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Examination of Aircraft Interior Emergency Lighting in a Postcrash Fire Environment

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June 1982

Final Report

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16. Abstract

This report describes the effectiveness of emergency interior lighting in a wide-body aircraft test fuselage subjected to elevated temperatures and dense smoke generated by an external fuel fire and interior materials fire. Photometric measurements show significant smoke stratification. The dense smoke at the ceiling can reduce the effectiveness of emergency lighting sources in the upper one third of the aircraft cabin in the very early stages of a cabin fire, while temperatures are survivable in the lower two thirds of the cabin. Placing emergency lighting sources at or below the height of the passenger seat armrest can increase the time span over which the lights are effective.

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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

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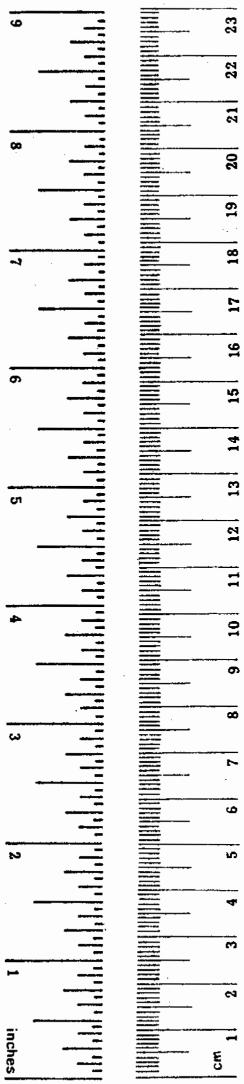
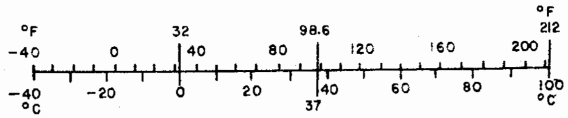
*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



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 Dr. Thor Eklund in the data analysis and the mathematical analysis to determine the value of "dense smoke" is gratefully acknowledged.

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INTRODUCTION

PURPOSE.

The purpose of this report is to: (1) examine typical and advanced aircraft emergency lighting systems and concepts under postcrash fuel-fire and smoke conditions; (2) characterize cabin smoke levels under realistic external fuel-fire conditions; (3) to compare black fuel-fire smoke with an enert white screen fog (references 1 and 2); (4) evaluate the integrity of certain wide-body aircraft emergency exit signs at elevated temperatures (reference 3); (5) to compare fuel-fire versus artifical smoke, the effect of ceiling-mounted emergency illumination sources versus emergency illumination sources mounted near the floor (reference 4).

BACKGROUND.

The National Transportation Safety Board (NTSB) conducted a special study (reference 5) of several air carrier accidents that were survivable from a crash impact viewpoint. Postcrash evacuation was carried out at night or in the presence of fire and/or smoke. The NTSB concluded that the ability of the passengers to locate emergency exits and to move through the cabin was hindered by inadequate cabin illumination levels.

Present Federal Aviation Administration (FAA) Regulations (FAR) govern the general illumination level in the passenger cabin (FAR 25.812(c)). The average illumination must not be less than 0.05 foot-candles, as measured every 40 inches along the centerline of the main aisle(s) and cross-aisle(s) at an armrest height, and with 0.01 foot-candle, the minimum illumination at any point in the 40-inch interval. The location of each passenger emergency exit must be indicated by a sign recognizable from a distance equal to the width of the cabin. Each passenger exit sign must be internally illuminated with a background brightness of 25 foot-lamberts.

Tests conducted at the FAA's Civil Aeromedical Institute (CAMI) to determine the adequacy of emergency interior lighting in a smoke environment were accomplished using a theatrical white smoke in a cabin mockup or a darker smoke generated in a test chamber from cotton waste, crankcase, oil and rubber tires (reference 1). These tests indicated a need to conduct full-scale tests under controlled conditions in which aviation jet fuel (JP-4) and cabin materials would be burned to provide more realistic smoke. These realistic test conditions could help determine criteria for improving cabin illumination during evacuation from a darkened or smoke filled cabin and define the term "dense smoke," used in FAR 25.811(c). The FAA's Flight Standard Service issued a research and development (R&D) request (FAA-9550, AFS-100-76-151) to evaluate emergency lighting under realistic fire/smoke conditions. A second request was issued to evaluate the performance of cabin exit/threshold lights from each of the L-1011, DC-10, and B-747 airplanes under cabin thermal conditions which caused a similar light to fail during preliminary tests. An internal report (reference 3) describes the examination of existing wide-body interior lighting systems and several advanced/improved lighting systems under fuel-fire smoke cabin conditions.

EXPERIMENTAL OBJECTIVE.

The first experimental objective was to examine the following aircraft interior emergency lighting systems or concepts under fuel/materials fire smoke conditions:

(a) present passenger emergency awareness signs and cabin illumination lights; (b) lights lowered to various elevations; (c) lights with increased brightness; and (d) new lighting systems, including floor-mounted electroluminescent and flashing light strips, selfpowered light sources for aisle identification and armrest lights. The second objective was to study the distribution of smoke for a range of experimental fire smoke conditions in order to define the term "dense smoke." The third objective was to evaluate the integrity of certain wide-body exit signs when subjected to elevated air temperatures. The final objective was to use the above findings to recommend an effective and practical emergency lighting system for evaluation at CAMI in an evacuation simulator using naive subjects.

DISCUSSION

DESCRIPTION OF THE TEST ARTICLE.

A surplus military C-133 aircraft was modified to resemble a wide-body aircraft test article by the installation of a raised floor and drop ceiling. The test article layout is shown in figure 1. The cabin floored area (76 feet long, 15 feet wide, and 8 feet high) provides approximately 9,000 ft^3 of enclosure volume. The volume forward and aft of the installed floor provides a total cabin volume of 13,200 ft^3. The cabin area was lined with noncombustible materials and was without seats or hat racks; however, the next phase of testing will provide these components. The fuselage area around the fire entry door, sized to that of a standard wide-body entrance door, was fire hardened with stainless and mild steel. A carbon dioxide system was installed to protect the aircraft test article during fire tests. An external fuel-pan arrangement, adjacent to the fire entry door, provided a base fire size ranging from 4 by 4 feet to 8 by 10 feet, using 15 to 50 gallons of jet fuel, respectively, to provide a 4- to 5-minute fire duration.

TEST LIGHTING — LOCATION AND ARRANGEMENT.

A standard L1011 cabin lighting system (partial) was installed in the aft cabin area of the test article as shown in figure 1 and listed in table 1. The aft cabin portion of the test article was chosen because this area would present the least hostile environment and provide some protection to the instrumentation. This lighting system consisted of one exit locator, one cross-aisle light, two locator exit lights, four aisle lights, and was capable of providing the 0.05 foot-candle average illumination at the armrest height as required by FAR 25.812(c)1. These lights were all ceiling mounted except for the exit locator light, which was mounted on a bulkhead 78 inches above the floor level. An emergency exit signal/threshold light was also installed on the bulkhead, 78 inches above the floor. This installation simulated an over-the-door exit sign.

To study the effects of brightness and vertical location, five cargo compartment-type lights were used as source lights. Three lights in a horizontal plane, 61 1/2 inches above the floor, were compared at different brightness levels, and three lights of equal brightness in a vertical plane, 78, 61 1/2, and 38 inches above the cabin floor, were compared to examine the importance of location (figure 1). The voltage to these lights was adjustable from zero to greater than 1,250 foot-lamberts from the forward observation booth.

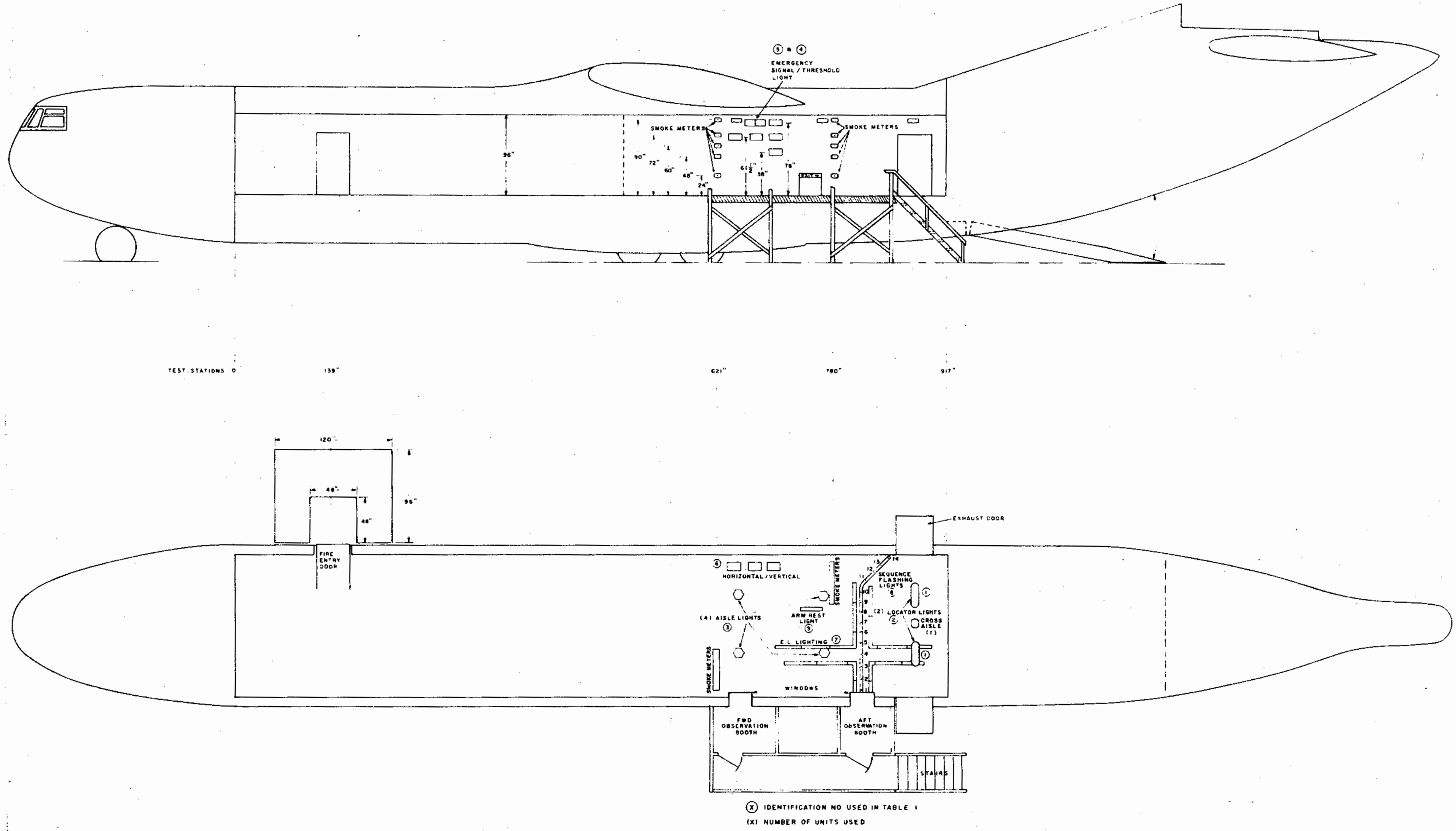

FIGURE 1. C-133 CABIN AND EMERGENCY LIGHTING LAYOUT

TABLE 1. LIGHTING EQUIPMENT INSTALLED IN CABIN TEST AREA

	LIGHT	MFG/MODEL NO.	CABIN USAGE
1.	Illuminated Locator Exit (Exit locator)	GRIMES/10-0481	Rear aisle to exit
2.	Light, Emergency Exit and Cross-Aisle (used to illuminate aisle intersections)	GRIMES/10-0544	Rear cross-aisle
3.	Light, Assembly Aisle and Emergency (general aisle and cabin illumination)	GRIMES/10-0452	Over cabin aisles
4.	Sign, Interior Illuminated-Exit Locator (used for exit direction)	GRIMES/10-0535	Cabin side wall (to simulate a bulkhead mounting)
5.	Sign, Emergency Exit Overdoor/Threshold Light (identify exit/illuminate threshold)	GRIMES/10-1705-1	Bulkhead over door position
6.	Light, Cargo Floor (used in the horizontal and vertical placement arrays)	GRIMES/B-5820A	Horizontal and vertical location arrangement
7.	Capsul Light Electroluminescent	Atkins & Merrill	Rear cabin floor aisle and cross-aisle to the door
8.	Sequential Flashing Light System	DME Corporation	Rear cabin floor cross aisle to door
9.	Armrest Light	Plumly Indus.	Rear cabin area armrest location

The above lights are shown in figure 3 and identified by corresponding number.

