POSTCRASH FUEL FIRE HAZARD MEASUREMENTS IN A WIDE-BODY AIRCRAFT CABIN

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DECEMBER 1979

FINAL REPORT

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Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
National Aviation Facilities Experimental Center
Atlantic City, New Jersey 08405

Technical Report Documentation Page

1. Report No. FAA-NA-79-42	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle POSTCRASH FUEL FIRE HAZARD MEASUREMENTS IN A WIDE-BODY AIRCRAFT CABIN		5. Report Date December 1979
		6. Performing Organization Code
7. Author(s) Richard G. Hill, George R. Johnson, Constantine P. Sarkos		8. Performing Organization Report No. FAA-NA-79-42
9. Performing Organization Name and Address Federal Aviation Administration National Aviation Facilities Experimental Center Atlantic City, New Jersey 08405		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. 181-521-100
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration National Aviation Facilities Experimental Center Atlantic City, New Jersey 08405		13. Type of Report and Period Covered Final March 1977-December 1978
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This report describes results obtained utilizing a full-scale, wide-body test article for studying postcrash cabin fire hazards produced by an external fuel fire adjacent to a cabin door opening. Seventy-two tests were conducted at various ambient wind conditions and fire sizes in a fire-hardened cabin devoid of interior materials. This work was the first phase of a study to realistically characterize postcrash cabin fire hazards. Temporal data, taken at a large number of cabin locations, are presented and discussed pertaining to the effect of ambient wind on the rate of hazard accumulation inside of the cabin; stratification of heat, smoke, and toxic gases; the effect of fire size of thermal radiation through the opening; and the relative importance of heat, smoke, and carbon monoxide in a fuel-dominant fire. It is concluded that major stratification of hazards occurs in the cabin when the hazards are created by an external fuel fire, and that ambient wind determines the amount of hazards entering a cabin due to a given external fuel fire.

17. Key Words	18. Distribution Statement
Fuel Fire Cabin Fire Aircraft Radiation Full-Scale	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	95	

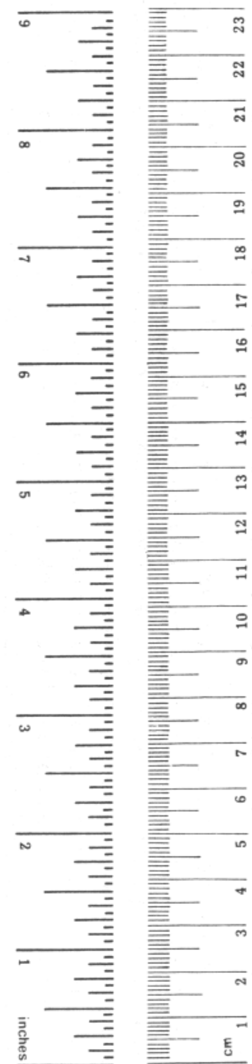
Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

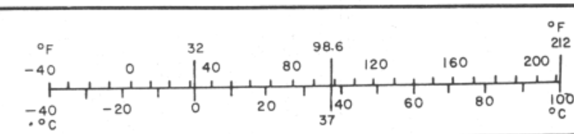
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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



PREFACE

The assistance of the following NAFEC personnel in the varying activities of installation of instrumentation, test, and data reduction and analysis is gratefully acknowledged; James D. Leach, Samuel V. Zinn, David R. Blake, Irwin R. Block, Gary Haffke, Donald E. Eastes, Franklin Fann, Dr. Joe C. Spurgeon, Louise Speitel, Robert Filipczak, Stanley J. Sternik, and Ray E. Feher.

Also, the following personnel for their assistance in fabrication of specialized equipment; Ross L. Glidewell, Walter M. Sturko, John E. Staniszewski, Joseph P. Bruckler, Edward Call, and Norman Minuth.

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INTRODUCTION

PURPOSE.

The main objectives of the test program were: (1) to study the relationships between an external fuel fire adjacent to a fuselage opening and cabin environmental conditions as related to survivability under the varying effects of fire size, windspeed, and wind direction; (2) to measure the heat flux and temperatures created by the fuel fire at various fuselage stations within the cabin for the purpose of defining what test conditions should be used in laboratory fire tests for cabin materials, and (3) to determine the relative importance of heat, smoke, toxic gases, and oxygen depletion, from an external fuel fire, on occupant survivability.

BACKGROUND.

It is believed that a minimum of 15 percent of all fatalities in transport aircraft accidents are a result of fire (reference 1). There is some evidence which indicates that in low-impact, highly survivable accidents, some of these deaths may be attributable to the hazards created by burning cabin materials. Cognizant of this, the Federal Aviation Administration (FAA) has, since 1947, placed restrictions on the allowable flammability behavior of interior materials. The purpose of these regulations is to minimize the likelihood of an in-flight fire from a small ignition source and to reduce the flame spread or involvement of the cabin interior materials in the event of an uncontrollable fire. Periodically, the FAA has upgraded the flammability requirements as improved fire-resistant materials are developed and made available for cabin usage. However, a number of accidents have occurred which reveal the dangers associated with the smoke and toxic gas emissions generated by the burning interior materials. Smoke accumulation within the cabin can obscure visibility and seriously impede rapid cabin evacuation. Some products of combustion are irritants which cause lachrymation of the eyes and attack the respiratory system. Others, such as carbon monoxide (CO) and hydrogen cyanide (HCN) are systemic poisons which, in sufficient concentrations, can be incapacitating and lethal.

There is general disagreement surrounding the role of plastic and natural materials in cabin survivability and the ability to predict the behavior of interior materials during a cabin fire based on laboratory tests. The authors believe these areas of disagreement can be resolved by conducting realistic, full-scale cabin fire tests. The basic questions that must be answered are: How do interior materials contribute to the cabin fire hazard, and how can interior materials be selected to confidently minimize cabin fire hazards?

Although some full-scale cabin fire tests have been performed in the past, many have been either insufficient or inconclusive. Others have been "one shot" affairs that left more questions than answers. Some have been unrealistic, uncontrollable, or lacking in basic instrumentation. This has prompted the FAA to undertake a three-phase, full-scale cabin fire test program at the National Aviation Facilities Experimental Center (NAFEC), using a surplus C133 cargo aircraft modified into a simulated wide-body configuration. The first phase, reported herein, consists of determining the cabin fire hazards arising soley from an external fuel fire adjacent to an open door in an intact fuselage. The second phase determines, for the same fuel fire scenario, the involvement and contributions of interior materials to the overall cabin fire hazard. A 20-foot length of the fuselage in the fire entry area will be lined and furnished with wide-body materials including: carpeting, seats, sidewall panels, overhead stowage bins, and ceiling panels. This configuration of materials will be subjected to a fire, selected during the first phase, which produces a previously determined cabin hazard. In this manner, the additional hazards attributed to the burning interior materials (for this specific scenario) can be established. The third phase will consist of burn tests on large, single samples of interior materials for correlation with laboratory tests.

DISCUSSION

TEST ARTICLE.

A surplus United States (U.S.) Air Force C133A cargo aircraft, with the wings and tail surfaces removed, was utilized as the test article. This aircraft provided internal dimensions similar to those of wide-bodied jets currently in airline service. The C133 fuselage diameter is 200 inches, and internal usable length for test purposes is approximately 118 feet (figure 1). The fuselage cargo area was modified by the installation of a metal-covered plywood floor and a fire-resistant ceiling to provide an 8-foot floor-to-ceiling height. The cockpit area was sealed off and not used during the test program. The modification of the cargo area resulted in a calculated volume of interior airspace of 13,200 cubic feet (ft^3).

The fuselage was further modified by the addition of two door openings on the right-hand side of the aircraft. The forward door opening was 76 inches high and 42 inches wide and was the location used for the external test fire penetration. The rear opening was a type A configuration and provided an exit point for smoke and gases to exhaust into the atmosphere. This opening had a hinged door that was normally open and a square wooden barrier external to the opening to prevent extraneous wind gusts from affecting flow characteristics through the fuselage. These openings were approximately 60 feet apart.

On the left-hand side of the fuselage were two escape hatches (each 27 by 21 inches). The hatches were covered by an aluminum, box-like windbreak with an open bottom. These windbreaks provided the same protection as the rear door wind barrier. The test article rested on the aircraft landing gear tires, and jacks were used under the rear of the fuselage to maintain a level attitude. The rear cargo door remained operable throughout the test program to allow installation and removal of large equipment or instrumentation as required.

To prevent erroneous data from being obtained during test fires due to ignition of the normal combustible components of the aircraft, such as wiring etc., and to prevent the aluminum fuselage shell from possibly melting, the fuselage was completely stripped of these items and the interior walls covered with fire-resistant materials (Kaowool® insulation and fiberglass cloth, figure 2). The area surrounding the forward fire opening had additional protection in the form of a Refasil® fireproof covering around the door frame and over the ceiling material. The actual test section was approximately 76 feet long.

Station numbers used in this report have no relation to aircraft manufacturers' station numbers and represent a scale containing 1-inch increments along the test section originating at the forward end of the installed floor. Entrance to the test article was through the normal crew entrance door on the right side of the fuselage.

EXTERNAL FIRE SOURCE.

The external fire was provided by a measured amount of jet fuel (JP-4) placed in steel pans of various sizes located on a framework adjacent to the fire door. The fire pan was located at the bottom edge of the door, rather than on the ground, in order to best assure that a solid sheet of flame would cover the entire door opening, as would result from a large ground fuel fire. There were four pans, all having a 4-inch-sidewall height. These pans were used singly or grouped together to provide the necessary area required for any particular test (figure 3). Pan sizes were as follows: two 6- by 4-foot pans and two 8- by 2-foot pans.

INSTRUMENTATION TRAILER.

The instrumentation trailer was positioned at the forward left-hand side of the fuselage. The trailer housed the visual readout faces of the CO and carbon dioxide (CO_2) concentration analyzers, the oxygen (O_2) concentration readout and amplifier, sample flow-control flowmeters and valves, various direct current (d.c.) voltage power units, the computer analog-to-digital converter, patch panels for the thermocouples, and other d.c. millivolt (mV) output instrumentation used during testing. Activation of fire-extinguishing components (both CO_2 and aqueous foam) along with the vacuum pump for the gas sampling lines were also controlled from the trailer. The test director and interested observers were able to view the fire area on closed-circuit video monitors installed in the trailer (figure 4).

FIRE-EXTINGUISHING SYSTEM.

The fire-extinguishing capability on the test fuselage was provided by two different systems. The primary system was a CO_2 system that protected the entire test article (figure 5). The fuselage was divided into four fire protection zones: (1) the fire pan area, (2) the above-test section ceiling, (3) the test section, and (4) below-test section floor. All zones utilized Atkomatic "DYMO"® 15,000 series solenoid valves to control agent discharge, which were mounted immediately upstream from discharge points and electrically controlled from the instrumentation trailer. The fire pan area had one discharge nozzle positioned to direct CO_2 toward the fire at an angle that would prevent burning fuel being blown out of the pans during agent discharge. The above ceiling system was a 0.75-inch-diameter perforated copper tube mounted on the aircraft structure with the agent discharge being directed downward toward the installed ceiling. Separate control was provided for the forward and aft sections, with the dividing point being the center wing section. Test section protection was provided by four discharge nozzles mounted on the upper left-hand interior wall, positioned to cover the floor area below. Each nozzle could be activated individually as required. Underfloor protection was from a single discharge nozzle mounted on the left-hand sidewall (figure 5). The second extinguishing system was used strictly to extinguish the external fire. The agent was a mixture of 6-percent aqueous film-forming foam (AFFF) mixed with water. This system proved more effective in extinguishing the pan fire than CO_2, since any slight ambient wind would blow the CO_2 away from the fire. The system consisted of a 1,000-gallon storage tank pressurized to 90 pounds per square inch (psi), an electric solenoid discharge valve, and four spray nozzles. A spray nozzle was positioned at each corner of the fire pan configuration and adjusted to cover the entire surface of the pans with foam upon actuation.

WIND GENERATOR.

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 (figure 4).

TEMPERATURE MEASURING SYSTEM.

Test section temperatures were monitored using chromel/alumel (type K) thermocouples installed at various test section stations and elevations. Temperatures in the area exposed to the test fire were measured using Ceramo thermocouples. The remaining thermocouples were 24-guage glass-on-glass-wire type. Figure 6 shows the location of cabin air thermocouples, while figure 7 indicates the location of ceiling thermocouples.

SMOKEMETERS.

Two smokemeter racks, consisting of three smokemeters each, were designed, assembled, and installed in the test section by project personnel (figure 8). The forward rack was positioned at test station 510, and the aft rack at test station 910. The smokemeters were mounted on the racks as follows: highest--

68 inches above floor, middle--42 inches above floor, and lowest--18 inches above floor. Each smokemeter assembly primarily consisted of a light source and light receiver unit. The latter was an airtight chamber containing a Weston 865YR photocell. The photocell was positioned behind a heat-resistant glass window to protect the cell. The chamber was insulated with Kaowool and cooled by a low-pressure airflow during the test. Light to the photocell was provided by a N-3C gunsight bench collimator attached to a 12-inch-long metal tube that was connected to the photocell chamber. This 2.6-inch-diameter tube had four 10.5- by 0.75-inch slots incorporated lengthwise at 90° increments on the tube. These slots allowed smoke to pass between the photocell and the collimated light source (figure 9). The reduction in light transmission produced a calibrated millivolt signal from the photocell. Prior to each test, the photocell windows and collimator lens were cleaned of soot accumulation from the previous test.

HEAT FLUX SYSTEM.

Nine Hy-Cal® asymptotic rapid-response calorimeters were installed in the area of the test fire penetration (figure 10). The calorimeter units were installed in a copper water jacket with only the face exposed to the heat (figure 11). Fire-resistant wire was spliced to the normal signal wire and the splices inserted into the water jacket cavity which was then filled with Kaowool insulation. Cooling water was circulated through all units during the test and exhausted overboard.

GAS ANALYSIS SYSTEM.

Test section gas analysis was performed using instrumentation specifically designed to measure concentrations of CO, CO_2, and O_2. Gas samples were drawn through the sampling system by a vacuum pump installed downstream of the analyzers. Samples entered the system through a 0.25-inch outside diameter (o.d.) copper tube installed at a selected test station. A filter was installed in this line to remove large carbon particles from the sampling stream. After passing through this filter, the gases were directed to the individual analyzers through identical tubing. Each line contained a 15-micron steel filter in the portion of the line above the test section floor (figure 12). Prior to entering the analyzer protective cabinet beneath the floor, an additional 0.2-microfilter was installed in each line to prevent any contaminants from entering the analyzer sample cell. The CO and CO_2 concentrations were measured using Beckman Model 865® infrared analyzers. Oxygen concentration was measured utilizing a Beckman Model 715® process oxygen monitor. The sensor for the O_2 system was installed in the analyzer cabinet and the amplifier in the instrumentation trailer. Upon leaving the analyzers, the sample gases were routed to the instrumentation trailer where the proper flow rate was maintained using Dwyer adjustable flowmeters. Downstream of the flowmeters, the sample passed through the vacuum pump and was exhausted to atmosphere. Location of the two sample stations are shown in figure 13. At the forward station, samples were taken at 5 feet 6 inches and at the ceiling, while the aft sampler point was at 5 feet 6 inches.

WINDSPEED AND DIRECTION.

Windspeed and direction were continuously monitored during testing utilizing two independent indicating systems. Both systems used a "cup and vane assembly" as the sensing units. These units were separated to prevent fire-generated thermal currents from producing erroneous readings during testing. The forward unit was mounted above the cockpit area of the fuselage and was a Taylor "Windscope"® with a single-dial, dual selection and calibration capability. The aft system was an electric speed indicator type FAA-377 with noncalibratable dual-dial readout. Both directional and speed indicators were located in the instrumentation trailer.

VISUAL RECORDING.

A closed-circuit video system was utilized to allow viewing of the fire from a protected area. Two Sony black-and-white cameras were installed external to the fuselage to view the actual fire area. One camera was mounted on a platform on the opposite side from the fire location and viewed the fire through a heat-resistant glass window installed in the fuselage sidewall at floor level. The second camera was mounted on a shelf located under a hood that projected up through the rear cargo door. The fire area was viewed through a glass window installed in the hood. A third Sony color camera was placed on a tripod, a distance from the fuselage, viewing the fire and forward portion of the test article (figure 14). The color and black-and-white pictures were monitored in the instrumentation trailer as well as being permanently recorded in a television viewing room in a separate trailer.

TEST DESCRIPTION AND SCENARIO

The scenario selected consists of a low-impact, highly survivable crash resulting in an external fuel spill fire adjacent to an opening in an otherwise intact fuselage. Figure 15 is a photograph of a typical test. As shown in the photograph, even a fuel fire of moderate size produces high flames and thick smoke and would appear to be overwhelming.

During all tests, the aft exit door and both escape hatches remained open. The test duration was approximately 4.5 minutes. The quantity of fuel (JP-4) placed in the fire pans was such that the fire would not decrease in intensity at the end of the test (50 gallons for an 8- by 10-foot fire).

PRELIMINARY TESTS.

A number of preliminary tests were conducted in order to checkout the facility and all instrumentation. After this initial checkout, 13 tests were conducted with a windbreak enclosing the test fire. It was determined that the windbreak was not effective (appendix B); therefore, it was removed. All test results reported herein are with the external fire in an open environment.

PRIMARY TESTS.

A total of 59 tests were conducted without shielding ambient wind at the fire door. Table 1 lists all tests and wind conditions. During some of the tests, a simulated wind was supplied by the external fan. Those tests are noted in the table.

TEST RESULTS

WIND EFFECT.

The wind was the single most important factor affecting the environmental conditions in the cabin during testing. Figures 16, 17, and 18 show the effect of wind on cabin air temperature using 4-by 6-foot, 6-by 8-foot, and 8- by 10-foot fires, respectively. The thermocouple plotted was 5 feet 6 inches high, 10 feet aft of the fire door and at the fuselage centerline. Windspeeds were averaged for the test duration. Windspeed listed in the parenthesis is the component of the windspeed entering the door perpendicular to the fuselage. Figure 19 shows the conversion for a typical test of the windspeed direction to the corrected windspeed perpendicular to the door.

Generally, the greater the wind towards the fuselage opening, the greater the hazard in the fuselage. However, exceptions to that rule were noted; one in particular, during test number 32, is seen in figure 17. Although the average windspeed and the corrected windspeed were lower than other tests, using the same size fire, the temperature at 5 feet 6 inches height, 10 feet from the fire door at the fuselage centerline was three to four times higher than those of the other tests.

A study of films of these tests and a comparison of windspeed and doorway heat flux indicate that wind fluctuation and drafts through the fuselage play an important role in flame penetration into the cabin. The heat-flux/ windspeed comparison for tests 32 and 55 are shown in figure 20. These data indicate the effect of wind fluctuation on heat and flame penetration into the cabin. The most dramatic example of this is the last minute of test 55. The sudden gust of wind caused sustained flame penetration, although steady winds of the same magnitude had not.

One positive statement can be made about the effect of the wind on the internal cabin hazard. When the windspeed is near or at zero, little or no fire penetration occurs, and conditions in the cabin remain relatively safe for the entire test duration. No exceptions were encountered to this during the test program.

It should be noted that although only temperature and heat flux have been discussed so far, it is only because of their ease of measurement and availability. The smoke and measurable toxic gases generally followed the same pattern (as will be shown later). It can be said that no tests were

TABLE 1. FULL-SCALE TEST SUMMARY

TEST NUMBER	PAN SIZE (feet)	WINDSPEED AND DIRECTION	FAN SPEED
14	4 x 4	8 mph	6 mph on at 100 sec
15	6 x 4	1-3 mph SE	
16	6 x 4	Inoperative	
17	6 x 4	7 mph SSW	
18	6 x 4	Inoperative	
19	6 x 4	20-28 mph SW	
20	6 x 4	5-10 mph NNE	
21	6 x 4	5-8 mph NNW	
22	6 x 4	4-12 mph NW	
23	6 x 4	2 mph NW	
24	6 x 4	3-14 mph N	
25	6 x 4	5-18 mph WSW	
26	6 x 4	0 mph	
27	6 x 4	0-2 mph	
28	6 x 8	2-4 mph NE	
29	6 x 8	0-1 mph S	
30	6 x 8	2-13 mph	
31	6 x 8	3-7 mph WSW	
32	6 x 8	4-12 mph WNW	
33	6 x 8	1-4 mph S	
34	6 x 8	2-4 mph S	
35	6 x 8	0-1 mph W	
36	6 x 8	3-5 mph NW	
37	6 x 8	0-10 mph WNW	
38	6 x 8	4-8 mph WNW	
39	6 x 8	3-7 mph NE	
40	6 x 8	Inoperative	
41	6 x 8	0 mph	
42	6 x 8	3 mph NNE-NNW	
43	6 x 8	5 mph NNE-NNW	

TABLE 1. FULL-SCALE TEST SUMMARY (Continued)

TEST NUMBER	PAN SIZE (feet)	WINDSPEED AND DIRECTION	FAN SPEED
44	6 x 8	1-10 mph S	
45	6 x 8	2-5 mph NNW	
46	6 x 8	3-12 mph NW	
47	8 x 8	0-1 mph NW	
48	8 x 8	2-5 mph NW	
49	8 x 8	0 mph	
50	8 x 8	0-2 mph SSW	
51	8 x 8	2.5-7 mph SSW	
52	8 x 8	3-4 mph W	
53	8 x 8	9 mph N	
54	8 x 8	5 mph NW	
55	8 x 10	3-10 mph NNW	
56	8 x 10	5-7 mph S	
57	8 x 10	0 mph	
58	8 x 10	0 mph	
59	8 x 10	4-8 mph WNW	
60	8 x 10	2-7 mph NW	
61	8 x 10	0 mph	
62	8 x 10	0 mph	
63	8 x 10	1.5 mph SW	
64	8 x 10	SW	
65	8 x 10	3-7 mph NNE	3.57 mph
66	8 x 10	0 mph	3.57 mph
67	8 x 10	0.8 mph N	
68	8 x 10	2.2 mph N	3.57 mph
69	8 x 10	0.08 mph	3.57 mph intermittent
70	8 x 10	0 mph	3.57 mph
71	8 x 10	0 mph	3.57 mph
72	8 x 10	0 mph	3.57 mph

encountered where large amounts of smoke and little heat, or the inverse, entered the cabin.

EFFECT OF FIRE SIZE.

By varying the fire size, the effect of the wind on the fire also varied. The smaller the fire, the greater the bending of the flame by the wind (figure 21). The heat flux in the doorway shows more penetration through the lower area of the door for the smaller fires, indicating a greater bending of the flame. Therefore, although a smaller fire puts out less heat, smoke, and toxic gases than a bigger fire, a larger portion of the smaller fire can penetrate a fuselage opening for a given wind condition.

Since, for the sake of realism, it was desirable to simulate a large external fuel fire adjacent to a fuselage opening, a determination as to what size fire constituted a large or infinite fire had to be made. Modeling experiments conducted at NAFEC (reference 2) provided data on thermal radiation through a fuselage opening geometrically similar to the C133 from an infinite fire under quiescent wind conditions. Figure 22 shows the heat flux at a height of 3 feet 6 inches at the centerline of the C133 fuselage for the various fire sizes with zero wind. As the fire size was increased, the radiant heat increased. The largest practical fire size which can be tolerated without jeopardizing the fuselage integrity is that produced by a 8- by 10-foot pan. As shown in figure 22, the radiant heat from the 8- by 10-foot fire was about 80 percent of the value produced by an infinite fire. Based on modeling experiments addressing thermal radiation through the fuselage opening, the C133 8- by 10-foot pan fire is representative of a very large external fuel fire.

CABIN ENVIRONMENTAL CONDITIONS.

The cabin environmental conditions fall into two catagories: (1) conditions affecting passenger survivability directly (air temperature, smoke density, and toxic gas concentration), and (2) conditions affecting material involvement (heat flux and temperature around fire opening).

SURVIVABILITY.

As stated previously, the cabin hazard is dependent upon ambient wind conditions and fire size with zero wind or with the fire downwind of the fuselage. Very little hazard from the fuel fire alone is created in the cabin. However, with the wind blowing a fire adjacent to a fuselage toward an opening, a serious cabin hazard can be created very rapidly.

The DC10 accident at Los Angeles International Airport in March 1978 has imparted credibility to the scenario used in this study which was selected prior to the date of the accident. (References to the Continental DC10 accident were from observations made by the author during his participation in the NTSB investigation of the accident.) The accident, caused by tire failure, created a large fuel fire on the left side of the intact fuselage.

Fortunately, the wind direction was from the right side, which caused the major portion of the fire to be bent away from the fuselage. Although portions of the external aluminum skin were melted, the fire did not penetrate the fuselage shell, composed of skin, structure, insulation, and interior paneling, over the time of fire exposure (foam was applied "within 100 seconds after ignition" (reference 3). The cabin interior was not ignited although there were open doors next to the intense fire. There was no evidence of flame penetration into the cabin. Any damage to the interior appears to have resulted from radiation through door openings and some of the windows which eventually melted through. Flames also did not penetrate these window openings. Thus, the C133 scenario consisting of an intact, nonmelting fuselage with an external fuel fire adjacent to an open door is very similar to the DC10 accident.

The cabin conditions resulting from that accident are similar to those found in the C133 under similar wind conditions (little temperature rise, little smoke, and radiant heat near any opening adjacent to the fire) (figure 23). Less smoke should be expected in the C133 tests, since no materials were present to char. Thus, smoking of some the materials occurred during the DC10 fire. Zero-wind conditions created the same type of cabin environment as a wind blowing the fire away from the fuselage (figure 24). A wind blowing the flame toward the cabin can very quickly create a serious hazard in the cabin.

Figure 25 represents the temperature, smoke, and heat flux from the worst test conducted, test number 32. During this test, the windspeed was 5.5 miles per hour (mph) out of the southwest with a corrected windspeed of 4.07 mph. The fuel pan size was 4 by 6 feet. Since the fire scenario and fuselage configuration of these tests represent one of an infinite number of possibilities, the quantitative measurements mean only that they are obtainable levels dictated by the ambient wind and cabin draft conditions. An important study in these tests was that of the flow of hazards through the cabin, namely: heat, smoke, and gases.

HEAT. A major finding of this test program is the stratification of cabin hazards that occur during a cabin fire. Significant stratification occurred for all fire sizes and wind conditions. The most significant stratification was with high winds pushing the flames toward the fuselage, since that condition produced the highest interior cabin termperatures. A temperature-time plot of seven symmetry plane elevations located 50 feet aft of the fire door is shown in figure 26. Note the distinct layer of hot gases that extended from the ceiling down to the 6-foot level. The hot upper layer eventually heated the much cooler lower layer and some mixing occurred. This generally increased the temperature of the lower levels. Figure 27 is a replot of the data from figure 26 and is a better indication of the mixing process. The upper layer of hot gases was very distinct, and the gradual heating of the lower region with time was quite evident. Figures 28 and 29 are different representations of data indicating the cabin temperature from the fire door through the cabin to the aft exit. There is a large increase in temperature early in the tests (1 minute) near the fire door, with very little increase during this time near the exit door. However, after this initial period, the rate of temperature rise for a given height was fairly constant throughout the cabin (figure 28).

SMOKE. The only measurement of smoke taken during this test program was its effect on visibility (the amount of light reduction over 1 foot). In all tests conducted, a large degree of stratification of the smoke occurred. The ceiling and sidewall remained fairly clean. Figures 30 and 31 show smoke stratification during a typical large pan fire test with the wind blowing the flame toward the opening. The "A" portion of both figures show smoke levels 30 feet from the fire. The amount of stratification can easily be seen at that location. The "B" portion of the figures is the smoke level at 60 feet from the fire door adjacent to the exit door. A great deal of mixing and turbulence occur in that area as evidenced by the 5-foot 6-inch and 3-foot 6-inch smoke levels eventually equalizing. Even with the mixing, the smoke level at 1 foot 6 inches remained much less than the higher elevations.

GASES. Practically no significant CO concentrations were measured during any of the tests. A peak of 5,000 parts per minute (ppm) of CO was measured during the most severe fire condition. That measurement was taken 30 feet from the fire at the fuselage centerline and at the ceiling. For the same location, CO was not detectable (at the 5-foot 6-inch level). (The gas analyzer, Beckman Model 864 , was sensitive to concentrations less than 100 ppm). Thus, there was very significant stratification of CO within the cabin. CO_2 was measured at both heights in amounts far below human tolerance limits, with concentrations at the ceiling larger than at 5 foot 6 inches. The amount of O_2 depletion at this station was also insignificant. As expected, the lowest O_2 concentration was detected at the ceiling, but never dropped below 18 percent. Five-foot six-inch levels never dropped below 20 percent. The analytical procedures routinely used for measuring toxic gas emission from cabin materials (reference 4) were applied during several tests (test 66 through 70). Only trace amounts of nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) were measured, but no HCN was detected.

TOTAL CABIN HAZARD.

Increases in cabin temperature were accompanied by corresponding increases in smoke and toxic gases (CO, CO_2) and O_2 depletion. Figures 32, 33, and 34 show the relationship between heat and smoke in the cabin due to an external fuel fire. In figure 32, the light reduction is plotted versus temperature increase for six 8- by 10-foot fire tests. There are 40 points per test shown (a point every 6 seconds of every test). Figure 33 is a plot of the total temperature versus total smoke measurements for those same six tests. The total temperature is the area under the temperature curve, and the total smoke is the area under the optical density curve. The smoke and temperature for figure 34 were calculated in the same manner as for figure 33. Figure 34 shows that the relationship between the total smoke and temperature holds true for all levels, not just 5 feet 6 inches.

When cabin hazards are dominated by an external fuel fire, it is apparent that smoke and heat are individually greater deterrents than toxic gas (CO) to survivability. Take the cabin location 30 feet aft of the fire at a height of 5 feet 6 inches (figure 32). A temperature of 300° Fahrenheit (F) produces a light reduction from smoke of 75 percent at certain test times depending on the wind velocity. This temperature would make "mouth breathing difficult" (reference 5) and the smoke would obscure visibility of a backlighted sign beyond 6 feet (reference 6). However, even if the CO concentration was near the measurable threshold limit of 100 ppm, there would be "no poisoning symptoms, even for long periods of time" (reference 7).

MATERIAL INVOLVEMENT.

Data from three tests will be presented: (1) zero wind with large (8- by 10-foot) fire (test 62), (2) the worst test in terms of cabin hazards (test 32), and (3) the worst large (8- by 10-foot) fire in terms of cabin hazards (test 66).

Two main considerations should be given as to whether cabin material will ignite from an external fire; (1) heat flux levels, and (2) flame impingement. During test 32 and 66, flames entered the cabin quite extensively. With zero wind, test 62, very little flame penetrated into the cabin. Figure 35 shows heat flux levels around the doorway, as per figures 10 and 11, for the zero wind condition. Heat flux readings ranged as high as 15 British thermal units per square foot second (BTU/ft^2-s) in the doorway and 0.6 BTU/ft^2-s across the fuselage on the opposite wall. Figures 36 and 37 show the heat flux levels in the same locations as figure 35 for tests 32 and 66, respectively. Much higher heat flux levels were obtained in the cabin than during test 62. During test 32, flames reached past the centerline of the fuselage, causing very high heat flux levels in that area. The temperature profiles shown in figure 38 indicate that flame impingement at the ceiling centerline occurred for test 32.

SUMMARY OF RESULTS

From the full-scale fire scenario studied, there are five important findings with regard to the cabin hazard characteristics of an external fuel fire:

1. Ambient wind conditions dictate the hazard created in the cabin,

2. Significant stratification of heat, smoke, and toxic gases occur in the cabin,

3. Heat and smoke individually are more hazardous than carbon monoxide in the cabin,

4. Oxygen depletion is insignificant when the cabin is ventilated, and

5. Fire size dictates the radiant heat level through a cabin opening under zero-wind conditions.

CONCLUSIONS

1. Major stratification of hazards occur in the cabin when the hazards are created by an external fuel fire.

2. Ambient wind determines the amount of hazards entering a cabin due to a given external fuel fire.

3. When cabin hazards are dominated by an external fuel fire, smoke and heat are individually greater deterrents than toxic gas (CO) to survivability.

4. High heat flux levels can be encountered in and around the fire entry door with very little increase in cabin hazards.

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7. Pryor, A. J. and Yuill, C. H., Mass Fire Life Hazard, Southwest Research Institute, report prepared for Office of Civil Defense, Department of the Army OSA under work unit 2537A, September 1966.

