throughout the cabin. Gardon gage-type calorimeters, primarily clustered around the fire door, measured the radiant and convective heat flux from the jet fuel fire and ensuing cabin fire. Smoke density was measured by light transmissometers, consisting essentially of a light source and photoelectric cell receiver. Gas concentrations were measured by continuous analyzers and from post-test analysis of batch samples taken at regular intervals during the test. The gases analyzed continuously at four cabin locations included carbon dioxide (CO_2), carbon monoxide (CO), and oxygen (O_2). The remaining gases analyzed from batch samples consisted of two classes: acid gases (e.g., hydrogen fluoride (HF), hydrogen chloride (HCl), etc.) and organic gases (e.g., hydrogen cyanide (HCN), etc.). The acid gases, particularly HF and HCl, were analyzed by ion chromatography of samples collected in small tubes filled with glass beads that were coated with a sodium carbonate solution. The organic gases, particularly HCN, were analyzed by gas chromatography of samples collected on Tenax™ tubes.

A detailed description of the analytical methodology for the acid and organic gases is contained in reference 17. Exclusive of the gases analyzed from batch samples, the cabin hazard measurements were recorded on a computer data acquisition system, and converted into engineering units and plotted after completion of a test. Cabin fire growth was monitored during a test by video coverage. Color photography documentation included 35mm sequential photographs at 5-second intervals, and 16mm movies.

Table 2 lists the type of instrumentation used, with references containing greater detail on the measurement of that parameter.

The type, amount and location of instrumentation varied with the test scenario, and will be described later in this report.

TEST SCENARIOS.

Three major test scenarios were studied; post-crash fires, in-flight cabin fires, and ramp type cabin fires. For each of the major scenarios, various configurations and ignition sources were tested. Table 3 is a list of all the tests conducted inside the C133 test article. Other seat fire tests, not conducted inside the aircraft, are described later in this report.

TEST RESULTS

POST-CRASH CABIN FIRES.

Six series of tests were conducted to evaluate the effectiveness of seat blocking in a post-crash fire environment. Series one through five used limited materials (seats only) and were designed to study the effectiveness of various seat blocking materials under various fire scenarios. Series six consisted of full-scale tests designed to investigate the characteristics of a post-crash cabin fire, and to determine the benefits of seat blocking in increasing survival time in a realistic post-crash cabin fire environment.

The basic scenario for all post-crash fire tests was an external fuel fire (8 feet by 10 feet) adjacent to an opening in the cabin. A second opening in the cabin, the size of a type "A" door, was provided at the other end of the fuselage. Instrumentation for the first five series of tests was located forward of the galley, whereas, for the full material tests in series six, the instrumentation was located throughout the cabin, with most of the gas data taken aft of the galley.

During some of the tests, a large fan adjacent to the fuel fire (reference 24) was used to produce wind, causing fuel-fire penetration into the cabin.

TABLE 2. HAZARD MEASUREMENT INFORMATION

HAZARD	TYPE OF INSTRUMENTATION	TIME INTERVAL OF MEASUREMENT	REFERENCE
Heat:			
Temperature	Chromel/Alumel Thermocouple	Continuous	30
Heat Flux	Calorimeters	Continuous	30
Smoke:	Photocell and Light Source	Continuous	30
Gases:			
CO	Beckman Model 864 Infra-Red Analyzer	Continuous	30
CO^2	Beckman Model 864 Infra-Red Analyzer	Continuous	30
02 Depletion	Beckman Oxygen Analyzer, Type OM-11	Continuous	30
HF	Dionex Model 10 ION Chromatograph	Point every 30 seconds	31
HCL	Dionex Model 10 ION Chromatograph	Point every 30 seconds	31
HBr	Dionex Model 10 ION Chromatograph	Point every 30 seconds	31
HCN	Perkin-Elmer 3720 Gas Chromatograph	Point every 30 seconds	31
Flame and Smoke:	Cameras		
	16 mm Color Film	Continuous	30
	35 mm Color Film	1 to 5 Seconds	30
	Black and White Video	Continuous	30

TABLE 3. LISTS OF C133 TESTS

Test No.	Wind Speed (Mph)	Test Series	Materials Blocking Layer/Cushion	Other Comments
1	0	Post-Crash #1	None/FR urethane	
2	0	Post-Crash #1	None/LS-200	
3	0	Post-Crash #1	Vonar 3(FG)/FR urethane	
4	0	Post-Crash #1	Vonar 3(PE)/FR urethane	
5	0	Post-Crash #1	LS-200 (3/8")/FR urethane	
6	0	Post-Crash #1	None/None (background empty frame)	
7	0	Post-Crash #2	None/LS-200	
8	1.5	Post-Crash #2	Vonar 3(PE)/FR urethane	
9	1.5	Post-Crash #3	None/FR urethane	
10	1.5	Post-Crash #3	PBI fabric/FR urethane	
11	1.5	Post-Crash #2	Vonar 3 (FG)/FR urethane	
12	1.5	Post-Crash #2	LS-200 (3/8")/FR urethane	
13	1.5	Post-Crash #3	Vonar (FG)FR urethane	
21	1.5	Post-Crash #3	Background-None/None	
25	3.0	Post-Crash #4	Background-None/None	
27	3.0	Post-Crash #4	None/FR urethane	
28	3.0	Post-Crash #4	None/LS-200 full	
30	3.0	Post-Crash #4	None/Pyrothane	
32	3.0	Post-Crash #4	Vonar (FG)FR urethane	
33	1.5	Post-Crash #6	Vonar (PE)/FR urethane	
34	0	Post-Crash #6	Vonar (PE)FR urethane	
35	0	Post-Crash #6	None/FR urethane	
39	1.5	Post-Crash #3	Preox 1202/FR urethane	
40	1.5	Post-Crash #5	None/FR urethane	
41	0	Post-Crash #6	None/Kaowool	
43	1.5	Post-Crash #5	Vonar (FG)/FR urethane	

TABLE 3. LISTS OF C133 TESTS (Continued)

Test No.	Wind Speed (Mph)	Test Series	Materials Blocking Layer/Cushion	Other Comments
46	0	In-Flight #3	None/FR urethane	Int. Airflow
47	0	Ramp	None/FR urethane	
48	0	Ramp	Foam Blocking (LS-200 3/8") or Vonar 3 (PE)/FR urethane	
49	0	In-Fligth #3	LS-200(3/8")/FR urethane	Int. Airflow
50	0	In-Flight #3	None/FR urethane	Int. Airflow
51	0	Carry-On Bag	None/FR urethane	
52	0	Carry-On Bag	None/FR urethane	
53	0	Carry-On Bag	None/FR urethane	
54	0	No Bag	None/FR urethane	
55	0	No Bag	None/FR urethane	
56	0	FR vs NFR	Preox/FR urethane	
57	0	FR vs NFR	Preox/NFR urethane	
58	0	Carry -On Bag	None/FR urethane	In O/H Rack
59	0	Ramp	Cloth Blocking (Perox)/ FR urethane	
60	0	In-Flight #3	Perox/FR urethane	
61	0	In-Flight #3	None/FR urethane	
62	0	Post-Crash #6	Norfab/NF urethane	
63	0	Post-Crash #6	None/FR urethane	
64	0	Post-Crash #6	None/FR urethane	

A calibrated orifice produced a repeatable wind. Figure 4 shows the repeatability for three tests using an average windspeed through the opening of 1.5 miles per hour (mph), and no combustible materials in the cabin.

SERIES ONE: ONE DOUBLE STEEL FRAME SEAT.

Objective of Tests. The objective of this series of tests was to study seat cushion fire involvement due to radiant heat only, without the influence of other cabin materials and in zero wind conditions.

Description of Test Setup and Instrumentation. A double metal seat frame was constructed from steel angle, with a sheet metal back and an open bottom, to simulate a double aircraft seat. Four cushions were mounted on the seat frame. The seat frame was centered at 20 inches in from the edge of the fire door opening (figure 5).

Instrumentation was positioned at various locations forward of the galley, as shown in figure 5.

Description of Each Test. This series consisted of the following six tests:

Test No.	Material (Blocking Layer/Cushion)
1	None/FR urethane
2	None/LS-200
3	Vonar 3 (FG)/FR urethane
4	Vonar 3 (PE)/FR urethane
5	LS-200 (3/8 inch)/FR urethane
17	None/None (background empty frame)

Presentation and Analysis of Data. Temperature profiles from Station 270, 5-foot height are shown in figure 6. The two Vonar blocking layer materials provide a similar improvement to that of the LS-200 (full). The LS-200 (3/8 inch) blocking layer over the FR urethane provided a lesser improvement.

Small quantities of gases (CO and CO_2) were measured for tests 2, 3, 4, and 17 (figure 7). Tests 1 and 5 produced measurable amounts of CO and CO_2. These graphs show the relative effectiveness of the blocking layers as compared by the gaseous decomposition products. Similar results were achieved with the smoke profiles (figure 8). Very little smoke was measured during tests 2, 3, 4, 5, and 17. The blocking layers appear to inhibit smoke production from the urethane cushions under this scenario.

Heat flux profiles also provide similar comparisons (figure 9). Test 1 shows an increasing heat flux profile as the fire is drawn into the fuselage by the burning urethane cushion. Test 5 shows a pulsing heat flux profile as the LS-200 (3/8-inch) blocking layer becomes less effective. Heat flux profiles for the other tests fall into a lower range, as was evidenced for temperature, smoke, and gases.

This series of tests showed that it is possible that radiant heat alone from an external pool fire can ignite the aircraft interior materials. The blocking-layer materials provide a significant improvement in the fire behavior of urethane seat cushions. The cabin hazards from the post-crash fire are intensified by seat cushion involvement, which appears to draw the fire into the fuselage. With the blocking-layer materials, seat cushion involvement is impaired.

Figure 10 shows a comparison of the blocking-layer materials and full Neoprene™ to the FR urethane at 4 minutes from the start of the test.

SERIES TWO: FOUR DOUBLE STEEL FRAME SEATS.

Objective of Tests. The objective of this series of tests was to evaluate the flame spread from seat-to-seat and across an aisle without the influence of other cabin materials, but with flame impingement on the seat in the doorway, caused by a 1.5 mph wind.

Description of Test Setup and Instrumentation. Four double metal seat frames were constructed from steel, angled to simulate double aircraft seats. Three seat frames were located at 10 inches inboard of the fire side of the fuselage. Each seat frame contained four cushions. A fourth seat frame (figure 11) was located 20 inches across the aisle, opposite the seat by the fire door. Instrumentation was positioned at various locations forward of the galley, and the heat flux transducers were placed on and around the seat frames (figure 11).

Description of Each Test. This series consisted of the following six tests:

Test Number	Material (Blocking Layer/Cushion)
6	None/FR urethane
7	None/LS-200
8	Vonar 3 (PE)/FR urethane
11	Vonar 3 (FG)/FR urethane
12	LS-200 (3/8 inch)/FR urethane
21	None/None (background-empty frames)

Presentation and Analysis of Data. Temperature profiles from Station 270, 5-foot height are shown in figure 12. The same trend is shown in this figure as was apparent in series one. Smoke optical density is presented in figure 13 for Station 270, 5 feet 6 inches. Heat flux is shown for the back calorimeter, looking at the seats (figure 14).

This series showed that the seat cushions covered with blocking-layer materials greatly reduced the hazard in the cabin by impairing flame propagation across the seats and aisle. These tests show that the Vonar blocking layer provides comparable results to that of the full LS-200 cushions. Figure 15 shows a dramatic comparison of the blocking-layer materials and full Neoprene to the FR urethane at 4 minutes from the start of the test.

SERIES THREE: SINGLE B747 SEAT.

Objectives of tests. The objectives of this series of tests were as follows:

1. Evaluate the behavior of various seat cushions on actual aircraft seats when exposed to direct flame contact and radiant heat, and

2. Study the flame propagation from one cushion to another and compare the general fire involvement of various seat cushions.

Description of Test Setup and Instrumentation. An actual aircraft triple seat frame was outfitted with various seat cushions. The seat assembly was centered at

10 inches in from the edge of the fire door opening (figure 16). A 1.5 mph wind (measured in the doorway opening) was generated in order to bend the flames of the fuel fire into the cabin. Instrumentation, with the exception of the heat flux transducer locations, was the same as the previous series. Test documentation was also identical to the previous series.

Description of Each Test. This series consisted of the following five tests:

Test Number	Material (Blocking Layer/Cushion)
9	None/FR urethane
10	PBI Fabric/FR urethane
13	Vonar (FG)/FR urethane
39	Preox™ 1202/FR urethane
21	Background-None/None

Presentation and Analysis of Data. Temperature profiles from Station 270, 5-foot height are presented in figure 17. Only one foam-blocking layer was tested in this series. The other two blocking layer materials were fabrics. The PBI fabric blocking layer also served as an upholstery cover. Results for the two fabric-type blocking layers were similar to the background test. The foam-blocking layer showed improvement over the FR urethane.

Smoke optical density is presented in figure 18 for station 270, 5 foot 6 inches. Smoke production was inhibited by the blocking layers.

Heat flux is shown for the back calorimeters looking at the seats (figure 19). The blocking layers showed much lower heat flux, with the exception of the pulse, in test number 10, around 100 seconds. Heat flux data was not collected for test number 13. Figure 20 shows a comparison of the blocking layer materials to the FR urethane at 4 minutes from the start of the test.

This series of tests demonstrated that two fabric-type blocking layers provided improvements to seat cushion flammability that were similar to one another. It was demonstrated that other seat materials (armrests, trays, etc.) do not significantly override the benefits of blocking layer materials by enhancing flame propagation from seat to seat.

SERIES FOUR: FOUR METAL SEAT FRAMES (SMALL OPENING).

Objective of Tests. The objective of this series of tests was to evaluate seat blocking materials under a fire scenario with a small fuselage opening or rupture.

Description of Test Setup and Instrumentation. This series was similar to series number two except that a small 2-foot by 2-foot opening was employed. To conserve cushion materials, only eight cushions were used for each test (figure 21). Three seat frames were located at 10 inches in from the fire side of the fuselage. A fourth seat frame was located 20 inches across the aisle, opposite the seat by the fire door. A 3-mph wind (measured in the opening) was used in all the tests in this series. Instrumentation was positioned at various locations forward of the galley as in the previous series, with the exception of heat flux transducers, which were placed on and around the seat frames (figure 21).

This series consisted of the following five tests:

Test Number	Material (Blocking Layer/Cushion Foam)
25	Background None/None
27	None/FR urethane
28	None/LS-200 full
30	None/pyrothane
32	Vonar (FG)/FR urethane

Presentation and Analysis of Data. Temperature profiles from Station 270, 5-foot height are shown in figure 22. Heat flux for the back calorimeter looking at seats is presented in figure 23.

The results of this test series exhibit data crossover and small discrimination in the performance of different materials. For these reasons, this scenario was not utilized except for the above tests. The data also demonstrate that wind conditions created significant fuel-fire hazards inside the cabin. Under the conditions tested, approximately 50 percent of the cabin hazards were caused by the fuel fire.

SERIES FIVE: STANDARD SEATS FORWARD AND AFT OF OPENING.

Objective of Tests. The objective of these two tests was to evaluate the effectiveness of a blocking layer employed in a situation involving an external fuel fire and passenger seats being installed forward and aft of that doorway.

Description of Test Setup and Instrumentation. These tests were conducted in the C133 fuselage utilizing actual aircraft seats. Two triple passenger seats were placed forward and aft of the fire door (figure 24). Instrumentation was similar to the previous series. A 1.5 mph wind (measured in the doorway) was used to provide flame penetration into the cabin.

Description of Each Test.

Test Number	Material (Fire Blocking Layer/Cushion Foam)
40	None/FR urethane
43	Vonar (FG)/FR urethane

Presentation and Analysis of Data. Temperature profiles are presented in figure 25 for Station 270 at the 5-foot height. Smoke optical density is presented for Station 270 at the 5-foot 6-inch height in figure 26. Heat flux is presented for the back calorimeter looking at seats in figure 27. Figure 28 shows a comparison of these two tests at 4 minutes.

In the test with protected cushions, the seat fire damage was minor and confined to the upholstery cover and seat components; the flammable urethane foam cushion did not become involved. Therefore, the cabin hazards were barely measureable in the test with blocking layers, as evidenced by the low temperatures and smoke densities plotted in figures 25 and 26. By contrast, in the test with unprotected cushions, the fire became out of control in 3 to 4 minutes. Thus, under the door opening fire scenario, the reduction in hazards from the use of blocking layers was far greater than under the fire scenarios studied containing a fuselage rupture.

SERIES SIX: FULL-SCALE POST-CRASH FIRE TESTS.

Objectives of Tests. Study the characteristics of a post-crash cabin fire and determine the effectiveness of seat fire blocking under realistic post-crash fire conditions.

Description of Test Setup and Instrumentation. In order to study and measure the full-scale hazards of cabin interior materials subjected to an external fuel fire, a section of the C133 test article, centered at the opening adjacent to the fuel pan, was lined and furnished with wide-body type materials. Samples of the various materials were tested using a number of lab tests. The results of those tests are presented in appendix A. As shown in the cutaway isometric drawing in figure 29, the materials were arranged in a realistic fashion. The following summarizes the materials' loading: (1) 12 flat, honeycomb composite panels, each 4 by 6 feet, comprised a 24 foot-long drop ceiling; (2) 6 lengths of honeycomb composite overhead stowage bins were mounted on both sides of the cabin; (3) 8 contoured honeycomb composite sidewall panels with window reveals, each 3.3 by 5.5 feet were fastened to the insulated inner fuselage; (4) a total of 21 seats, including 6 doubles and 3 triples, composed of wool (90 percent)/nylon (10 percent) upholstery covers and FR urethane cushions, were arranged into 3 rows to form a duel aisle interior; and (5) a wool (100 percent) pile carpet was placed over the aluminum-faced cabin floor. The ceiling panels and carpet were new, while the sidewall panels, storage bins, and seats were obtained from refurbished wide-body aircraft.

In all the tests, except test No. 33 where a 1.5 mph wind was employed, the materials were subjected to a zero wind fuel fire. The zero wind condition was selected because the cabin hazards solely arising from the fuel fire would be minimal and clearly survivable as shown in the previous tests (reference 17). In this manner, the cabin hazards with materials installed in the test article would be greatly dependent on the burning materials and not by the fuel fire.

Figure 30 shows the fuselage configuration for all of the full-scale post-crash material tests.

Description of Each Test.

Test Number	Material (Blocking Layer/Cushion)	Wind Velocity (mph)
33	Vonar (PE)/FR urethane	1.5
34	Vonar (PE)/FR urethane	0
35	None/FR urethane	0
41	None/Kaowool	0
62	Norfab/NF urethane	0
63	None/FR urethane	0
64	None/FR urethane	0

Presentation and Analysis of Data.

Fire characteristics. A revealing account of the fire growth inside the cabin using standard materials was obtained from the color photographic coverage, including 35mm motorized stills and 16mm movies during test No. 35. Examination of these films demonstrated that for approximately 2 minutes, the cabin fire was limited to the area in the immediate vicinity of the fuselage opening adjacent to the fuel fire. The outboard double seat at the fire opening was almost completely engulfed in flames, as was the back of the outboard seat forward of the opening and the front of the seat behind. Fire had not progressed to the triple seats comprising the center section, although some smoldering was evident. Also in evidence was intermittent flashing in the smoke layer under the ceiling by the opening. Although the heavy smoke obscured the upper cabin, the high temperatures recorded in this area and the existence of flashes indicated that ceiling and storage bins near the opening were pyrolyzing and, perhaps, burning. At approximately 2 minutes, within a matter of 10 seconds or less, the remaining interior materials were suddenly set aflame or underwent pyrolysis. This event has been observed in many types of enclosure fire tests and has been given the name "flashover." Photographs taken at 5-second intervals shown in figure 31, illustrate the suddeness and totality of the flashover.

The major hazards produced by the cabin fire, aft of the galley partition, are shown plotted as a function of time in figure 32. The survivability is of interest in this section of the cabin because (1) the evacuation process is usually in a direction away from the fire origin and (2) in some past accidents victims have been found clustered near exits.

The occurrence of flashover indicates that conditions throughout the cabin will become nonsurvivable within a matter of seconds. Of concern, thus, is whether any of the preflashover hazards were at a level to impair or prevent escape. An examination of figure 32 indicates that the acid gases, HF and HCl, accumulated in the aft cabin at least 1 minute before any of the remaining hazards. A detailed description and analysis of the acid gas measurements is found in appendix B. Concentrations used in the main body of this report are "as recorded." Possible problem areas associated with the analysis of acid gases are discussed in appendix B. These gases were produced by the burning honeycomb composite panels which comprise the ceiling, storage bins, and hatrack. A past study of thermal degradation products from aircraft materials indicated that HF and HCl, the latter in higher yields, are produced by some panels (reference 25). The source of HF was the 3mil Tedlar polyvinylfluoride decorative film which covers the panels. The source of HCl is probably the flame retardants used in the epoxy resin which impregnates the fiberglass facings and adheres the panel components together. Another source of HCl was the polyvinylchloride (PVC) seat components (armrest covers, side panels) and those components containing chlorinated fire retardants (cushions). It appears the initial gas peak was caused by the rapid thermal degradation of the decorative film and fiberglass facing, resulting from the intense radiant heat from the fuel fire at the beginning of the test. The second gas peak was caused by the rapid fire involvement associated with flashover of all the interior materials. The early concentrations of acid gases (e.g., 300 parts-per-million (ppm) and 140 ppm for HCl and HF, respectively, at 60 seconds) are considered to be significant levels. Composite panel lining materials — the source of these gases — are important potential contributors to cabin fire hazards because of their large surface area and, in many cases, vulnerable location in the upper cabin area.

Elevated temperature, smoke, and HCN were the remaining hazards detected before the onset of flashover. Flaming conditions during a post-crash cabin fire, as opposed to a smoldering fire, make the presence of high temperatures expected. More unexpected was the low concentration of HCN, considering that wool is used for seat upholstery and carpet, and that wool produces high yields of HCN, approximately 40 milligrams per gram (mg/g), when pyrolyzed oxidatively (reference 25). A number of explanations for the low HCN concentrations are plausible, including (1) burning of the HCN during flashover, (2) because of the prominence of flaming, production of nitrogen oxides by the wool rather than HCN (reference 26), or (3) insufficient fire involvement of the wool due to relatively low loading and to its location in the lower cabin. An interesting result was the late detection of smoke at approximately 100 seconds, in contrast to HF and HCl which were detected much earlier into the test.

In order to assess the relative importance of each cabin fire hazard, a hypothetical human survival model was formulated. (The structure of the model was suggested by Dr. Charles Crane at the FAA's Civil Aeromedical Institute. The authors are grateful for his important contribution to this paper.) The model computes incapacitation in a fire environment composed of a number of toxic gases and elevated temperature, each varying with time. The major assumptions were twofold: (1) the hazards are additive and (2) for the toxic gases, the classical hyperbolic relationship exists between gas concentration and time of incapacitation. Thus, based on the latter assumption, for a gas species i

$$c_i T_i = K_i$$

and

$$FED_i = \int_0^t c_i \, dt$$

where

c_i=concentration of gas species i
T_i=time-of-incapacitation
K_i=incapacitation dose of gas species i, a constant
FED_i=fractional effective dose, or the ratio of the actual dose due to gas species i to the incapacitation dose
t=time

The incapacitation dose constants, K_i, were calculated from the best available data in the literature (reference 27), and are tabulated below:

Gas Species i	K_i (ppm - minutes)
CO	24,000
CO_2	750,000
HCN	480
HF	1,140
HCl	2,400

The table reflects the relative toxicity of the gas species of interest; e.g., HCN is five times as toxic as HCl.

The effect of elevated temperature on incapacitation was taken into account by utilizing the empirically based curve fit, derived by Crane (reference 28), shown below

where

$$t_c = Q_o/T^{3.61}$$

where

t_c=time to thermal collapse (incapacitation), minutes
T=air temperature, degrees centigrade
Q_o=4.1 x 108 a statistically derived proportionality constant

The above relationship is based on data from human exposure to a constant temperature. In order to apply this relationship to the more common time-dependent fire environment, the thermal history curve was divided into 1-second intervals. By considering Q_o as a heat factor related to the caloric intake that a body must absorb to produce thermal collapse, the thermal fractional effective dose, FED_T, becomes

$$FED_T = \frac{\Delta t \sum T^{3.61}}{Q_o}$$

Therefore, assuming the hazards to be additive, the fractional effective dose for the mixture, FED, becomes

$$FED = FED_T + \sum FED_i = \frac{\Delta t \sum T^{3.61}}{Q_o} + \sum \frac{\int_o^t C_i dt}{K_i}$$

The hypothetical time-of-incapacitation for the mixture is the time at which FED = 1.0.

The survival model described above is hypothetical. Its main purpose is to provide a means of predicting the time-of-incapacitation within a fire enclosure, based on measurements of elevated temperature and toxic gas concentrations which change, in some cases, substantially with time. Thus, it is a tool for reducing a fairly large number of somewhat abstract measurements into a single, cogent parameter: time-of-incapacitation, or the hypothetical time at which an individual can no longer escape from a fire environment. How well the model relates to actual escape potential is unknown and, realistically, cannot be determined. It is known that segments of the model are deficient for lack of available information. For example, no data exist on the effect of irritant gases (e.g., HCl, HF) on acute human escape potential. (FAA has sponsored new research at Southwest Research Institute to determine "the threshold concentration for escape impairment by irritant gases (HCl and acrolein, initially) using a nonhuman primate model and a relevant behavioral task that can be extrapolated to man."). Thus, the HCl and HF incapacitation doses utilized in the model are simply based on extrapolation from threshold limit values (TLV's) for an 8-hour work environment. Confidence in the model is greater for the prediction of the relative escape time between tests on different material systems than on prediction of absolute escape times.

The human survival model was applied to predict the survivability in the aft cabin based on the hazard measurements taken at the location plotted in figure 32. As shown in figure 33, the hypothetical survival time was 159 seconds when wide-body materials were installed in the cabin. Conversely, when no materials were installed in the cabin, corresponding to an idealistic and unrealistic completely noncombustible interior, there was no detectable loss in survivability, i.e., FED = 0 throughout the test. The slope of the survival curve, with wide-body materials installed in the cabin, increased drastically shortly after the flashover because of the rapid increase in hazards caused by the flashover. Until this test time, the survival curve was entirely driven by HF and HCl. As discussed earlier, the incapacitation doses of these irritant gases are unknown and the values used in the survival model are calculated estimates. If one ignores the hazards of HF and HCl, the survival curve becomes driven primarily by temperature and, to a lesser degree, CO. Also, the fractional effective dose will not increase above zero until 135 seconds, and will exhibit a much steeper slope than when the irritant gases are included. Four of the six hazards considered in the model eventually exceeded their incapacitation dose, as follows: temperature at 180 seconds, HF at 210 seconds, CO at 237 seconds, and HCl at 248 seconds. The fractional effective doses of the remaining hazards, CO_2 and HCN, were comparatively insignificant (0.2 and 0.04 at 240 seconds, respectively).

It has long been recognized that a margin of safety xists near the floor inside an enclosure fire. The wisdom of this advice was examined by measuring the major hazards at three elevations at test Station 650 and calculating the survival time at each elevation. These survival curves are plotted in figure 34(a) and verify that survivability is possible for a longer period the closer one is to the floor. A 34-second improvement was calculated between 5 feet 6 inches, and 3 feet 6 inches, but the improvement was only 9 seconds between 3 feet 6 inches, and 1 foot 6 inches. In figure 34(b) the relative importance of each hazard at the calculated survival time is graphed. The irritant gases HF and HCl again drove the survivability calculation at all three elevations. Although a contributing factor at 5 feet 6 inches, heat (elevated temperature) became negligible at the two lower elevations. Instead, CO was found to be a more important factor, although this is not adequately shown in figure 34(b). This is more apparent when the survivability calculation is extended beyond the survival time, within several minutes CO will become the dominant hazard at the two lower elevations. Thus, if it is assumed that the HCl and HF incapacitation doses utilized in the model are low, and, if they are raised (i.e., the incapacitating effect of these irritant gases is made less potent in the model), then CO will be the dominant factor affecting incapacitation. Also, since CO is a more lethal agent than either HF or HCl, it may be argued that CO would be primarily responsible for any fatalities caused by inhalation of gases near the floor. It may also be argued that a plausible scenario for demise of an individual during a cabin fire is incapacitation, while standing, from exposure to irritant gases and heat, and, after collapsing to the floor, death from CO asphyxiation.

Figure 35 shows the buildup of the various hazards, and the effect of eliminating hazards in the time-to-incapacitation. If HCl is ignored, as in figure 36, the incapacitation dosage is reached approximately 10 seconds later. Ignoring HF, HCl, and HCN, as in figure 37, produces and extra 17 seconds. From the shape of the curves it can be seen how important flashover is.

The most striking feature of a cabin fire is the smoke layer, which, because of buoyancy appears to cling to the ceiling. Figure 38 is a graph of the vertical temperature profile at various test times at test Station 270, which was the first thermocouple pole station aft of the last seat row. The inflection point in the temperature profile defines the smoke layer thickness. Figure 38 illustrates that the cabin environment may be approximately described by two zones: a hot zone at the ceiling, which thickens as the fire progresses, with a linear temperature profile, and a much cooler zone in the lower cabin with a uniform, but above ambient, temperature. The temperature differential between the ceiling and lower cabin was very large; e.g., at 2 1/2 minutes the differential was higher than 1000° Fahrenheit (F). This finding has a bearing on the relevance of small-scale tests (ceiling materials are exposed to higher convective heat fluxes than are carpets, for instance). For example, at a station only 12 feet aft of the fire (figure 38), conditions would be clearly survivable from convective thermal exposure, as late as 2 minutes (10 to 15 seconds before flashover), for an individual who crouches in order to avoid exposure to the hot smoke layer. Moreover, a hot, smokey layer can nullify the benefit of ceiling-mounted emergency lighting, possibly by causing thermal failure in the units, or by obscuring exit signs or blocking illumination.

The existence of large heat losses into the walls of an enclosure during a fire and the entrainment of lower zone cool air into the hot smoke layer creates corresponding losses in the heat content, or temperature of the smoke layer gases as they are transported away from the fire origin. Figure 39 is a graph of the symmetry plane air temperature at the ceiling throughout the cabin at various times into the test. Because of the aforementioned heat losses, the ceiling temperature decreased significantly with distance away from the fire. Although measurements near the fire were off-scale at 1800° F after 2 1/2 to 3 minutes into the test, because the thermocouples were not shielded from radiation, these readings may be higher than the actual air temperature. The temperature profile at 2 minutes indicates that a large area of the ceiling was subjected to temperatures in excess of the thermal decomposition temperature of the composite panels, approximately 200° to 350° centigrade (C), before the occurrence of flashover (reference 29). Examination of figure 39 illustrates that the galley partition tended to confine much of the heat to the cabin section forward of the partition. A related observation has been made in accident aircraft where fire damage was more extensive on the fire origin side of a class divider than on the protected side. It is of interest to note that the ceiling temperature aft of the galley partition is more uniform than the ceiling temperature in the forward cabin. This apparent uniformity may have resulted from more active mixing in the smoke layer caused by the partition openings and by entrainment of fresh air through the exhaust door.

The effects of wind on survival time is shown in figure 40. The difference in temperature in the aft section of the fuselage is compared for test 33 (1.5 mph wind) and test 34 (no wind). It can easily be seen that the effect of a slight wind can be devastating.

Effectiveness of seat cushion blocking layers. Figure 41 is a plot of the calculated FED versus time in the aft cabin for the four full-scale fire tests. This plot indicates the safety benefit in terms of increase in survival time associated with seat blocking layer materials under the post-crash fire condition tested. The calculated FED does not include the effect of HCl in any of the tests because of a malfunction in the analysis of HCl in one of the tests. The safety benefit of Vonar™ and Norfab™ blocking layer materials 60 and 43 seconds, respectively, is considered significant, especially since the benefit is incurred without changes to the remaining interior materials. In addition, the results indicate that the amount of protection provided by Vonar is nearly equivalent to that of a noncombustable cushion under the fire condition studied. (Note that the improvement in survival time with the noncombustible cushions was only 8 seconds better than with the Vonar protected cushions.) The shape of the FED profiles indicate, to some degree, the rapidity by which conditions become non-survivable after the onset of flashover. In fact, the calculated safety benefit (survival time increase) for each of the protected cushion tests corresponds to the increase in time before the onset of flashover relative to the unprotected cushion test. Figure 41 also indicates that FED = 0 throughout the time framework of interest when the interior is noncombustible. This finding indicates that potential safety benefits exist beyond that provided by seat blocking layers, by making improvements in the fire performance of other important interior materials; e.g., ceiling panels and overhead stowage bins.

Smoke was not a component of the human survival model. However, the impact of visibility obscuration resulting from smoke was calculated (reference 6). Figure 42 is a plot of cabin visibility in the aft cabin versus time for the four full-scale material tests. The most striking feature of the curves is the rapidity by which visibility becomes obscured, e.g., in some cases visibility was reduced from the length of the cabin to less than the width of the cabin in approximately 15 seconds. Also, by comparing figures 41 and 42, it is apparent that smoke becomes an important factor anywhere from 30 to 60 seconds before survival is no longer theoretically possible. This comparison also reveals that the ranking of results from best to worst for visibility loss was identical to the rankings for loss in survival time (i.e., noncombustible cushions were the best followed by Vonar, Norfab, and unprotected cushions).

Data from full-scale tests numbers 33, 34, 35, and 41 are presented in appendix C.

OTHER POST-CRASH TESTING AND OBSERVATIONS.

Fire Retardant Versus Non-Fire Retardant Foam. Two tests were conducted using a triple passenger aircraft seat as described in series three. The first test, number 56, used Preox fire blocking over FR urethane. The second test, number 57, used Preox fire blocking over non-fire retarded urethane. No noticeable difference was observed between these two tests. Figure 43 is a comparison of temperatures for those two tests with that of a standard unblocked seat.

Effects of Carry-On Baggage. Tests were conducted as described in series three, in which a carry-on bag was placed under the seat next to the fire penetration opening. There was little or no effect observed due to the presence of the bag (figure 44). A test was also conducted in which an overhead stowage compartment was installed and baggage placed in it. The baggage in the compartment did not become involved until very late in the test and had little or no affect on the test results.

Polyimide Foam. During the seat blocking program a number of tests were conducted using an experimental foam developed for NASA, named "Polyimide" (reference 30). During some of the tests, the performance of this foam was outstanding, however, during others, the results were very poor. Various batches of the foam were tested, possibly explaining the difference in test results.

IN-FLIGHT CABIN FIRES.

Three series of in-flight fire tests were conducted. The first series consisted of seat ignition tests conducted using a single seat assembly in an open test bay. The second series of tests was conducted in the C133 test article using a single seat assembly with one quart of gasoline poured on it. The third series was the large-scale in-flight tests using six sets of aircraft passenger seats with the ignition source in a carry-on bag under a seat.

SERIES ONE: SINGLE SEAT IGNITION TESTS.

Objective of Tests. The objectives of this series of tests were as follows:

1. Compare fire blocked seats (both foam and cloth) to standard fire retardant urethane seats for various in-flight fire scenarios.

2. Determine the effectiveness of fire blocked seats that are damaged (slits are cut in blocking material) against in-flight type fires.

3. Compare the use of fire retardant and non-fire retardant urethane foam under a blocking layer against in-flight fires.

Description of Test Setup and Results.

All tests were conducted in the large open test bay of the Full-Scale Fire Test Facility. In the majority of the tests, the two outer seat sections of a triple passenger seat were used with the center seat section removed (figure 45). Tests 9B, 10B, and 11B used only a single seat.

No instrumentation other than photographic coverage and visual observation was used. Seat and test configurations and generalized results are listed in table 4.

TEST 1B

TEST CONFIGURATION

Seat A: Vonar 3 over FR urethane
Seat B: Vonar 3 over NF urethane

SCENARIO

Lit cigarette dropped into crevice that is formed where the seat and back cushion meet.

RESULTS

The cigarettes on both seats burned for approximately 1 1/2 minutes, at which time they were both observed to be extinguished. The cigarettes were relit and burned for an additional 7 minutes when replaced in the crevice. The resulting damage was negligible with only a small charred spot on the covering material of all four cushions involved.

TABLE 4. LIST OF SMALL IGNITION SEAT TEST

TEST NO.	SEAT CONFIGURATION	TEST CONFIGURATION	RESULTS
1B	SEAT A: VONAR 3 OVER FR URETHANE SEAT B: VONAR 3 OVER NF URETHANE	LIT CIGARETTE BETWEEN EACH SEAT AND BACK	SEAT A: SMALL CHAR SEAT B: SMALL CHAR
2B	SEAT A: VONAR 3 OVER FR URETHANE SEAT B: VONAR 3 OVER NF URETHANE	LIT CIGARETTE IN SLASH ON EACH SEAT	SEAT A: LITTLE DAMAGE SEAT B: LITTLE DAMAGE
3B	SEAT A: VONAR 3 OVER FR URETHANE SEAT B: VONAR 3 OVER NF URETHANE	TWO (2) DOUBLE SHEETS OF CRUMPLED NEWSPAPER ON SLASH IN EACH SEAT	SEAT A: SELF-EXTING SEAT B: SELF-EXTING
4B	SEAT A: VONAR 3 OVER FR URETHANE SEAT B: VONAR 3 OVER NF URETHANE	FOUR (4) DOUBLE SHEETS OF CRUMPLED NEWSPAPER UNDER EACH SEAT	SEAT A: SELF-EXTING. SEAT B: SELF-EXTING.
5B	SEAT A: VONAR 3 OVER FR URETHANE SEAT B: VONAR 3 OVER NF URETHANE	SLASH IN SEAT BACK, TWO (2) DOUBLE SHEETS OF CRUMPLED NEWSPAPER ON EACH SEAT	SEAT A: MIN. DAMAGE SEAT B: MIN. DAMAGE
6B	SEAT A: VONAR 3 OVER FR URETHANE SEAT B: VONAR 3 OVER NF URETHANE	SLASH IN BOTTOM OF EACH SEAT AND 18 SHEETS OF COMPUTER PAPER UNDER SEAT	SEAT A: SELF-EXTING. SEAT B: SELF-EXTING.
7B	SEAT A: VONAR 3 OVER FR URETHANE SEAT B: VONAR 3 OVER NF URETHANE	ONE (1) PINT GASOLINE ON EACH SEAT	SEAT A: SELF-EXTING. SEAT B: SELF-EXTING.
8B	SEAT A: VONAR 3 OVER NF URETHANE SEAT B: VONAR 3 OVER FR URETHANE	TWO (2) DOUBLE SHEETS OF CRUMPLED NEWSPAPER UNDER EACH SEAT	SEAT A: SELF-EXTING. SEAT B: DESTROYED
9B	PREOX OVER NF URETHANE (ONE SEAT)	TWO (2) DOUBLE SHEETS OF CRUMPLED NEWSPAPER UNDER SEAT	SOME DAMAGE AND FOAM INVOLVEMENT
10B	PREOX OVER NF URETHANE (ONE SEAT)	THREE (3) DOUBLE SHEETS OF CRUMPLED NEWSPAPER UNDER SEAT	LITTLE DAMAGE
11B	PREOX OVER NF URETHANE (ONE SEAT)	FOUR (4) DOUBLE SHEETS OF CRUMPLED NEWSPAPER UNDER SEAT	LITTLE DAMAGE
12B	PREOX OVER NF URETHANE (ONE SEAT)	FOUR (4) DOUBLE SHEETS OF CRUMPLED NEWSPAPER UNDER SEAT	LITTLE DAMAGE
13B	SEAT A: NORFAB OVER NF URETHANE SEAT B: FR URETHANE	FOUR (4) DOUBLE SHEETS OF CRUMPLED NEWSPAPER ON EACH SEAT	SEAT A: LITTLE DAMAGE SEAT B: DESTROYED
14B	SEAT A: PREOX OVER NF URETHANE SEAT B: FR URETHANE	ONE (1) PINT GASOLINE ON EACH SEAT	SEAT A: FOAM DAMAGE SEAT B: DESTROYED
15B	SEAT A: VONAR 3 OVER NF URETHANE SEAT B: FR URETHANE	FOUR (4) DOUBLE SHEETS OF CRUMPLED NEWSPAPER UNDER EACH SEAT	SEAT A: LITTLE DAMAGE SEAT B: DESTROYED

TEST 2B

TEST CONFIGURATION

Seat A: Vonar 3 over FR urethane
Seat B: Vonar 3 over NF urethane

SCENARIO

Large slash in seat cushion covering and blocking layer material allowing for a lit cigarette to come in direct contact with the core foam.

RESULTS

Both cigarettes burned for approximately 12 minutes, at which time they self-extinguished. Upon removal of the ashes, damage was found to be negligible. The foam surface was blackened; the area of the blackened surface being slightly greater on the FR foam than on the NF foam.

TEST 3B

TEST CONFIGURATION

Seat A: Vonar 3 over FR urethane
Seat B: Vonar 3 over NF urethane

SCENARIO

A small paper fire, fueled by two double sheets of crumpled black and white newsprint on top of the slashed seat cushion.

RESULTS

After approximately 1 minute, the paper was consumed on both seats and both foams were observed to be burning at this time. The blocking layer appeared to have a large damping affect on the fires. The FR foam continued to burn with only a small 1- to 2-inch flame being emitted from the slash. After 25 minutes, the fire was manually extinguished. The non-fire retardant foam burned more intensely but was still confined to the small area of the slash. Average flame height was approximately 6 to 8 inches. This flame self-extinguished after 21 minutes, but the cushion continued to smolder producing heavy smoke. Approximately 80 percent of the NF foam was consumed and approximately 65 to 70 percent of the FR foam was consumed. Both blocking layers were still intact except for the original slash.

TEST 4B

TEST CONFIGURATION

Seat A: Vonar 3 over FR urethane
Seat B: Vonar 3 over NF urethane

SCENARIO

Small paper fire under seat, fueled by four double sheets of crumpled black and white newsprint.

RESULTS

The fires burned for approximately 2 minutes, at which time no visible flame was observed. Damage was contained to the bottom of the seat cushions where the covering fabric was totally consumed on both seats, however, the blocking layer was charred but still intact.

TEST 5B

TEST CONFIGURATION

Seat A: Vonar 3 over FR urethane
Seat B: Vonar 3 over NF urethane

SCENARIO

Slash in seat back cushion with a small paper fire, fueled by two double sheets of crumpled black and white newsprint, on the seat bottom cushion.

RESULTS

Paper was consumed with minimal damage to seat. Some charring of the covering fabric occurred in the area of the slash. Foam appeared to be unaffected.

TEST 6B

TEST CONFIGURATION

Seat A: Vonar 3 over FR urethane
Seat B: Vonar 3 over NF urethane

SCENARIO

Slash underneath seat bottom cushion, with small paper fire, fueled by 18 sheets of computer type paper, under each seat.

RESULTS

All visible flame had self-extinguished by 2 1/2 minutes into the test. Damage was confined to the seat bottom with most of the seat covering fabric and a small volume of foam being consumed. Neither foam ignited.

TEST 7B

TEST CONFIGURATION

Seat A: Vonar 3 over FR urethane
Seat B: Vonar 3 over NF urethane

SCENARIO

One pint of gasoline poured on the back cushion of each seat.

RESULTS

The fire was very intense for the first minute on both seats. The fires died out rapidly after this time, apparently because the gasoline was consumed. The FR foam self-extinguished 5 minutes into the test. The NF foam had only residual flames after 3 minutes. Considering the initial intensity of the fire, the damage to both seats was light. On both seats, the covering fabric was completely consumed on the front of the cushions. The blocking layers were heavily charred and the foams behind them slightly discolored.

TEST 8B

TEST CONFIGURATION

Seat A: Vonar 3 over untreated urethane
Seat B: Standard FR urethane

SCENARIO

Comparison of NF foam covered with a blocking layer and a standard seat of FR urethane foam. Small paper fire under seat fueled by two double sheets of crumpled black and white newsprint.

RESULTS

Both the paper fires were out by 1 1/2 minutes into the test. No visible flame appeared on the blocking layer seat after the paper fire was out. The urethane seat quickly became fully involved and was totally destroyed.

TEST 9B

TEST CONFIGURATION

One seat, Preox over NF urethane

SCENARIO

Small paper fire under seat fueled by two double sheets of crumpled black and white newsprint.

RESULTS

The paper fire died out about 1 minute into the test. The fire burned the back of the seat, fueled by the covering fabric and plastic food tray. The fire eventually self-extinguished. The blocking layer remained intact but core foam was completely consumed in back and headrest cushions.

TEST 10B

TEST CONFIGURATION

One seat, Preox over FR urethane

SCENARIO

Small paper fire under seat fueled by three double sheets of crumpled black and white newsprint.

RESULTS

The paper was consumed after approximately 40 seconds, leaving small flames and smoldering under the seat botton cushion, which extinguished after 3 minutes and 30 seconds. Little damage was done to the seat.

TEST 11B

TEST CONFIGURATION

One seat, Preox over FR urethane

SCENARIO

Small paper fire under seat fueled by four double sheets of crumpled black and white newsprint.

RESULTS

More intense fire than that in test 10B. The paper was consumed after 35 seconds. The fire extinguished after 3 minutes and 10 seconds. The covering fabric underneath the seat bottom cushion was destroyed and the blocking layer became brittle and cracked, allowing partial discoloration of the foam. However, the foam did not ignite.

TEST 12B

TEST CONFIGURATION

One seat, Preox over NF urethane

SCENARIO

Small paper fire under seat fueled by four double sheets of crumpled black and white newsprint.

RESULTS

The paper fire went out after 45 seconds, leaving a small fire on the seat bottom cushion consisting of small flames and smoldering until it self-extinguished at 3 minutes and 15 seconds. The covering fabric under the seat bottom cushion was destroyed and the blocking layer was left brittle but fully intact. The NF urethane was discolored under the blocking layer on the bottom side of the seat cushion, and a small portion had been consumed.

TEST 13B

TEST CONFIGURATION

Seat A: Norfab over NF urethane
Seat B: Standard FR urethane

SCENARIO

Four sheets of crumpled black and white newsprint on each seat.

RESULTS

Seat "A" self-extinguished shortly after the paper was consumed. Damage to the seat was limited to slight burning of the wool/nylon fabric and scorching of the aluminized coating on the Norfab. Seat "B" was completely destroyed by the fire. The seat was fully engulfed in flames at approximately 90 seconds after ignition of the paper.

TEST 14B

TEST CONFIGURATION

Seat A: Preox over NF urethane
Seat B: Standard FR urethane

SCENARIO

One pint of gasoline poured on each seat.

RESULTS

Seat "B" was rapidly and completely destroyed by the fire. Seat "A" burned at a much slower rate and almost self-extinguished. However, because other parts of the seat (armrests and table tray) became involved, some of the foam burned out from under the seat blocking layer. Both seats were manually extinguished after 5 minutes into the test.

TEST 15B

TEST CONFIGURATION

Seat A: Vonar 3 over NF urethane
Seat B: Standard FR urethane

SCENARIO

Four sheets of crumpled black and white newsprint under each seat.

RESULTS

There was minimal damage to the wool/nylon upholstery cover on the bottom of seat "A", which self-extinguished after the newspapers were consumed. Seat "B" was totally destroyed. The fire on seat "B" built-up slowly. The entire seat was ablaze at approximately 4 to 5 minutes after ignition of the newspapers.

SERIES TWO: GAS FIRE ON SEATS.

Objective of Tests. The objective of this series of tests was to study the effect of a gasoline fire on blocking layer materials in an enclosed cabin environment.

Description of Test Setup and Instrumentation. These tests were conducted in the C133 fuselage with all fuselage openings covered or closed. The cushions were placed on a double metal seat frame. One quart of gasoline was poured on the seat (figure 46). Instrumentation was similar to test series one through five of the post-crash test. There were no heat flux measurements taken. Video documentation was taken from the forward camera location only.

Description of Each Test. This series consisted of the following two tests:

Test Number	Material (Blocking Layer-Cushion)	Conditions
4A	Vonar 3 FG/R urethane	gasoline
5A	None/FR urethane	gasoline on seat

Presentation and Analysis of Data. Temperature profiles are presented for station 270 at the 8-foot height (figure 47). The Vonar blocking layer self-extinguished, in comparison to the FR urethane, which sustained combustion. The temperature increase for test 4A was due mostly to the burning of the gasoline. The gasoline fire reached its peak intensity at approximately 40 seconds into the test. In test 5A, the gasoline ignited the urethane foam with the curve in figure 47 indicating the contributions of the gasoline and the seat materials. For the initial 10 to 20 seconds, the majority of burning was due to the gasoline (curve for test 5A follows that of test 4A). After that initial period, the seat materials became more intensely involved in the burning. The difference in temperature between tests 4A and 5A shows the temperature increase due to the burning seat materials. The temperature decrease at 80 seconds in test 5A was due to the gasoline fire decreasing in intensity faster than the seat material fire increased. The decrease in temperature after 200 seconds was due to the consumption of a majority of the seat materials, thus, the fire began to diminish, due to lack of fuel.

Smoke optical density is presented in figure 48 for station 270, 5 feet 6 inches. The effectiveness of the blocking layer material is clearly shown in these two tests, resulting in reduced heat, smoke, and gas emissions.

SERIES THREE: LARGE SCALE IN-FLIGHT FIRE TESTS.

Objective of Tests. To determine the benefit of seat fire blocking in preventing or minimizing in-flight aircraft fires.

Description of Test Setup and Instrumentation. The C133 aircraft was used for these tests. The forward fire penetration door was covered with metal and sealed, and the aft entrance door was closed. An in-flight airflow system was installed as shown in figure 49. A ventilation rate of 4100 CFM was used. This resulted in a complete airchange every 3 to 4 minutes.

Six sets of triple seats were arranged as shown in figure 50. A strip of aircraft carpet was placed under the center row of seats. No other materials were installed. A small carry-on type bag was placed under the center aisle seat (figure 50). The bag was made of nylon and contained two shirts and two sheets of newspaper (total weight: approximately 22 oz.) The bag was remotely ignited, using two matches and a spark ignitor. During the fire blocking tests, only the seats in the immediate area of the ignition source were protected.

Description of Each Test. This series consisted of the following tests:

Test Number	Material (Blocking/Cushion)	Condition
46	None/FR urethane	airflow
49	LS-200(3/8")/FR urethane	airflow
50	None/FR urethane	airflow
60	Preox/FR urethane	airflow
61	None/FR urethane	airflow shutoff at t = 3 minutes

Presentation and Analysis of Data. Characteristics of an in-flight seat fire.

Using a small ignition source (a match igniting the material in a carry-on bag under a seat), the initial fire buildup was rather slow. As shown in figure 51, very little heat buildup occurred during the first 3 minutes. However, between 3 and 4-minutes, the fire intensity rapidly increases, quickly reaching flashover conditions. Temperature profiles from test 61 are shown in figure 52. Close to the fire (station 35), the stratification is not as great as it was for the post-crash fire.

Also, there is much more stratification at a greater distance from the fire. Figures 53, 54, 55, and 56 show some of the other hazards associated with an in-flight fire. At time of flashover there is rapid temperature, smoke and gas buildup, as well as oxygen depletion.

Test number 61 differed from tests 46 and 50 in that the in-flight airflow was shut off during the test to simulate an in-flight fire culminating at landing, when cabin ventilating system flow could be terminated. During all the in-flight tests, except test 61, the fire was allowed to build up with in-flight airflow on, however, when smoke began to build up in the aft cabin of the C133, the airflow was turned off (at approximately 220 seconds).

There were many similarities between tests 61, 46, and 50, and a few differences. As shown in figures 57 and 58, flashover occurred about the same time during both types of tests. Temperature levels in the forward cabin and oxygen concentrations in the cabin were similar. However, in test 61, when the airflow was shut off, the smoke (and probably gases) stratified and shortly thereafter, a flash fire occurred. (A flash fire is defined as the ignition of combustible gases collected in the cabin causing extremely rapid flame propagation). Figure 58 shows that during test 61 much more heat was produced in the aft cabin at a faster rate than in test 50. This was due to the flash fire.

Blocking Layer Effectiveness. Two tests were conducted using fire-blocking layers. One test (No. 49) used a foam blocker, LS-200, and the other, a cloth blocker, "Preox." Both of these materials proved to be very effective against this type of fire. Figures 59 and 60 show the vast difference between an uncontrolled in-flight fire with standard FR urethane seats and the use of a cloth or foam fire-blocking layer. It should be noted that with the use of a fire-blocking layer the fire is confined to the seat over the ignition source, and eventually the fire self-extinguishes. Minimal hazard levels were encountered when using the fire-blocking materials. No detectable concentrations of gases were measured and the oxygen level remained at 21 percent. It was noted, however, that the cloth blocker produced more smoke and heat than did the foam blocker. (This is shown in figures 61 and 62). This was due to the fact that the urethane in the seat became more involved when the cloth was used than it did when the foam was used. Figure 61 shows the range of cabin temperature at station 35 for both the cloth and foam seat-blocking tests. Note the larger cabin temperature increase for the cloth blocker. Smoke measurements for the cabin-blocking test are shown in figure 62. Note, that because of the airflow and small amount of heat generated, that the most smoke is not at the upper level but in the middle level of the cabin.

RAMP TYPE CABIN FIRE.

OBJECTIVE OF TESTS. To determine the benefit of seat blocking in preventing or minimizing ramp type aircraft cabin fires.

Description of Test Setup and Instrumentation. The test setup was similar to that used for the in-flight tests, in that six sets of triple passenger seats were used. However, for the ramp type fire tests, no airflow was used and all test article doors were closed, including a sheet metal cover over the post-crach fire entry opening. Figure 63 shows the position of the seats and the instrumentation used for comparison of test. Also shown in figure 63 is the location of the ignition source. For all tests, a plastic trash bag containing paper trash, weighing approximately 18 ounces, was placed next to the right side of the right hand center seat. Ignition was accomplished using two wooden matches positioned between the electrodes of a spark ignitor located at the bottom corner of the bag.

It should be noted that, as with the in-flight fires, not all seats were fire-blocked during the fire blocking tests. Only those in the immediate area of the trash bag were protected for the foam type blocking tests, most of the blocked seats were LS-200, 3/8 inches thick over FR urethane, with a few seats being Vonar 3 over FR urethane. All of the cloth blocked seats used Preox (11 oz. per sq. yd.) over FR urethane.

A single 4-foot wide aircraft carpet was used under both the trash bag and the two center sets of seats (shown in figure 63).

The tests were allowed to continue undisturbed for at least 10 minutes. At this time the front and rear doors of the C133 test article were opened. If, as in the case of the standard foam, the fire persisted, it was then extinguished using the aircraft total flood CO_2 system.

Description of Each Test.

Test Number	Material(Blocking Layer/Cushion)
47	None/FR urethane
48	Foam blocking (LS-200 3/8" or Vonar 3 (PE)/FR urethane
59	Cloth blocking (Preox)/FR urethane

PRESENTATION AND ANALYSIS OF DATA. Characteristics of ramp fires.

Before the benefit of fire-blocking aircraft seats could be determined for a ramp fire, the hazards of a ramp fire with inservice materials were explored. For the ramp fire, the most important parameter is temperature. Since there are no occupants, the main emphasis in a ramp fire is to minimize structural damage to the aircraft. Figure 64 shows the temperature profiles at Station 35, 480, and 880. Note the high temperatures reached in the forward section of the aircraft. Peak temperatures were reached approximately 6 minutes into the test. This was not due to the total consumption of materials, but to the starvation of oxygen which reduced the fire intensity to almost a smoldering state. Figure 65 shows the oxygen, CO_2, and CO levels in the aft section of the aircraft. It should be noted that the gases were produced by burning seats, trash bag, and carpet only, since no other materials were installed for these tests. The intensity of the fire can best be shown by examining the heat flux produced. Figure 66 shows a peak measured heat flux in the fire of approximately 9 Btu/ft^2 second, and a flux of about 3.5 Btu/ft^2 second at position 2.

Unlike heat flux and temperature, the smoke level does not drastically decrease as the intensity of the flaming diminishes. In figure 67, the smoke density at 5 feet 6 inches is shown to continually increase. Persistent thick smoke, high levels of toxic gas, and oxygen levels could cause problems to fire fighters attempting to enter the cabin to combat the fire.

Although not shown on the curves, a violent fire erupted shortly after the cabin was reopened. The fire had to be extinguished using the aircraft total flood CO_2 system. The C133 fuselage is completly protected against burn-through with an interior covering of a fibrous ceramic insulation. The case of an actual ramp fire may cause the fuselage to be penetrated by the fire and the flaming combustion may or may not subside.

BLOCKING LAYER BENEFITS. The benefits of fire blocking the seats were examined for both cloth and foam layers.

Since, as stated before, the most important hazard in a ramp fire is heat, the most important comparisons are that of temperature and heat flux (figures 68 and 69). Therefore, for both cloth and foam blocking layers, the majority of heat is from the trash fire itself. There was some involvement of other seat components, such as arm rests and table trays, and some involvement of the foam in one seat when the cloth blocker was used. However, in both fire-blocked tests, the fire was confined to one seat and self-extinguished. Note the vast difference in temperatures and heat flux (figures 68 and 69) between the blocked and the standard seats.

When fire blocking was used, a small amount of smoke and gases were produced in the cabin. As was the case for heat flux amd temperature, the gas and smoke levels were slightly greater using the cloth blocker than foam, however, more then ten times less than standard foam (figures 70 and 71).

SUMMARY OF BENEFITS

The following is a brief summary of the expected benefits of seat blocking of urethane foam based on the results of the reported tests.

For a post-crash fire, if the fuselage stays intact and the fire enters the fuselage through a rupture or burn-through of the aircraft skin, survival time in the cabin can be increased as much as 35 percent by using a fire blocking layer over the urethane cushions. The amount of additional time depends on such factors as windspeed and direction, location of openings, and size of rupture. Tests indicate that if the fire were to enter the cabin through an open door, fire blocking of seats near the door could provide even a greater increase in survival time.

Since tests indicate that the use of a blocking layer over urethane would safely allow the use of NF foam, this should reduce the gas and smoke production from the seat foam during a fire. The use of NF foam would also reduce the weight of the cushions, helping to negate some of the weight penalty of the blocking layer.

For fires resulting from smaller ignition sources, there is a greater and more pronounced benefit. For a ramp fire, when the ignition source (trash bag) was next to the seats, a blocking layer seat can stop the fire with very minimal damage. The aircraft could be completely destroyed if standard non-blocked seats were used. For in-flight fires, where seats are involved and prompt manual extinguishment cannot be undertaken, blocking layers can provide the difference between a very survivable fire that self-extinguishes and a fire that completely destroys the aircraft and its occupants.

The benefit of blocking layers is conceptually illustrated in figure 72. The "y" axis of the curve was generated by drawing an exponential curve for the FR urethane and matching the condition location on the "y" axis to that curve. The curves for the foam and cloth blocking were then generated based on the "y" axis. For the lower fire intensities, the blocking layer can be the difference between survival and non-survival. As the fire intensity grows, the difference between the blocked and non-blocked seats decreases. Survival is more dependent on the fire source and involvement of other materials.

SIMPLIFIED BENEFIT/COST ANALYSIS.

COST ANALYSIS. The following is a rough cost analysis based on the use of aluminized Norfab (reference 22).

Assumption.

(1) Average seat size - Bottom: 20 inches x 22 inches x 4 inches
Back: 18 inches x 20 inches x 2 inches
Headrest: 18 inches x 8 inches x 5 inches

(2) Average weight of FR urethane - 2.2 pounds per cubic foot

(3) Average weight of non-FR urethane - 1.8 pounds per cubic foot

(4) Weight of scrim or slip covers - 2 ounces per square yard

(5) Weight of aluminized Norfab blocking layer - 11 ounces per square yard

(6) Cost of blocking material- $17.00 per square yard

(7) Cost of fabrication of blocking slip covers is $3.00 greater than fabrication and materials of present slip covers, per seat.

(8) Cost of flying one additional pound for one year - $20.00

(9) Life of fire blocking covers is 4 years

Therefore:

(1) Average seat foam volume - 1.859 per cubic foot

(2) Total seat area = 2.03 per square foot

(3) Total material required for slip cover (including overlap at seam) - approximately 2.5 per square yard

(4) Cost of material and fabrication of aluminized blocking layer seat per seat -

(Cost/Yard)x(Quantity of Material) plus cost of fabrication

17.00 x 2.5 square yards plus 3.00 = $45.50 per seat

(5) Weight of seat cushion with alumnized Norfab and non-FR foam (excluding external cover) -

(Amount of Foam x Density of Foam) plus (amount of blocking material or slip-cover x density)

(1.859 x 28.8) + (2.5 x 11) = 81.039 ounces

Standard Seat is: (1.859 x 35.2) plus (2.5 x 2) = 70.437 ounces

Added Weight per seat due to blocking layer:

81.039 minus 70.437 = 10.602 ounces or approximately 11 ounces/seat

The cost for flying an aluminized Norfab seat over its 4 year life:

initial cost plus (weight x cost/weight) x four years

+$45.50 plus (11 ounces x 1.25) x 4 = 100.50

-OR-

approximately - $25.00 per year

BENEFIT/COST ANALYSIS. It is impossible to project the number or type of accidents that will or are even likely to occur in the future. This report has demonstrated performance improvements of blocking layered seats for various fire scenarios. However, this data cannot be used to project future benefits. What can be done is to examine the world fleet of United States built jet aircraft, calculate the cost over the past 4 years of flying aluminized Norfab, and estimate the benefits for accidents which occurred over that period that could have been derived from seat blocking layers. The following is a simple calculation, using today's cost as a basis.