A prototype armrest light was installed in the cabin test area (figure 1) for visual observation during the test program. This light was designed and manufactured by the Plumly Corporation for installation in the aisle-side armrest of aisle seats and provided exit direction information and illumination to the aisle floor.

A sequence flashing light system was installed on the rear cabin floor (figure 1) and consisted of a 16-foot-long multiconductor bus strip with 14 lights attached, approximately 1 foot apart. These lights were wired in seven groups of two each and flashed in pairs (1 and 8, 2 and 9, 3 and 10 etc.), each over a duration of 250 milliseconds. This light system was installed across the cabin floor starting at the aft observation window and terminating near the aft cabin exit door (smoke exhaust door) on the right side of the aircraft. This system was designed and manufactured by the DME Corporation, and the sequence of flashing lights was intended to provide direction-of-travel information to passengers.

Atkins and Merrill's electroluminescent light (EL) system (capsul light) was attached to the rear cabin floor and formed an aisle/cross-aisle configuration (figure 1). These lights were 1 inch wide and consisted of butted random lengths totaling 40 feet. The capsul light system was powered by 115-volt, 400-hertz (Hz) current. The brightness of this lighting system is a function of the frequency over a range of 60 to 400 Hz. During these tests, the EL lights were always operated at the 400-Hz level.

Saunders-Roe's Betalight self-powered illuminated markers were attached to the aft cabin floor to outline the aisle/cross-aisle intersection. Thirty of these units were secured to the floor at 12-inch intervals (figure 1). Each light unit is 2.68 inches long (68mm), 0.59 inches wide (15mm), and 0.31 inches deep (8mm). The illuminated area is 0.98 inches (25mm) by 0.14 inches (3.5mm) with an available brightness of 420 microlamberts.

Four Betalight markers were attached to the floor at the center of the aisle/cross-aisle intersection, as shown in figure 2. These units are 3.86 inches (95mm) long, 0.63 inches (16mm) wide and 0.55 inches (14mm) deep. The illuminated area is 2.54 inches (64.5mm) by 0.29 inches (7.25mm) with an available brightness of 160 microlamberts. The use of the self-powered illuminated markers outlining the aisle/cross-aisle is intended to provide passenger awareness and evacuation path identification in the absence of electrical powered illumination sources due to power failure, or smoke obscuration of ceiling mounted fixtures.

INSTRUMENTATION AND TEST EQUIPMENT.

Ten smokemeters, manufactured by the National Bureau of Standards (NBS), were installed in the rear cabin as shown in figure 3. These meters incorporated a collimated light source projected over a 1-meter distance that is received on a 1P39 phototube. The electronic circuitry was contained in a control console located in the aft observation room. A complete description of these meters is contained in a instruction manual "National Bureau of Standards Photometeric Smoke Measurement System" (reference 6).

Two "stacks" of five smokemeters were located in the rear cabin: one was on the left side (test station 621) and the other was on the right side (test station 780) of the cabin. Thus, the "stacks" were 13 feet apart. The light-path of the meters was perpendicular to the fuselage center-plane-line, and each stack had a smoke-meter at 2, 4, 5, 6, and 7 1/2 feet above the floor. The outupt of these

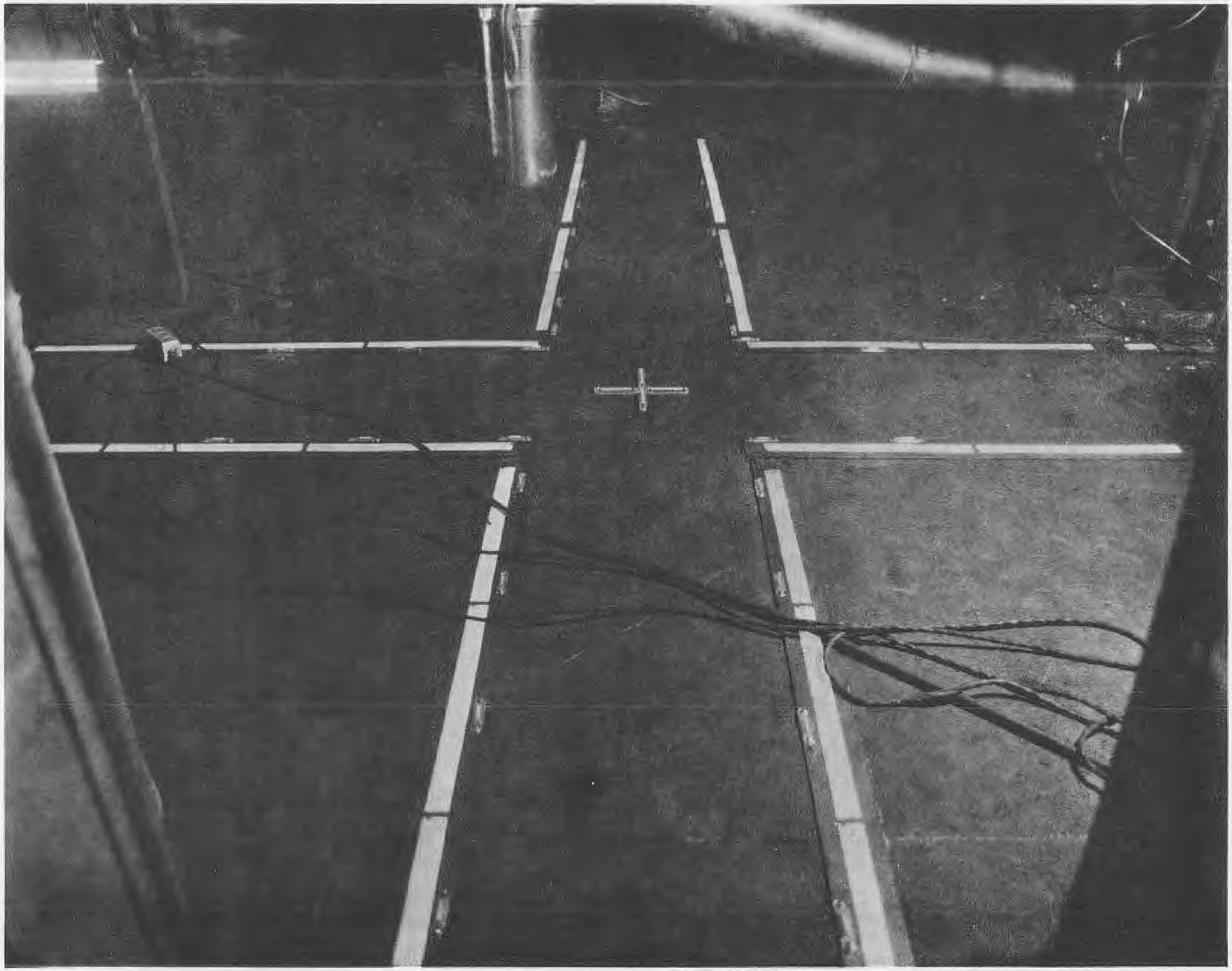

FIGURE 2. SELF-POWERED ILLUMINATION MARKERS

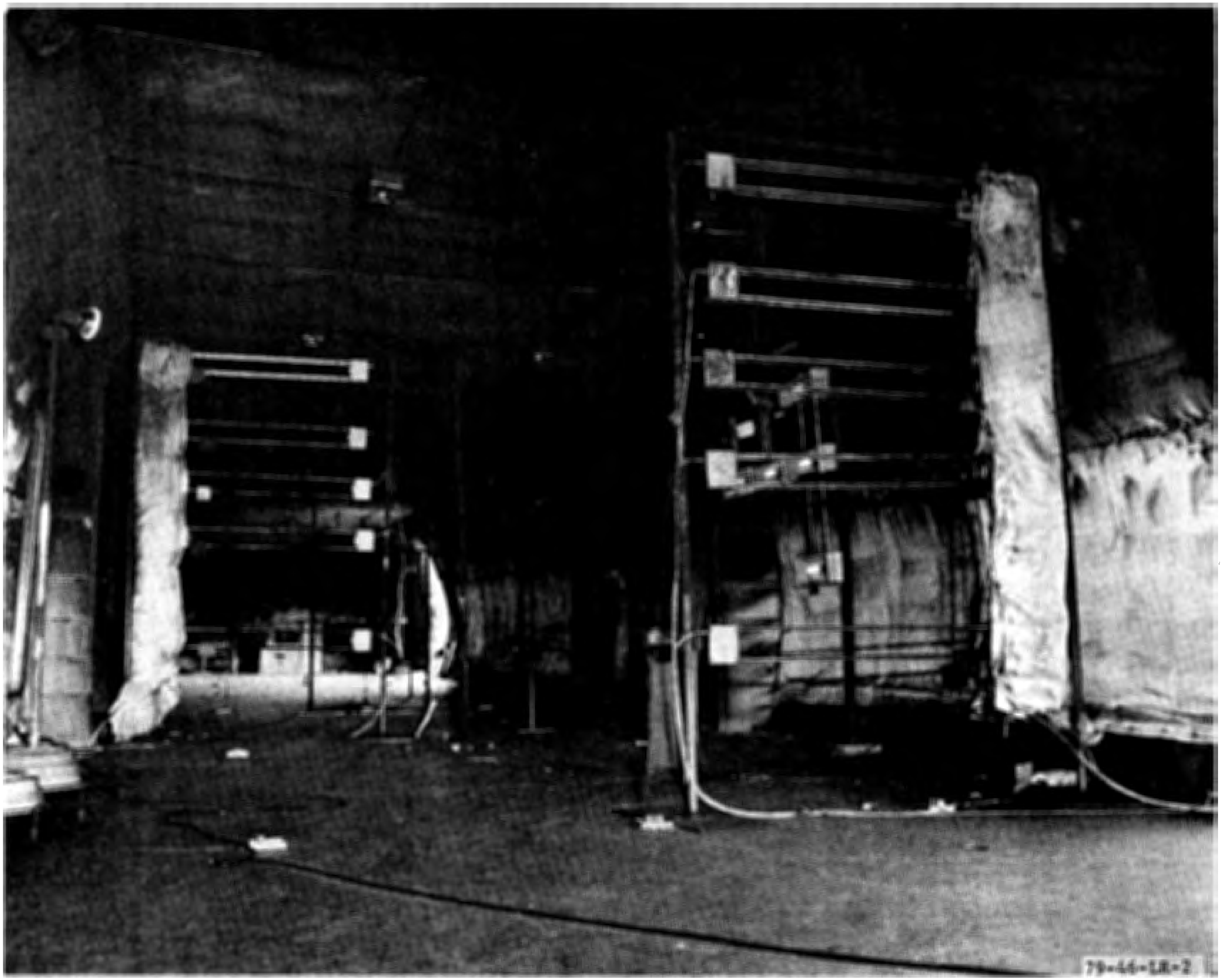

FIGURE 3. NATIONAL BUREAU OF STANDARDS SMOKEMETERS

meters was recorded on a Data General Nova 3 computer system and is presented as percent-of-light transmission or optical density.