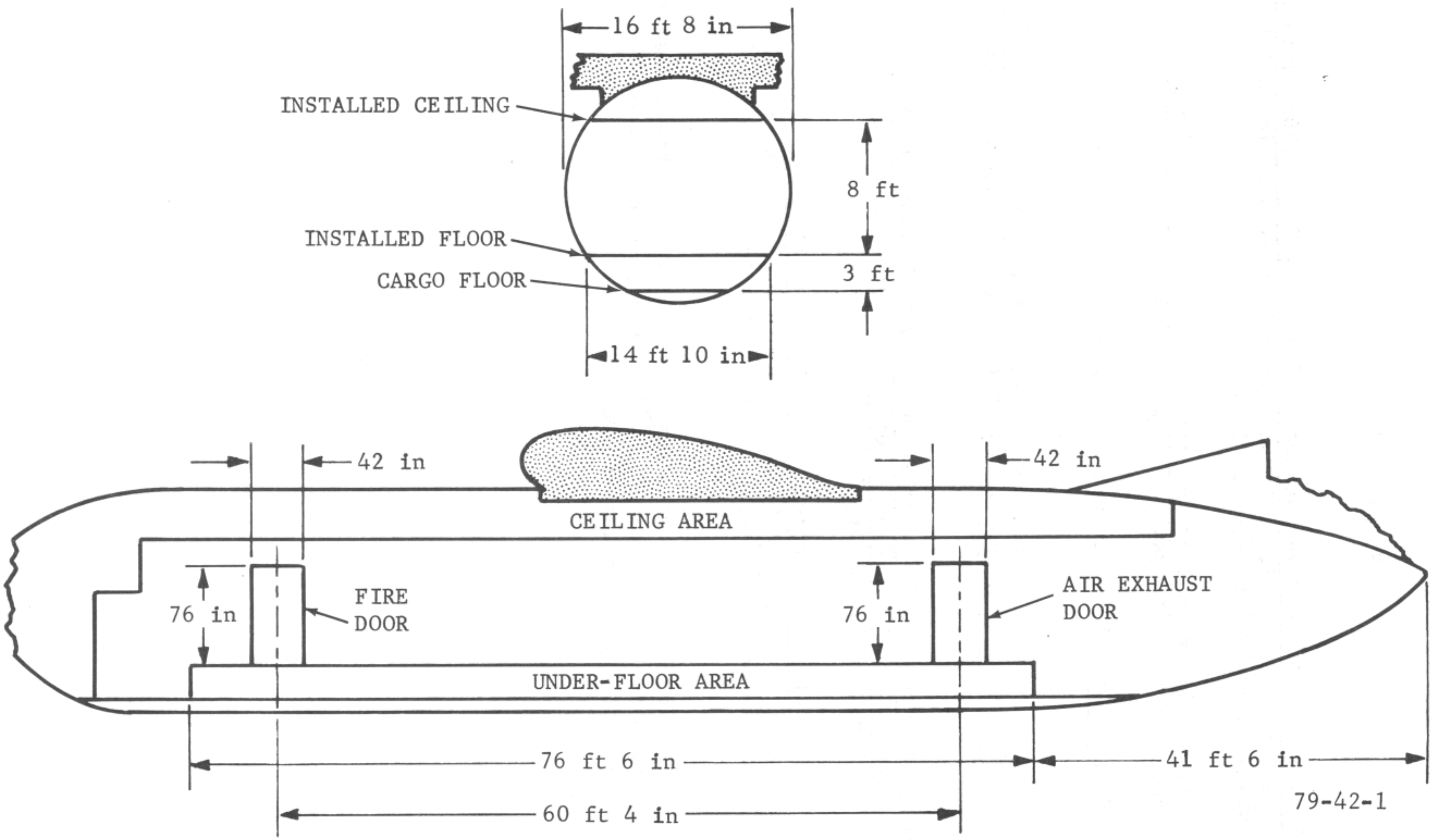


FIGURE 1. C133 WIDE-BODY CABIN FIRE TEST ARTICLE

FIGURE 2. INTERIOR VIEW OF C133 PRIOR TO TESTING

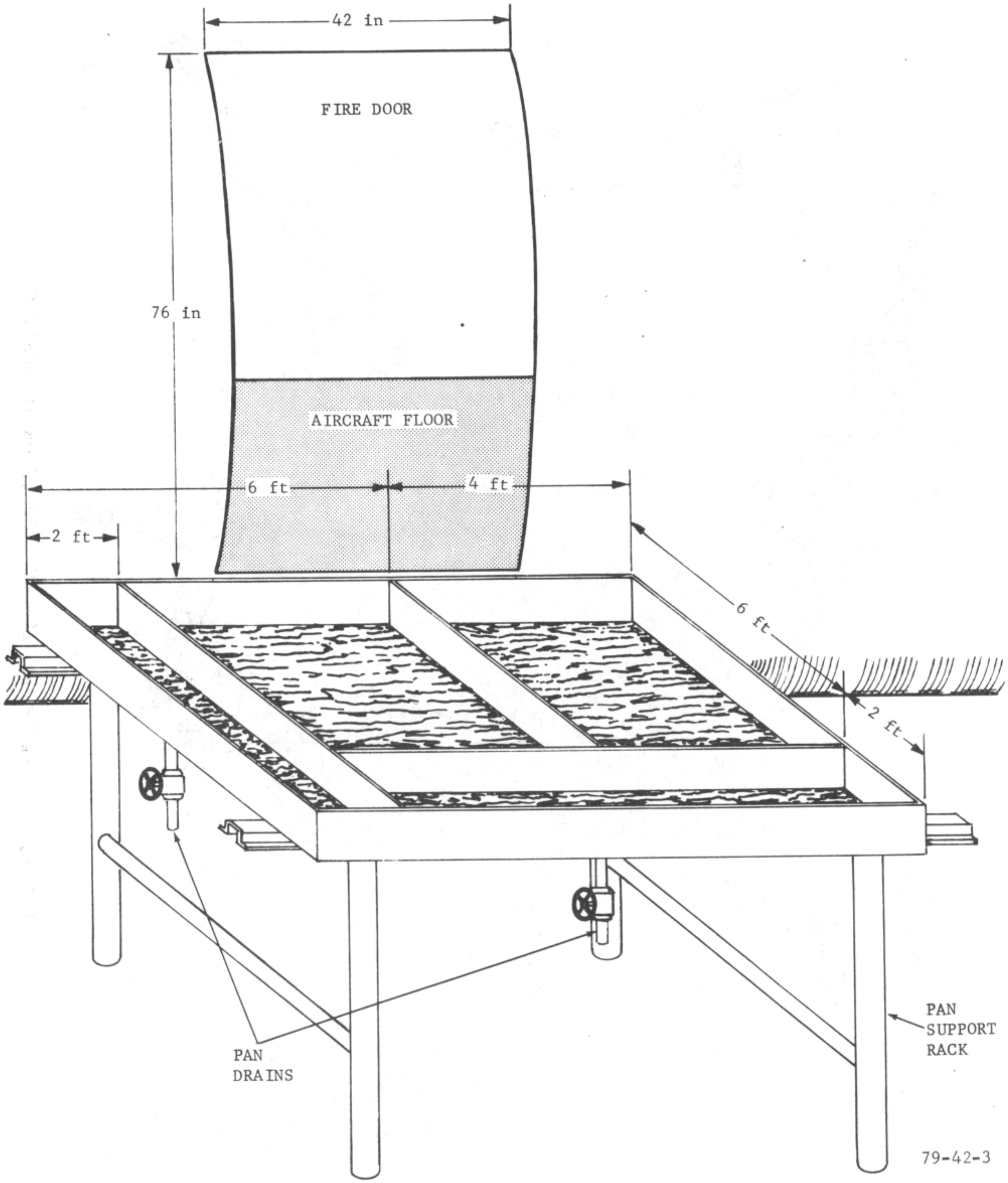


FIGURE 3. FIRE PAN INSTALLATION

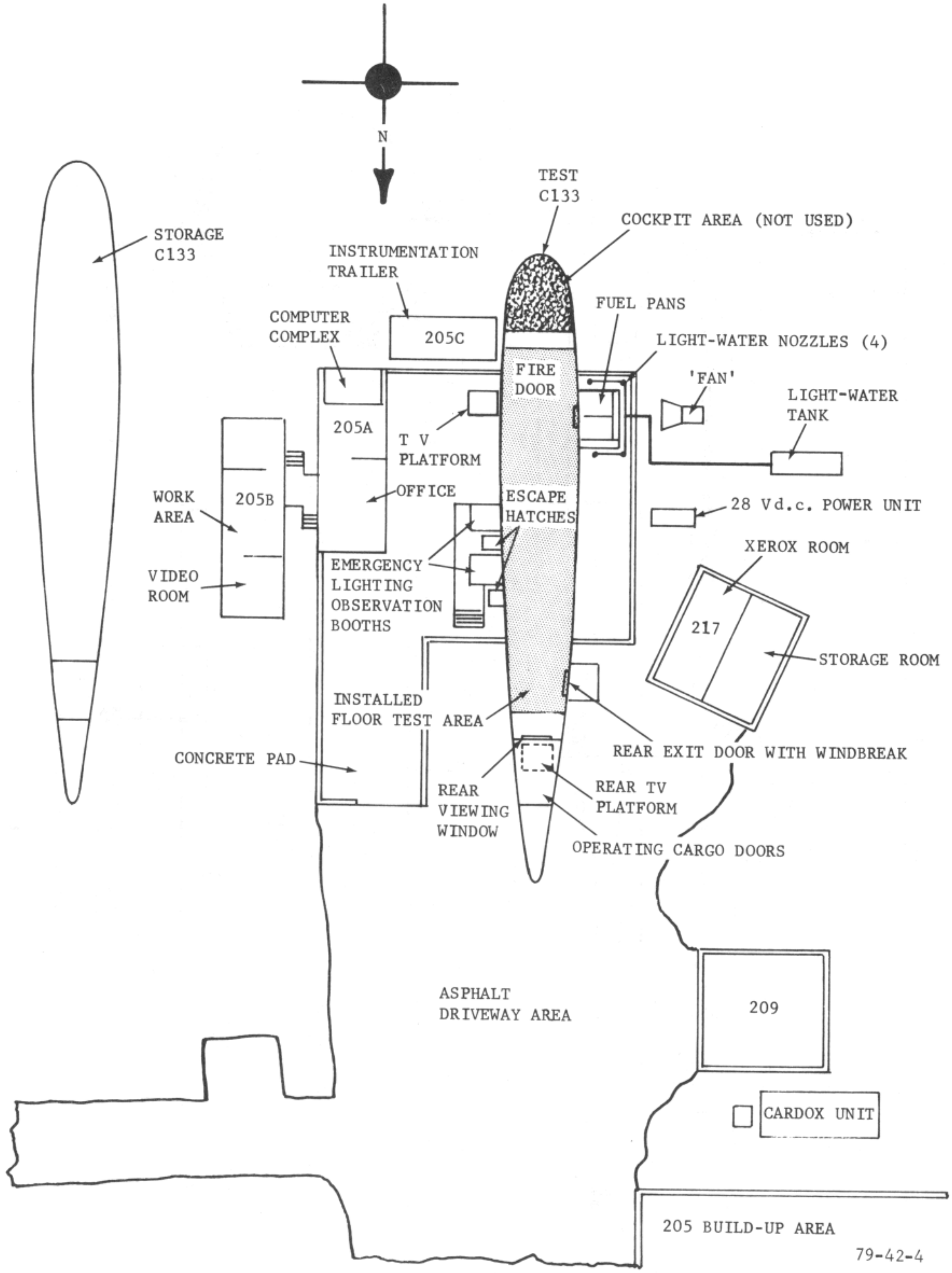


FIGURE 4. FULL-SCALE FIRE TEST FACILITY

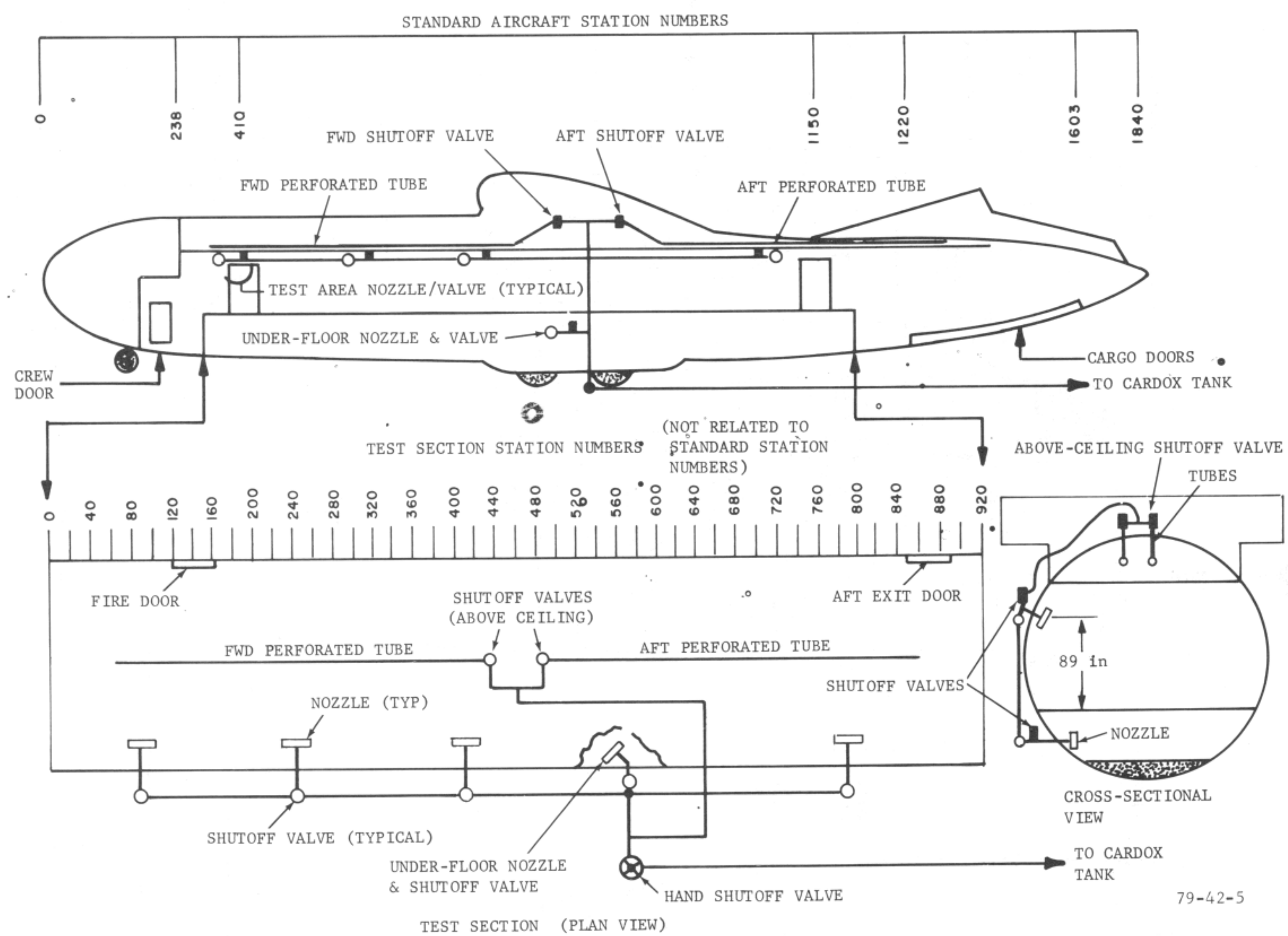


FIGURE 5. TEST ARTICLE FIRE PROTECTION SYSTEM

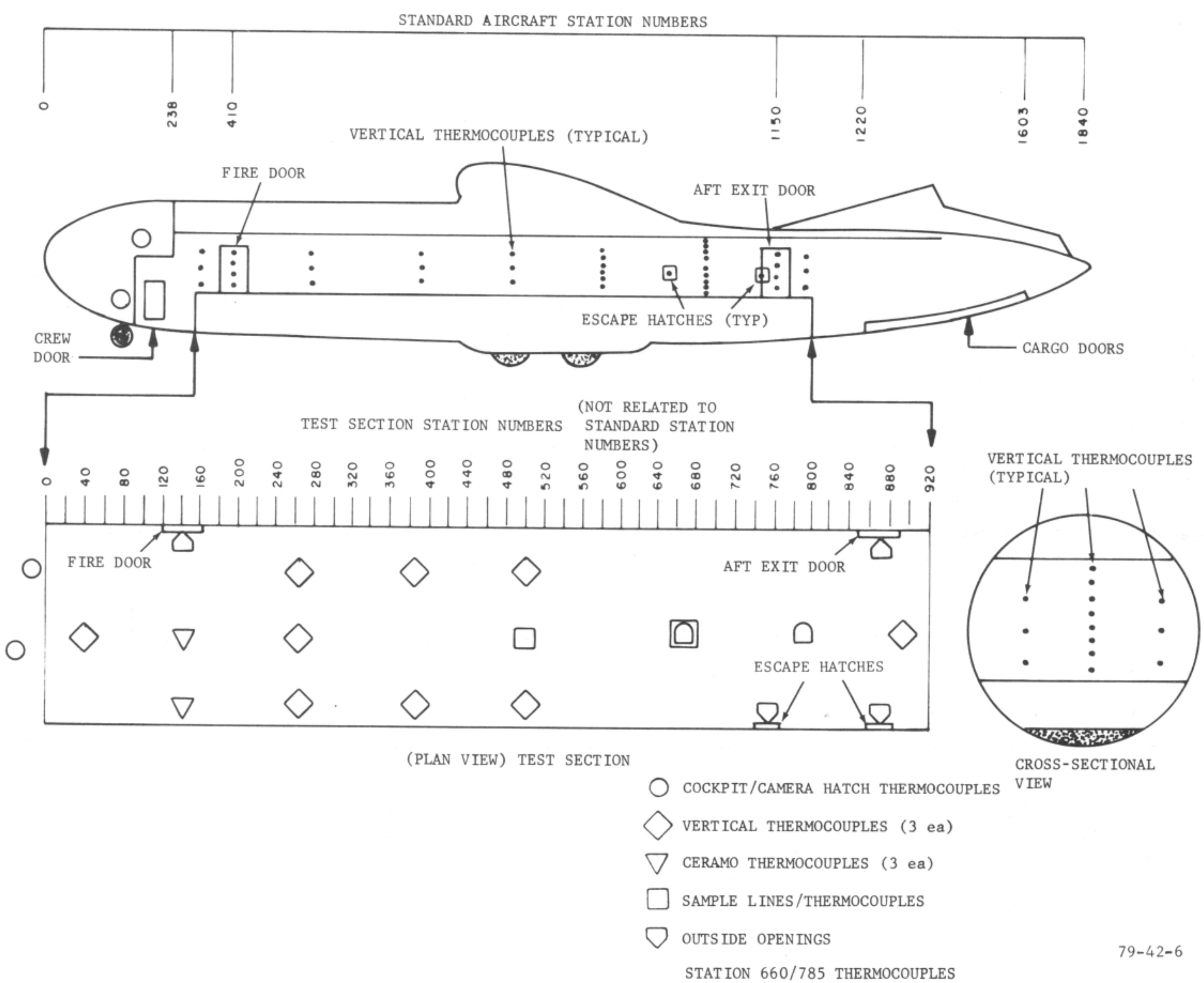


FIGURE 6. TEST ARTICLE AIR THERMOCOUPLE LOCATIONS

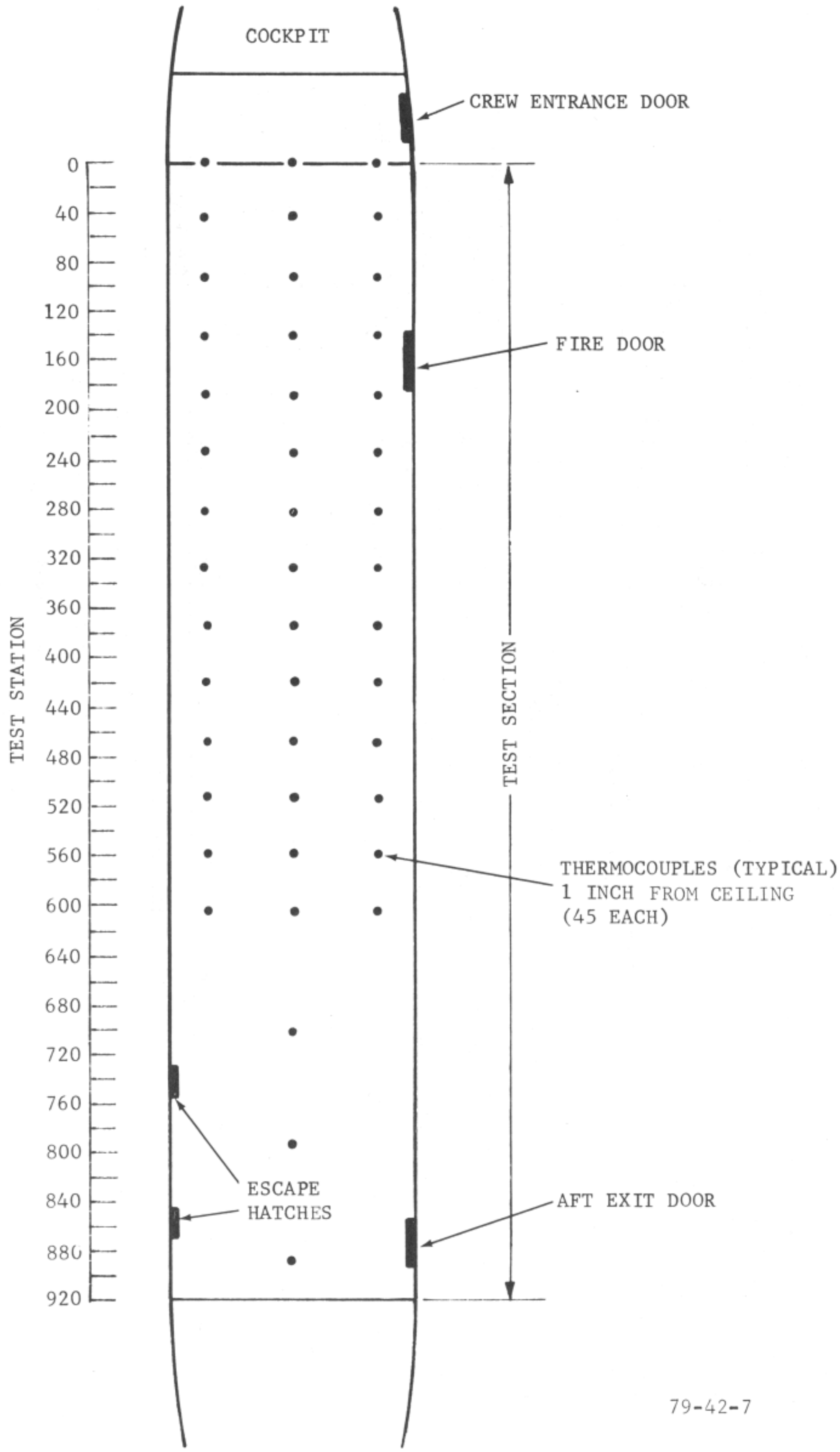


FIGURE 7. TEST ARTICLE CEILING THERMOCOUPLE LOCATIONS

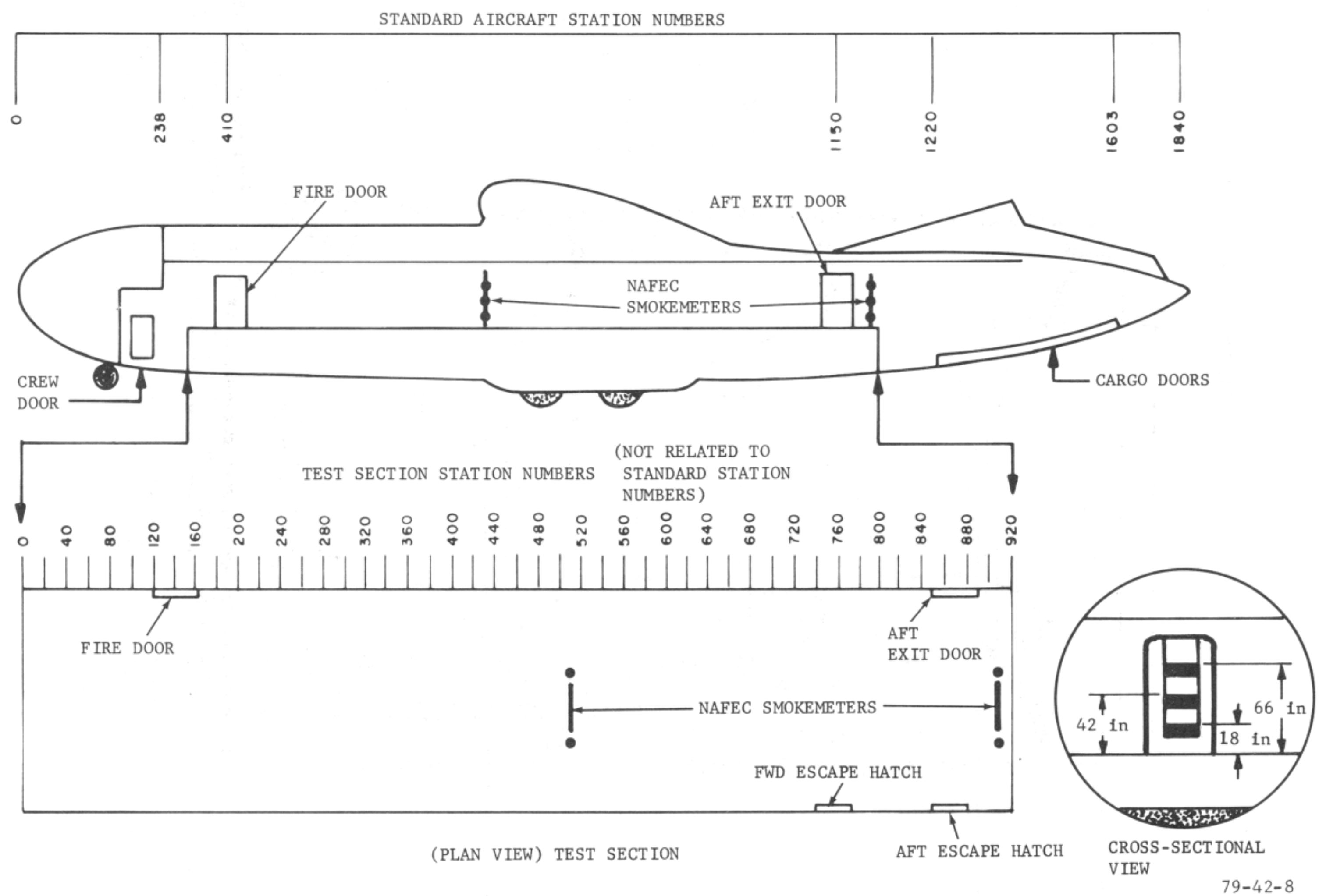


FIGURE 8. SMOKEMETER LOCATIONS

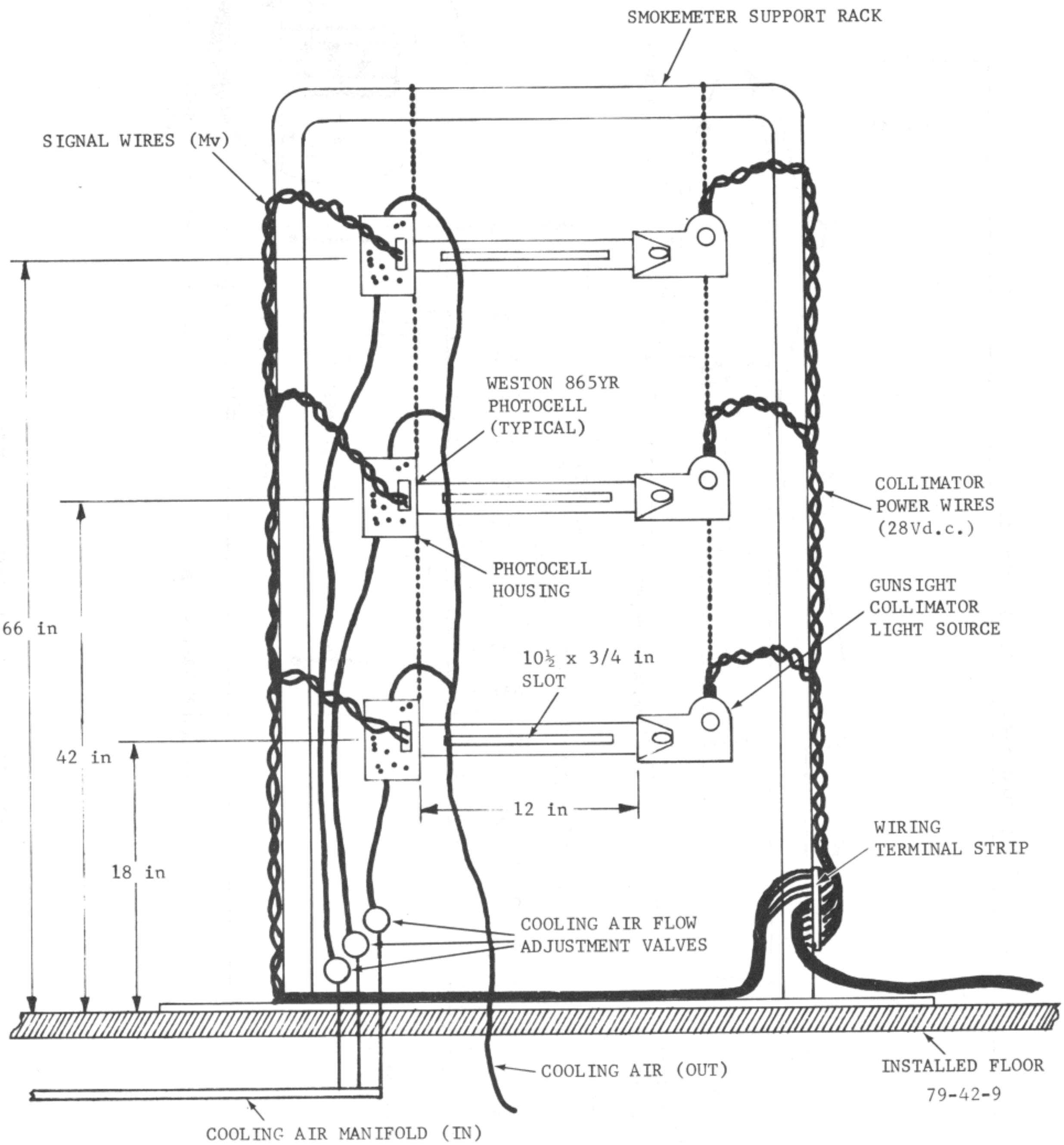


FIGURE 9. SMOKEMETER RACK INSTALLATION

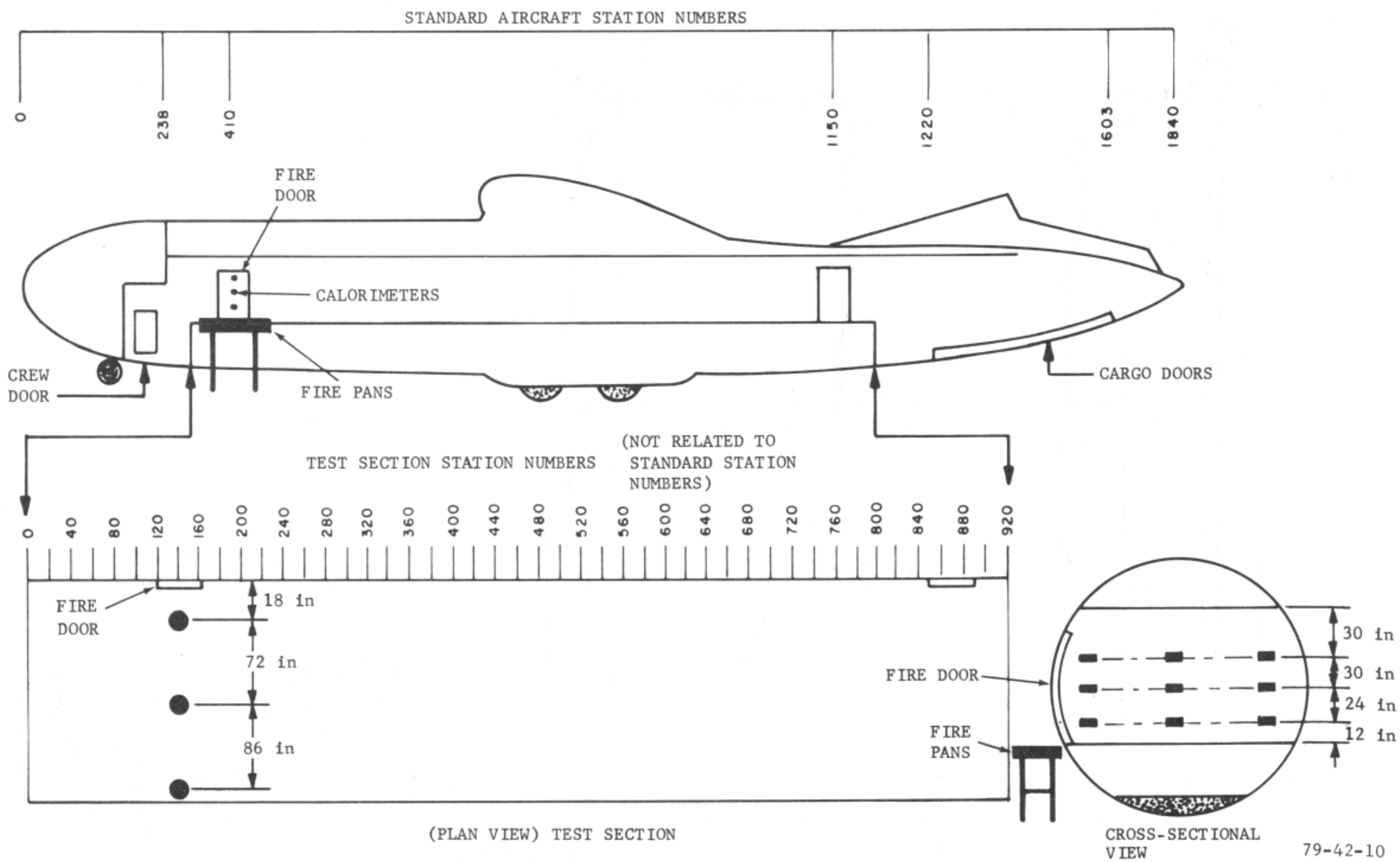


FIGURE 10. LOCATION OF ASYMPTOTIC RAPID-RESPONSE CALORIMETERS

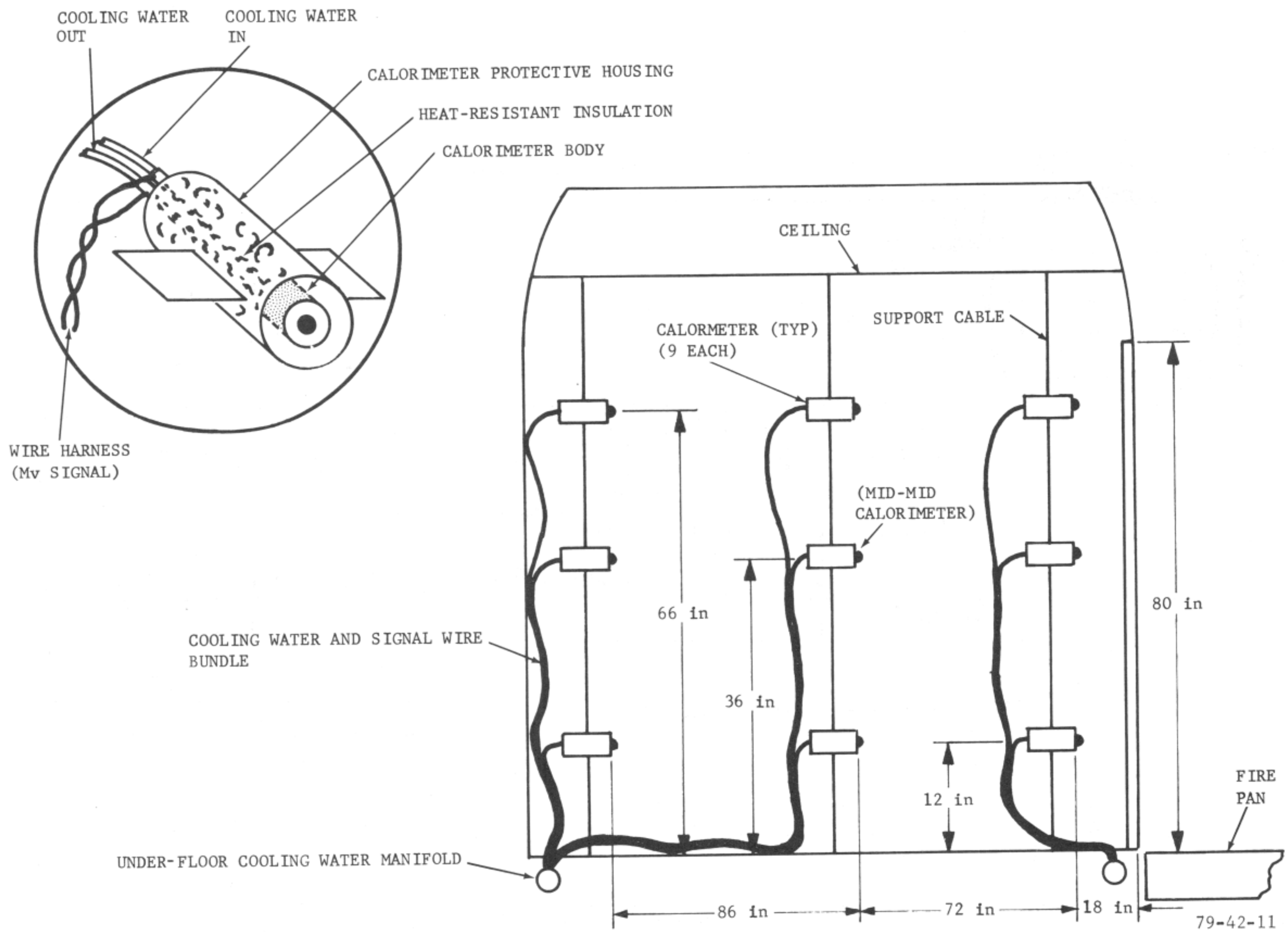


FIGURE 11. CALORIMETER INSTALLATION