(1) The worldwide fleet of United States jet aircraft is 4,482 (reference 31).

(2) The average number of seats per aircraft is 170.

(3) Therefore, there are 761,940 seats worldwide in United States built jet aircraft.

(4) At an approximate cost of $25.00 per seat, the total cost of aluminized Norfab blocked seats would be $19,048,500.00 per year on United States jet aircraft worldwide.

(5) To calculate a benefit over the past 4 years, accident and incident statistics were analyzed and a judgement made on the effectiveness of seat blocking for various cases. The following is a computation of cases in which, in the author's opinion, property or lives would have been saved by seat blocking:

(a) October 79: Ramp fire in United 727 in Miami, Florida
Damage: $3,200,000.00
Approx. savings from seat blocking:
$3,000,000.00

(b) August 80: Saudia L1011 fire in Riyadh, Saudi Arabia
Fatalities: 301
Damage: $50,000,000.00
Approx. savings from seat blocking:
$49,000,000.00 and 301 lives

(c) November 80: Korean 747 in Seoul, Korea
Fatalities: 14
Damage: $50,000,000.00
Approx. savings from seat blocking:
$40,000,000.00 and 14 lives

(d) September 82: Spantax DC-10
Fatalities: 56
Damage: $50,000,000.00
Approx. savings from seat blocking: 28 lives

There were also two other accidents/incidents that the authors are aware of, however, not enough information is known about these accidents/incidents to assess the effectiveness of seat blocking layers.

They were:

1. A Pakistan 707 in flight over Saudi Arabia in 1979. The aircraft and all onboard were lost.

2. A Pakistan DC-10 in Karachi, India was completely destroyed by a cabin fire on February 2, 1981, while in a hangar.

Based on the discussed accidents/incidents, the benefit/cost ratio of seat cushion fire blocking layers is:

$$\frac{\text{92 million plus (343) lives (for 4 years)}}{\text{76.194 million dollars}} =$$

1.20 plus 85.75 lives per year

SUMMARY OF RESULTS

POST-CRASH FIRE.

1. With zero wind conditions and a large pool fire next to an opening, the conditions throughout the full-scale wide-body test article, devoid of interior materials, remained survivable for the entire 5-minute test exposure.

2. For the same test condition, with standard wide-body materials installed, the survival time in the aft cabin was reduced to approximately 2-minutes and 40 seconds.

3. During all of the post-crash full-scale tests, a flashover condition occurred, which was followed by loss of survivability throughout the cabin.

4. During some of the full-scale post-crash tests, irritant gases, HF, HCl, and smoke, were the only hazards measured in significant levels in the aft section of the cabin prior to flashover.

5. The use of a Vonar fire blocking layer on the seat cushions increased survival time during the post-crash fire test to approximately 3 minutes and 40 seconds (60 seconds greater than standard seats).

6. The use of a cloth blocking layer, Norfab, for the same tests conditions produced a survival time of approximately 3 minutes 20 seconds (40 seconds greater than standard seats but twenty seconds less than Vonar protected seats).

7. The use of non-combustible cushion produced a survival time of 3 minutes and 58 (an 18-second improvement over the Vonar-protected urathane).

IN-FLIGHT FIRES.

8. In-flight fire tests using ignition sources of gasoline on a seat, or a carry-on bag under a seat, quickly produced non-survivable conditions in the cabin when standard aircraft seats were used.

9. When a blocking layer of cloth (Norfab or Preox) or foam (Vonar or LS-200) was used, the fires eventually self-extinguished and the cabin remained survivable.

10. The foam blocker provided slightly more protection from smoke, heat, and gases than did the cloth blocker.

RAMP FIRES.

11. For a ramp fire ignited in a trash bag, adjacent to a standard seat, a large fire destroyed a majority of the materials in the cabin and reduced the oxygen level to a point of supporting only smoldering combustion. When the aircraft doors were opened, the fire returned to a flaming condition and destroyed the remaining material.

12. When the seats were fire blocked with cloth or foam, the fire self-extinguished with very little involvement of the seating materials.

OTHER RESULTS.

13. Standard seats were ignited with as little as two sheets of newspaper burning under the seat.

14. Fire blocking over non-fire retardant urethane foam was as effective as fire blocking over fire retardant urethane.

CONCLUSIONS

1. Fire blocking of urethane seat cushions can effectively prolong survivable conditions in an aircraft cabin during a post-crash fire.

2. Fire blocking of urethane seat cushions can control certain in-flight or ramp type fires (those in which seat involvement is important).

3. Non-fire retardant urethane can safely be used under a fire blocking layer.

4. Burning cabin interior materials can be the primary factor affecting occupant survivability in certain types of post-crash fires, despite the presence of a large fuel fire.

5. Uncontrolled fires in an aircraft cabin can produce a flashover condition, which will be followed by a loss in survivability throughout the cabin.

6. In a survivable post-crash cabin fire dominated by burning interior materials, primary hazards prior to flashover will be irritant gases, HF and HCl, and smoke produced by burning composite panels and seats.

7. Potential benefits to cabin fire safety beyond those provided by seat cushion blocking layers may be realized from improvements made to the remaining interior materials.

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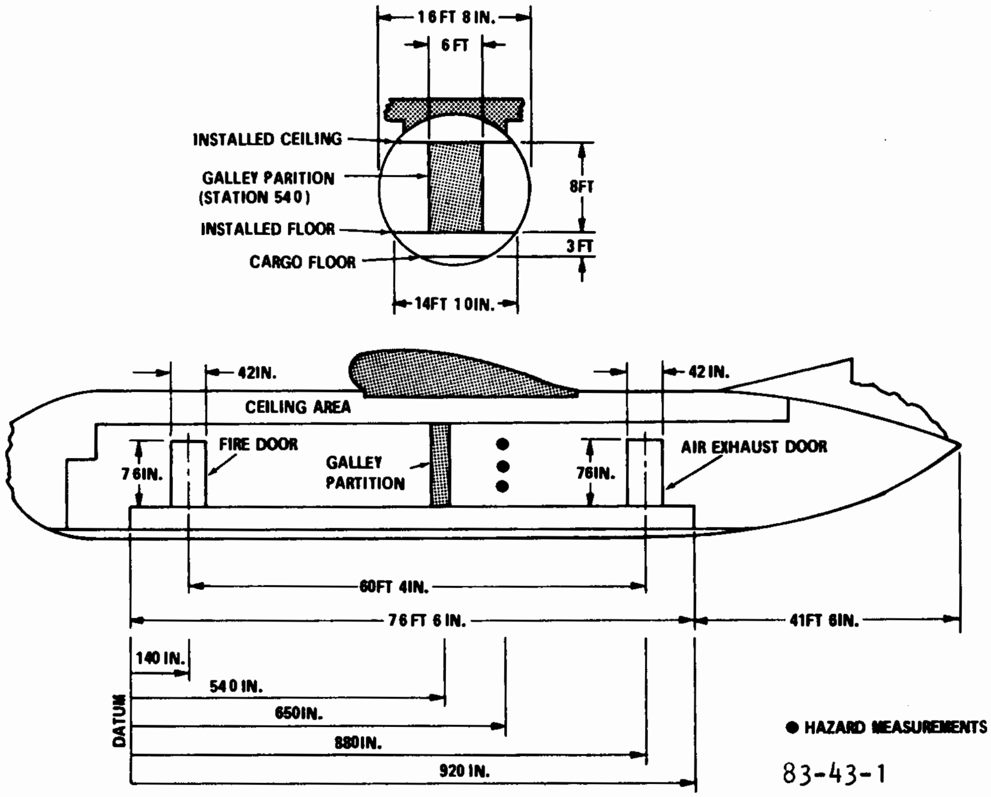


FIGURE 1. SCHEMATIC OF C133 WIDE-BODY CABIN FIRE TEST ARTICLE

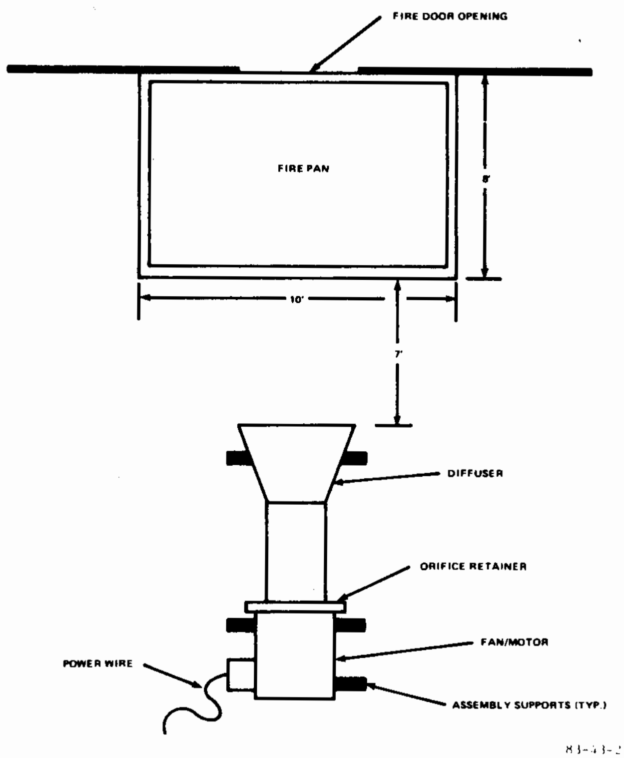


FIGURE 2. SIMULATED WIND CONFIGURATION

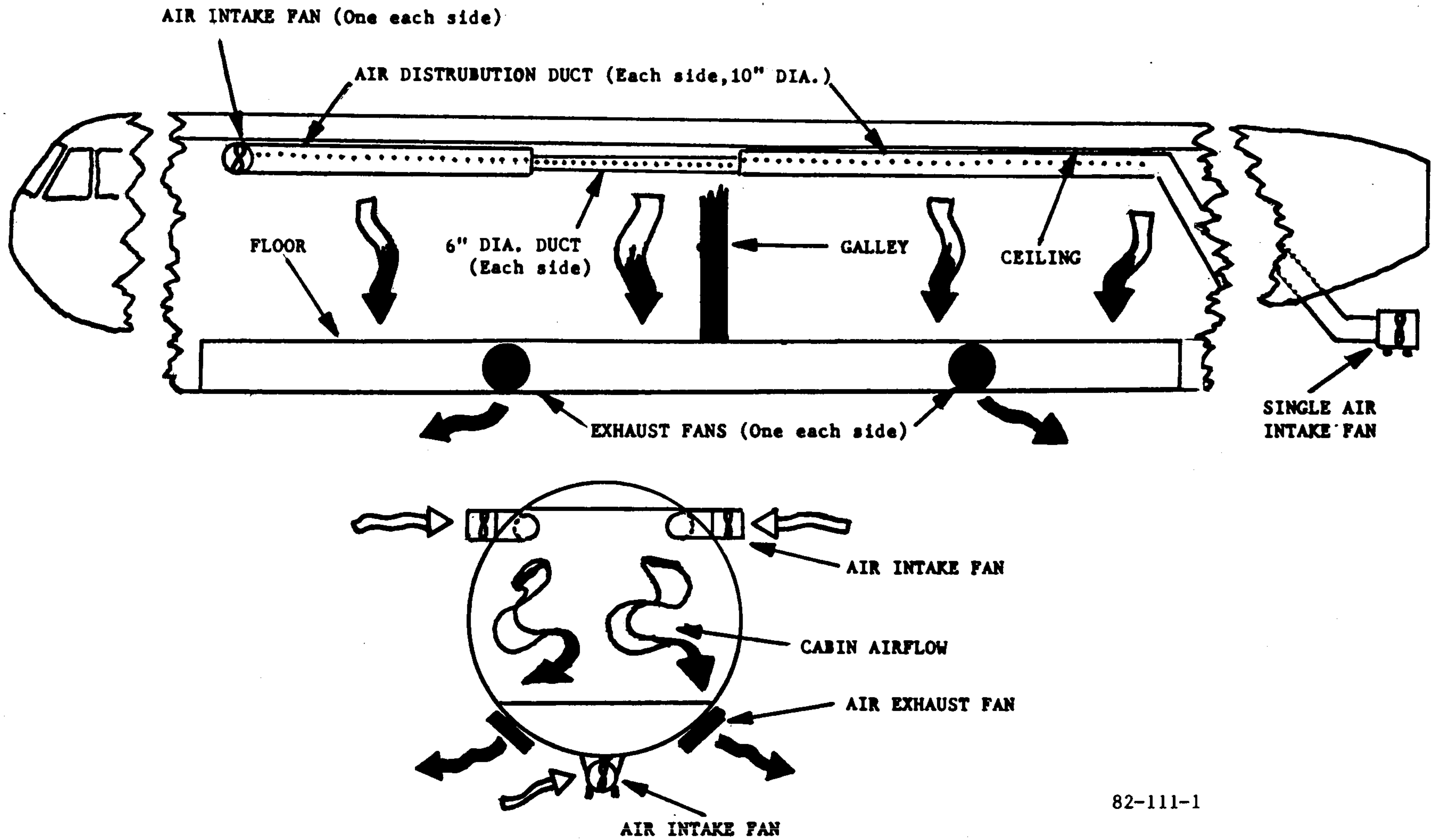
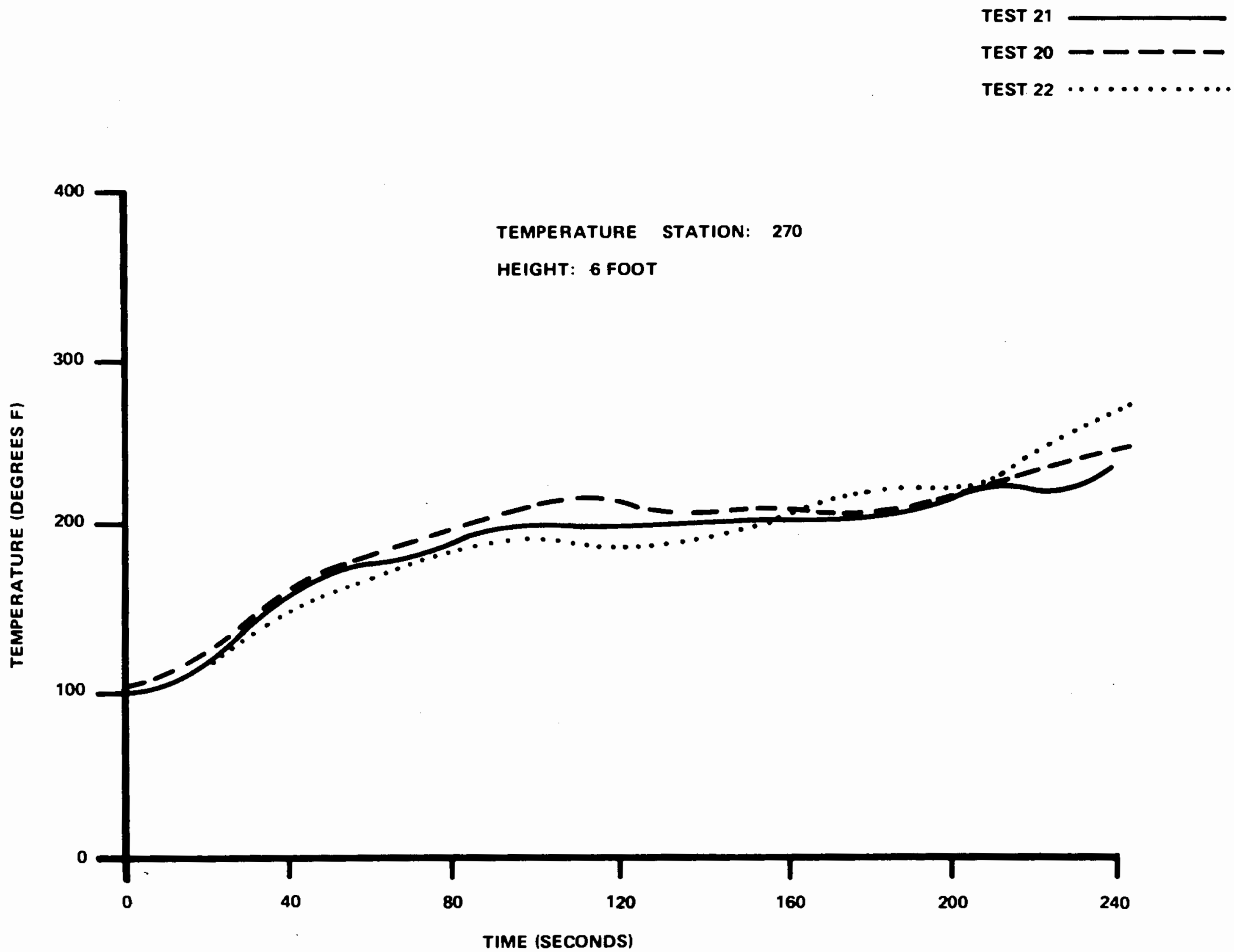


FIGURE 3. C133 TEST ARTICLE CABIN AIR DISTRIBUTION SYSTEM



83-43-4

FIGURE 4. REAPEATABILITY OF POST-CRASH FIRE WITH 1.5 MPH WIND

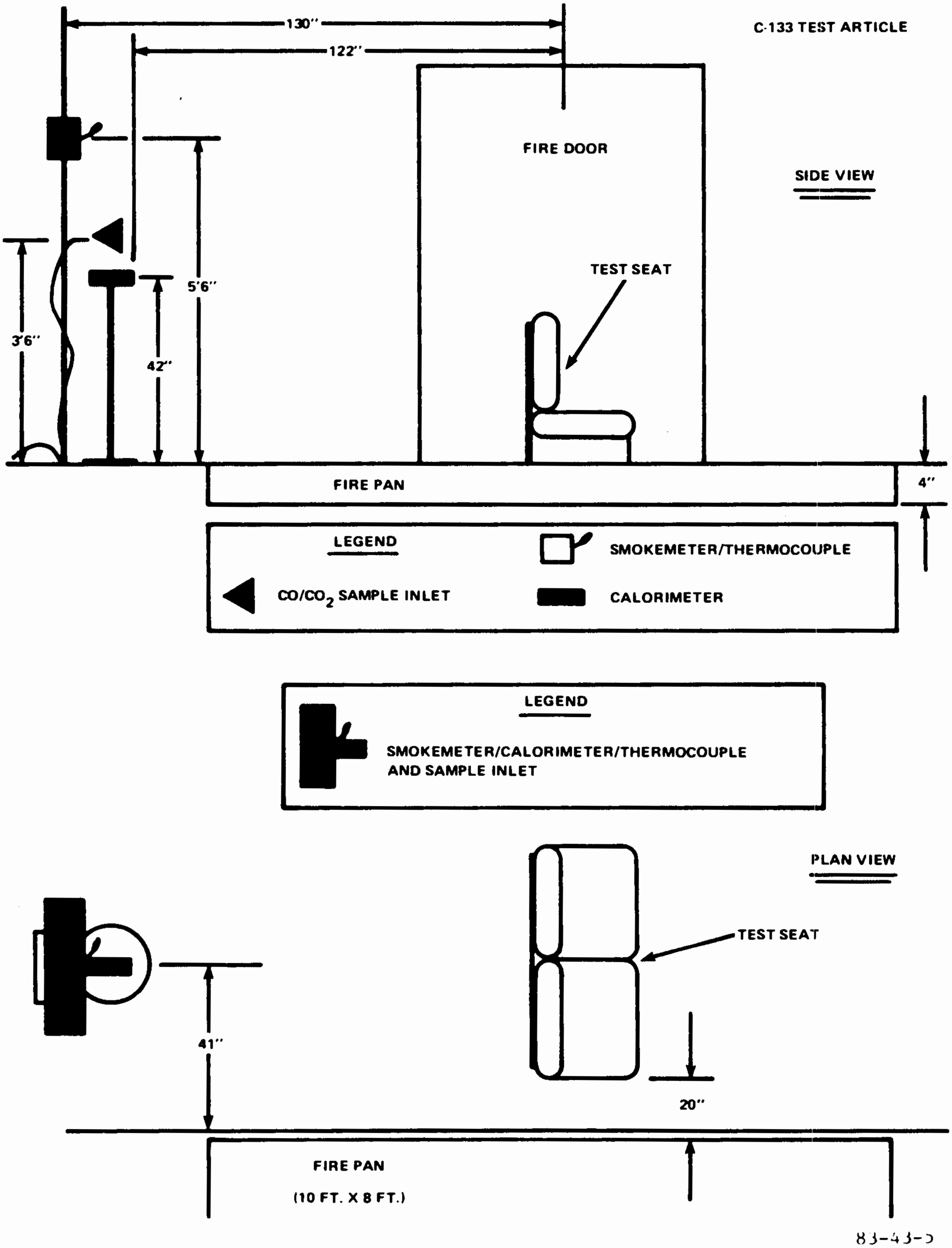
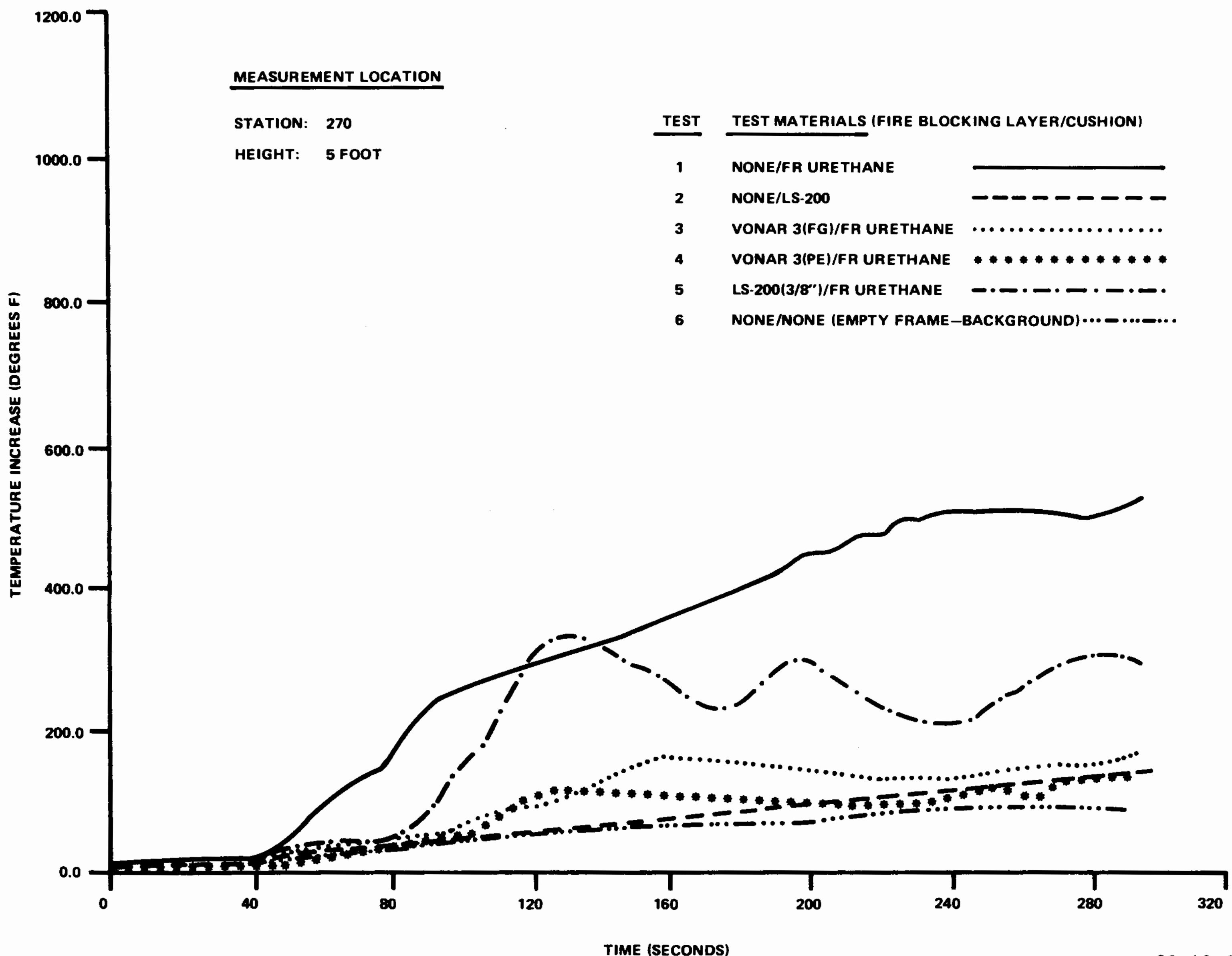
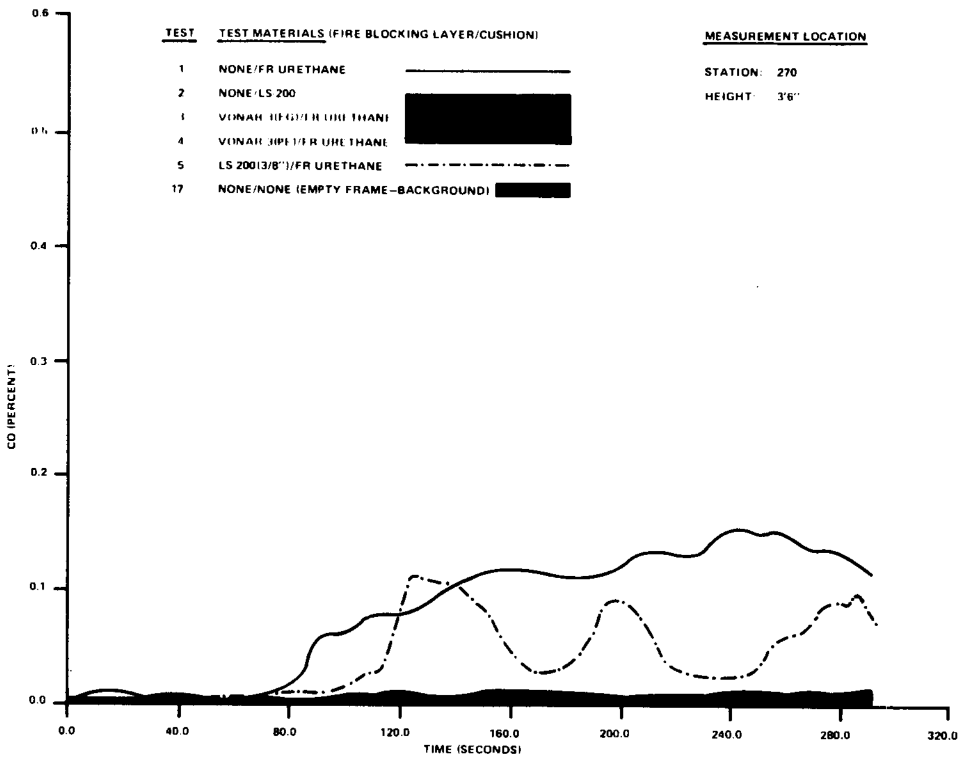


FIGURE 5. POST-CRASH SERIES ONE CONFIGURATION

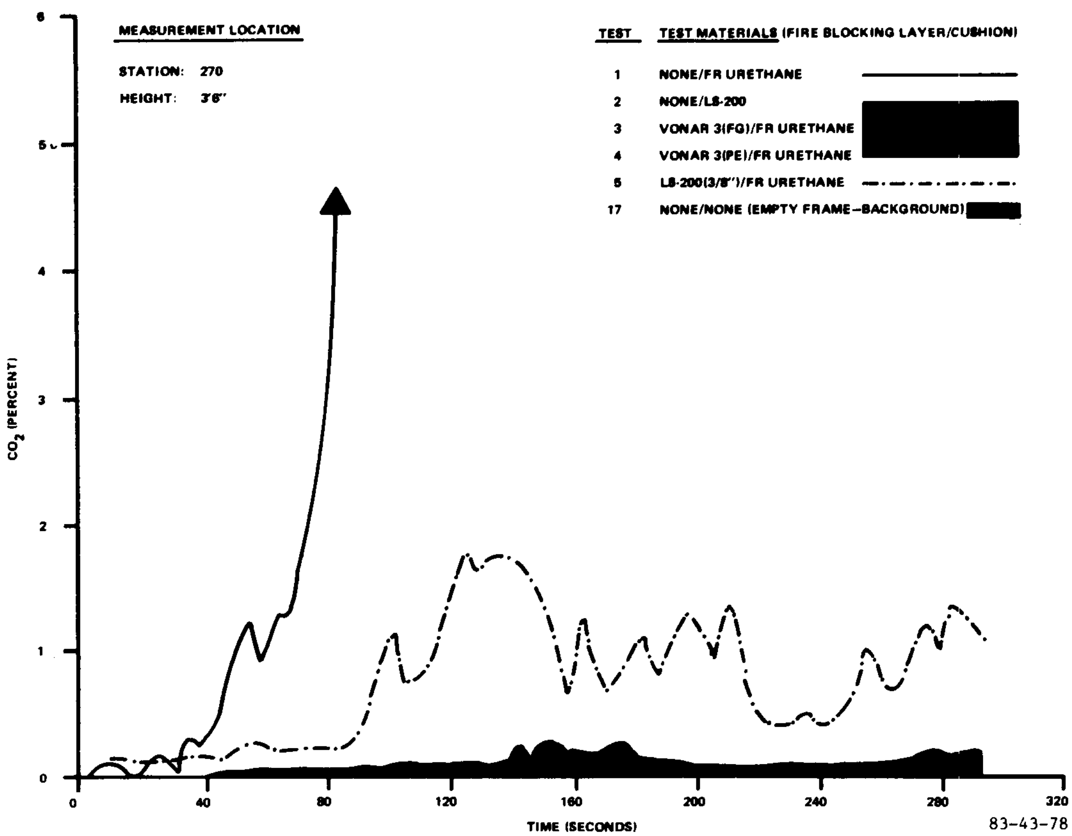


83-43-6

FIGURE 6. POST-CRASH SERIES ONE TEMPERATURE COMPARISON



(a)



(b)

FIGURE 7. POST-CRASH SERIES ONE GAS COMMPARISON

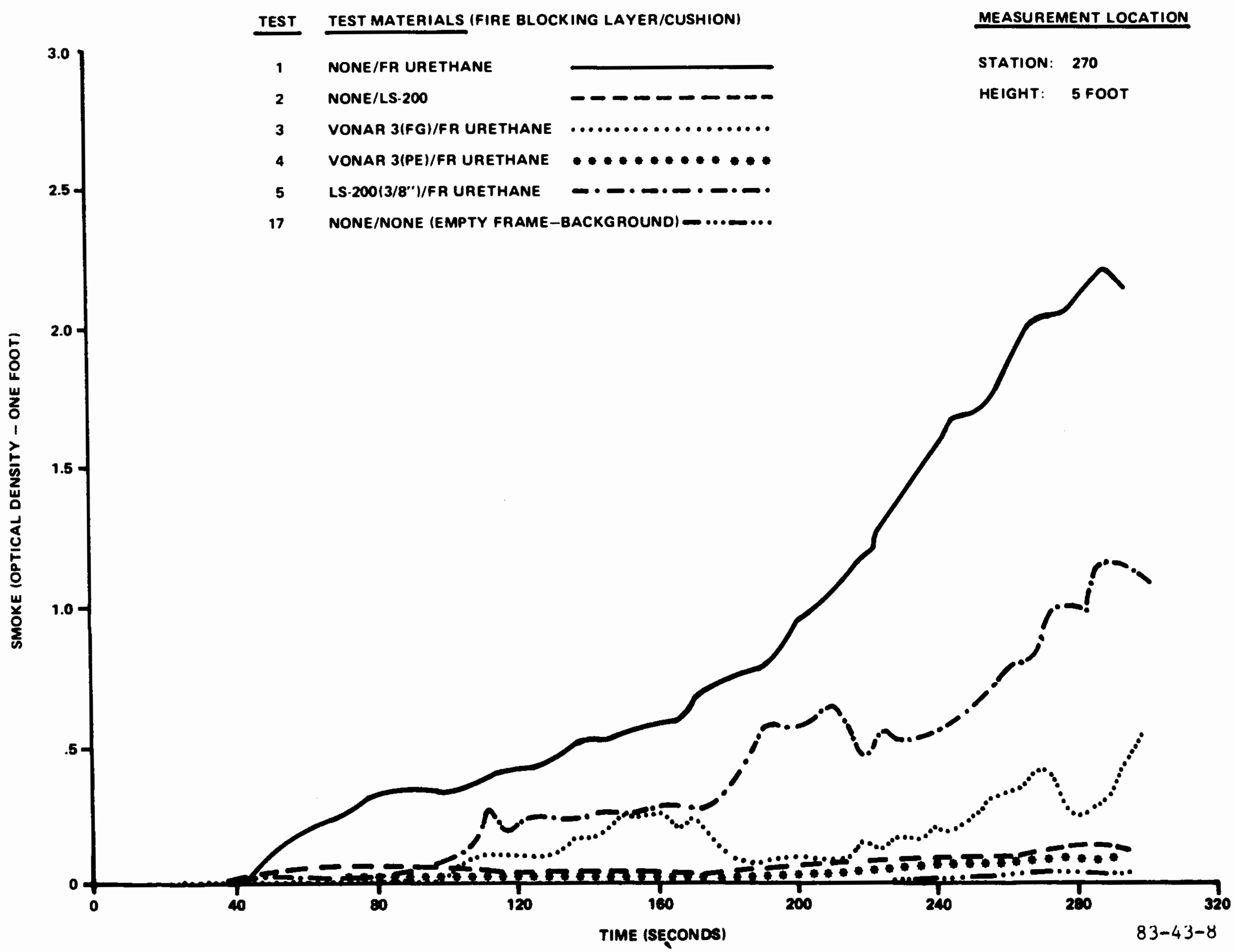


FIGURE 8. POST-CRASH SERIES ONE SMOKE COMPARISON

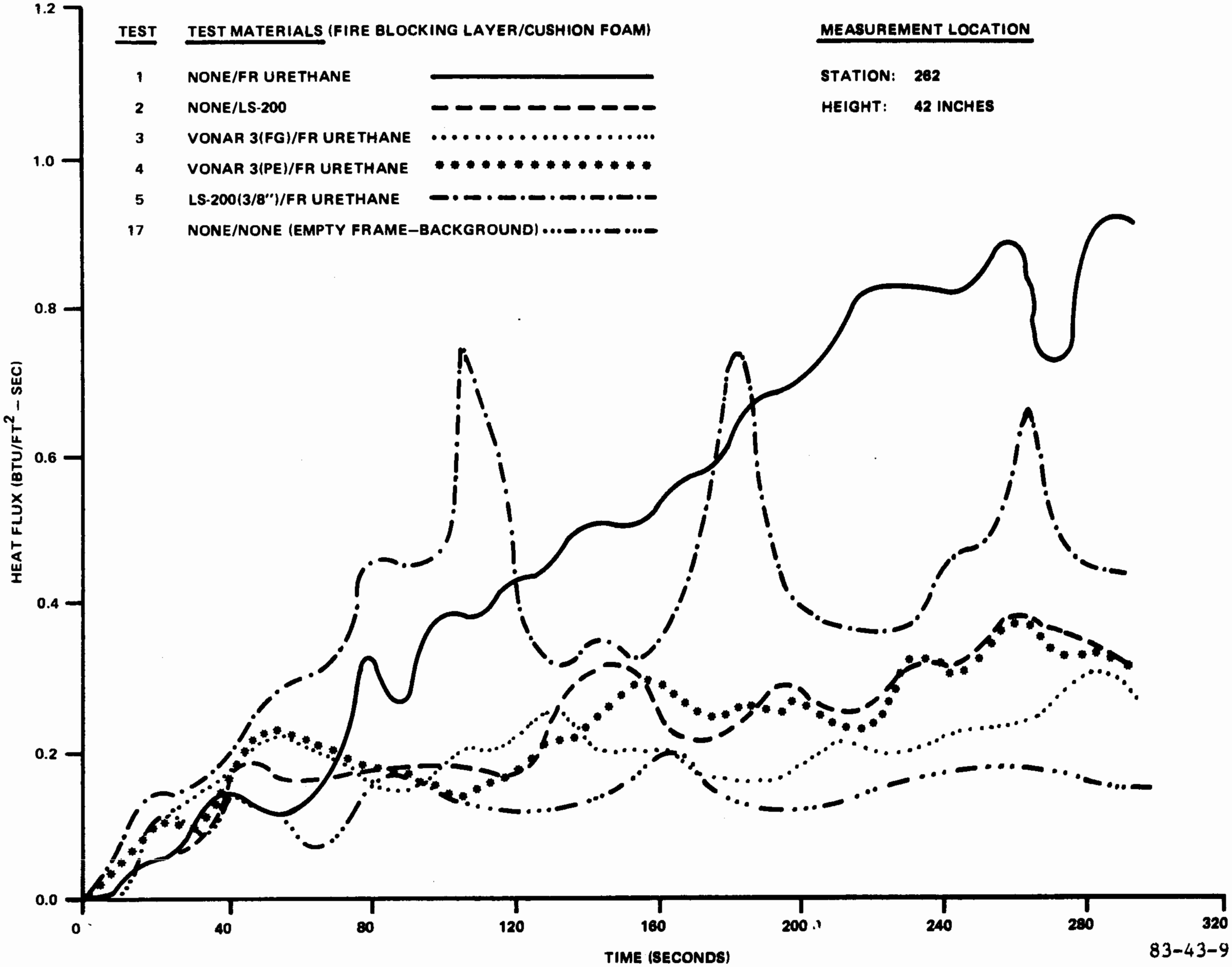
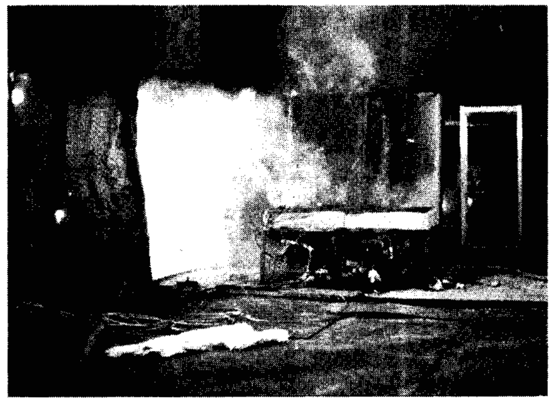
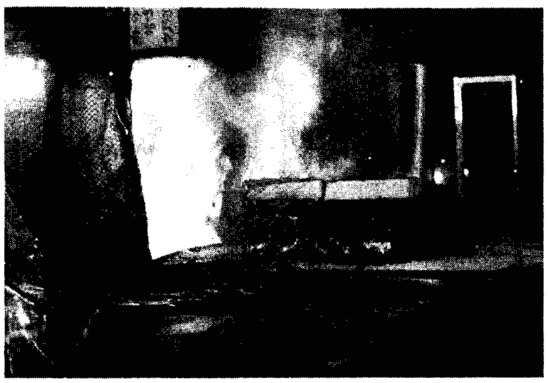


FIGURE 9. POST-CRASH SERIES ONE HEAT FLUX COMPARISON

Test 1
4 min.



Test 2
4 min.



Test 3
4 min.

Test 4
4 min.

Test 5
1 min. 45 sec.

FIGURE 10. PICTORIAL COMPARISON OF POST-CRASH SERIES ONE TESTS

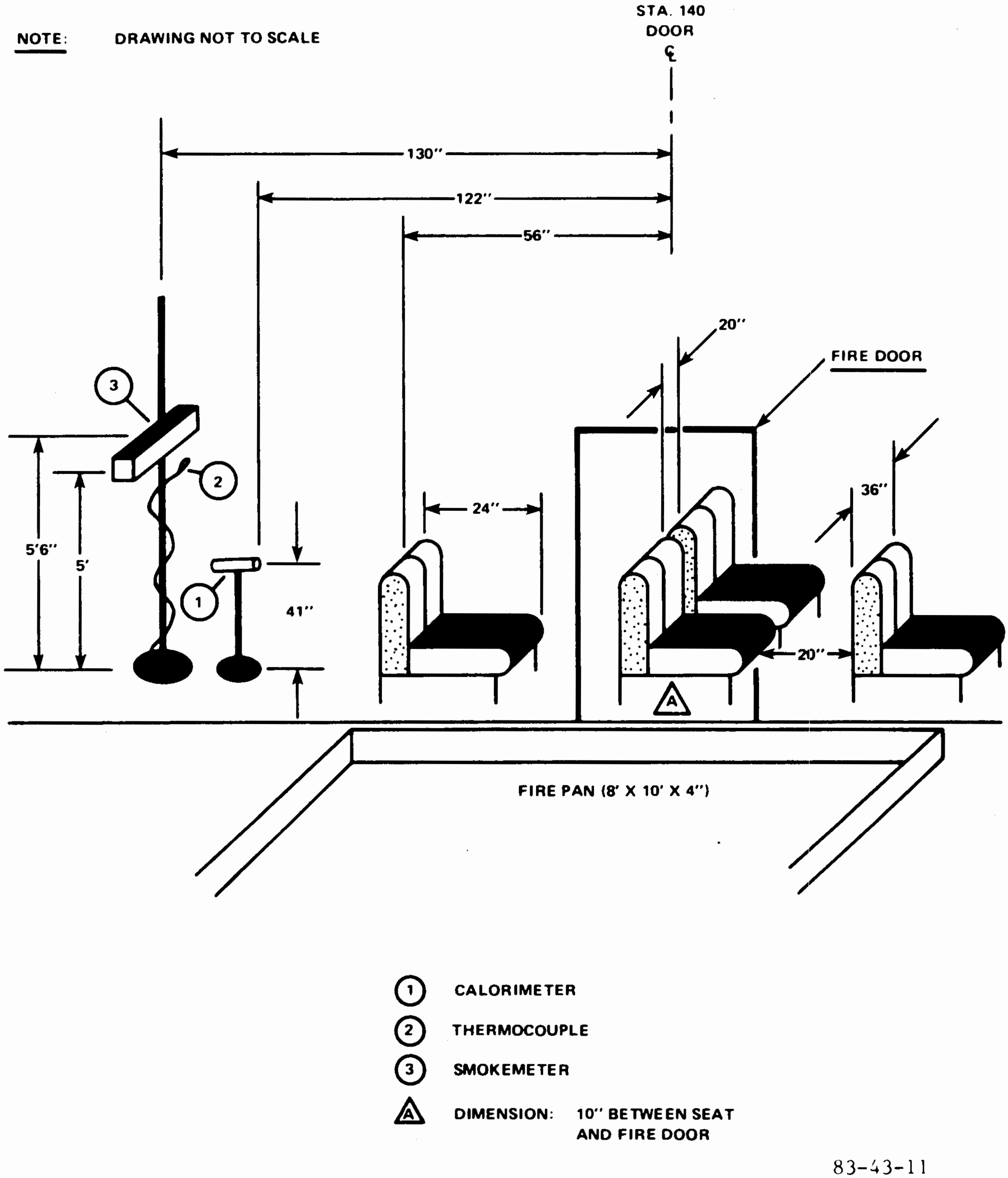


FIGURE 11. POST-CRASH SERIES TWO CONFIGURATION

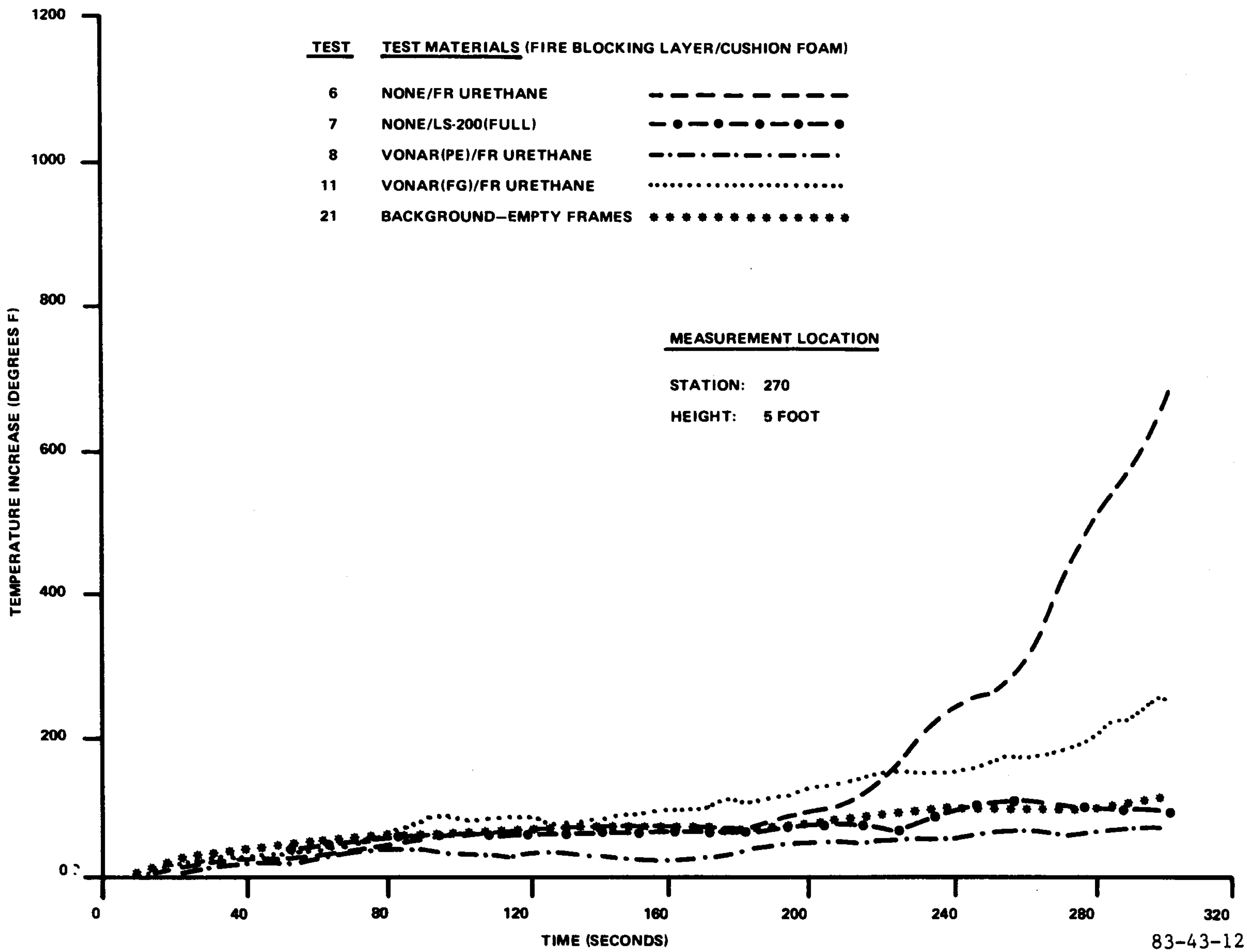


FIGURE 12. POST-CRASH SERIES TWO TEMPERATURE COMPARISON

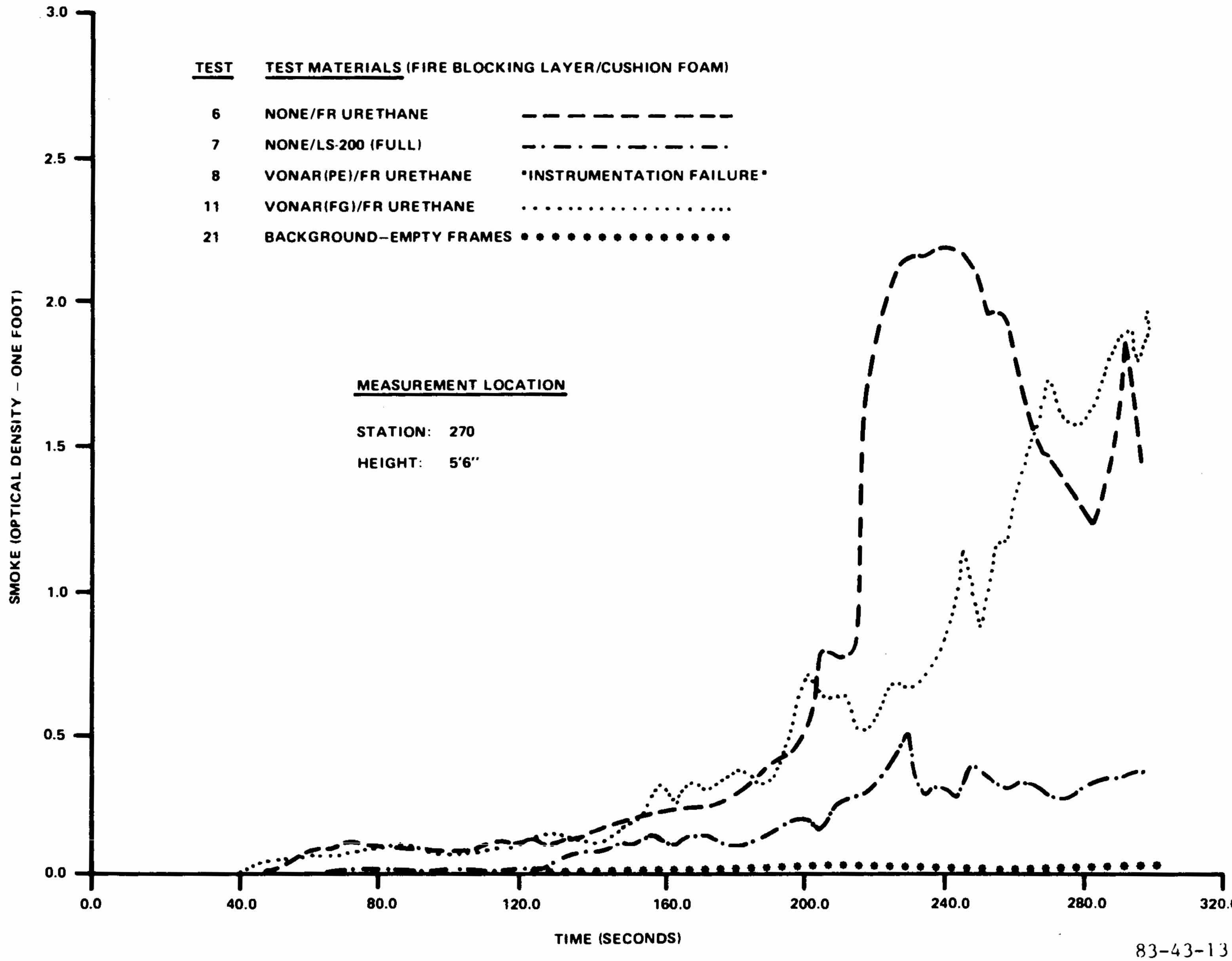


FIGURE 13. POST-CRASH SERIES TWO SMOKE COMPARISON

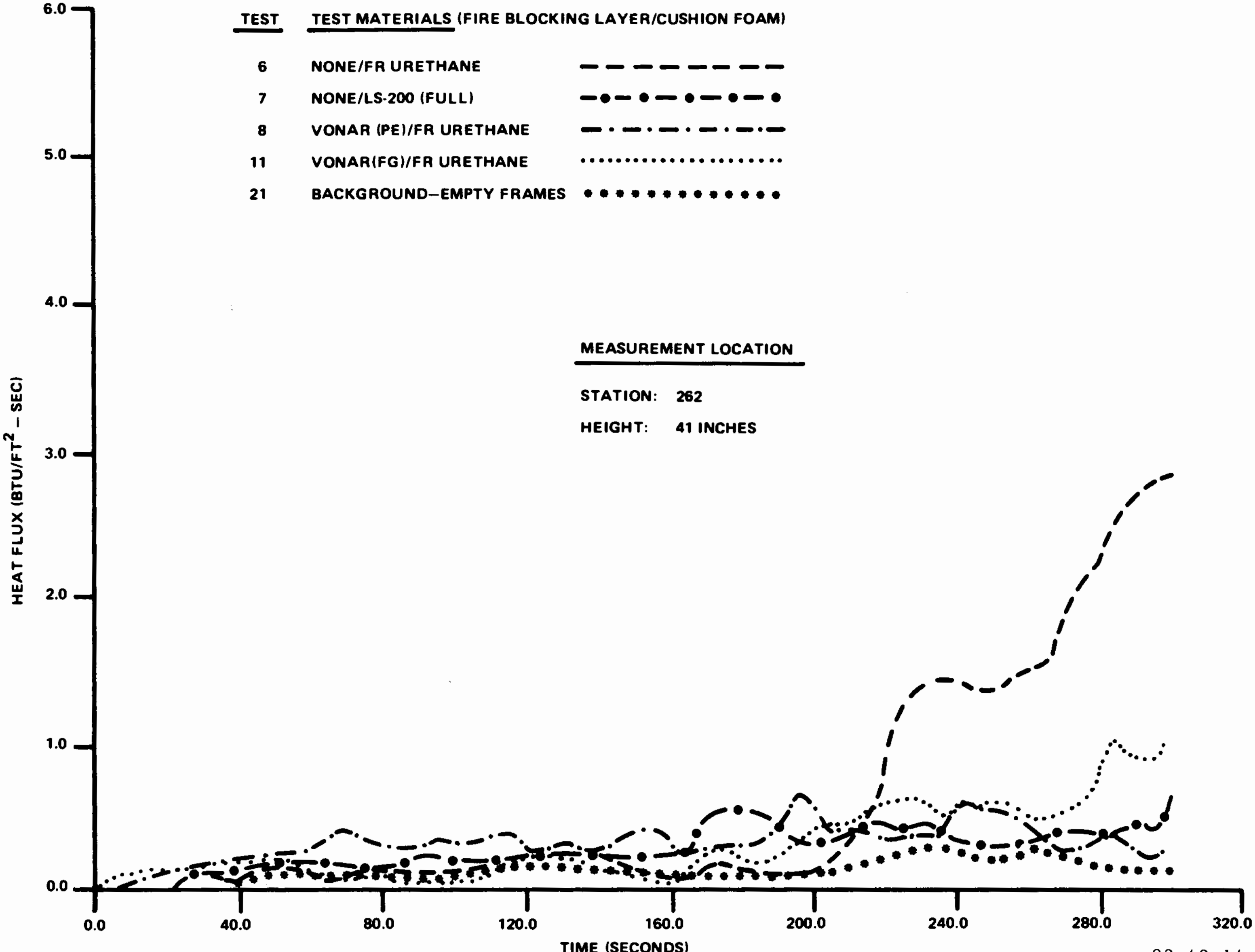


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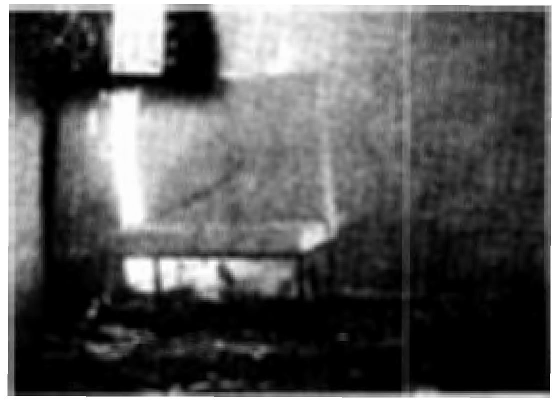
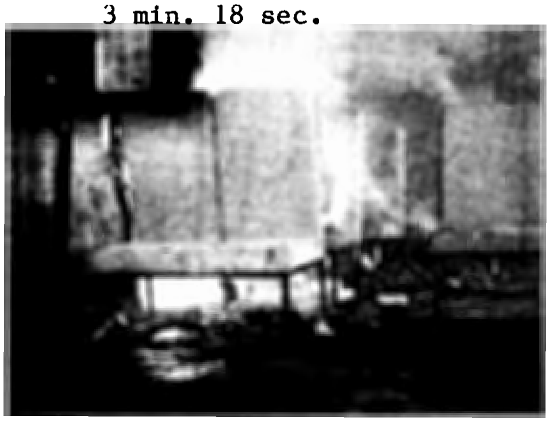
FIGURE 14. POST-CRASH SERIES TWO HEAT FLUX COMPARISON

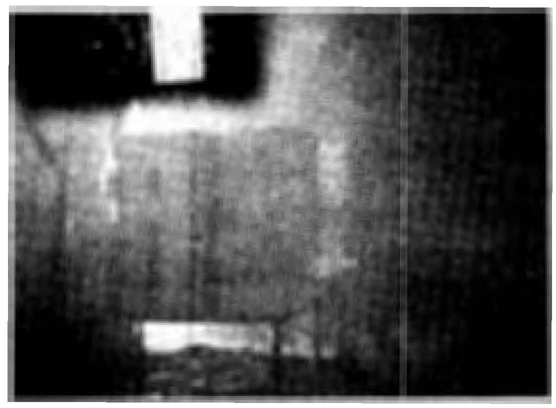
Test 6
3 min. 18 sec.