Three Spectra spotmeters; model UBD 1/2 degree, were used to measure the luminance of the cargo lights used in the vertical location and the brightness evaluation. These spotmeters are capable of measuring luminance at any distance from 2 1/2 inches to infinity, with a 1/2 degree viewing angle.

Two Spectra photometers, model FC-200, with remote photocell probes were used to measure cabin luminance provided by the emergency interior cabin lighting system.

Spectra BSR-100 brightness source was used to periodically calibrate the light-measuring equipment.

Closed-circuit television, motion pictures, and still photography were all used during this evaluation. Both a miniature tape recorded and a light emitting diode (LED) stopwatch were used to record observer comments and visual data during the conduct of the tests.

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. Tests were conducted during the early morning hours to assure predictable and uniform wind conditions.

During the test program the winds ranged from zero to 22 miles per hour. A more detailted description of the test article and data obtained under simulated postcrash fuel-fire conditions is documented elsewhere (references 7 and 8).

The initial tests were conducted with the interior devoid of combustible materials. A second series of emergency lighting tests was conducted after the C-133 was moved inside the FAA's full-scale fire test facility. The purpose of these tests was to compare results of fuel-fire smoke to the smoke environment created by interior materials ignited from an outside postcrash fire.

TEST RESULTS

SMOKE DISTRIBUTION PATTERN AND CHARACTERISTICS.

During the C-133 fuel-fire tests conducted while the aircraft was outdoors, the most important variables affecting the interior cabin smoke conditions for a given fire size were ambient wind speed and direction (reference 7). At zero wind, and when ambient wind pushed the flames away from the fuselage, there were insignificant levels of smoke within the cabin. When a component of the wind vector pushed the flames into the cabin, an accumulation of smoke resulted. For the fuel-fires the greatest smoke accumulation occurred when the wind direction was perpendicular to the fuselage, although wind fluctuations also had an influence on the cabin smoke level (reference 7). Thus, tests were conducted over a range of wind conditions in order to study a wide range of cabin smoke densities (table 2).

TABLE 2. FULL-SCALE TEST SUMMARY (C133)

Test No.	Fuel Pan Size (Ft)	Fuel Quantity (gal)	Windspeed (mph)	Wind Direction*	Aux. Fan (mph)**	Results
24	6 x 4	15	3-14	N		Dense smoke down to 24" level
28	6 x 8	30	2-4	NE		0.05 foot-candle general cabin lighting evaluation
30	6 x 8	30	2-13	South Variable		Light smoke accumulation to 90" level
31	6 x 8	30	3-7	WSW		Medium smoke accumulation to 72" level
32	6 x 8	30	4-12	WNW		Very dense smoke accumulation below 24" level
46	6 x 8	30	3-12	NW		Horizontal/brightness evaluation
66	8 x 10	50	1	---	3.57	Vertical/location evaluation
72	8 x 10	50	0	---	3.57	0.05 foot-candle general cabin lighting evaluation
33***	8 x 10	50	0	---	1.5	Very dense smoke self-powered aisle markers
						Interior materials fire/smoke

* Test aircraft oriented nose-south, tail-north, fire entry door-west

**Auxiliary fan used to provide air-flow directed through the fire entry door. Airspeed calibrated at this constant velocity.

***ARE TESTS CONDUCTED INSIDE FULL-SCALE FIRE TEST BLDG.

Increasing cabin smoke density was accompanied by a corresponding increase in temperature. During some test intervals, the temperatures were high enough to be considered non-survivable as shown in reference 9. Temperature and optical density during smoke obscuration periods were used to derive an equation which accounts for temperatures in the aircraft cabin at fixed levels and light transmission at fixed levels with a resulting value of optical density. For example:

According to page 59 of FAA-NA-79-42, (see figure 4),

$$\frac{\Delta\ (\text{percentage light reduction/foot})}{\Delta T} = \frac{60}{200}$$

where Δ T is temperature increase in degrees Fahrenheit. Thus,

$$\frac{I}{I_o} = 1\text{-}3(\Delta T)\ 10^{-3} \qquad (1)$$

where I_o is light intensity at 100 percent transmission, and I is the measured light transmission over a foot during obscuration.

According to reference 8 (figure 5), the cabin vertical temperature profile is uniform over the top one-third of the cabin and decreases linearly to ambient over the bottom two-thirds of the cabin. Thus, if we tie the profile to any ceiling temperature T_H, we get two zones of actual temperature T*

$$T^* = T_H \text{ for the upper zone} \qquad (2)$$

and

$$T^* = T_A + (T_H - T_A)\ \frac{3h}{2H} \quad \text{for the lower zone} \qquad (3)$$

where H is cabin height, h is the height above floor at the measuring point, and T_A is ambient temperature. Since

$$T = T^* - T_A \qquad (4)$$

inserting equation (2), (3), and (4) into equation (1),

$$\frac{I}{I_o} = 1\text{-}3(T_H - T_A)\ 10^{3} \quad \text{for the upper zone} \qquad (5)$$

and

$$\frac{I}{I_o} = 1\text{-}3(T_H - T_A)\ \frac{3h}{2H}\ 10^{-3} \quad \text{for the lower zone} \qquad (6)$$

Thus, the optical density per foot is

$$D_{1\ \text{ft.}} = \log \left\{ \frac{1}{1\text{-}3\ (T_H - T_A)\ 10^{-3}} \right\}, \text{ for the upper zone} \qquad (7)$$

and

$$D_{1\ \text{ft.}} = \log \left\{ \frac{1}{1\text{-}3\ (T_H - T_A)\ \frac{3h}{2H}\ 10^{-3}} \right\}, \text{ for the lower zone} \qquad (8)$$