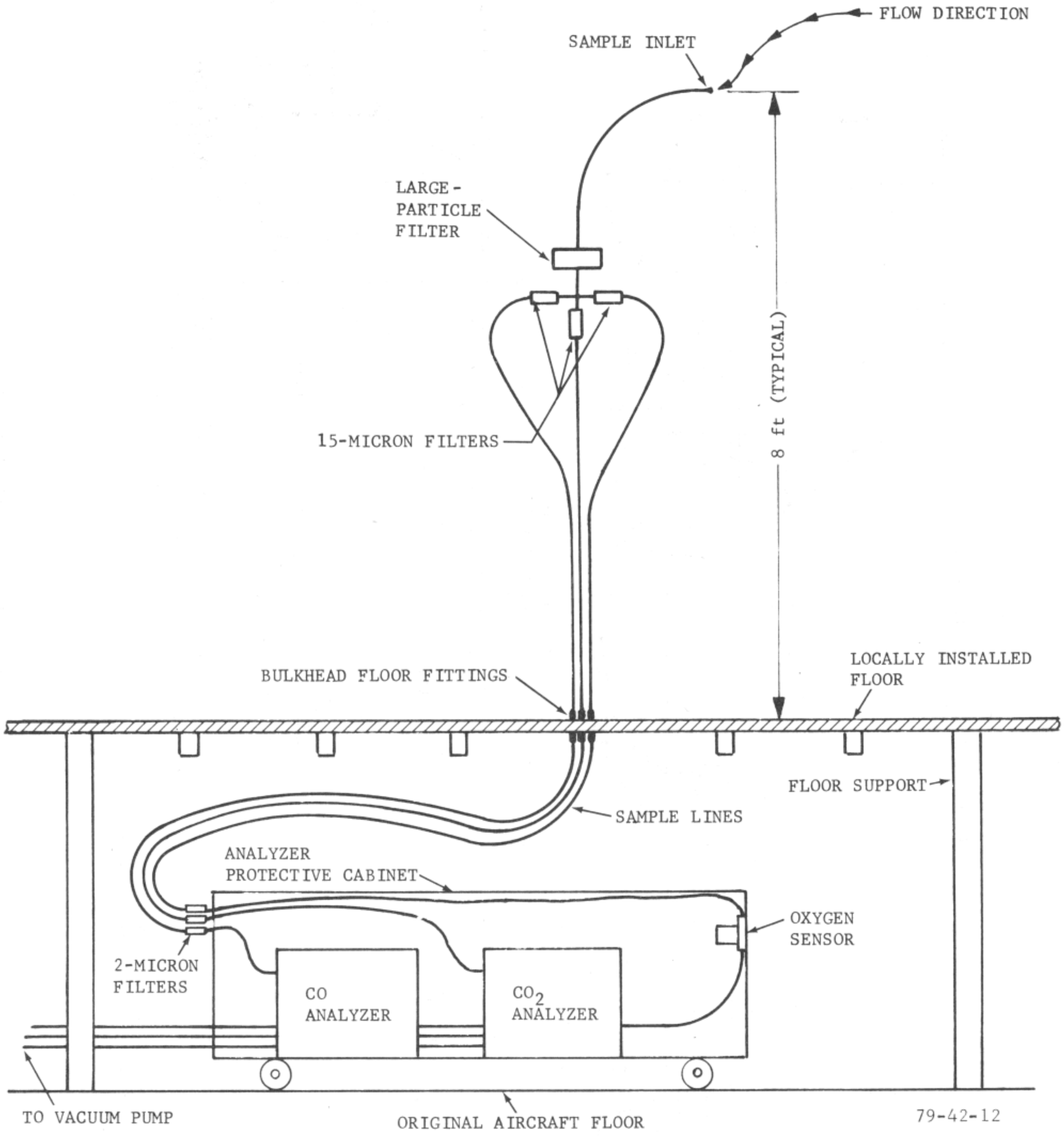
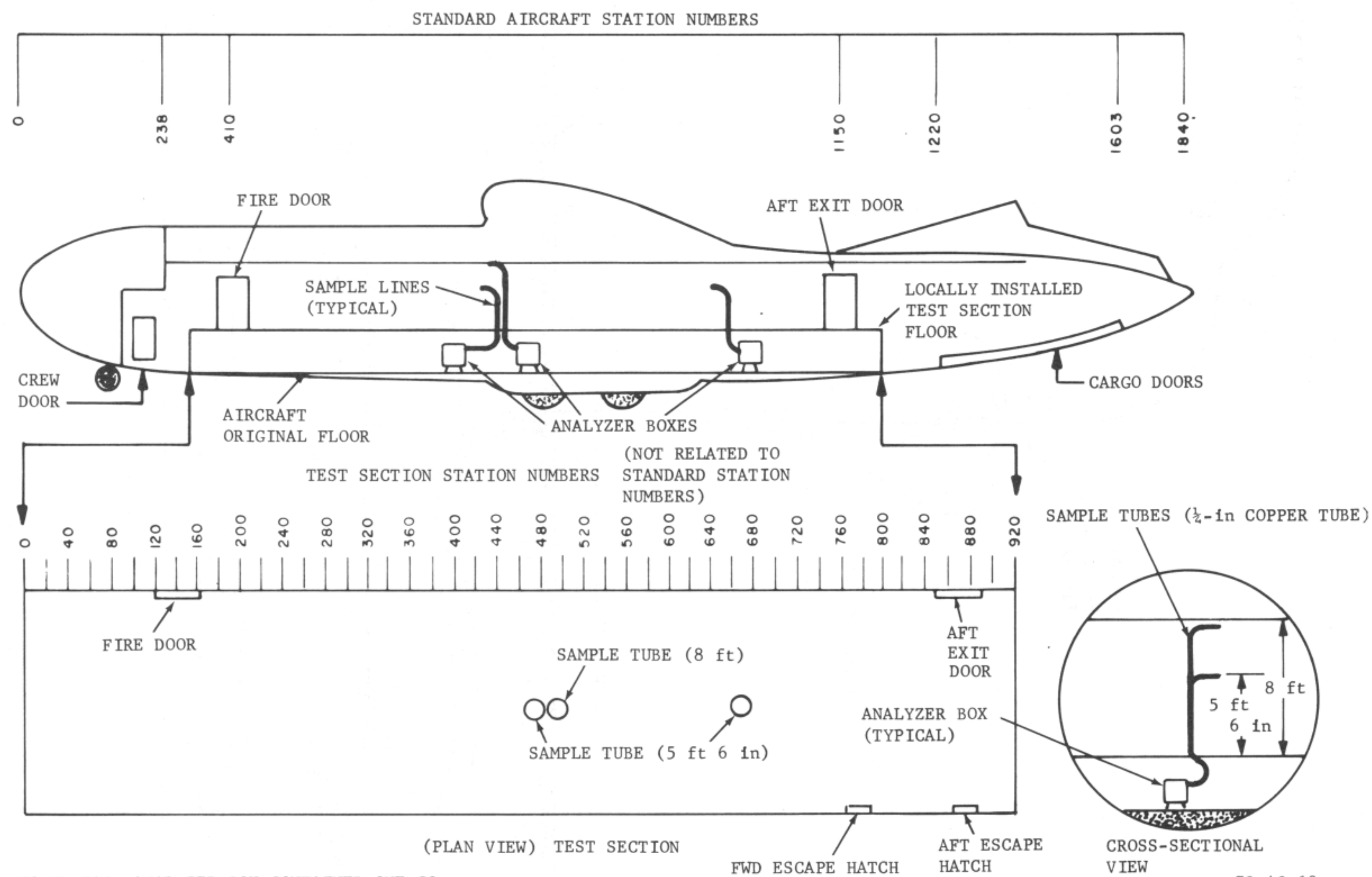


FIGURE 12. TYPICAL GAS SAMPLING LOCATION



NOTE: EACH ANALYZER BOX CONTAINED ONE CO ANALYZER, ONE CO_2 ANALYZER, AND ONE O_2 SENSOR.

FIGURE 13. LOCATION OF GAS SAMPLE STATIONS

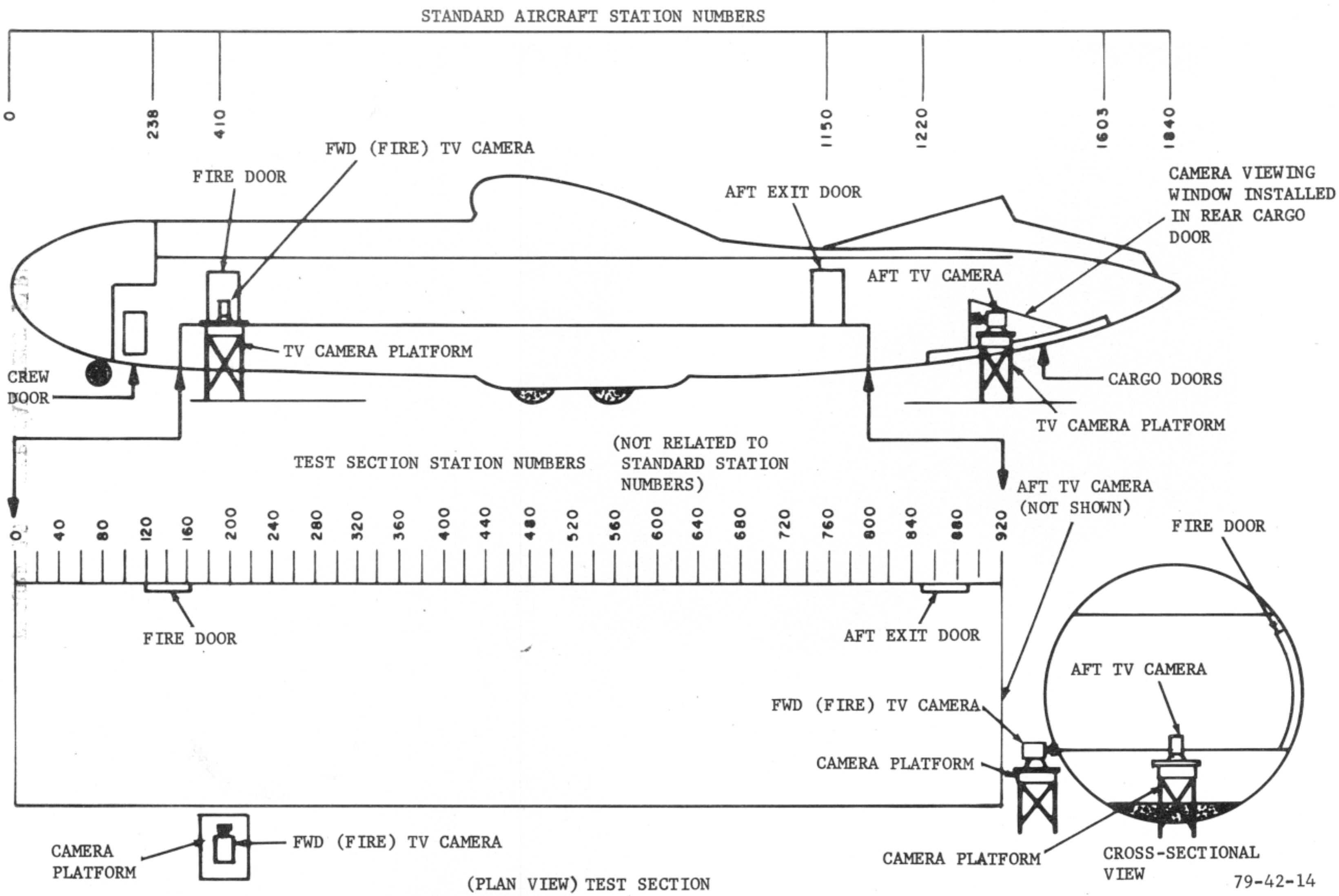


FIGURE 14. TELEVISION CAMERA LOCATIONS

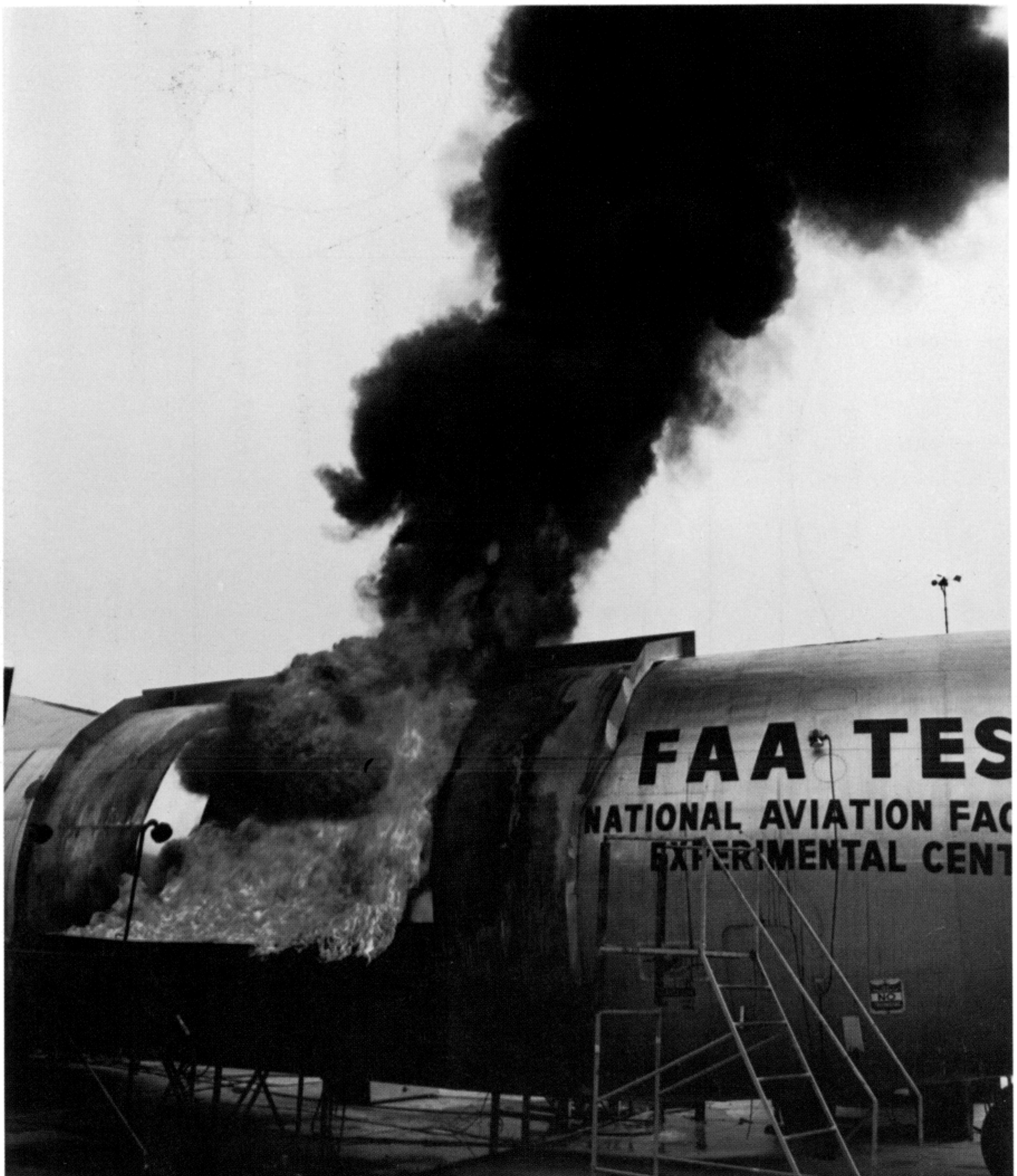


FIGURE 15. TYPICAL TEST FIRE

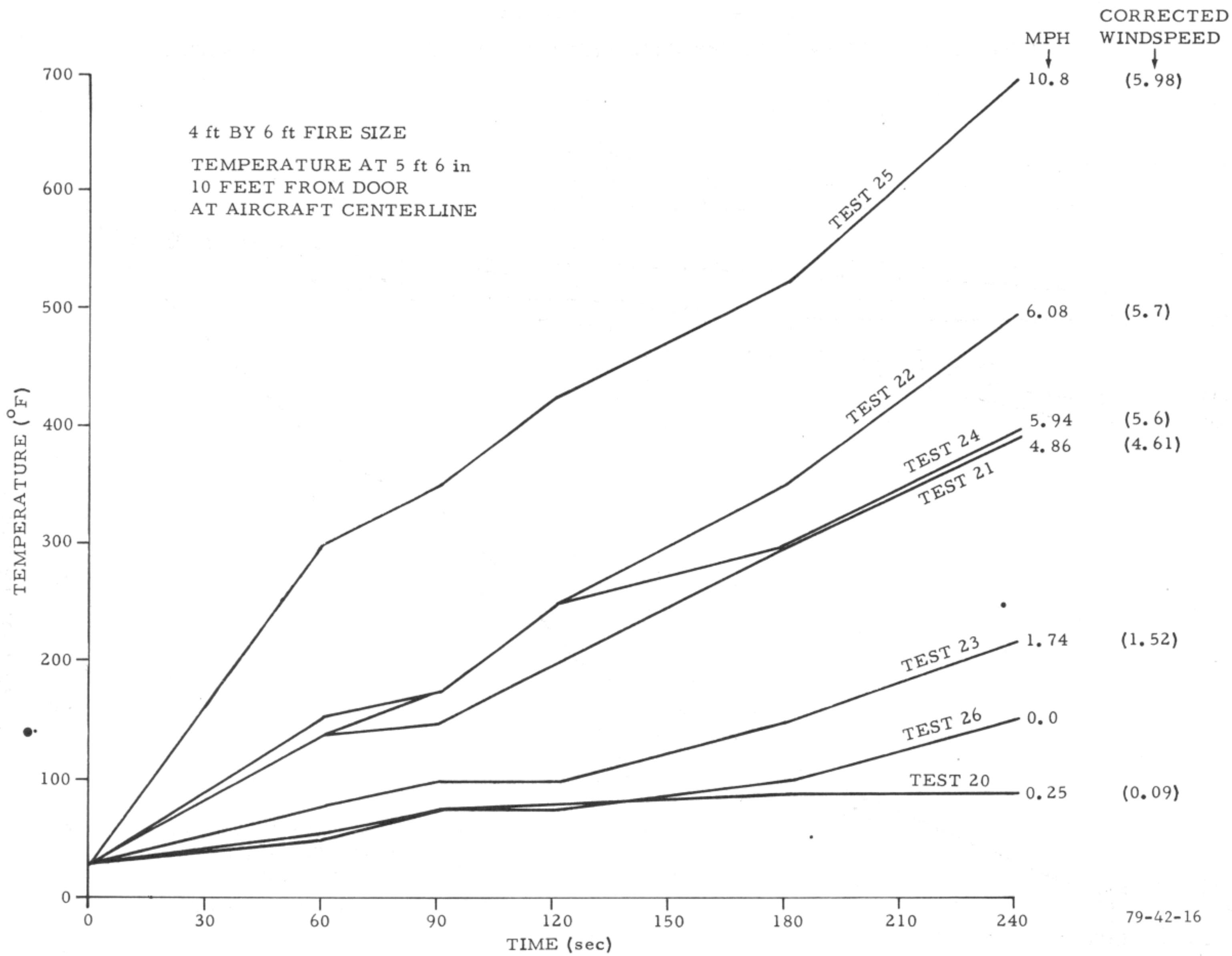


FIGURE 16. EFFECT OF WIND ON CABIN TEMPERATURES (4- BY 6-FOOT FIRE)

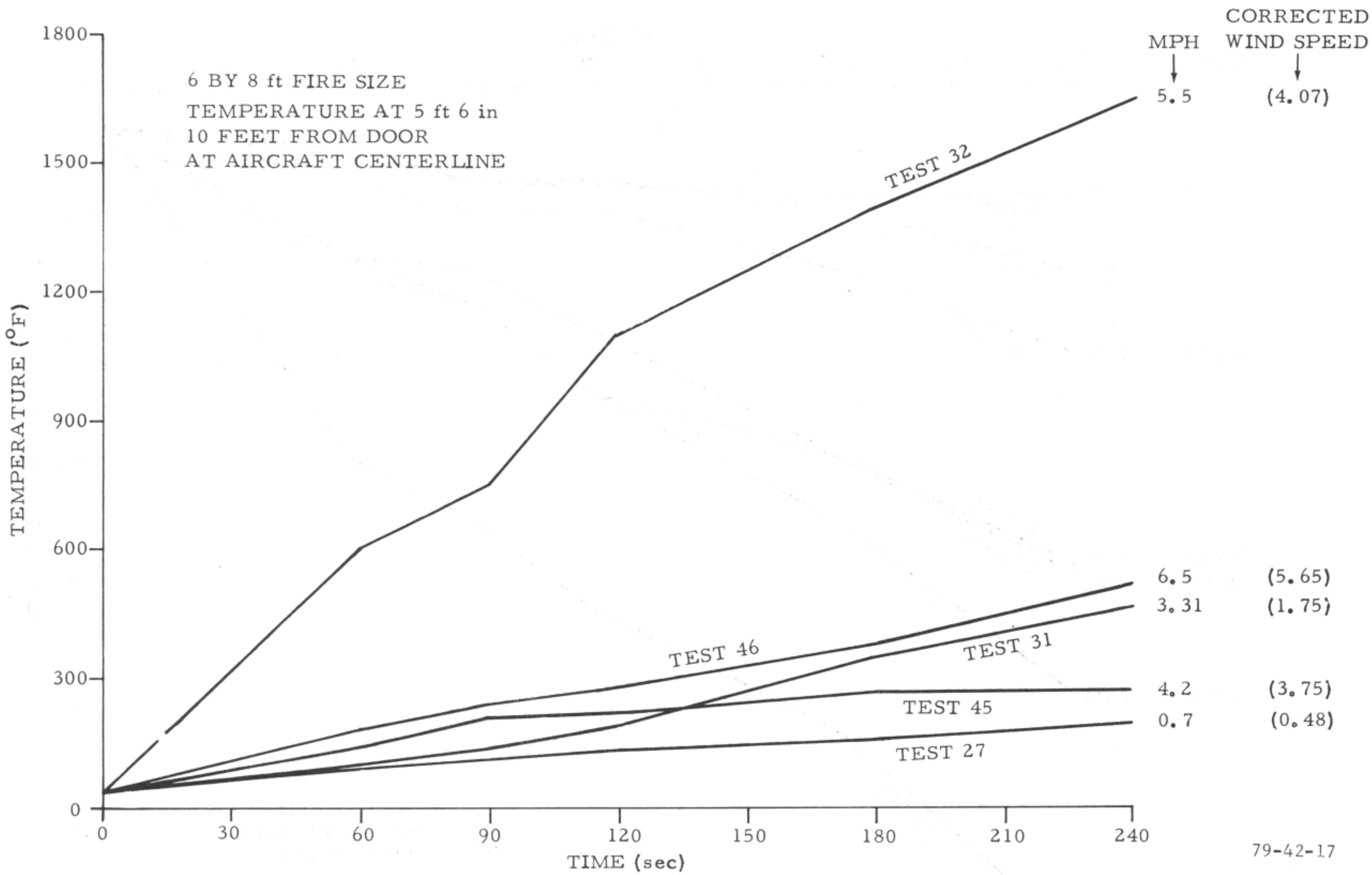


FIGURE 17. EFFECT OF WIND ON CABIN TEMPERATURES (6- BY 8-FOOT FIRE)

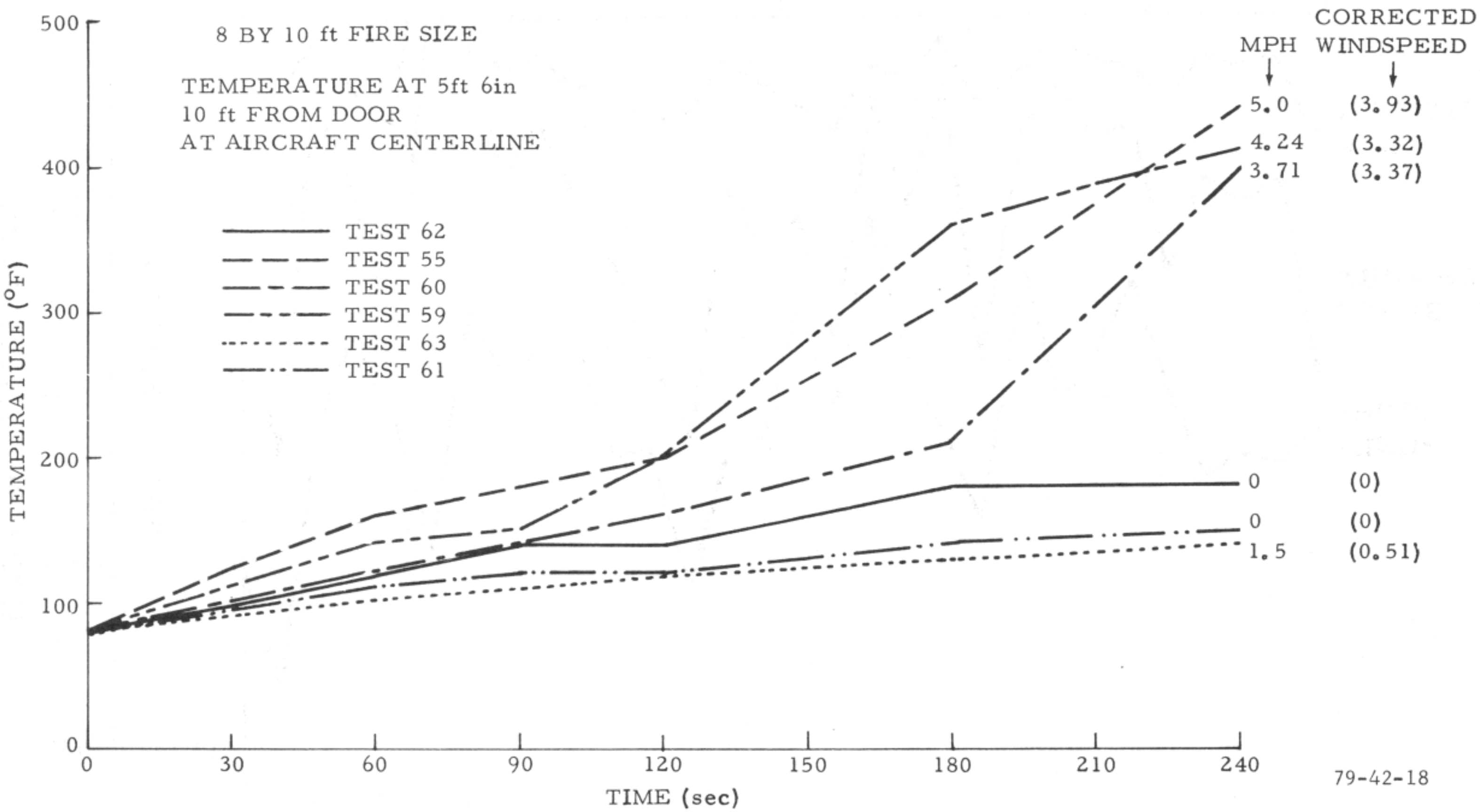


FIGURE 18. EFFECT OF WIND ON CABIN TEMPERATURES (8- BY 10-FOOT FIRE)

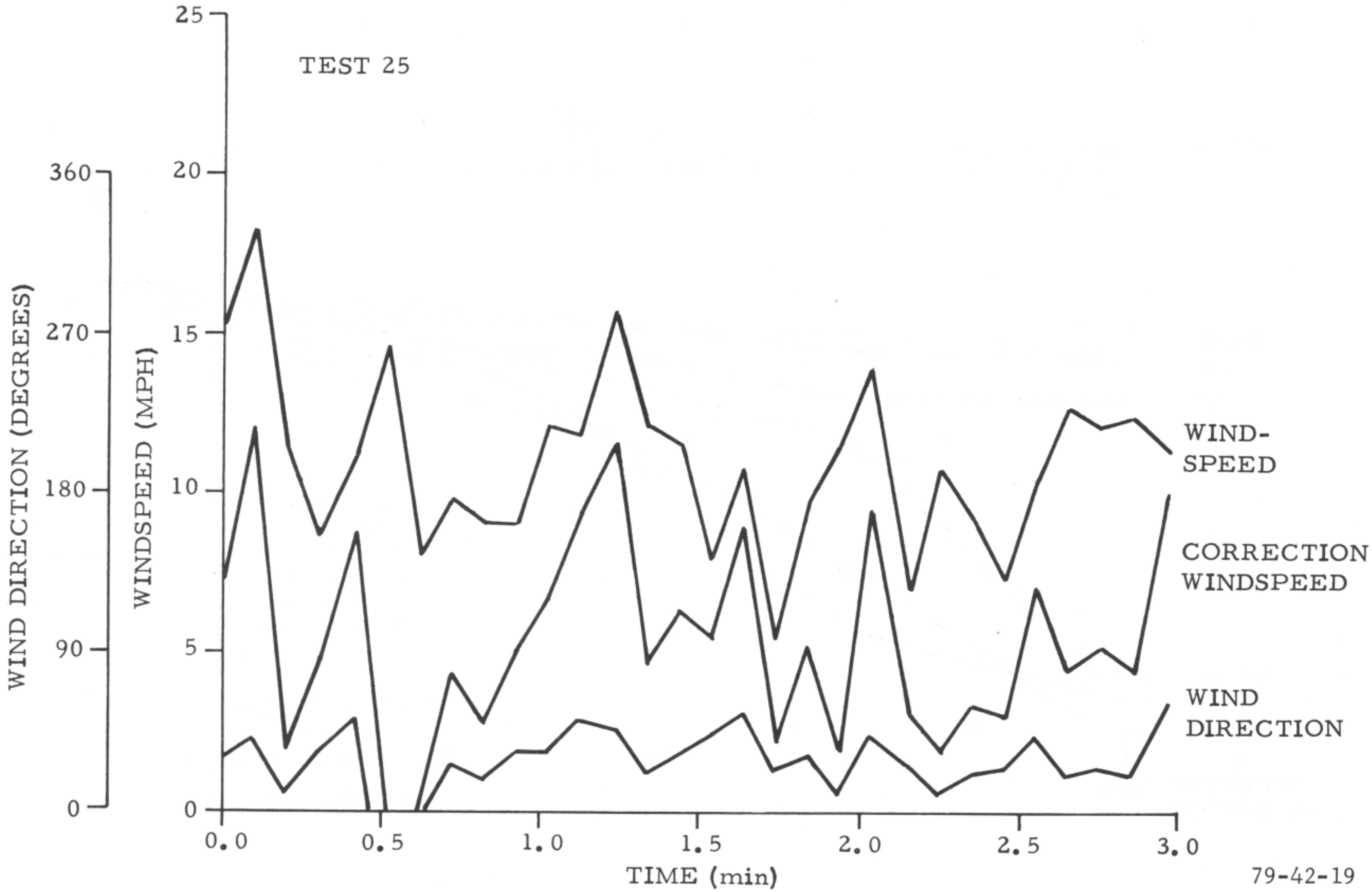


FIGURE 19. CORRECTED WINDSPEED DETERMINATION

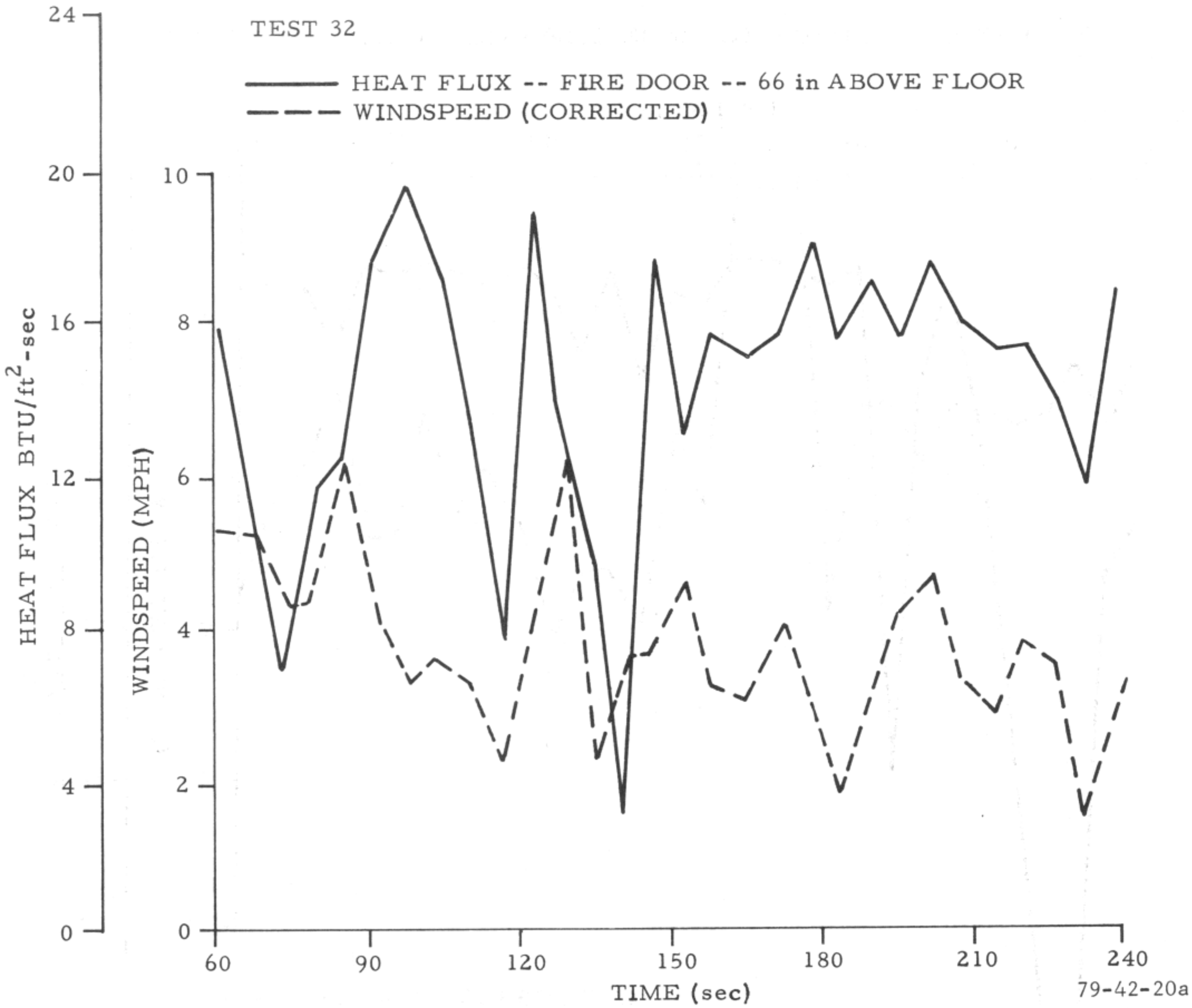


FIGURE 20. EFFECT OF WIND VARIATION ON WIND ENTERING FUSELAGE (Sheet 1 of 2)