Test 7



Test 8



Test 11

Test 12

FIGURE 15. PICTORIAL COMPARISON OF POST-CRASH SERIES TWO TESTS AT 4 MINUTES

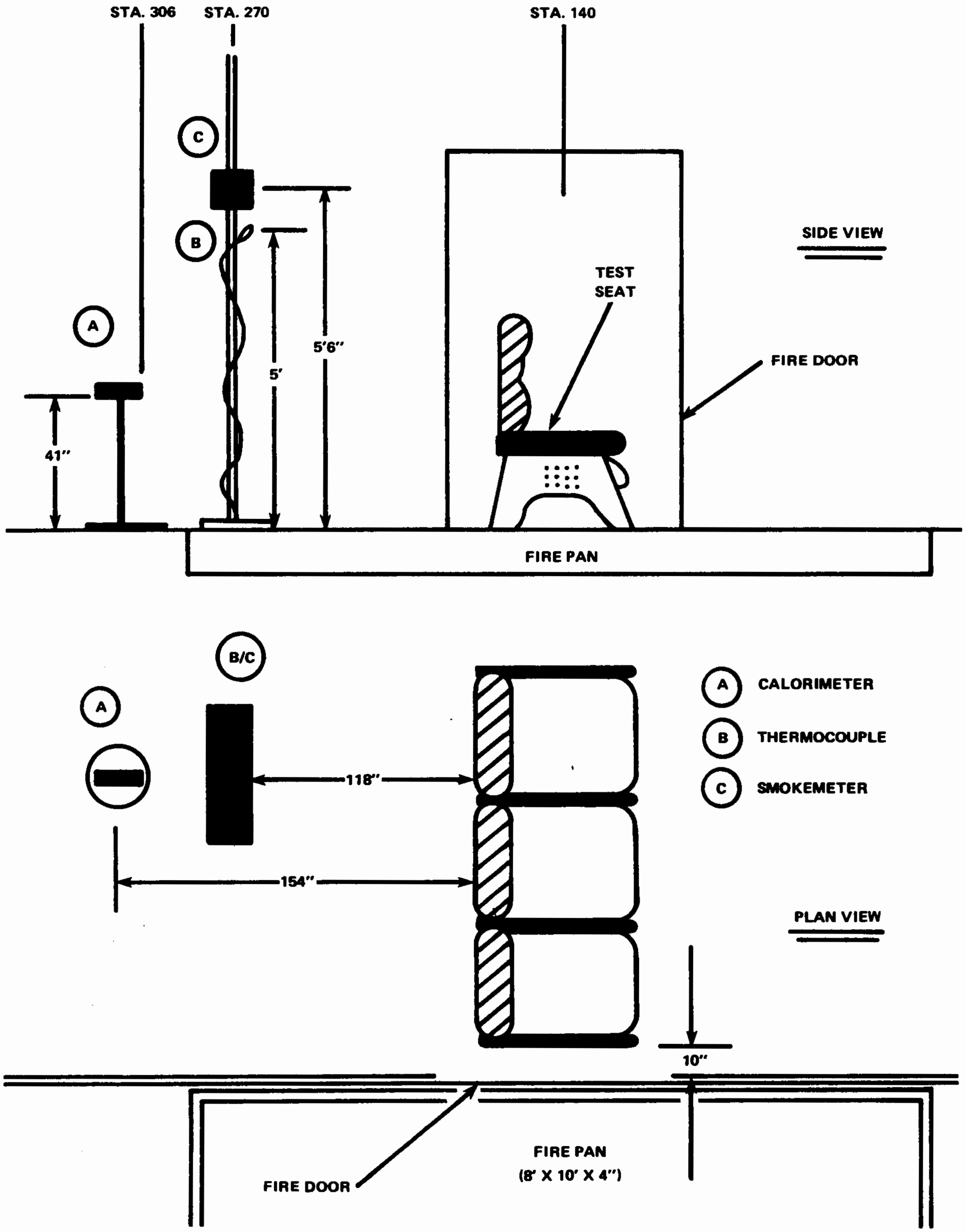


FIGURE 16. POST-CRASH SERIES THREE CONFIGURATION

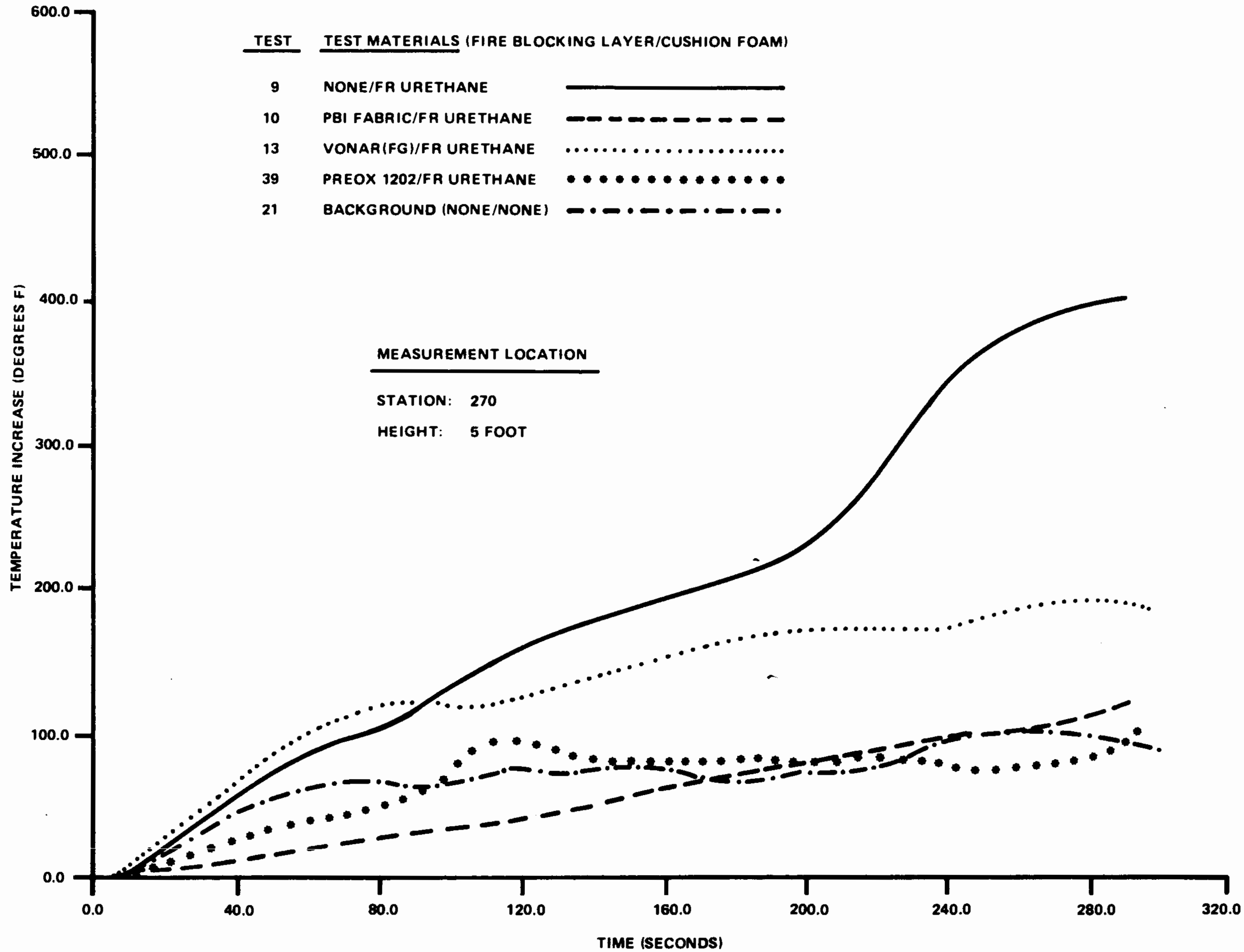


FIGURE 17. POST-CRASH SERIES THREE TEMPERATURE COMPARISON

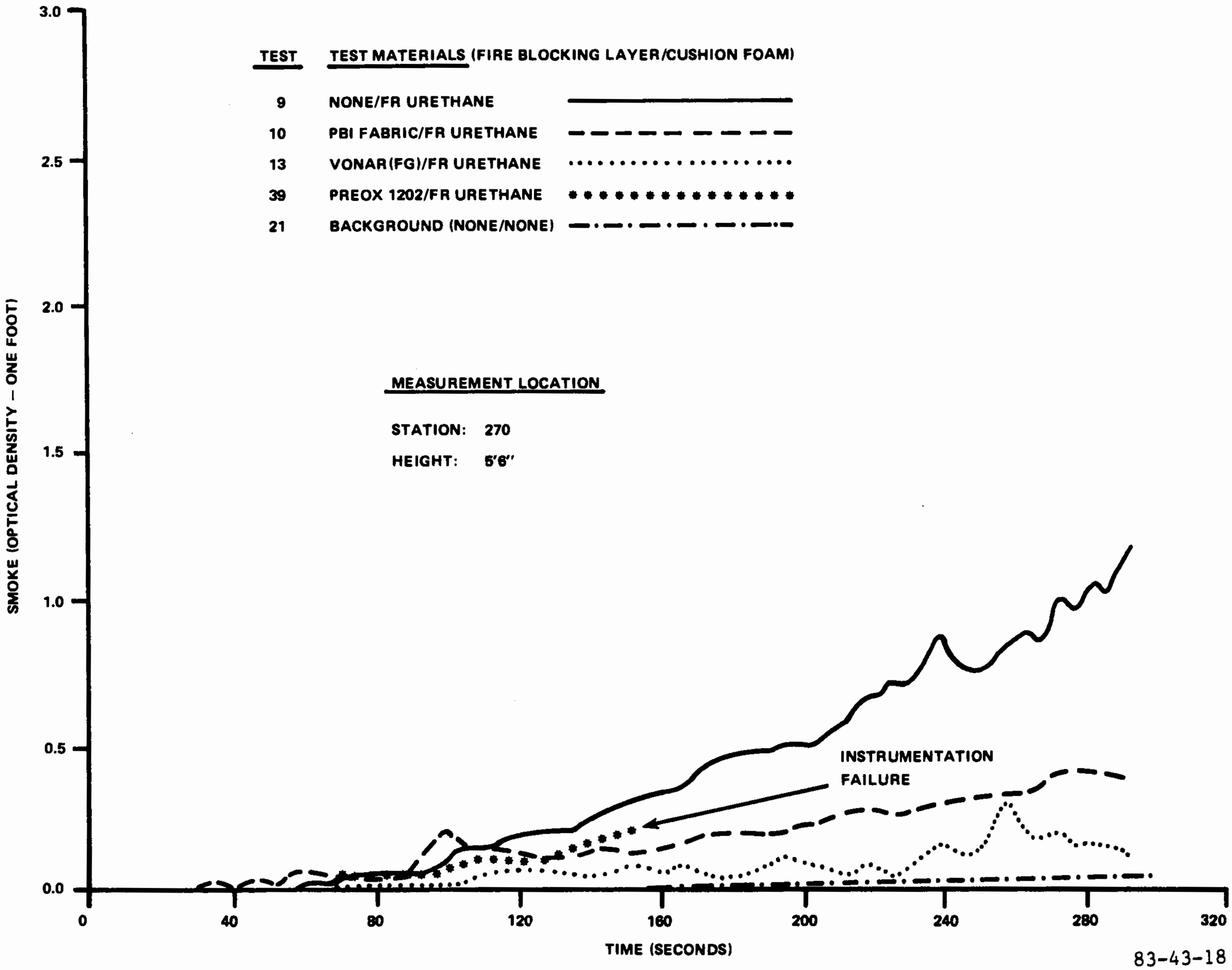


FIGURE 18. POST-CRASH SERIES THREE SMOKE COMPARISON

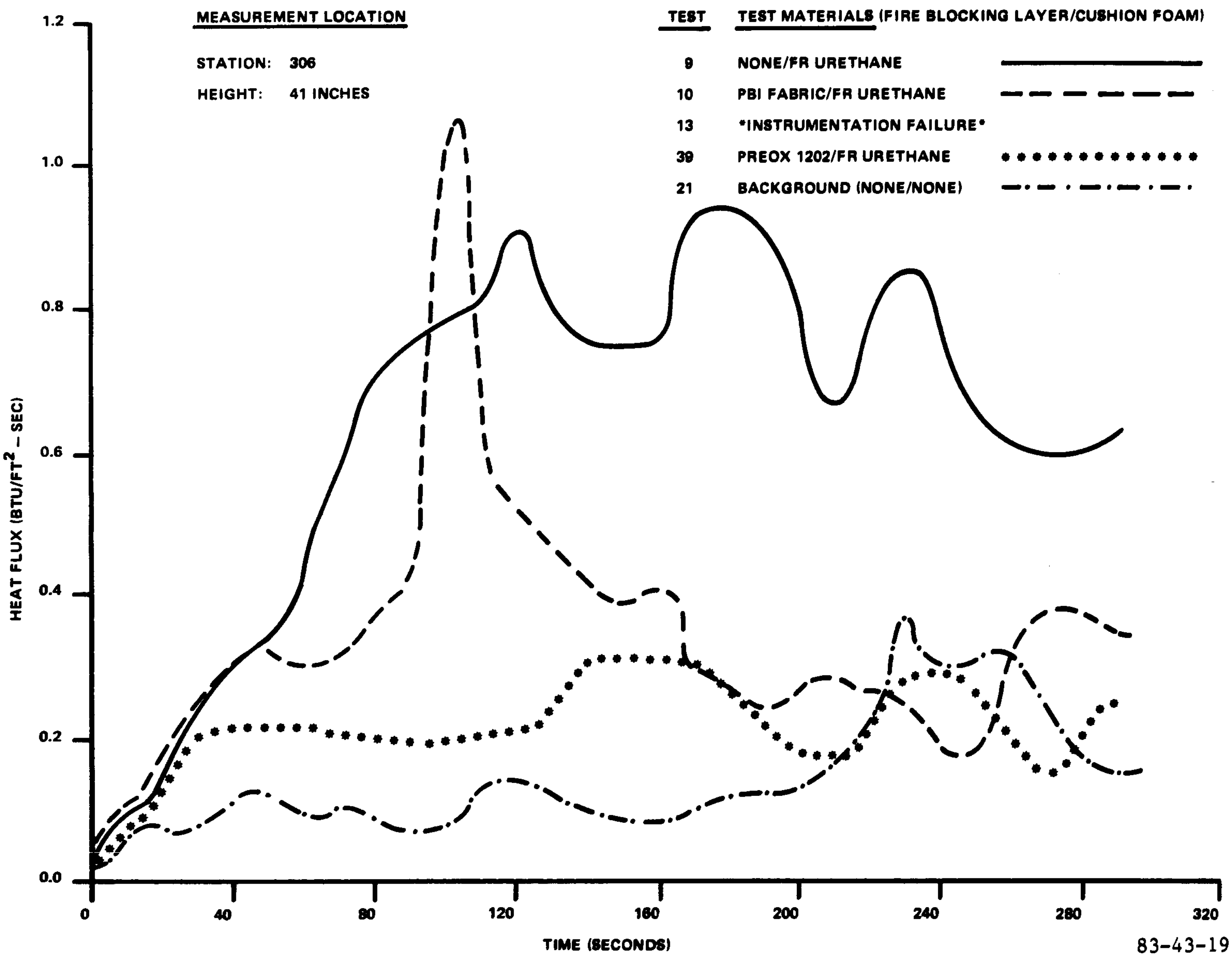


FIGURE 19. POST-CRASH SERIES THREE HEAT FLUX COMPARISON

Test 9

Test 13

Test 39

FIGURE 20. PICTORIAL COMPARISON OF POST-CRASH SERIES THREE TESTS AT 4 MINUTES

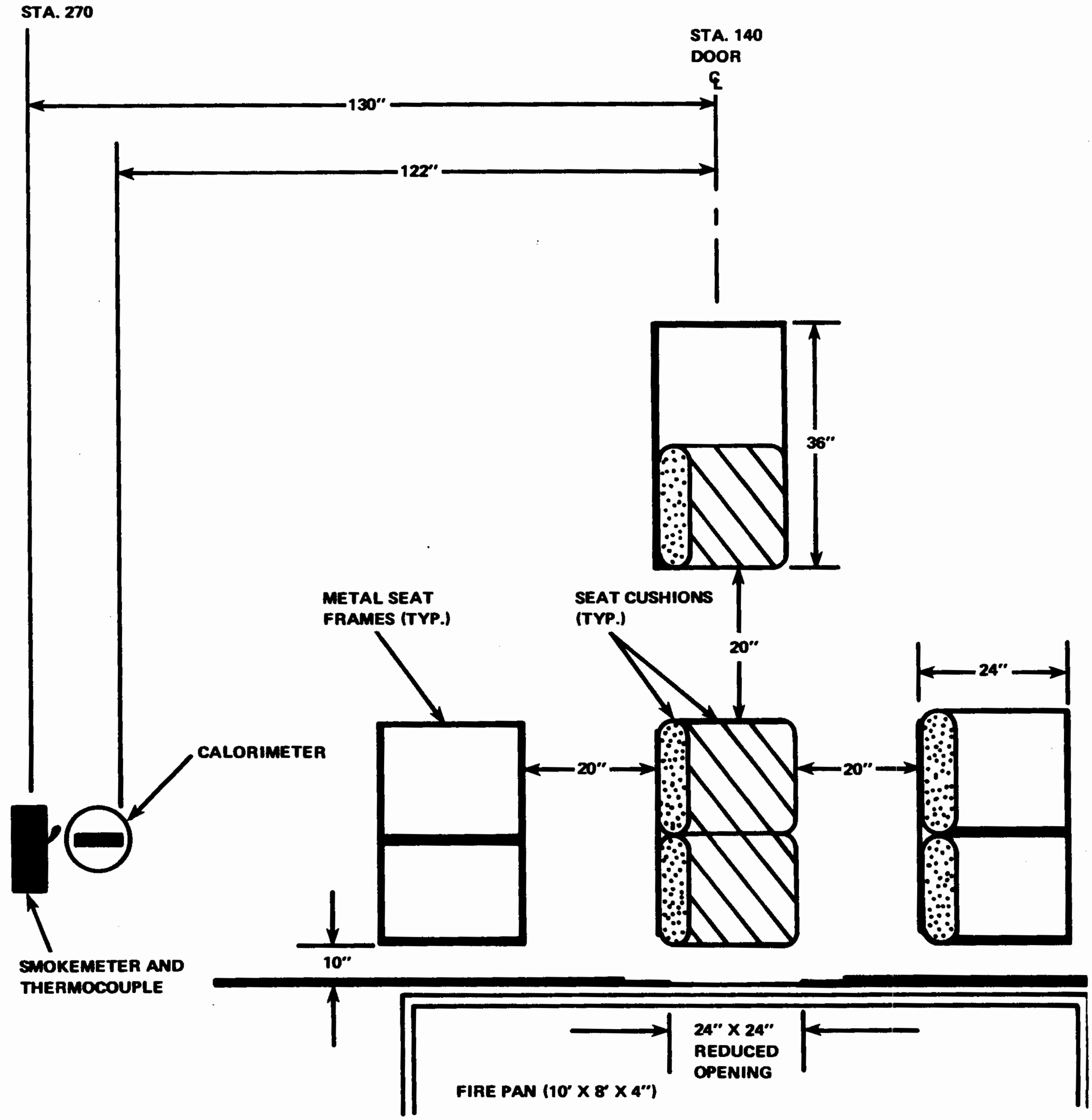


FIGURE 21. POST-CRASH SERIES FOUR CONFIGURATION

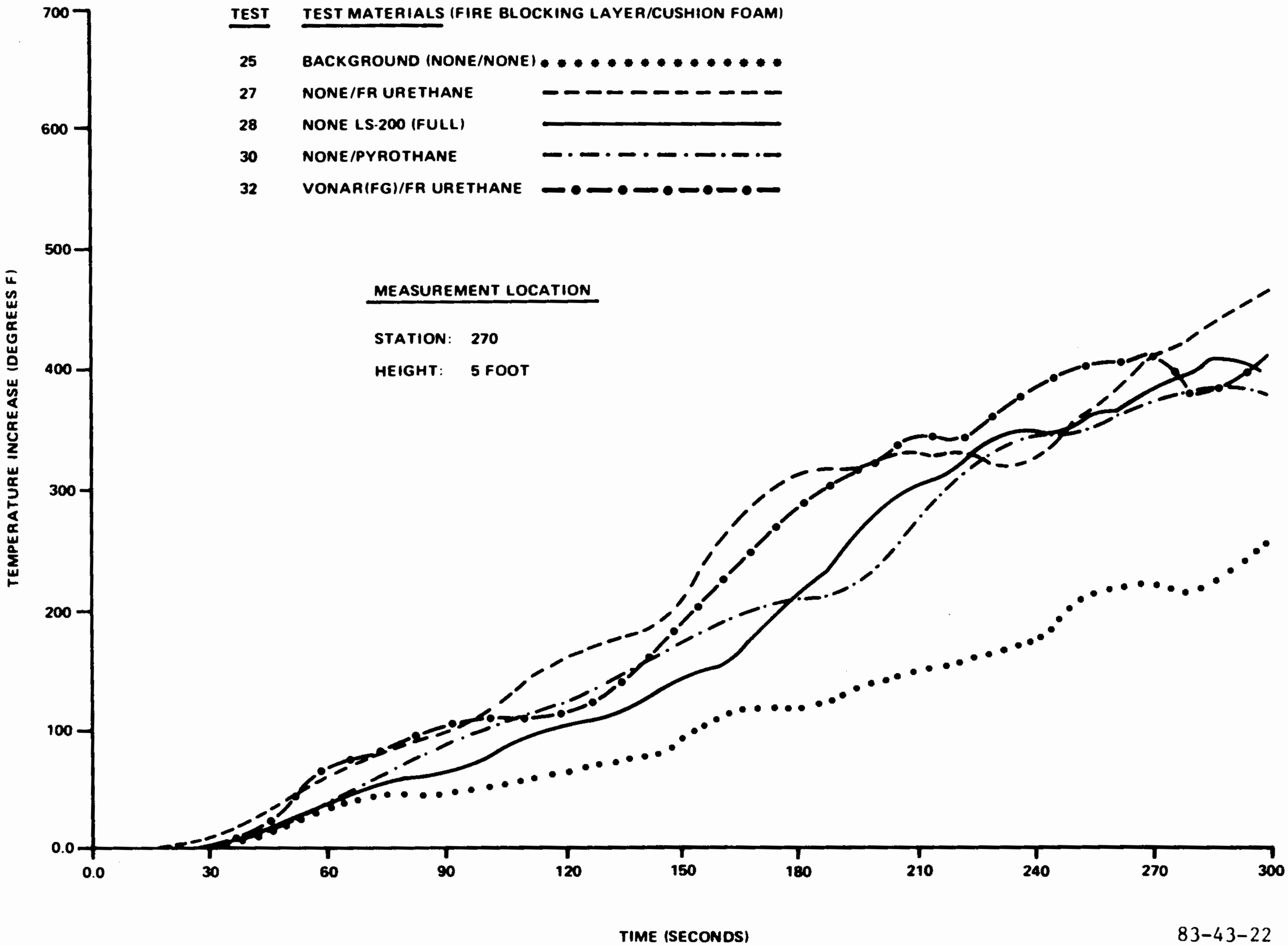


FIGURE 22. POST-CRASH SERIES FOUR TEMPERATURE COMPARISON

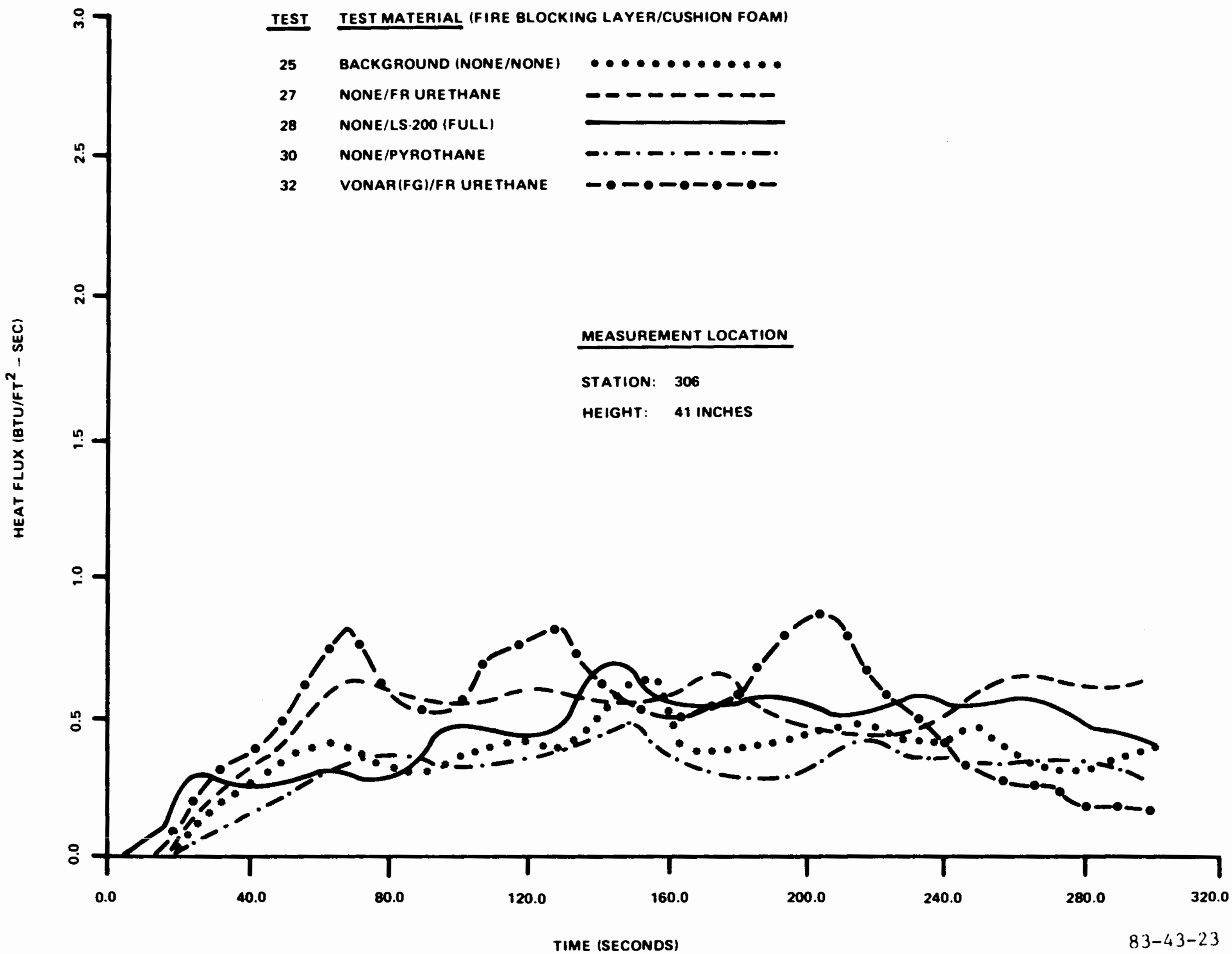


FIGURE 23. POST-CRASH SERIES FOUR HEAT FLUX COMPARISON

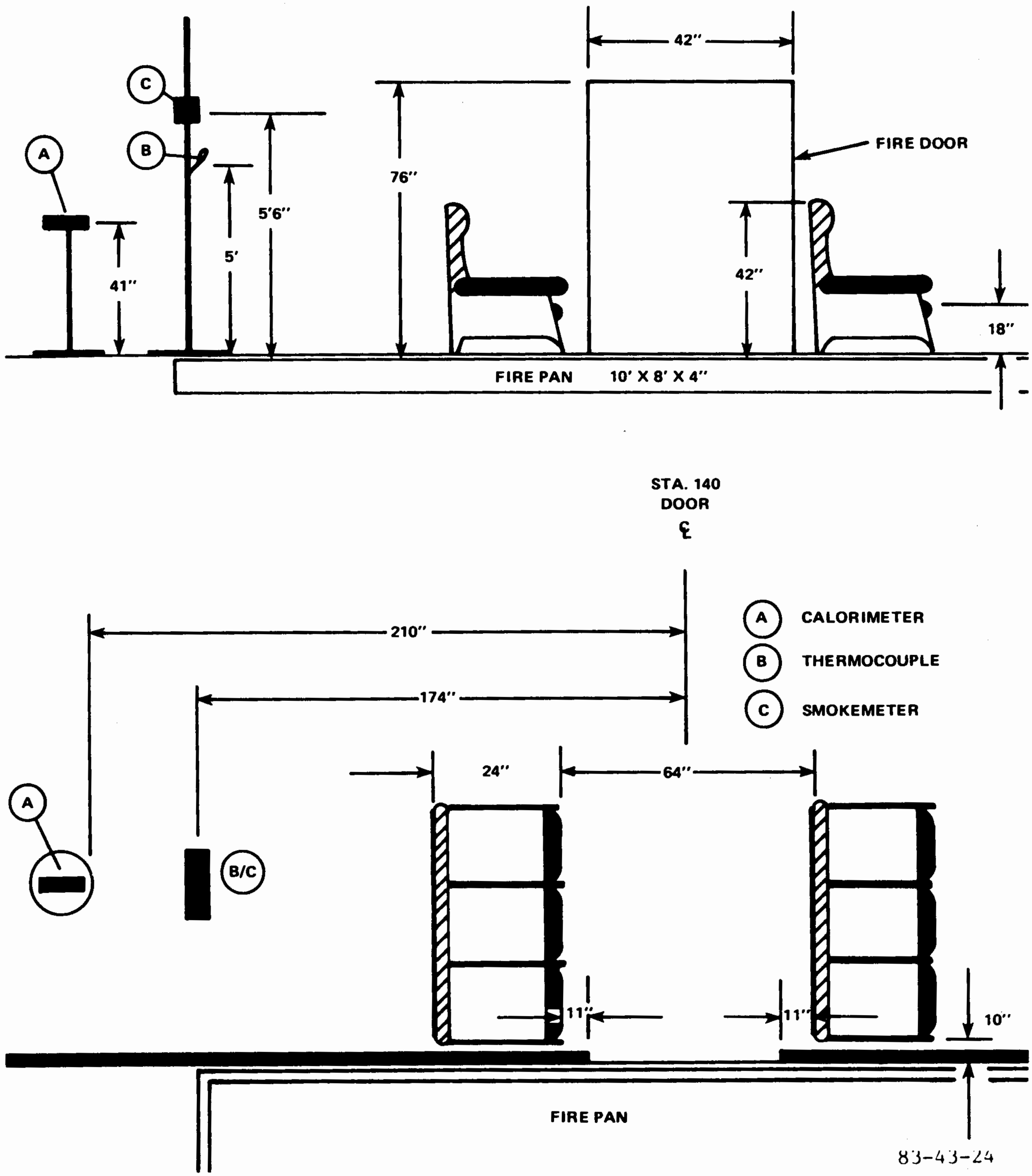


FIGURE 24. POST-CRASH SERIES FIVE CONFIGURATION

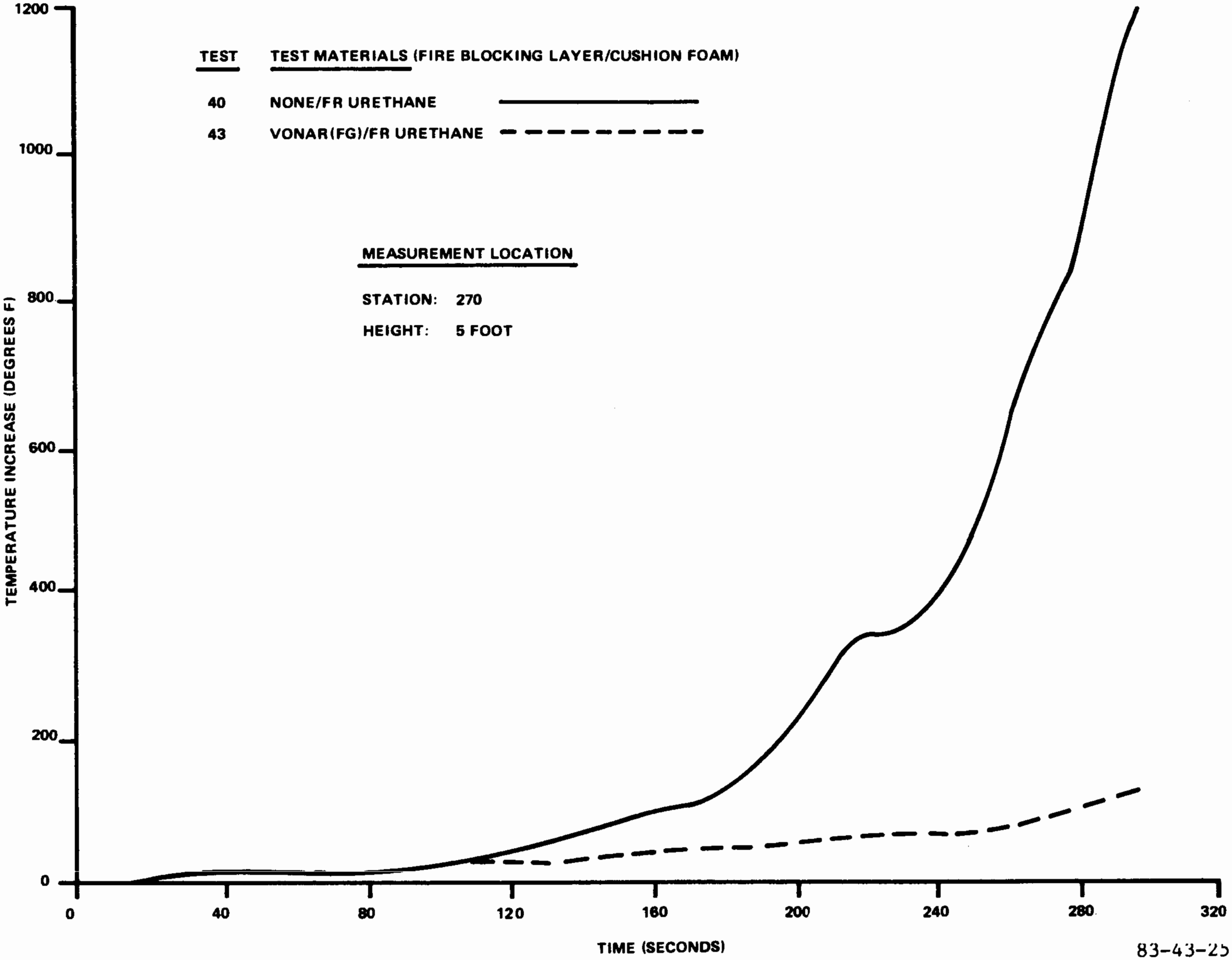


FIGURE 25. POST-CRASH SERIES FIVE TEMPERATURE COMPARISON

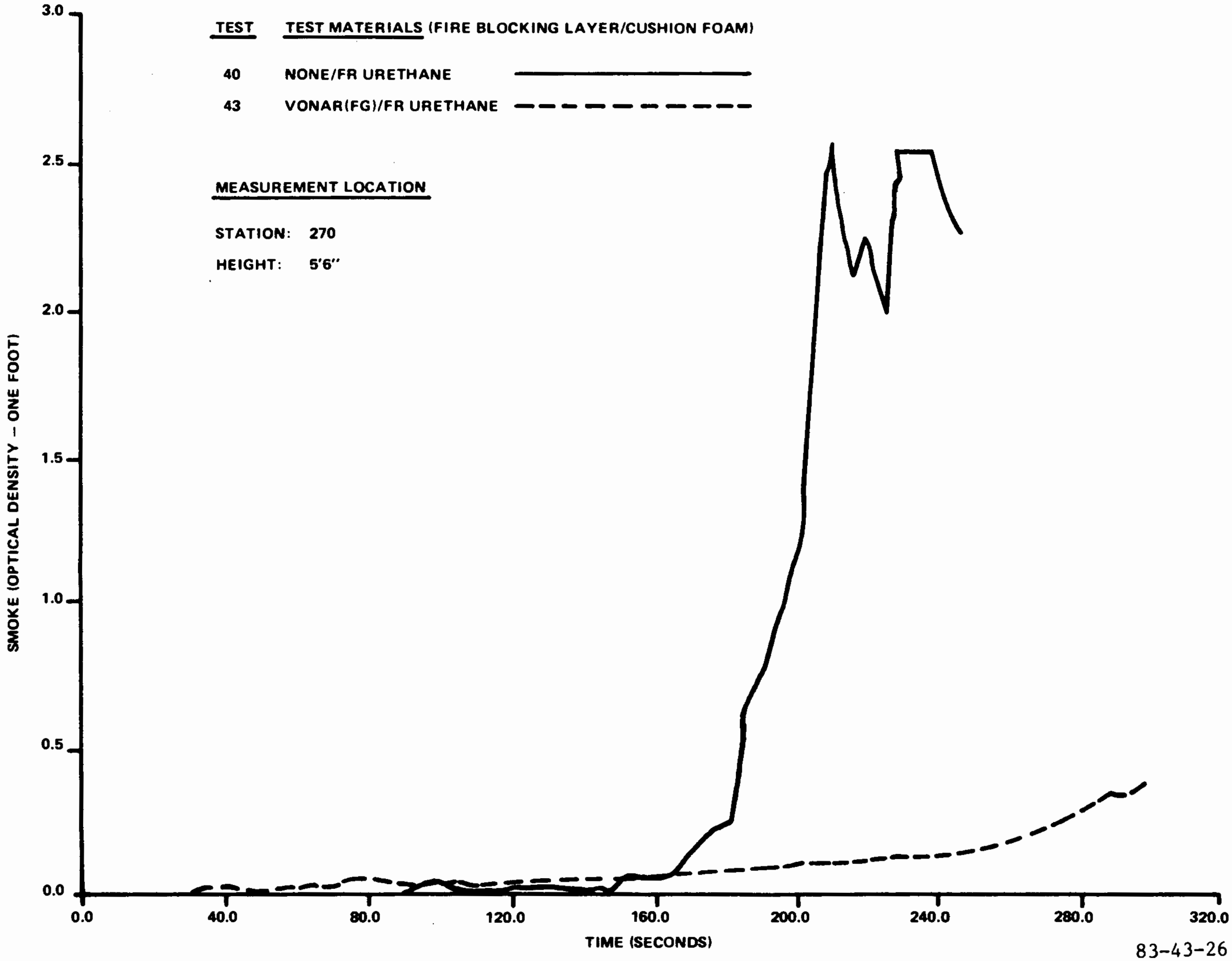


FIGURE 26. POST-CRASH SERIES FIVE SMOKE COMPARISON

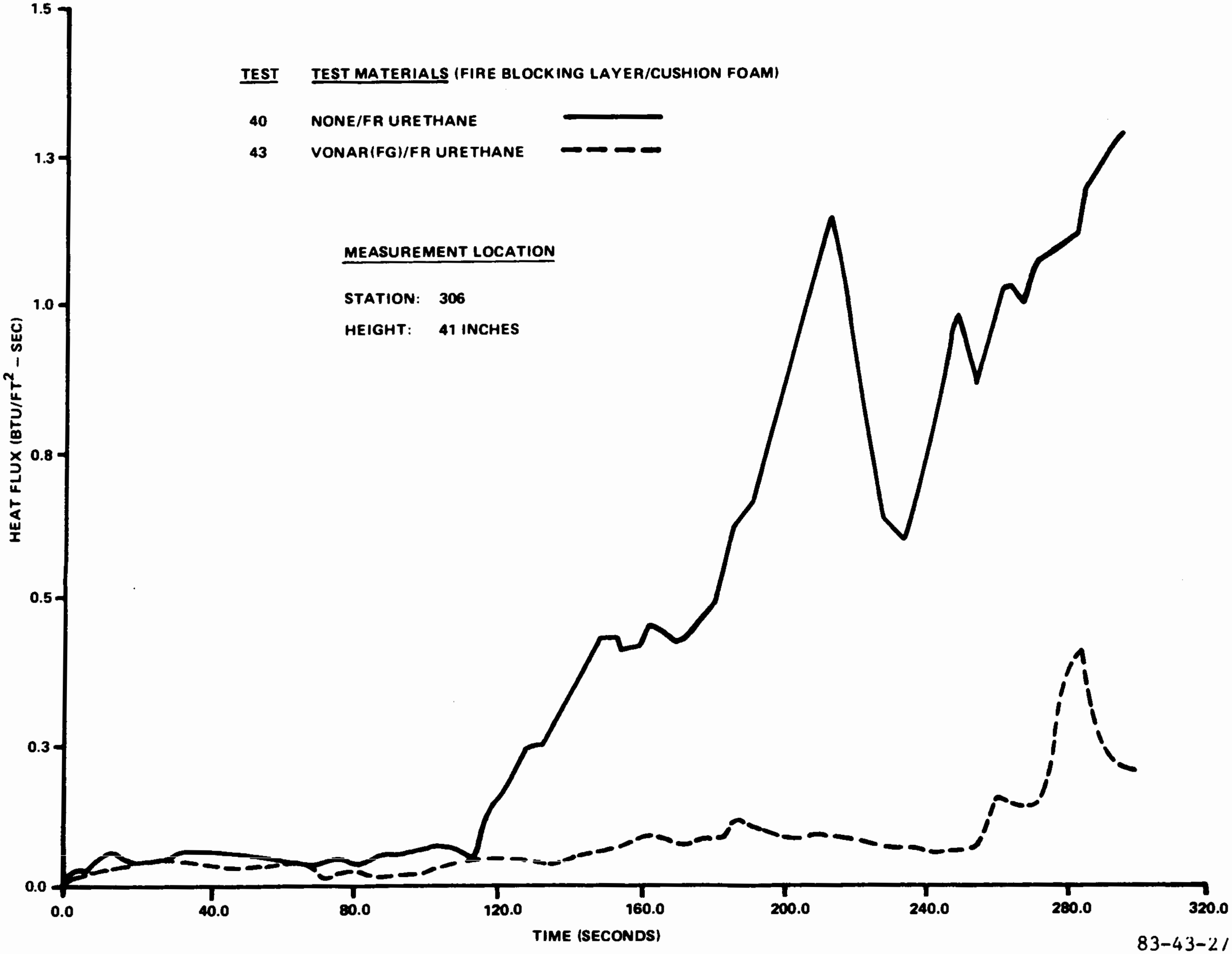
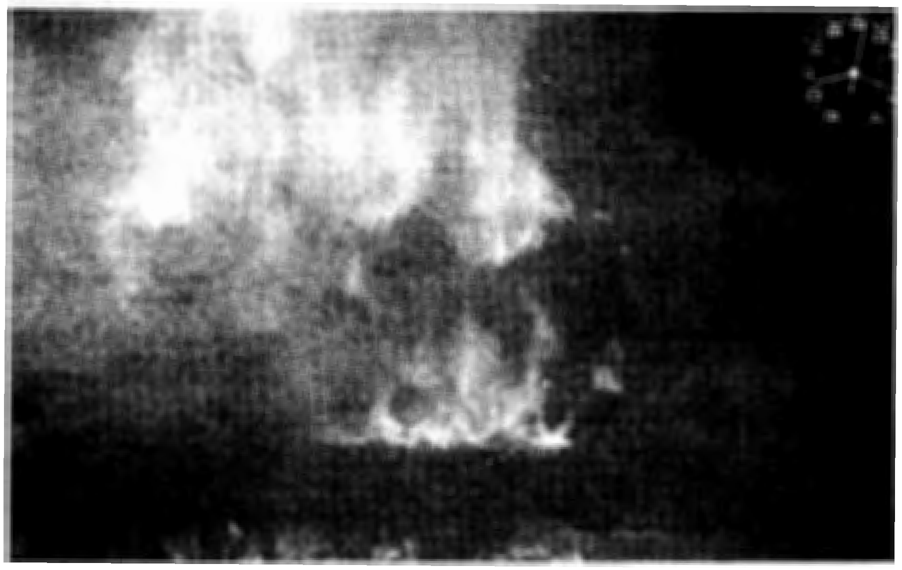
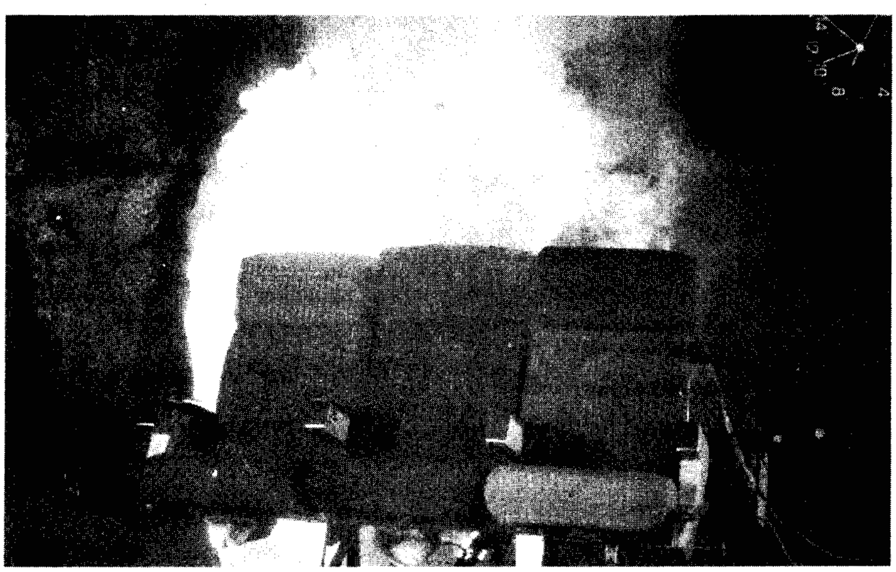


FIGURE 27. POST-CRASH SERIES FIVE HEAT FLUX COMPARISON



Test 40
2 min. 50 sec.



Test 43
4 min.

FIGURE 28. PICTORIAL COMPARISON OF POST-CRASH SERIES FIVE TESTS

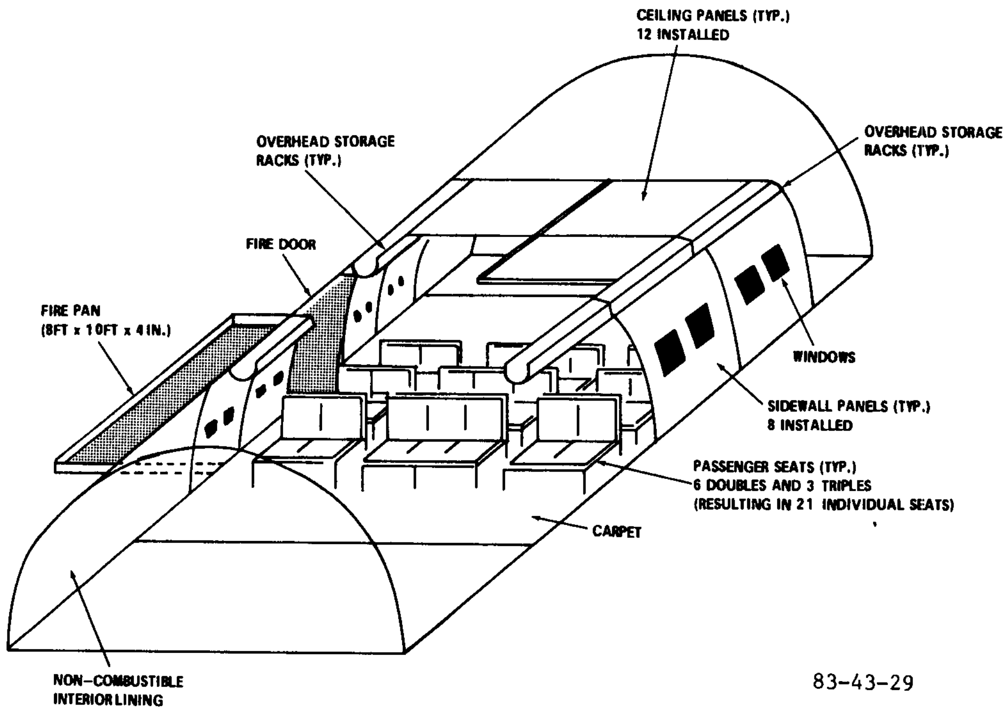


FIGURE 29. INSTALLATION OF WIDE-BODY MATERIALS INSIDE C-133 TEST ARTICLE

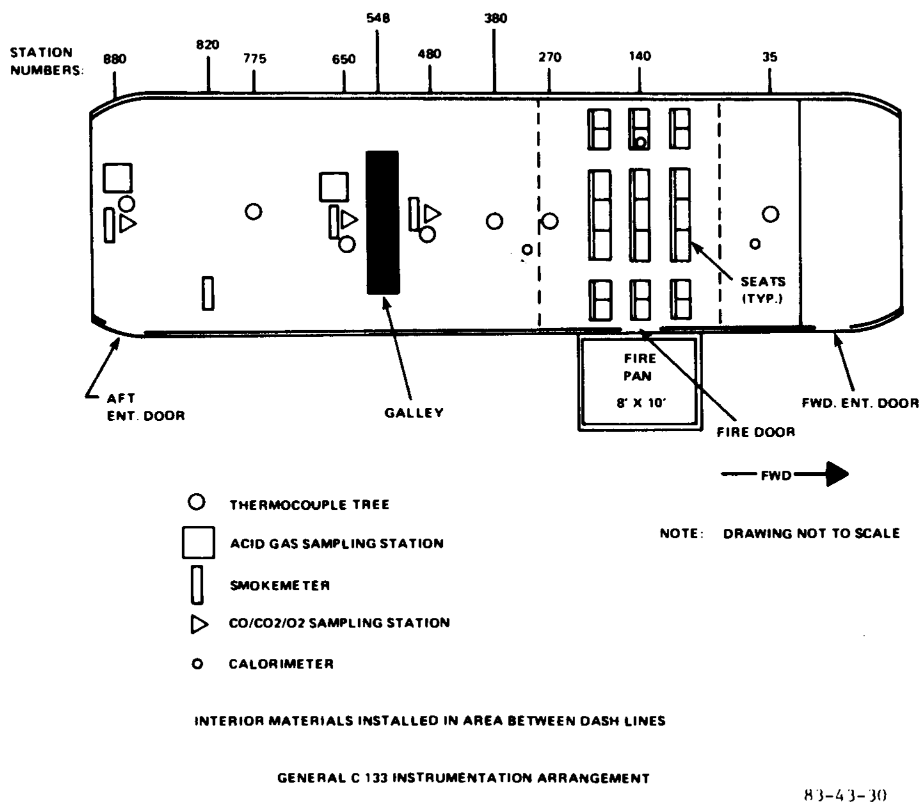


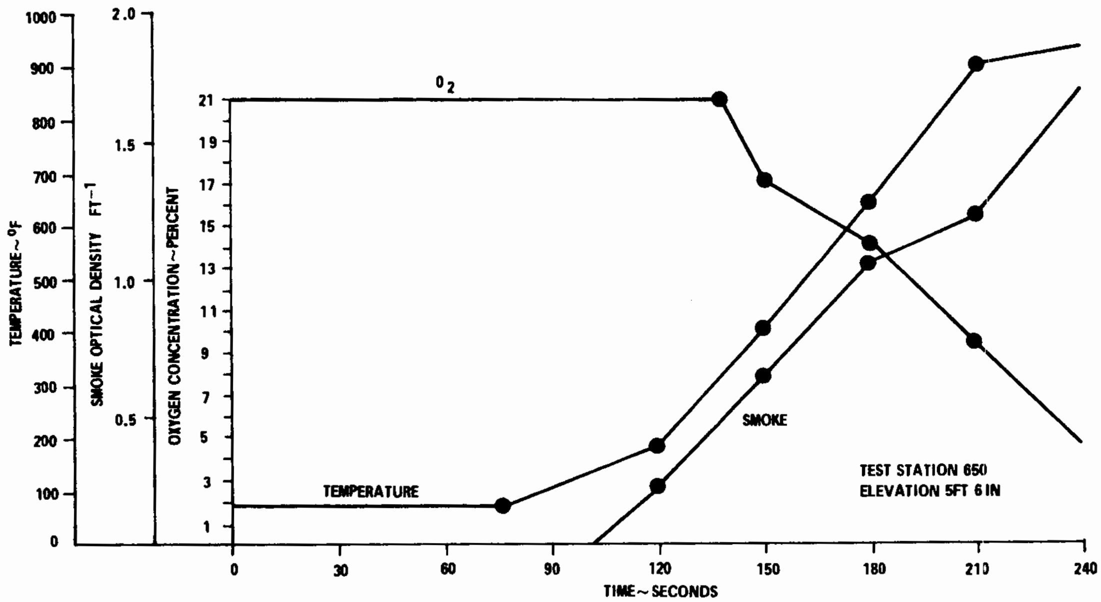
FIGURE 30. POST-CRASH SERIES SIX CONFIGURATION

(a) Time "Zero"

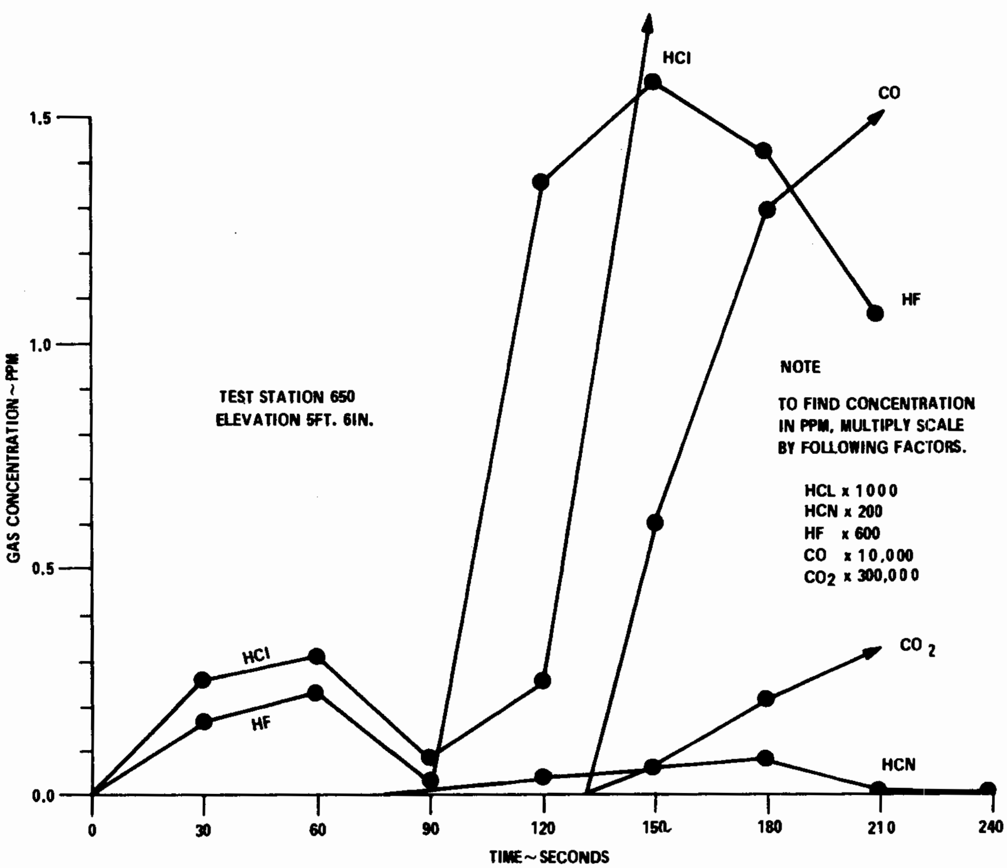
(b) Time "Zero + 5 Seconds"

(c) Time "Zero + 10 Seconds"

FIGURE 31. PHOTOGRAPHIC DOCUMENTATION OF FLASHOVER



(a)



(b)

FIGURE 32. HAZARDS IN AFT CABIN PRODUCED BY BURNING INTERIOR MATERIALS

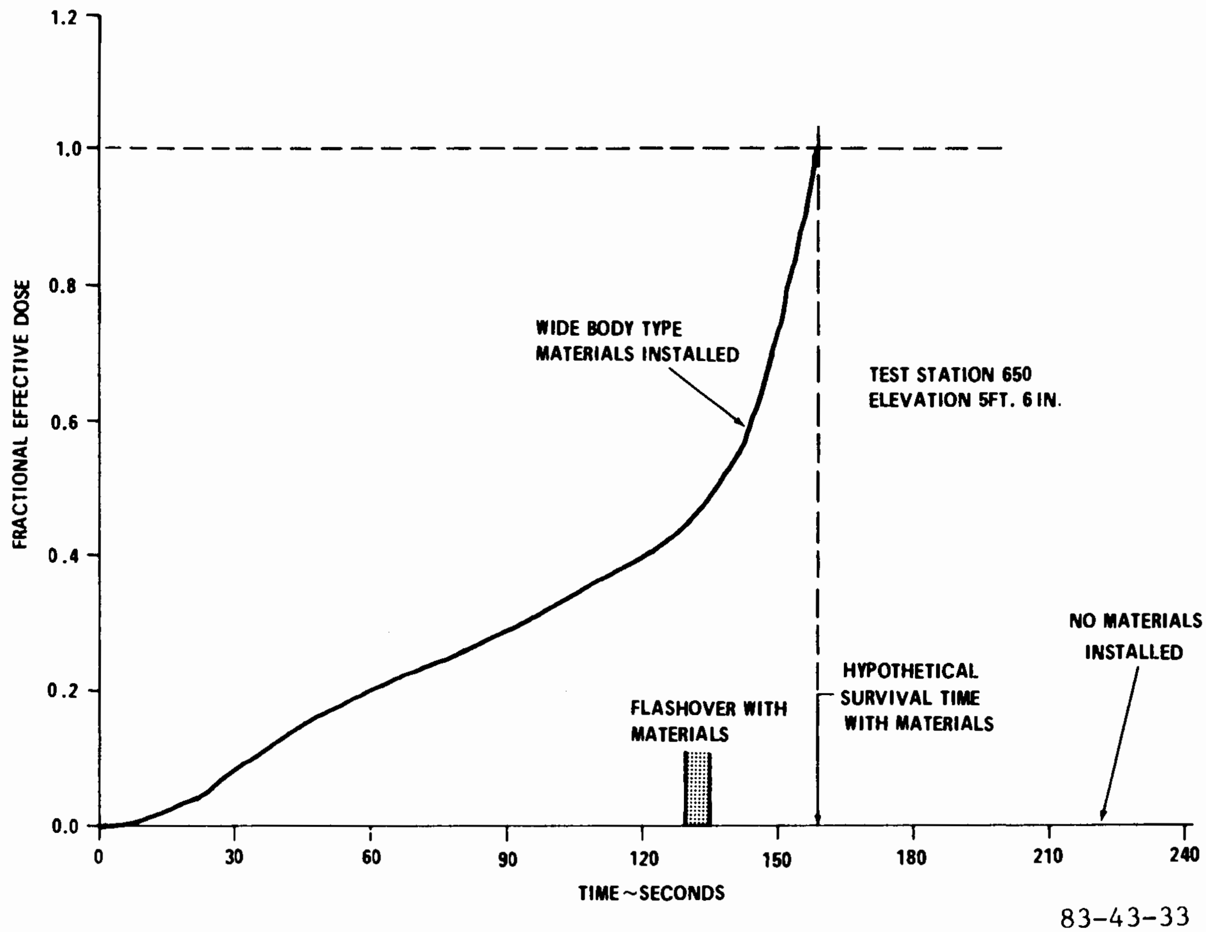
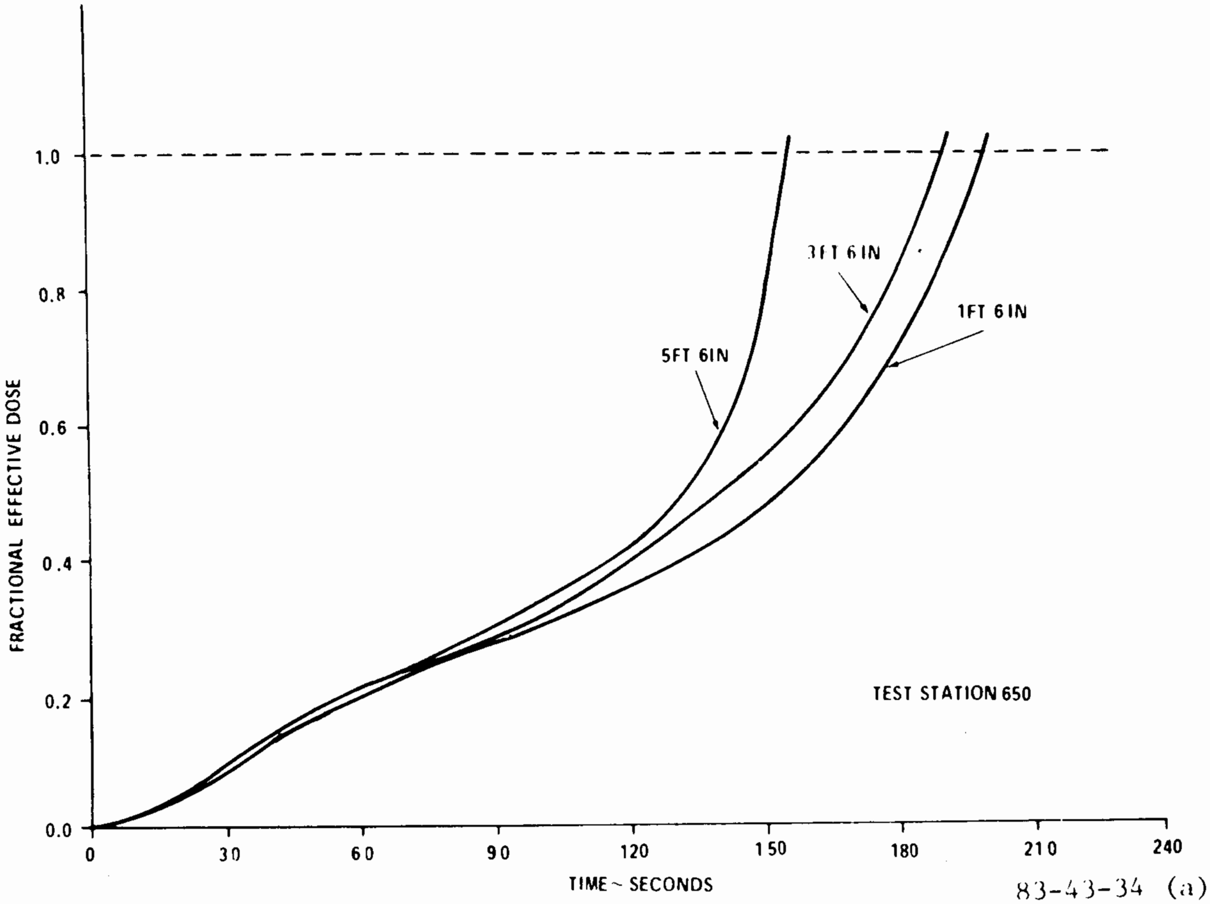
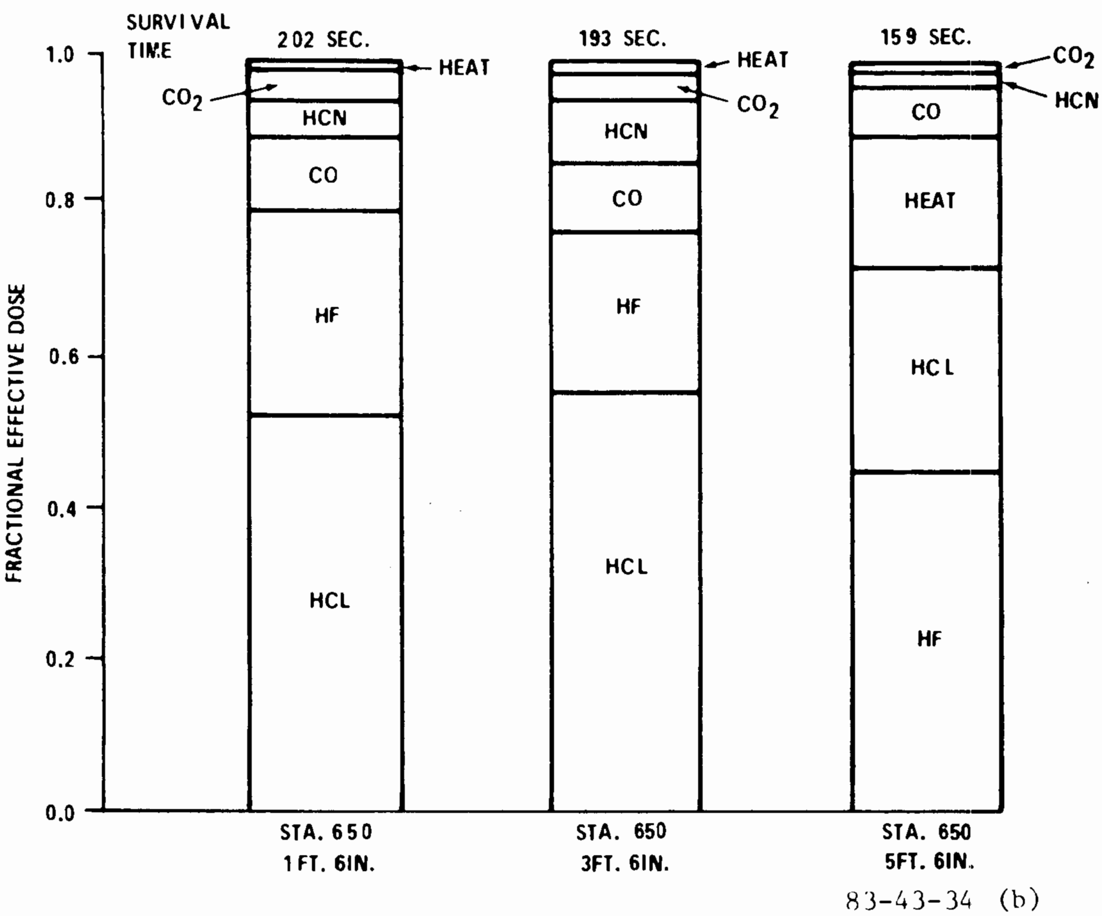