To obtain optical density per meter, multiply optical density per foot by 3.281

$$D_{1_m} = (3.281)\ (D_1\ \text{ft.})$$

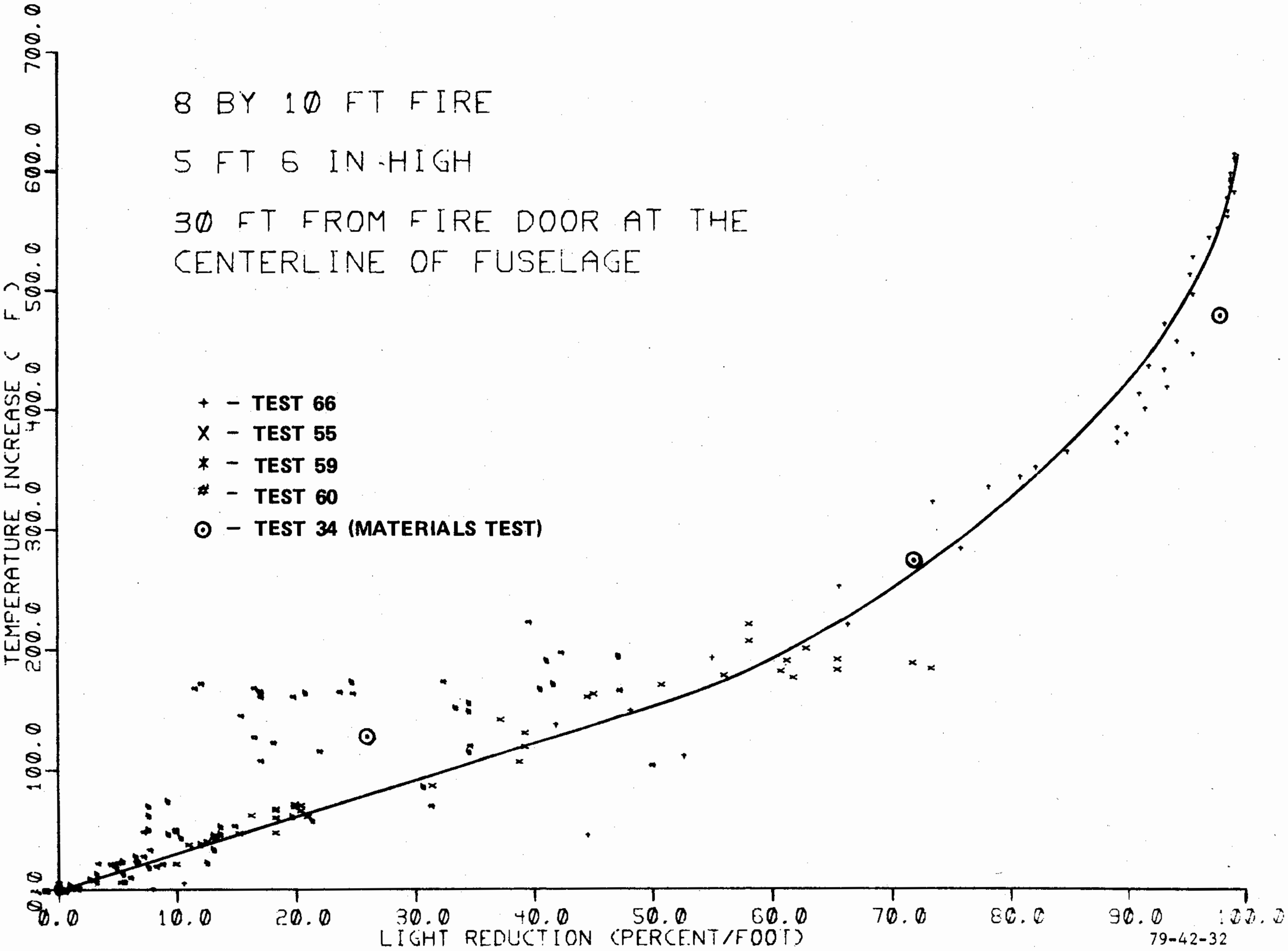

FIGURE 4. RELATION OF SMOKE-TO-TEMPERATURE INCREASE

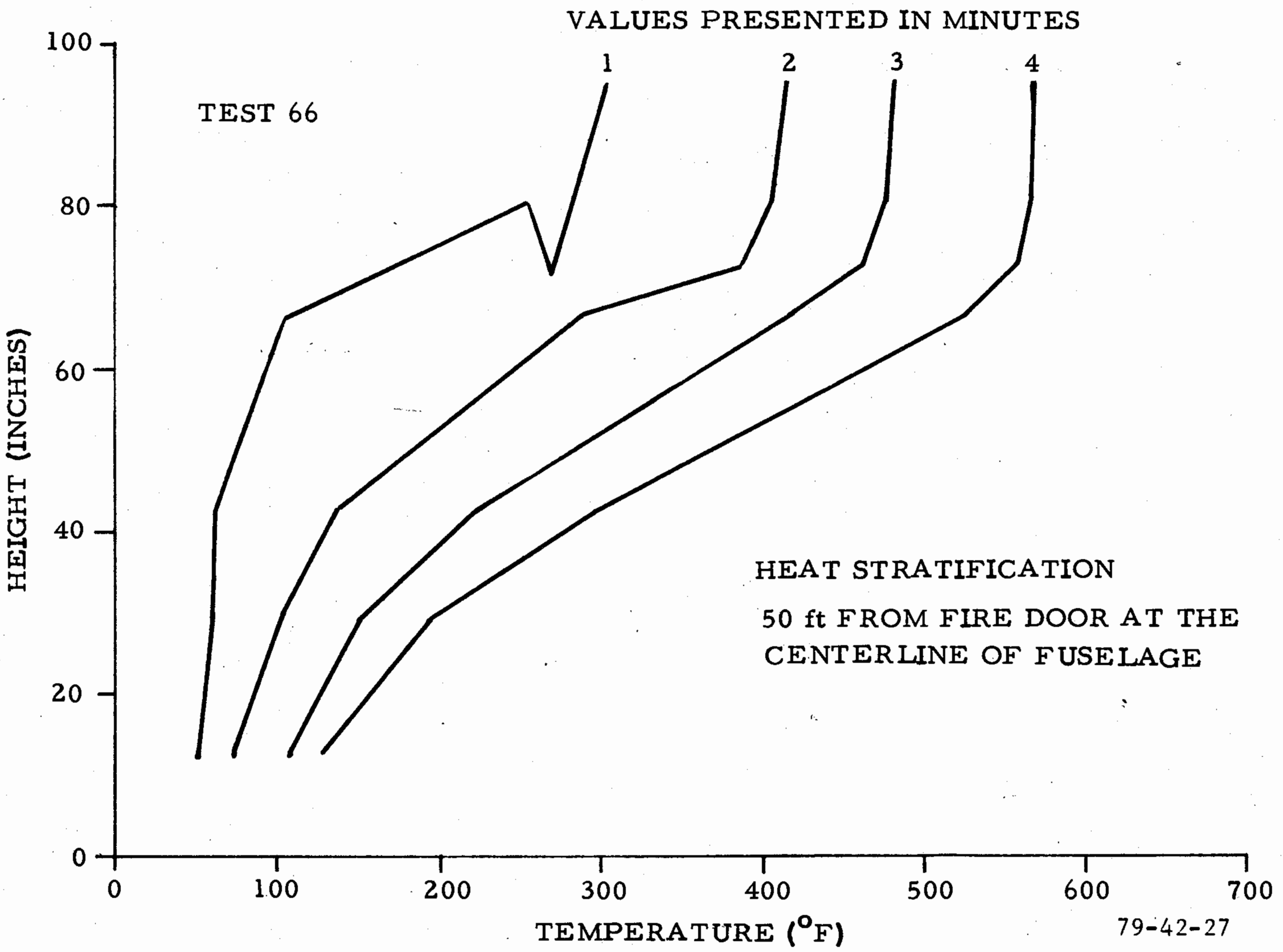

FIGURE 5. CABIN HEAT STRATIFICATION (REPLOT)

The smoke accumulation in the cabin was classified as light, medium, dense, and very dense. The following paragraphs describe a selected number of C-133 tests that produced these different regions. The light transmission data obtained from the top smoke meter, located approximately 6 inches below the ceiling, gave the best indication of the smoke density near the ceiling. In some tests or test intervals, a "thin" layer of smoke near the ceiling obscured the ceiling-mounted interior emergency aisle lights.

The light smoke conditions existing in test 30, shown plotted in figures 6 and 7, were a good example of a "thin" smoke layer. The light obscuration at 7 1/2 feet was significantly greater than at the remaining smoke meter locations (6 feet and below). Below the thin ceiling smoke layer, visibility was hardly impaired, and the temperature increase was insignificant (figure 8). Yet, although visibility was good and the conditions were survivable from a thermal viewpoint (reference 9), cabin illumination provided by the ceiling-mounted lights would have been significantly reduced by the "thin" layer of smoke near the ceiling.

Light transmission data from test 31, is plotted in figures 9 and 10 and is an example of a medium smoke condition. Again, a very pronounced smoke layer is evident from the data presented, exhibiting a thickness of approximately 2 to 3 feet over the duration plotted. Thus, total light obscuration can occur within the smoke layer dimensions without subjecting a standing individual (66 inches) to a significant amount of heat stress (figure 11).

Significantly elevated cabin thermal conditions, but below human survivable levels, were produced in test 24. By 100 seconds, the temperature at the head of a standing individual was approximately 200° Fahrenheit (°F) (figure 12). Smoke accumulation data is plotted in figures 13 and 14. Although smoke stratification was still significant, it was not as pronounced as in tests 30 and 31.

Test 32 was one of the most severe tests and was an example of a nonsurvivable cabin thermal environment. At 2 minutes, the temperature at the head level of a standing individual exceeded 300 °F and was increasing (figure 15). A very pronounced smoke stratification was again evident. At 60 seconds, total light obscuration was measured 3 feet below the ceiling. Yet, the amount of light obscuration was only approximately 5 percent at a location 1-foot lower in the cabin (see figures 16 and 17). The smoke conditions measured at 60 seconds in test 32 were in excess of the maximum smoke densities that were used in the CAMI studies of the effect of smoke and cabin lighting on passenger visibility and emergency evacuation (reference 4). Optical density data at 60 seconds were in excess of 4.0 per meter, while during the CAMI evacuation tests, optical density values per meter ranged from 1.2 to 1.7 at the 72-inch level.

Figures 17 and 18 exhibit a "crossover" in smoke density at the 2- and 4-foot elevations. This "crossover" or inversion was observed in some tests and is believed to be a result of the entrainment of air at the exhaust door and recirculation of smoke near the floor.

DISCUSSION OF SMOKE OPTICAL DENSITY CLASSIFICATION (FIGURE 18).

If smoke is injected into an enclosure, the resulting visibility depends on the volume of the enclosure, the rate of smoke generation, the geometry of the enclosure, and the physical and fluid dynamic actions sustained and effected by the