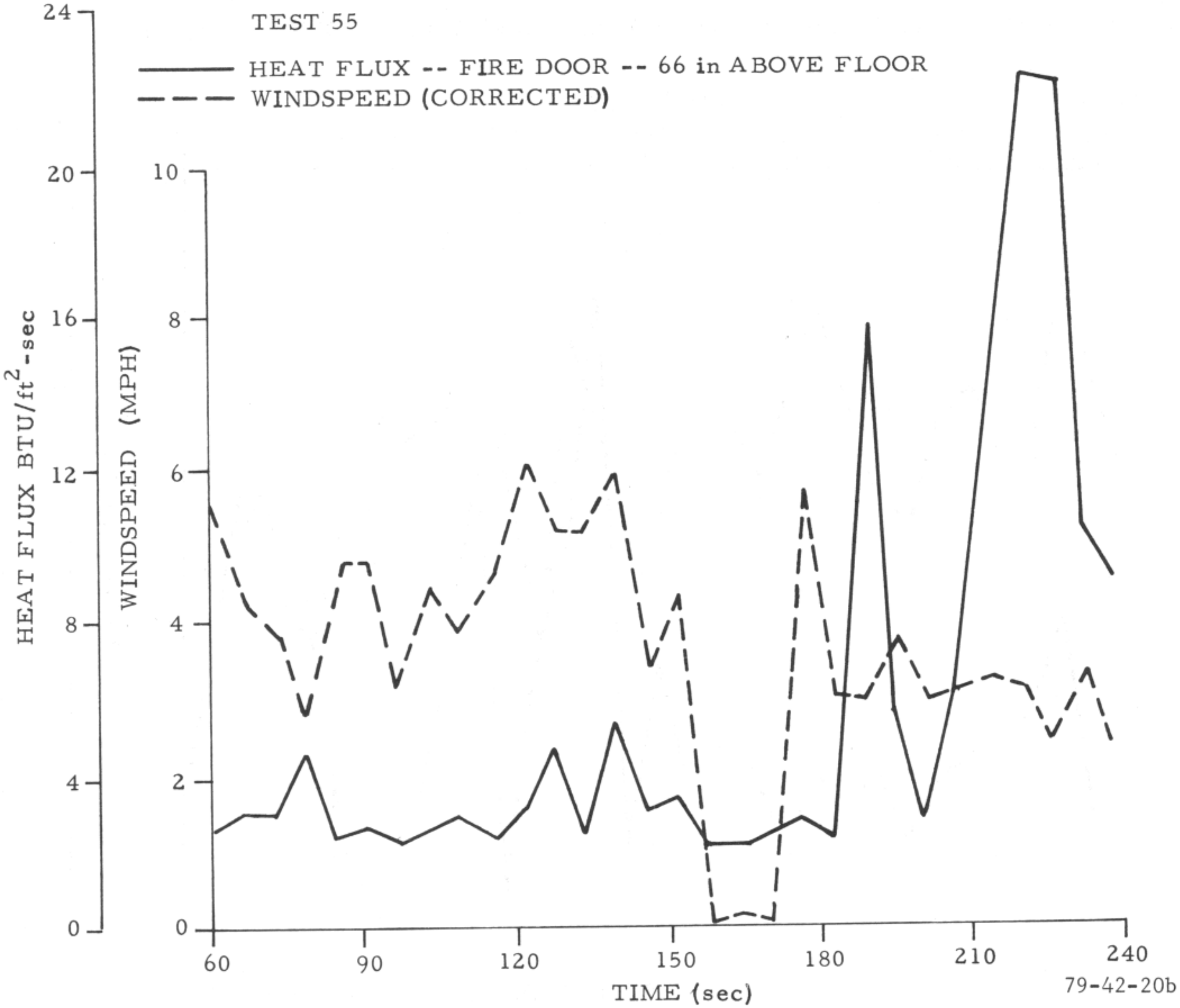


FIGURE 20. EFFECT OF WIND VARIATION ON WIND ENTERING FUSELAGE (Sheet 2 of 2)

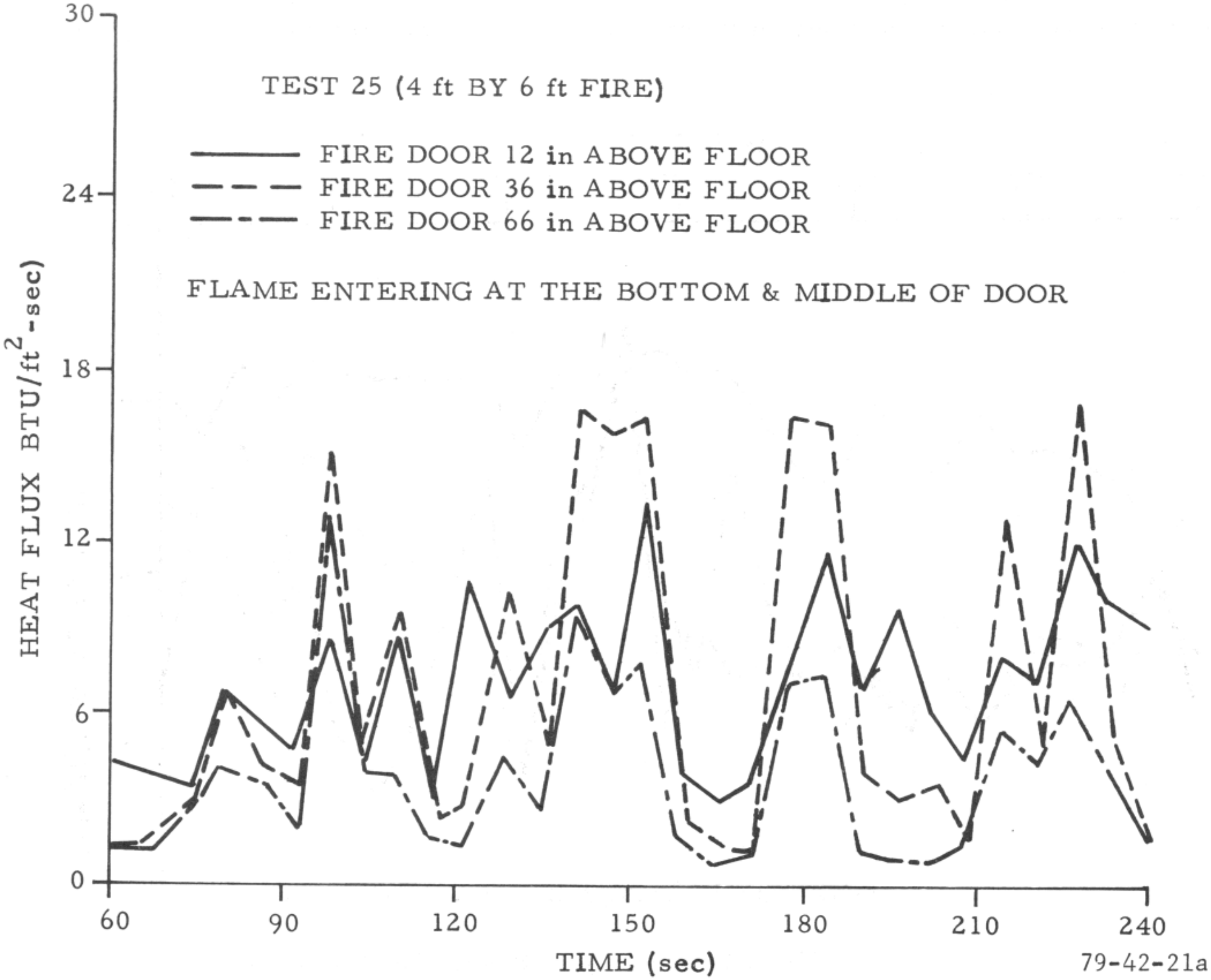


FIGURE 21. EFFECT OF FIRE SIZE ON FLAME PENETRATING FUSELAGE OPENING (Sheet 1 of 3)

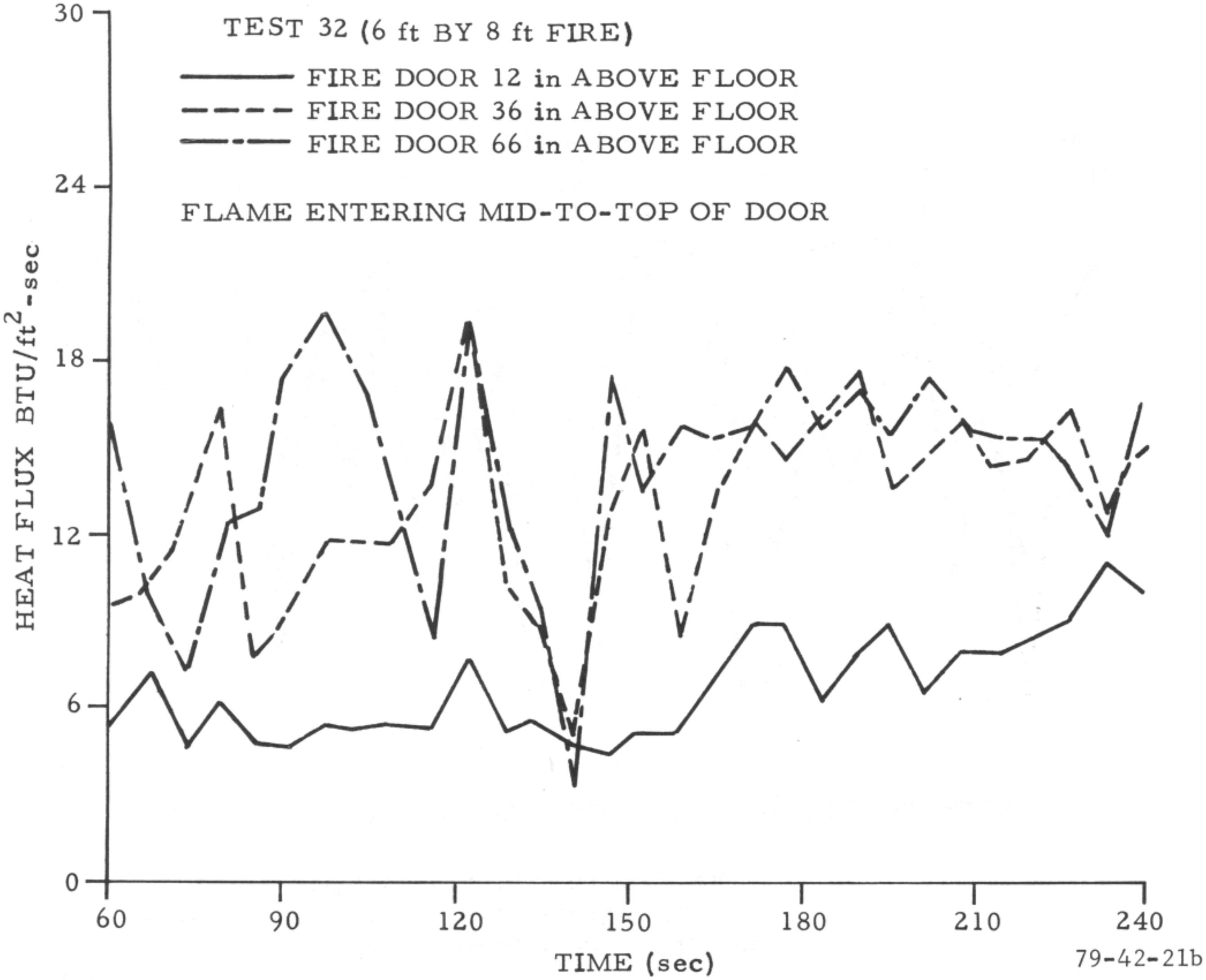


FIGURE 21. EFFECT OF FIRE SIZE ON FLAME PENETRATING FUSELAGE OPENING (Sheet 2 of 3)

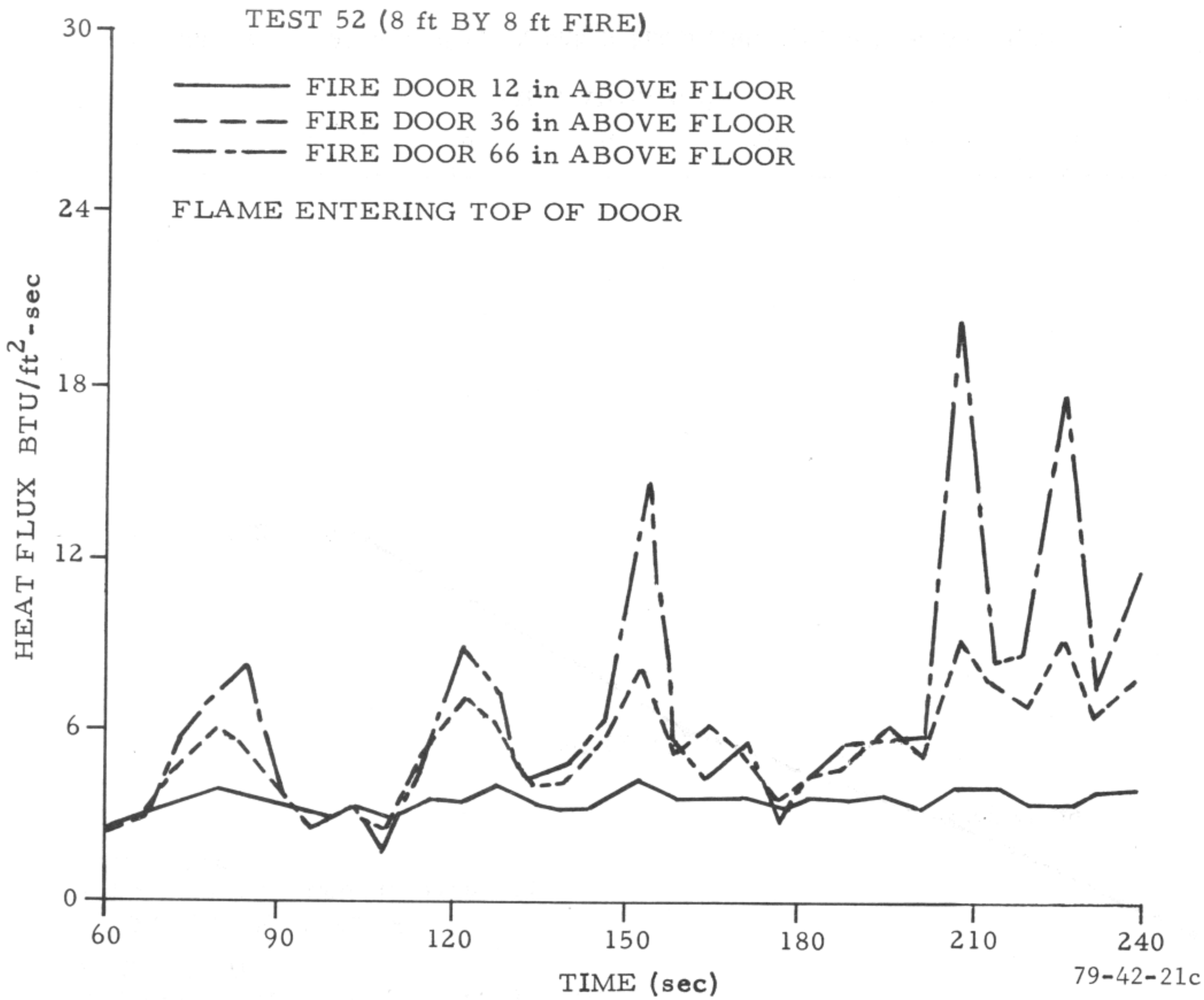


FIGURE 21. EFFECT OF FIRE SIZE ON FLAME PENETRATING FUSELAGE OPENING (Sheet 3 of 3)

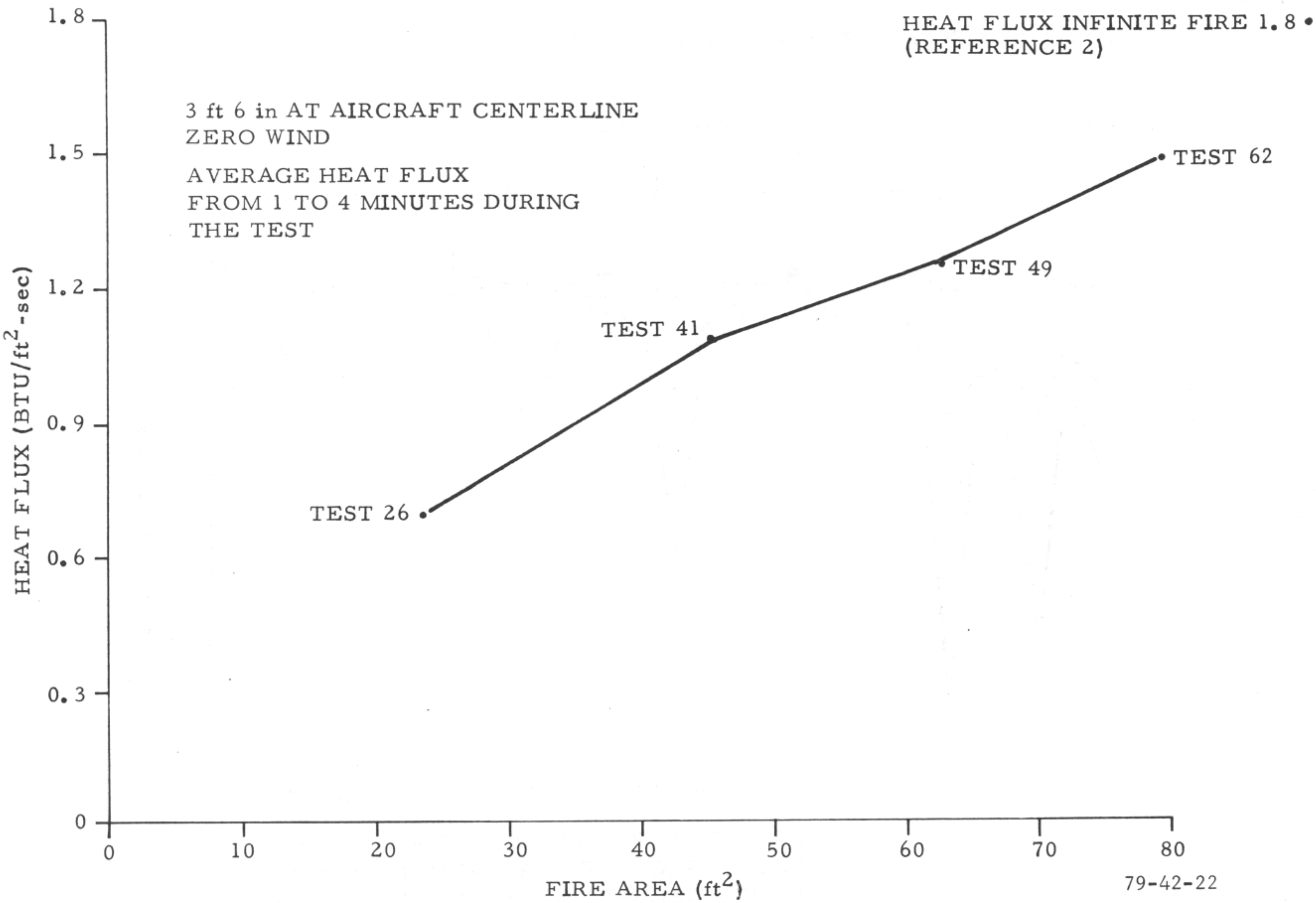


FIGURE 22. RADIANT HEAT IN CABIN RESULTING FROM ZERO-WIND FIRES

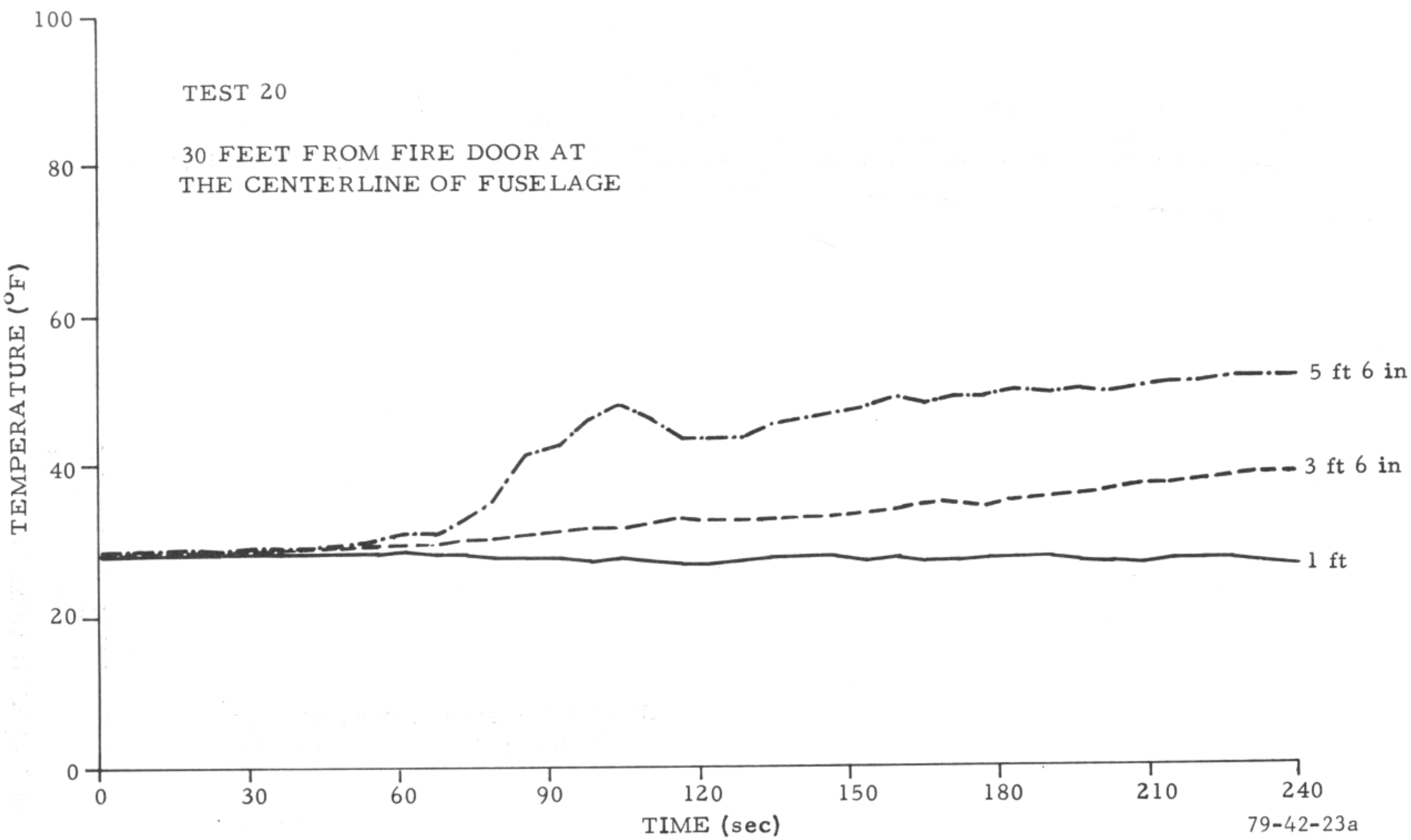


FIGURE 23. CABIN HAZARDS ASSOCIATED WITH CROSS-FUSELAGE WINDS (Sheet 1 of 3)

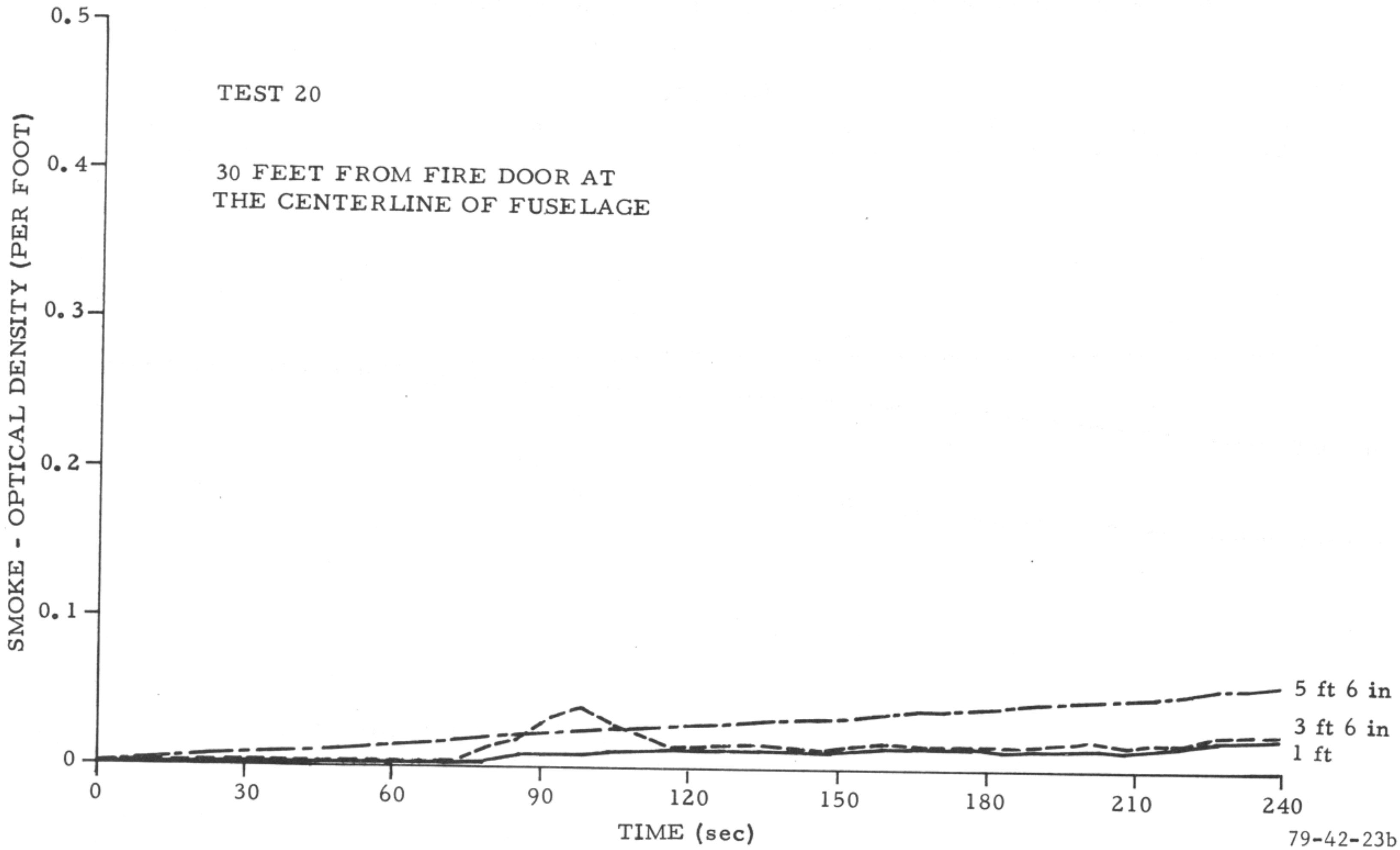


FIGURE 23. CABIN HAZARDS ASSOCIATED WITH CROSS-FUSELAGE WINDS (Sheet 2 of 3)

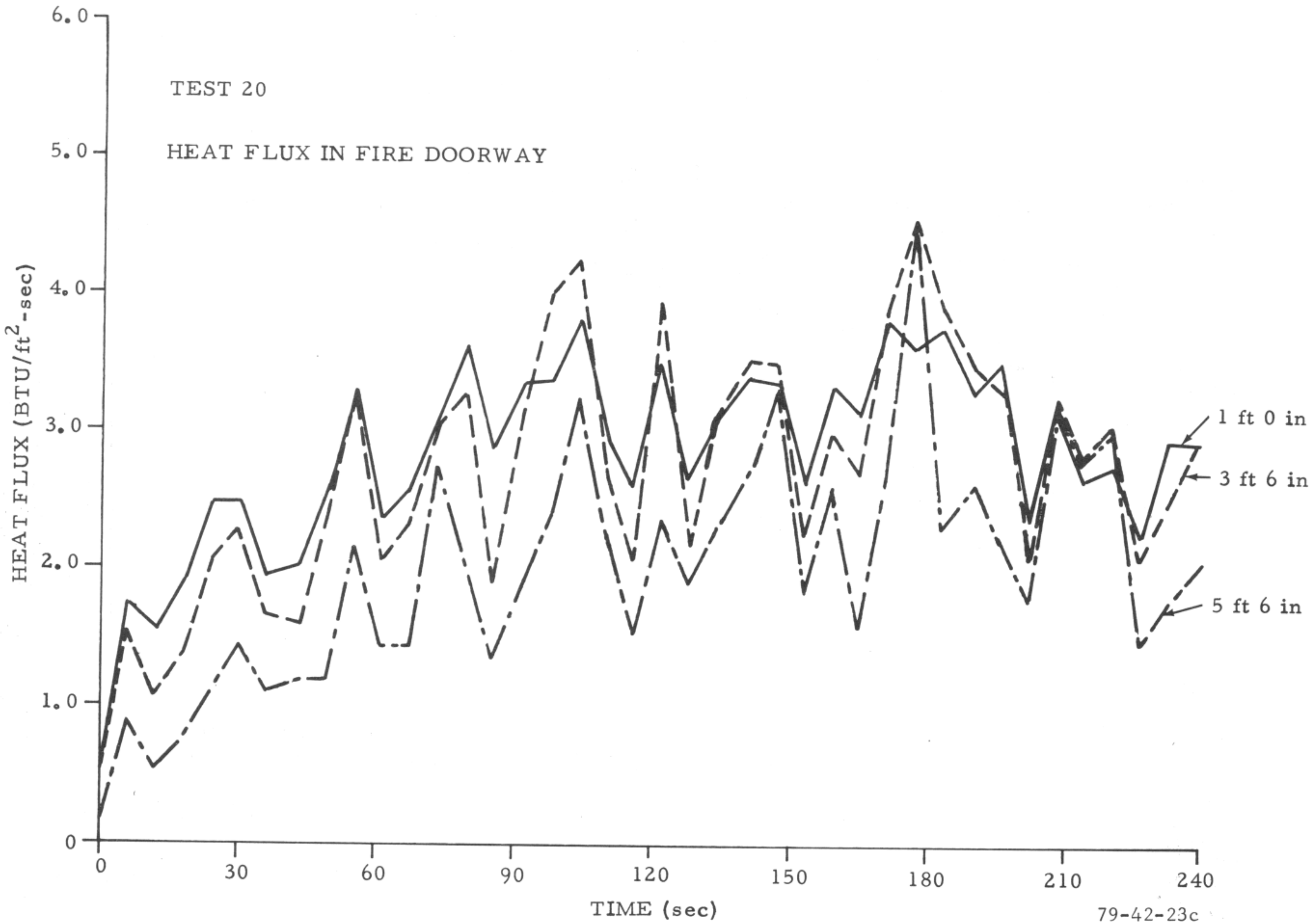


FIGURE 23. CABIN HAZARDS ASSOCIATED WITH CROSS-FUSELAGE WINDS (Sheet 3 of 3)

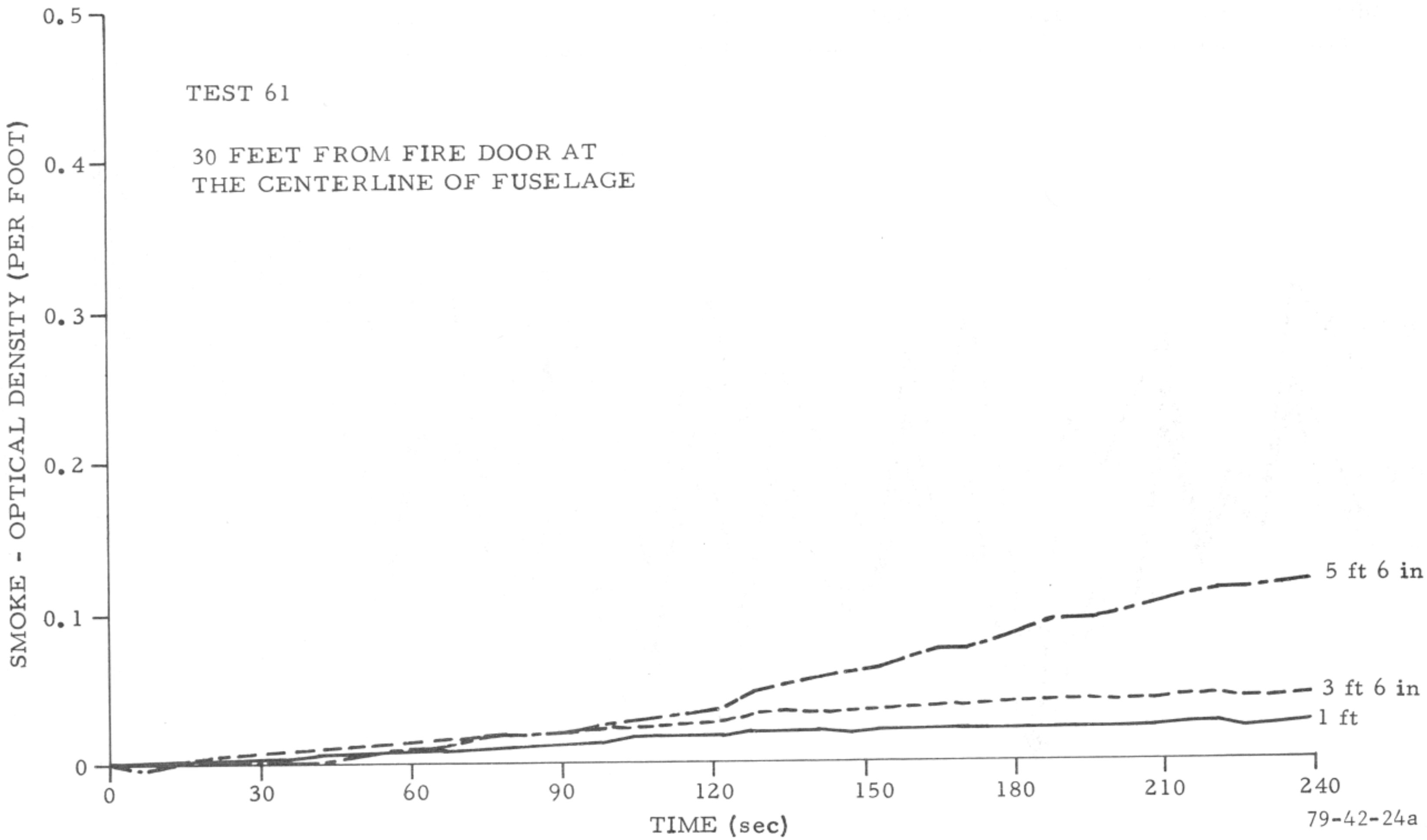


FIGURE 24. CABIN HAZARDS ASSOCIATED WITH ZERO WINDS (Sheet 1 of 3)