FIGURE 33. HYPOTHETICAL SURVIVAL CURVE IN AFT CABIN



(a)



(b)

FIGURE 34. EFFECT OF ELEVATION ON SURVIVABILITY IN AFT CABIN

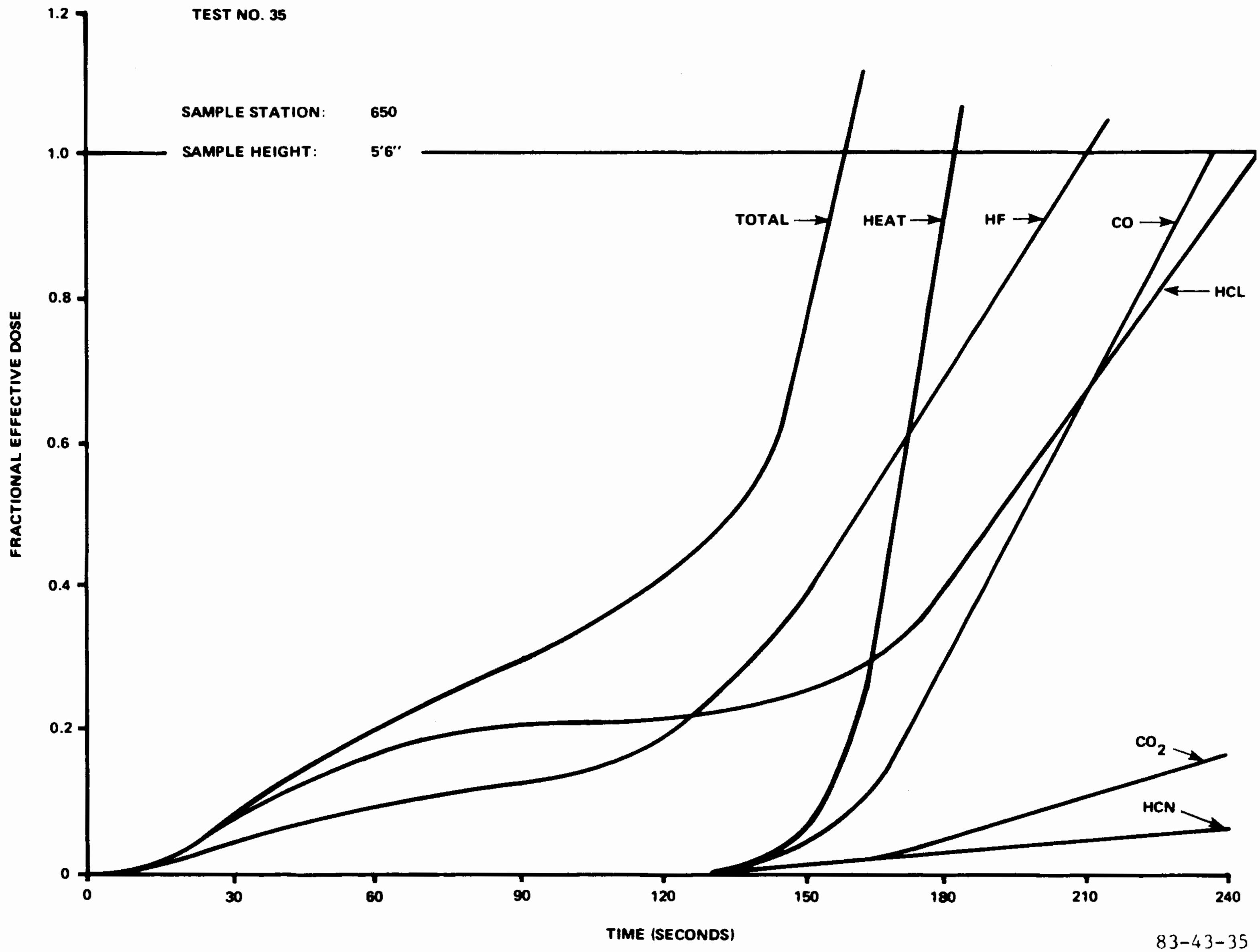


FIGURE 35. FRACTIONAL EFFECTIVE DOSE PLOT FOR TEST NUMBER 35 (ALL HAZARDS)

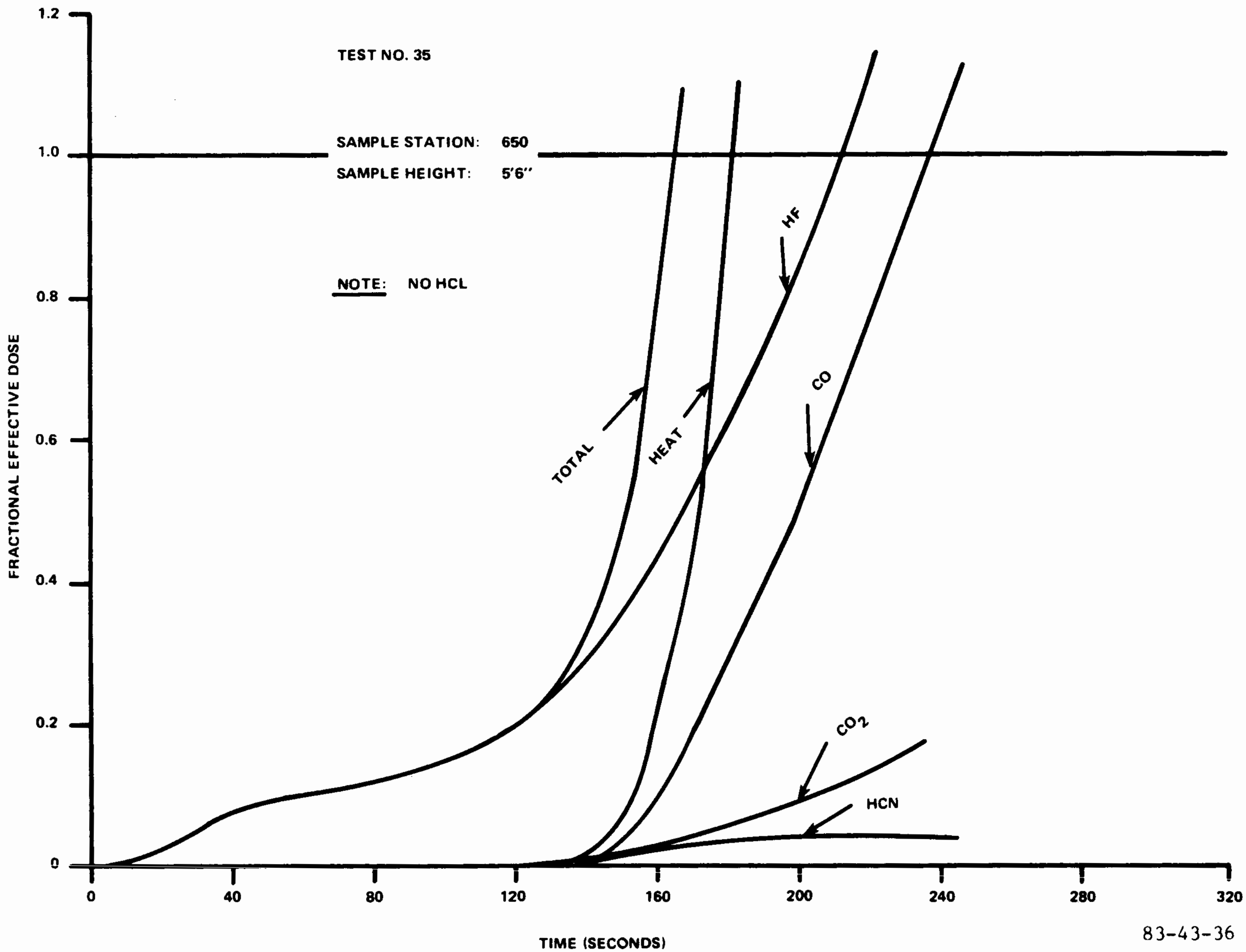


FIGURE 36. FRACTIONAL EFFECTIVE DOSE PLOT FOR TEST NUMBER 35 (NO HCl)

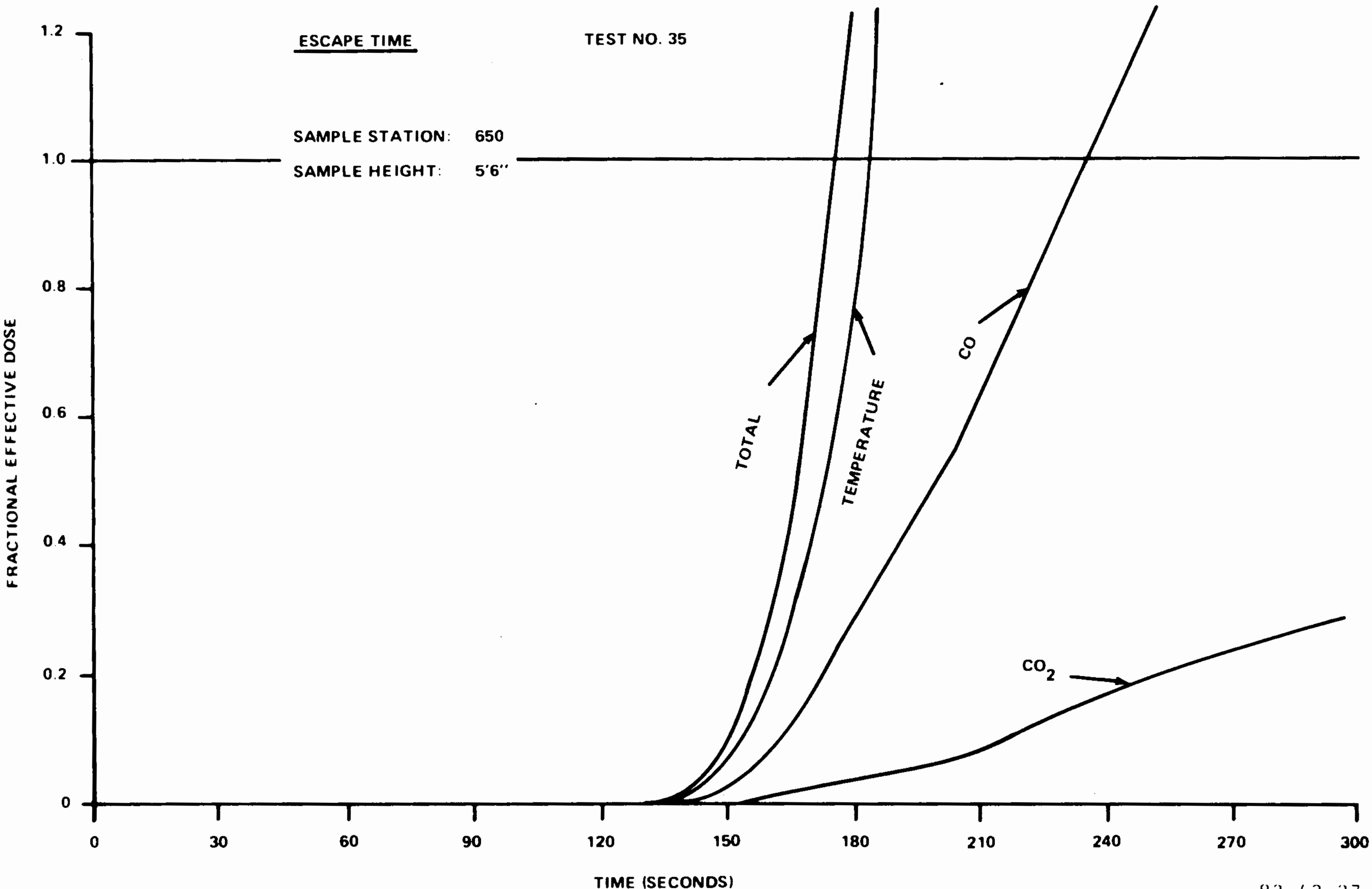


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FIGURE 37. FRACTIONAL EFFECTIVE DOSE PLOT FOR TEST NUMBER 35 (NO HCl, HF, HCN)

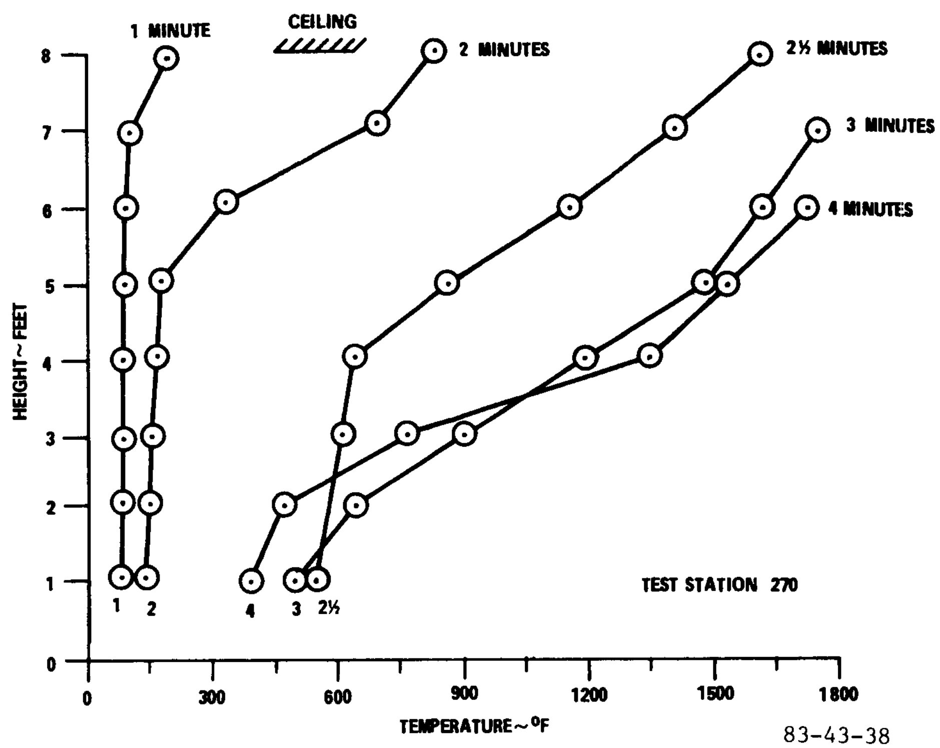

FIGURE 38. HEAT STRATIFICATION IN FORWARD CABIN

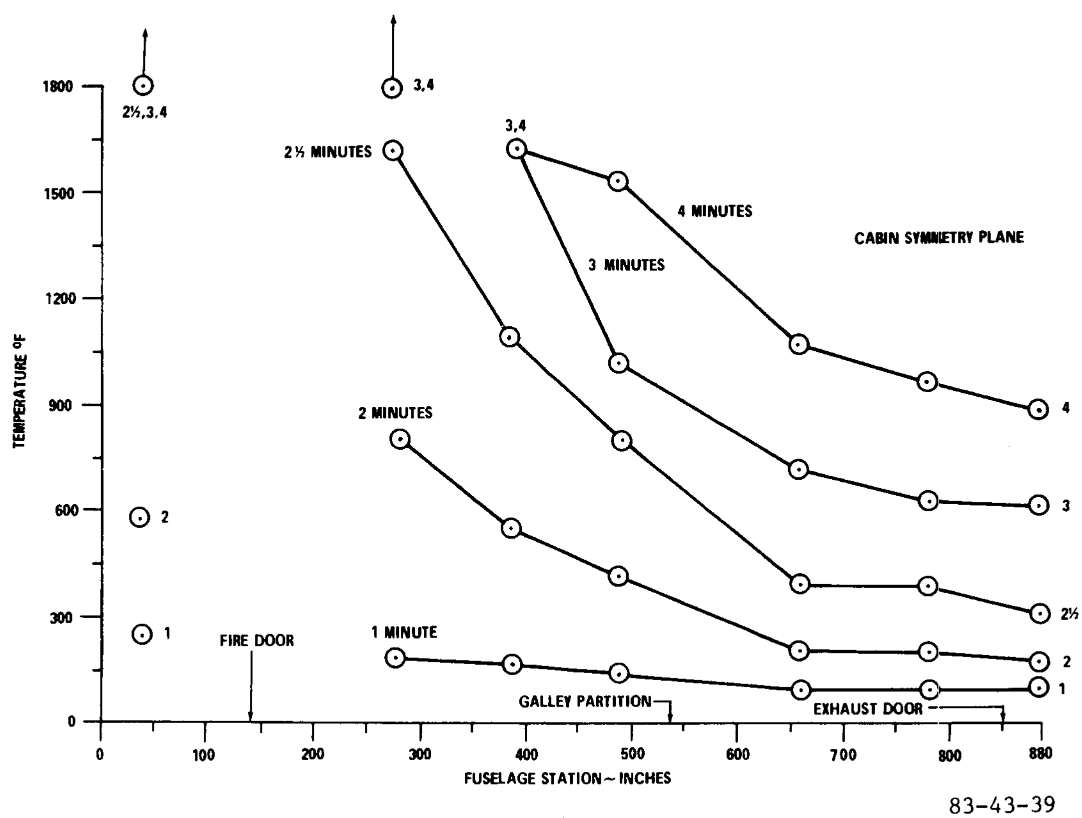

FIGURE 39. LONGITUDINAL TEMPERATURE PROFILE AT CEILING

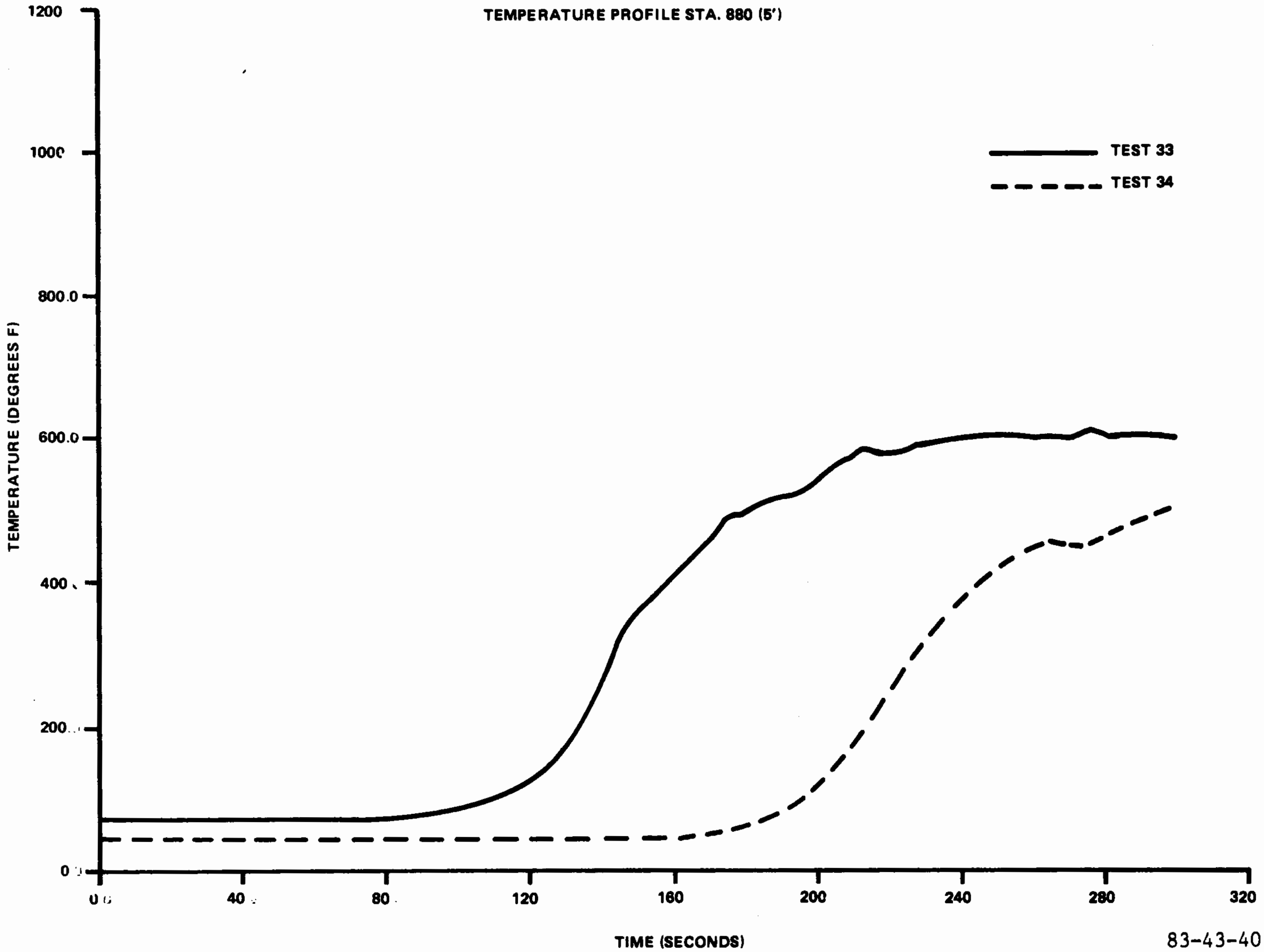

FIGURE 40. TEMPERATURE COMPARISON OF FULL-SCALE TESTS WITH AND WITHOUT WIND

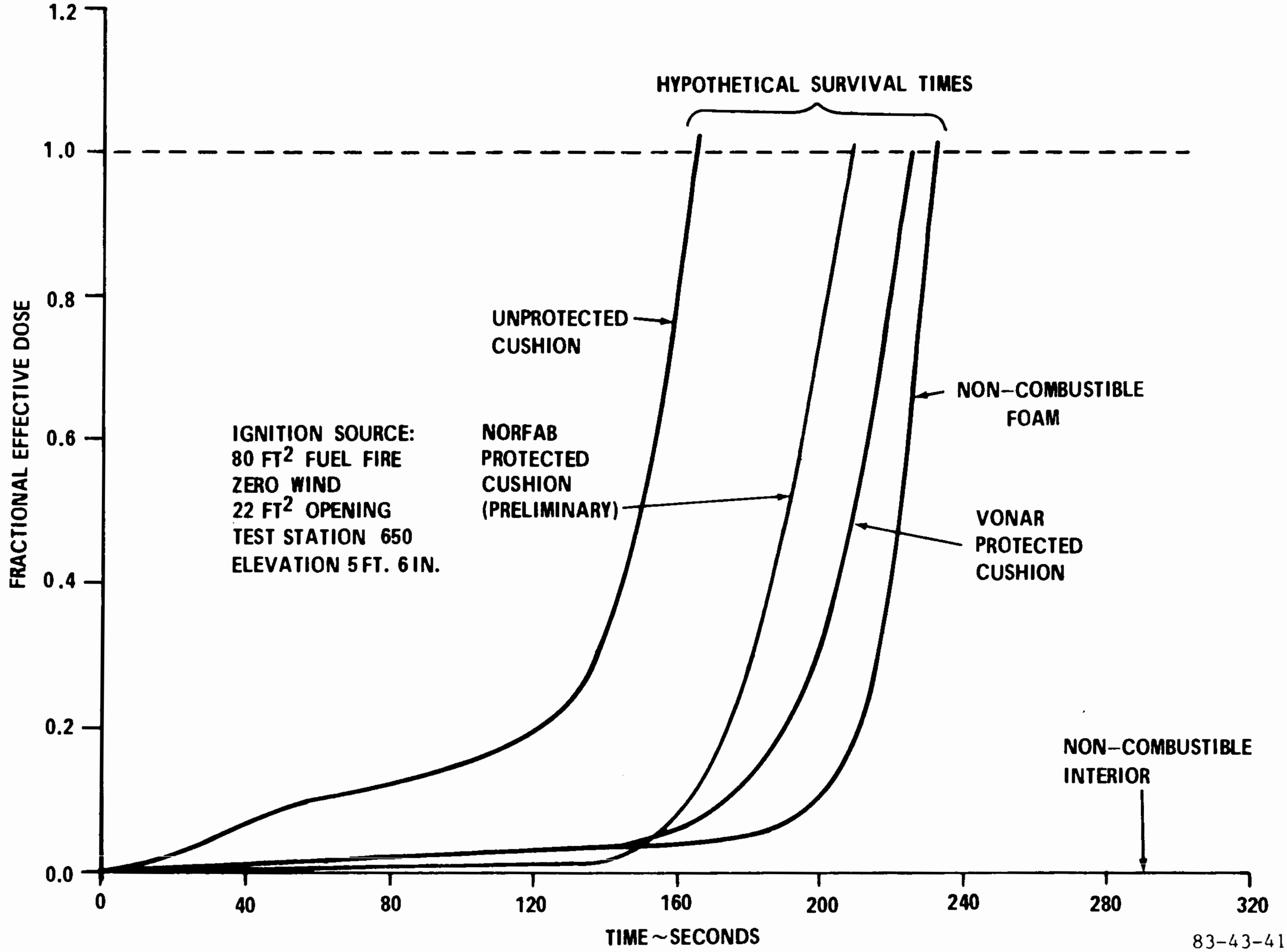

FIGURE 41. EFFECT OF CUSHIONING PROTECTION ON CALCULATED SURVIVAL TIME UNDER FULL-SCALE POST-CRASH FIRE CONDITIONS

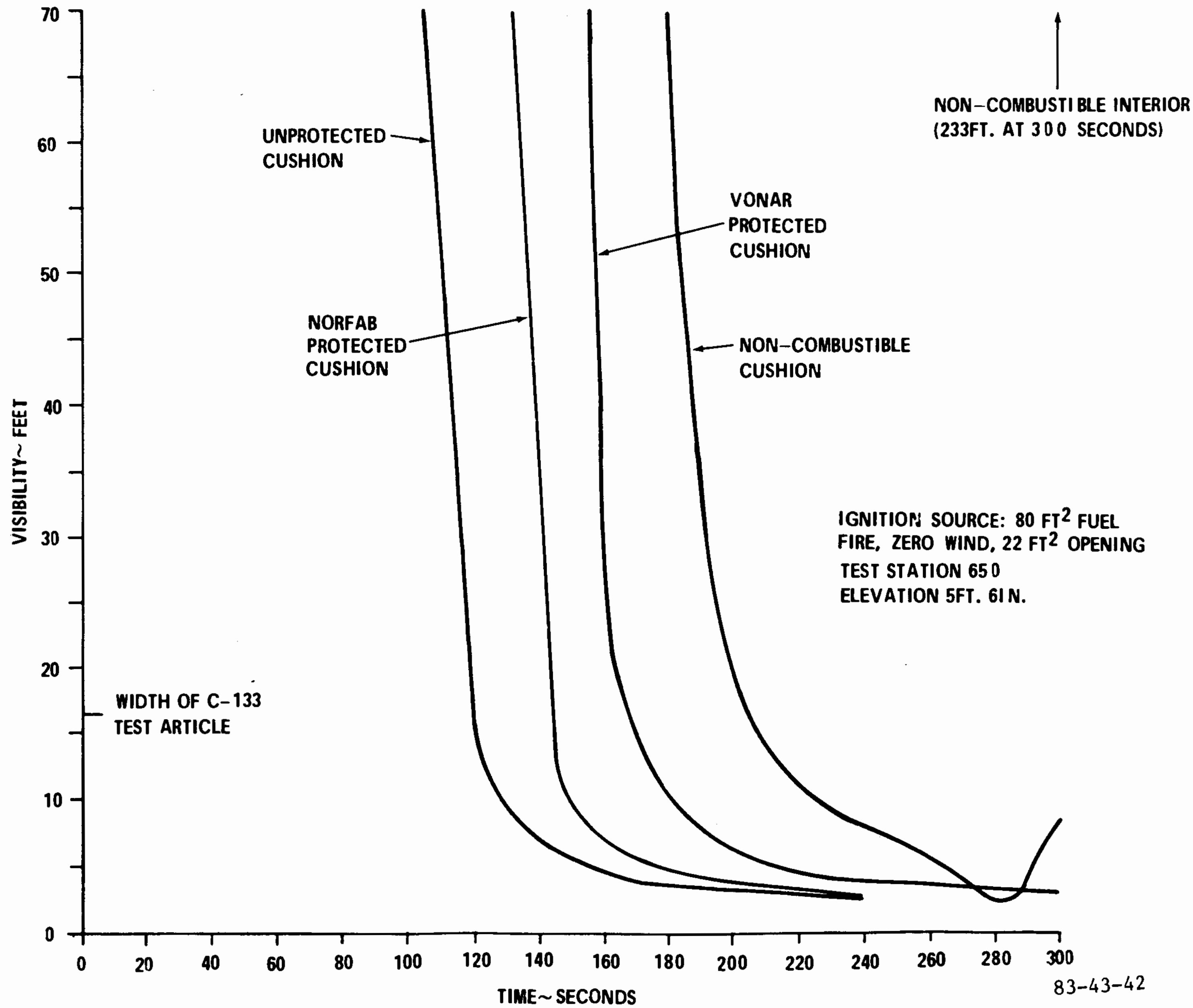

FIGURE 42. EFFECT OF CUSHIONING PROTECTION ON CALCULATED VISIBILITY THROUGH SMOKE UNDER FULL-SCALE POST-CRASH FIRE CONDITIONS

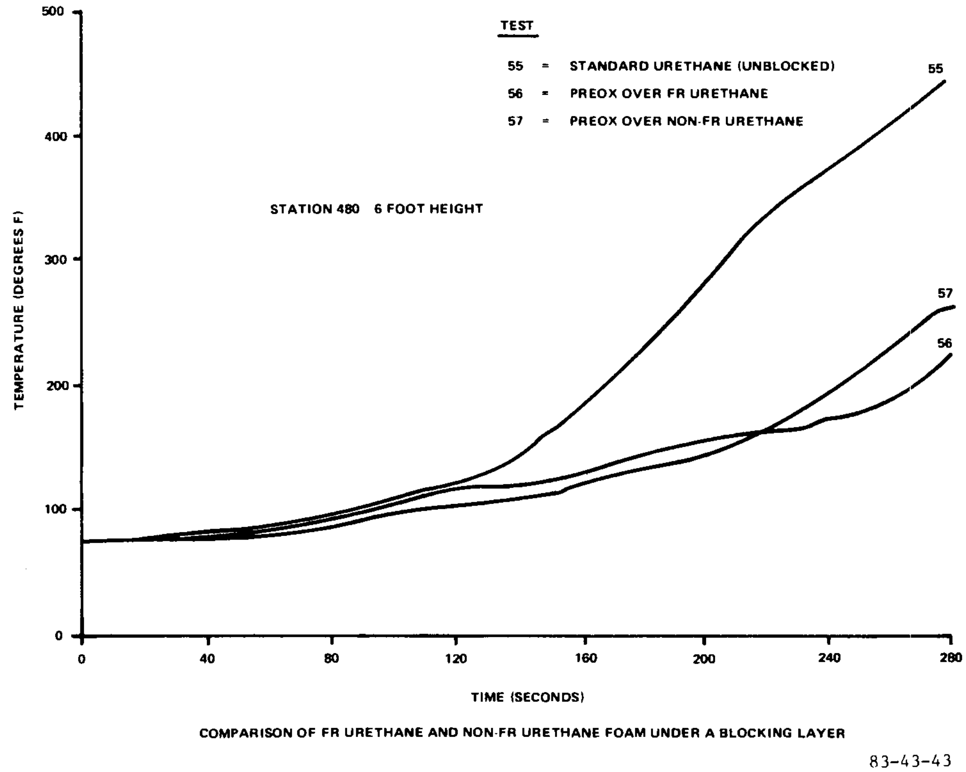

FIGURE 43. COMPARISON OF FR URETHANE AND NON-FR URETHANE FOAM UNDER A BLOCKING LAYER

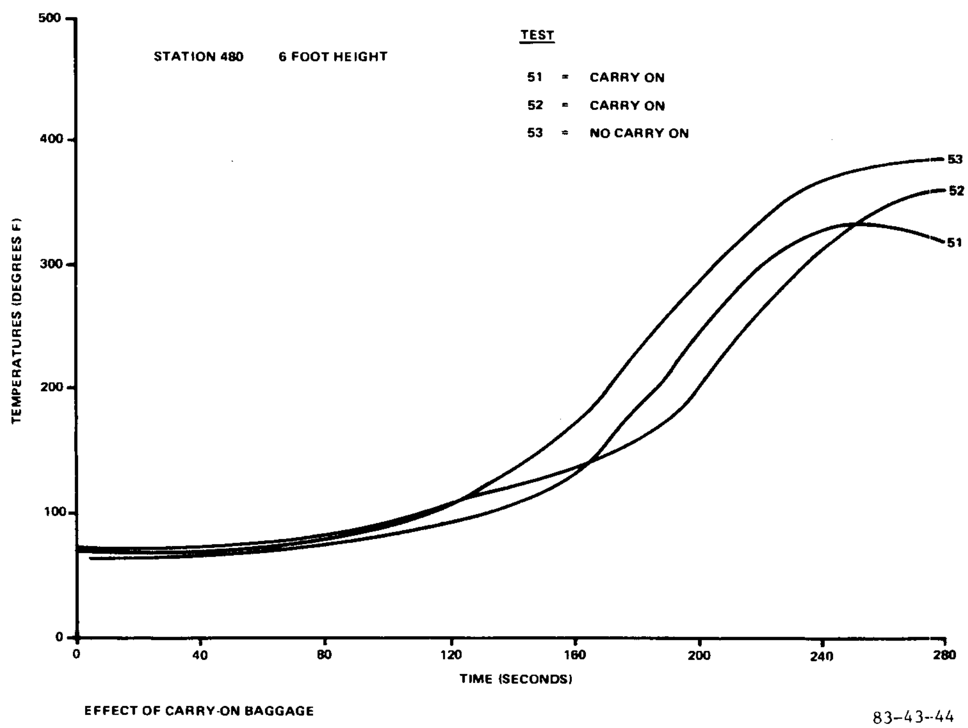

FIGURE 44. EFFECT OF CARRY-ON BAGGAGE

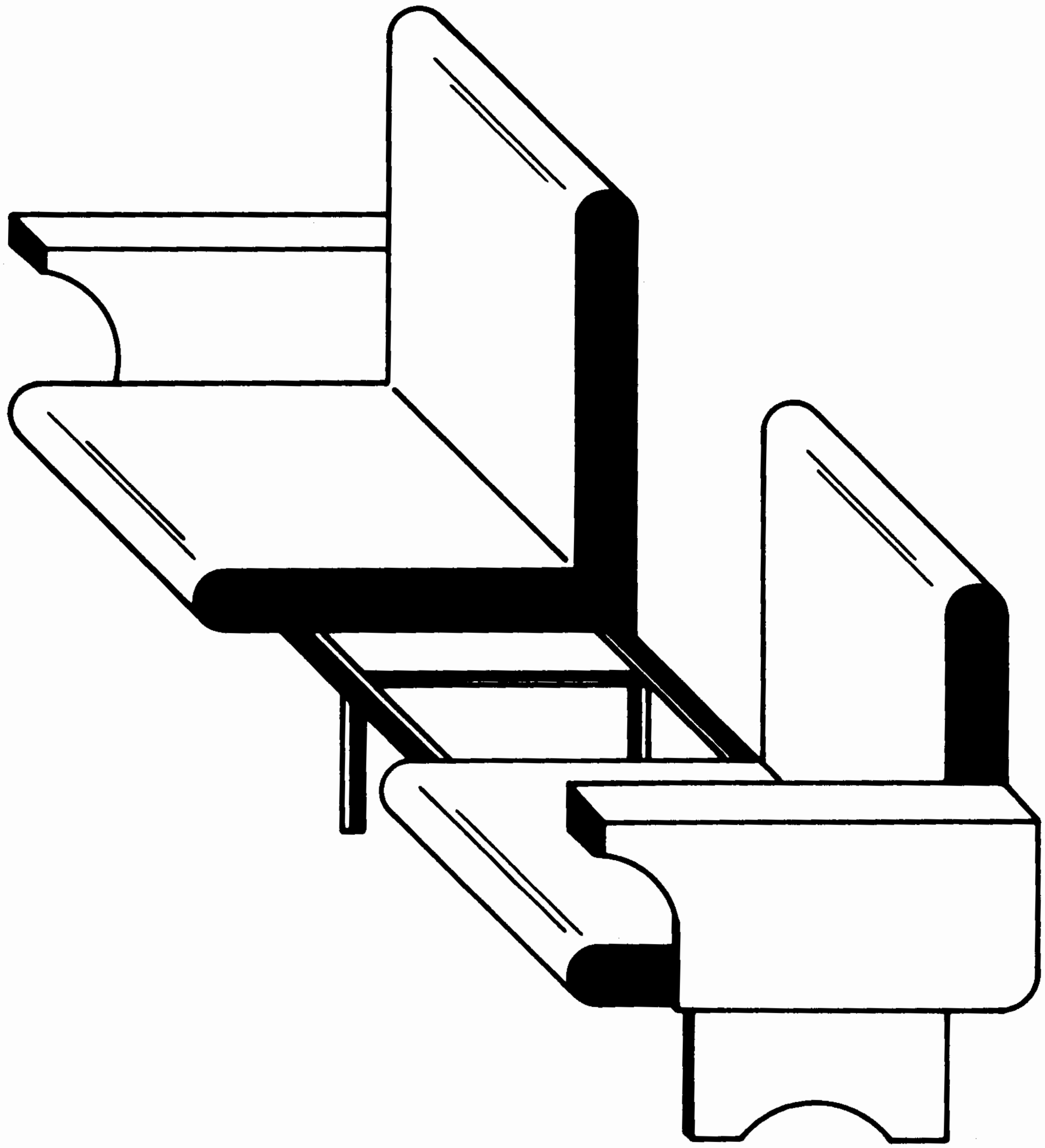

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FIGURE 45. SEAT CONFIGURATION FOR SMALL IGNITION TESTS

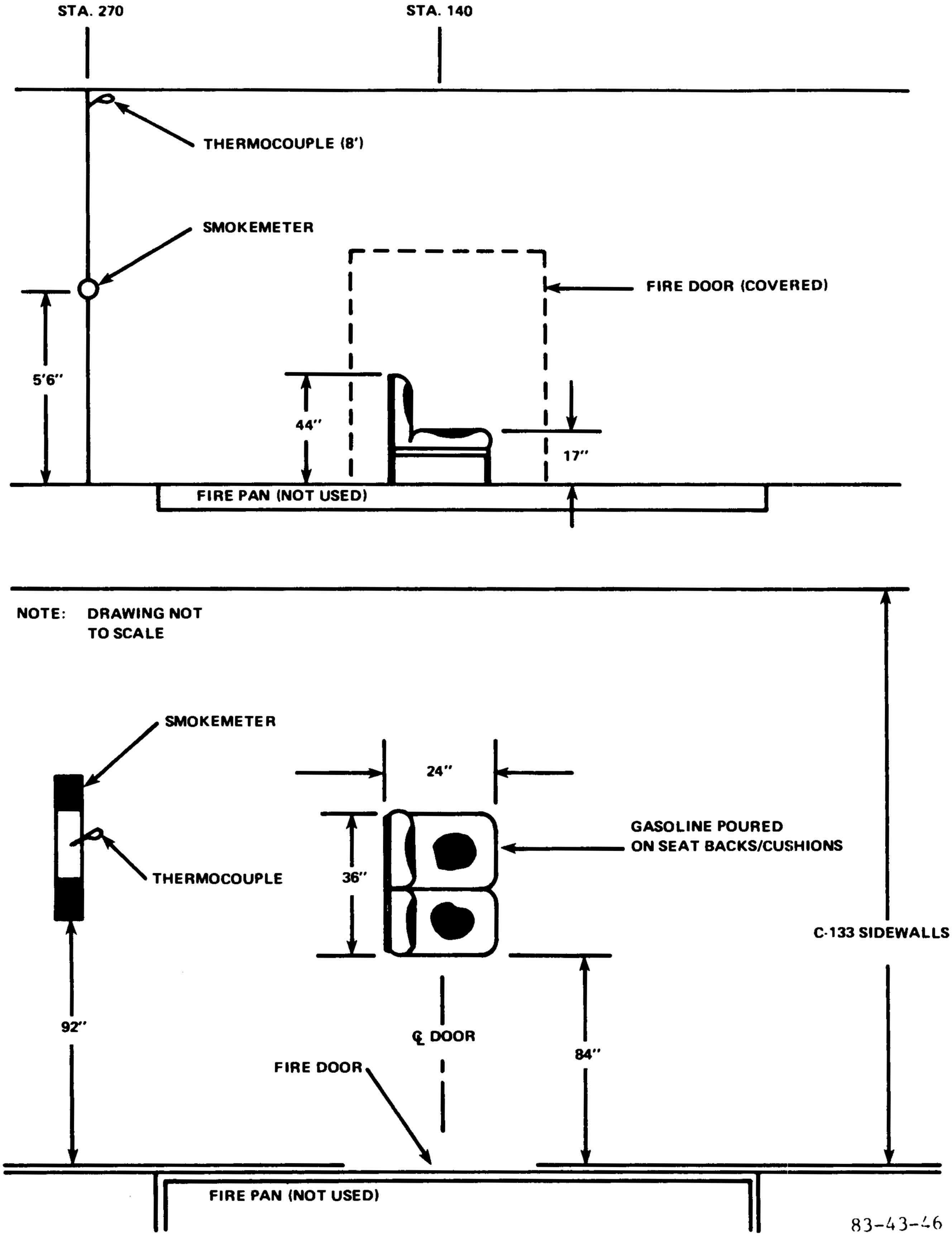

FIGURE 46. IN-FLIGHT GASOLINE TEST CONFIGURATIONS

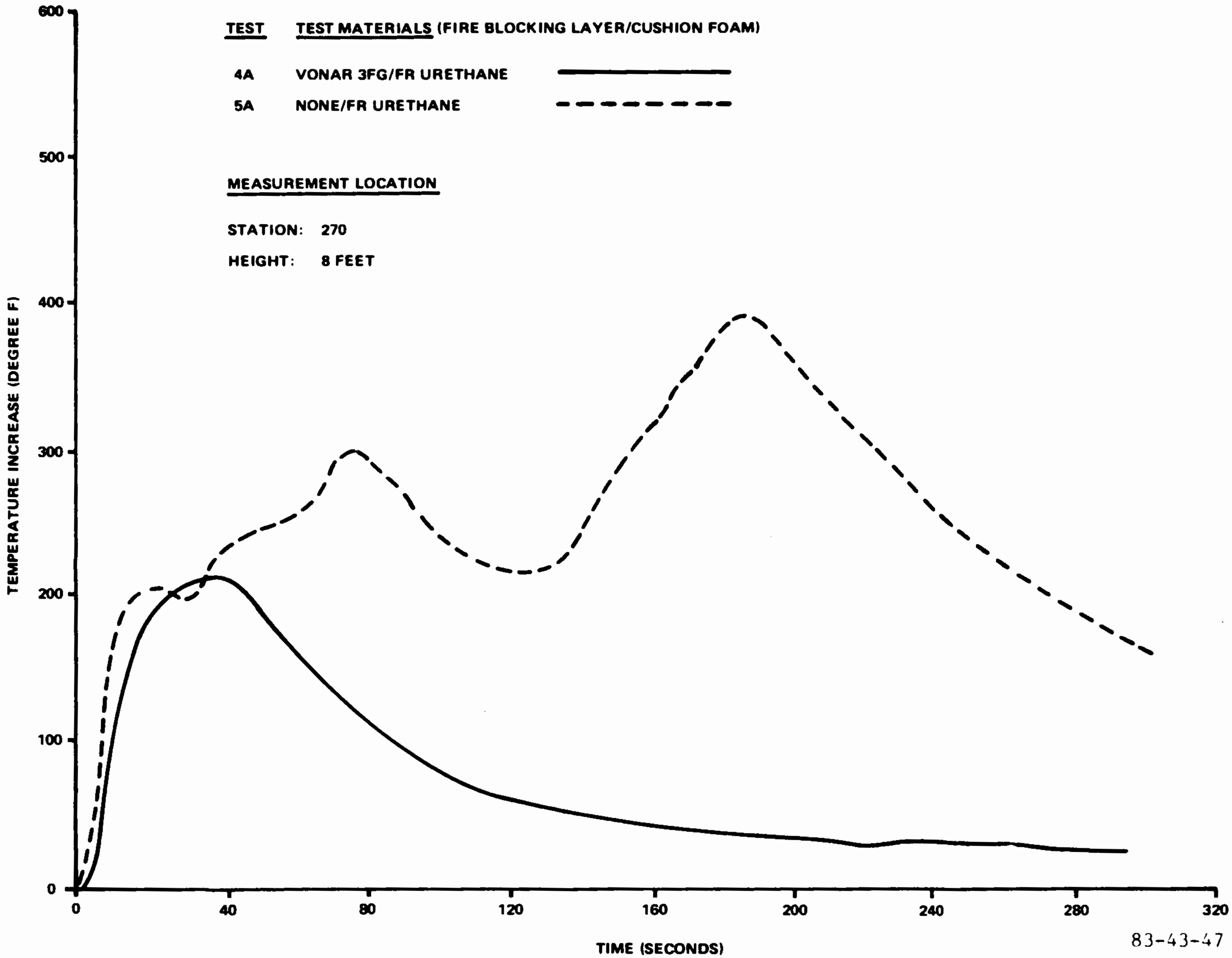

FIGURE 47. IN-FLIGHT GASOLINE TEST TEMPERATURE COMPARISON

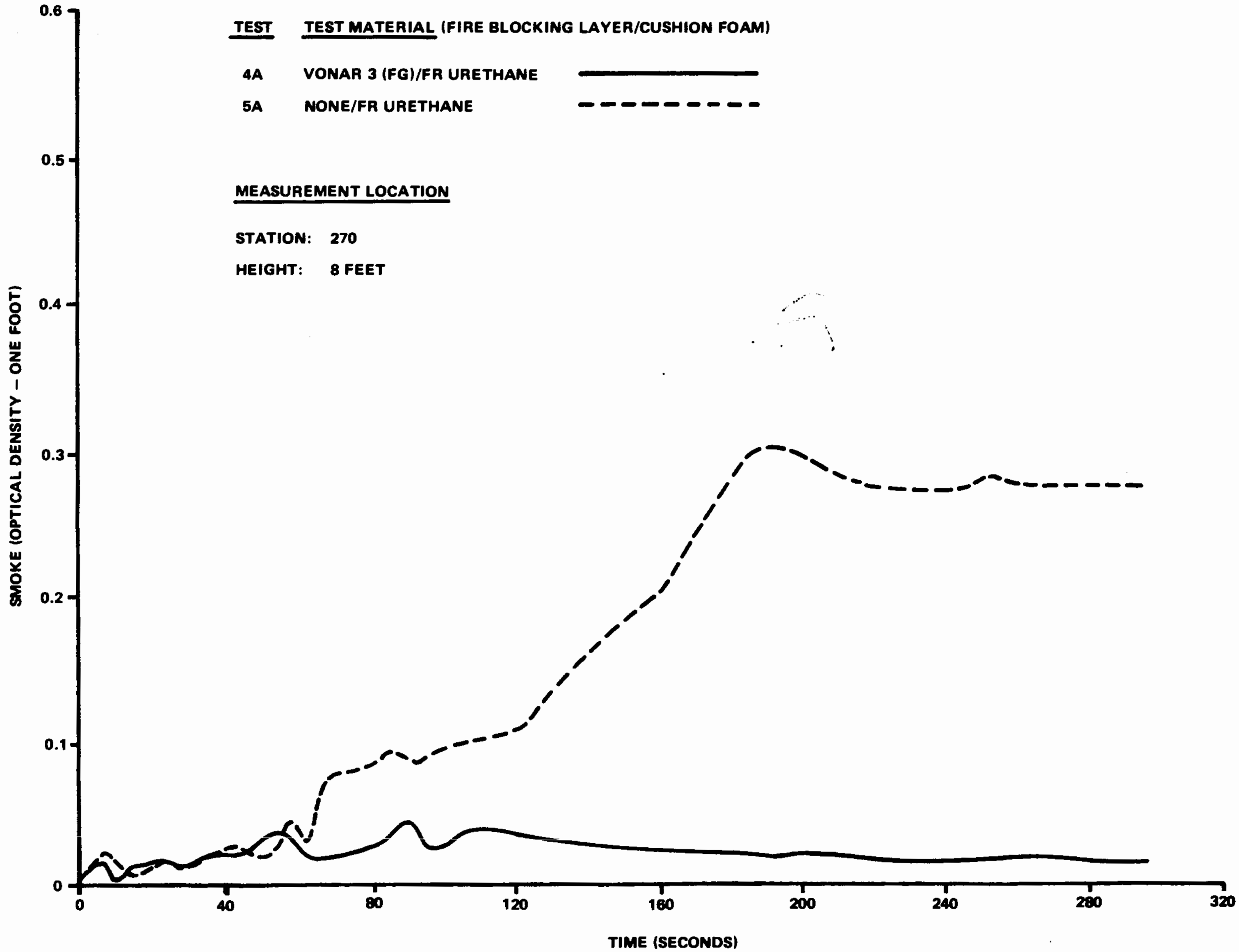

FIGURE 48. IN-FLIGHT GASOLINE TEST SMOKE COMPARISON

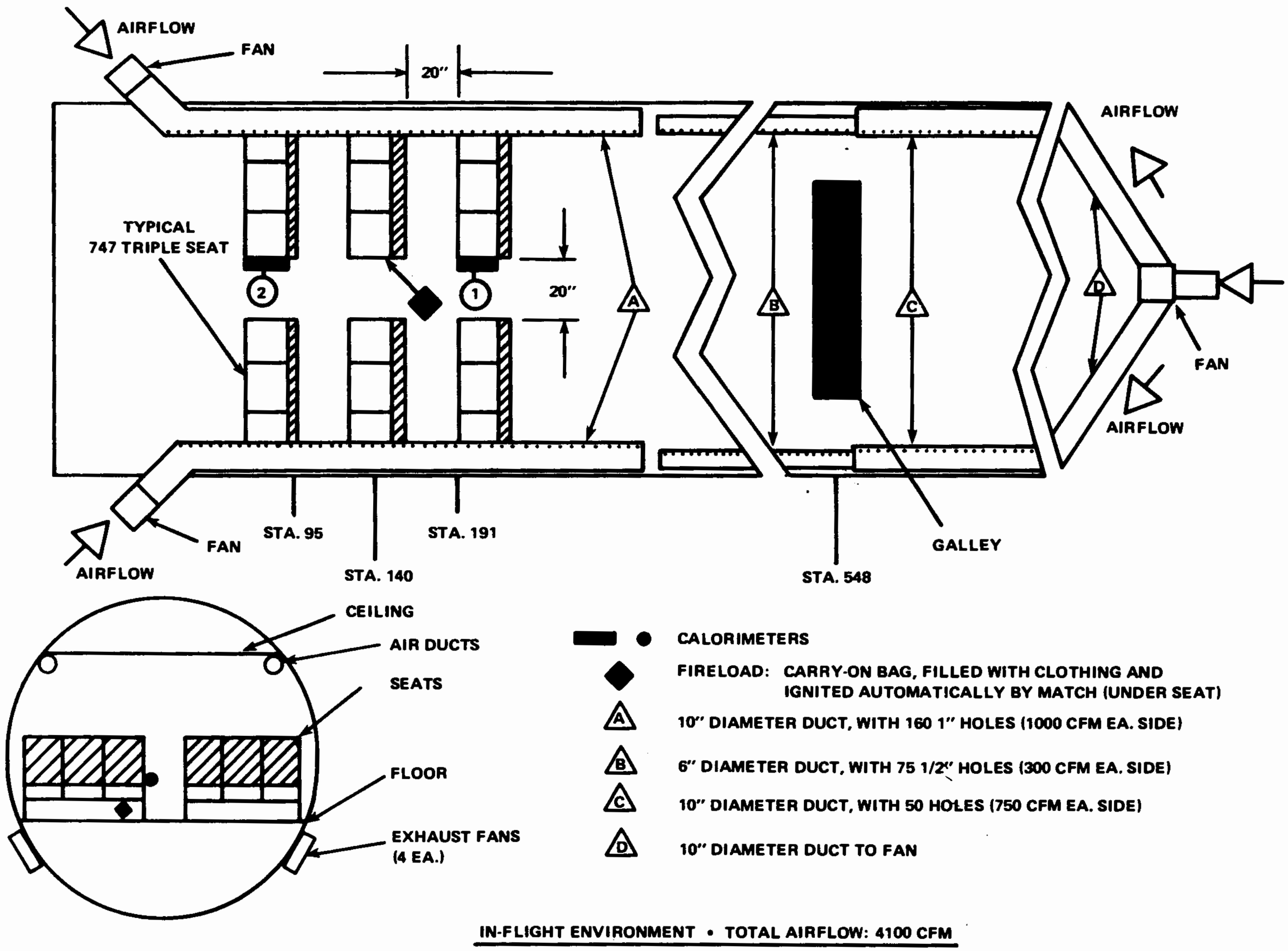

FIGURE 49. FULL-SCALE IN-FLIGHT TEST CONFIGURATION

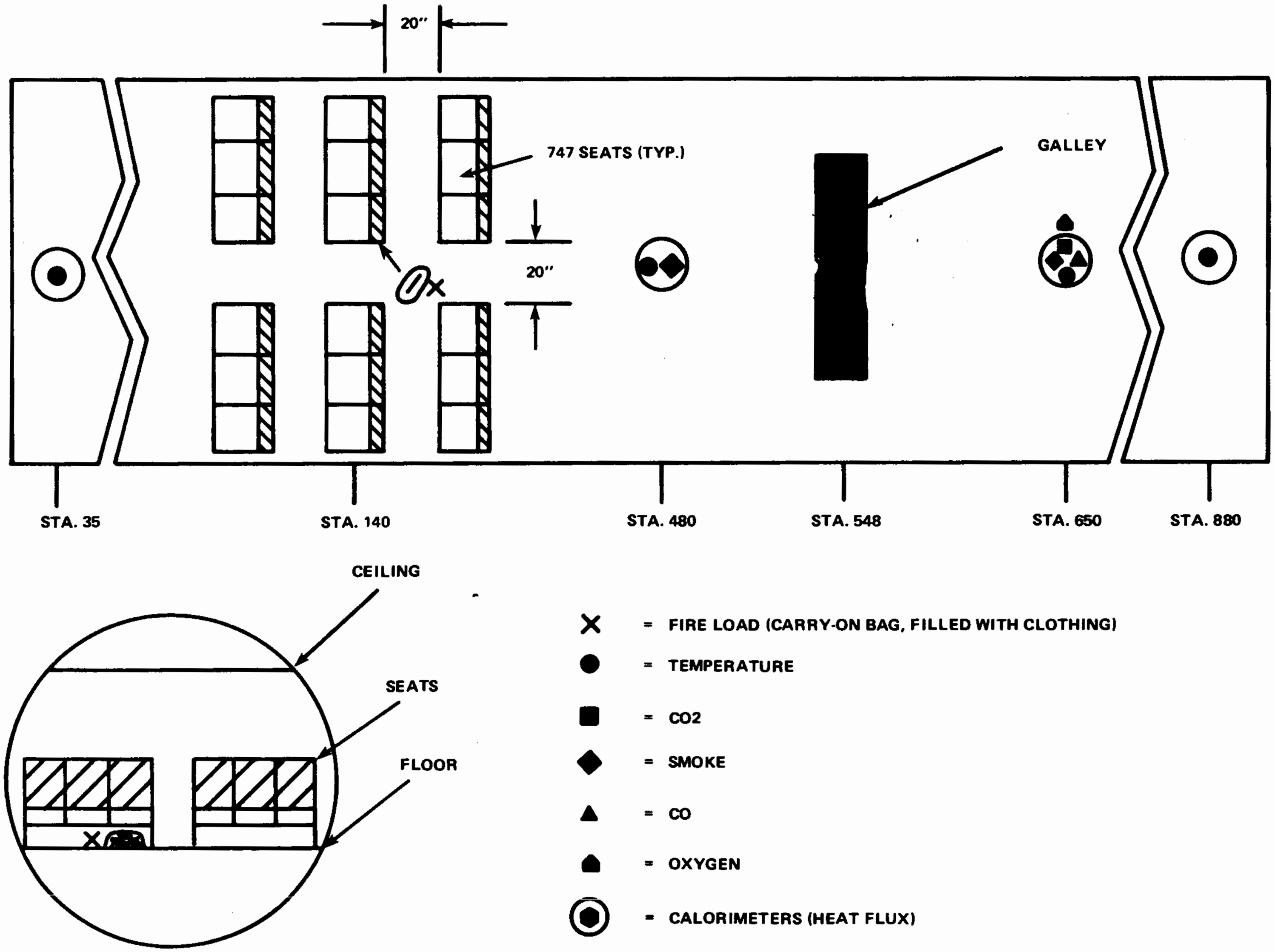

FIGURE 50. IN-FLIGHT SIMULATION TEST INSTRUMENTATION DIAGRAM

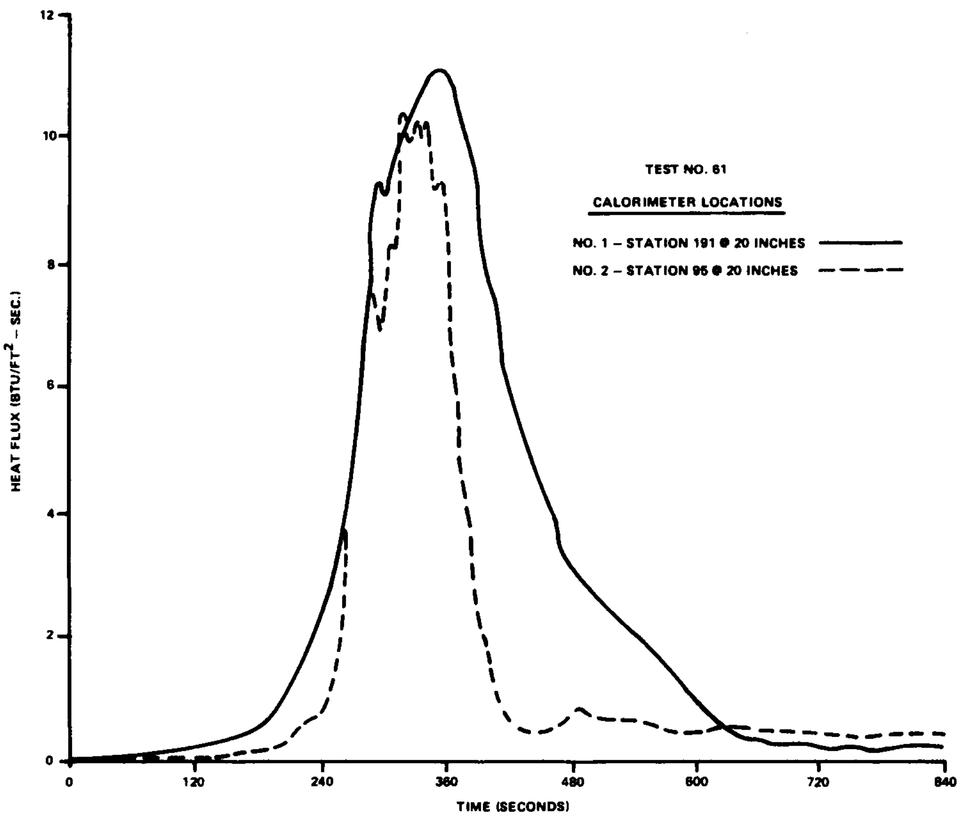

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FIGURE 51. FULL-SCALE IN-FLIGHT HEAT FLUX