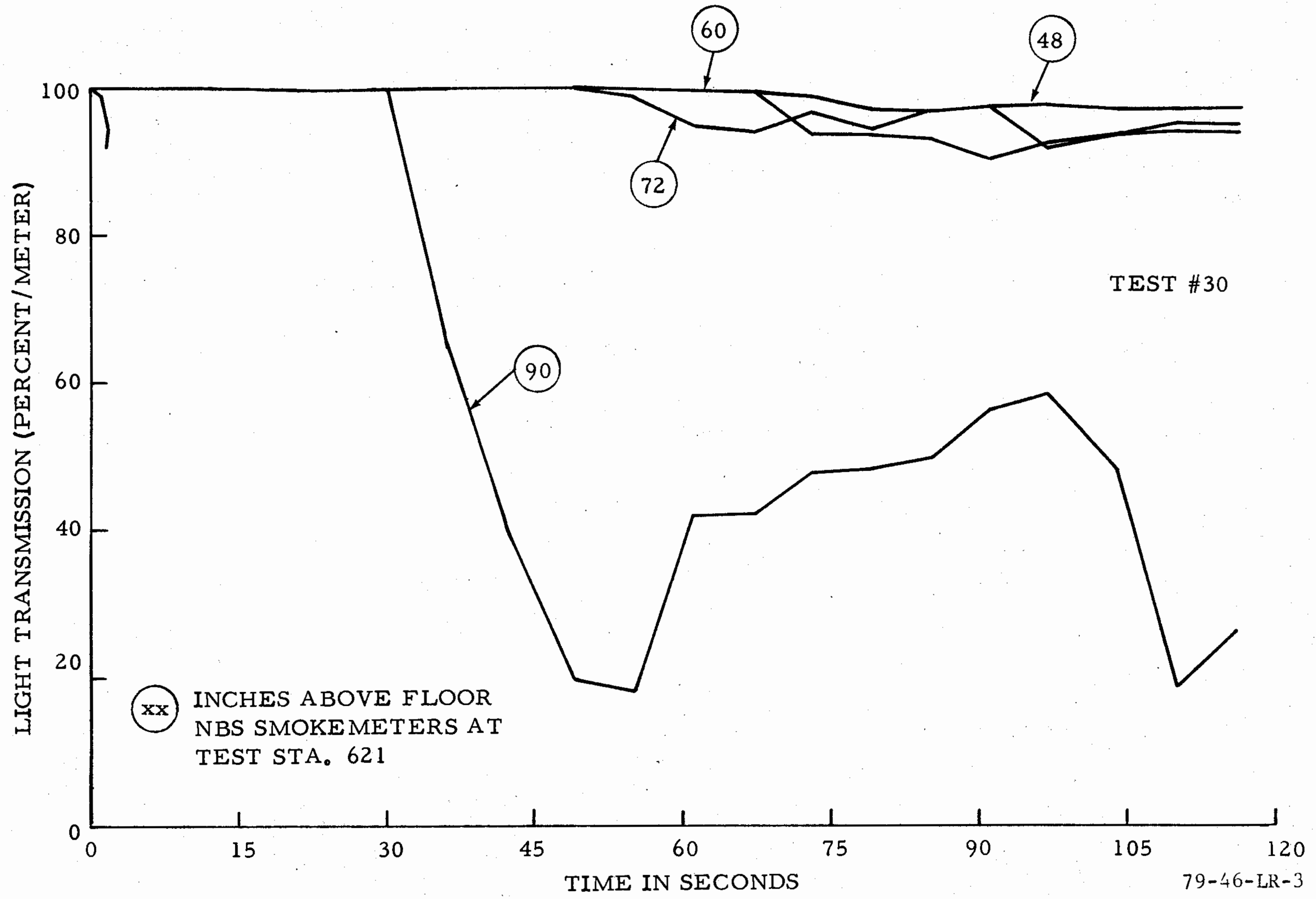

FIGURE 6. LIGHT TRANSMISSION (SMOKEMETER) PROFILE FOR "LIGHT SMOKE" ACCUMULATION AT STATION 621

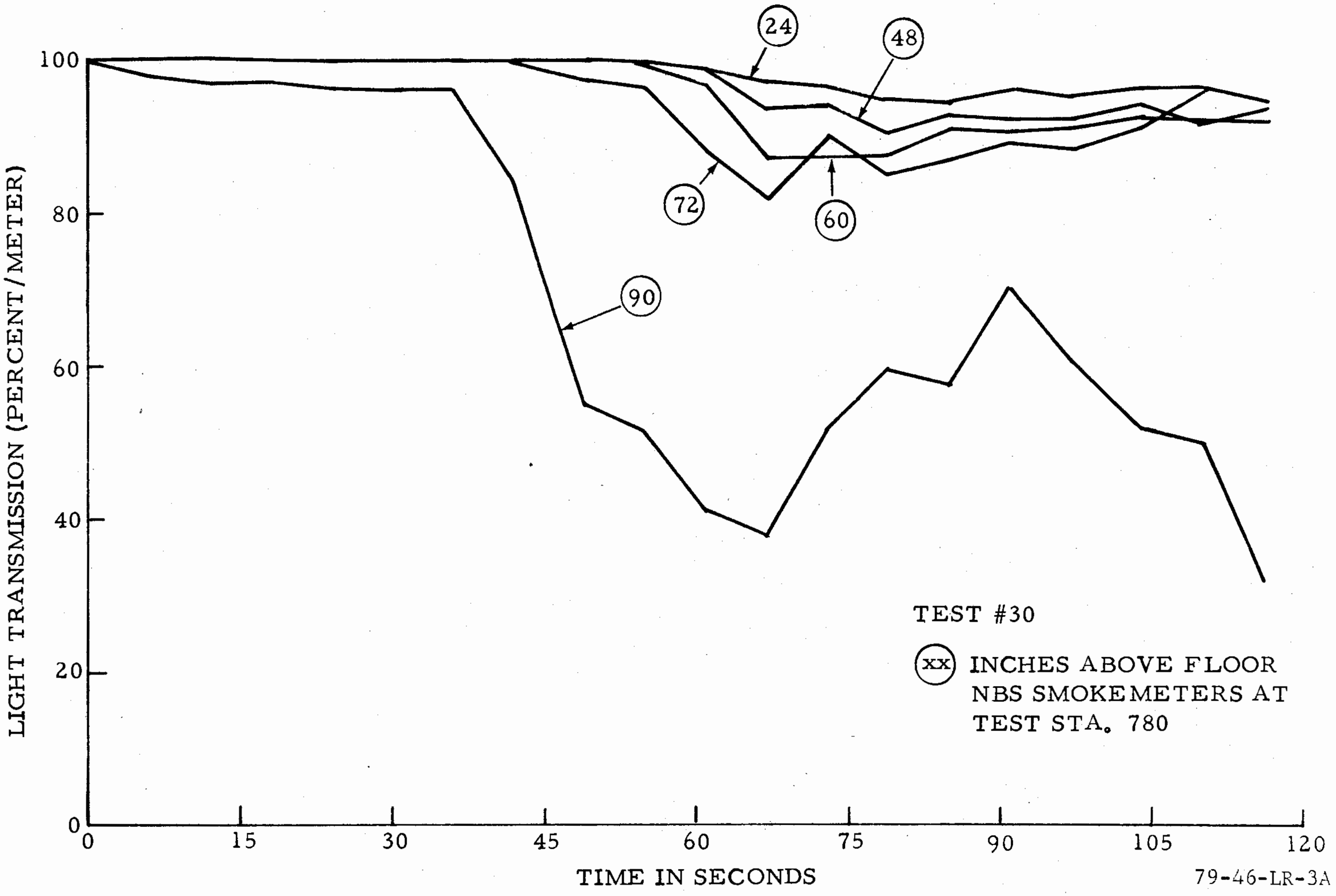

FIGURE 7. LIGHT TRANSMISSION (SMOKEMETER) PROFILE FOR "LIGHT SMOKE" ACCUMULATION AT STATION 780

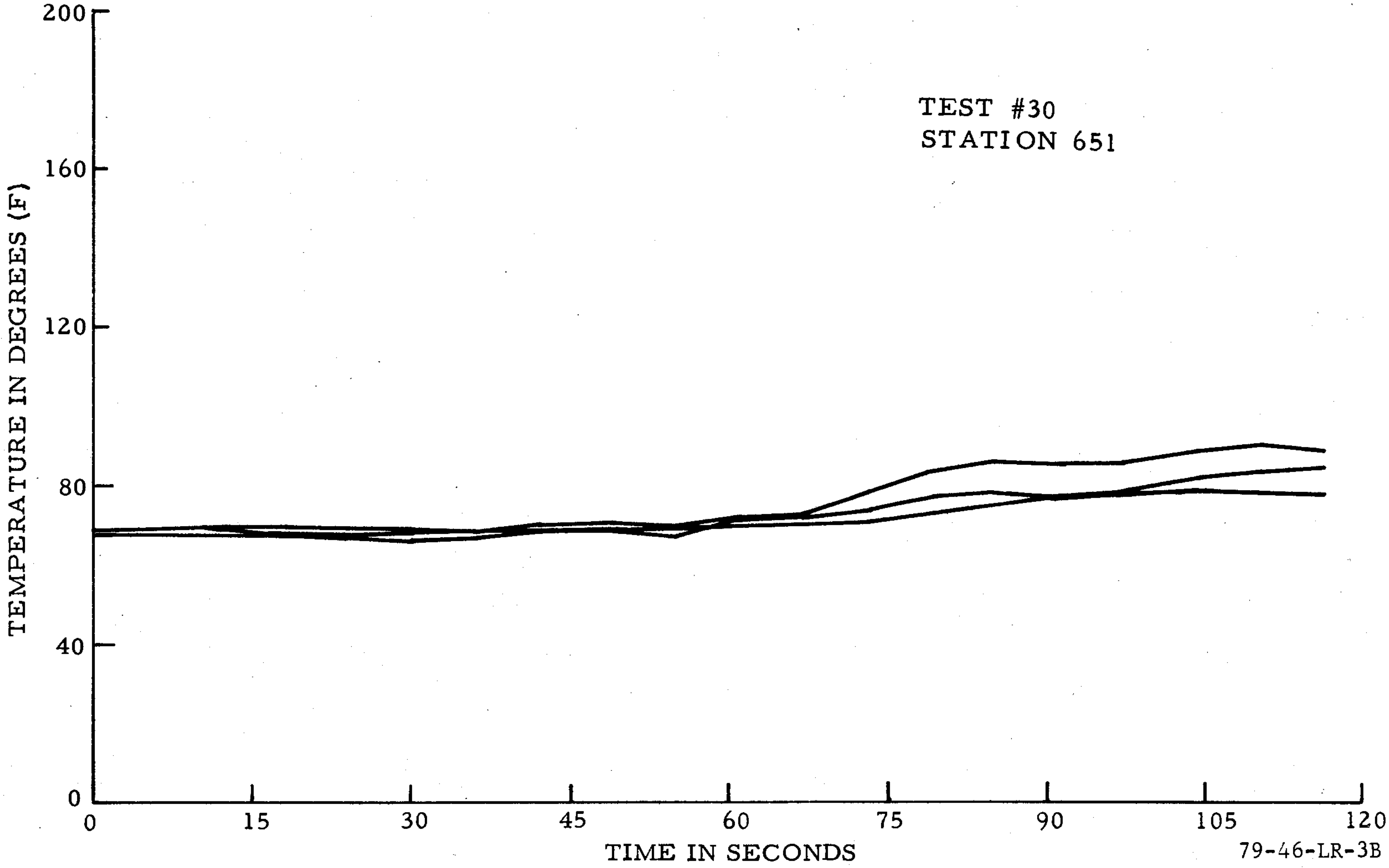

FIGURE 8. TEMPERATURE PROFILE AT THE 78-INCH LEVEL (EXIT SIGN LOCATION) DURING "LIGHT SMOKE" ACCUMULATION

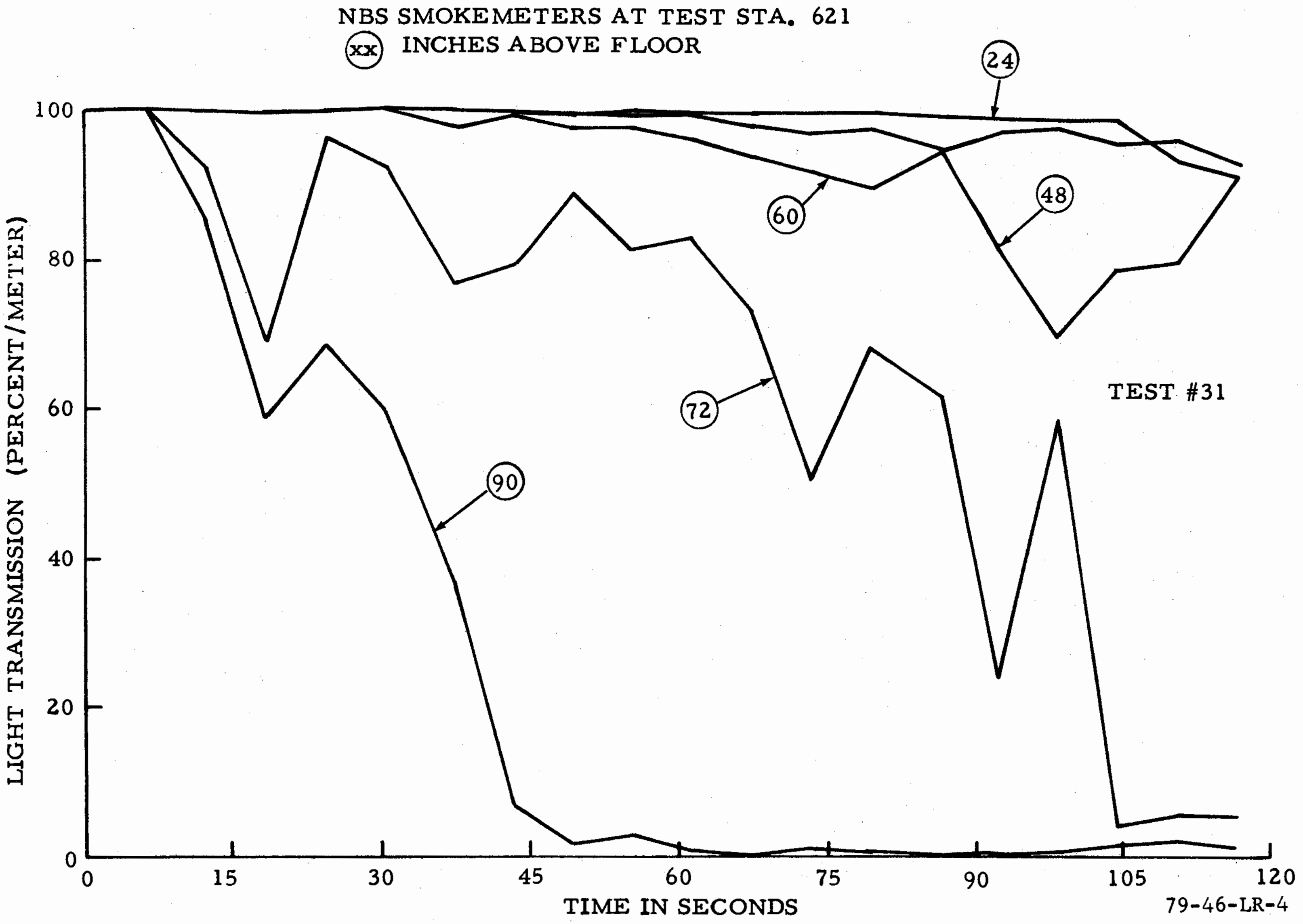