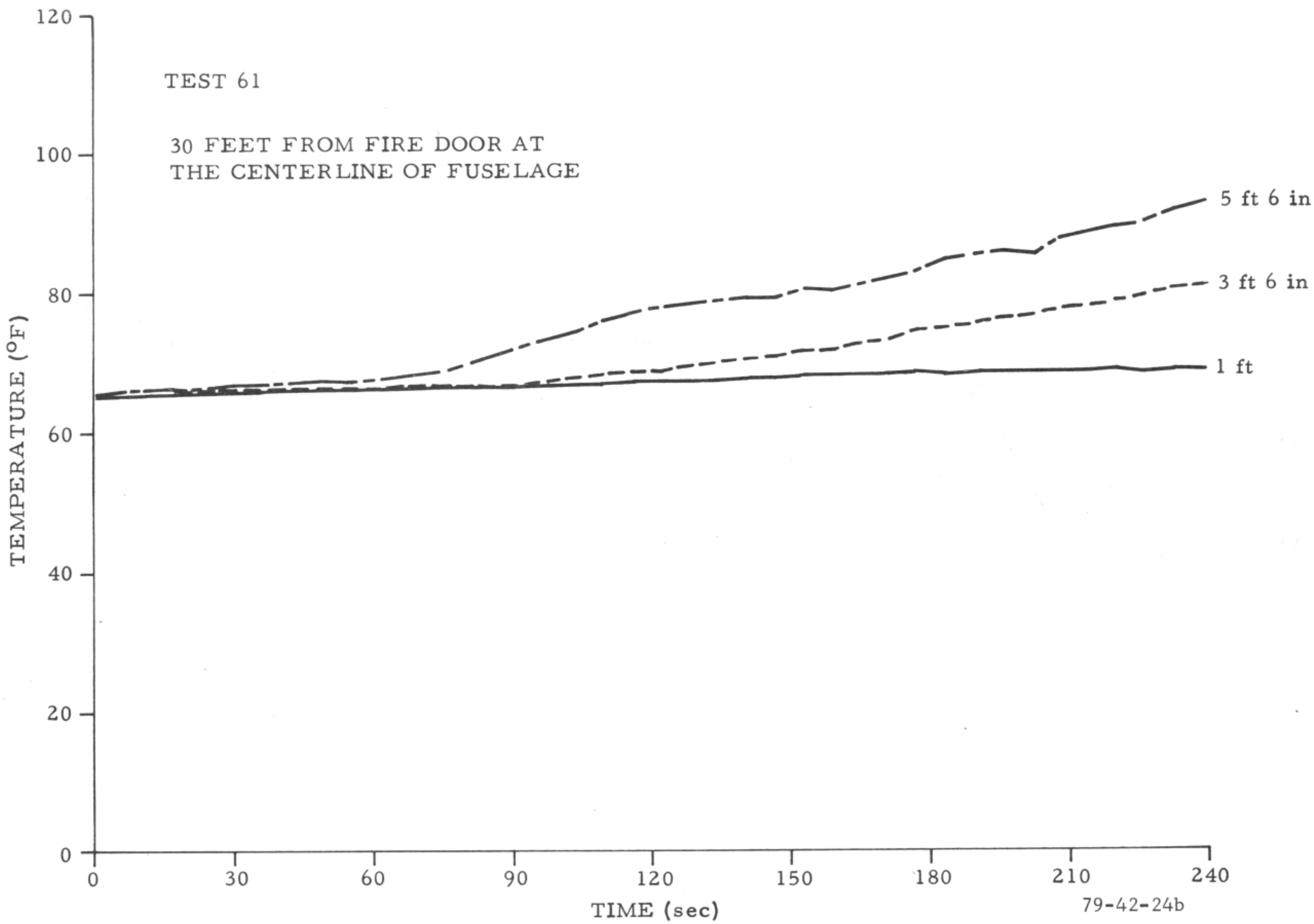


FIGURE 24. CABIN HAZARDS ASSOCIATED WITH ZERO WINDS (Sheet 2 of 3)

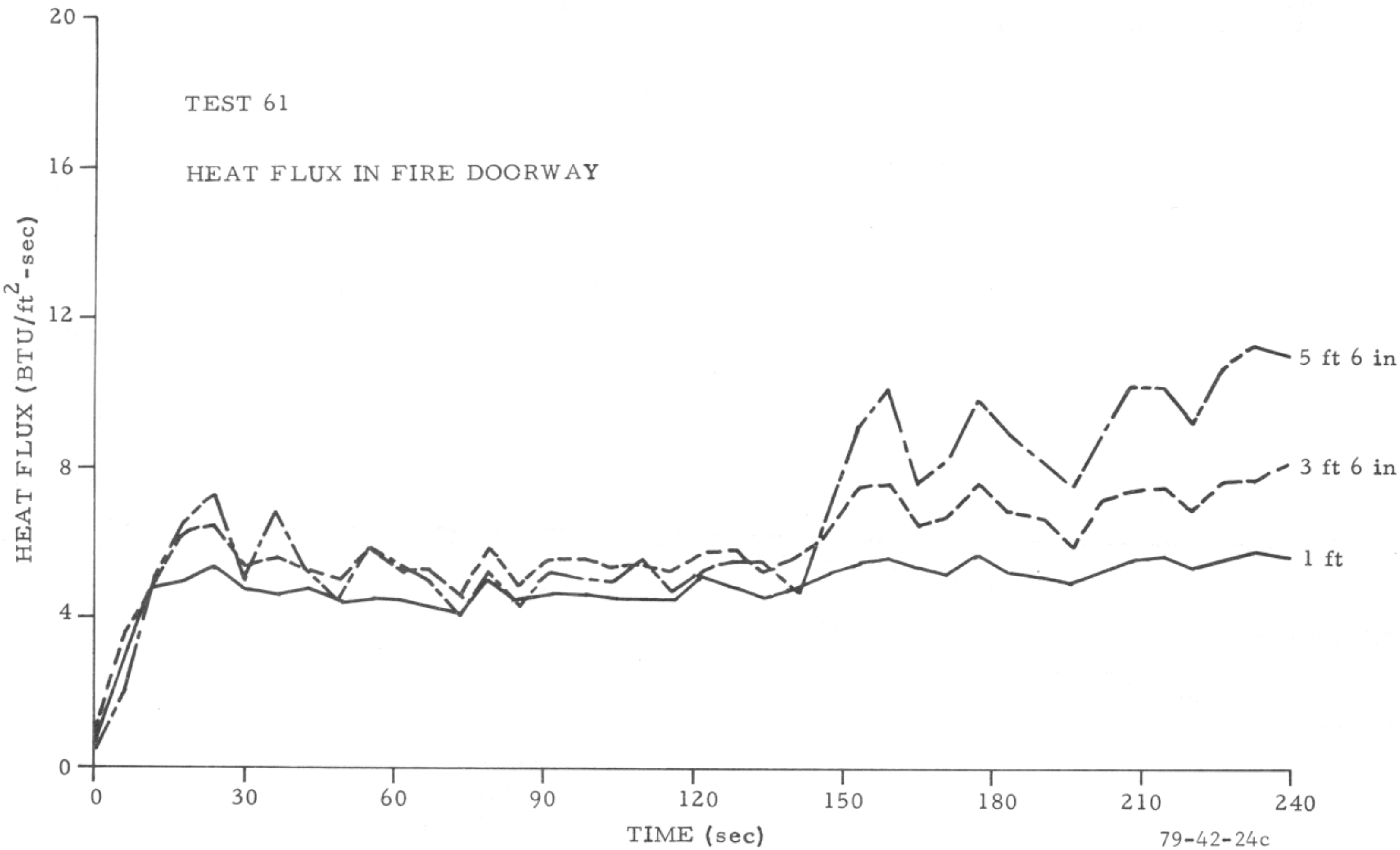


FIGURE 24. CABIN HAZARDS ASSOCIATED WITH ZERO WINDS (Sheet 3 of 3)

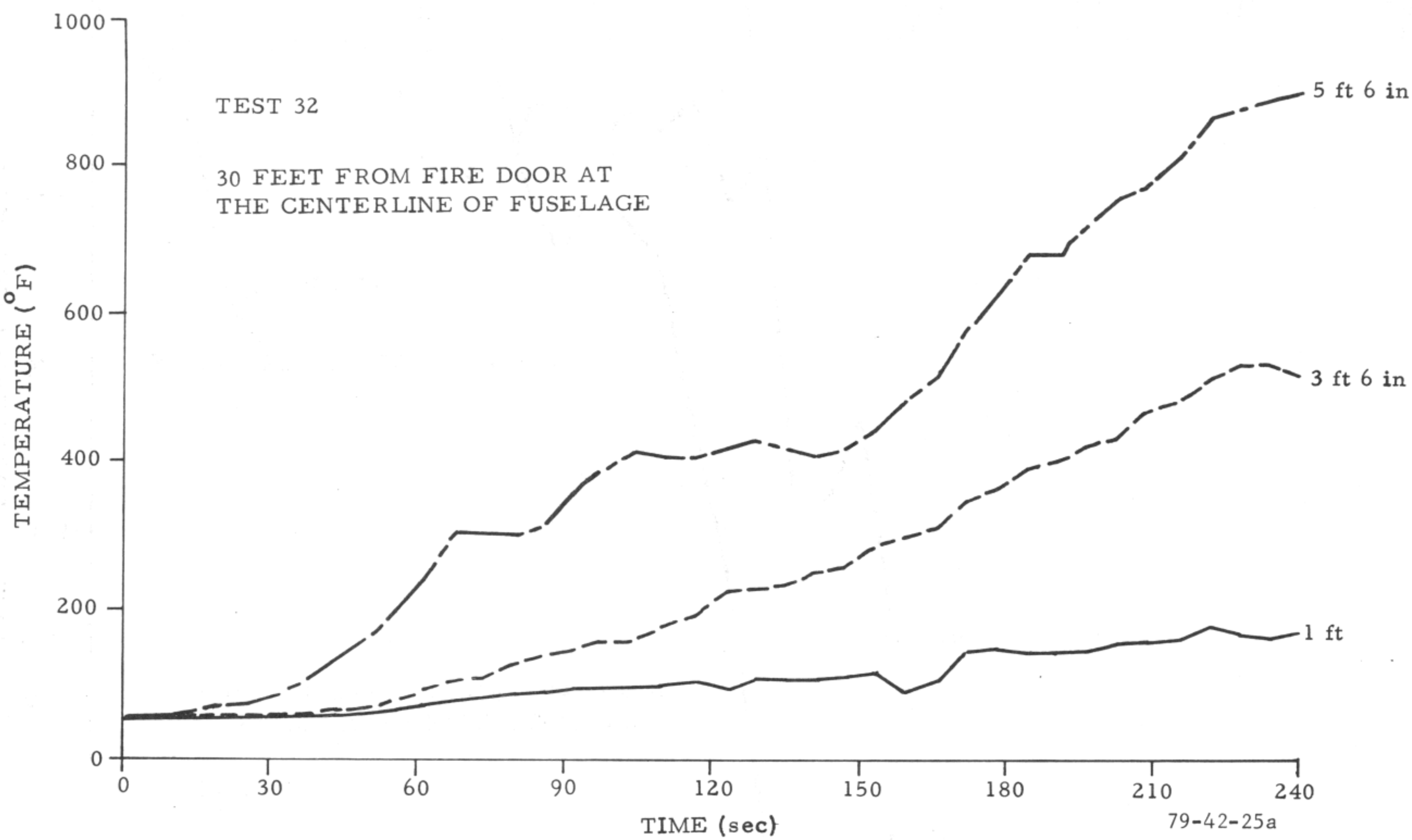


FIGURE 25. CABIN HAZARDS ASSOCIATED WITH WINDS INTO FUSELAGE OPENING (Sheet 1 of 3)

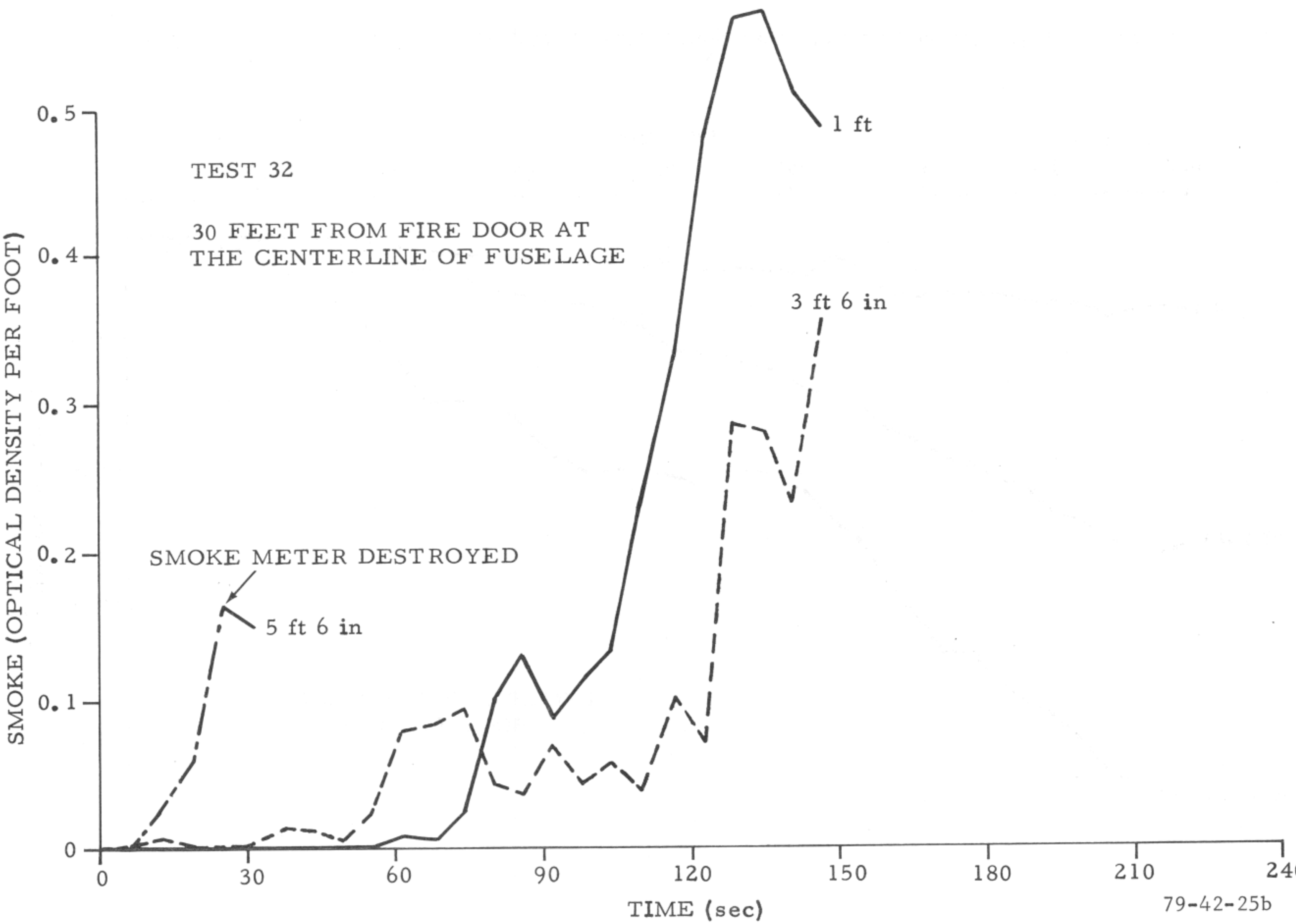


FIGURE 25. CABIN HAZARDS ASSOCIATED WITH WINDS INTO FUSELAGE OPENING (Sheet 2 of 3)

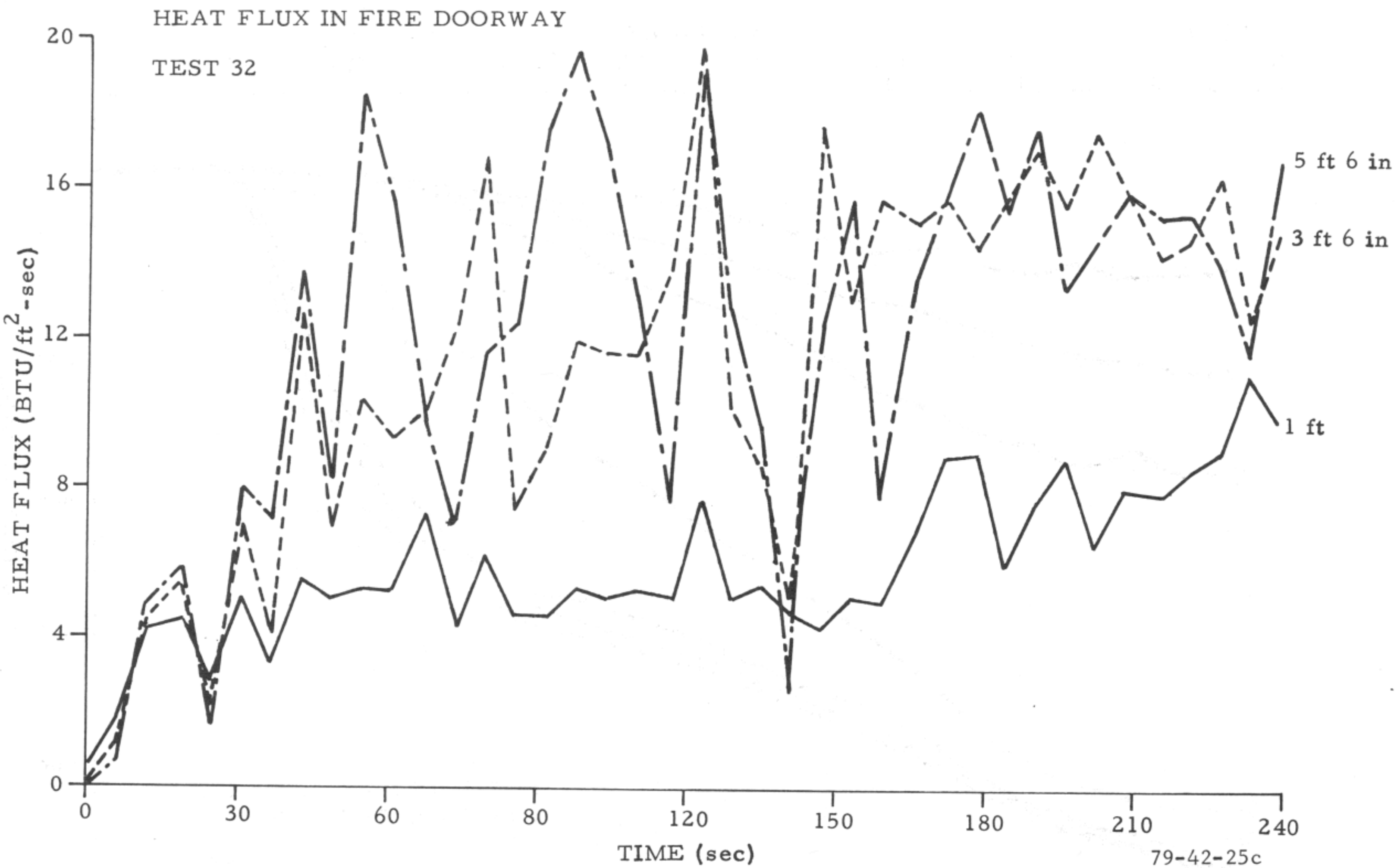


FIGURE 25. CABIN HAZARDS ASSOCIATED WITH WINDS INTO FUSELAGE OPENING (Sheet 3 of 3)

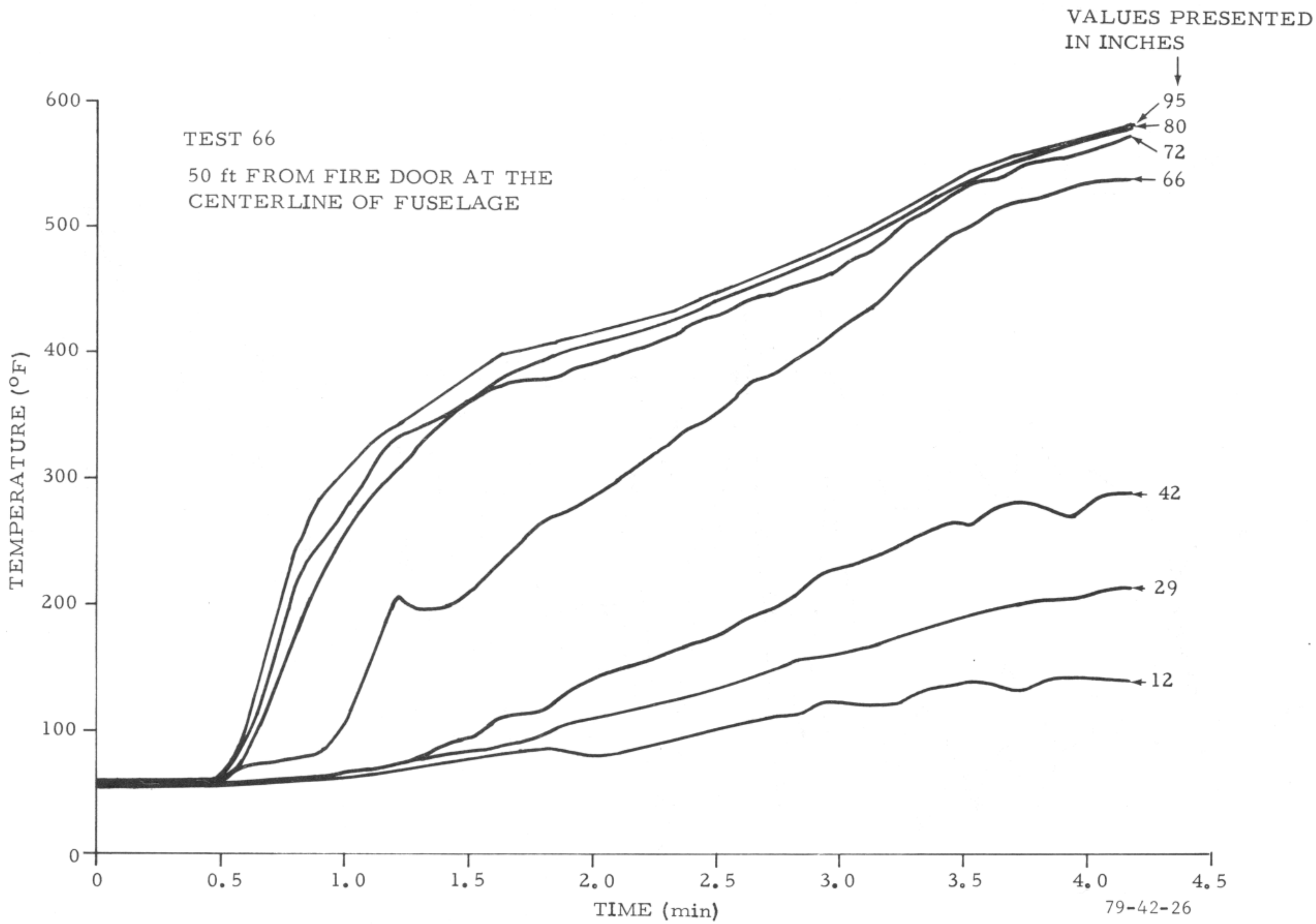


FIGURE 26. CABIN HEAT STRATIFICATION

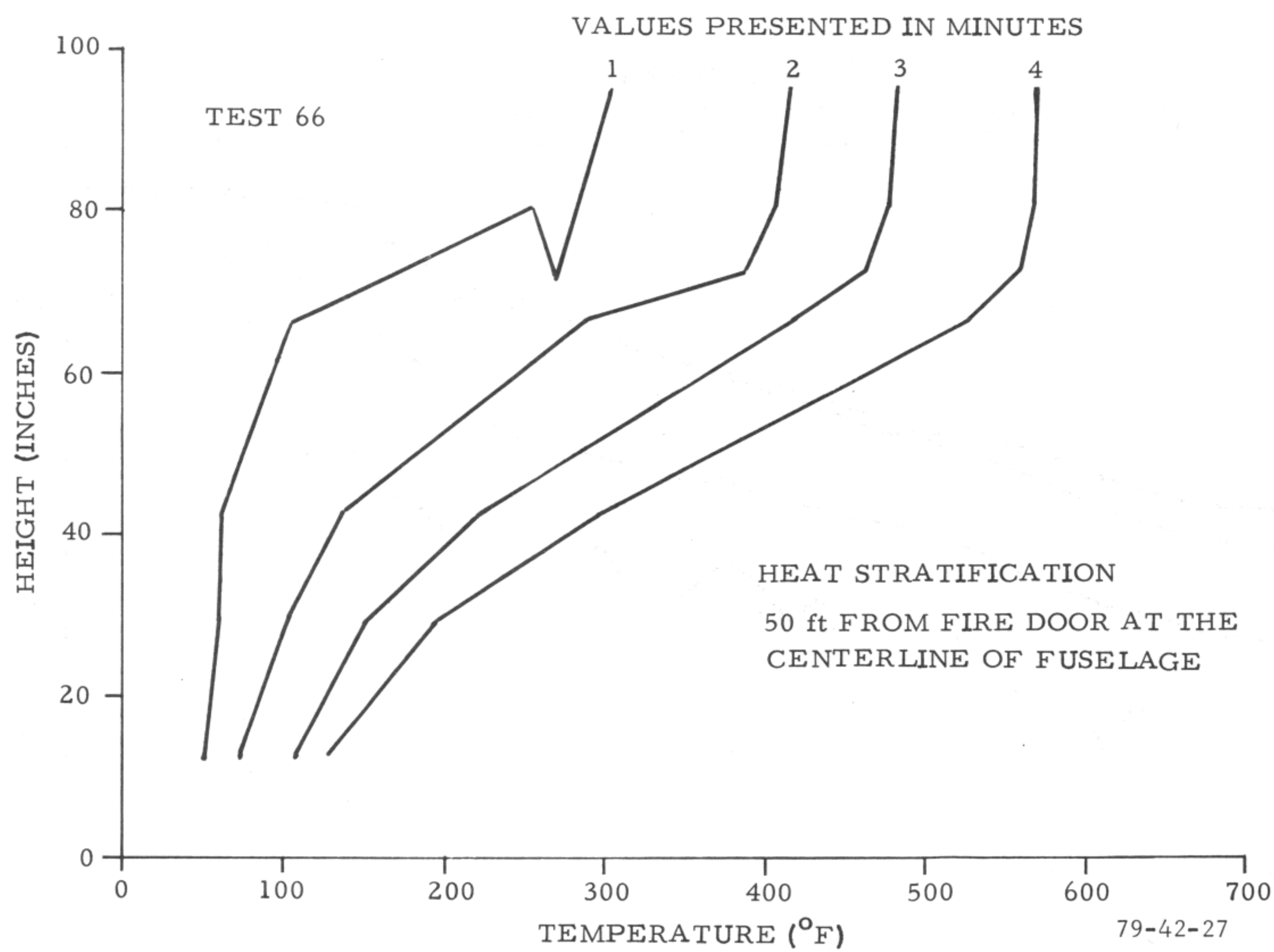


FIGURE 27. CABIN HEAT STRATIFICATION (REPLOT)

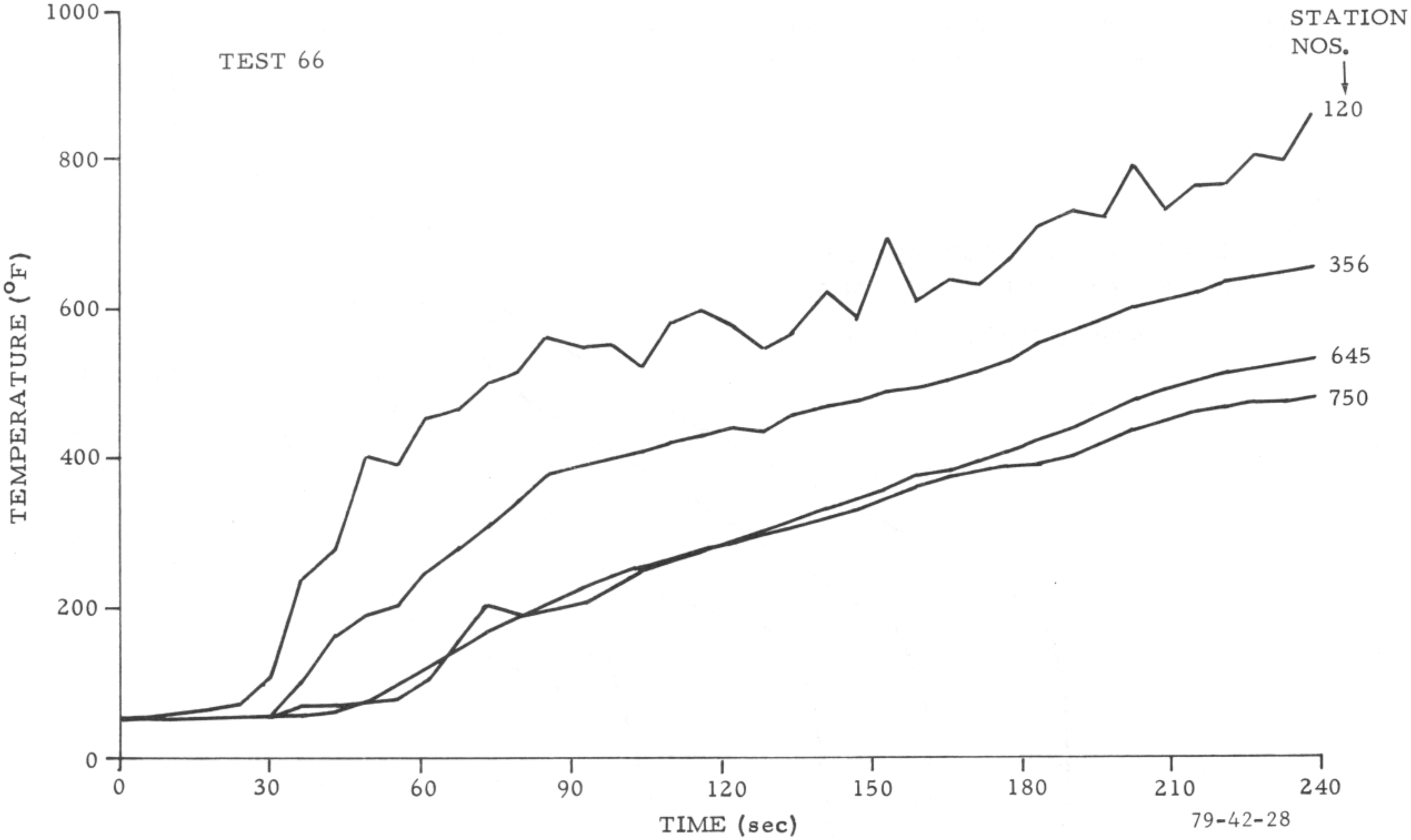


FIGURE 28. TEMPERATURES AT VARIOUS FUSELAGE STATIONS

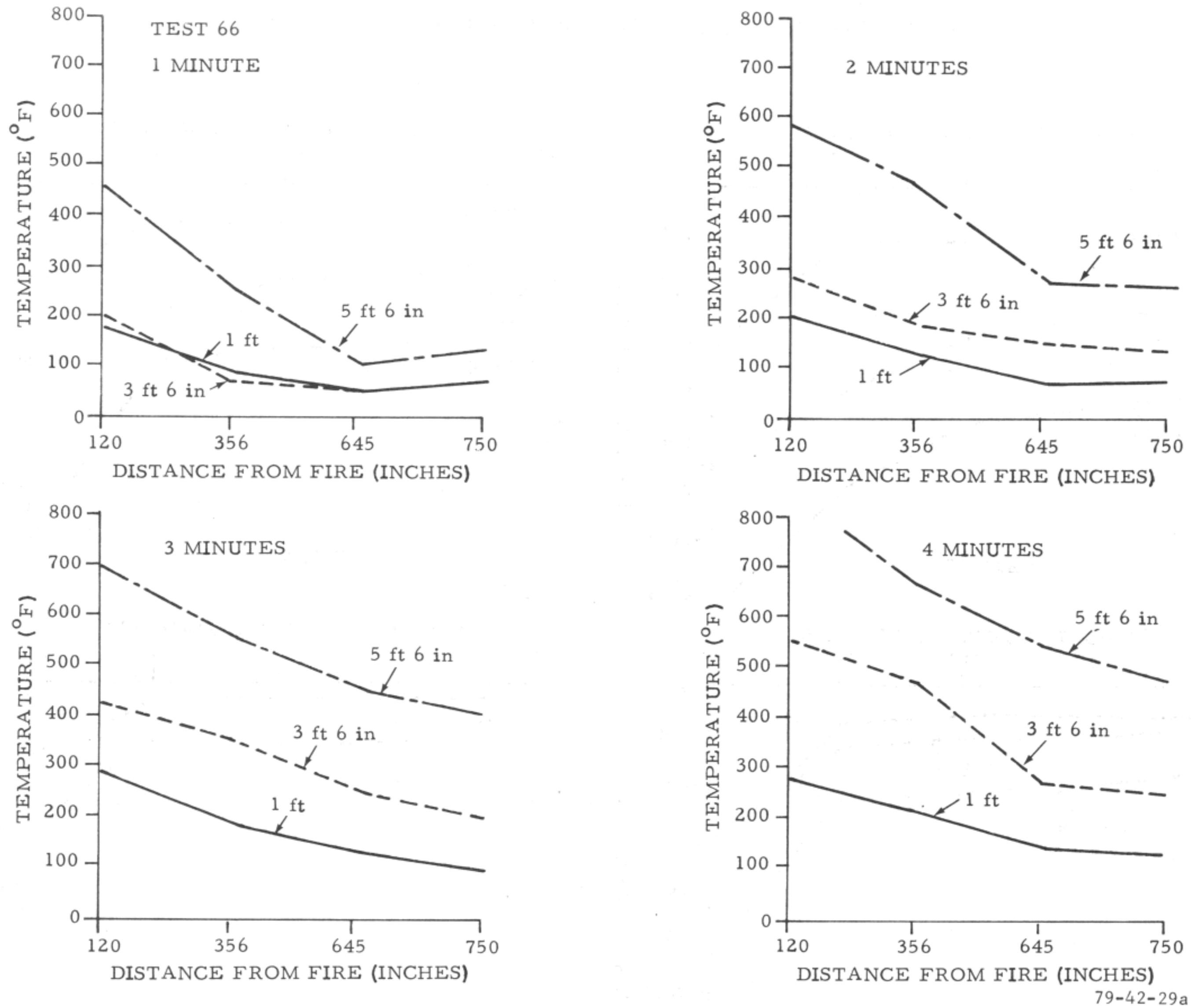


FIGURE 29. CABIN TEMPERATURE PROFILES (Sheet 1 of 2)