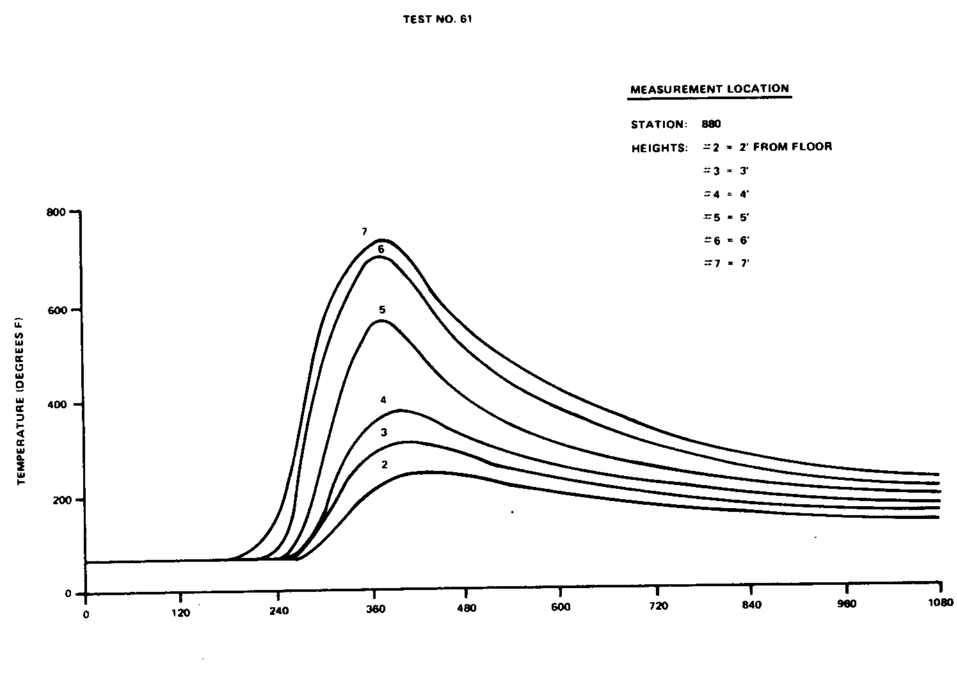
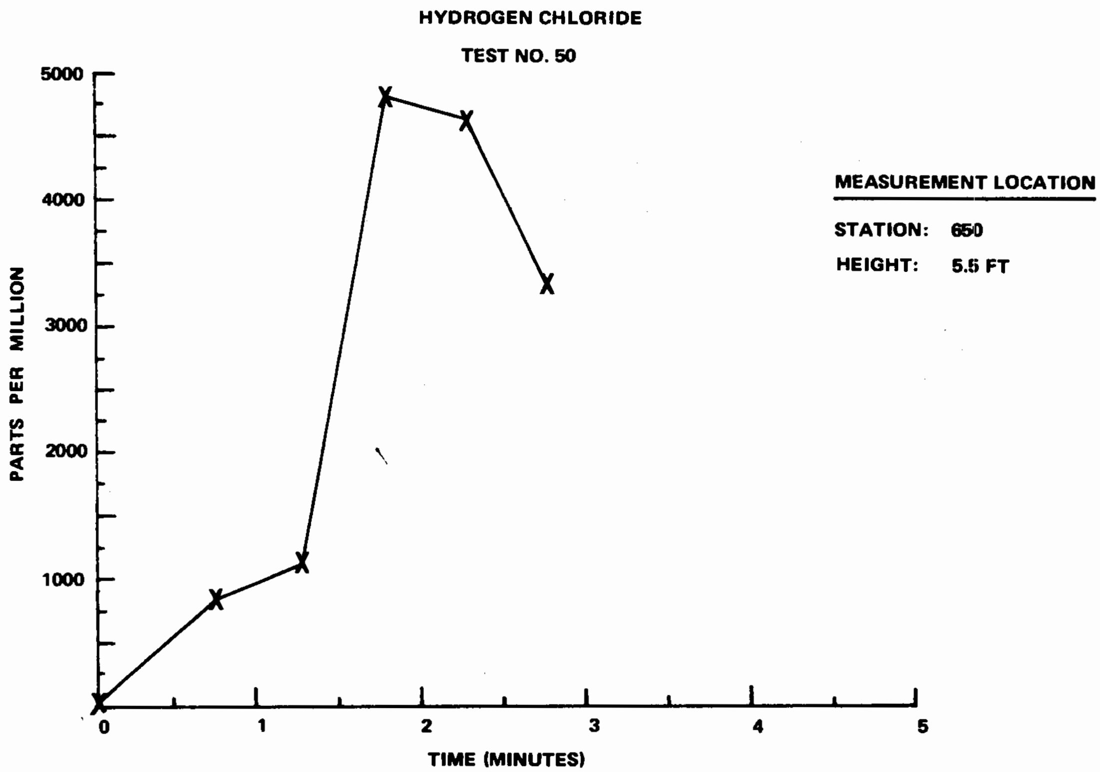


FIGURE 52. FULL-SCALE IN-FLIGHT TEMPERATURE PROFILE



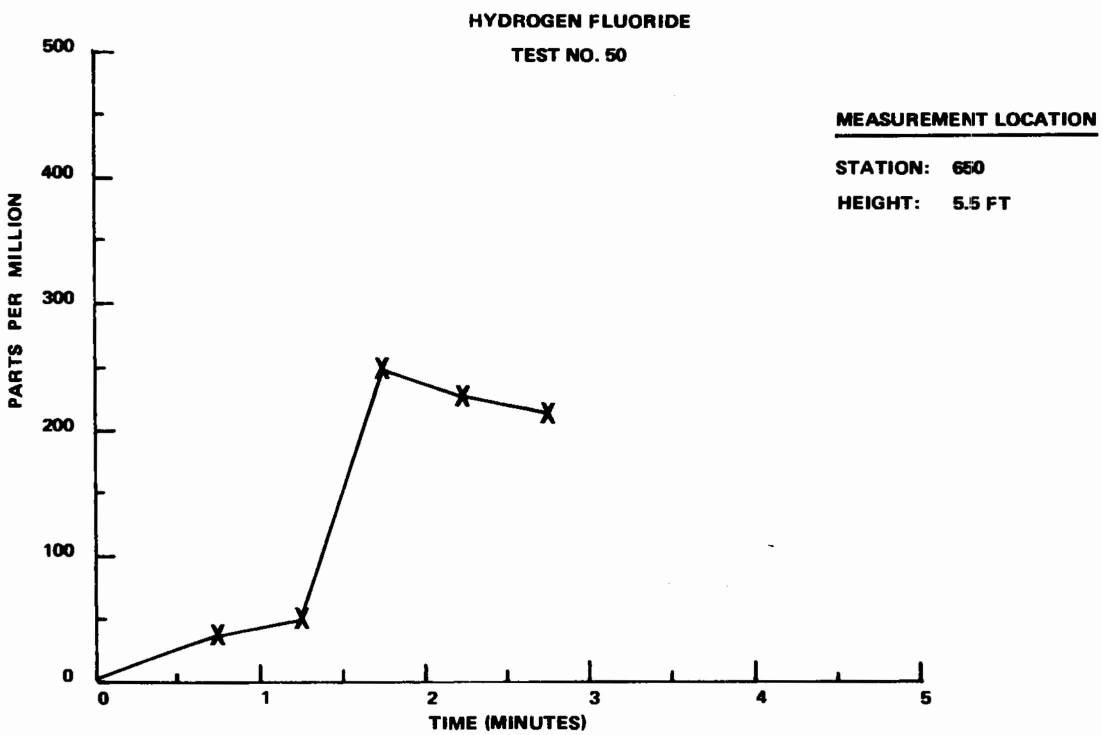


FIGURE 53. FULL-SCALE IN-FLIGHT ACID GAS MEASUREMENTS

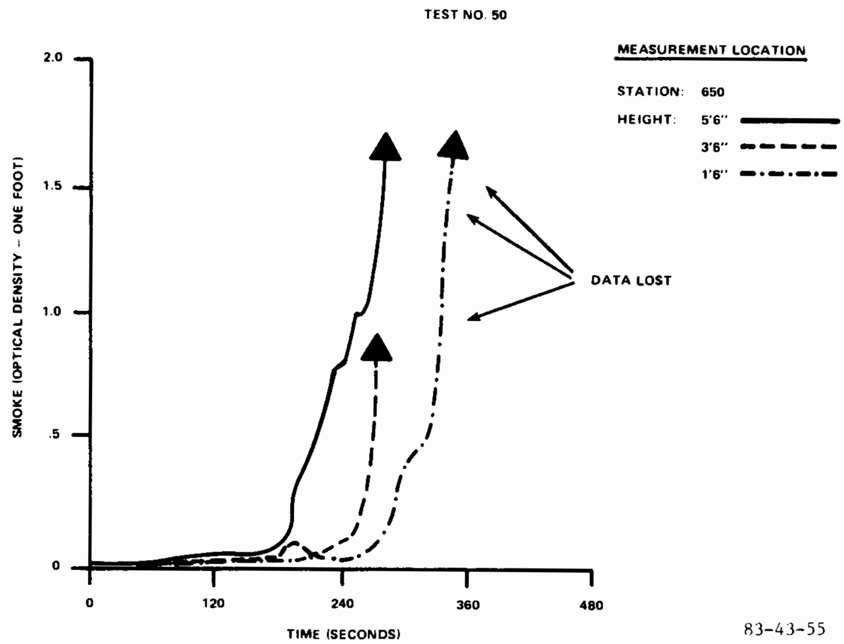


FIGURE 54. FULL-SCALE IN-FLIGHT GAS MEASUREMENTS

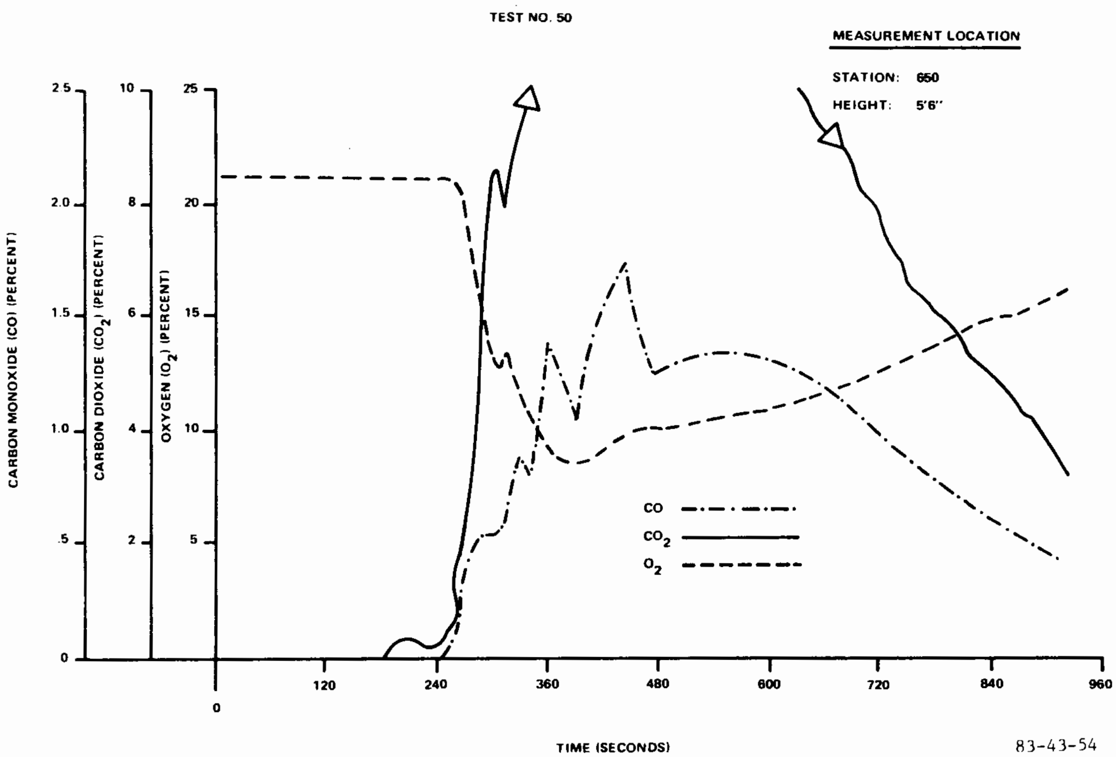


FIGURE 55. FULL-SCALE IN-FLIGHT SMOKE MEASUREMENTS

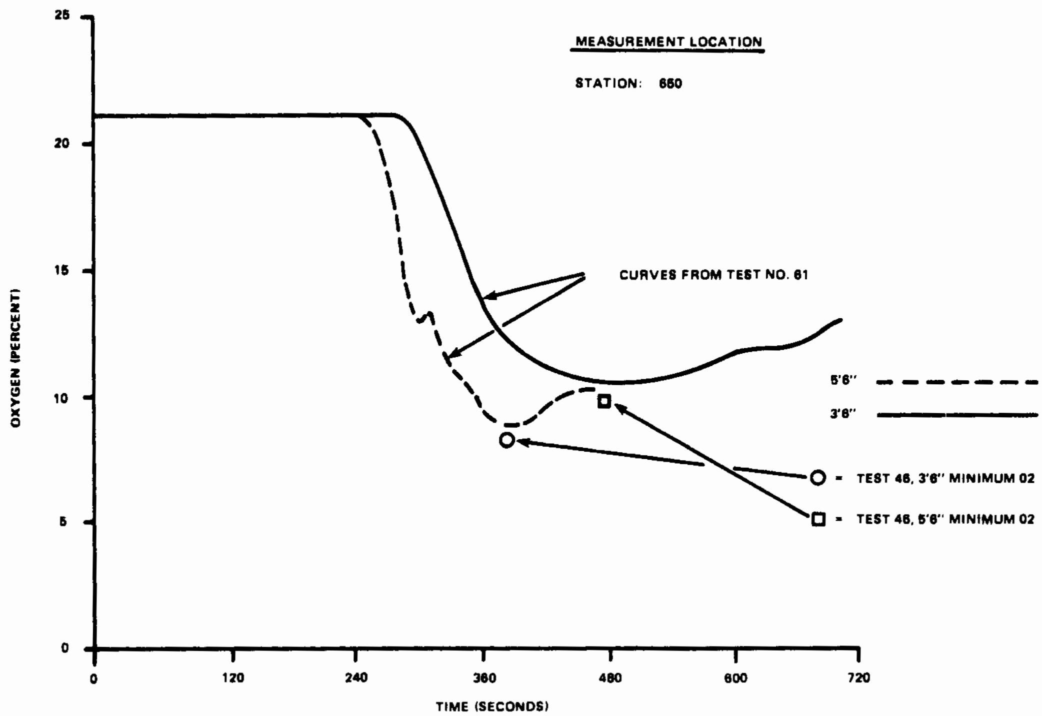


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FIGURE 56. FULL-SCALE IN-FLIGHT OXYGEN COMPARISONS

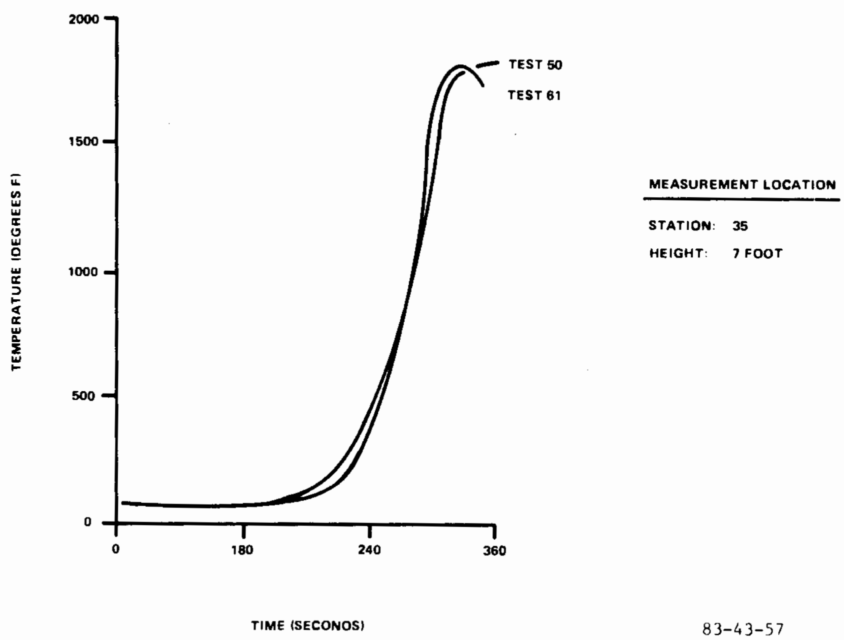

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FIGURE 57. FULL-SCALE IN-FLIGHT TEMPERATURE COMPARISONS, STATION 35

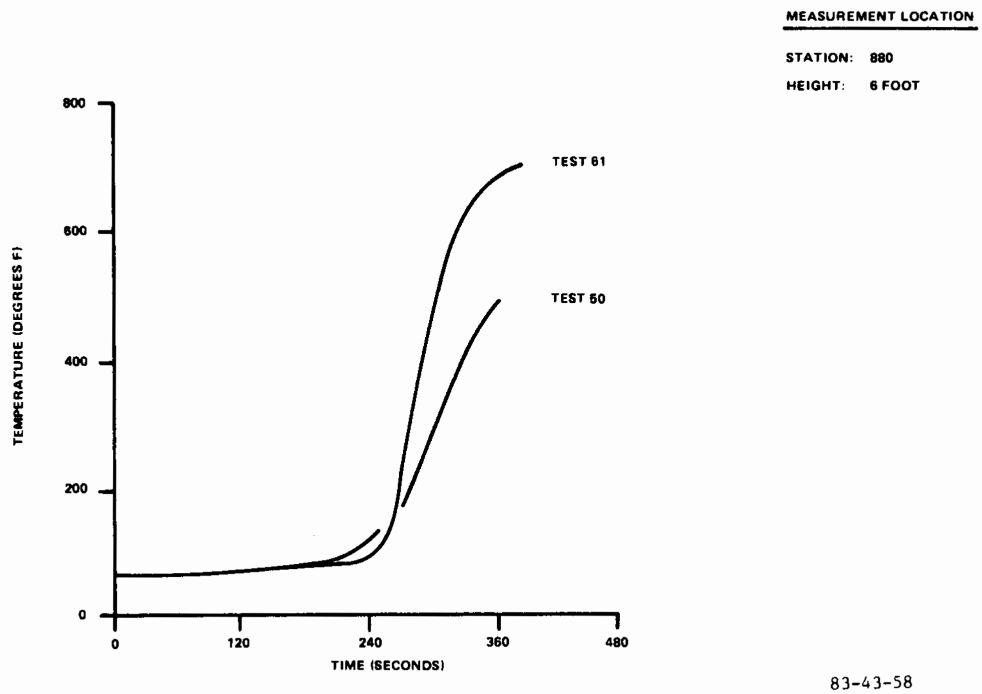


FIGURE 58. FULL-SCALE IN-FLIGHT TEMPERATURE COMPARISONS, STATION 880

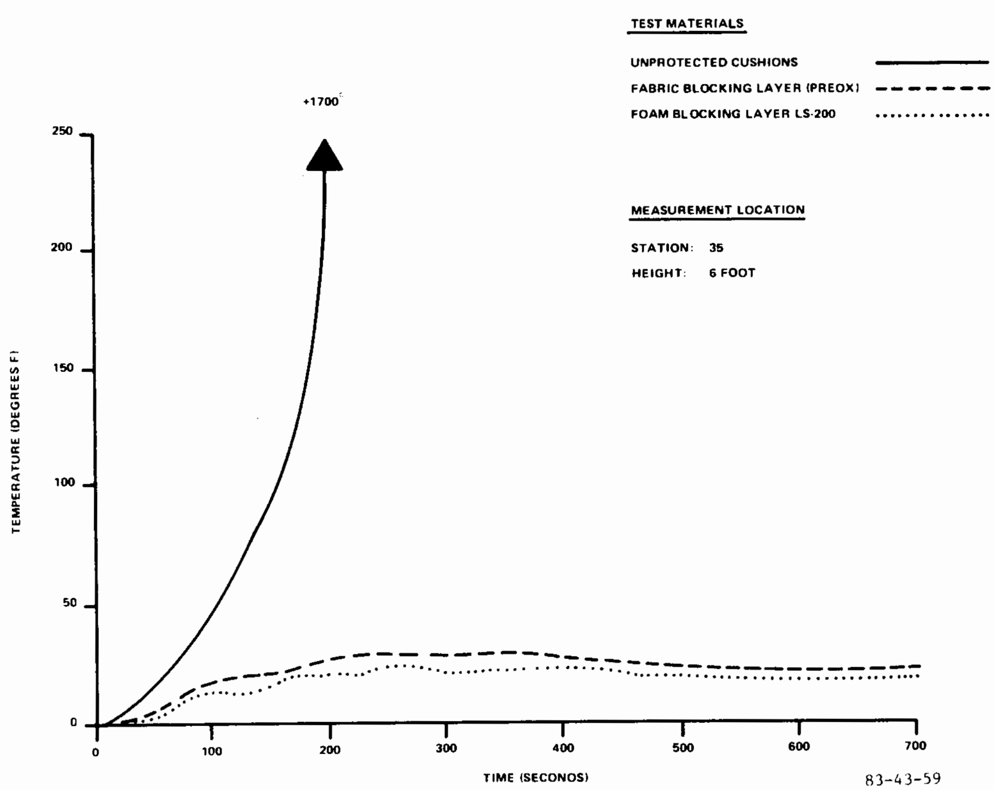


FIGURE 59. FULL-SCALE IN-FLIGHT BLOCKING LAYER COMPARISON TEMEPRATURE

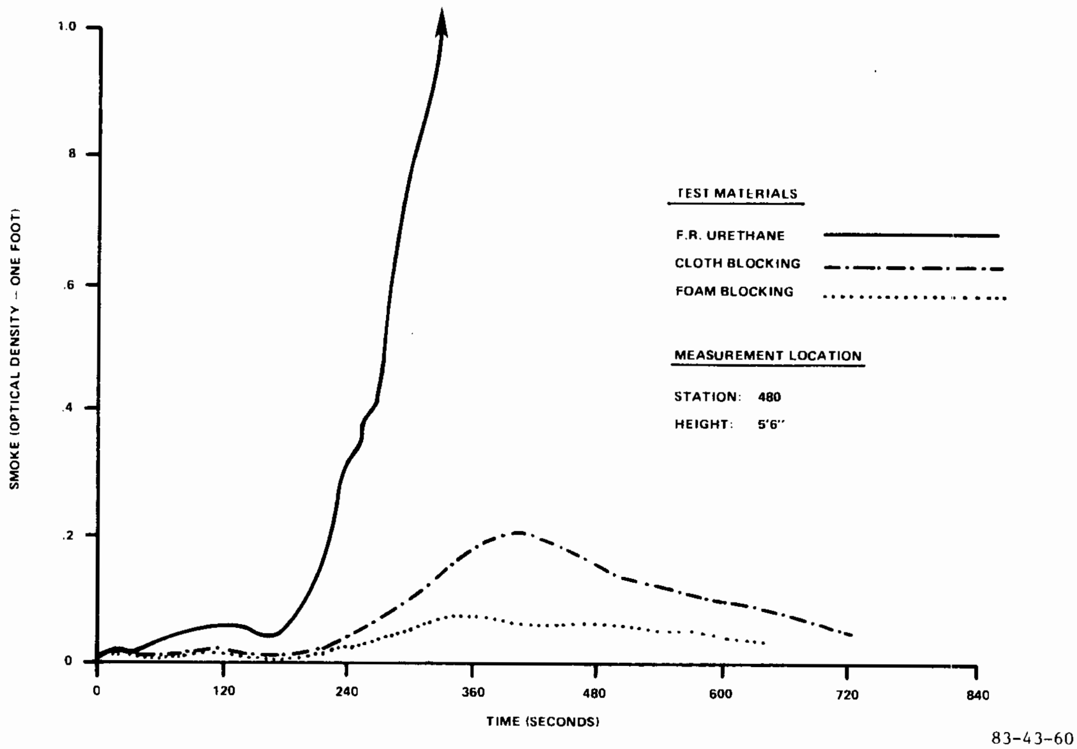


FIGURE 60. FULL-SCALE IN-FLIGHT BLOCKING LAYER COMPARISON (SMOKE)

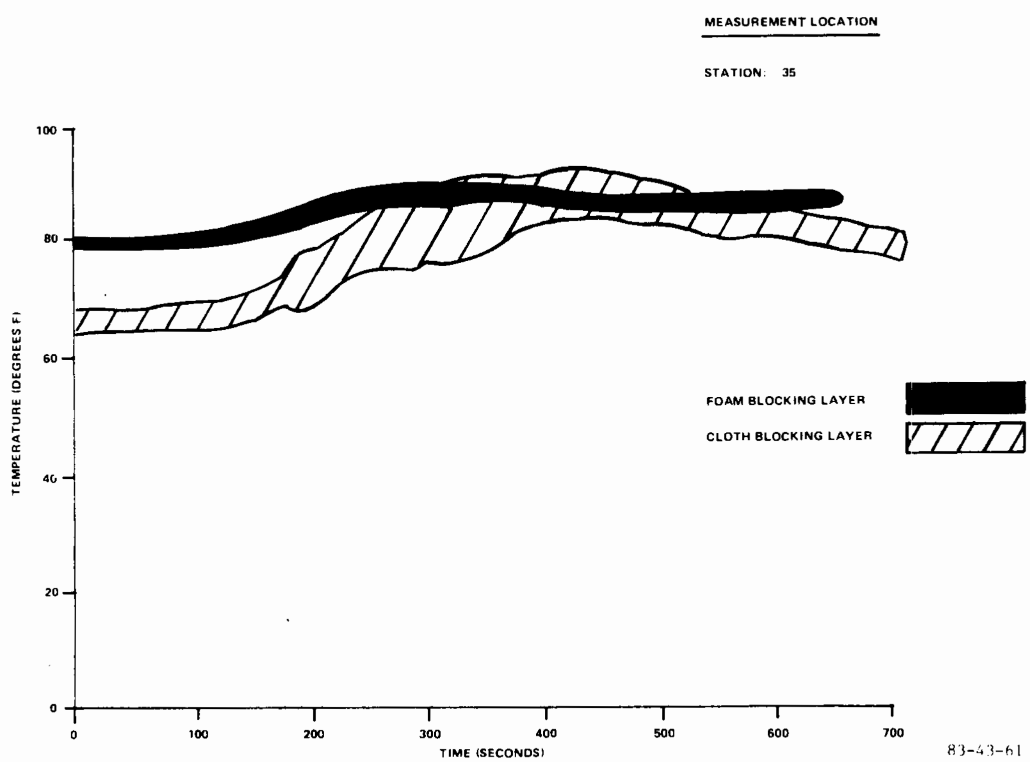


FIGURE 61. RANGE OF TEMPERATURE MEASUREMENTS FROM FLOOR TO CEILING

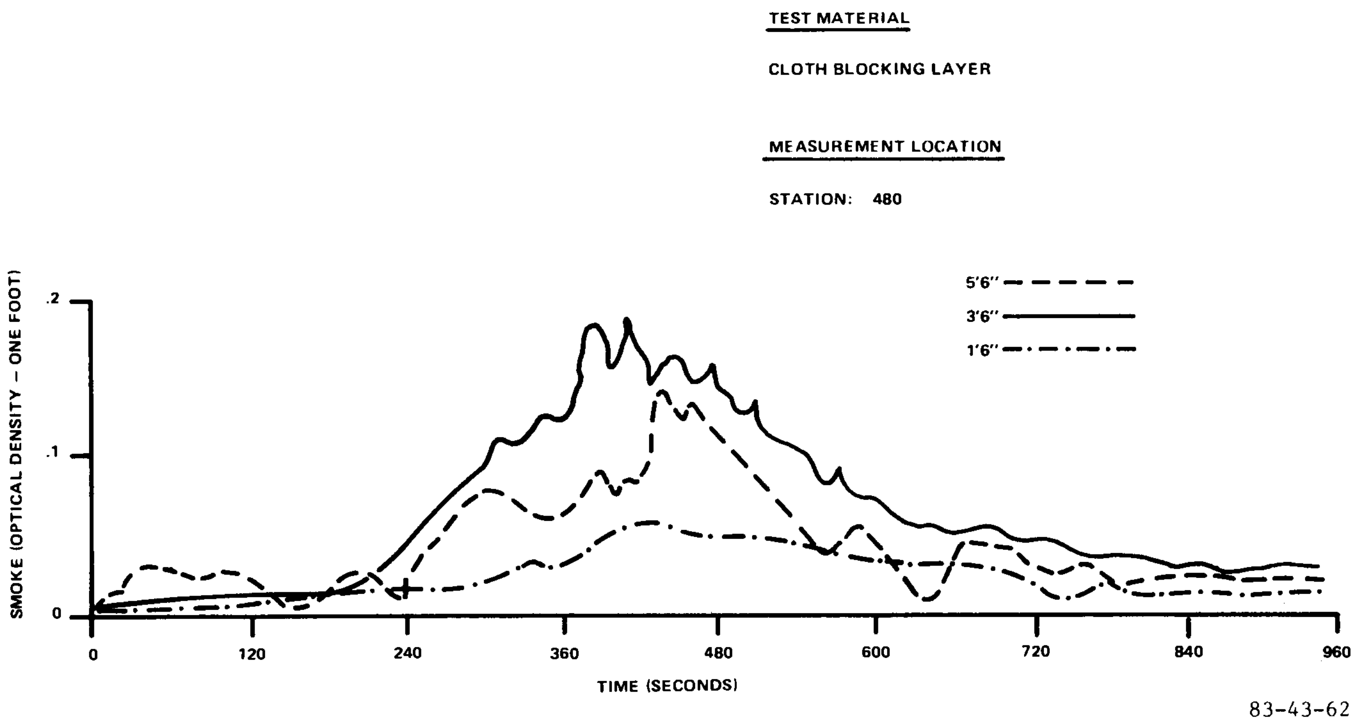


FIGURE 62. SMOKE STRATIFICATION PROFILE

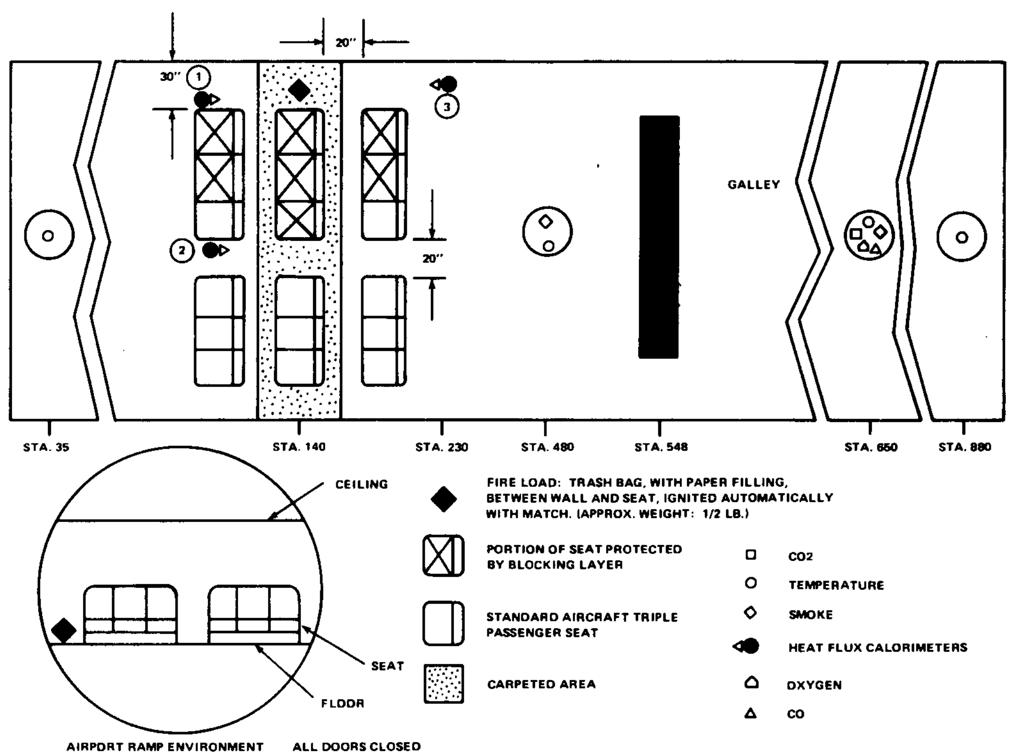
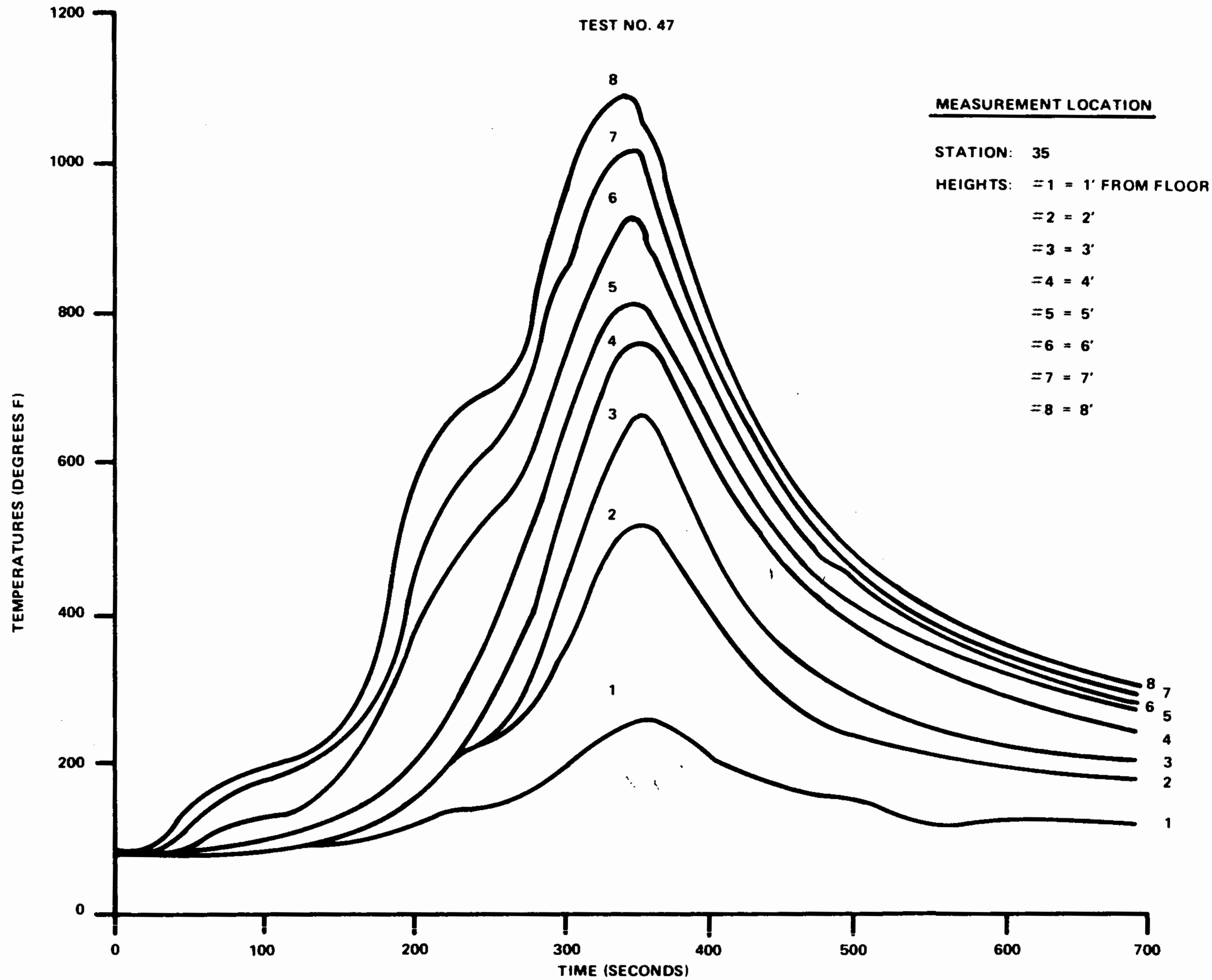
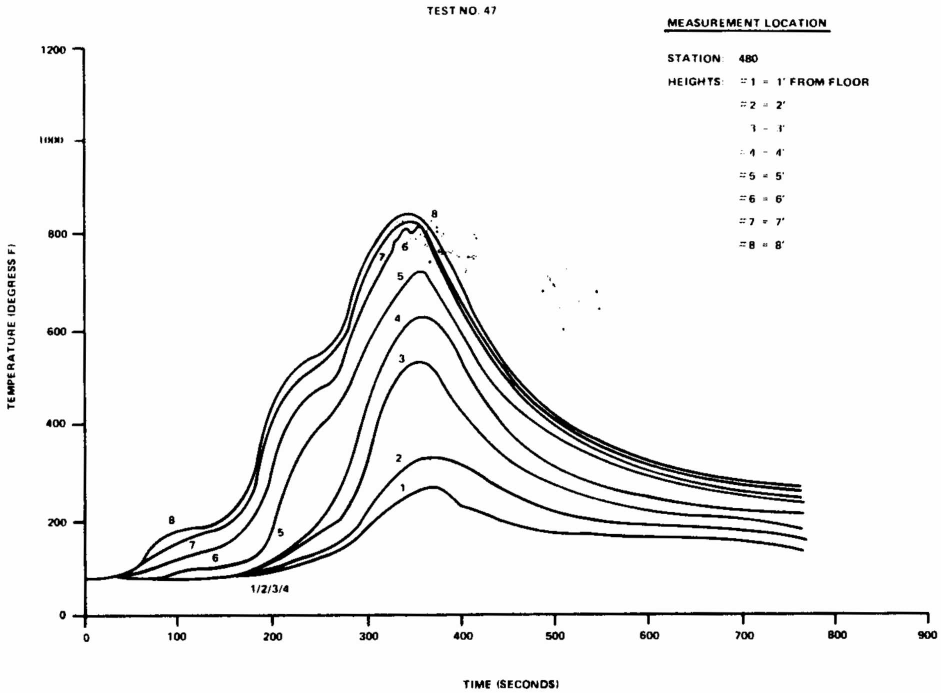


FIGURE 63. FULL-SCALE RAMP FIRE CONFIGURATION

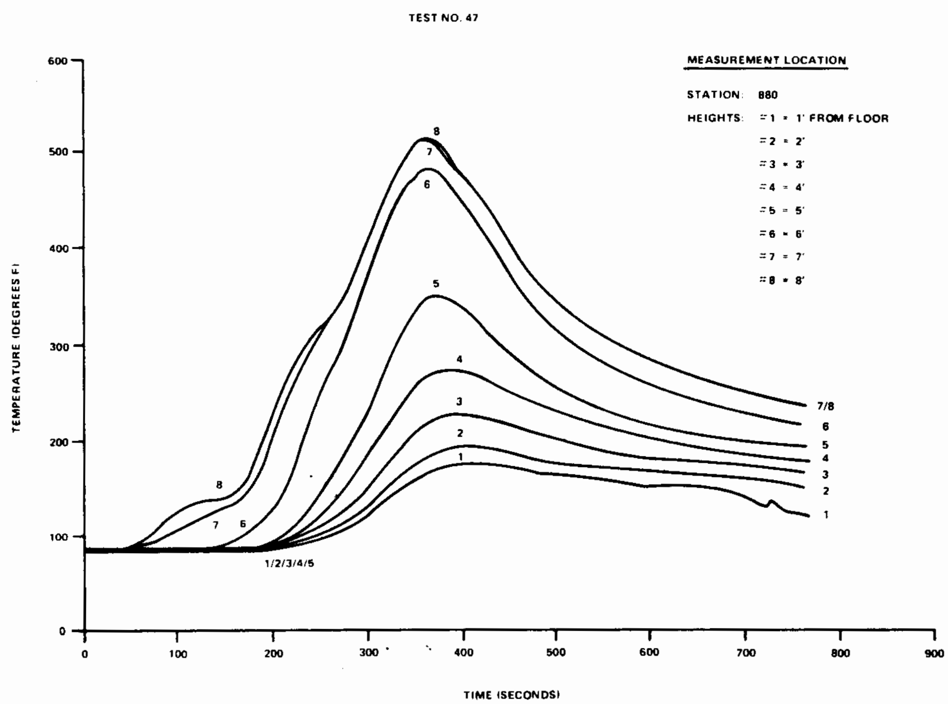


(a)

FIGURE 64. RAMP FIRE TEMPERATURE PROFILES (1 of 2 Sheets)



(b)



(c)

FIGURE 64. RAMP FIRE TEMPERATURE PROFILES (2 of 2 Sheets)

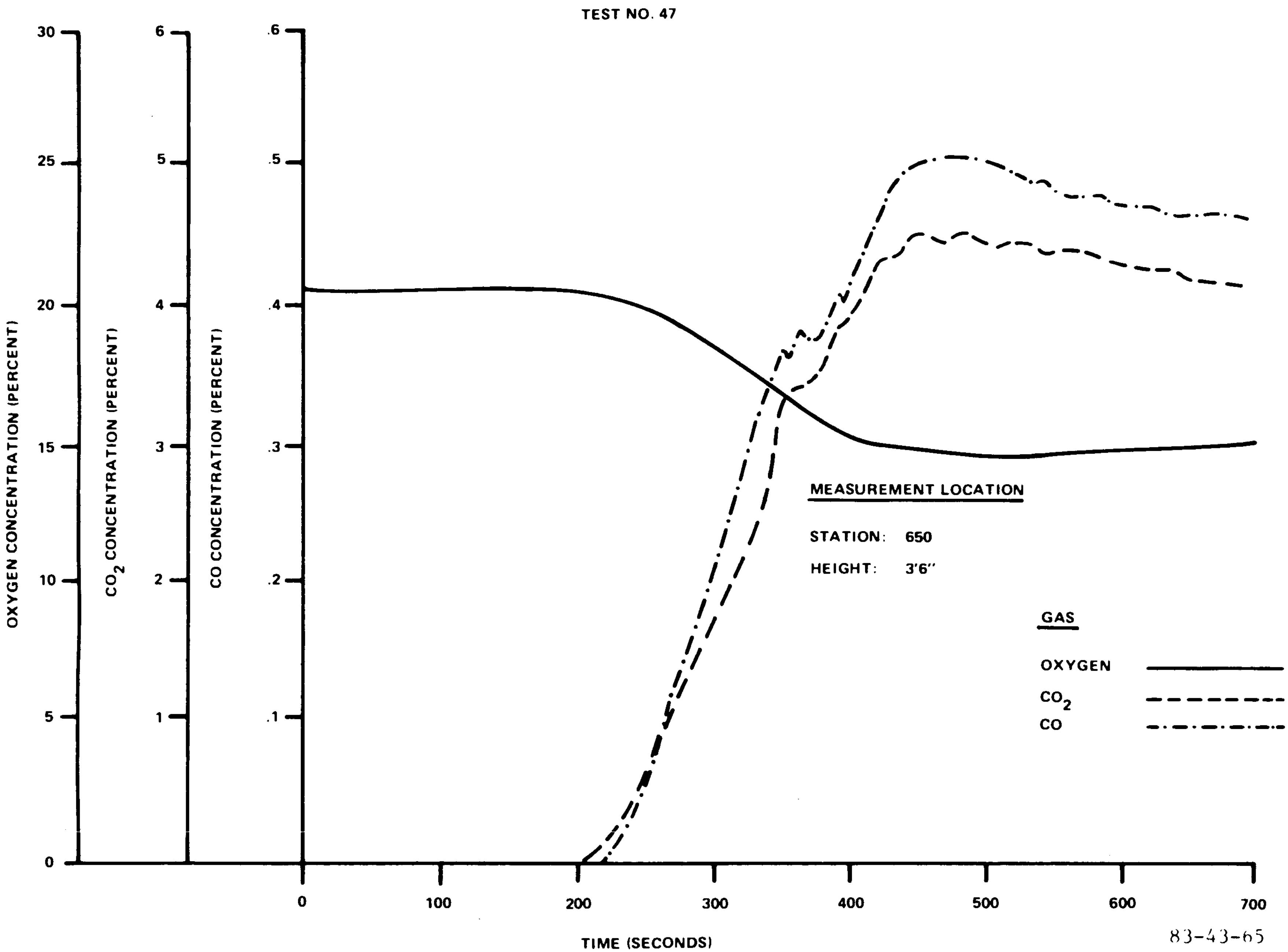


FIGURE 65. RAMP FIRE GAS CONCENTRATIONS

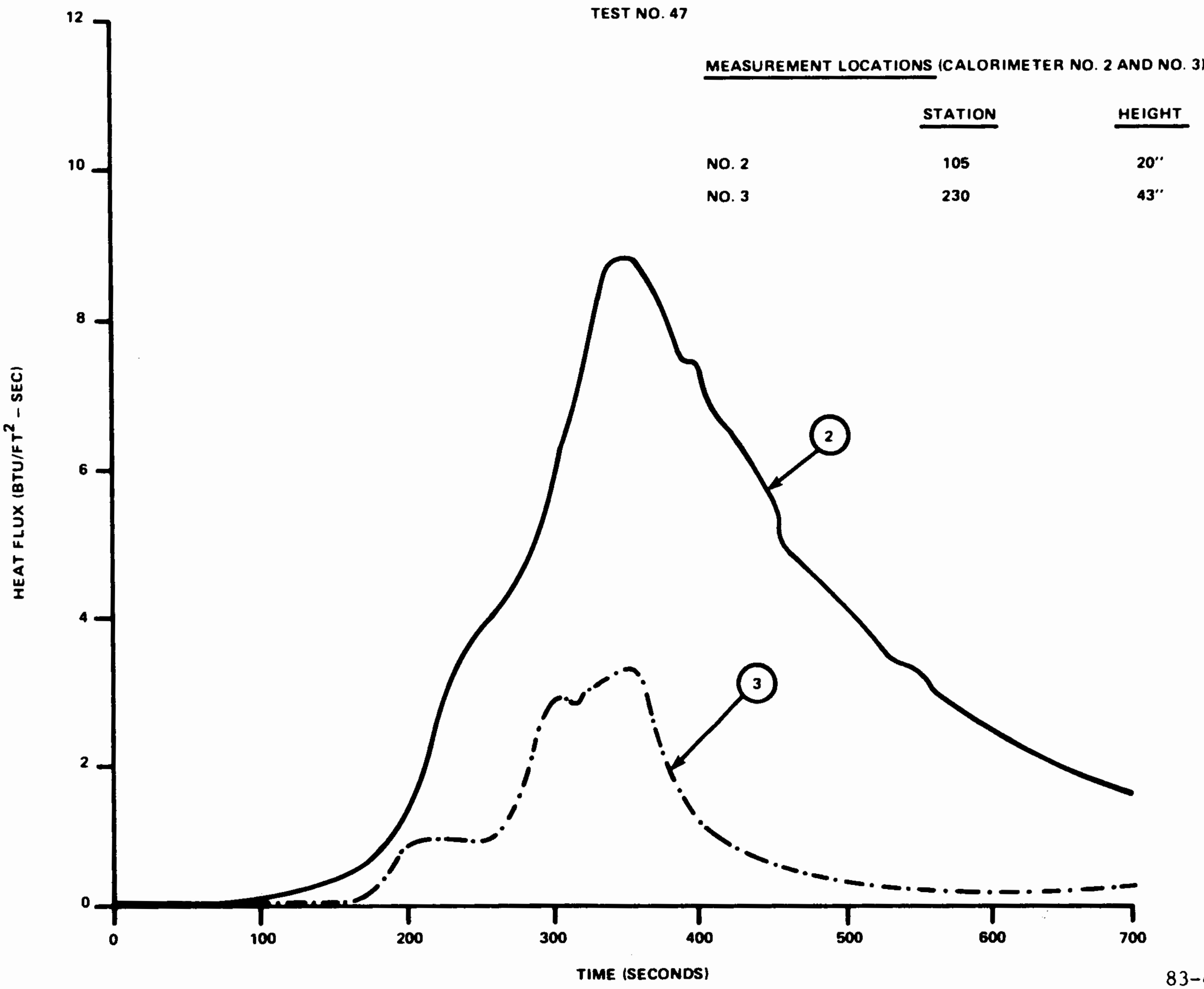


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FIGURE 66. RAMP FIRE HEAT FLUX MEASUREMENTS

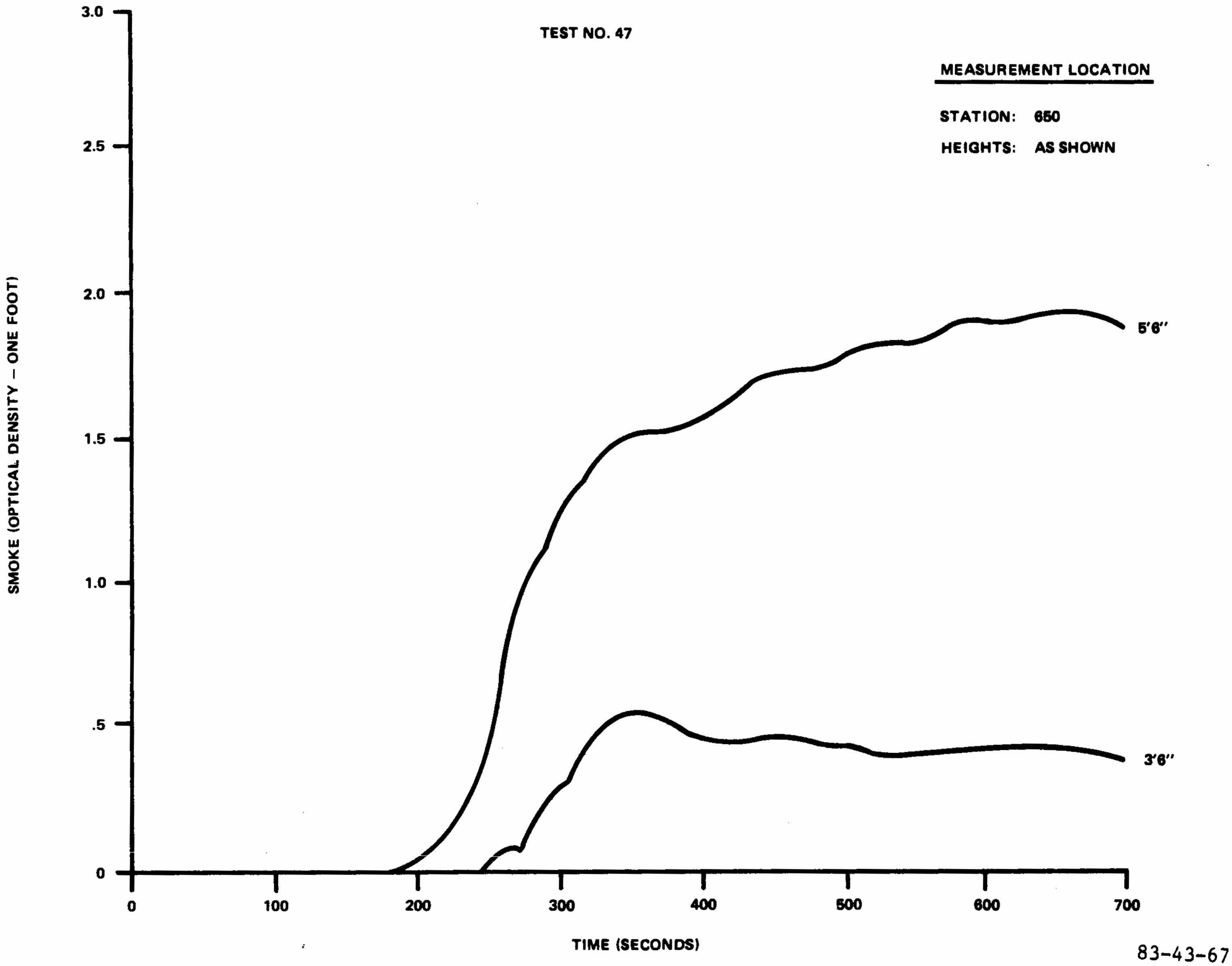


FIGURE 67. RAMP FIRE SMOKE PROFILE

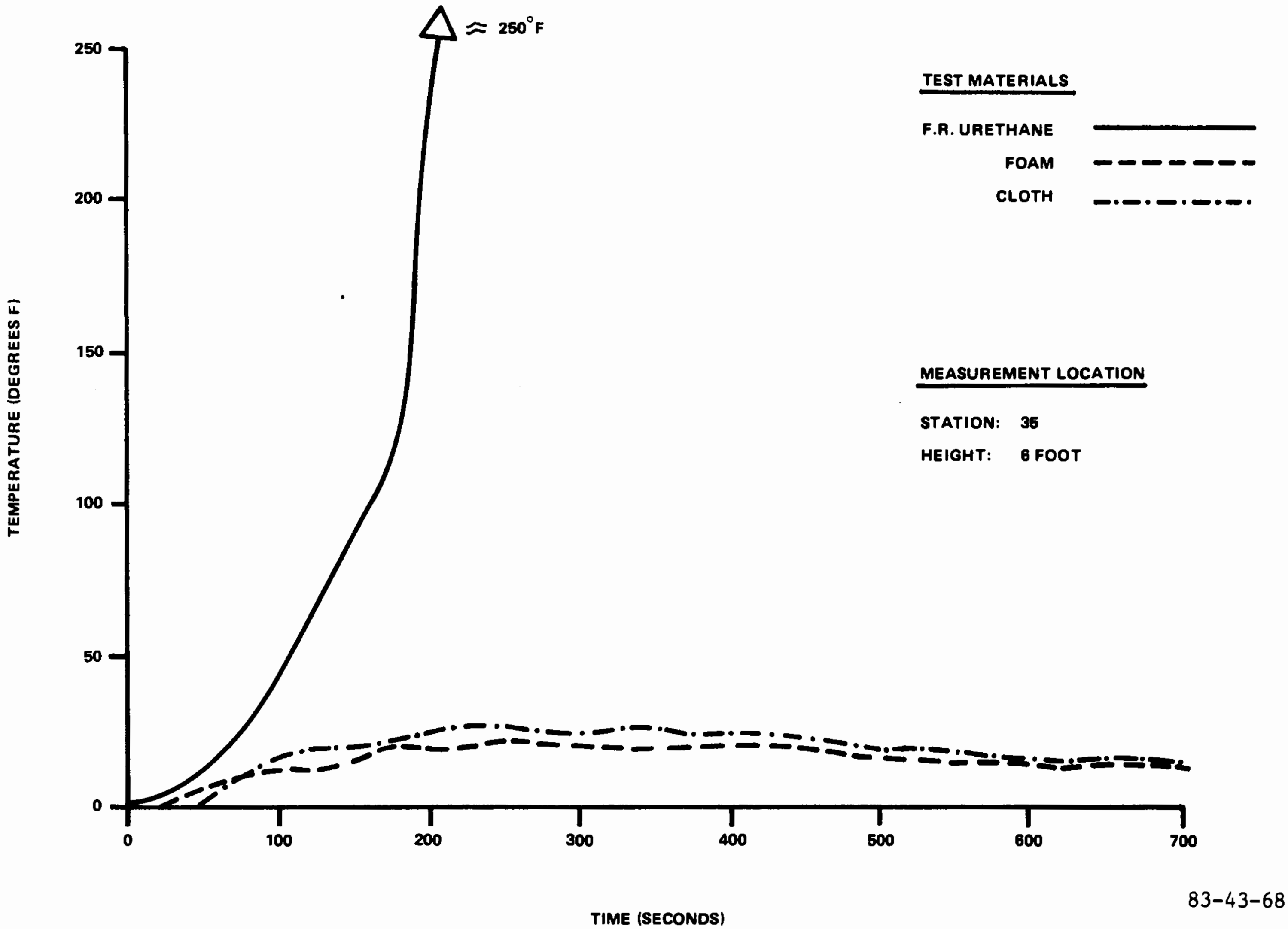


FIGURE 68. RAMP FIRE BLOCKING LAYER TEMPERATURE COMPARISON

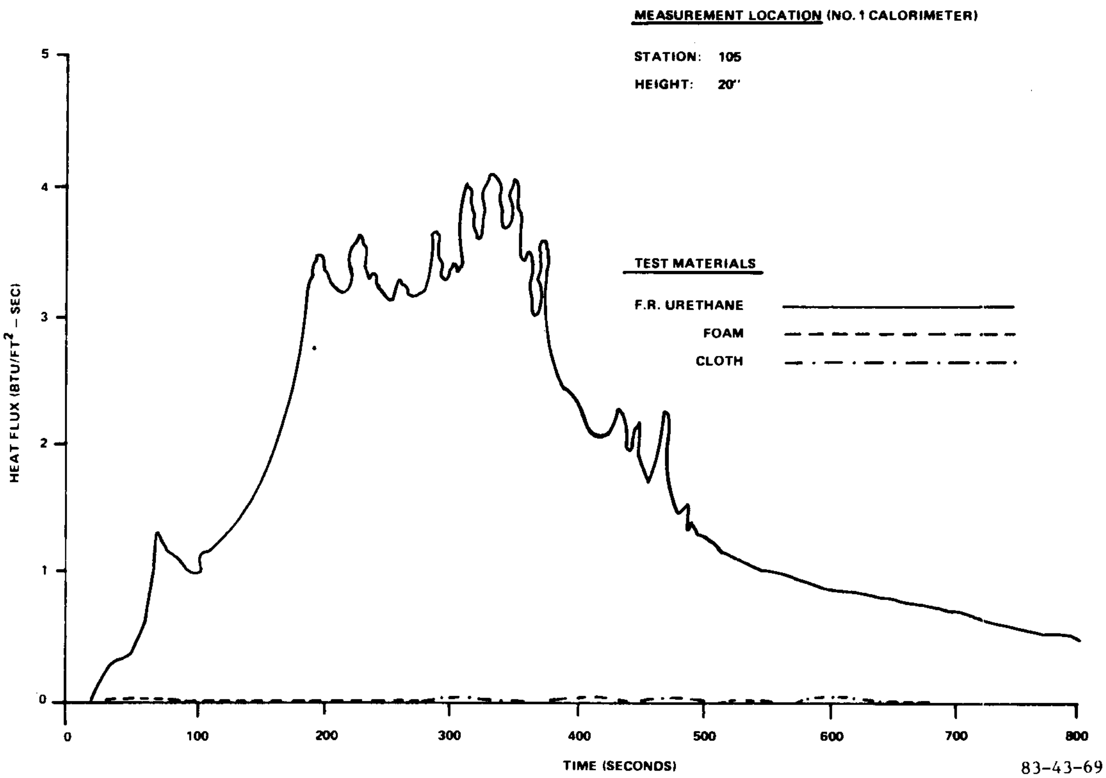


FIGURE 69. RAMP FIRE BLOCKING LAYER HEAT FLUX COMPARISON

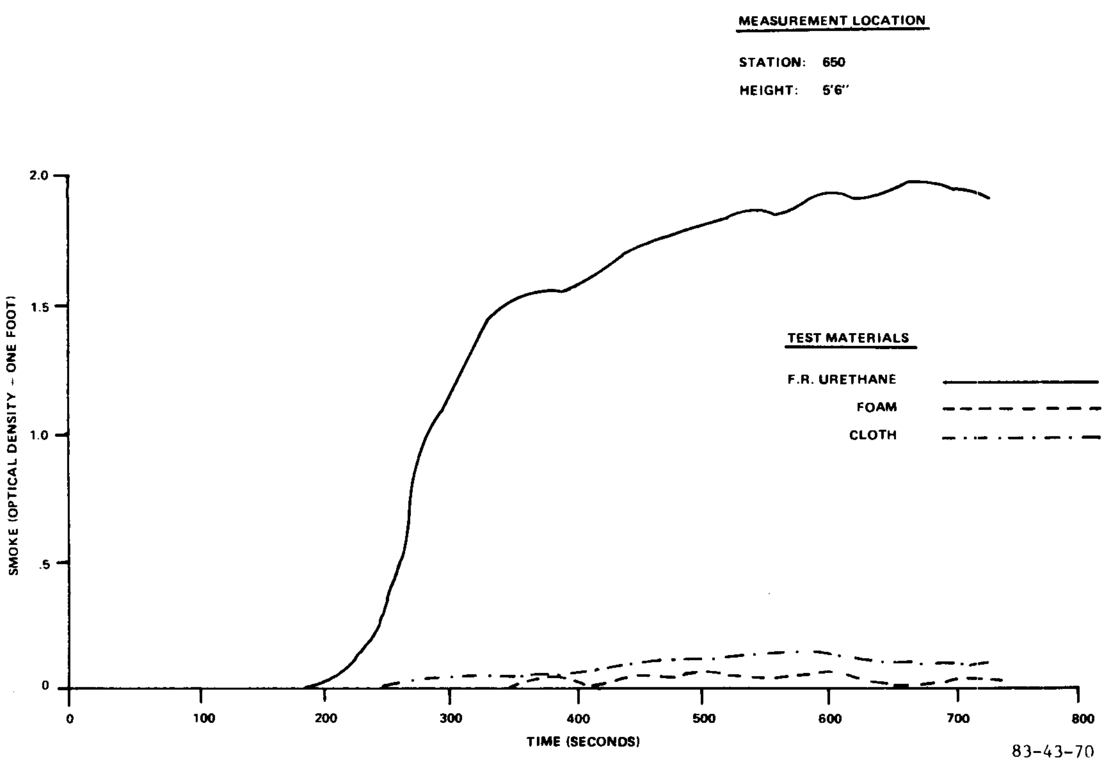


FIGURE 70. RAMP FIRE BLOCKING LAYER SMOKE COMPARISON

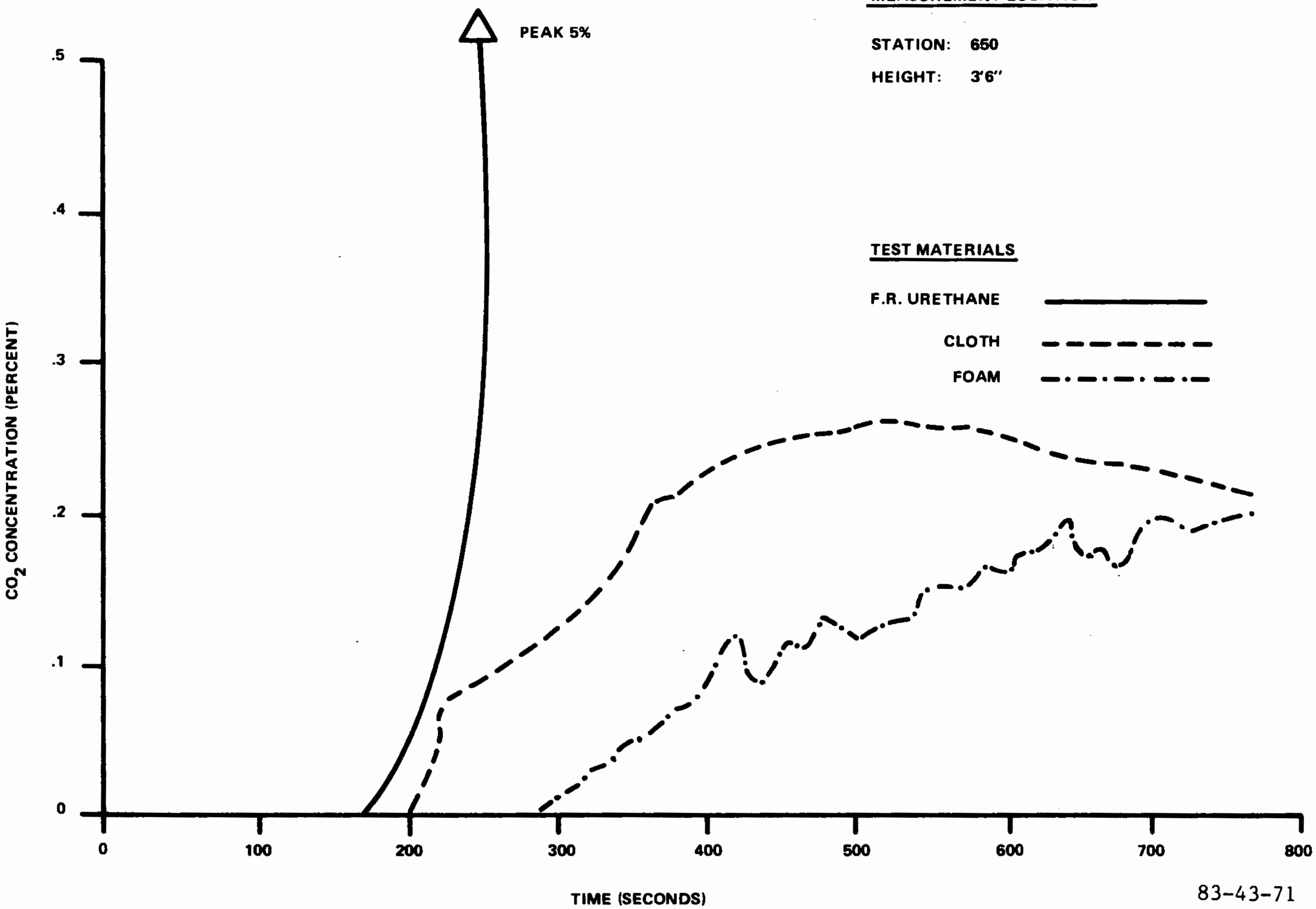


FIGURE 71. RAMP FIRE BLOCKING LAYER CO_2 COMPARISON

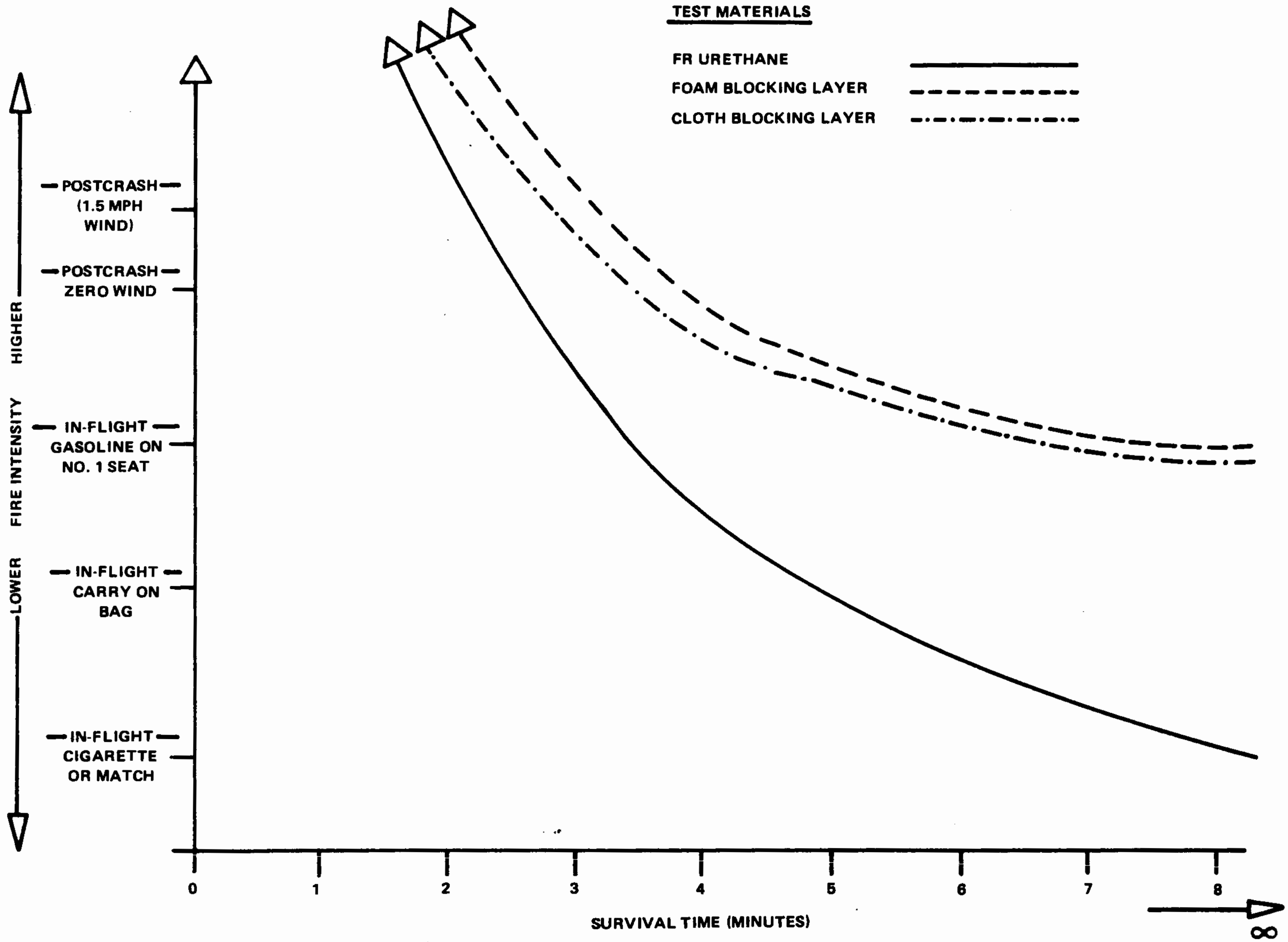


FIGURE 72. PREDICTION OF SURVIVAL TIME BENEFIT FROM IMPROVED AIRCRAFT

APPENDIX A

LABORATORY TEST DATE OF MATERIAL USED IN C133 TESTS

TABLE A-1. LABORATORY TEST RESULTS

Material Type	Usage	Material No.	Vertical FAR 25.853 (2/6) Flame Out (Sec.)	Burn Length (In.)	Radiant Panel ASTM E-162 Fs	Is
Polycarbonate	Window Sidewall	1	10.4	1.6	6.76	27
Sunscreen	Window	2	.5	.5	5.87	63
Polycarbonate	Window Blind	3	8.6	1.6	4.81	42
Honeycomb	Sidewall Panel	4			5.37	4
Polycarbonate	Hatrack Fairing Panel	5	9.5	1.3	4.66	23
Honeycomb	Hatrack Panel	6	-20	2.1	14.96	11
Foam	Seat	7			55.29	249
Thermoplastic	Siding of Fold-Down Tray	8	.8	1.2	6.17	23
Thermoplastic	Inside Tray Space	9			7.17	48
Thermoplastic	Rigid Armrest Tray	10	.5	2.1	8.21	129
Foam	Armrest Padding	12	245.8	5.5		
Honeycomb	Side/Ceiling Panel	13	-20	3.4		
Wool/Nylon Fabric		15	3.0	3.7		
Polymide		25	.5	2		
LS-200		17	.6	.1	1.00	2
VONAR -3		16	.8	1.4	5.89	33
Celiox		26	1.2	2.1		
Kermel Lane Wool/Blend		27	.7	5.9		
Wool 100%		14	3.7	2.6		

Note: These are general types of materials used. Exact composition of materials may have varied from test to test.