FIGURE 9. LIGHT TRANSMISSION (SMOKEMETER) PROFILE FOR "MEDIUM SMOKE" ACCUMULATION AT STATION 621

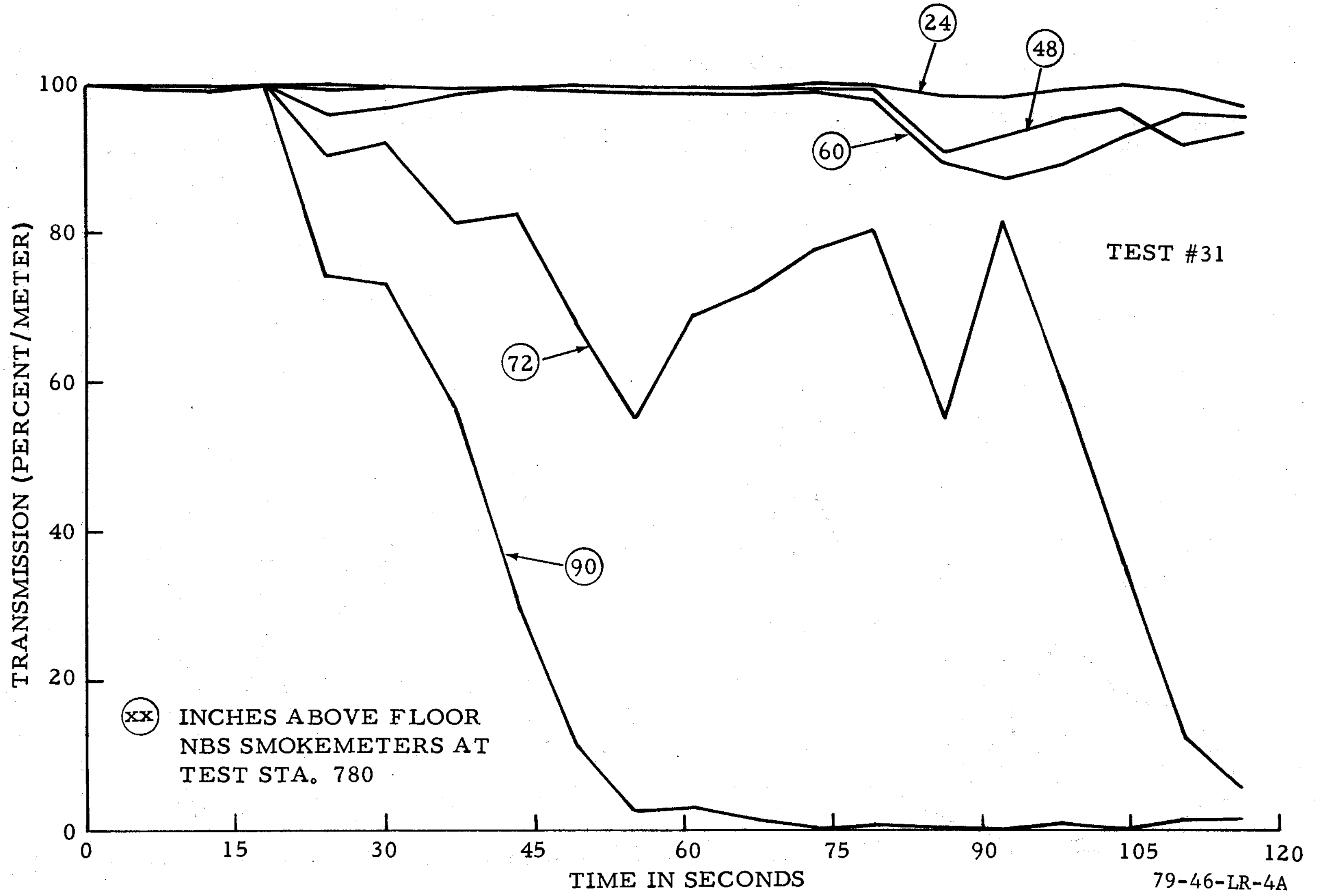

FIGURE 10. LIGHT TRANSMISSION (SMOKEMETER) PROFILE FOR "MEDIUM SMOKE" ACCUMULATION AT STATION 780

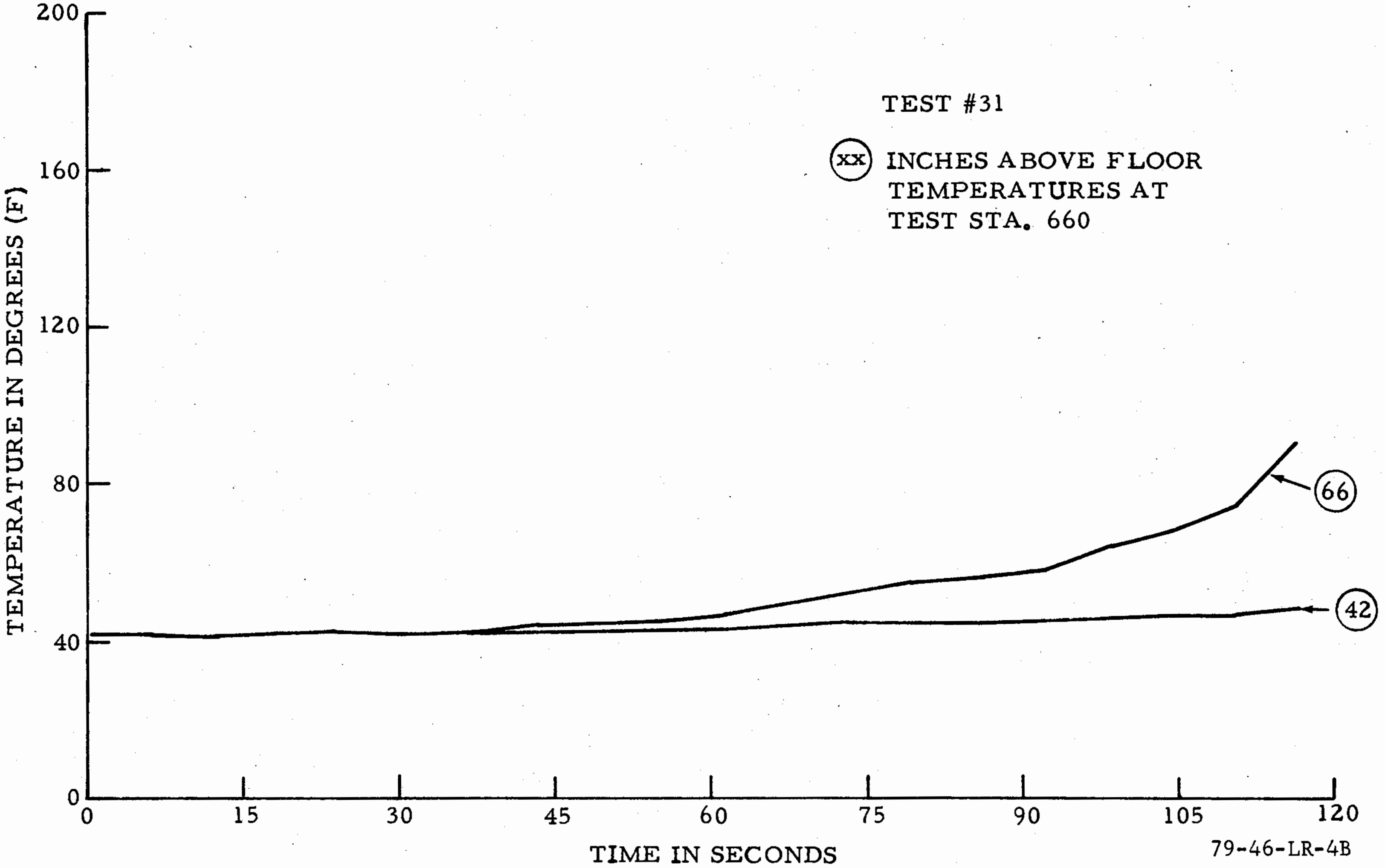

FIGURE 11. TEMPERATURE PROFILE FOR "MEDIUM SMOKE" ACCUMULATION AT STATION 660

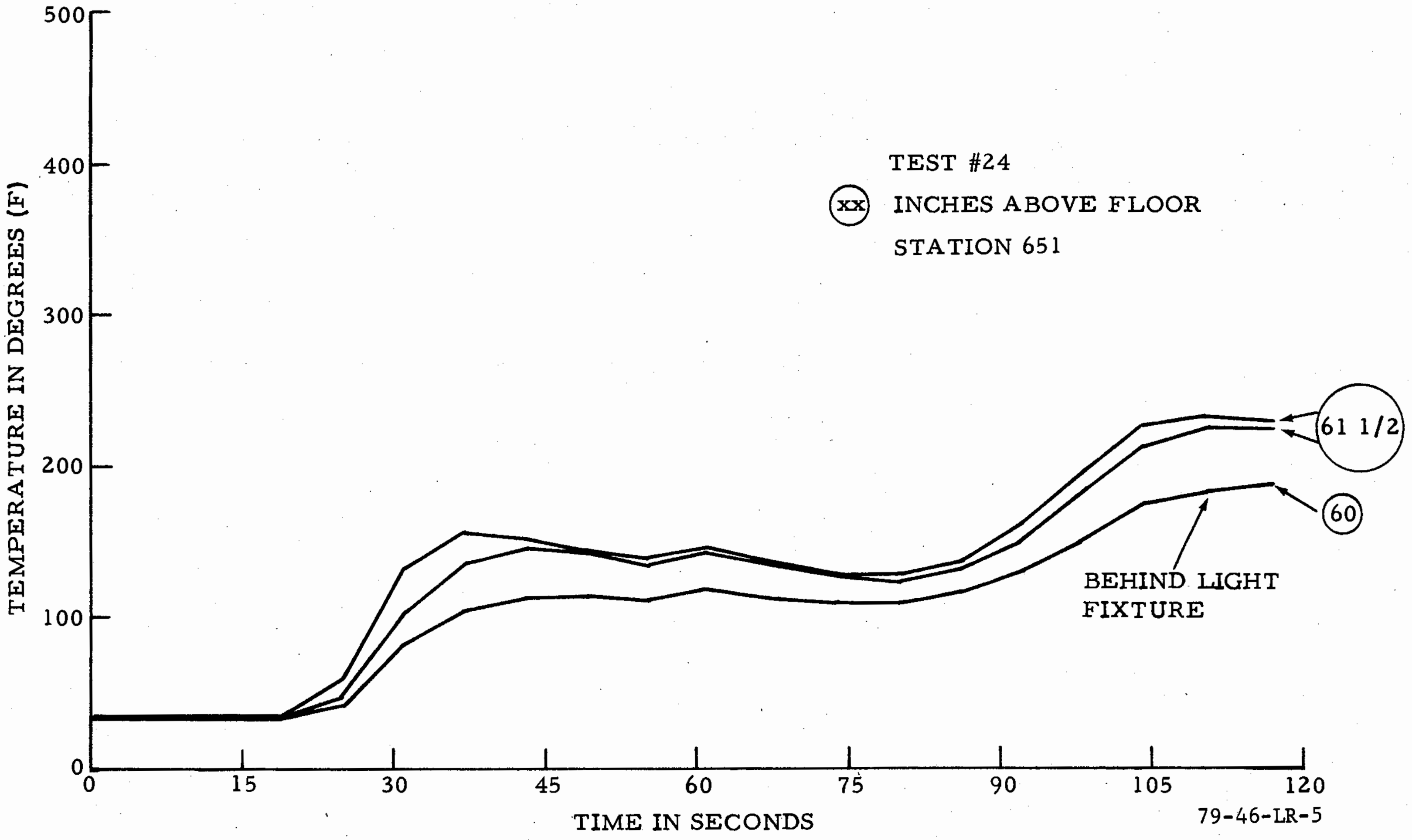

FIGURE 12. TEMPERATURE PROFILE DURING "MEDIUM SMOKE" "DENSE SMOKE" ACCUMULATION AT STATION 651