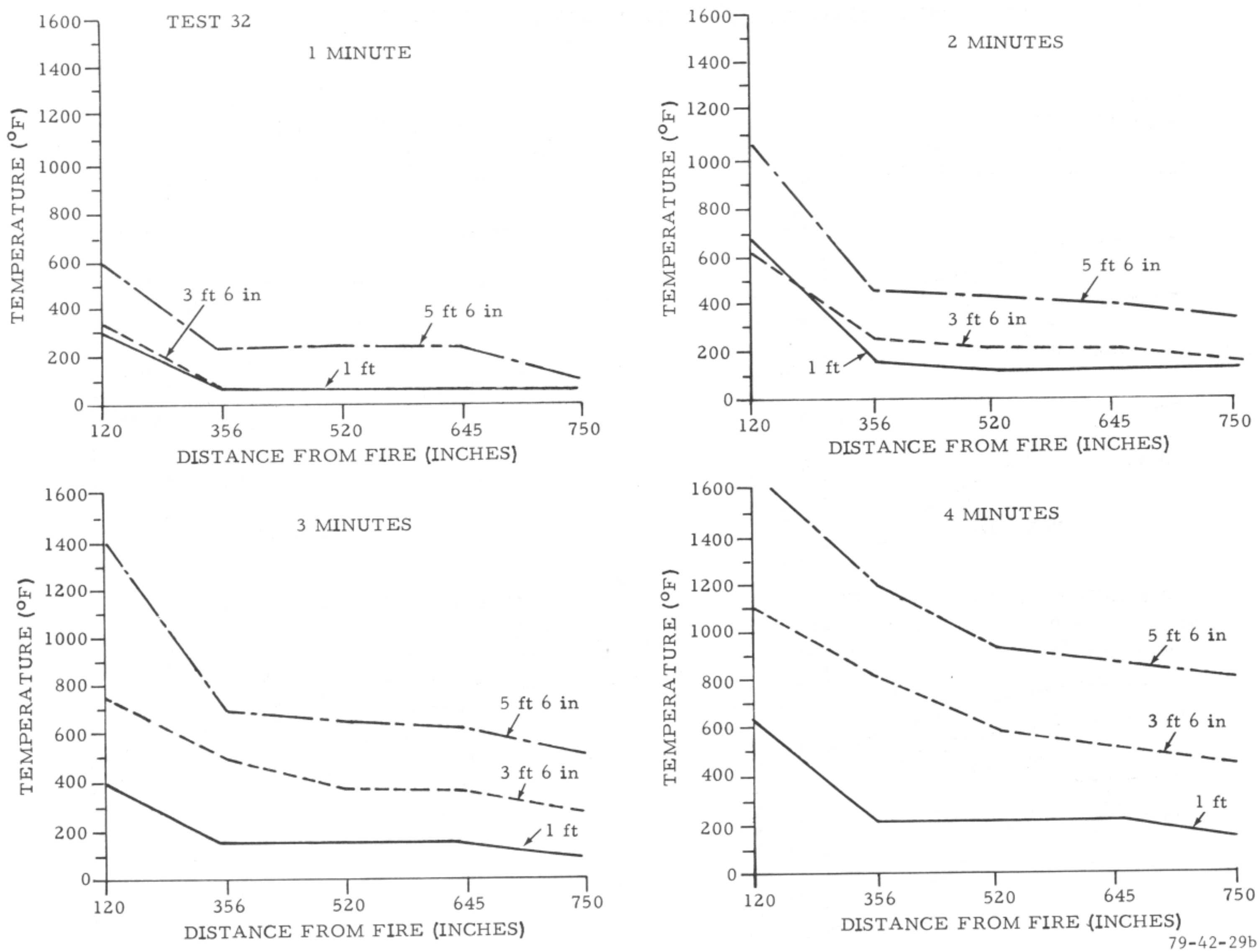


FIGURE 29. CABIN TEMPERATURE PROFILES (Sheet 2 of 2)

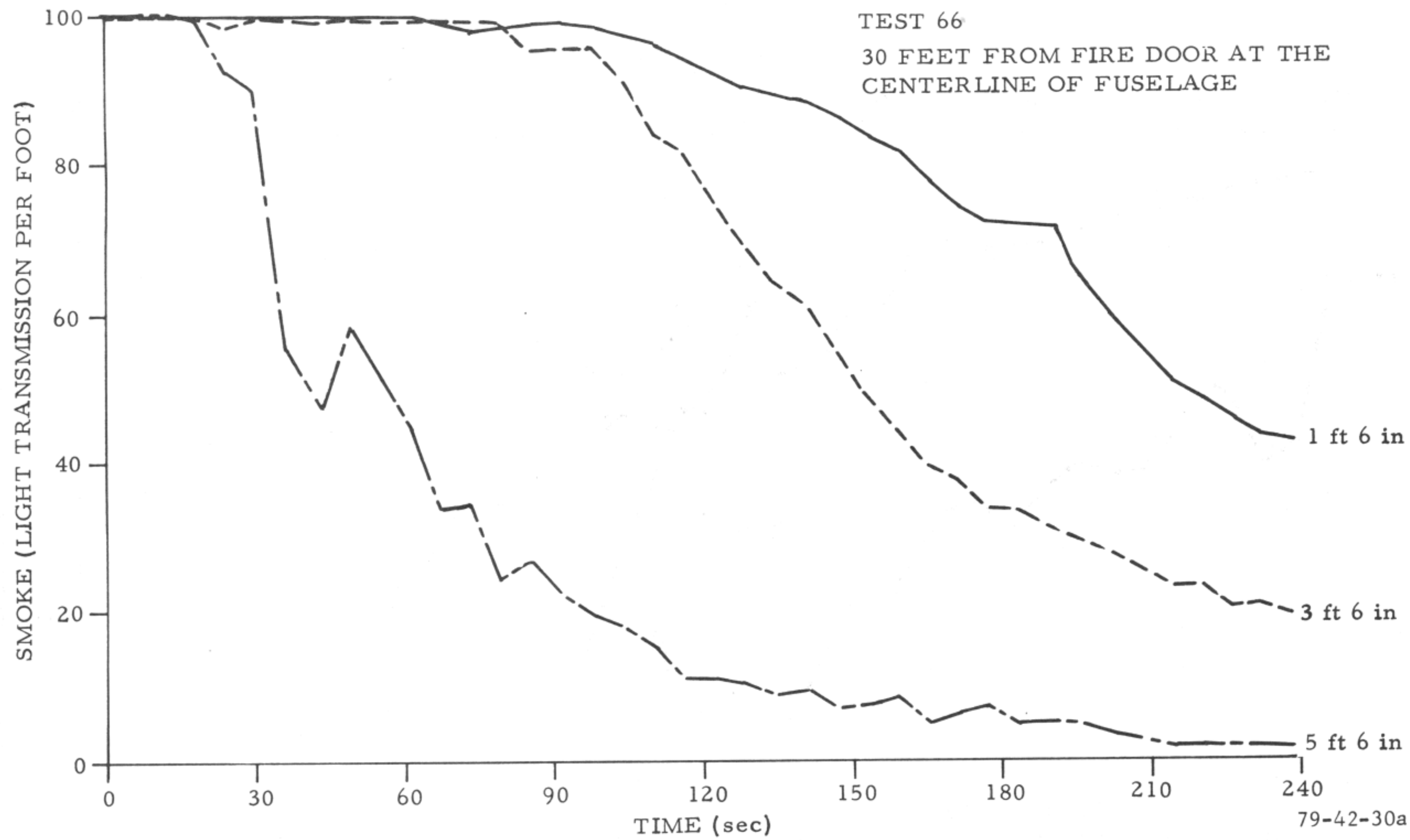


FIGURE 30. SMOKE STRATIFICATION (PERCENT LIGHT REDUCTION) (Sheet 1 of 2)

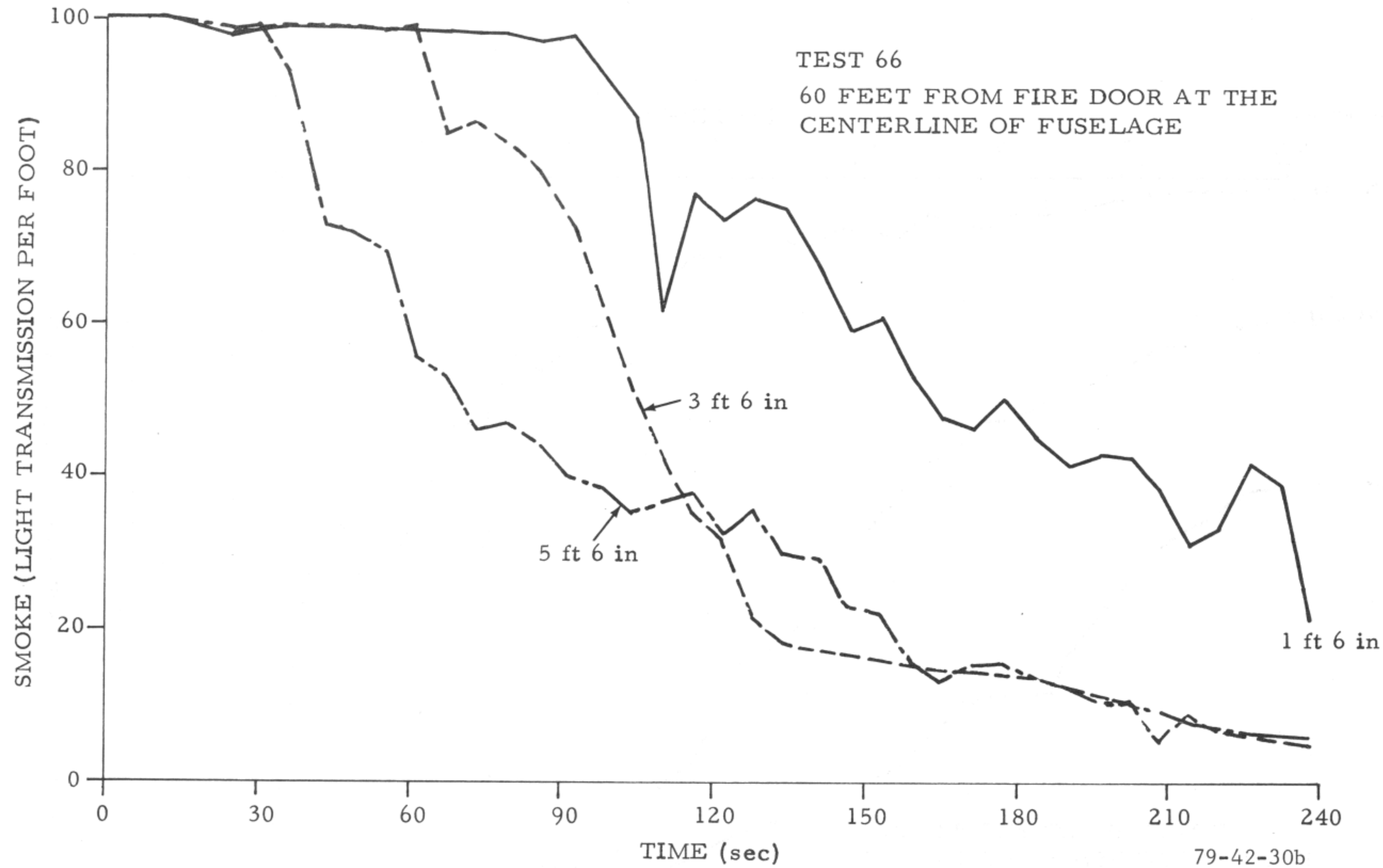


FIGURE 30. SMOKE STRATIFICATION (PERCENT LIGHT REDUCTION) (Sheet 2 of 2)

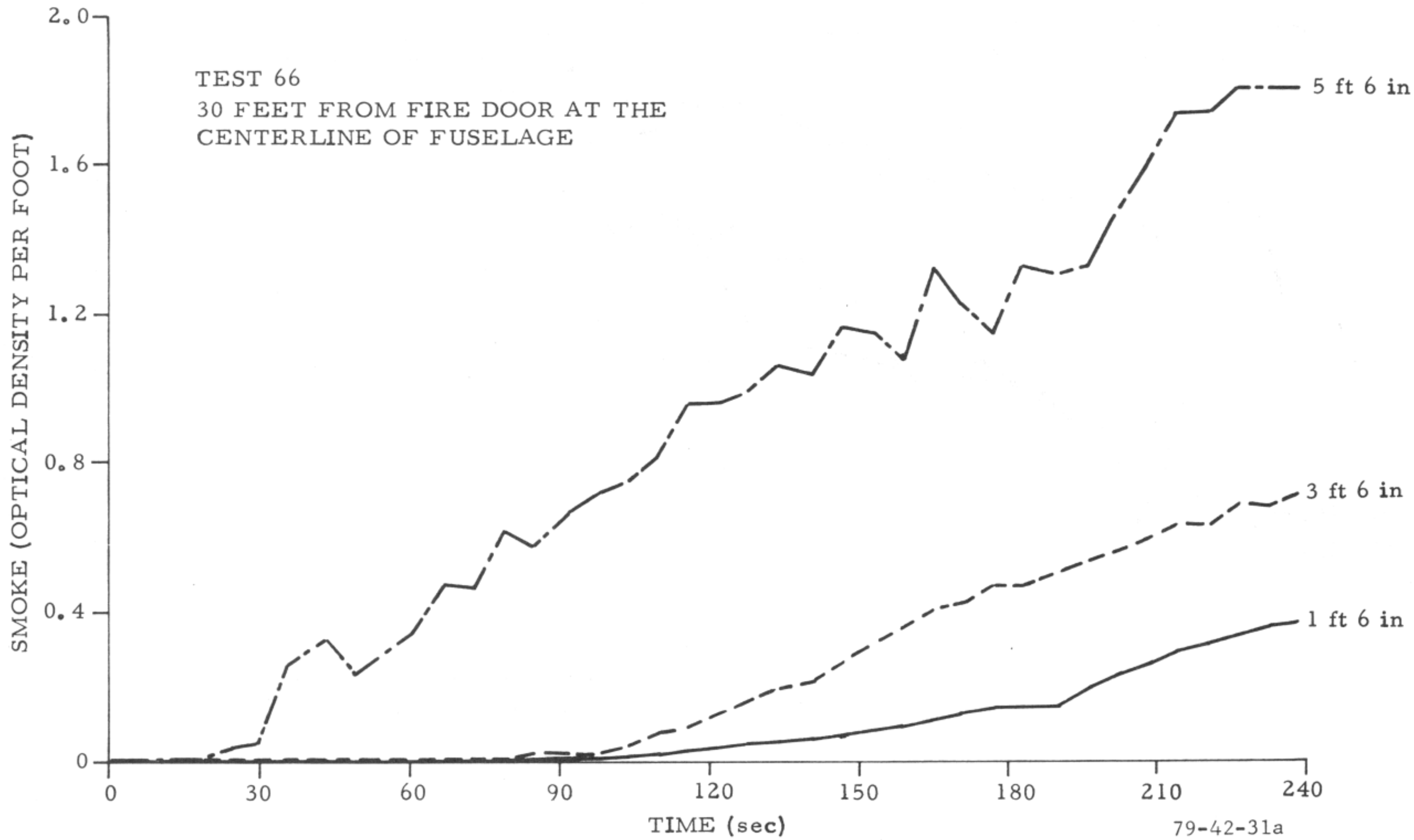


FIGURE 31. SMOKE STRATIFICATION (OPTICAL DENSITY) (Sheet 1 of 2)

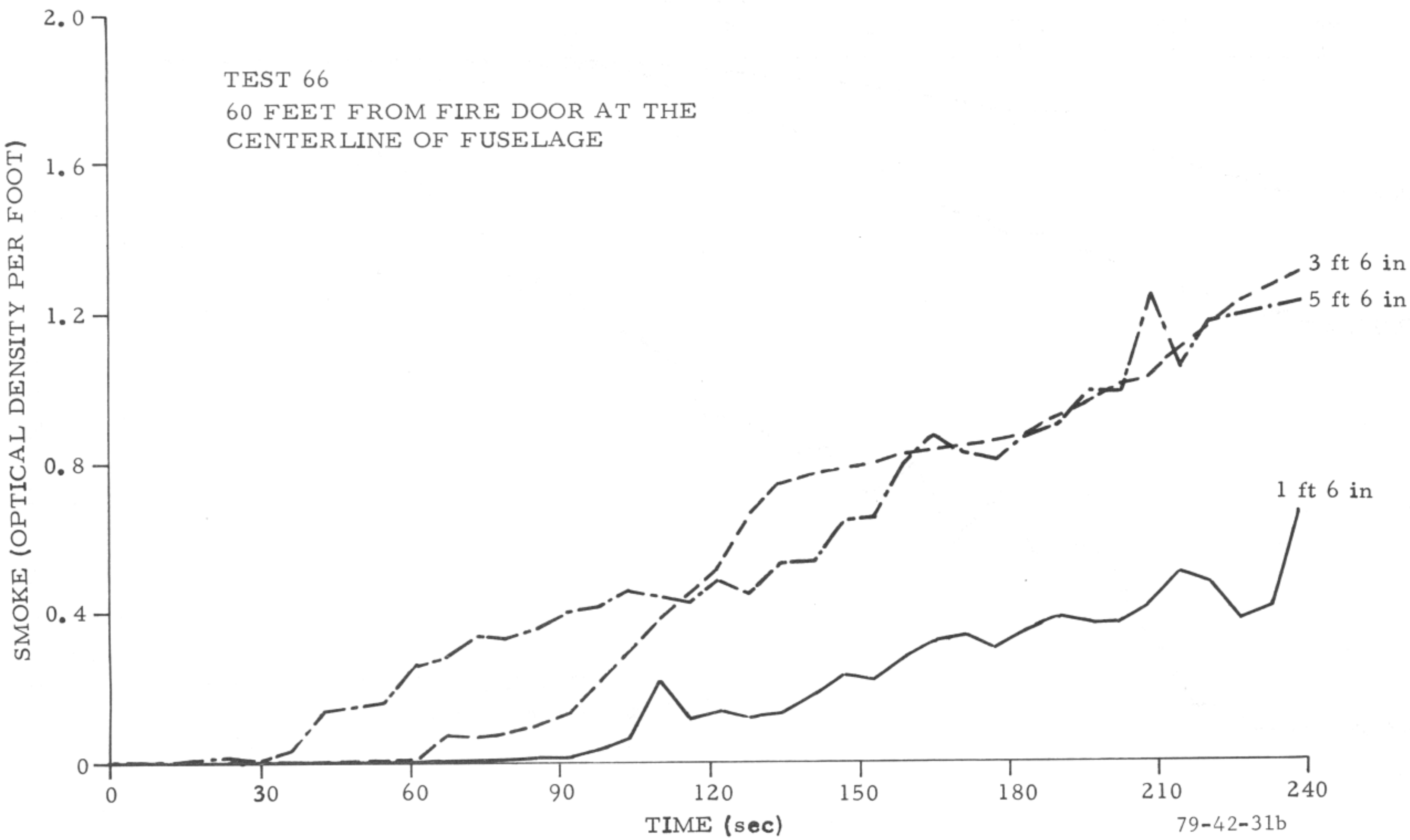


FIGURE 31. SMOKE STRATIFICATION (OPTICAL DENSITY) (Sheet 2 of 2)

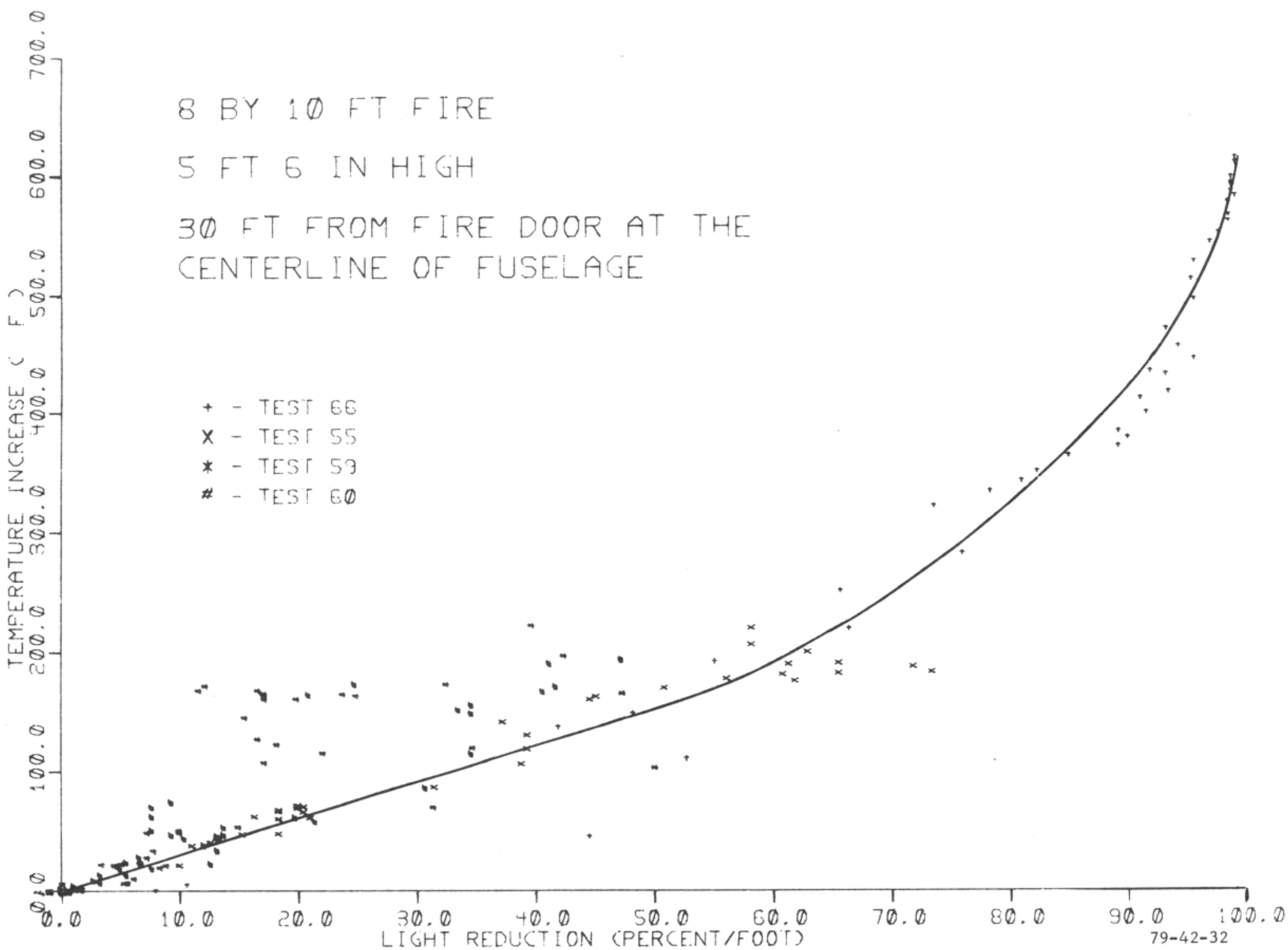


FIGURE 32. RELATION OF SMOKE-TO-TEMPERATURE INCREASE

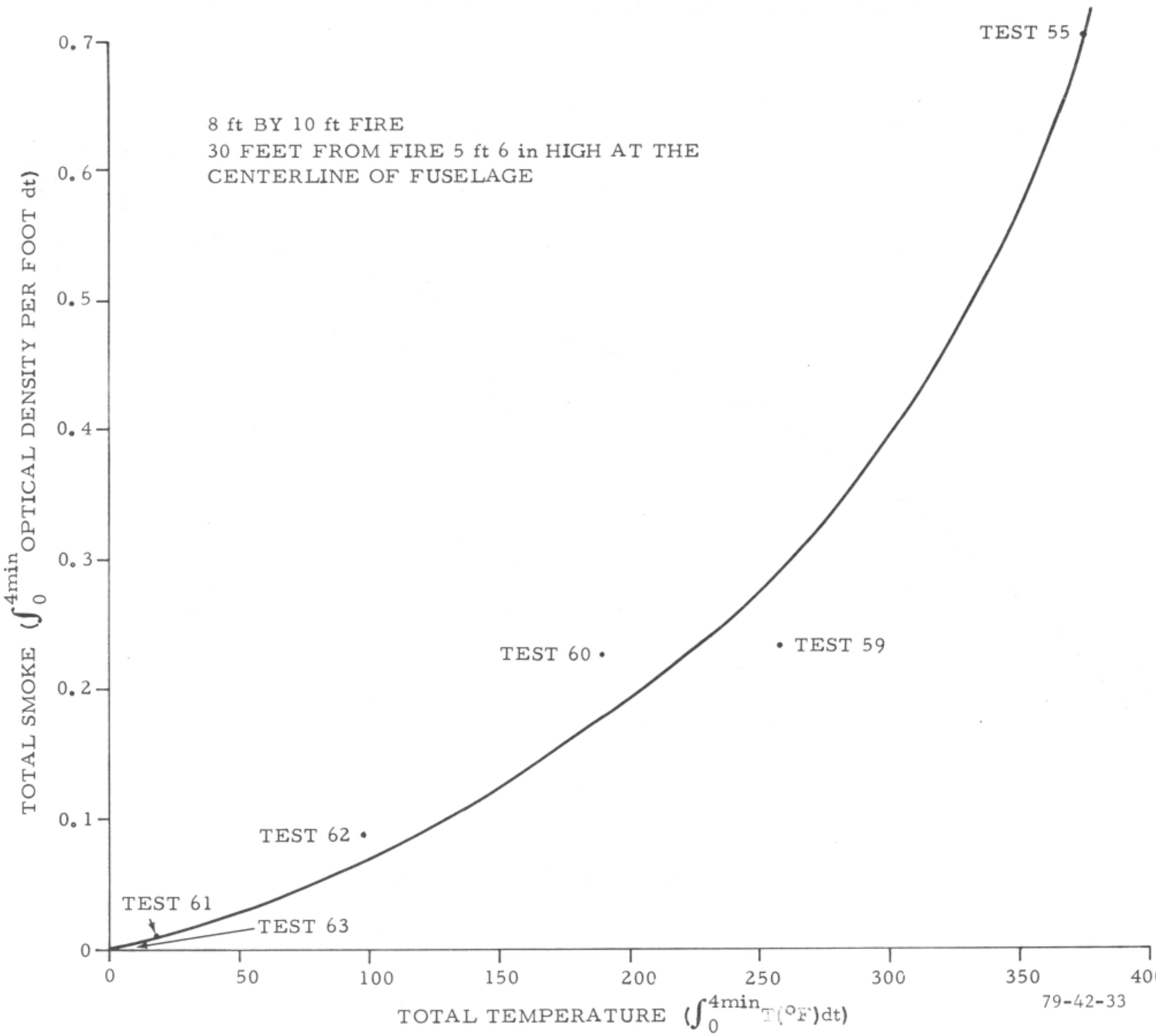


FIGURE 33. TOTAL HEAT VERSUS TOTAL SMOKE FOR 8- BY 10-FOOT FIRE

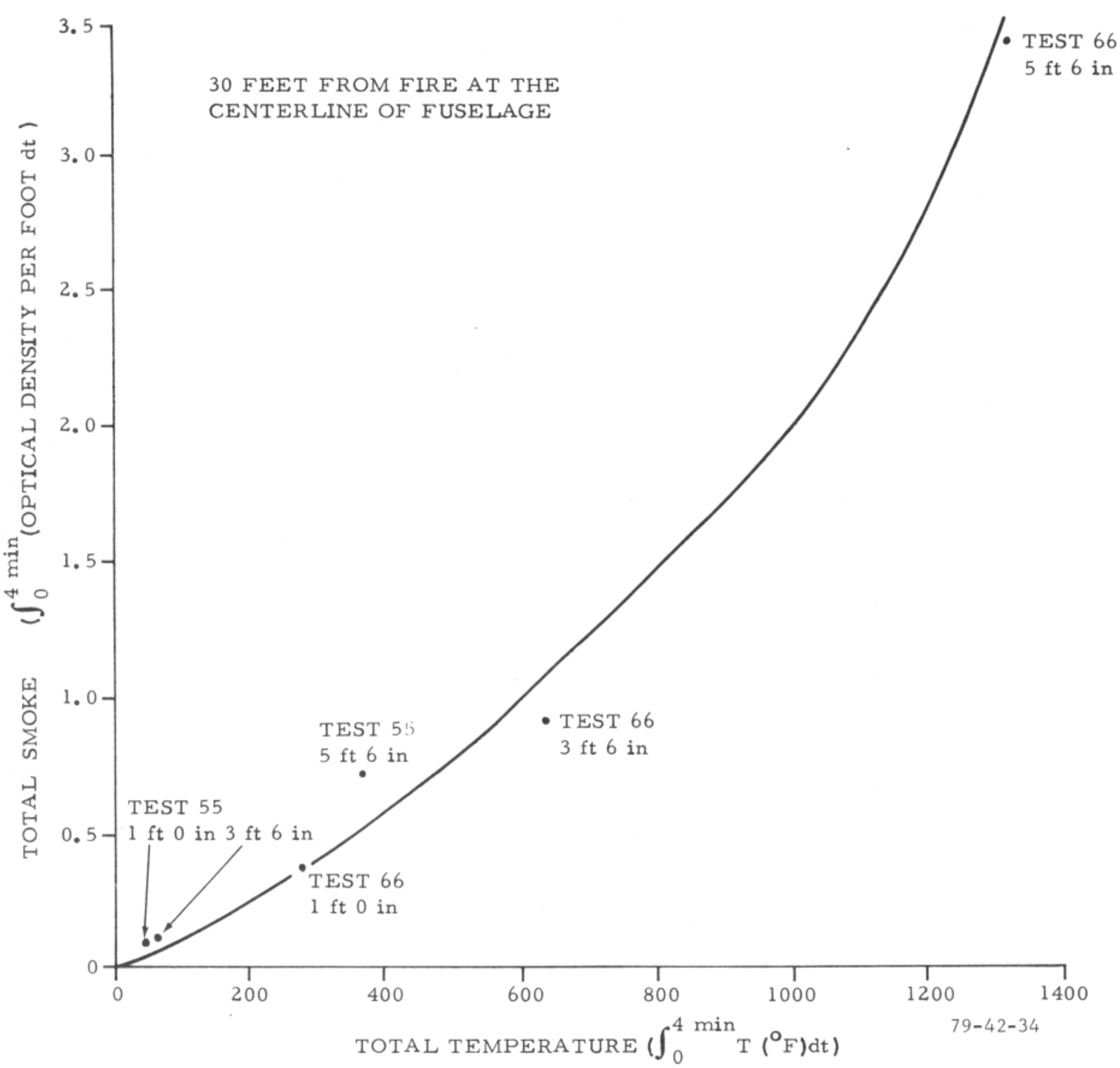


FIGURE 34. TOTAL SMOKE VERSUS TOTAL HEAT FOR VARIOUS FUSELAGE HEIGHTS

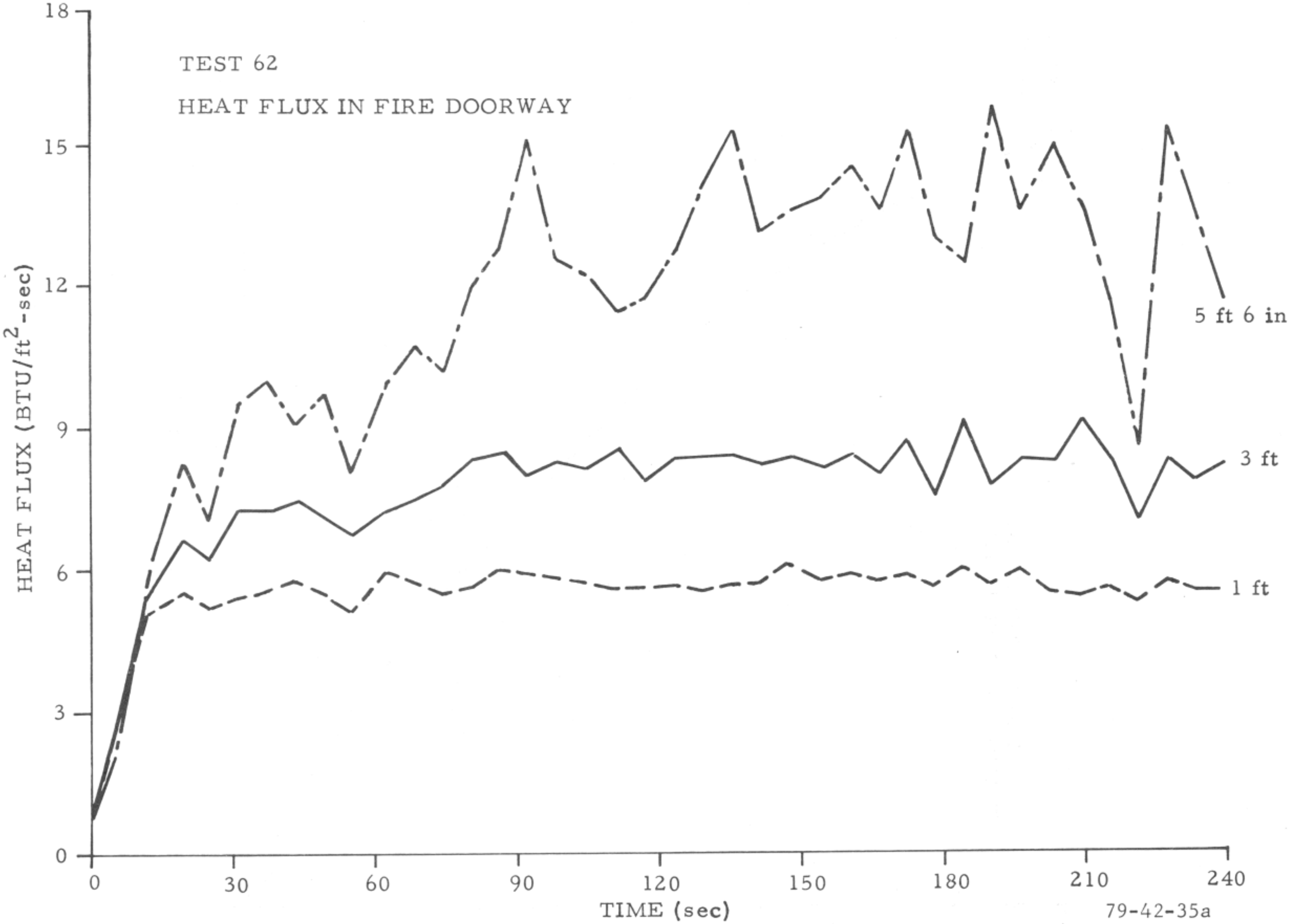


FIGURE 35. HEAT FLUK FOR ZERO-WIND TESTS (Sheet 1 of 3)