APPENDIX B

COLLECTION AND ANALYSIS OF HYDROGEN FLUORIDE AND HYDROGEN CHLORIDE

INTRODUCTION

PURPOSE.

The objective of this effort was to measure hydrogen fluoride (HF) and hydrogen chloride (HCl) gas concentrations both as a function of time and location during full-scale blocking layer tests in the C133 fuselage. The sources of these gasses are discussed in this paper. Data obtained using various seat blocking layers are compared to data obtained using unprotected seats. Comparisons of data are made for different sampling locations.

Potential sampling errors such as collection efficiency, diffusion, and convection of gases into the absorption tube, were evaluated by sampling system exposure to pure gas and combustion gases. The presence of test yields due to decomposition products from previous tests on the ceiling and walls of the fusalage was also investigated.

BACKGROUND.

The sampling procedure developed for these tests is simple, inexpensive, and capable of operating in the immediate vicinity of a moderately intense fire. The gases are collected at the sampling points using absorption tubes, which eliminate line losses. As many as 40 samples were obtained during each full-scale test. Both the free gas and particulates are collected.

The method of analysis is ion chromatography using ion selective electrodes as detectors. It has been shown that the HF and HCl yields obtained from the oxidative pyrolysis of several aircraft interior materials compare well using ion chromatography and other accepted methods of analysis of fire gases (reference 32). Thus, interference effects do not pose an error in the analysis for the typical materials examined.

DISCUSSION

ACID GAS COLLECTION.

Absorption tubes were used to collect HF and HCl samples during the tests. This procedure was developed at the Federal Aviation Administration Technical Center (reference 33) and modified subsequently to support full-scale fire tests.

The absorption tube is glass-lined, stainless steel, 16.5 centimeters long, with a 4-millimeter inside diameter (i.d). It is packed to a depth of 14 centimeters with glass beads (1 millimeter diameter) which are held in place by fine glass wool pressed into the tube at each end, leaving 0.5 centimeter of free tubing. Prior to use, the beads are rinsed with a one-molar sodium carbonate solution. Excess solution is blown from the tube by a syringe. The tubes are then sealed with plastic caps. The absorption tubes are housed in an ice water bath (an aluminum box, insulated with Kaowool™ board) (figure B-1). The tubes are mounted horizontally, with water-tight bulkhead fittings. The outside ends face forward and extend just beyond the insulation board. The plastic caps are removed before the test. The interior tube ends are attached to separate vacuum lines, which pass through the bottom of the box, and lead to the solenoid valve assembly below the floor of the plane (figure B-2). These vacuum lines are insulated in a Kaowool sleeve. The box has a drain line for the removal of ice water after a test.

The solenoid valve assembly is an array of 10 solenoid valves, remotely controlled by a 10-pole relay timer. The timer sequentially opens each sample solenoid valve for 30 seconds. The main vacuum line is "teed" to two solenoid valves, each connected to a 0.5 liter vacuum bottle. These two solenoid valves are always in opposite states. As one bottle is evacuated, the other draws a sample into an absorption tube. This is acheived with a buffer of 10 relays between the sample solenoid valves and the two main vacuum solenoid valves. This technique allows short sampling intervals and can handle a large number of samples. A thermocouple is mounted inside one of the two bottles to monitor bottle temperature during a test.

The sampling system was modified for the last several tests in the series to factor down an apparent potential "deposition error." The bottle size was increased from 0.5 liter to 3.5 liters, and the tube packing and retainers were changed to decrease the restriction and accomodate the higher flowrate through the tube. The new packing material is 3 millimeter diameter glass beads with a teflon retainer. Figure B-3 illustrates the two types of absorption tubes used. The first was used for tests 1 to 41, and the second was used for tests 49 to 64. The tube was further modified for the last test of the series, test 8202: A 2-inch length of glass capillary tubing (2-millimeter inner diameter) was placed prior to the sample tube to further factor down apparent deposition errors. The duration of sampling differs for the two absorption tube configurations. In the first configuration, about 80 percent of the sample is drawn within the first 10 seconds. The flowrate is initially constant and then drops off. In the second configuration, the duration of sampling is the full 30 seconds. The volume-time profile for each tube configuration is illustrated in figure B-4. The capillary tube modification has no affect on the flow rate.

Blank absorption tubes are used for both configurations to determine if the measured concentration is the "actual" concentration or higher, due to diffusion or convection into the tube. In the first absorption tube configuration, the sample drawn at 0 minutes served as the blank. The assumption is made that no acid gas decomposition products are present at the time and location of the first sample. In the second configuration, however, the duration of sampling is longer. An additional sample tube serves as the blank. A sample is drawn prior to the test and this tube is then capped inside the box, leaving the outside face of the tube to the same test atmosphere as the time-sequenced sample tubes.

ACID GAS (HF, HCl) ANALYSIS

The acid gases drawn through the sample tube are absorbed by the sodium carbonate solution coating the glass beads. After the test, the sample tubes are removed from the box, capped, and brought to the laboratory for analysis. Fluoride and chloride anions are recovered for analysis by rinsing the absorption tube in a backflush mode with a 10-milliliter alliquot of 0.05 molar sodium carbonate solution dispensed by a syringe connected directly to the tube. The washings are collected in autosampler plastic cuvettes for subsequent analysis by ion chromatography. A detailed description of the method of analysis and the computerized system of data acquisition and reduction can be found in reference 31.

ERROR ANALYSIS.

A number of potential errors were evaluated and monitored for the acid gas collection in the C133.

Contamination from Earlier Tests. Are the yields due to the thermal decomposition products (TDP's) of the materials, or is a significant percentage due to residual TDP's from previous test? As discussed in "sources," this is not a major problem.

Volume Reproducibility. The reproducibility of the volume drawn through the absorption tubes was determined. The volume drawn through each tube was measured before each test with a wet test meter. The percent relative standard deviation (RSD) of the volumes drawn range from 5 to 7 percent.

Timing Delay. A timing delay between activating the relay timer and drawing the first sample is estimated to be a maximum of 5 seconds.

Solenoid Valve "Sticking." Sample solenoid values can "stick" and remain partially open during a test. The sample solenoid valves were checked sequentially for air tightness before each test with a wet test meter. Leaking solenoid valves were replaced and the previous test samples used with that solenoid valve were discarded. This occurred for test 02, sample 3 at station 650, at a height of 5.5 feet.

Collection Efficiency. The collection efficiencies of the absorption tube for the acid gases of interest are high for the worst-case sample loading encountered in the test series. The collection efficiencies for configuation 2 were determined for C133 Test 64 (a full interior with standard urethane seats). Three absorption tubes were piggybacked, each 1/3 the length of a standard tube, and a sample was drawn at location 880 at a height of 5.5 feet from 3.5 to 4-minutes into the test. The gas yields, along with the percent collected per tube are found in table B-1. For each gas, 98 percent is collected within the first 2/3 of each standard tube. If the sample volume were reduced by a factor of 5 (as in configuration 1), the tube loading would be cut by a factor of 5 and the collection efficiencies would be even higher.

Deposition Error. The diffusion and convection of gas and particulates into the exposed face of the absorption tube can pose an error. Theoretically, the blank tube can correct for the deposition if the deposition for each of the 10 tubes is similiar in each sampling location. However, if the deposition is large and variable, one cannot determine whether the measured concentrations corespond to the drawn sample or are partially due to deposition. Tests 1 to 14 have no major deposition errors as early sample yields are low. However, the subsequent full interior tests had high yields within the first minute of the test. Tests 35 and 41 had very high yields for the blank tubes drawn at time zero into the test, indicating that deposition may be a major error in this series of tests.

TABLE B-1. FULL INTERIOR COLLECTION EFFICIENCY STUDY (C133 TEST 64)

TUBE	HYDROGEN FLUORIDE		HYDROGEN CHLORIDE	
	YIELD(PPM)	% COLLECTED	YIELD(PPM)	% COLLECTED
A	97.8	65	938.4	53
B	49.6	33	786.2	45
C	3.5	2	40.7	2
A+B+C	150.9	100	1765.3	100

Increasing the volume drawn by a large factor should factor down any deposition error. A larger bottle was used for later tests (tests 49 to 64 and 8202) and the volume drawn was increased by a factor of 5. These later tests all had significantly lower early yields, not only for the first minute, but during the first 2-minutes into the tests.

COMBUSTION TUBE FURNACE TESTS OF C-133 MATERIALS.

Samples of each of the materials used in the C133 tests were oxidatively pyrolyzed at 600° centigrade (C) in a combustion tube furnace. The acid gases produced were collected in liquid filled impingers and analyzed by ion chromatography. A detailed description of the test procedure and method of analysis can be found in reference 32. Three replicate burns were made for each material. The average yields of HF and HCl are reported in milligrams gas produced per gram of sample (mg/g) (table B-2).

The highest HF yields (5-8 mg/g) were found for the sidewall, hatrack, and ceiling panels (materials 4, 6, and 13), and also the wool/PVC fabric (material 23). The polyvinyl fluoride (PVF) film component of the decorative surface of the panel accounts for high HF yields. High HCl yields were found for materials in three usage categories: fabrics, foams, and thermoplastics. Material 9, a thermoplastic siding material for the fold-down tray had the highest HCl yield of 217 mg/g. Material 23, a wool/PVC (52 percent/43 percent) fabric had a yield of 172 mg/g HCl.

EXPERIMENTAL AND RESULTS

C133 BLOCKING LAYER TESTS.

Acid gas measurements were made for the C133 tests listed in table B-3. The materials used, test conditions, sampling locations, and sample tube configurations are listed. Tests were conducted under in-flight and post-crash conditions to evaluate the effectiveness of the blocking layers.

Material substitutions were made for some tests in the blocking layer series. Three different urethane foam cushions were used and two different fabrics. These substitutions are indicated in table B-3. Laboratory-scale tests using a combustion tube furnace were made for most of the materials utilized in the C133. A description of the materials tested and the milligram per gram (mg/g) yields of HF and HCl can be found in table B-2.

TABLE B-2. ACID GAS YIELDS OF C133 MATERIALS OBTAINED WITH THE COMBUSTION TUBE FURNACE

MATERIAL NO.	MATERIAL DESCRIPTION	ACID GAS YIELDS (MG/G) HF	HCL
1	THERMOPLASTIC (WINDOW SIDEWALL AREA)	0	0
2	PLASTIC WINDOW	0	2.4
3	THERMOPLASTIC (WINDOW BLIND)	0	0.2
4	SIDEWALL PANEL (HONEYCOMB)	8.2	0.5
5	THERMOPLASTIC (HATRACK FAIRING PANEL)	0	0.2
6	HATRACK PANEL (HONEYCOMB)	5.2	0.5
8	THERMOPLASTIC (FOLD-DOWN TRAY)	0	0.7
9	THERMOPLASTIC (SIDING OF FOLD-DOWN TRAY)	1.0	216.5
9A	RIGID FILLER FOAM INSIDE TRAY SPACE	0.2	5.9
10	THERMOPLASTIC (RIGID ARMREST TRAY)	0	0.6
11	FOAM (RIGID ARMREST)	0	2.4
12	FOAM (SEMISOFT ARMREST)	0.1	41.9
13	CEILING PANEL (HONEYCOMB)	6.9	0.7
14	CARPET (WOOL)	0	0.6
15	FABRIC (WOOL 90%/NYLON 10%)	0.8	17.0
16	VONAR 3/16"/POLYESTER	0	40.8
18	FR URETHANE CUSHION	0	0.5
20	UNTREATED URETHANE CUSHION	0	0
21	FR URETHANE CUSHION	0	2.5
23	FABRIC (WOOL 52%/PVC 48%)	4.3	172.0
24	NONCOMBUSTIBLE CUSHION (KAOWOOL)	0	0.3
N6	PANEL (NO DECORATIVE FINISH)	0	0

TABLE B-3. C133 TEST DESCRIPTIONS WITH HF AND HCL SAMPLING LOCATIONS

		SAMPLING LOCATION 650			880	
			HEIGHT			
TEST NO.	MATERIALS	5.5	3.5	1.5	5.5	TUBE CONFIGURATION
POSTCRASH CONDITIONS: EXTERNAL FUEL FIRE						
SEAT TESTS: SEATS ONLY						
01	URETHANE-1 SEAT (CUSHION-MAT.21)	X	X			1
02	LS200 -1 SEAT	X	X			1
04	VONAR 3/16"/POLYESTER/UR** -1 SEAT	X	X			1
06	URETHANE-4 SEATS (CUSHION-MAT.21)	X	X			1
07	LS200 -4 SEATS	X	X			1
08	VONAR 3/16"/POLYESTER/UR** -4 SEATS	X	X			1
11	VONAR/FIBERGLASS/URETHANE**	X	X			1
12	LS-200 3/8"/URETHANE**	X	X			1
14	IMIDE FOAM	X	X			1
SEAT TESTS: SEATS + FULL INTERIOR						
33	VONAR 3/16"/POLYESTER/UR** (1.5 MPH)		X			1
34	VONAR 3/16"/POLYESTER/UR**	X	X	X	X	1
35	URETHANE (CUSHION-MAT.21)	X	X	X	X	1
36	FUEL FIRE ONLY (1.5MPH)	X	X		X	1
41	NONCOMBUSTIBLE SEATS (FABRIC- MAT.23)***	X	X		X	1
62	NORFAB/URETHANE (FOAM-MAT.20)	X	X	X	X	2
63	URETHANE (CUSHION-MAT.21; PANEL-MAT.N6)*	X	X	X	X	2
64	URETHANE (CUSHION-MAT.21; PANEL-MAT. N8)*	XX			X	2
8202	URETHANE (CUSHION-MAT.21) (NO PANELS)	X				2 + CAPILLARY
INFLIGHT CONDITIONS: PAPER FIRE UNDER SEATS						
49	LS200-3 ROWS	X				2
50	URETHANE -3 ROWS (CUSHION-MAT.21)	X				2

* THIS PANEL WAS USED ON SIDEWALLS, CEILING, AND HATRACKS. PANEL MATERIALS 4,6 AND 13 WERE USED FOR OTHER TESTS. THE NUMBER OF PANELS WAS REDUCED.

** CUSHION MAT.18 WAS USED FOR BLOCKED SEATS.

*** THE FABRIC MATERIAL NO. 23 WAS SUBSTITUTED FOR THIS TEST ONLY. MAT. NO. 15 WAS USED FOR FOR OTHER TESTS.

TRENDS FROM ONE SAMPLING LOCATION TO ANOTHER FOR FULL INTERIOR POST-CRASH TESTS.

Four sampling locations were utilized: three at station 650 at heights of 5.5 feet, 3.5 feet and 1.5 feet, and one at station 880 at 5.5 feet. At station 650, gas levels generally increase with increasing height. Test 62 is fairly representative of this stratification (figure B-5). Variation of gas levels with position down the length of the fuselage is less dramatic. Tests 62 and 63 are the exception, where HF levels are significantly higher at the 880 location.

TRENDS FROM TEST TO TEST FOR FULL INTERIOR TESTS.

Post-Crash Fire. Seat cushion blocking layers delay and perhaps reduce the acid gas production in post-crash fires. Figure B-6 illustrates the HF and HCl concentrations as a function of time measured for the following tests:

Test No.	Test Description
34	Vonar Protected Cushion
35	Unprotected Cushion
41	Non-Combustible Foam Cushion
62	Norfab Protected Cushion

It can be seen that the use of the Vonar™ and the aluminized fabric Norfab™ resulted in a marked delay in the evolution of the acid gases and lower peak concentrations in the fuselage. The noncombustable foam (Kaowool™) results in the greatest delay of acid gas production. The seat cushion blocking layers delay the combustion of the cushions, and thus delay the fire involvement of the aircraft panels, the major HF source.

Removing the panels from the fuselage removes the HF hazard and delays the evolution of HCl. A comparison of test 35 and test 8202 (no panels) shows that the panels are the predominant source of HF (figure B7).

In-Flight Fire. Two tests were run in this series. Three rows of seats with paper crumpled under them were ignited. In-flight conditions were maintained during the test: one air exchange every 4-minutes and no open doors. LS200 seats were used in test 49; whereas FR urethane seats were used in test 50. Figure B-8 illustrates the extremely high concentrations (in excess of 4500 ppm) of HCl produced in test 50. These high levels come from the seats only. LS200 seats completely eliminate the acid gas hazards in in-flight fires of this type.

SOURCES OF GAS YIELDS.

The only significant source of HF in these tests is the honeycomb panels. The other materials contribute little to HF evolution. This can be seen from the combustion tube furnace gas yields of the individual test materials in table B-2. This is also illustrated in the results of test 8202 where no panels were installed. Otherwise, test 8202 is similiar to the full interior test 35. Peak HF yields in test 35 exceed test 8202 yields by a factor of 13. The low yields obtained for test 8202 also show that soot buildup on the walls and ceiling of the fuselage from previous tests, is an insignificant source of HF during full-scale C133 fire tests.

HF levels as high as 1100 ppm were seen in test 34 and 35. The presence of high levels of HF is predictable from the small-scale testing of the panels; based on the combustion tube furnace yields for the ceiling panel, about one 4-foot by 6-foot panel is needed to obtain a uniformly dispersed concentration of 100 ppm in the fuselage. Tweleve ceiling panels were used in these tests. Hatrack and side-wall panels also have high HF yeilds.

Removing panels from the fuselage delayed but did not substantially reduce the HCl levels. This can be seen by comparing test 35 (full interior) and 8202 (full interior, no panels) in figure B-7. Thus materials other than panels are largely responsible for the high HCl yields in this series of tests. Note, from table B-2 that HCl combustion tube furnace yields are low for all the panels used in the blocking layer tests. The cushions, carpeting, fabric, armrests, and panels collectively account for the high HCl yields.

DEPOSITION TEST SERIES.

Three tests were conducted to characterize the deposition error. The first test was conducted in the C133 with a full interior. For this test, convection and diffusion of gases and particulates contributed to the deposition error. The second test was a pure gas exposure of HCl. Diffusion was the only contributor to deposition in this test. The third test was an NBS smoke chamber test of a panel. Diffusion again was the only contributor to deposition in this study.

TEST 1: C133 DEPOSITION TEST

Full interior post-crash test 64 was run in the C133 to investigate the following:

(1) The effect of long vacuum lines on gas yields.

(2) The level and variability of blank sample yields.

(3) The effect of absorption tube orientation on deposition.

(4) The reproducibility of yields obtained using two sampling stations at the same location.

Figure B-9 illustrates the sampling station orientation. All sample boxes were at a height of 5.5 feet. Three boxes were at station 650 and one box at station 880. Two boxes at station 650 (boxes 1 and 2) were tilted at an angle of 30° as illustrated. Each of these boxes contained eight time-sequenced tubes and two blank tubes capped about 12 feet downstream along the sample solenoid assembly. Box 3 contains four blank tubes capped inside the box. This box faced forward. Box 4 at station 880 contained seven time-sequenced tubes and three blank tubes, one capped at the tube, the other two capped further downstream alongside the solenoid assembly. The results of this test are shown in table B-4. Concentration time profiles for this test can be found in figure B-10. Video coverage indicated high air velocity from forward to aft in the top layer of smoke: tissue streamers, each 2 feet long, hung from the ceiling at various stations in the fuselage, changed from a vertical (hanging) to diagonal position 1.5 minutes into the test (figure B-11). This suggests that high flowrate of the smoke steam into the faces of the sample tubes may account for the high blank yields for boxes 3 and 4.

TABLE B-4. DEPOSITION YIELDS AS A FUNCTION OF LOCATION AND ORIENTATION IN C133 FULL INTERIOR TEST 64

LOCATION — YIELDS (PPM)

LOCATION	HYDROGEN FLUORIDE: BLANKS		HYDROGEN FLUORIDE: FIRST 4 SAMPLES		HYDROGEN CHLORIDE: BLANKS		HYDROGEN CHLORIDE: FIRST 4 SAMPLES	
	CAPPED AT TUBE BOX 3	CAPPED DOWNSTREAM BOX 1+2	VALVE DOWNSTREAM BOX1	BOX2	CAPPED AT TUBE BOX3	CAPPED DOWNSTREAM BOX 1+2	VALVE DOWNSTREAM BOX1	BOX2
	9.0	2.6	1.4	1.2	109.2	21.0	7.2	10.0
	19.0	2.7	1.1	1.0	215.3	17.4	4.5	12.0
	9.4	1.6	1.3	0.9	94.1	27.0	7.3	10.7
650 AT 5.5FT	11.8	1.3	1.1	0.9	122.3	16.0	10.3	18.5
	$\bar{X}$= 12.3 SD= 4.6 %RSD=37.7	$\bar{X}$=1.4 SD=.61 %RSD=42.6			$\bar{X}$=135.2 SD=54.5 %RSD=40.4	$\bar{X}$=13.5 SD=6.6 %RSD=48.8		
	10.5	4.5	7.0	5.3	95.4	39.8	90.9	64.2
880 AT 5.5FT (BOX4)		9.7	4.4	5.7		59.9	71.5	55.9
	$\bar{X}$=10.5	$\bar{X}$=6.1 SD=2.0 %RSD=32.8			$\bar{X}$= 95.4	$\bar{X}$=63.7 SD=17.0 %RSD=26.7		

The two variables in this test were the length of the vacuum lines and the orientation of the sample boxes. The following trends were observed for the test data in table B-4.

1. At station 650, the blank tubes in box 3 absorbed about nine times more than the blank and early sample tubes in boxes 1 and 2. Average gas yields in boxes 1 and 2 were low: HF=1.4 ppm, HCl=13.5 ppm.

2. At station 880, the directly capped and remotely capped blanks and the early sample tubes have high depositions, similiar to those in box 3 at station 650.

3. At location 880, the directly capped blank has HF and HCl yields, 1.5 times greater than the remotely capped blanks and early sample tubes. This difference is small, relative to the difference at station 650.

4. The reproducibility of deposition for blank tubes in the same box is poor. Box 3 is the worst case: the four blank tubes had apparent early yields ranging from 94 ppm to 215 ppm HCl and a standard deviation of 55 ppm. The peak HCl concentration for this station is 2300 ppm. The deposition range for box 3 would be 470 to 1075 ppm if the sampling volume was decreased to 0.5 liters.

5. The reproducibility of gas yields obtained using two stations at the same location appears good. This can be seen by inspection of the concentration time profiles for boxes 1 and 2 in figure B-10.

Based on the first four observations and the video coverage of this test, it appears that the obstruction of the galley, and the orientation of the face of the boxes towards the direction of airflow, account for the differences in blank yields for the different sampling locations.

The first observation indicates that vacuum sampling line error is not significant in these tests. It also indicates that the long post-test exposure of the tubes to ambient conditions does not result in a significant deposition error. Boxes 3 and 4 have a similiar level of post-test exposure as do boxes 1 and 2 which had insignificant deposition levels.

TEST 2: PURE HCl DEPOSITION TEST

Four absorption tubes of each configuration were exposed to a constant level of HCl for 6 minutes. The exposure chamber is a 4-liter glass flask containing about 300 milliliters (ml) of hydrochloric acid solution, capped with a rubber stopper and constantly stirred to obtain an equilibrium gas concentration in the flask.

The absorption tube holder is a No. 10 rubber stopper with 8 holes bored to vertically mount the tubes (figure B-12). A small hole in the center accomodates a length of 0.8 mm i.d. teflon tubing which is submerged in the HCl solution during the test. As samples are drawn from the flask, ambient air will first bubble through the HCl solution and help maintain the equilibrium HCl gas concentration.

An evacuated bottle was used to draw the samples. The volumes drawn through each sample tube were measured with a wet test meter prior to the test. Three tubes of each configuration are blanks and the tops of the tubes are capped during the test. The bottoms are exposed to the equilibrium HCl concentrations for the 6-minute test duration. The other tubes are piggybacked sample tubes and are capped when not sampling.

After 5-minutes of equilibration, the solid rubber stopper was removed and was immediately replaced by the sample holder with capped tubes. Samples were taken at 2-minutes and 4-minutes into the test. The first sample was taken by two piggy-backed tubes of configuration 2 and the second sample was taken by two piggybacked tubes of configuration 1. Two identical test were run, each with different HCl concentrations. The test results are listed in table B-5. The collection efficiencies exceed 99 percent for both configurations. The deposition rate (percent deposition/minute) and the variability is about the same for both configurations. A deposition rate of 0.7 percent per minute was observed for test A and 0.4 percent per minute for test B. In addition, it appears that the level of deposition is independent of the tube configuration.

TABLE B-5. COMPARISON OF DEPOSITION YIELDS FOR PURE HCL EXPOSURES

		SAMPLES				BLANKS						
TEST	TUBE TYPE	SAMPLE VOLUME (LITERS)	HCL (PPM) A	HCL (PPM) B	COLL. EFF. (%)	HCL DEPOSITION (PPM)			$\bar{X}$	SD	% RSD	%DEP/MIN
A	2	.53	280.0	2.6	99.1	9.2	14.1	6.2	9.8	4.0	41.	0.7
	1	.53	236.2	1.9	100.0	9.2	10.2	25.4	14.9	9.1	61.	
B	2	.54	4033.	0.5	100.0	64.1	151.1	68.5	94.5	49.0	52.	0.4
	1	.54	3335.	4.7	99.9	113.7	50.2	66.0	76.7	33.1	43.	

TEST 3: DEPOSITION TEST FOR A CEILING PANEL

An exposure of an aircraft ceiling panel was conducted under flaming conditions in the National Bureau of Standards (NBS) smoke chamber. The test panel is a ceiling panel of the following composition: PVF/phenolic-fiberglass screen/aramid honeycomb filled with phenolic-fiberglass bat/phenolic-fiberglass. The sample size is 3 inches by 3 inches and the test duration is 6 minutes. Three blank tubes of each configuration and two sample tubes of configuration 2 were exposed to the test atmosphere using the tube holder in figure B-12. The tubes are mounted horizontally in the center of the chamber, 6 inches from the top. A separate line connects each sample tube to a bulkhead fitting at the top of the chamber. Each fitting is capped when a sample is not being drawn. An evacuated bottle was used to draw samples. A volume of 0.5 ℓ was drawn. Two tests were conducted with samples taken at different times for each test.

The test results are listed in table B-6. Again, as in the pure gas study, the level of deposition on the blank tubes is the same for both tube types. A deposition rate was calculated for each gas, based on the average concentration observed over the 6-minute test period. A deposition rate of 1.6 percent per minute for HF and 0.4 percent per minute for HCl was obtained. Note that the deposition rate for HCl is identical to the deposition rate obtained in the pure gas study.

CONTRIBUTION OF DIFFUSION TO DEPOSITION FOR FULL INTERIOR C133 TESTS.

The highest deposition rates for HF and HCl obtained from test 2 (pure HCl test) and test 3 (panel test) are listed in table B-7. These values were used to predict the contribution of diffusion to the deposition for the C133 full interior test 64. Table B-8 lists the gas concentrations measured for test 64 at box 2, station 650. The calculated depositions are also listed. Depositions of 1.0 and 3.8 ppm are predicted for HF and HCl, respectively. These values are low, indicating that deposition due to diffusion (during the 4-minute test duration) is a minor error.

Depositions of 1.4 and 13.5 ppm, respectively, were observed for HF and HCl in test 64 at box 2. These values are higher but reasonably close to the calculated values. However, the depositions observed at box 3 and 4 are far greater: 12.3 and 135.2 ppm, respectively, at box 3, and 10.5 and 95.4 ppm, respectively, at box 4. Convection effects probably account for this high deposition.

FINDINGS.

Some caution should be taken in the interpretation of early yields for blocking-layer tests with a full interior. Major deposition errors probably existed for tests 35 and 41. Early yields may be present in these tests, but are probably masked by higher deposition errors. Factoring down the potential deposition error by using larger sampling volumes resulted in lower early yields for subsequent tests (49 to 64 and 8202). No deposition errors were observed for tests 49, 50, and 62. Low but significant deposition errors were observed for tests 63 and 64.

These results are consistent with the large convective currents in post-crash conditions (tests 63 and 64) versus lower convection in in-flight conditions (tests 49 and 50).

Deposition effects for full interior fires under post-crash conditions caused some uncertainties in the early test data. These effects must be significantly reduced for future fire tests. This should be done as follows:

1. Use larger sampling volumes (2.5 liters versus 0.5 liters)

2. Place a short length of capillary glass tubing in front of the sample tube. This will factor down the deposition error by decreasing the area of the tube face open to the test atmosphere. For example, as the tube ID decreases from 4mm to 2mm, the error is decreased by a factor of 4.

3. Orient the tubes perpendicular to the convective smoke stream.

TABLE B-6. TEST DATA FOR A CEILING PANEL IN THE NBS SMOKE CHAMBER

TEST NO.	TUBE TYPE	SAMPLES				BLANKS			
				CONCENTRATION		DEPOSITION (6 MINUTE EXPOSURE)			
		TIME (MIN)	Ds	HF (PPM)	HCL (PPM)	HF (PPM)	$\bar{X}$	HCL (PPM)	$\bar{X}$
	2	0.5	63.	258.	384.	12.4		9.4	
	2	2.0	228.	157.	241.	14.7		5.3	
A	2	4.0	244.	117.	182.	12.7	13.3	7.6	7.4
	1					11.2		0.2	
	1					15.4		1.1	
	1					18.3	15.0	6.8	2.7
	2	-5.0	0.	15.3	12.6				
	2	.25	0.6	76.5	34.4				
B	2	2.0	217.	144.	251.				
	1					9.8		4.7	
	1					9.5		0.0	
	1					14.7	11.3	11.8	5.5
AVERAGE CONCENTRATION (PPM) (6 MIN. EXPOSURE) =				140.	221.				
					AVERAGE DEPOSITION (PPM) (6 MIN. EXPOSURE) =		13.1		5.2
					DEPOSITION/MIN (PPM/MIN) =		2.18		0.87
					% DEPOSITION/MIN =		1.6		0.4

* SAMPLE VOLUME = 0.53 liter

TABLE B-7. DEPOSITION RATES OF HF AND HCL DUE TO DIFFUSION ONLY

SAMPLE VOLUME (L)	GAS	%DEPOSITION/MIN	TEST NO.
0.5	HF	1.6	3 (PANEL TEST)
0.5	HCL	0.7	2 (PURE HCL)
2.5	HF	0.32*	3 (PANEL TEST)
2.5	HCL	0.14*	2 (PURE HCL)

* = calculated deposition rates decrease by a factor of 5, as sample volume increases by a factor of 5.

TABLE B-8. CALCULATED DEPOSITIONS FOR FULL INTERIOR C133 TEST 64. BOX 2, BASED ON DEPOSITION RATES OF SMALL SCALE TESTS

TIME (MIN)	HYDROGEN FLUORIDE CONC (PPM)	HYDROGEN FLUORIDE CALCULATED 30 SEC. DEPOSITION (PPM)	HYDROGEN CHLORIDE CONC. (PPM)	HYDROGEN CHLORIDE CALCULATED 30 SEC. DEPOSITION (PPM)
0-.5	1.4	.00	7.2	.01
.5-1	1.1	.00	4.5	.00
1-1.5	1.3	.00	7.3	.01
1.5-2	1.1	.00	10.3	.01
2-2.5	1.5	.00	27.7	.02
2.5-3	209.	.33	939.	.66
3-3.5	206.	.33	2156.	1.51
3.5-4	185.	.30	2189	1.53
TOTAL DEPOSITION	CALCULATED	1.0		3.8
	OBSERVED (BLANKS)	1.4		13.5

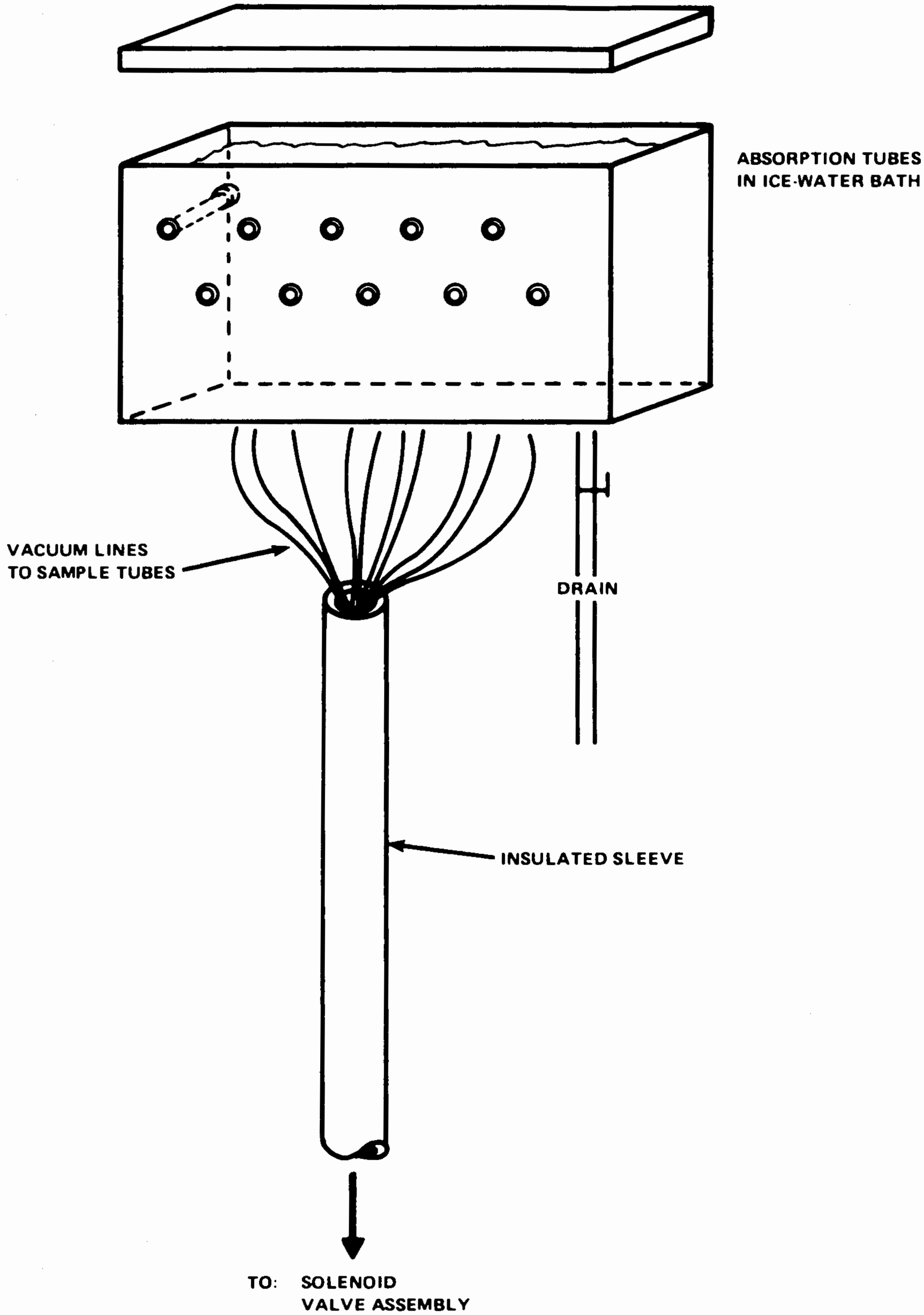


FIGURE B-1. C133 ACID GAS SAMPLING STATION

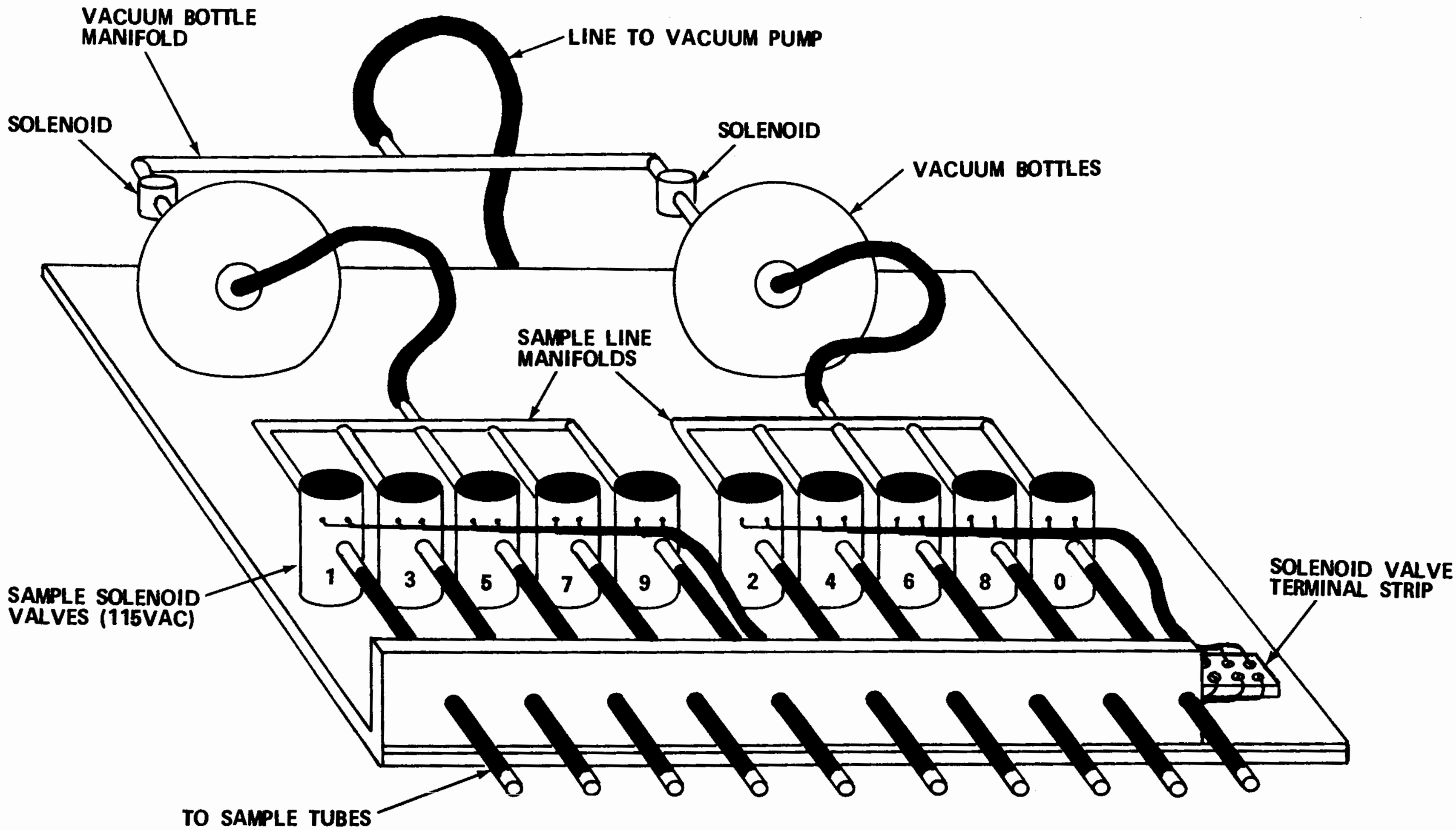


FIGURE B-2. SELENOID VALVE ASSEMBLY

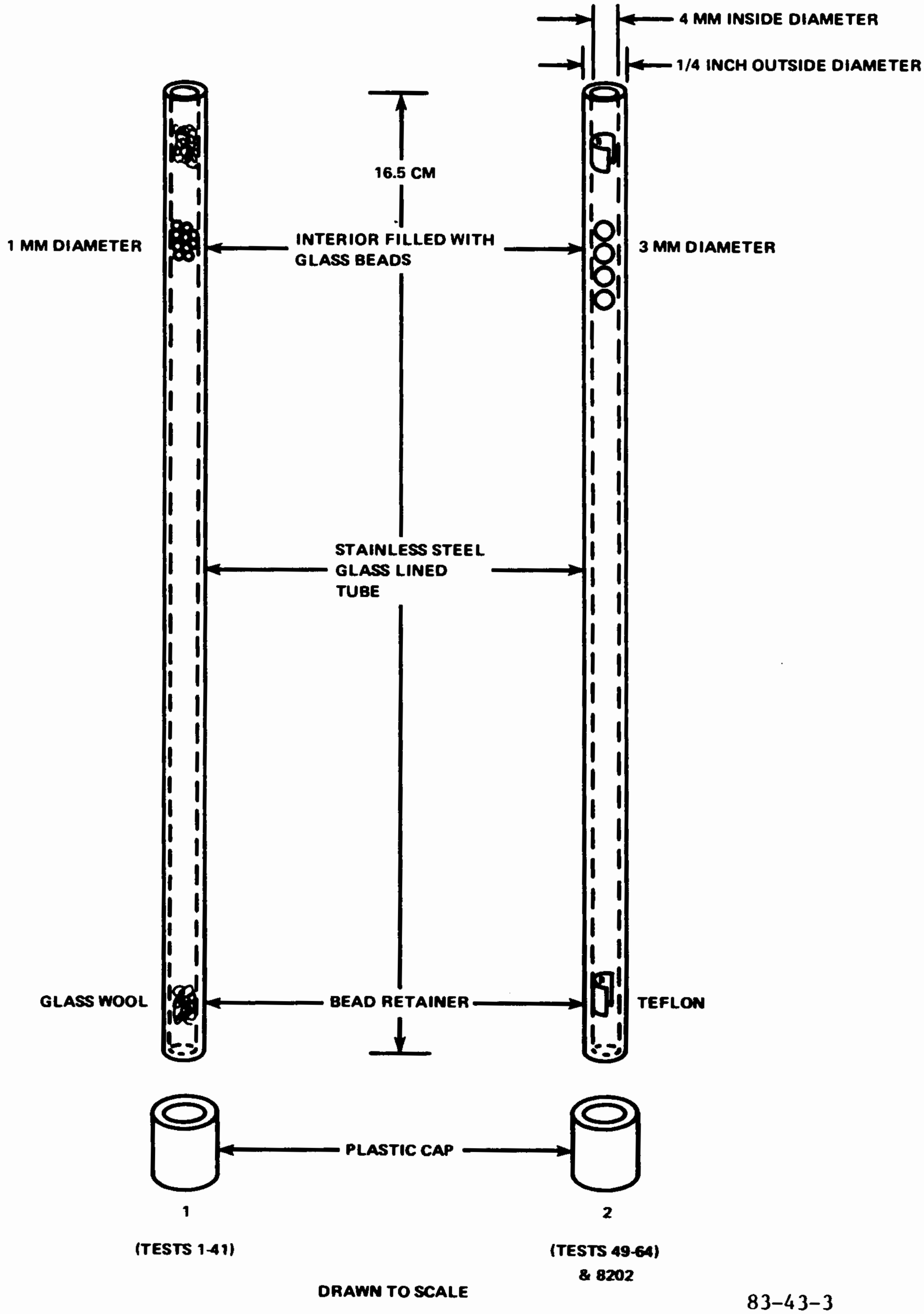


FIGURE B-3. ABSORPTION TUBES

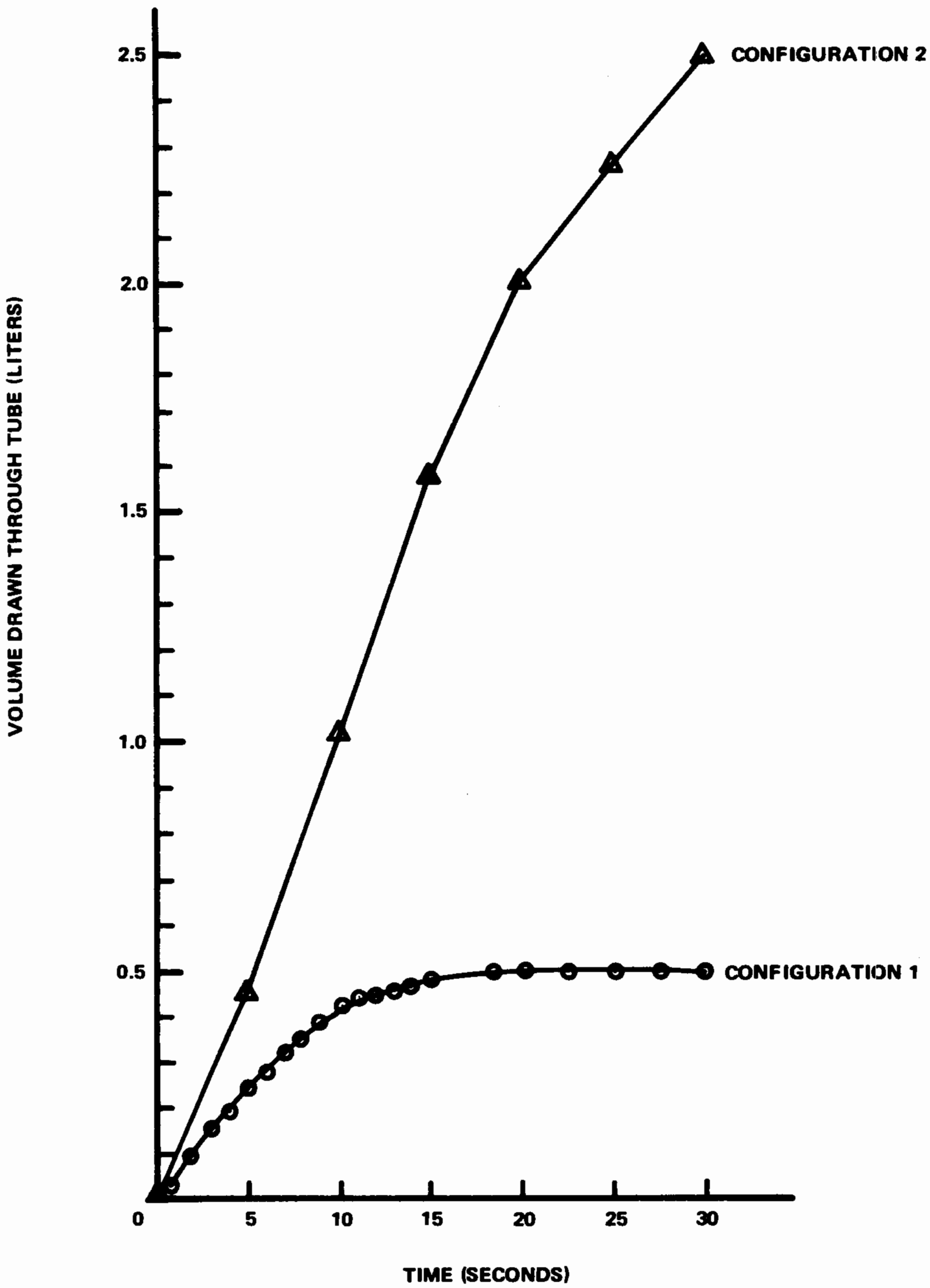


FIGURE B-4. VOLUME — TIME PROFILES FOR ABSORPTION TUBES

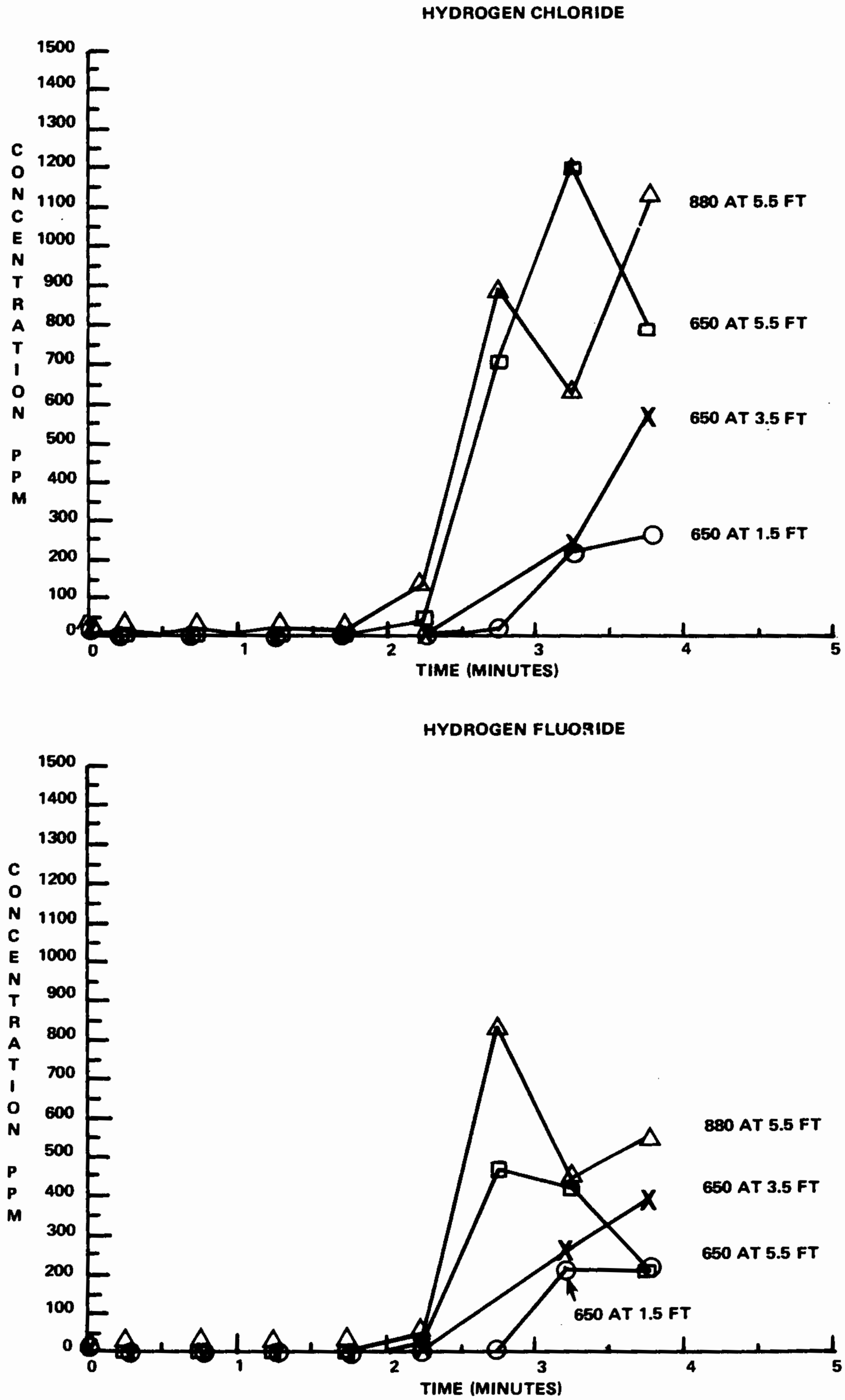
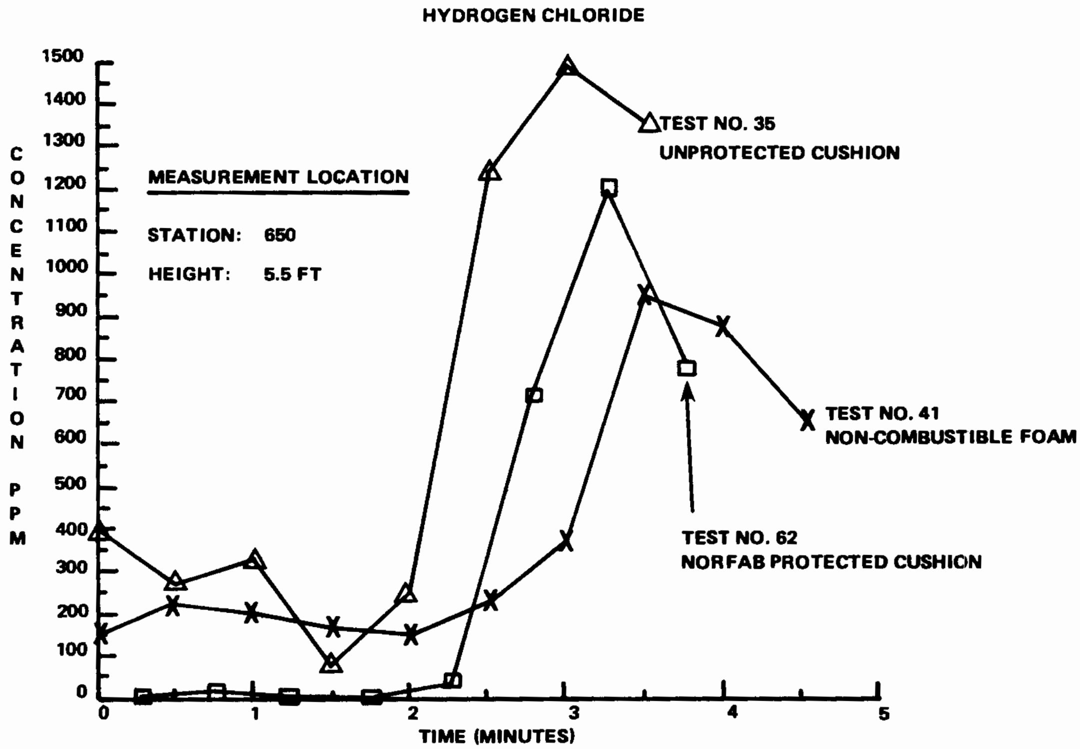