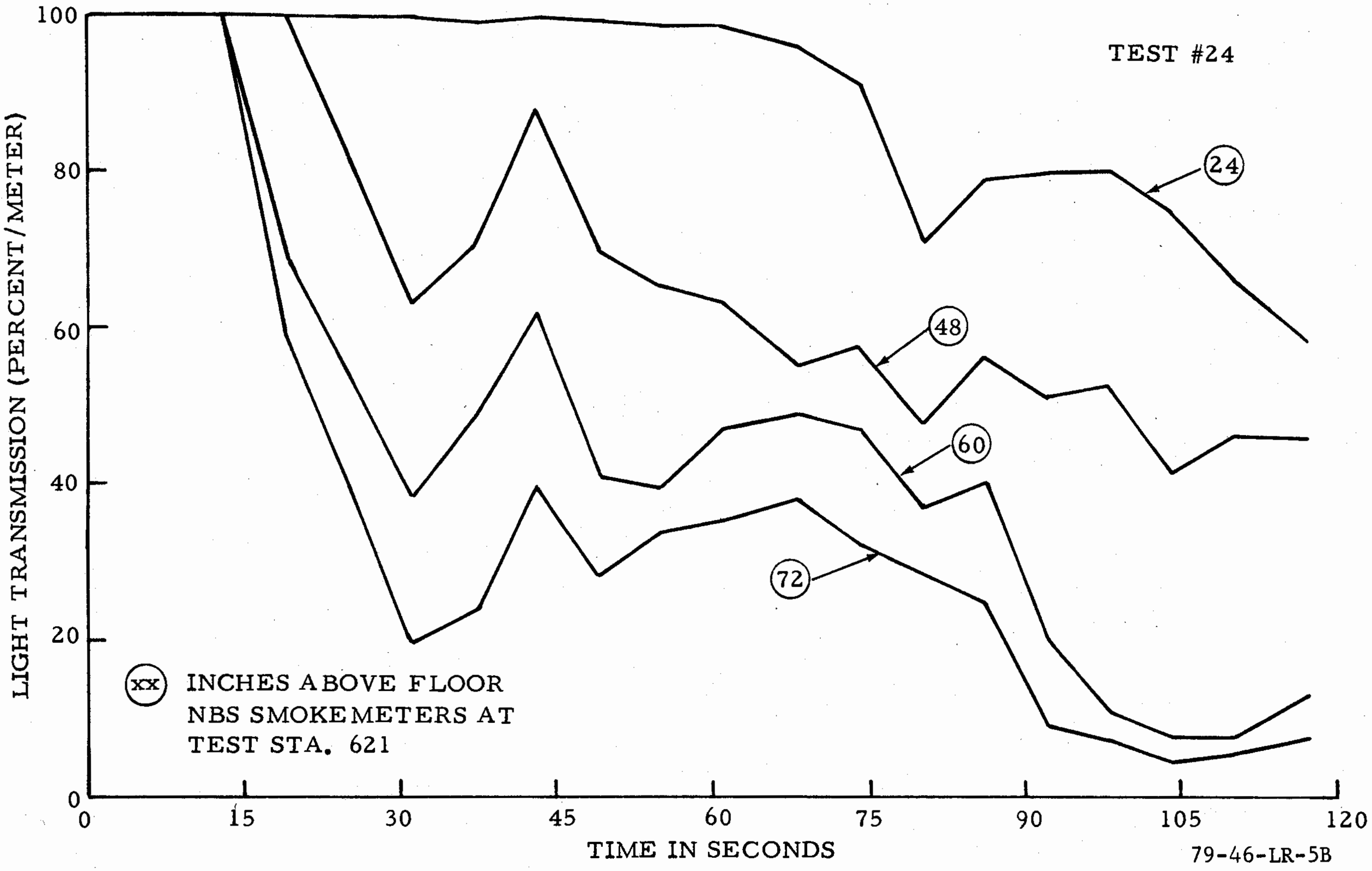

FIGURE 13. LIGHT TRANSMISSION (SMOKEMETER) PROFILE FOR "DENSE SMOKE" ACCUMULATION AT STATION 621

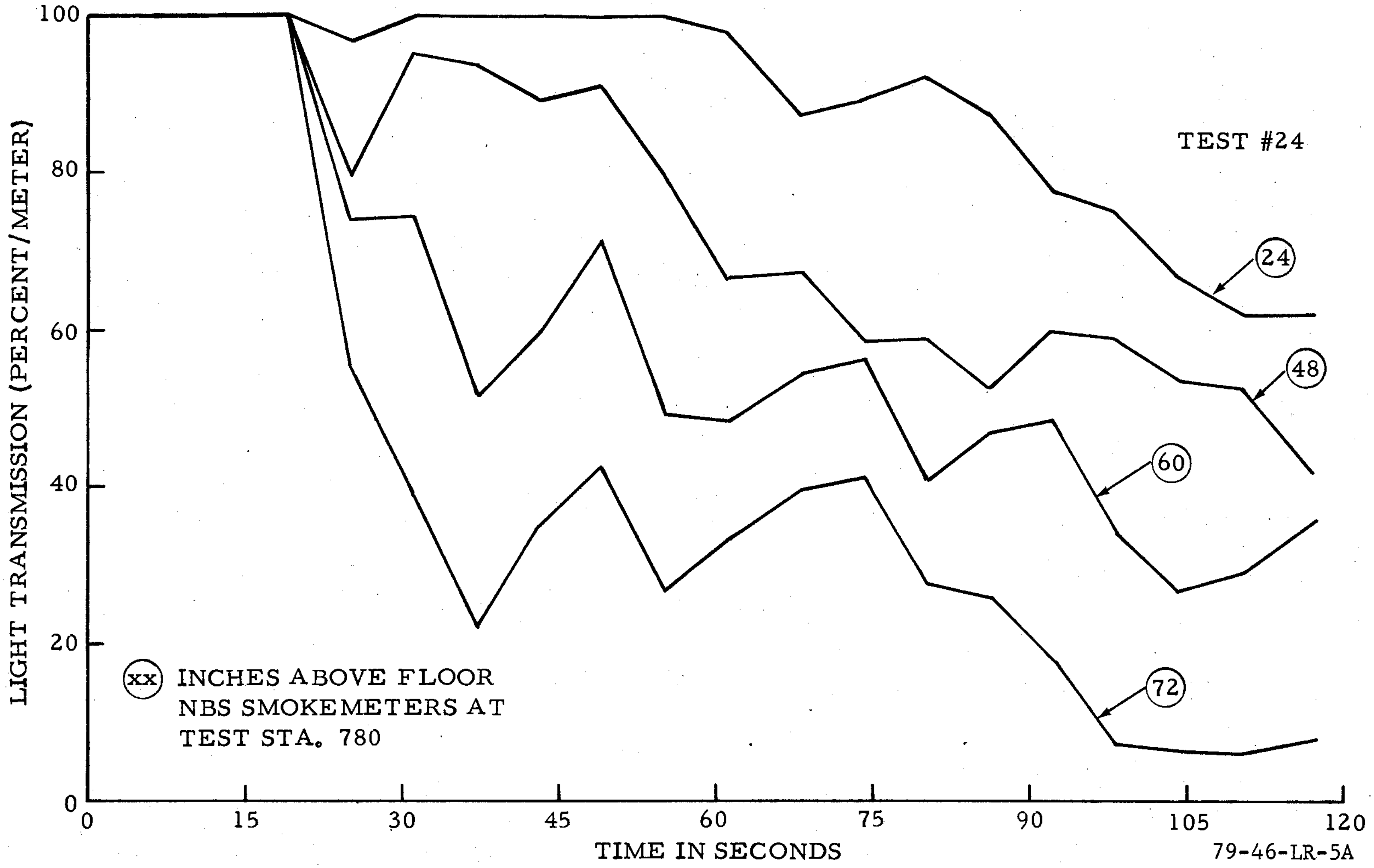

FIGURE 14. LIGHT TRANSMISSION (SMOKEMETER) PROFILE FOR "DENSE SMOKE" ACCUMULATION AT STATION 780

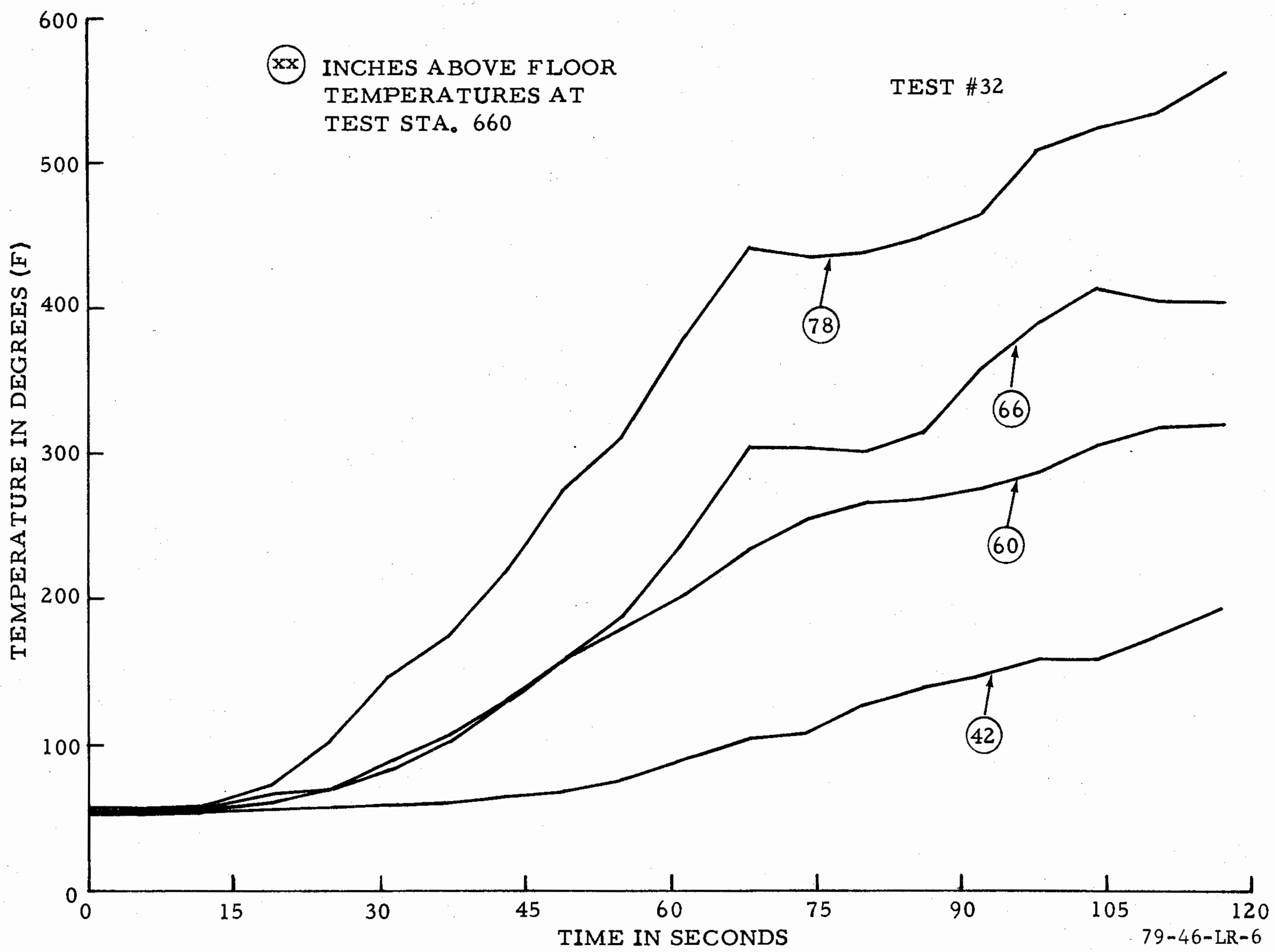

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FIGURE 15. TEMPERATURE PROFILE DURING "VERY DENSE SMOKE" ACCUMULATION AT STATION 660