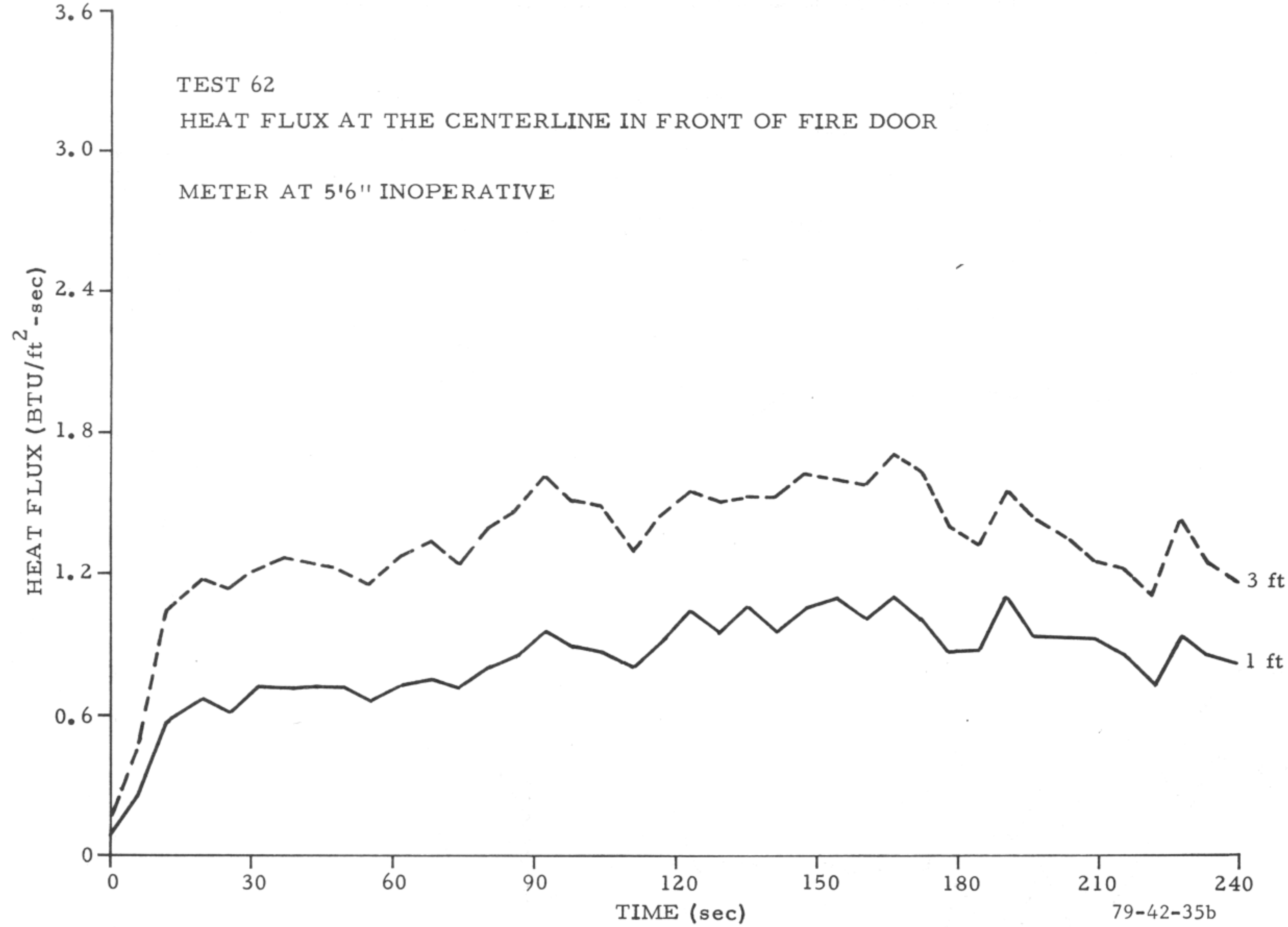


FIGURE 35. HEAT FLUK FOR ZERO-WIND TESTS (Sheet 2 of 3)

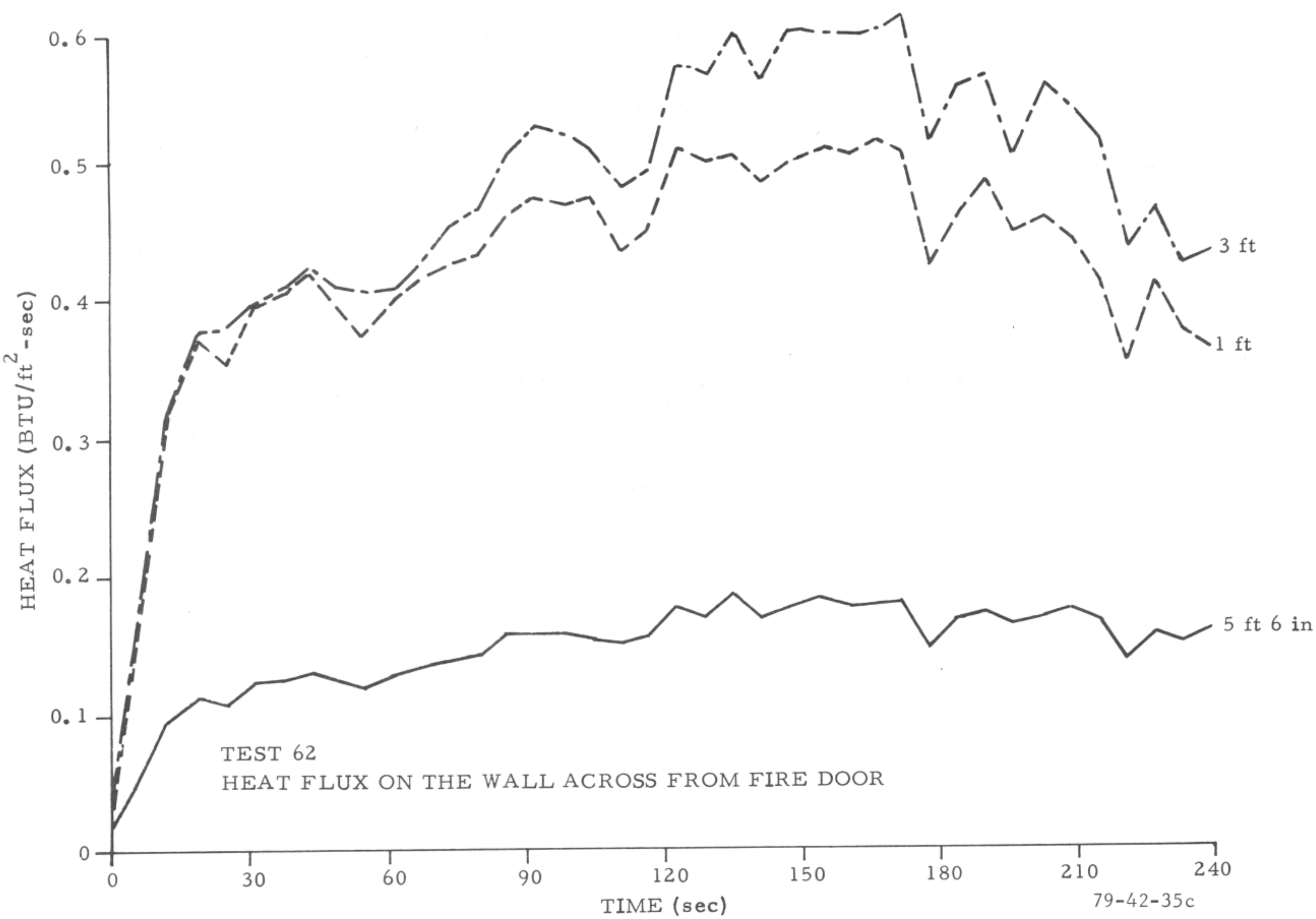


FIGURE 35. HEAT FLUK FOR ZERO-WIND TESTS (Sheet 3 of 3)

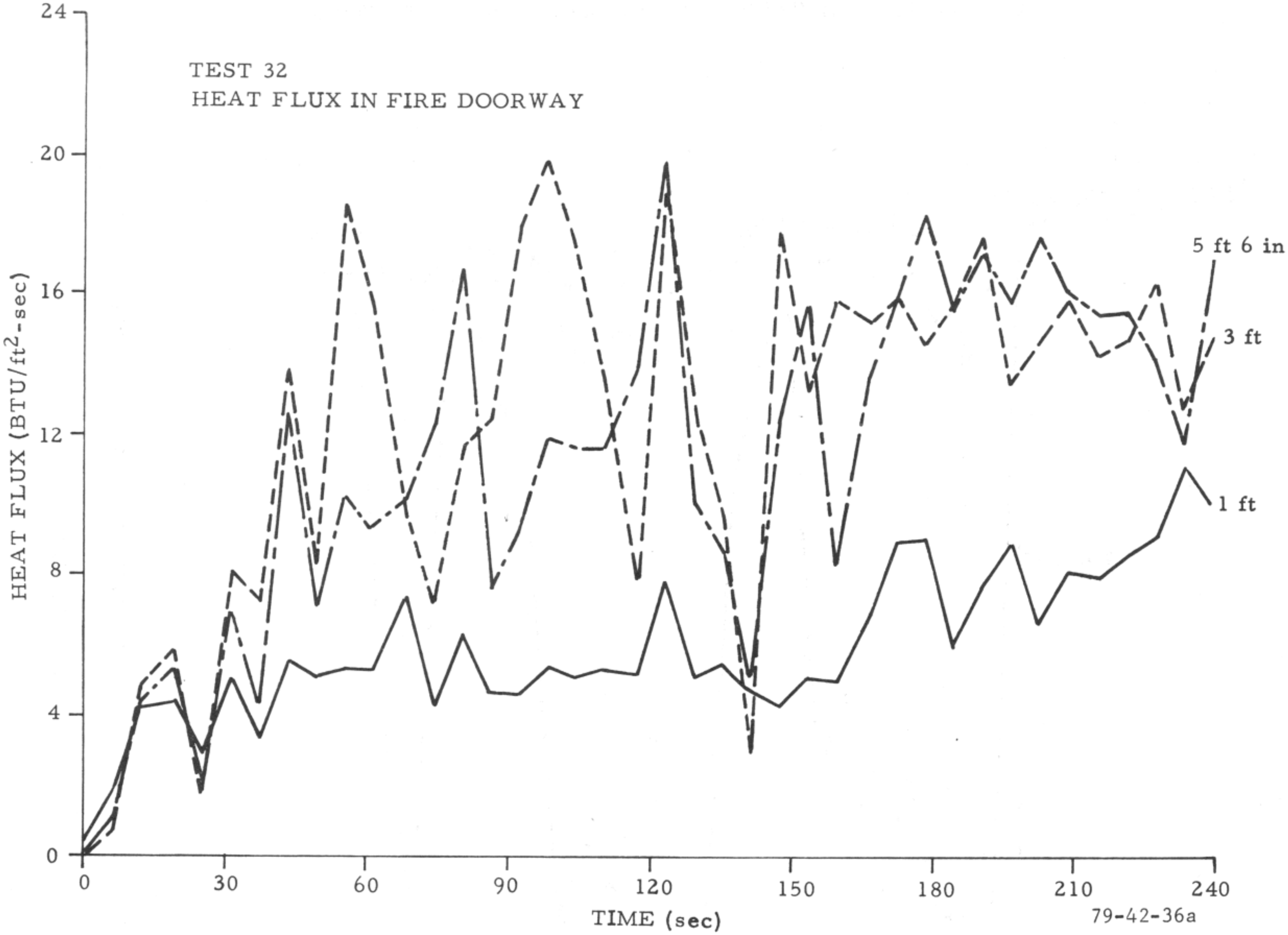


FIGURE 36. HEAT FLUX FOR MOST SEVERE TEST (Sheet 1 of 3)

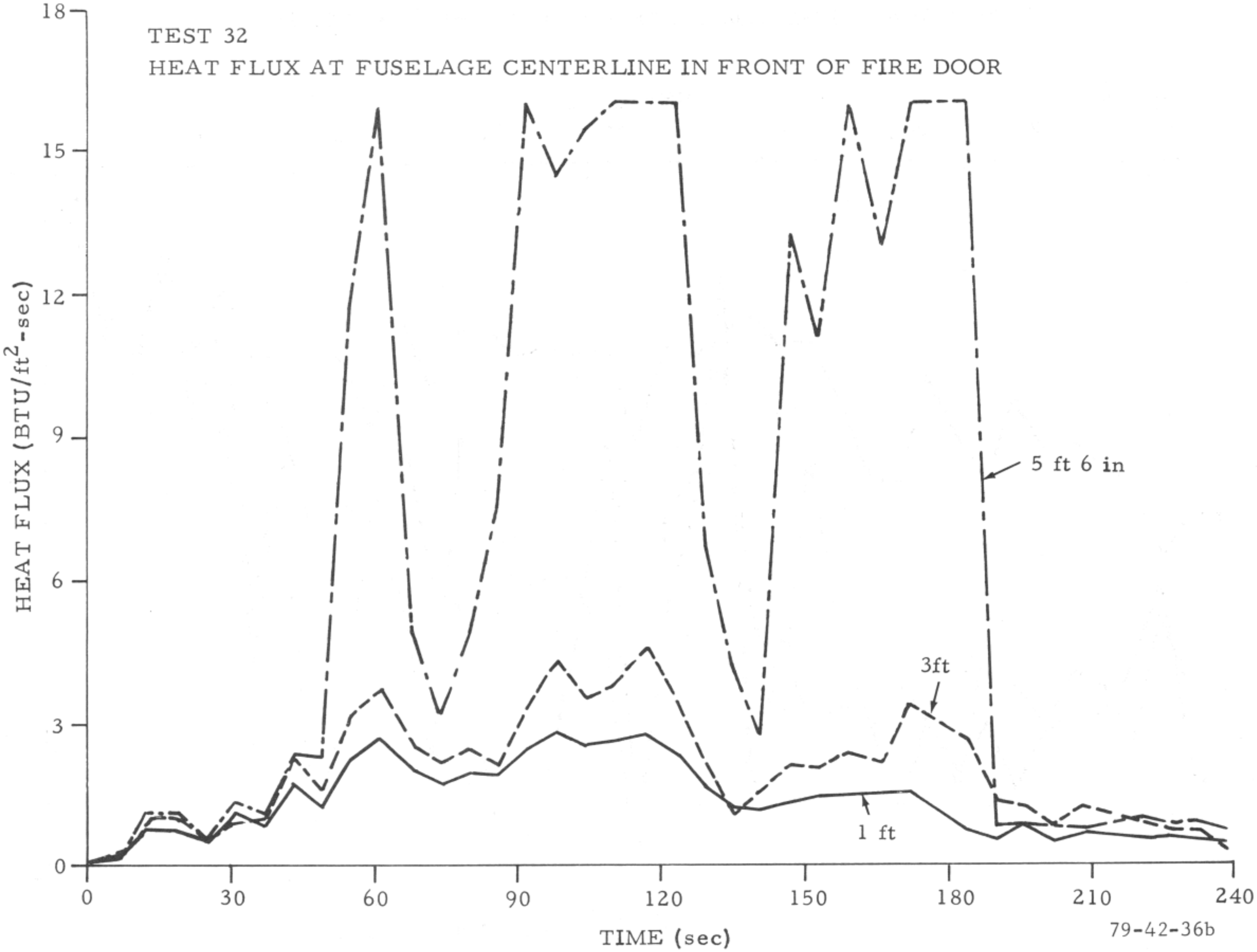


FIGURE 36. HEAT FLUX FOR MOST SEVERE TEST (Sheet 2 of 3)

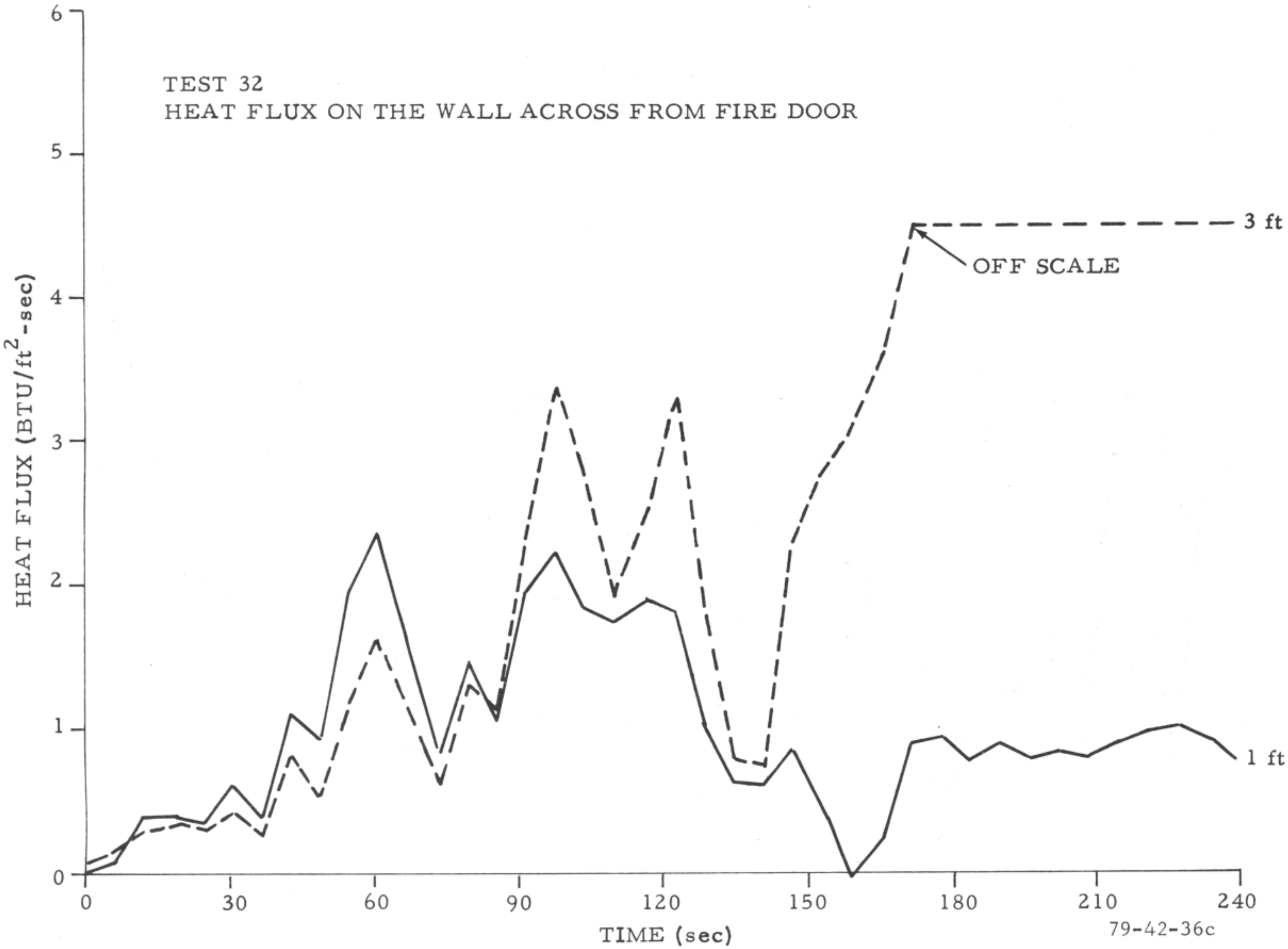


FIGURE 36. HEAT FLUX FOR MOST SEVERE TEST (Sheet 3 of 3)

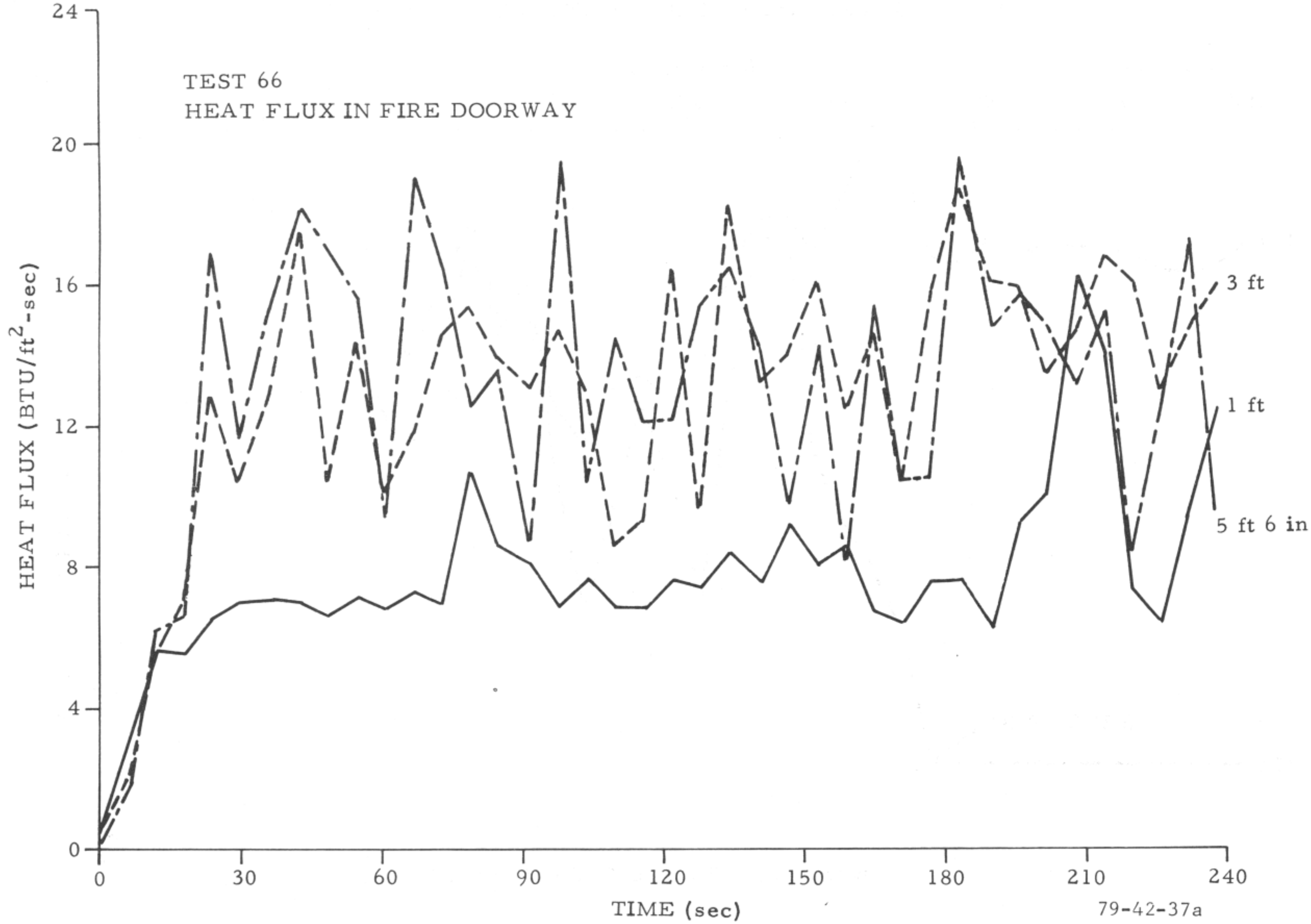


FIGURE 37. HEAT FLUX FOR MOST SEVERE 8- BY 10-FOOT TEST (Sheet 1 of 3)

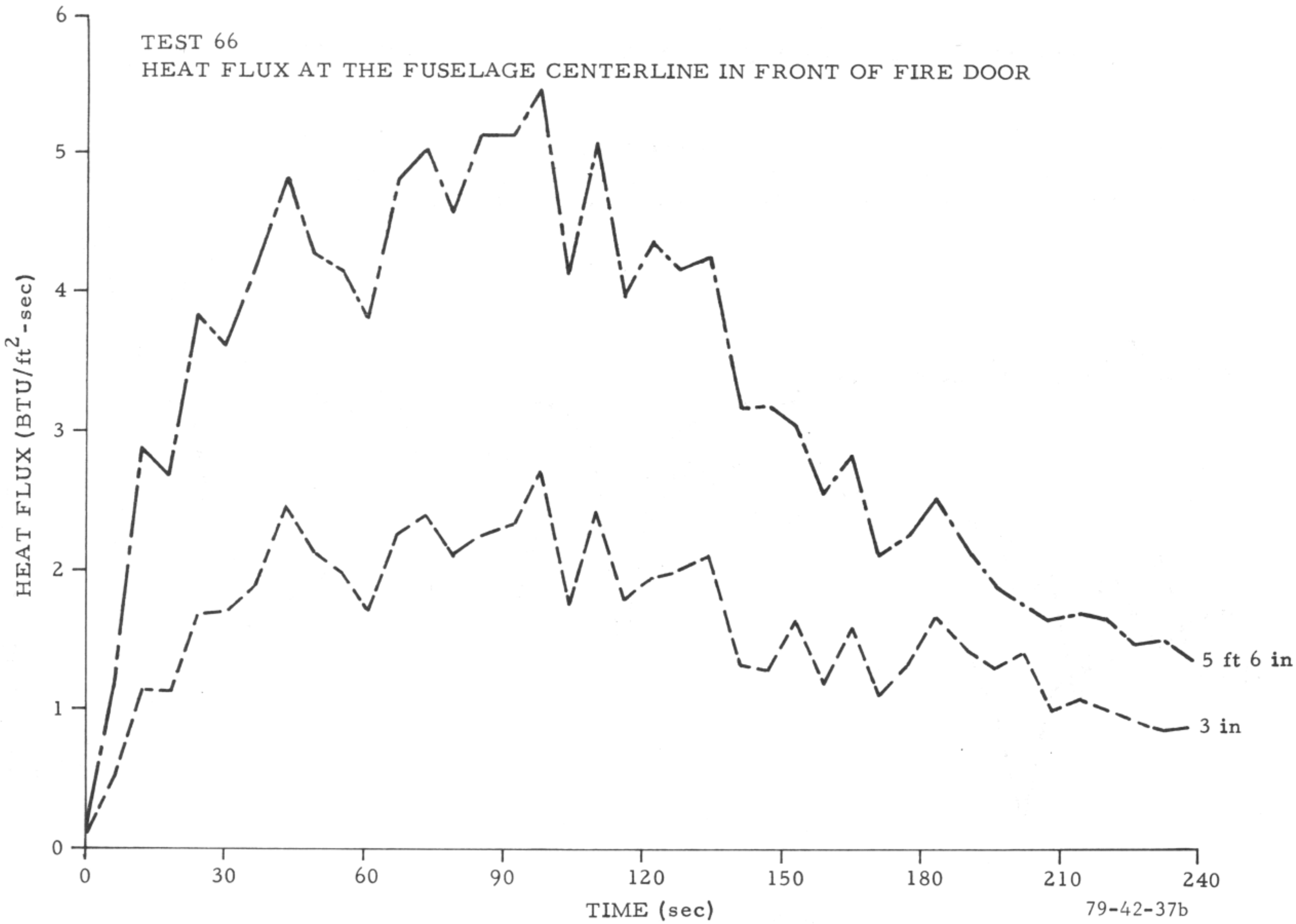


FIGURE 37. HEAT FLUX FOR MOST SEVERE 8- BY 10-FOOT TEST (Sheet 2 of 3)

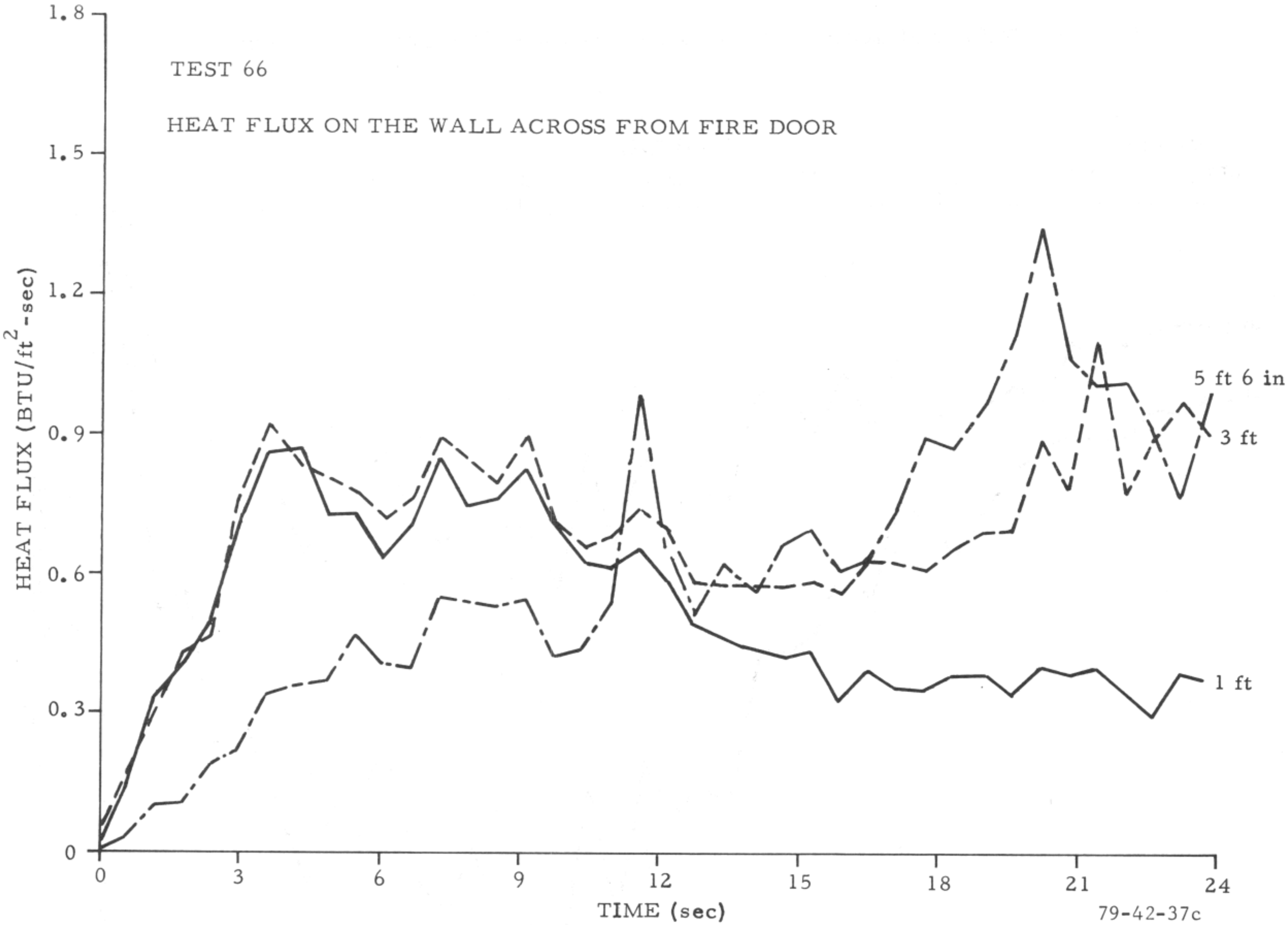


FIGURE 37. HEAT FLUX FOR MOST SEVERE 8- BY 10-FOOT TEST (Sheet 3 of 3)