FIGURE B-5. EFFECT OF POSITION ON HF AND HCl LEVELS IN POST-CRASH FIRES: TEST 62



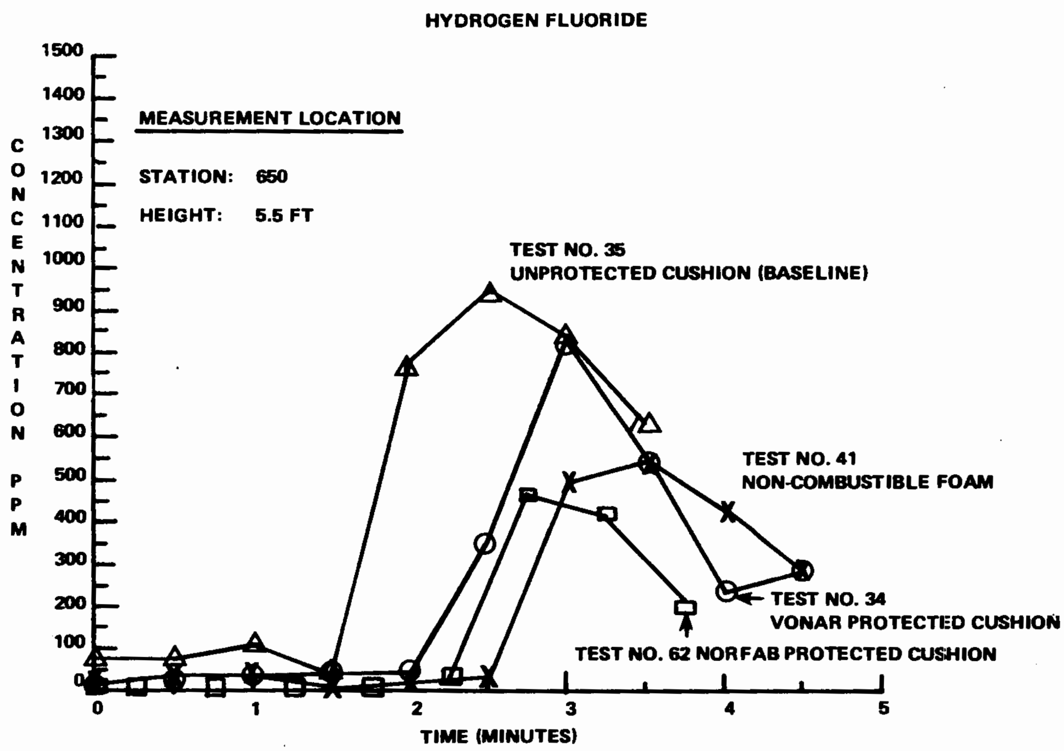
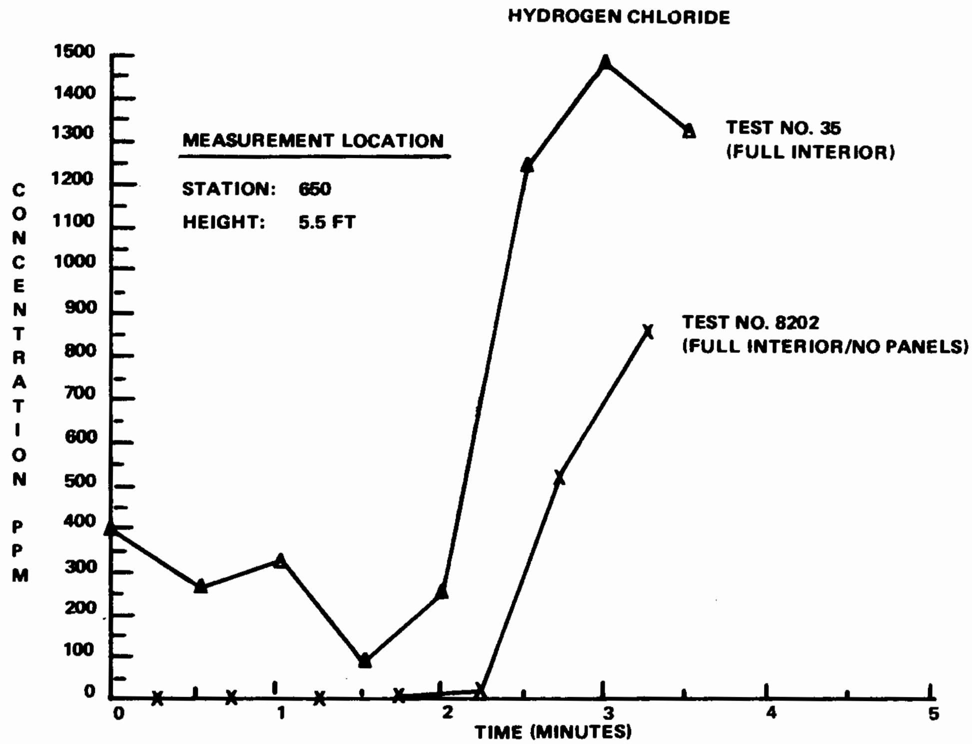


FIGURE B-6. EFFECT OF CUSHIONING PROTECTION AND MATERIALS ON HF AND HCl LEVES IN POST-CRASH FIRES



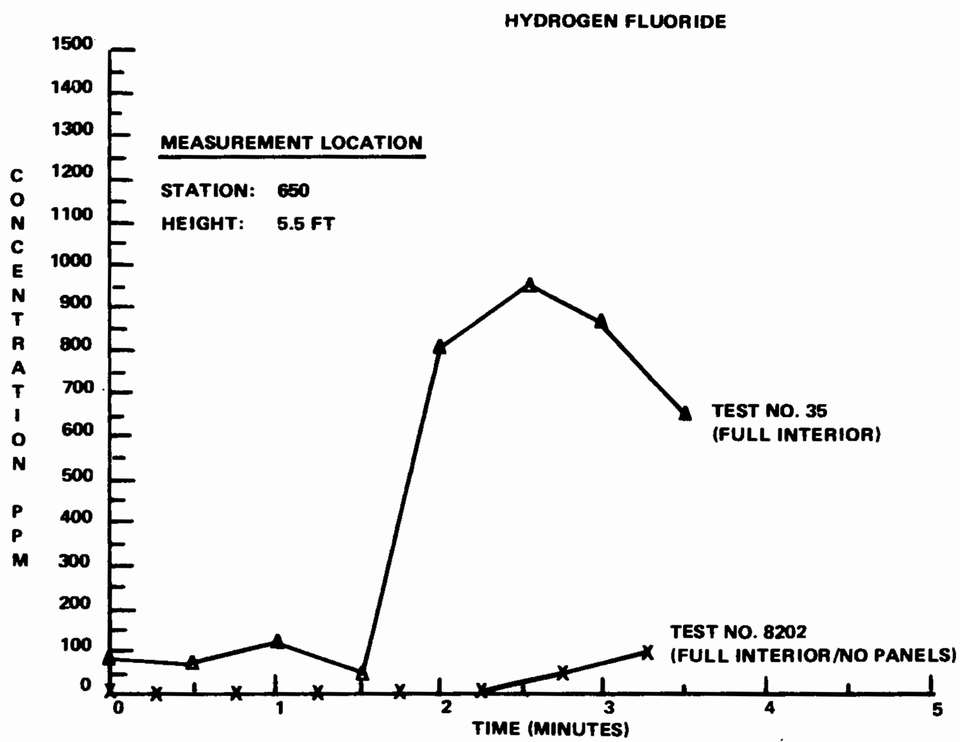
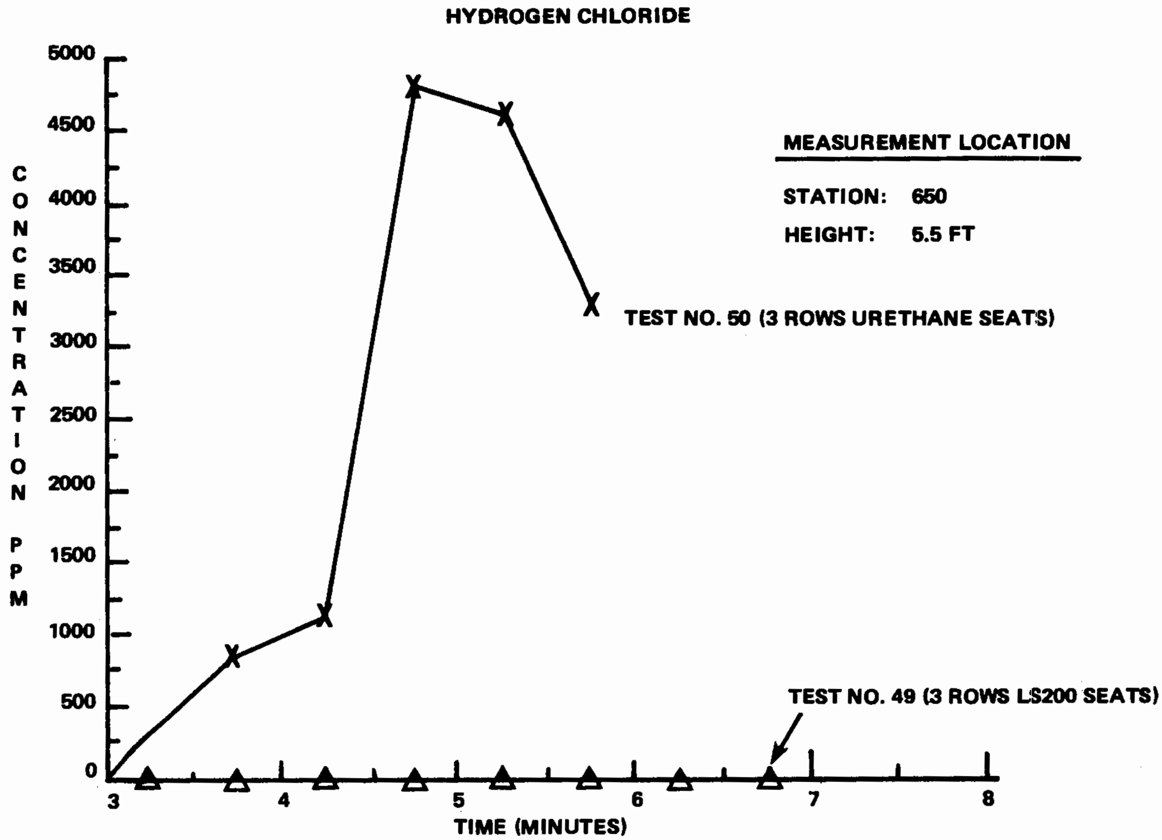


FIGURE B-7. EFFECT OF REMOVING PANELS ON HF AND HCl LEVELS IN POST-CRASH FIRES



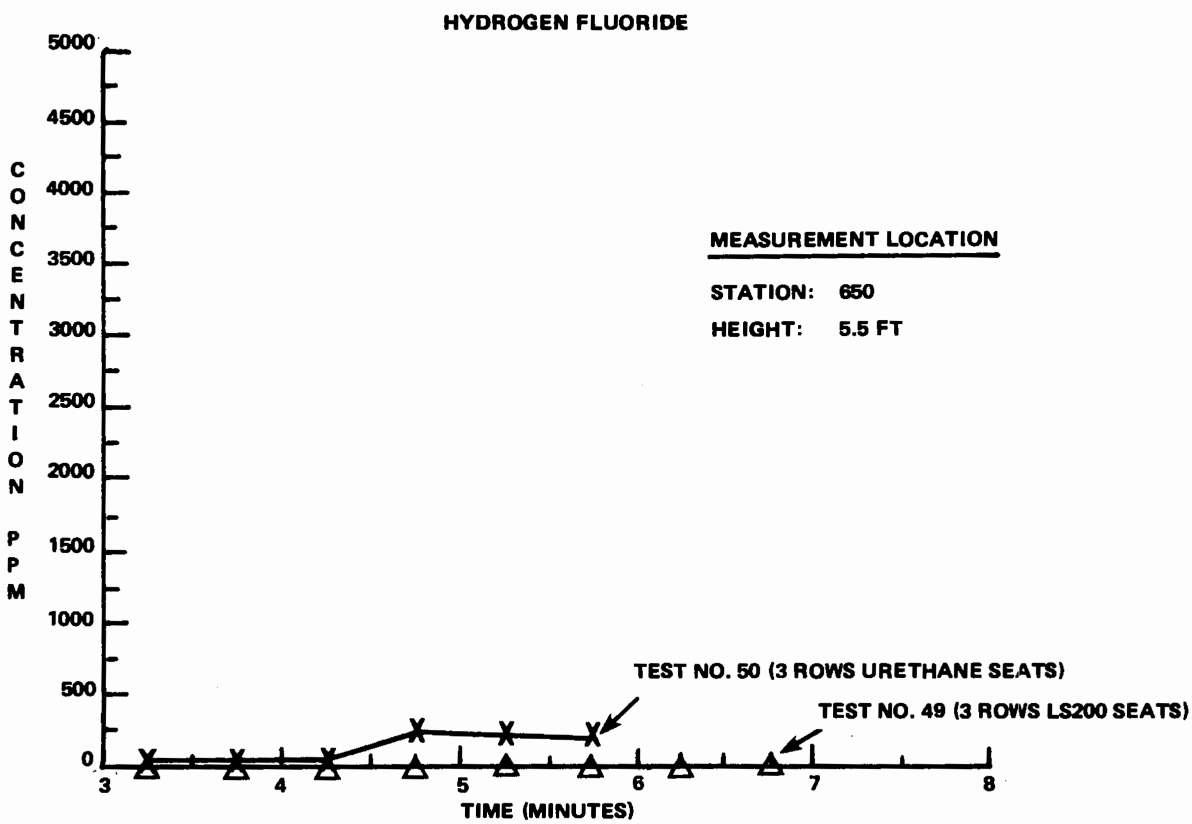


FIGURE B-8. EFFECT OF CUSHIONING PROTECTION AND MATERIALS ON HF AND HCl LEVELS IN IN-FLIGHT FIRES

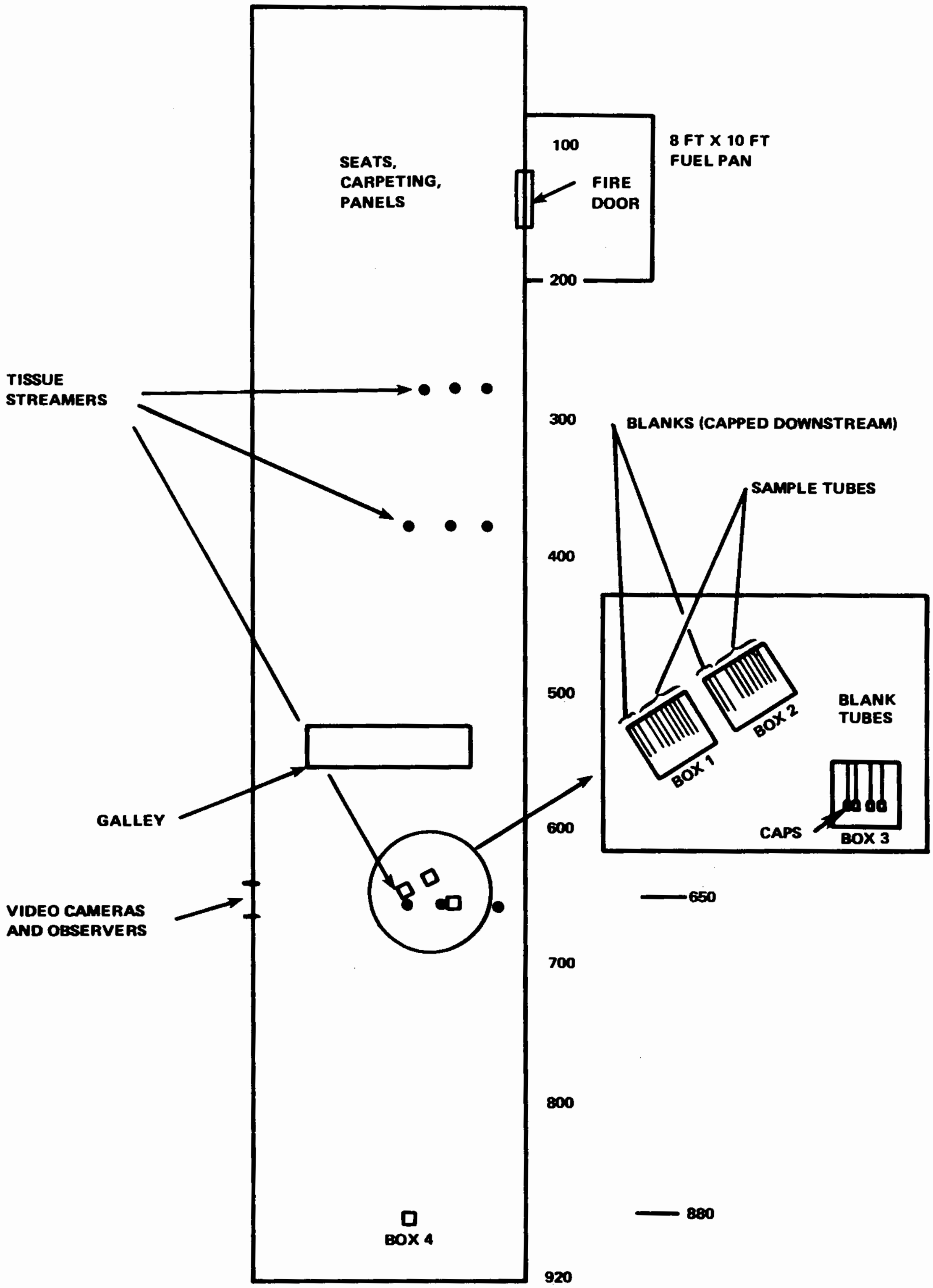
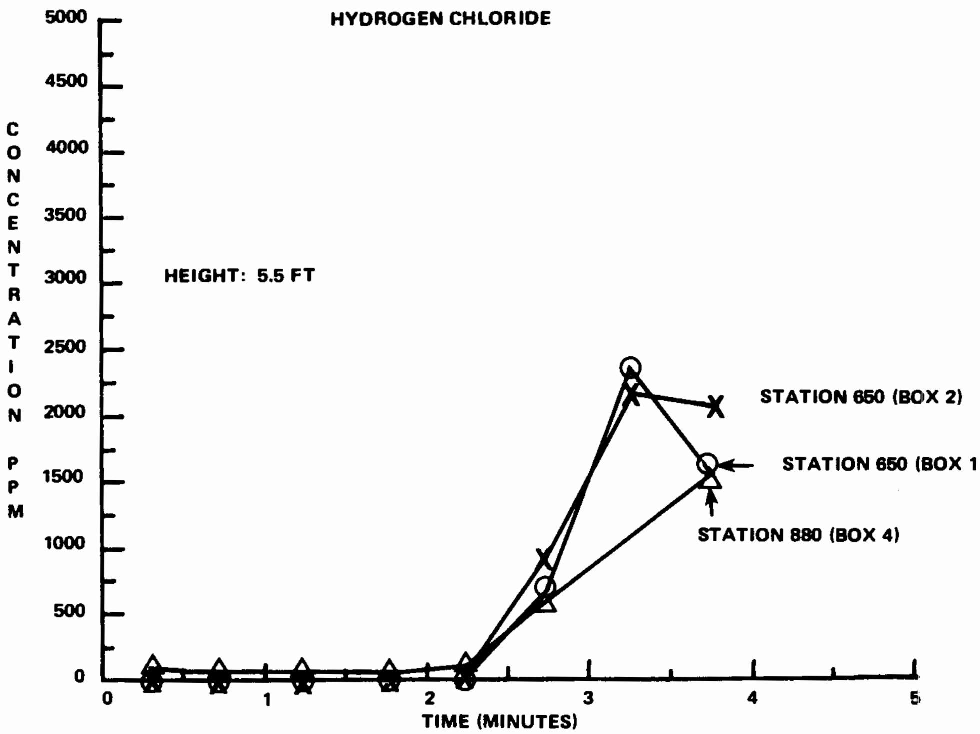


FIGURE B-9. POSITION DIAGRAM FOR ACID GAS SAMPLING STATIONS FOR C133 TEST 64



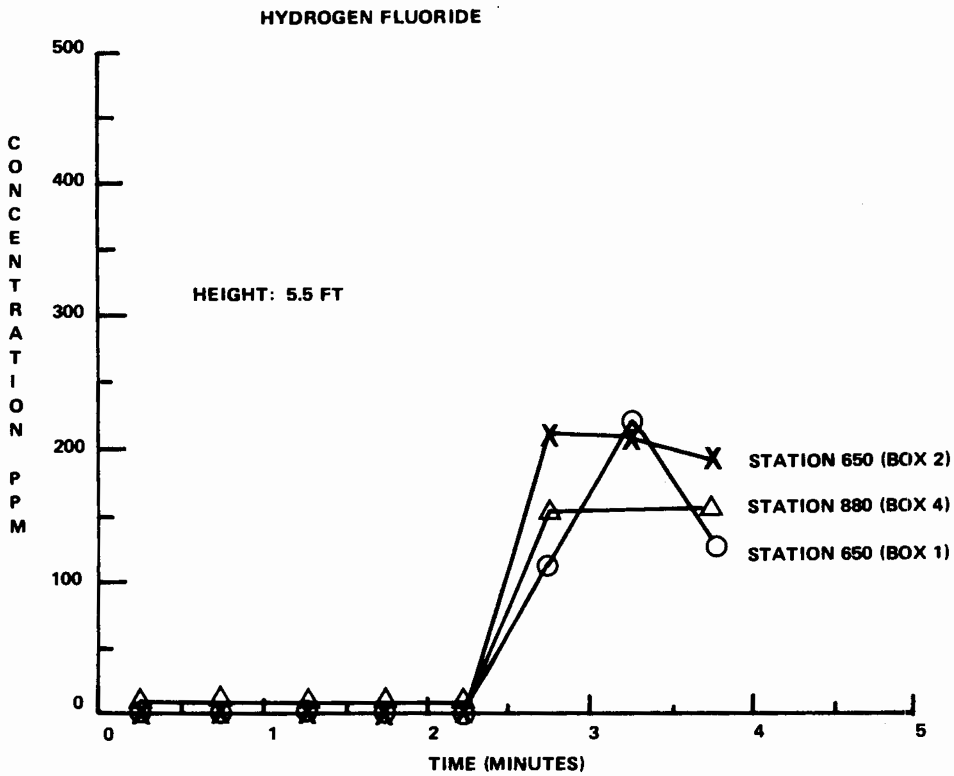
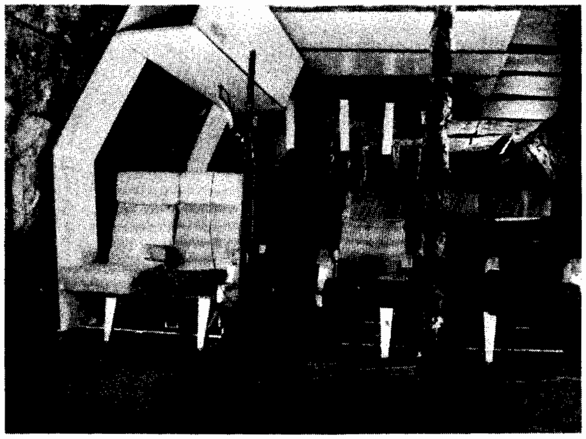


FIGURE B-10. CONCENTRATION — TIME PROFILES FOR C133 TEST 64



0 Seconds

75 Seconds

90 Seconds

FIGURE B-11. SEQUENTIAL PHOTOGRAPHS OF C133 TEST 64

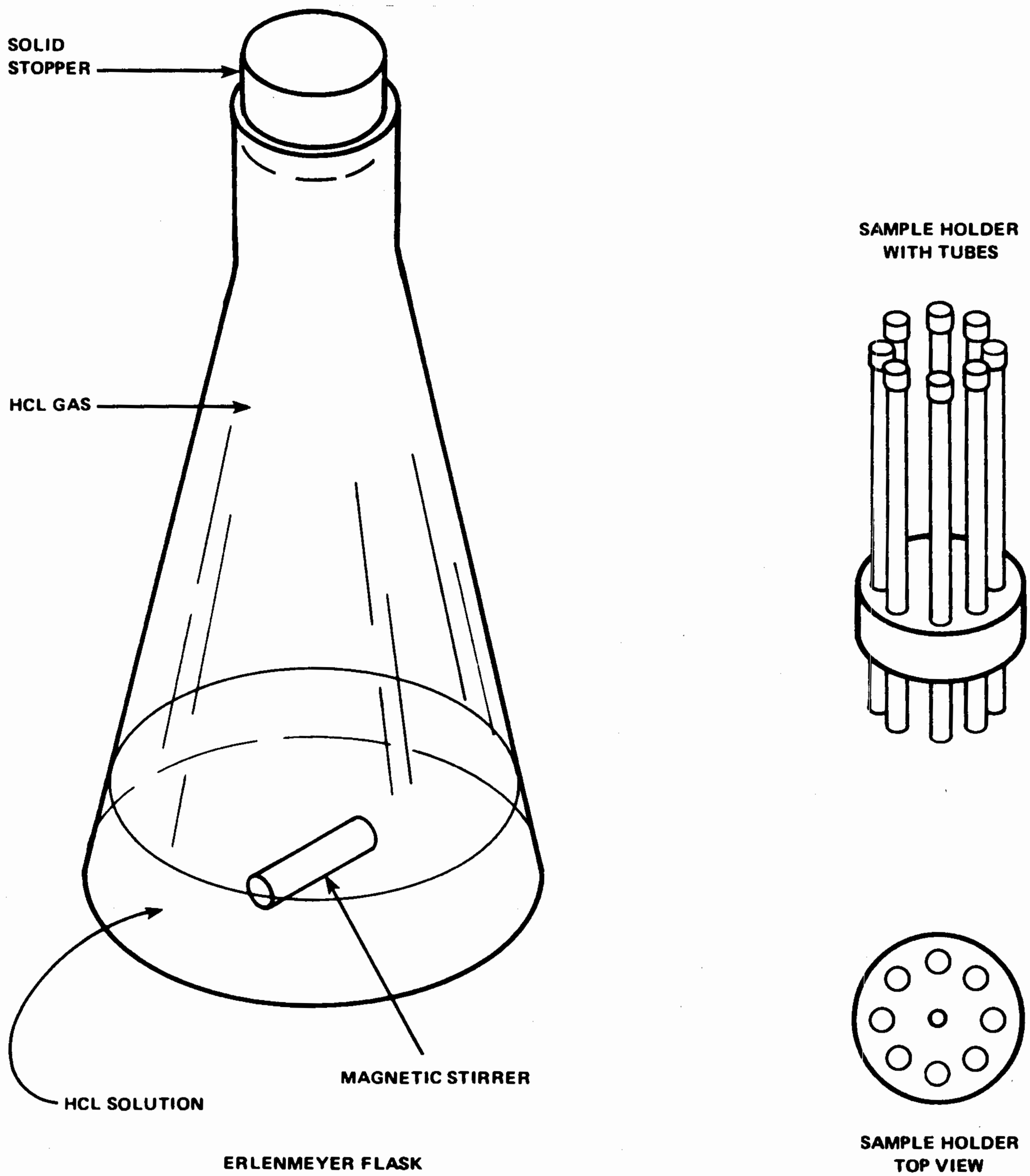


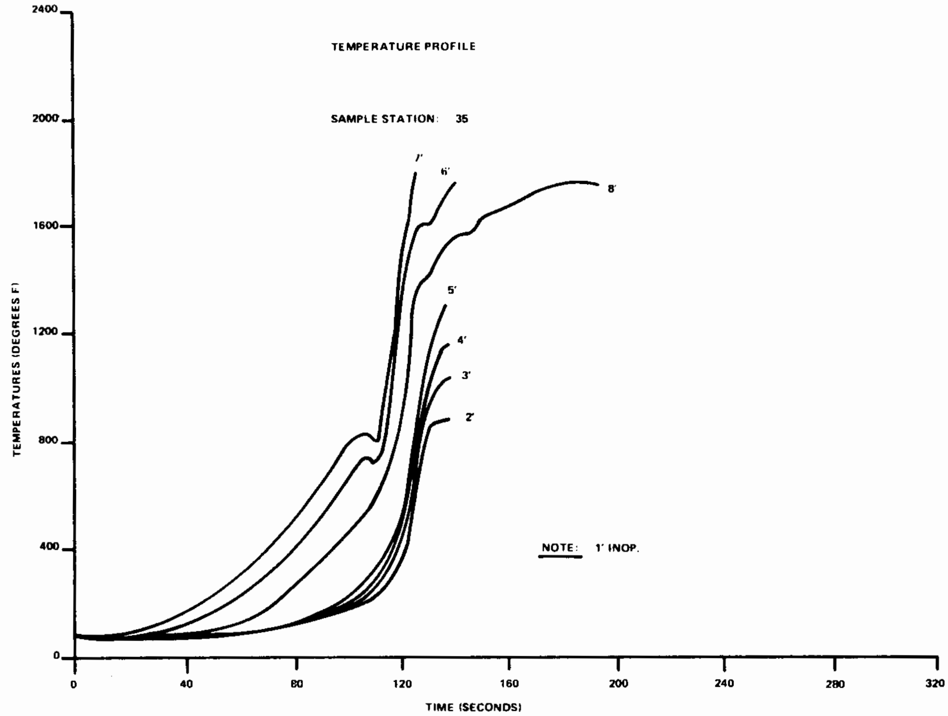
FIGURE B-12. PURE HCl EXPOSURE CHAMBER

APPENDIX C

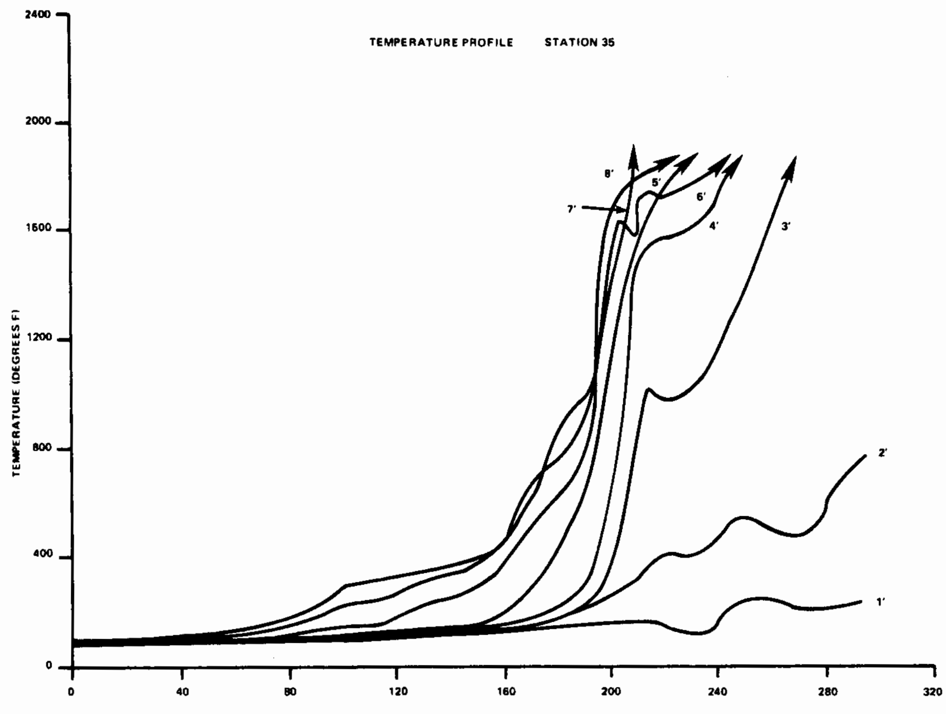
FULL-SCALE TEST DATA

Test Data shown is as follows for all figures:

(a) Test 33; (b) Test 34; (c) Test 35; (d) Test 41

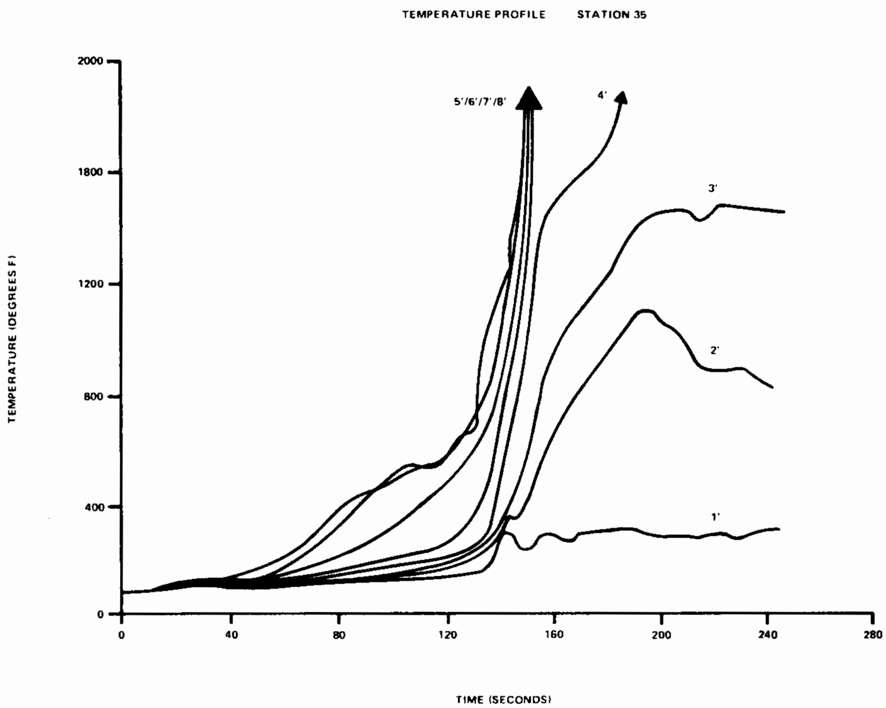


(a)

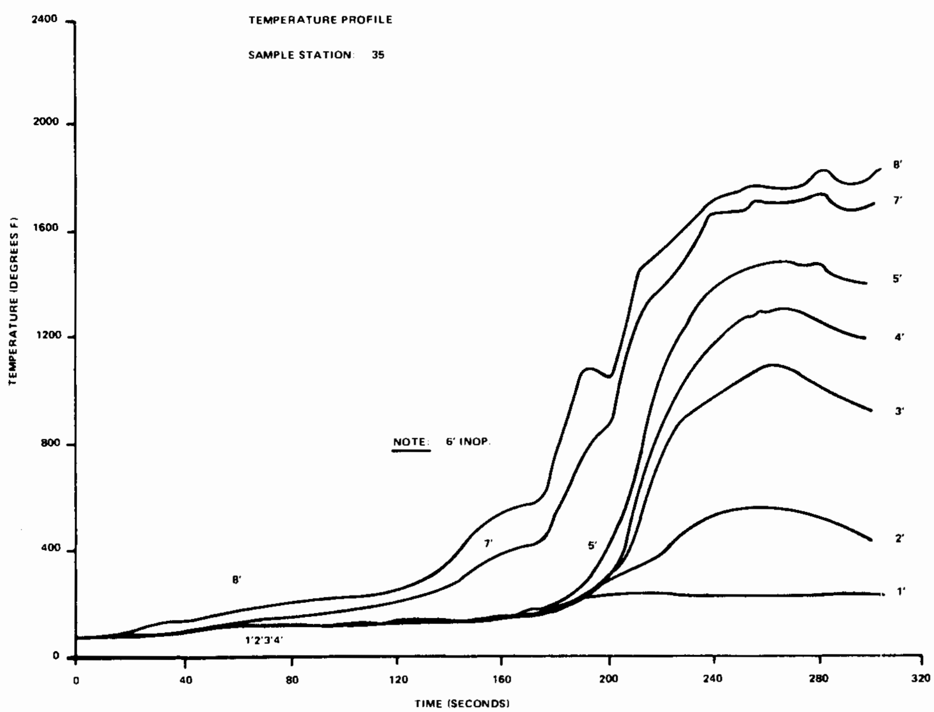


(b)

FIGURE C-1. TEMPERATURE PROFILE STATION 35 (1 of 2 Sheets)

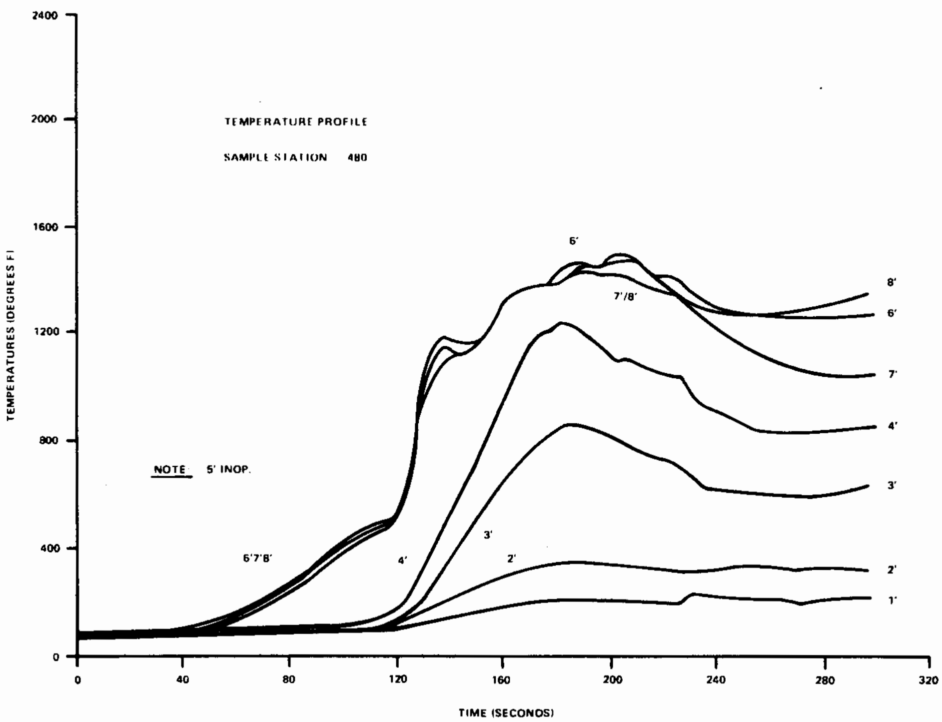


(c)

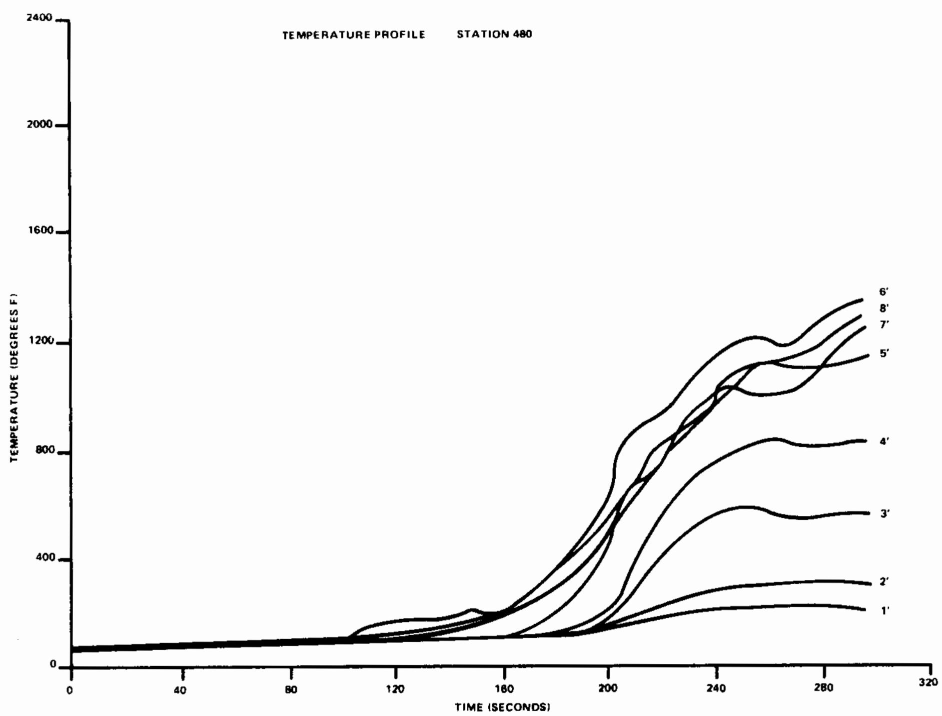


(d)

FIGURE C-1. TEMPERATURE PROFILE STATION 35 (2 of 2 Sheets)

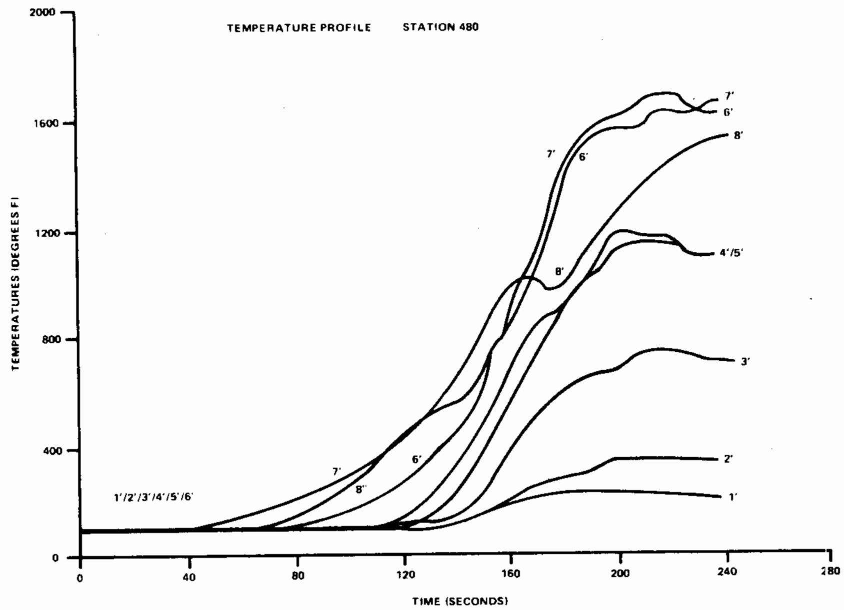


(a)

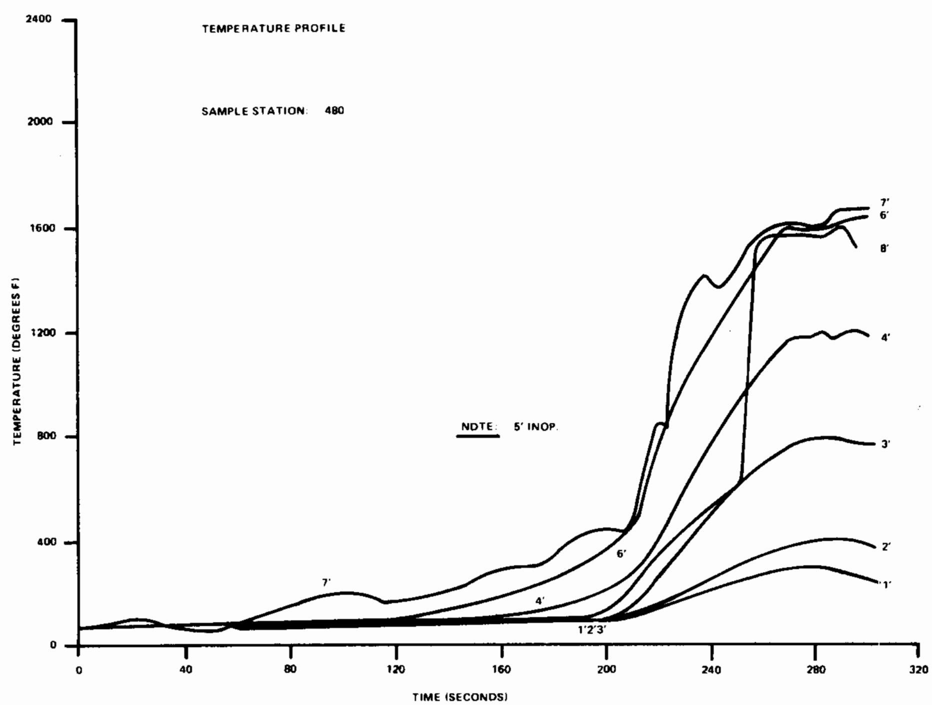


(b)

FIGURE C-2. TEMPERATURE PROFILE STATION 480 (1 of 2 Sheets)

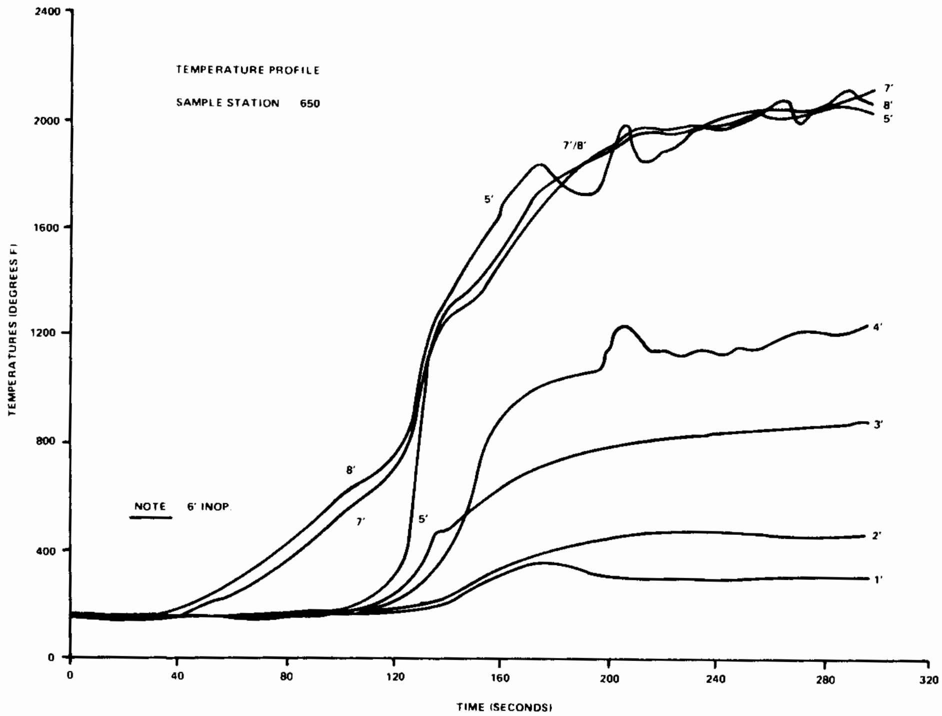


(c)

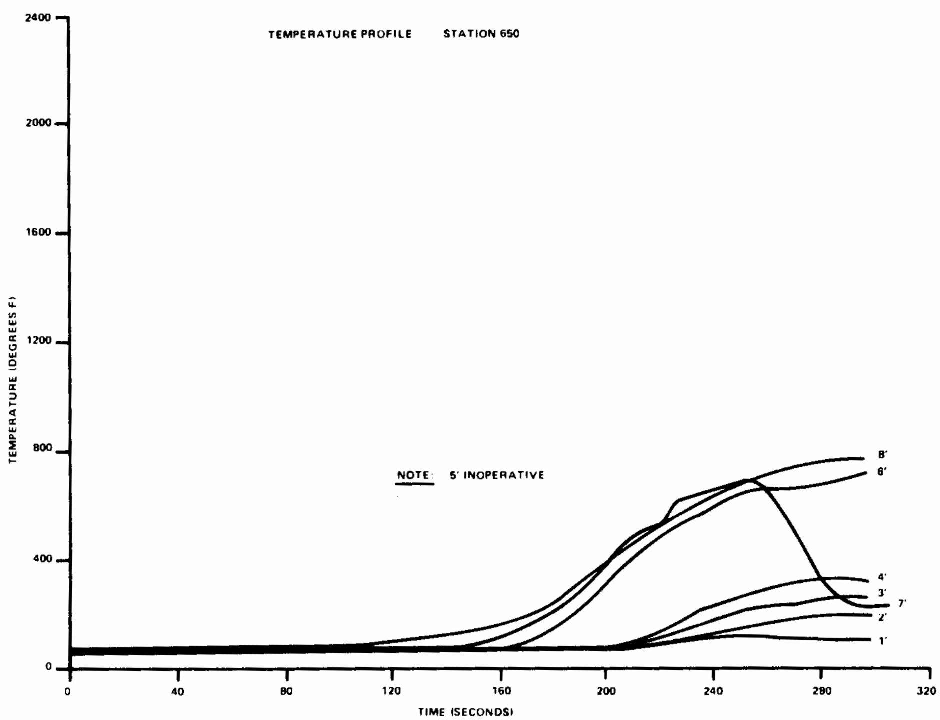


(d)

FIGURE C-2. TEMPERATURE PROFILE STATION 480 (2 of 2 Sheets)

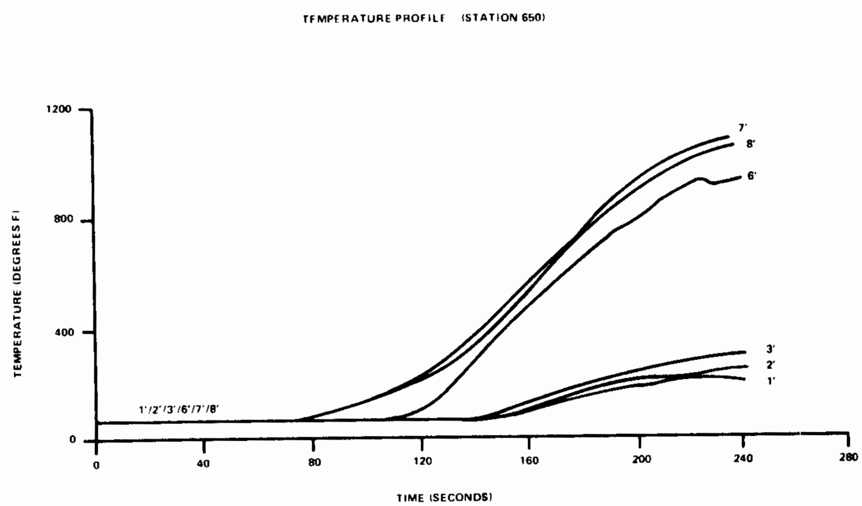


(a)

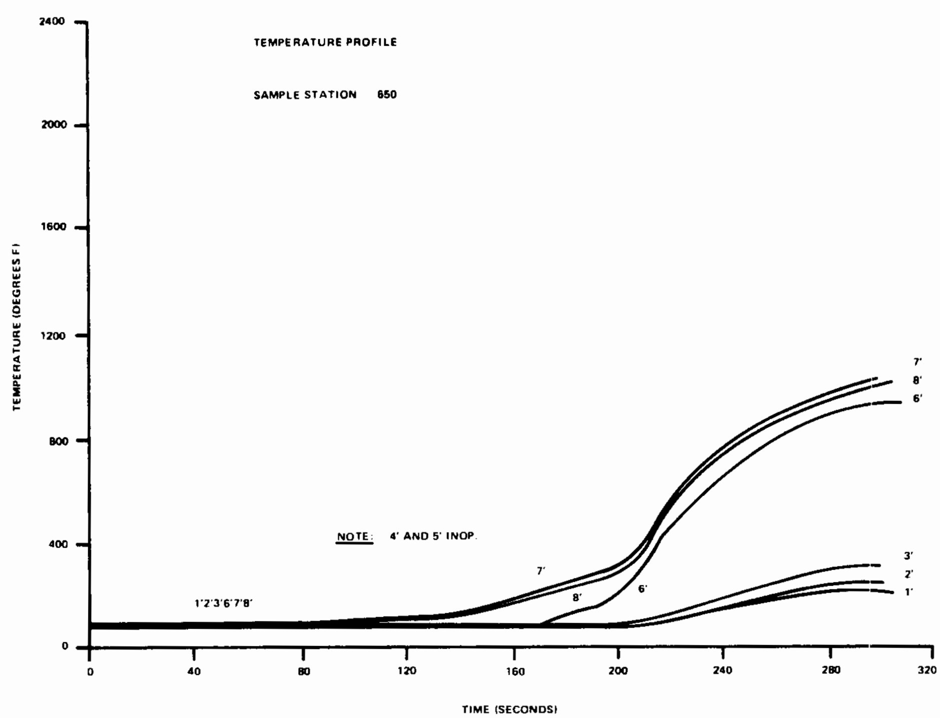


(b)

FIGURE C-3. TEMPERATURE PROFILE STATION 650 (1 of 2 Sheets)

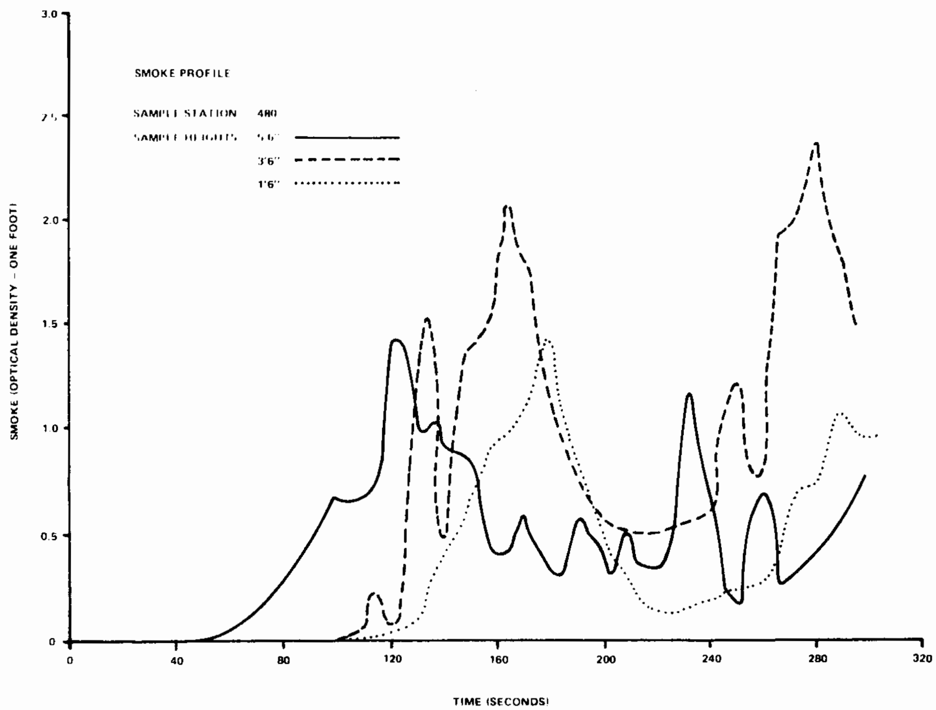


(c)

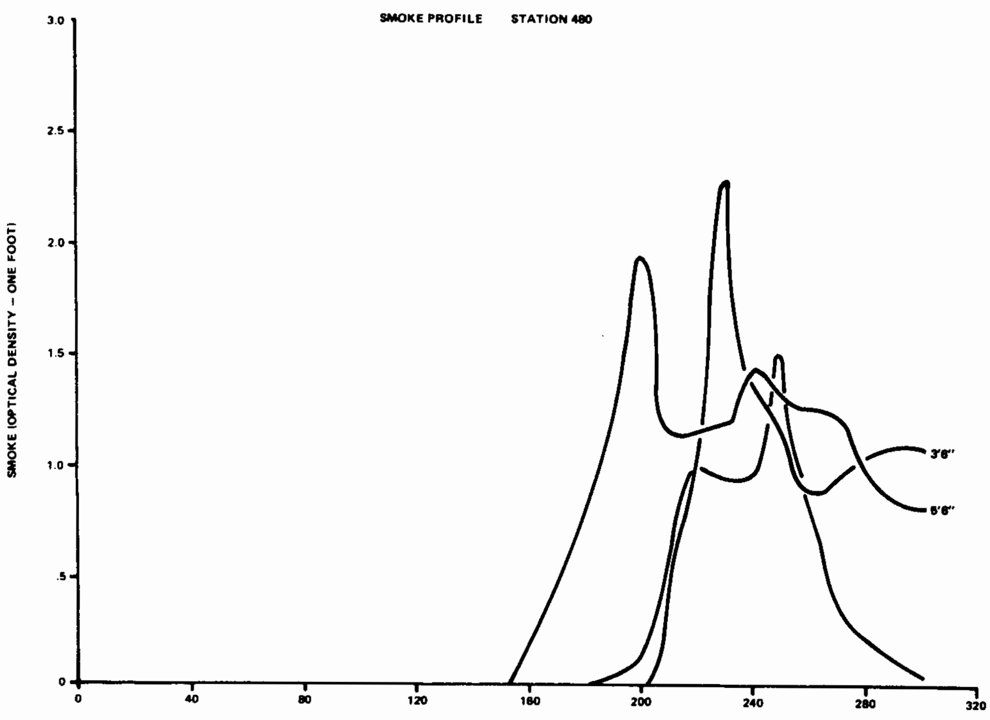


(d)

FIGURE C-3. TEMPERATURE PROFILE STATION 650 (2 of 2 Sheets)

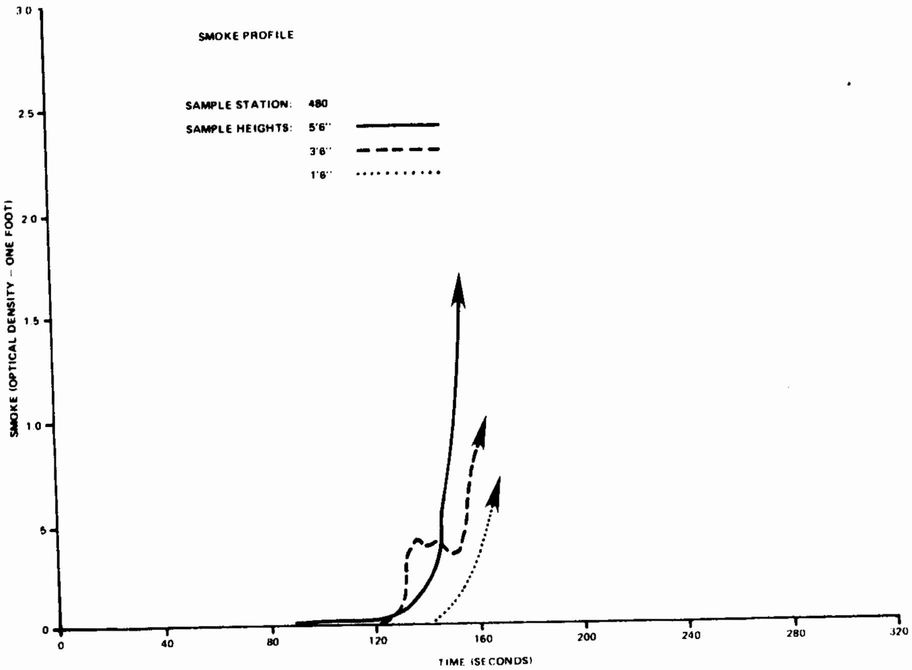


(a)

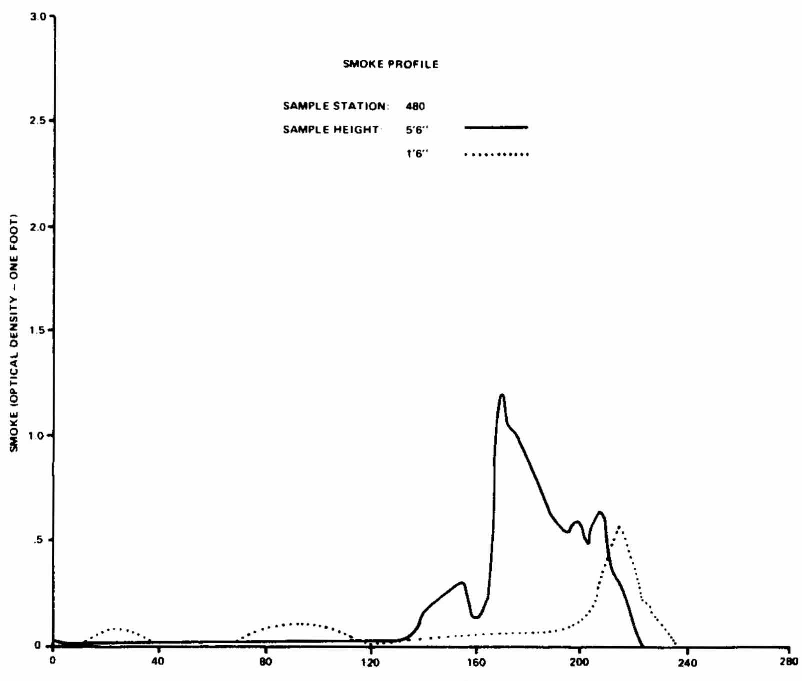


(b)

FIGURE C-4. SMOKE PROFILE STATION 480 (1 of 2 Sheets)

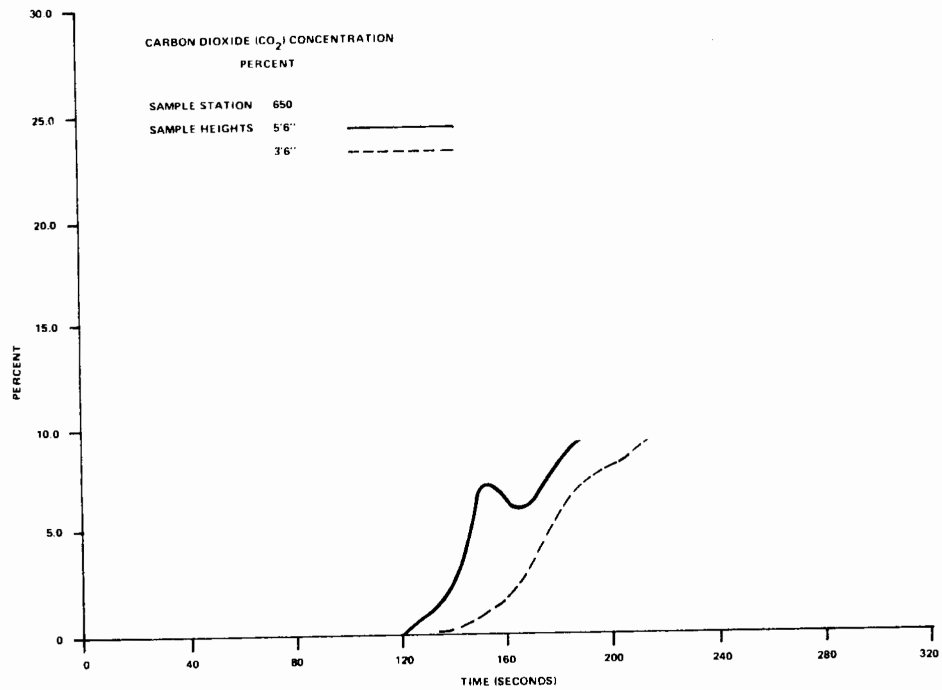


(c)

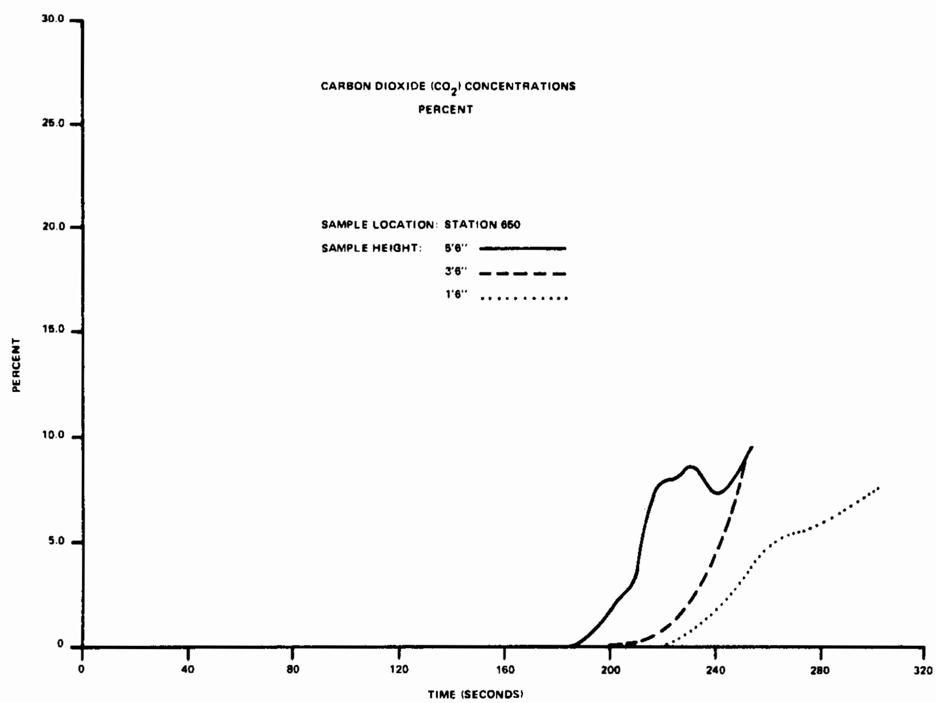


(d)

FIGURE C-4. SMOKE PROFILE STATION 480 (2 of 2 Sheets)

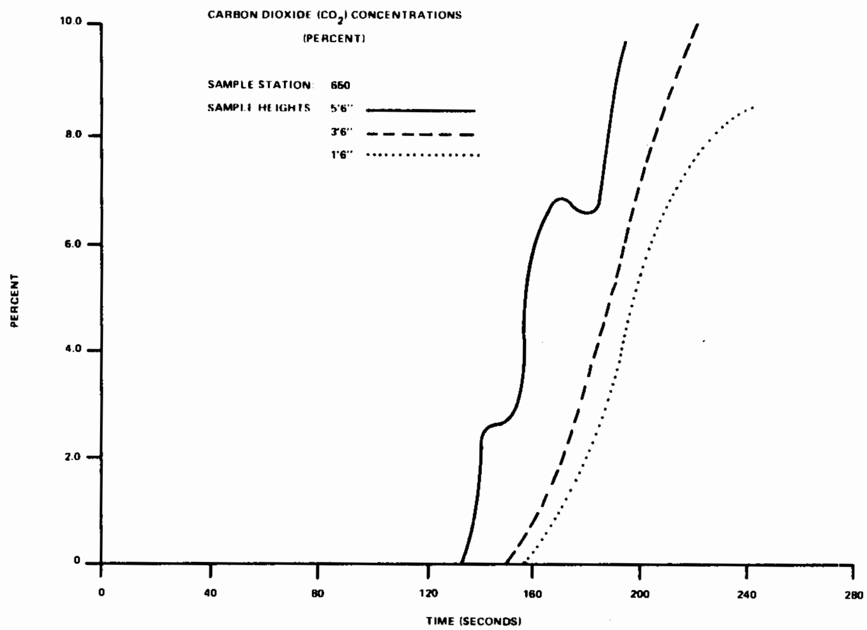


(a)

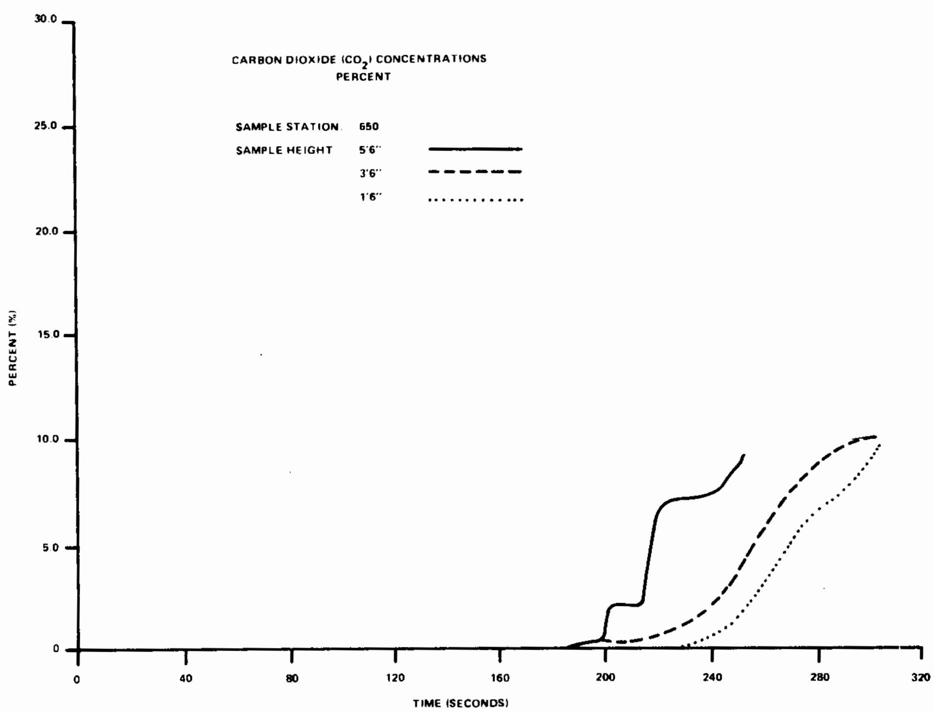


(b)

FIGURE C-5. CO_2 PROFILE STATION 650 (1 of 2 Sheets)

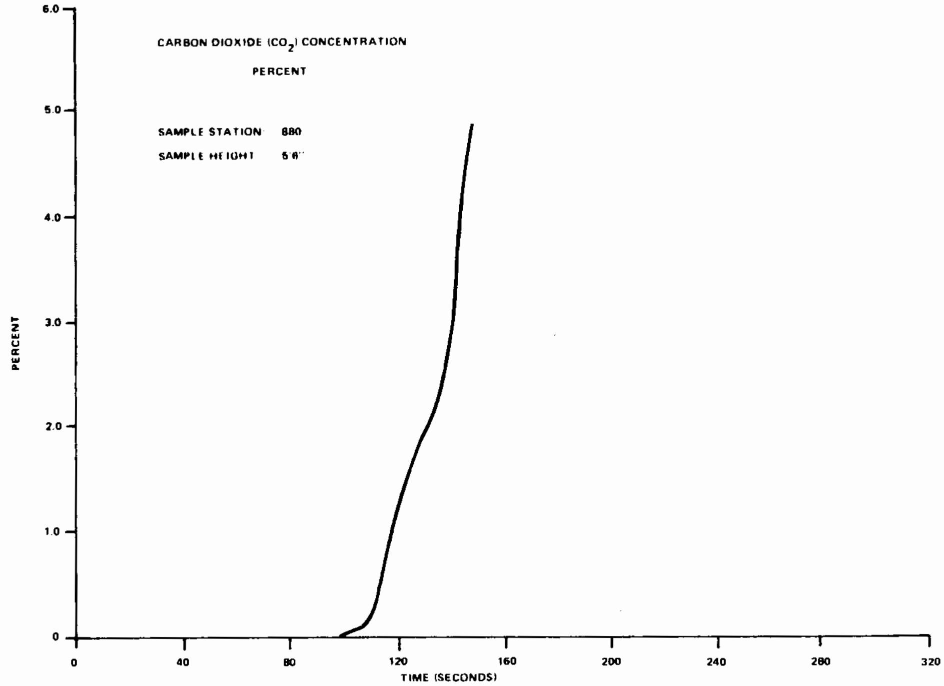


(c)

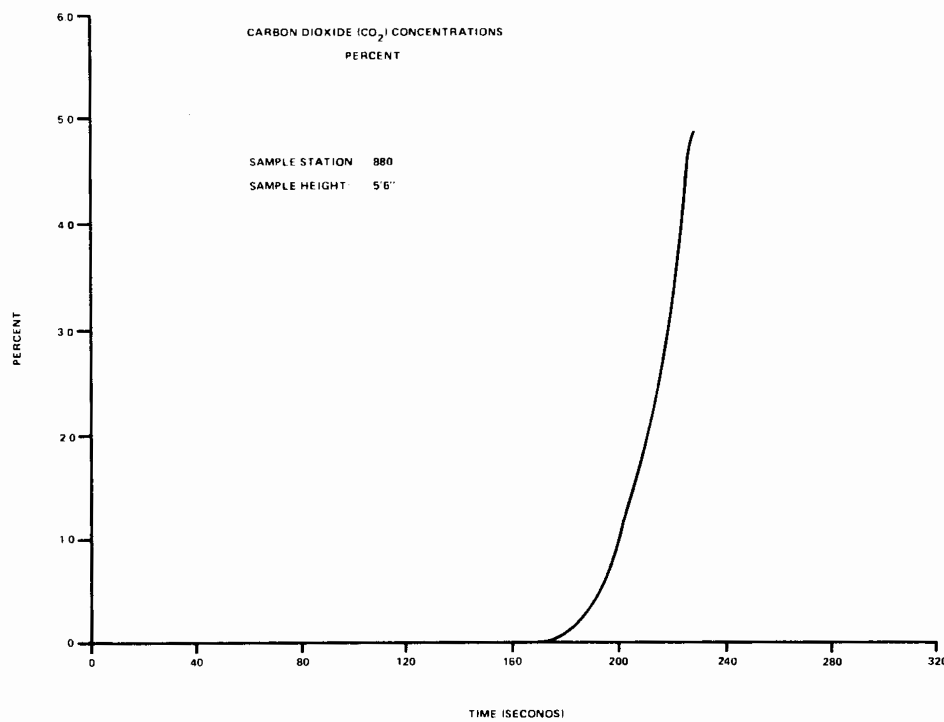


(d)

FIGURE C-5. CO_2 PROFILE STATION 650 (2 of 2 Sheets)

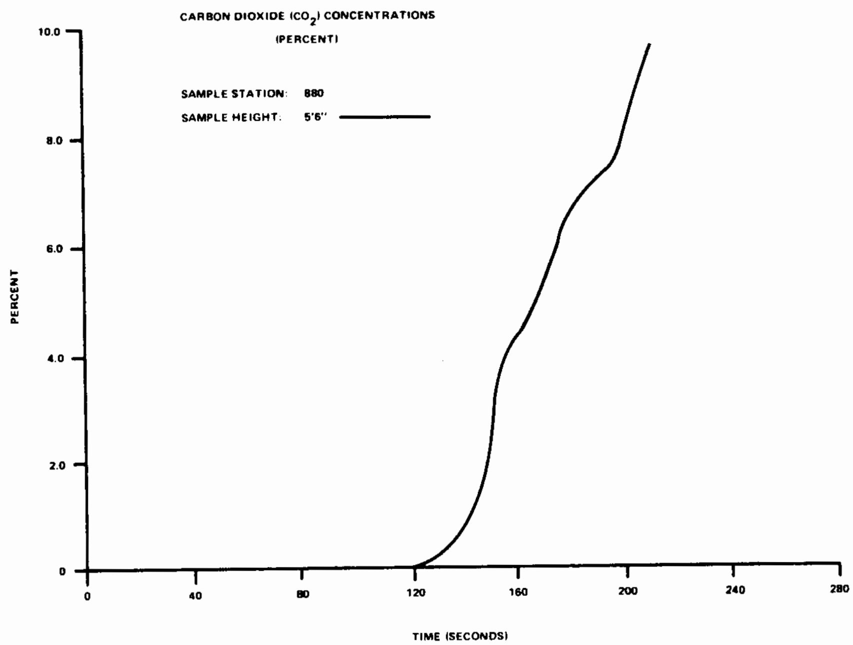


(a)



(b)

FIGURE C-6. CO_2 PROFILE STATION 880 (1 of 2 Sheets)



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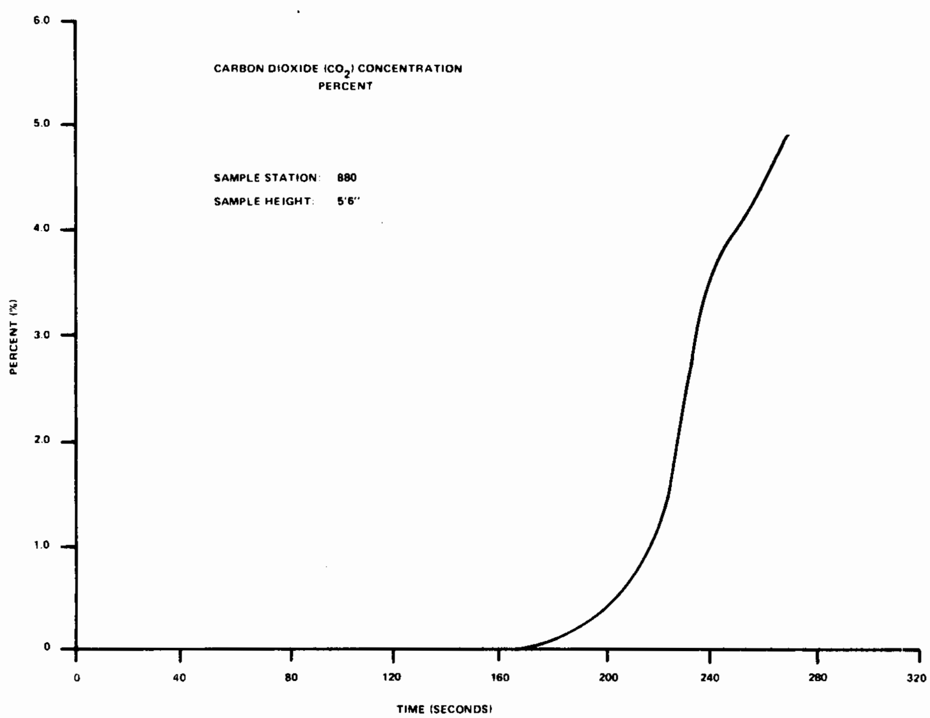
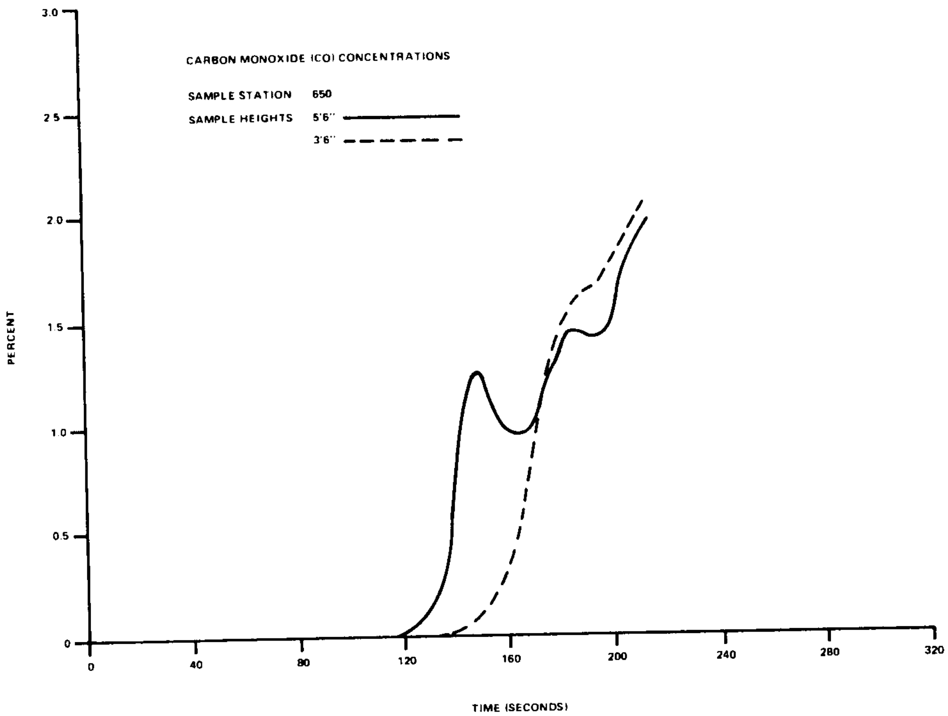
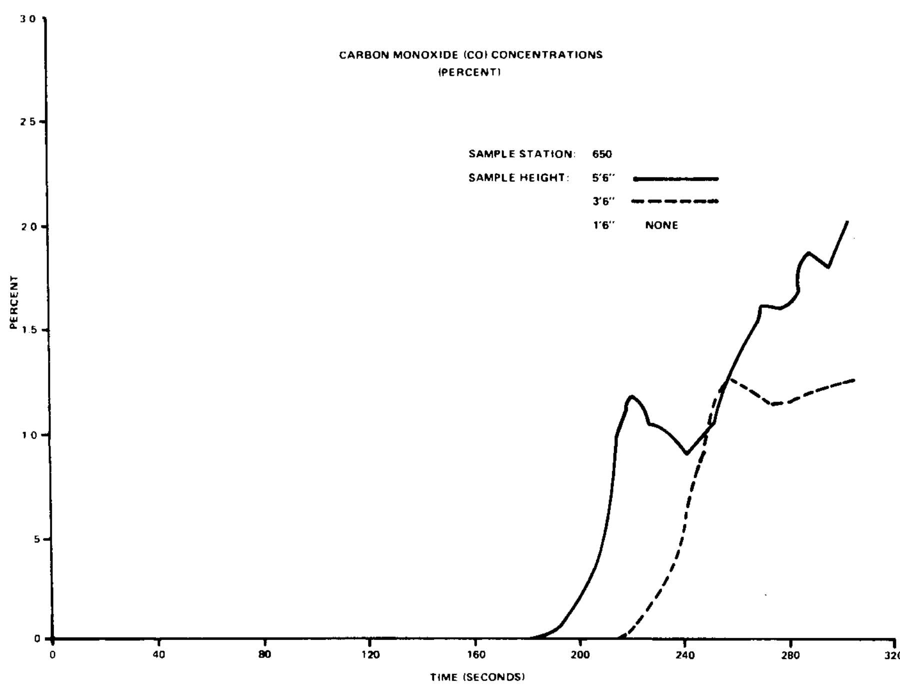


(d)

FIGURE C-6. CO_2 PROFILE STATION 880 (2 of 2 Sheets)

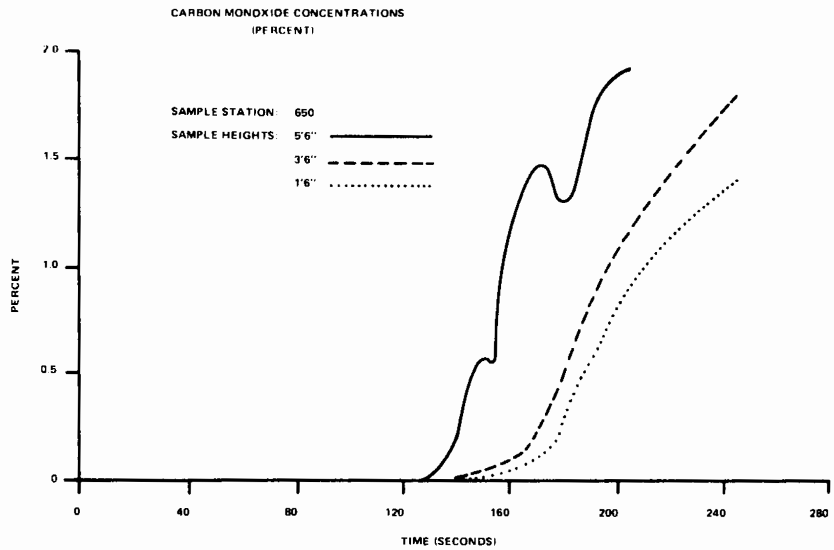


(a)

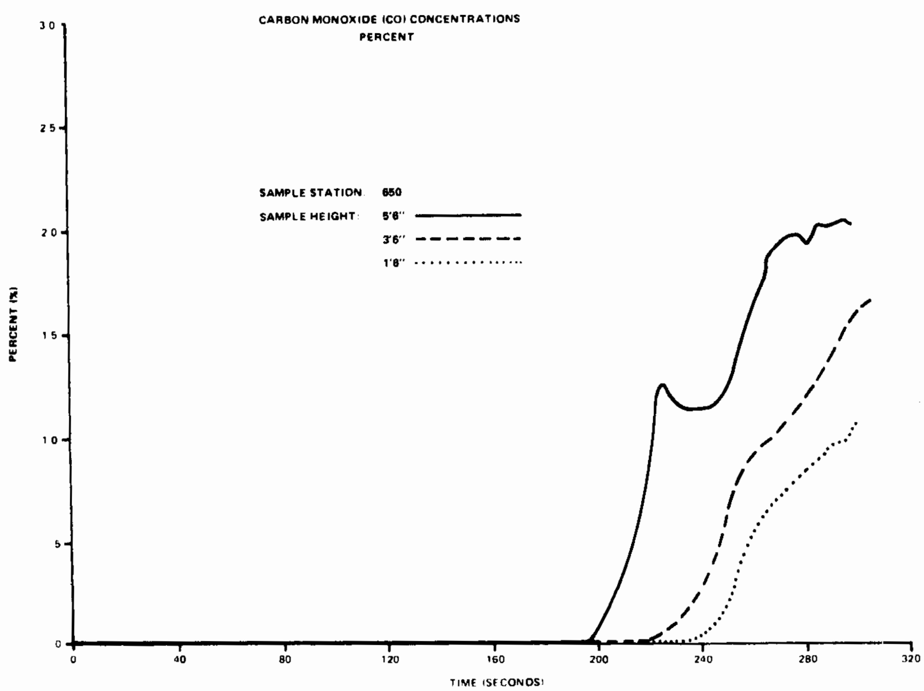


(b)

FIGURE C-7. CO_2 PROFILE STATION 650 (1 of 2 Sheets)

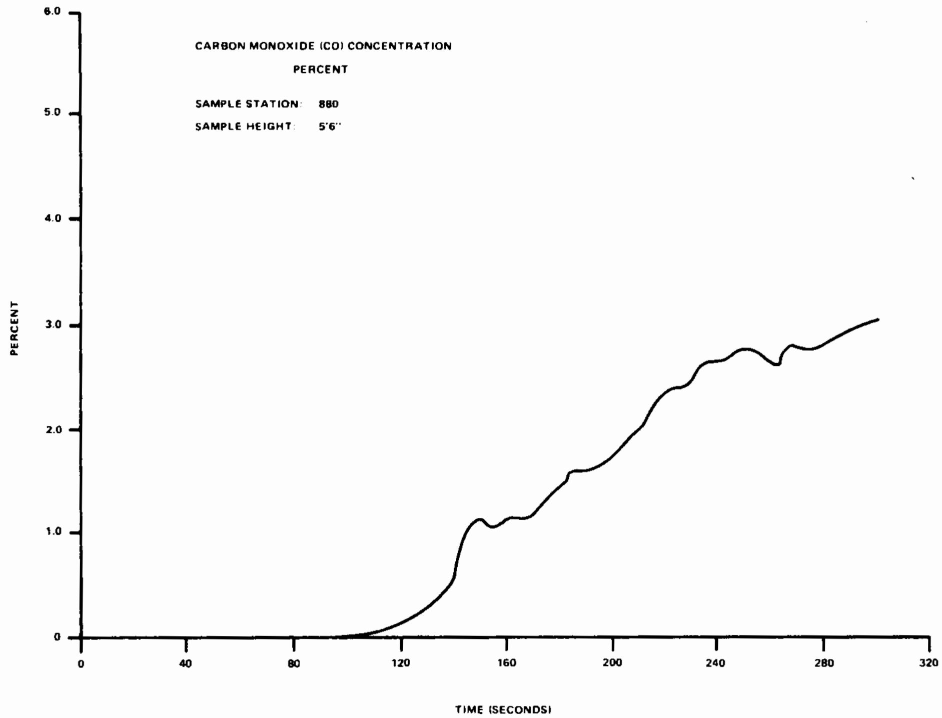


(c)

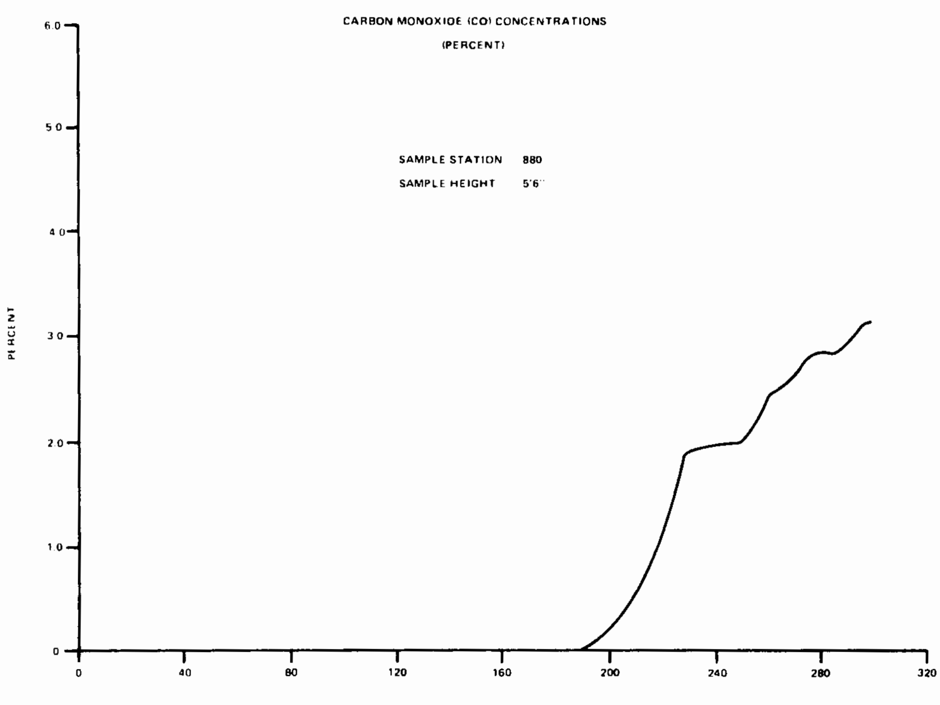


(d)

FIGURE C-7. CO_2 PROFILE STATION 650 (2 of 2 Sheets)

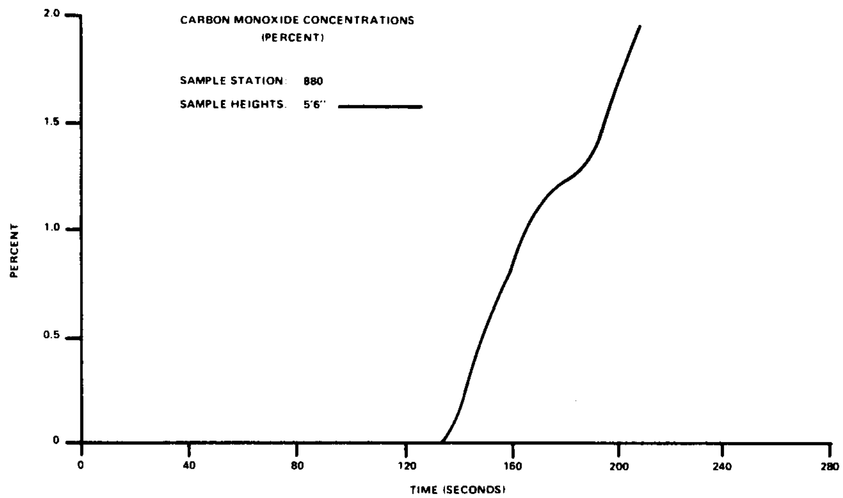


(a)



(b)

FIGURE C-8. CO_2 PROFILE STATION 880 (1 of 2 Sheets)



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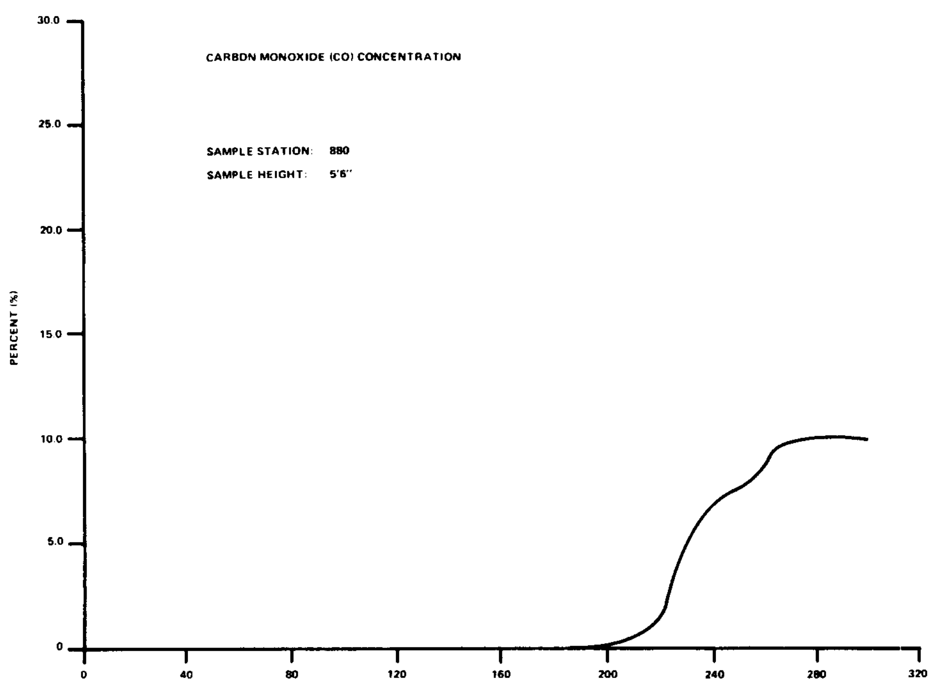

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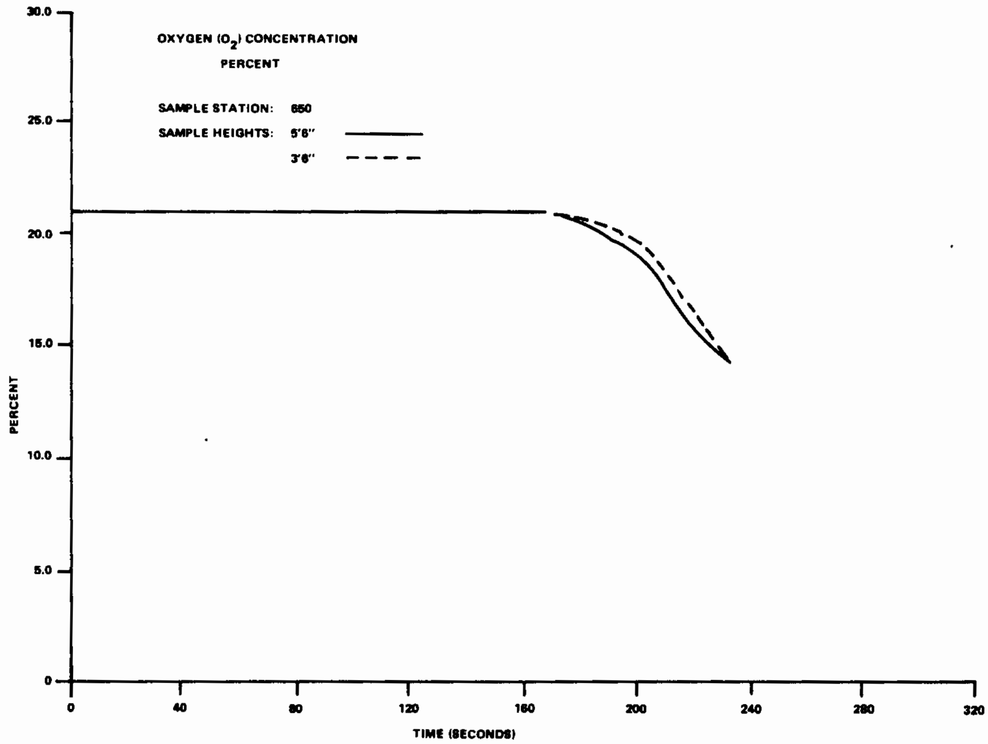
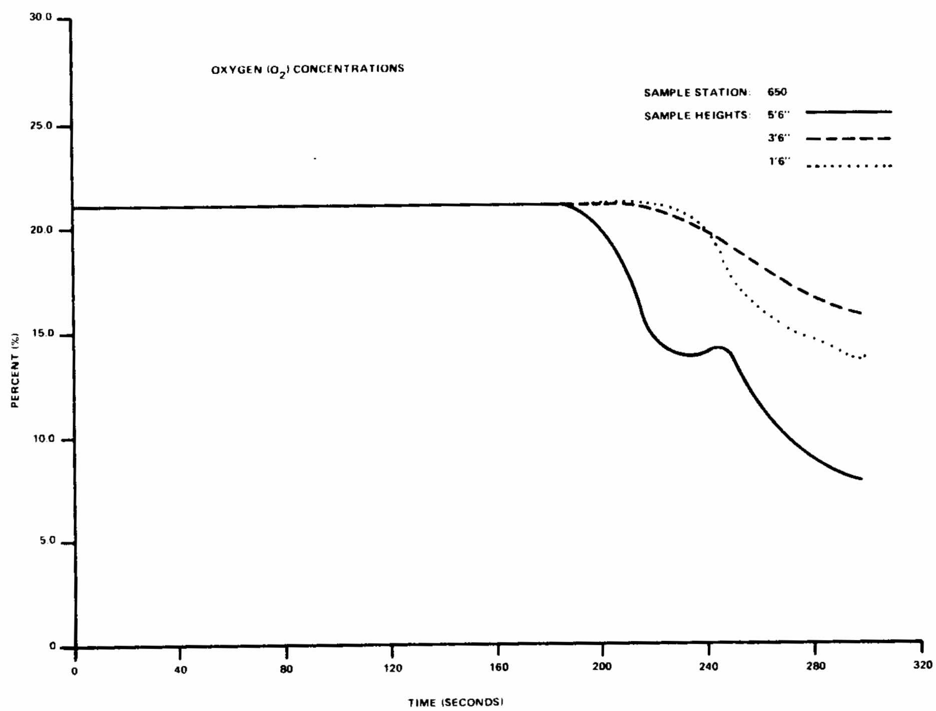
FIGURE C-8. CO_2 PROFILE STATION 880 (2 of 2 Sheets)

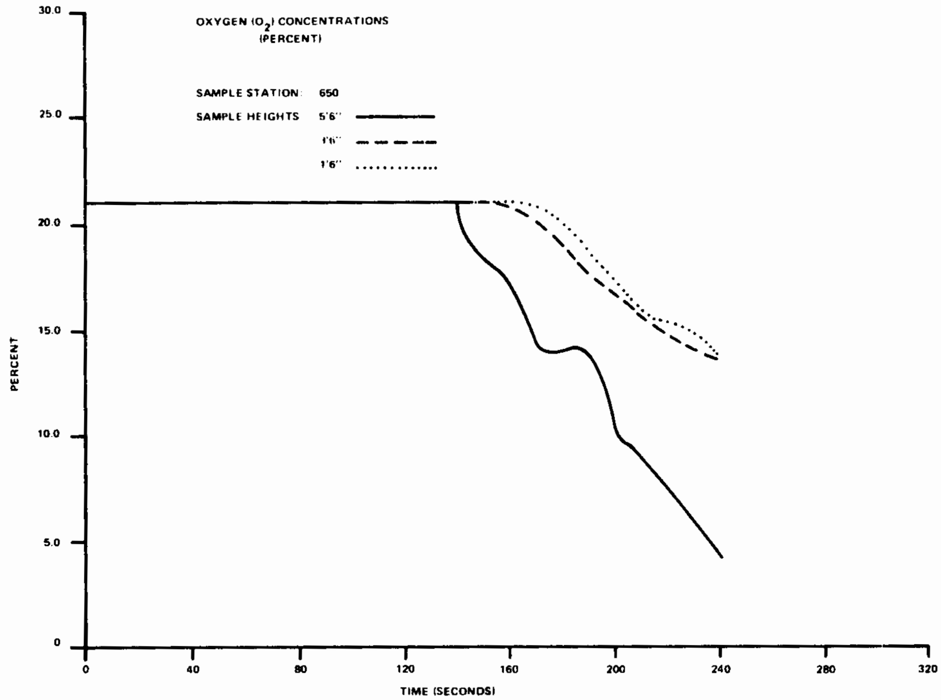


(a)



(b)

FIGURE C-9. O_2 PROFILE STATION 650 (1 of 2 Sheets)



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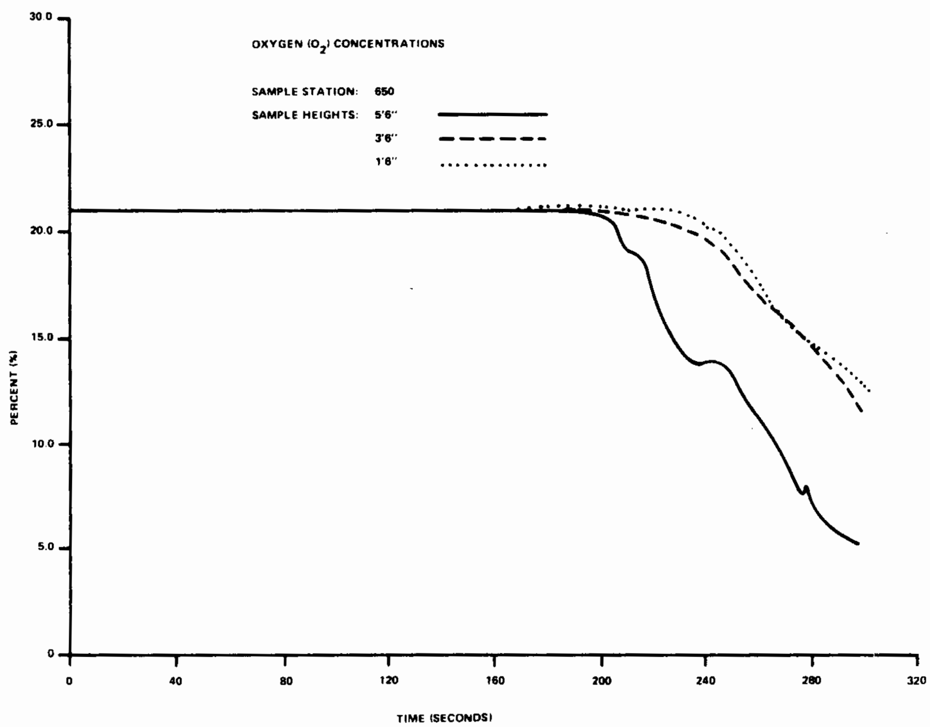
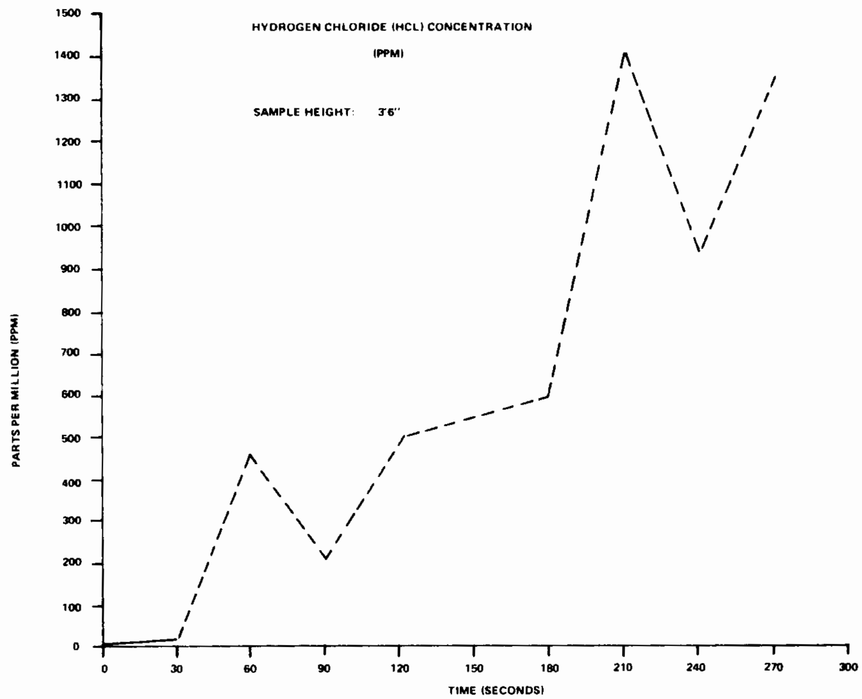


(d)

FIGURE C-9. O_2 PROFILE STATION 650 (2 of 2 Sheets)

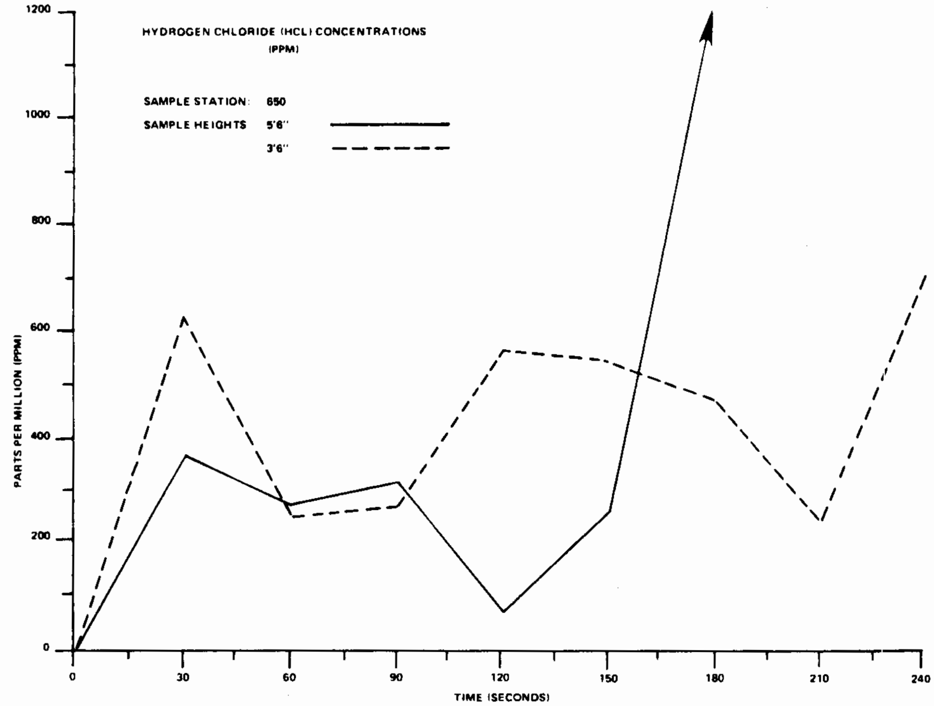


(a)

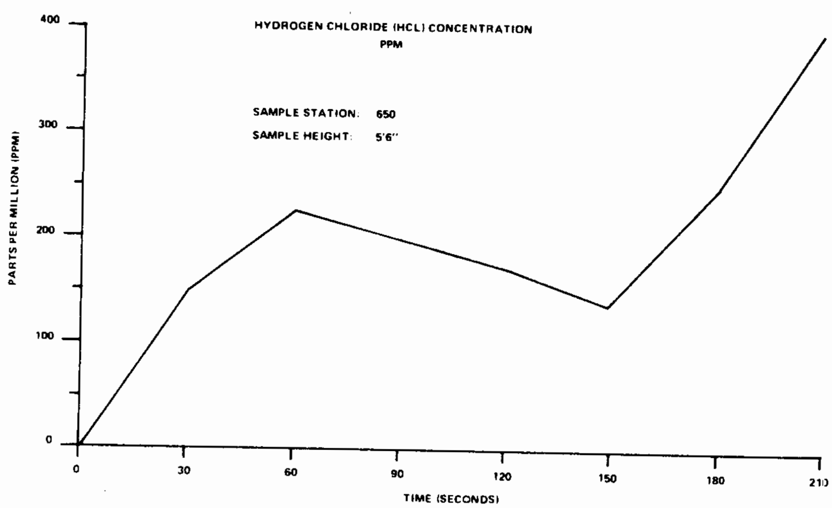
NO DATA COLLECTED

(b)

FIGURE C-10. HCL PROFILE STATION 650 (1 of 2 Sheets)

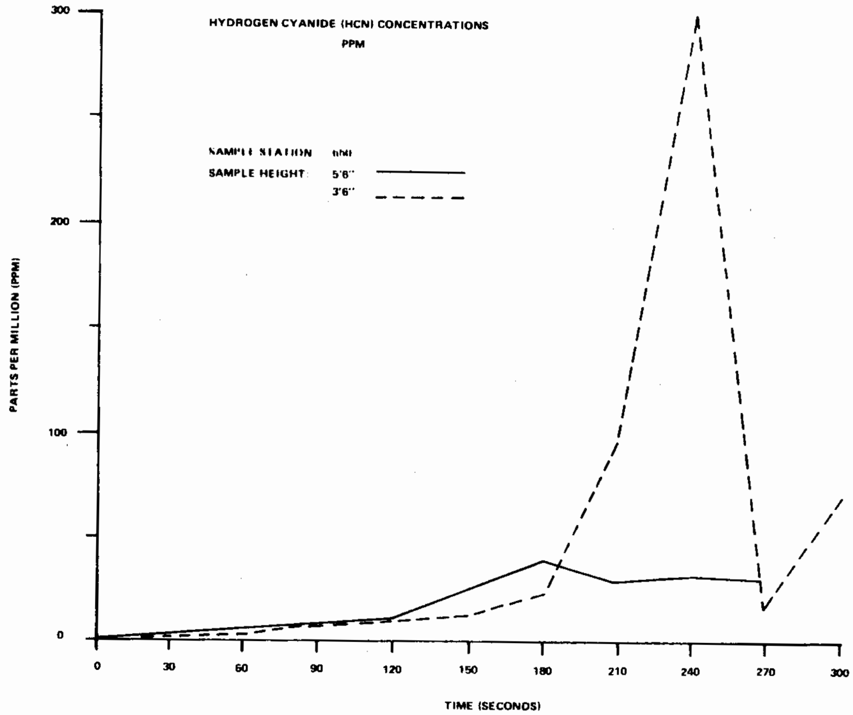


(c)

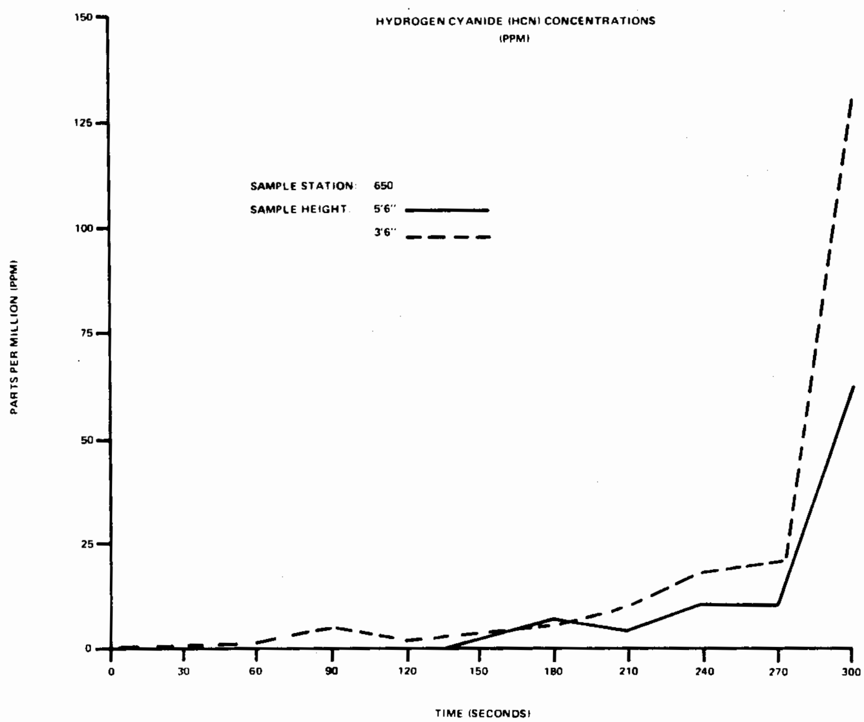


(d)

FIGURE C-10. HCL PROFILE STATION 650 (2 of 2 Sheets)

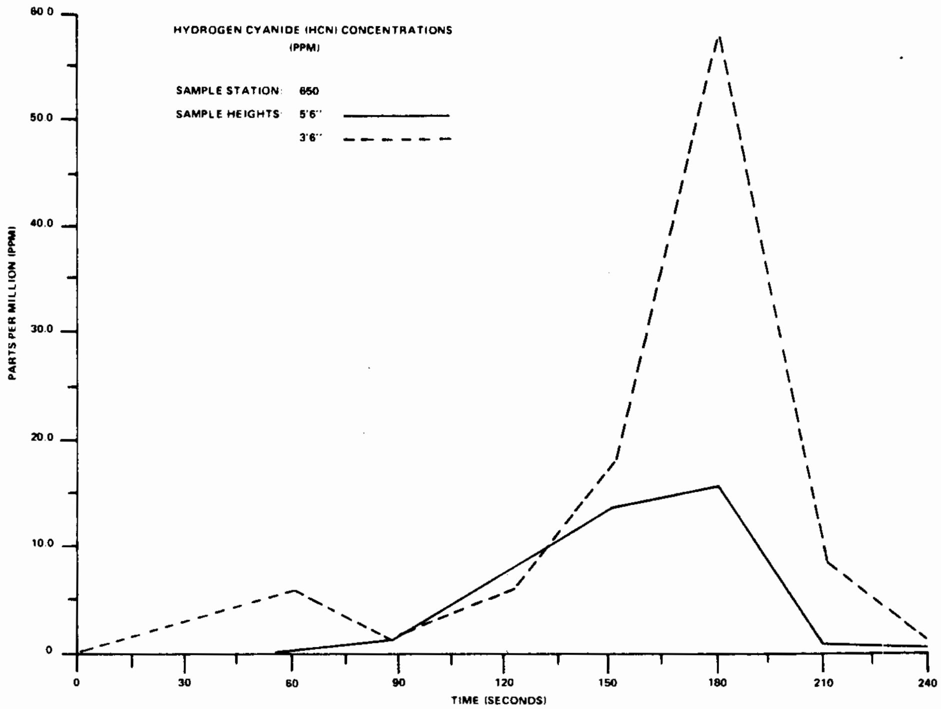


(a)

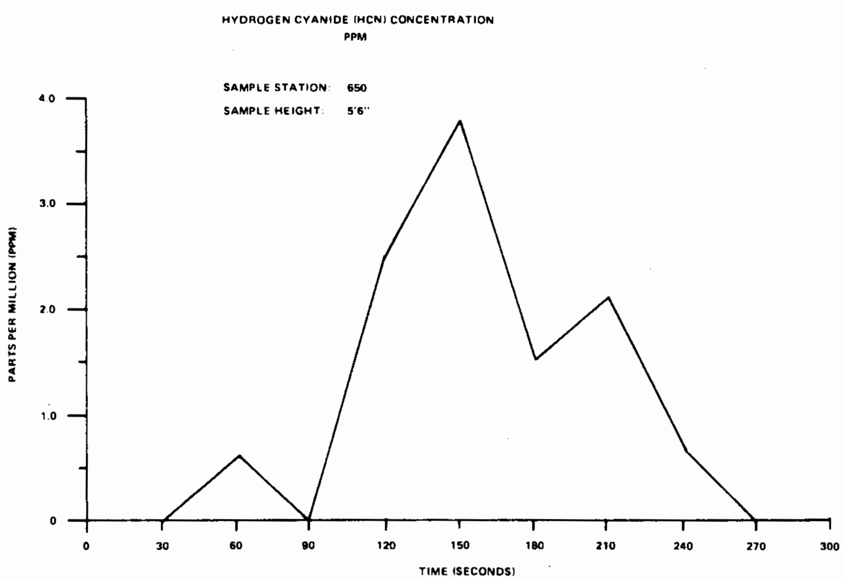


(b)

FIGURE C-11. HCN PROFILE STATION 650 (1 of 2 Sheets)

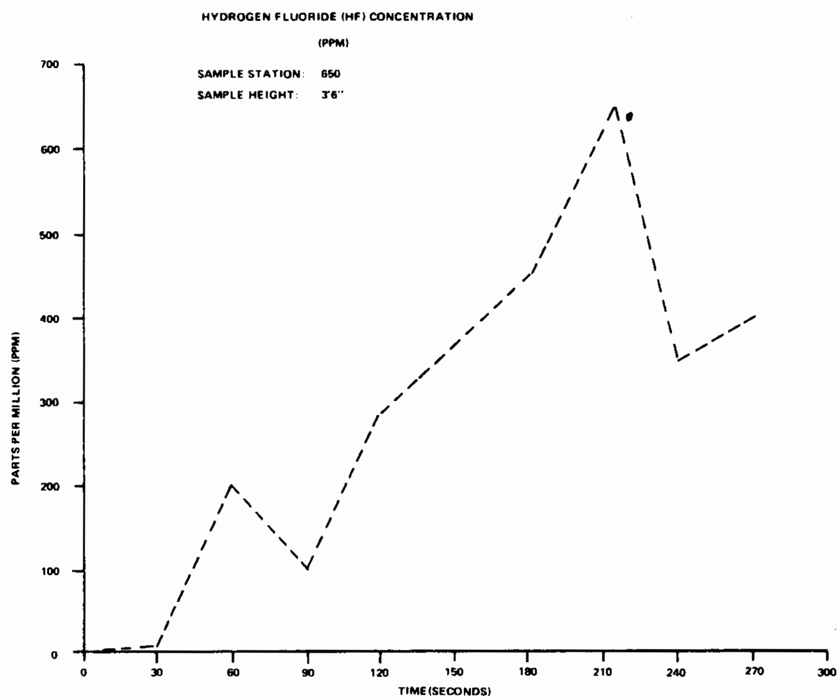


(c)

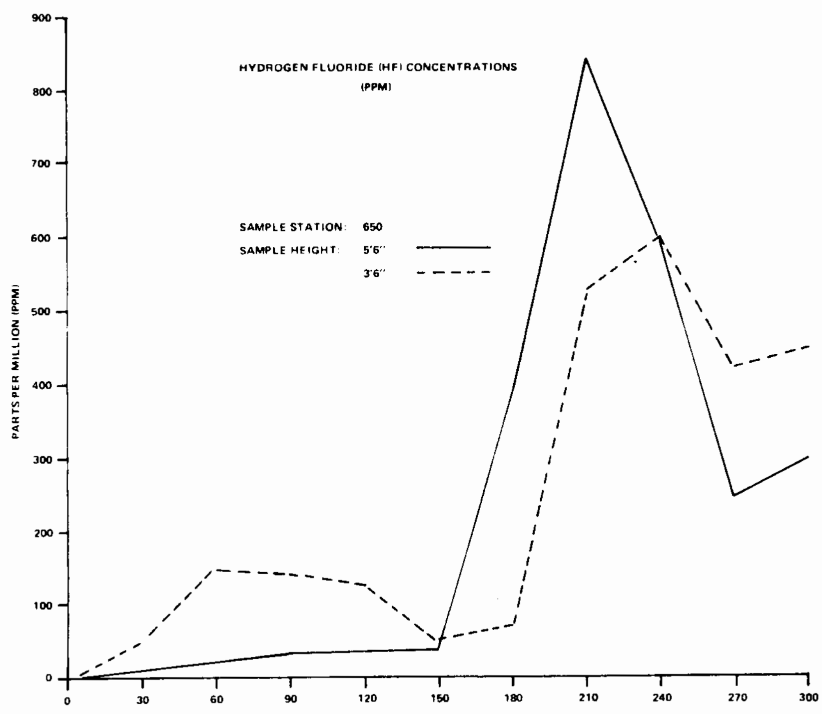


(d)

FIGURE C-11. HCN PROFILE STATION 650 (2 of 2 Sheets)

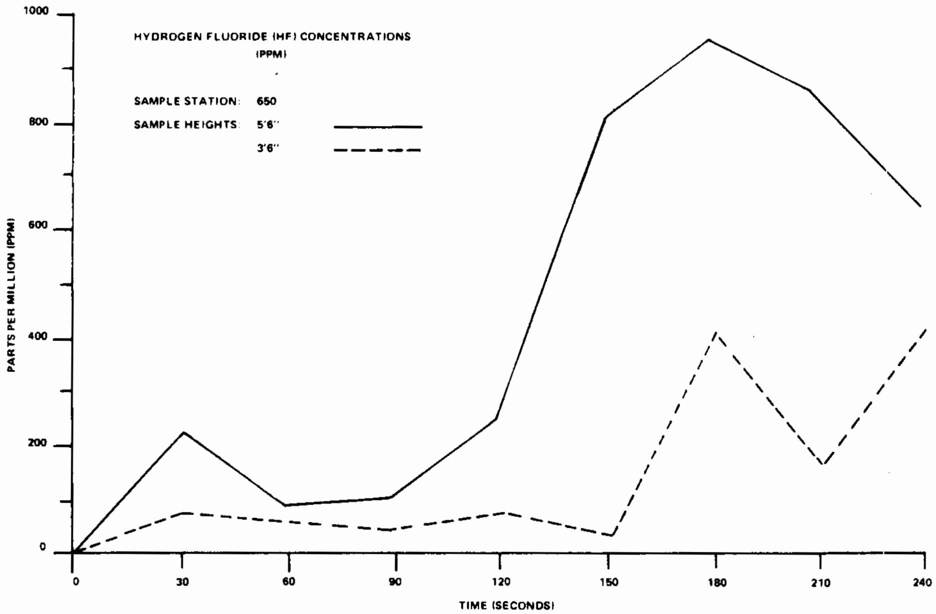


(a)



(b)

FIGURE C-12. HF PROFILE STATION 650 (1 of 2 Sheets)



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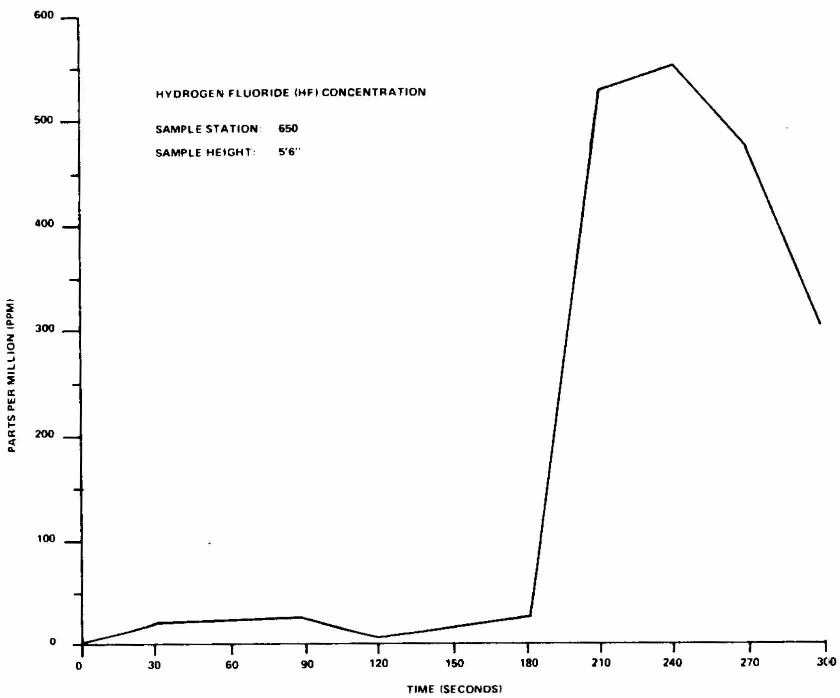

(d)

FIGURE C-12. HF PROFILE STATION 650 (2 of 2 Sheets)