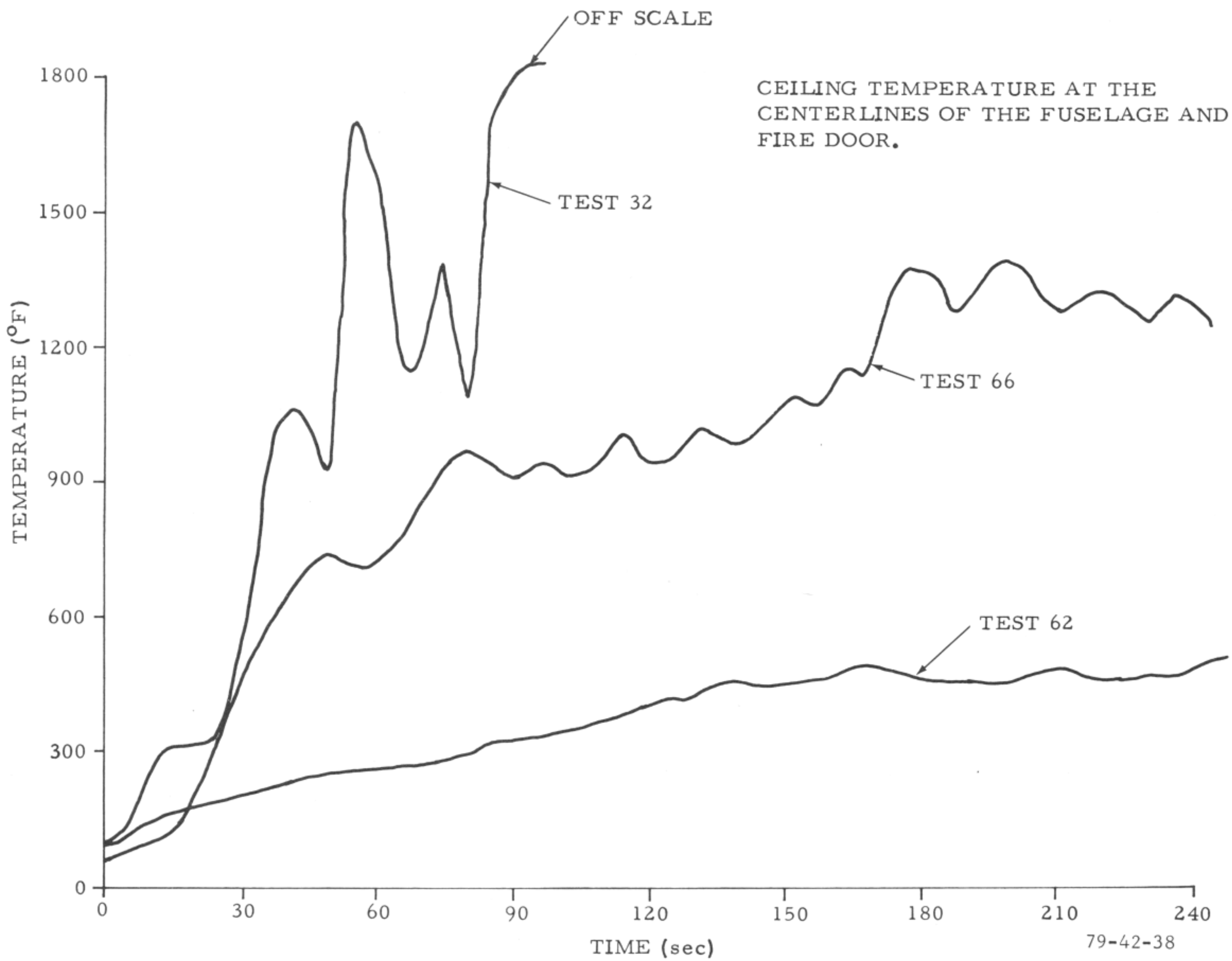


FIGURE 38. CEILING TEMPERATURES, FIRE DOOR AREA

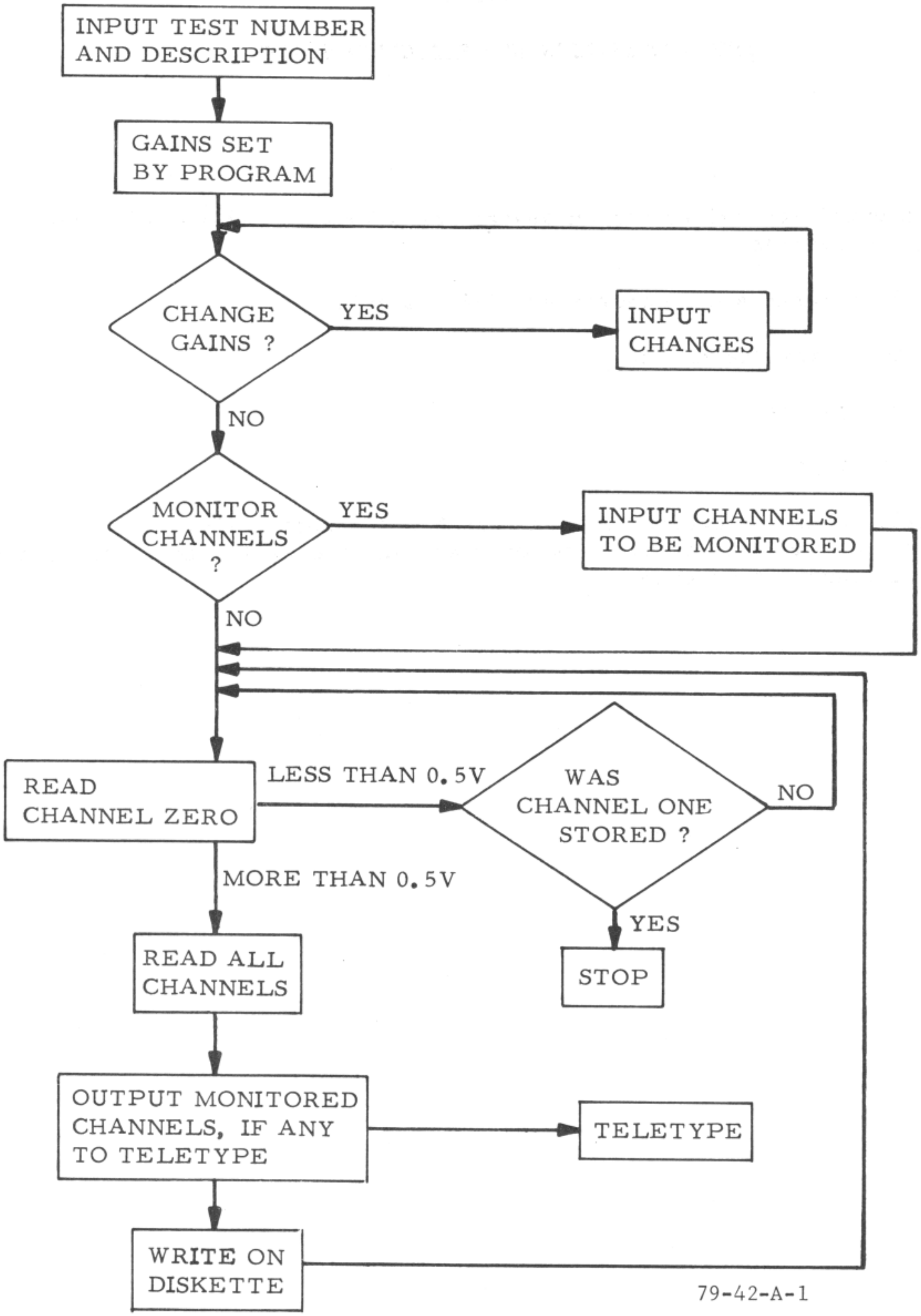
APPENDIX A

DATA ACQUISITION AND REDUCTION SYSTEM

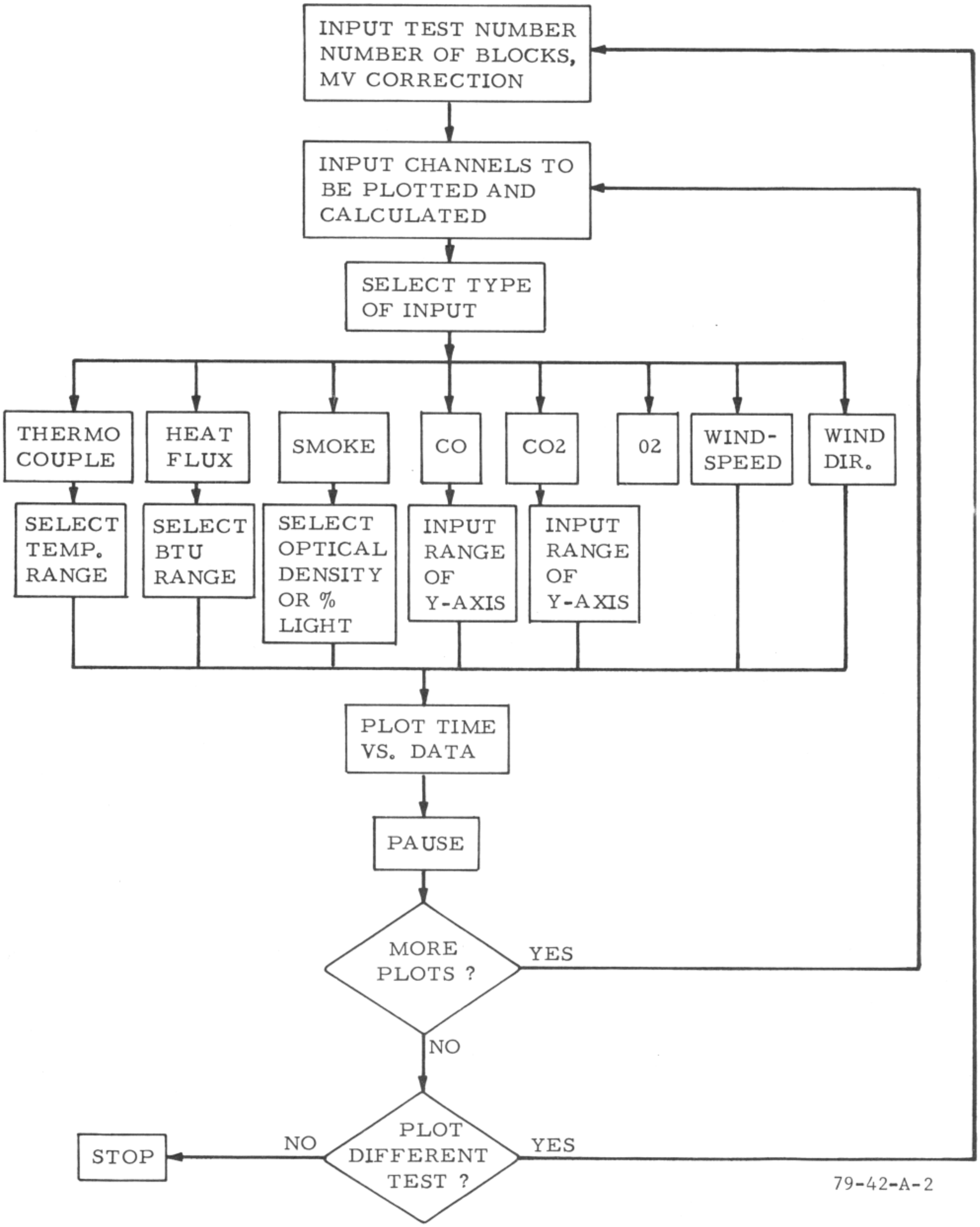
The data acquisition and reduction system was a Nova 3 computer with the following peripherals:

1. Wide-range A to D converter (128 channels)
2. Dual diskette drives
3. X-Y plotter
4. Teletype

The acquisition and reduction of data were handled separately. Figure A-1 is a flow chart of the data acquisition program, and figure A-2 is a flow chart of the data reduction program.


INPUT TEST NUMBER AND DESCRIPTION
GAINS SET BY PROGRAM
CHANGE GAINS ?
YES
INPUT CHANGES
NO
MONITOR CHANNELS ?
YES
INPUT CHANNELS TO BE MONITORED
NO
READ CHANNEL ZERO
LESS THAN 0.5V
WAS CHANNEL ONE STORED ?
NO
YES
STOP
MORE THAN 0.5V
READ ALL CHANNELS
OUTPUT MONITORED CHANNELS, IF ANY TO TELETYPE
TELETYPE
WRITE ON DISKETTE

79-42-A-1


INPUT TEST NUMBER
NUMBER OF BLOCKS,
MV CORRECTION
INPUT CHANNELS TO
BE PLOTTED AND
CALCULATED
SELECT TYPE
OF INPUT
THERMO
COUPLE
HEAT
FLUX
SMOKE
CO
CO2
02
WIND-
SPEED
WIND
DIR.
SELECT
TEMP.
RANGE
SELECT
BTU
RANGE
SELECT
OPTICAL
DENSITY
OR %
LIGHT
INPUT
RANGE
OF
Y-AXIS
INPUT
RANGE
OF
Y-AXIS
PLOT TIME
VS. DATA
PAUSE
MORE
PLOTS ?
YES
NO
PLOT
DIFFERENT
TEST ?
YES
NO
STOP

79-42-A-2

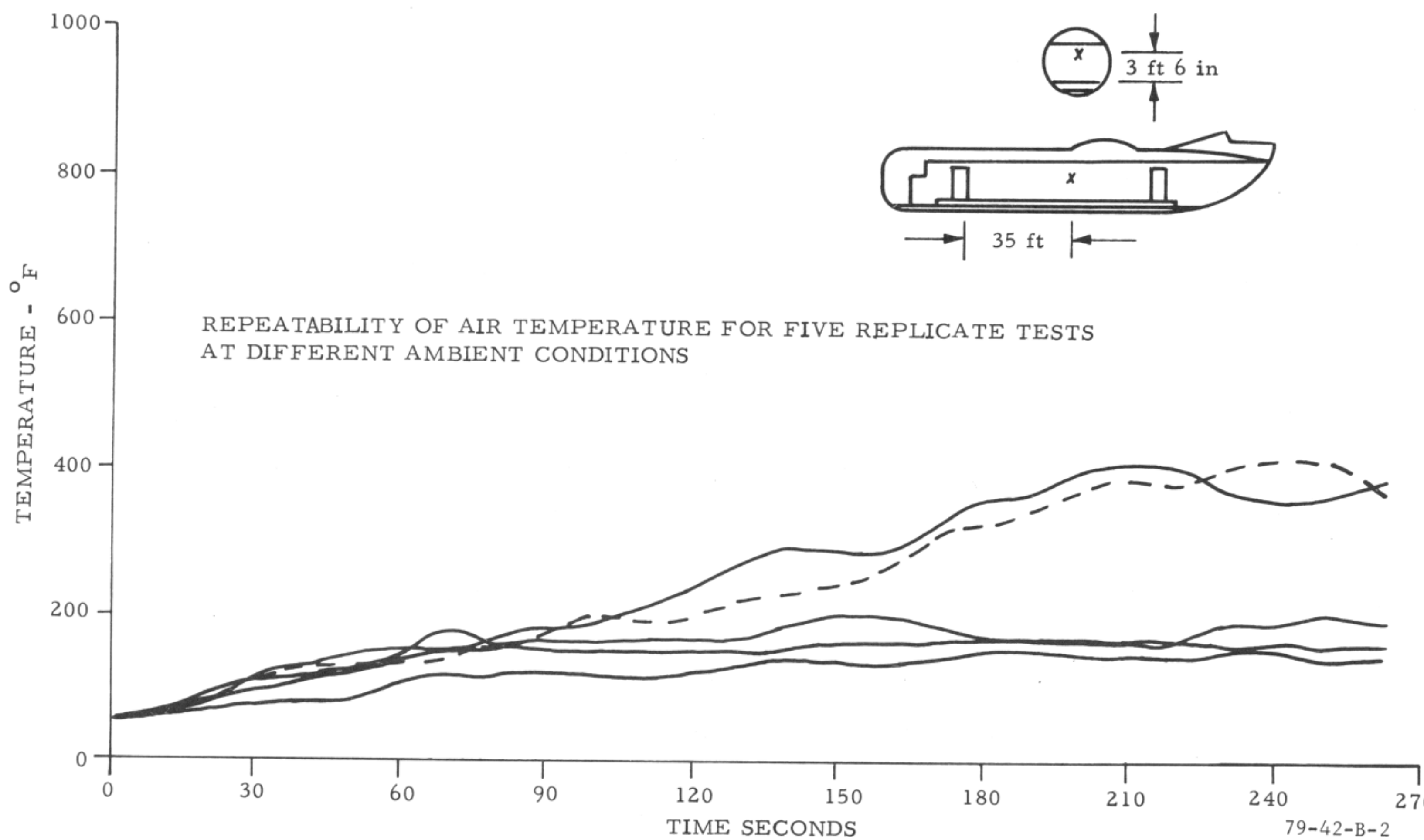
APPENDIX B

PRELIMINARY TESTS WITH WINDBREAK

Fourteen tests were conducted with a wind barrier around the external fuel fire (figure B-1). The wind barrier was used in hopes of minimizing the effect of variable ambient wind conditions. A fan was used to supply a constant controllable simulated wind.

Figure B-2 shows data from five "identical" tests. Two families of curves are evident. For one family, the flames continuously penetrated into the cabin, resulting in an ever-increasing cabin temperature: however, for the other family, the flames penetrated for about a minute at the beginning of the test but later receded, and the resulting cabin temperature leveled off. The two-family behavior was probably related to the ambient conditions, possibly in combination with the steel-covered wind barrier. However, no correlation could be made with measurement taken during each test of ambient windspeed and direction, temperature, and relative humidity. Therefore, there was no apparent means of predicting which of the two family curves would exist under a given set of ambient conditions. For this reason, the wind barrier was removed for all subsequent testing.

FIGURE B-1. EXTERNAL FIRE WITH WIND BARRIER


REPEATABILITY OF AIR TEMPERATURE FOR FIVE REPLICATE TESTS
AT DIFFERENT AMBIENT CONDITIONS
3 ft 6 in
35 ft
TEMPERATURE - °F
1000
800
600
400
200
0
0
30
60
90
120
150
180
210
240
270
TIME SECONDS
79-42-B-2

APPENDIX C

A PICTORIAL ACCOUNT OF THE PROGRAM

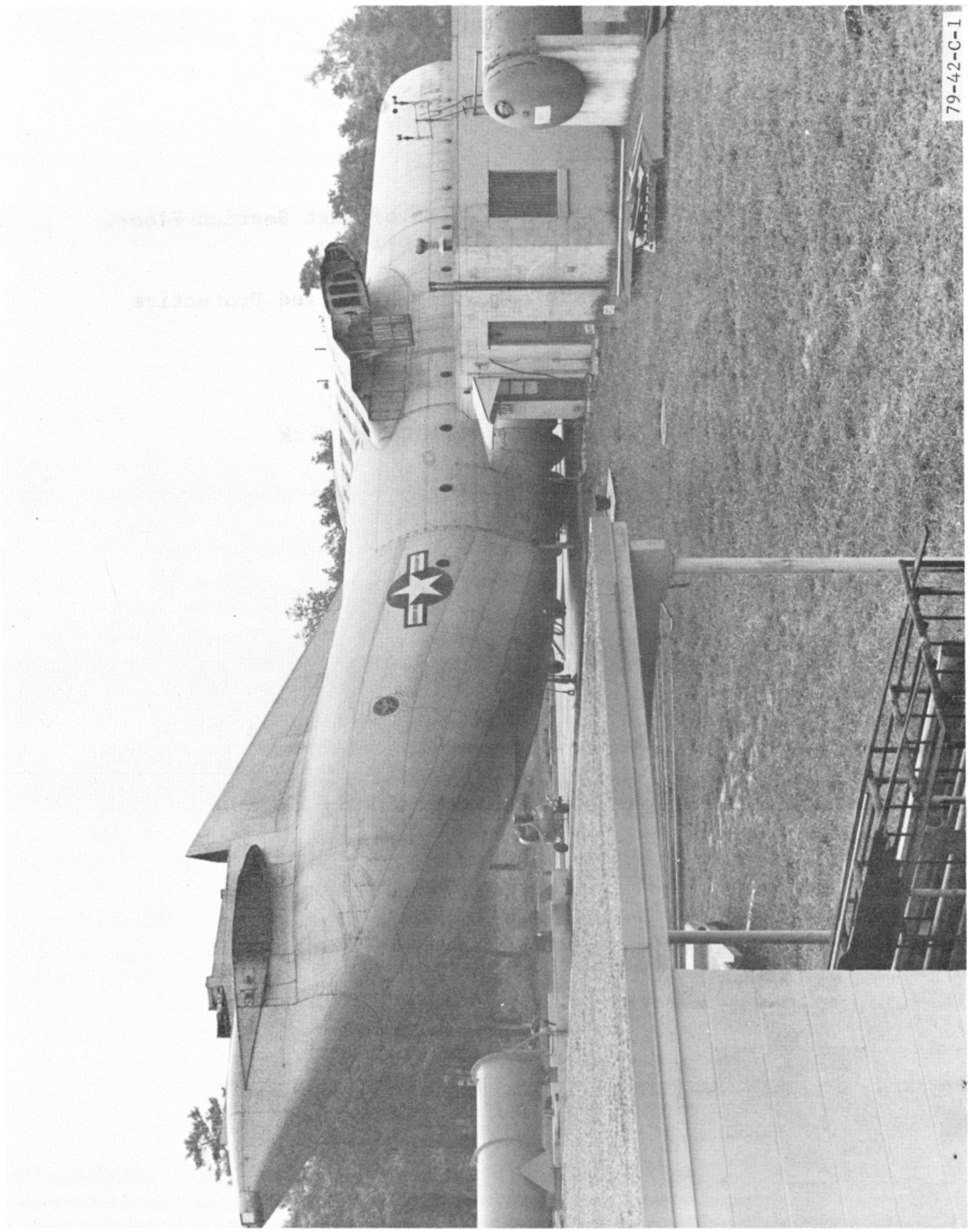


FIGURE C-1. C133 TEST ARTICLE

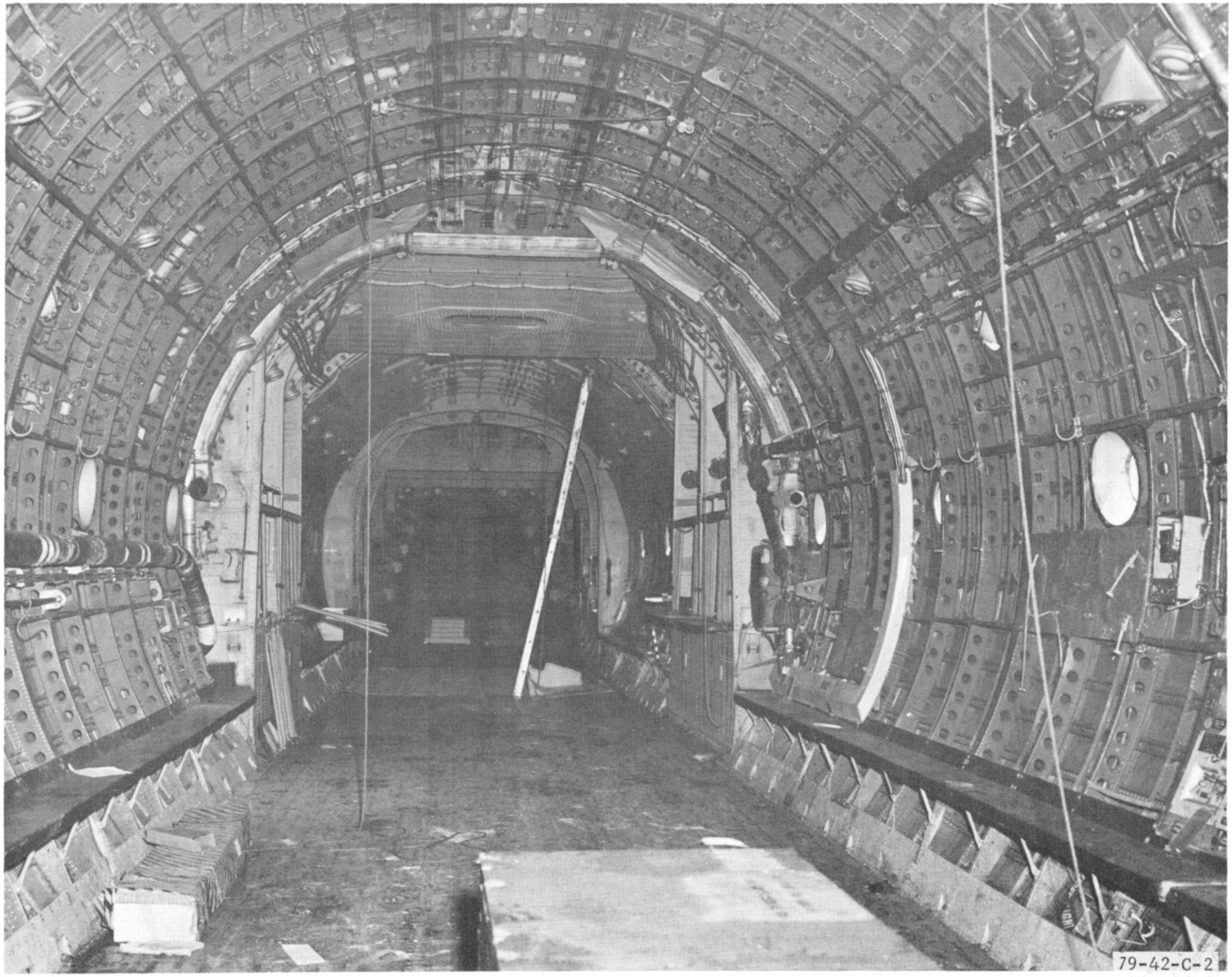


FIGURE C-2. FUSELAGE INTERIOR, PRIOR TO INSTALLATION OF TEST SECTION FLOOR, FIRE RESISTANT SIDEWALL COVERINGS AND CEILING

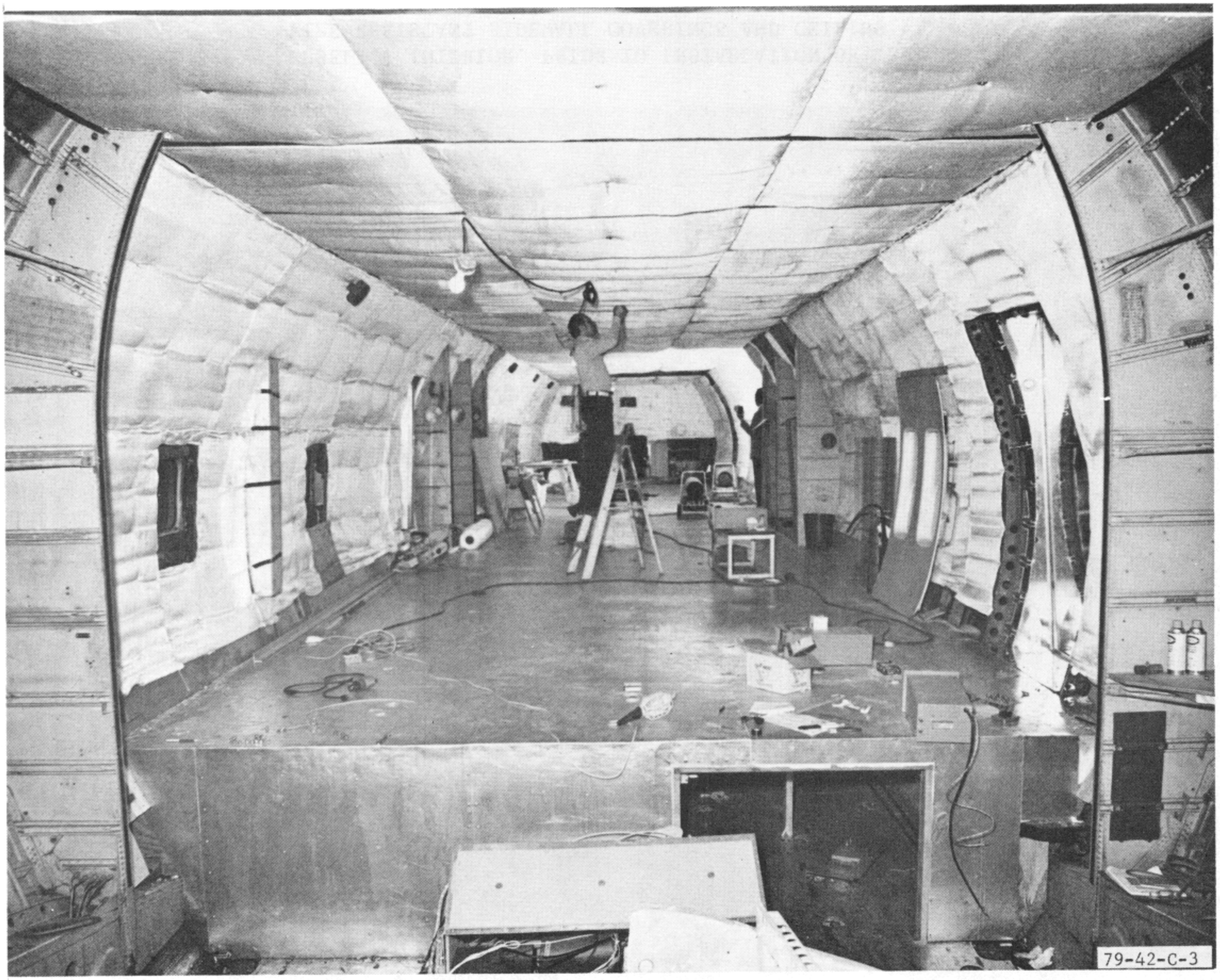


FIGURE C-3. FUSELAGE INTERIOR, AFTER INSTALLATION OF FLOOR AND PROTECTIVE COVERINGS

FIGURE C-4. EARLY MORNING TEST FIRE

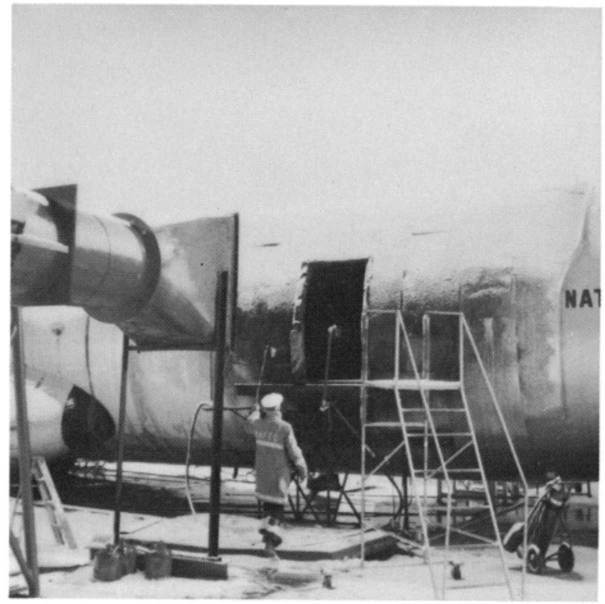


FIGURE C-5. NAFEC FIRE CAPTAIN ABOUT TO IGNITE FIRE USING WICK

FIGURE C-6. TYPICAL EXTERNAL FIRE

FIGURE C-7. TEST FIRE WITH FULL-DOOR COVERAGE

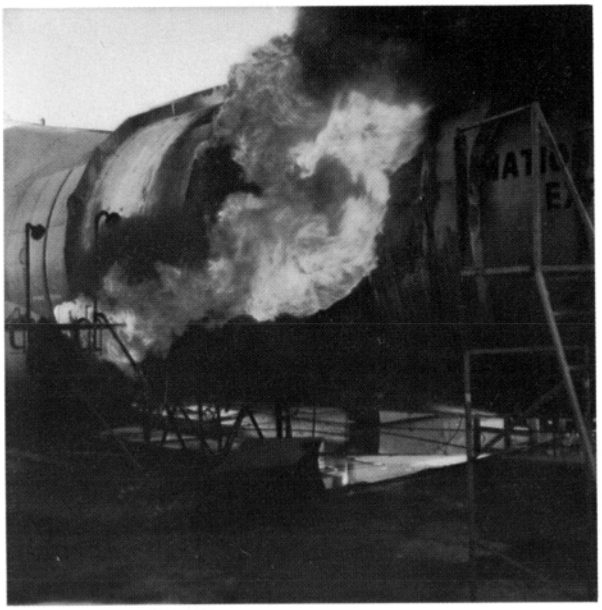


FIGURE C-8. EFFECT OF WIND GUST ON TEST FIRE

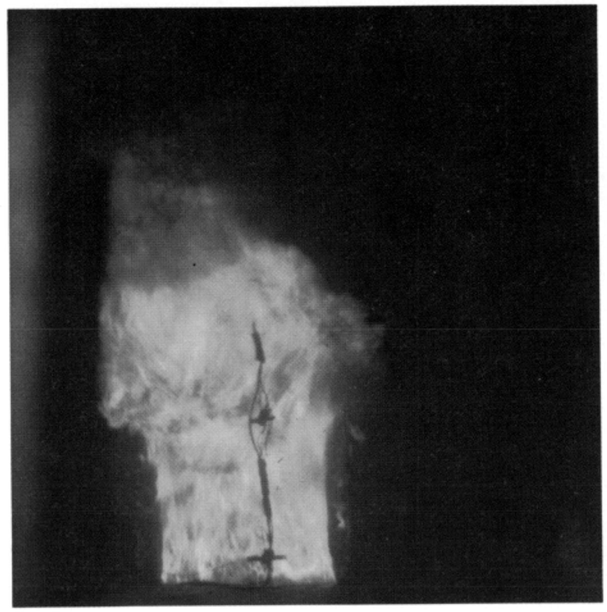


FIGURE C-9. INTERIOR VIEW OF EXTERNAL TEST FIRE

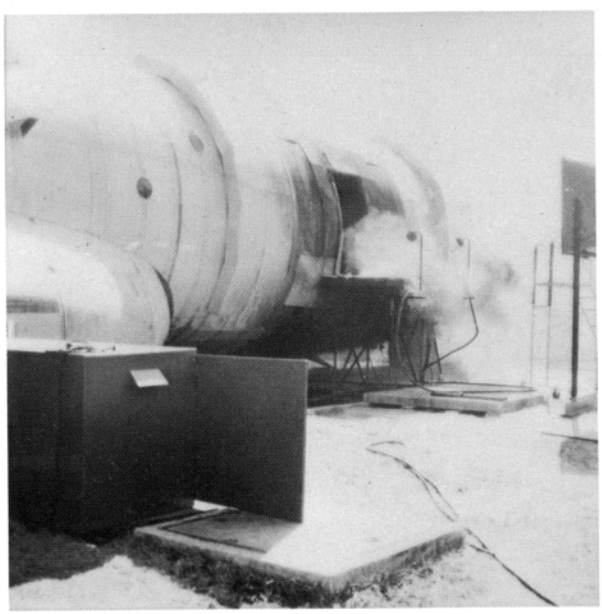


FIGURE C-10. TEST FIRE EXTINGUISHMENT USING CO_2

FIGURE C-11. POSTTEST FIRE DAMAGE (TEST 72)

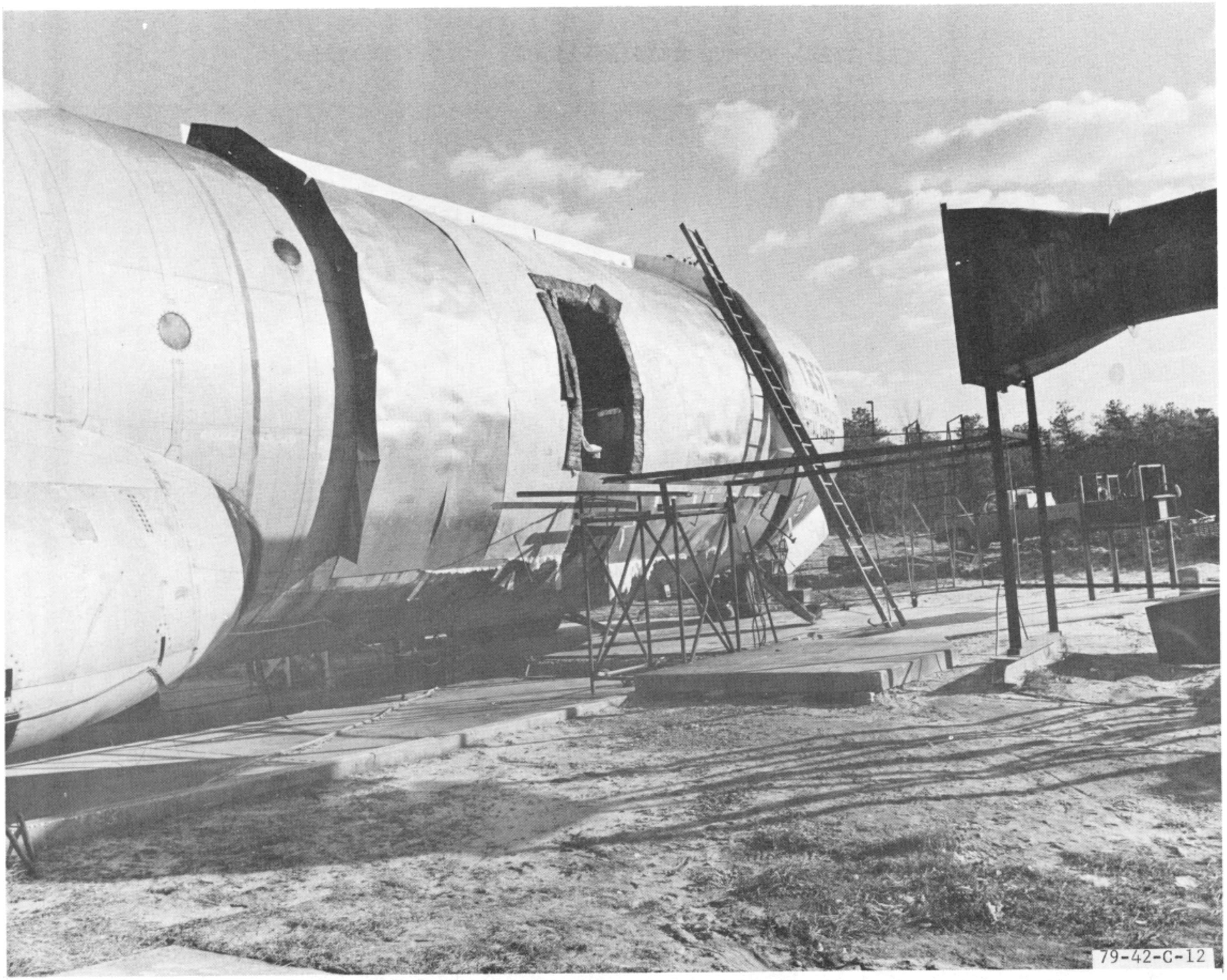


FIGURE C-12. FUSELAGE REPAIR OF DAMAGE CAUSED DURING TEST 72