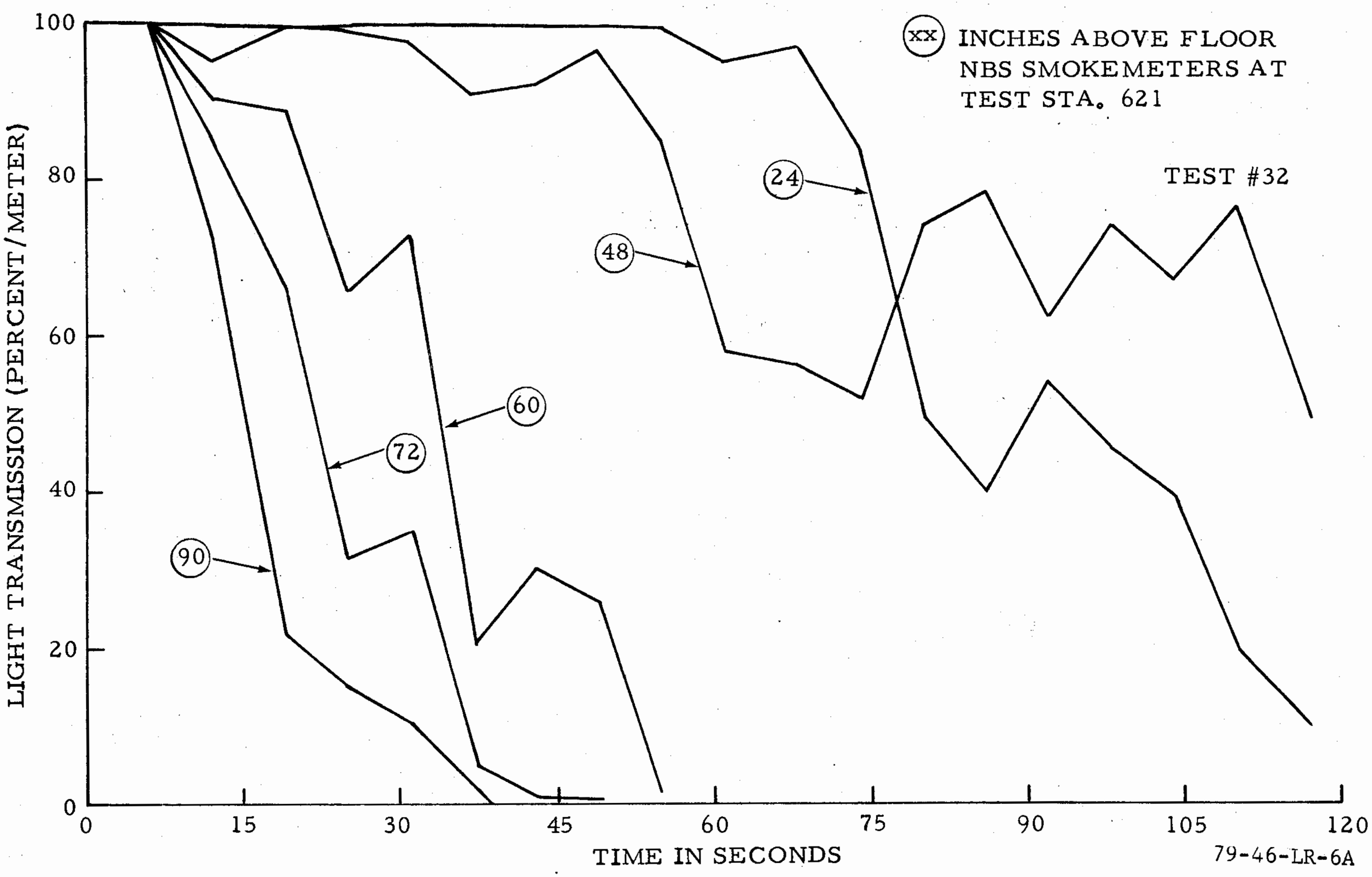

FIGURE 16. LIGHT TRANSMISSION (SMOKEMETER) PROFILE FOR "VERY DENSE SMOKE" ACCUMULATION AT STATION 621

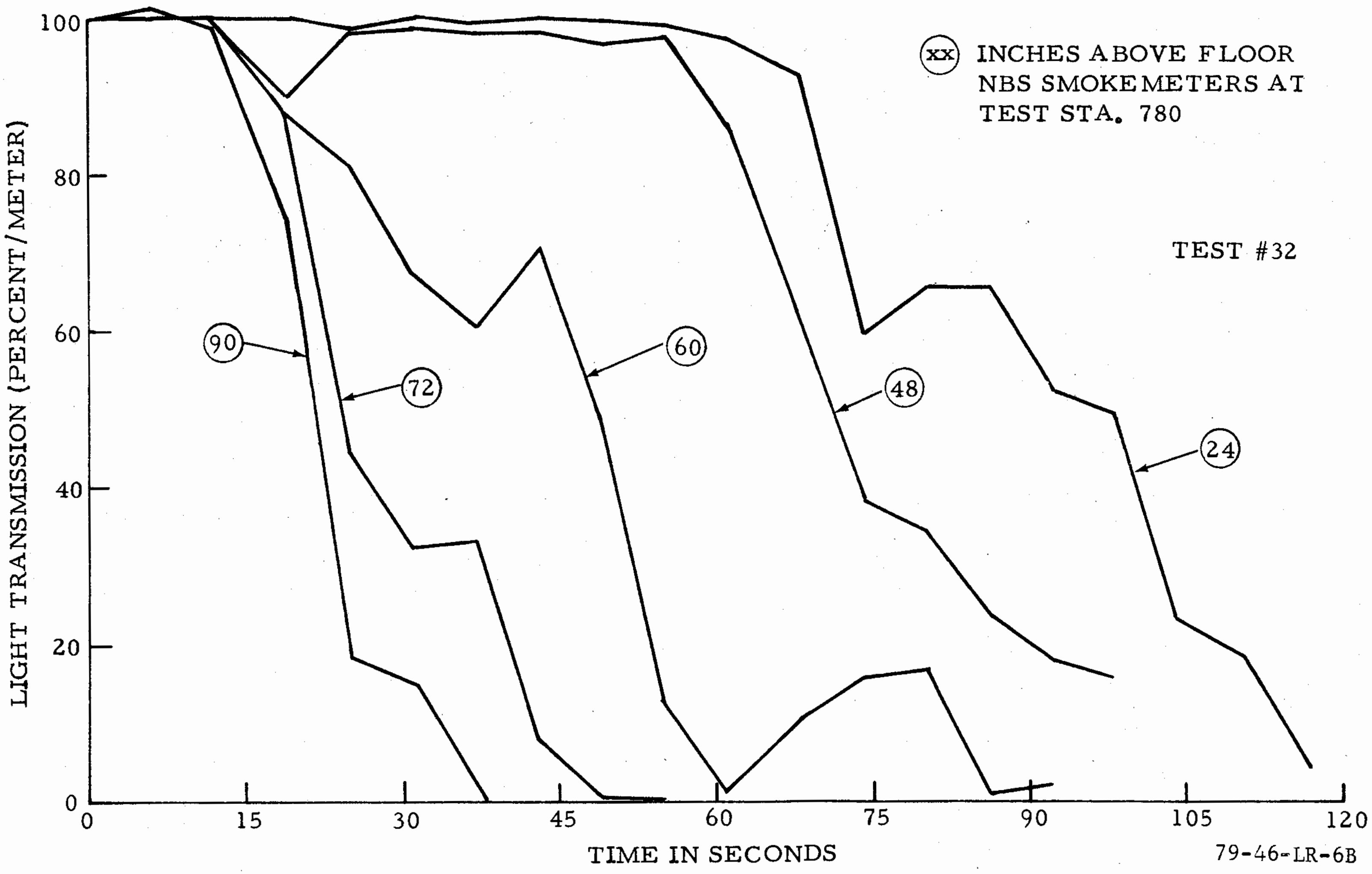

FIGURE 17. LIGHT TRANSMISSION (SMOKEMETER) PROFILE FOR "VERY DENSE SMOKE" ACCUMULATION AT STATION 780

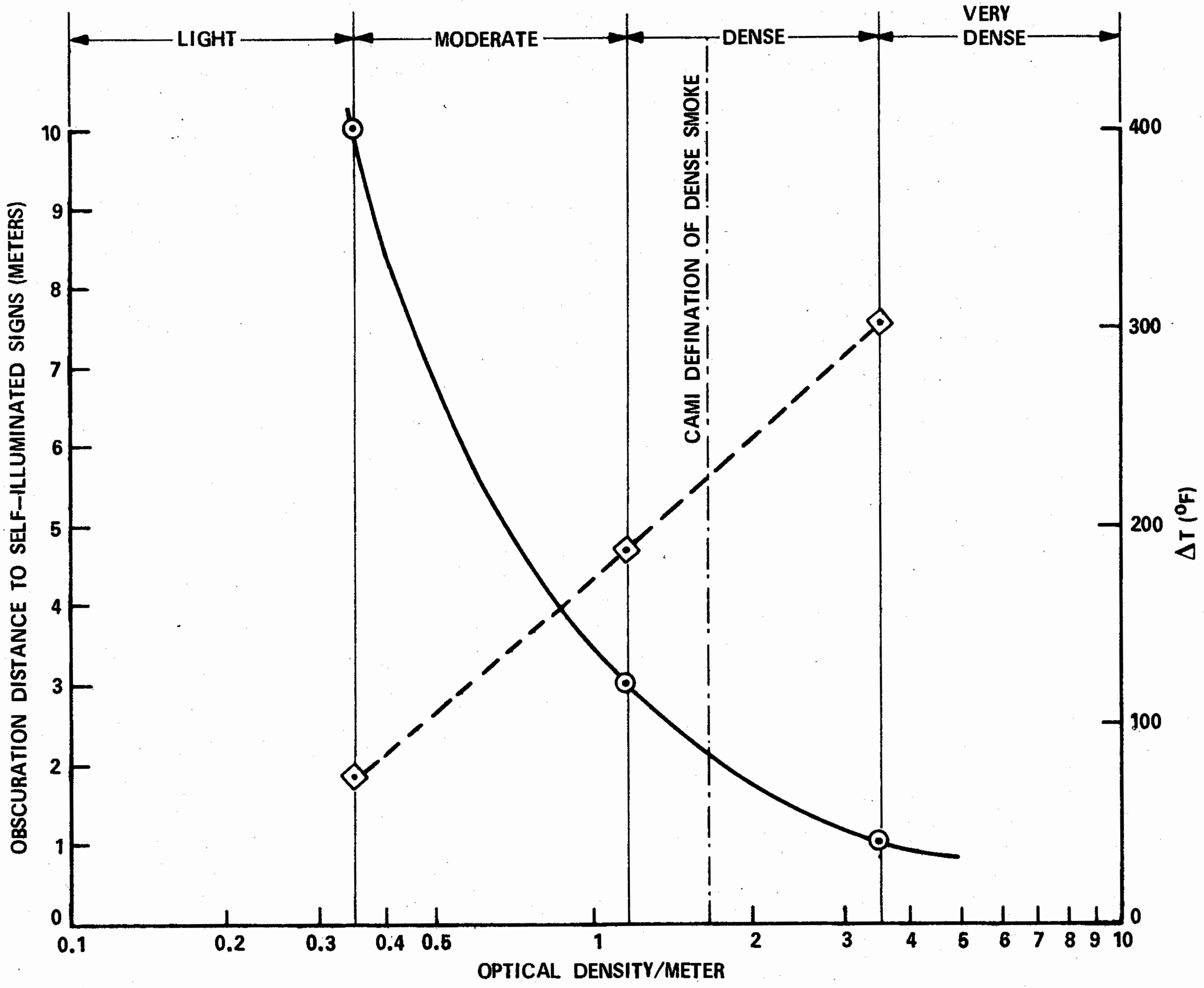

FIGURE 18. SMOKE-OPTICAL DENSITY CLASSIFICATION

particulators. In order to compare test results and methods at different installations, there would be some merit to generating some regimes of smoke covering the continum from light to very dense smoke. Such a definition would, by necessity, be environment oriented in that the distance to locators or doors controls the amount of smoke that can be tolerated from a visual standpoint. For instance, a very dense smoke would prohibit a car passenger from seeing the automobile door while a comparatively less dense smoke would obscure a bus door from a passenger some distance away. For visibility of light-emitting signs, Jin (reference 10) gives the following relationship:

$$C_f \times V = 8.0 \tag{9}$$

where C_f is an extinction coefficient with units of inverse meters and V is the obscurity threshold in meters. If one were to use optical density per meter (Dim) instead of C_f, one would get

$$D_{im} \times V = 3.5 \tag{10}$$

Now, this sort of relationship would be changed for non-illuminated signs or if irritating effects to the eyes were included. Nevertheless, the relationship above is consistent with the other visibility data of this report which were taken through a viewing window from outside the smoke filled cabin.

To apply the visibility relationship to the aircraft problem, one has to specify some significant distances. One might say that 10 meters is a significant type number for cabin length, 3 meters is related to cabin width and 1 meter would be related to an arm's length in front of a person's eyes.

If smoke were accumulating in a cabin, Jin's visibility relationship would say that once the optical density reached 0.35, the viewer would lose sight of a self-illuminated light at a 10-meter distance. Thus, smoke with an optical density less than 0.35 will be called light smoke. As the smoke continued to accumulate, and the optical density got to 1.17, the viewer could no longer see a sign at a distance of 3 meters. Thus, between optical densities per meter of 0.35 and 1.17 there is a regime defined as medium or moderate density smoke. As smoke accumulates beyond the 1.17 density number, a dense smoke regime is defined up to the point where the viewer can no longer see a sign at 1-meter distance. This upper bound corresponds to an optical density per meter of 3.5, and any smoke denser than this will be referred to as very dense smoke. In figure 18, the relationship regimes are identified. Also, identified in figure 18 is the CAMI definition of dense smoke based on evacuation trials. This value falls within the dense smoke regime defined in Jin's data. For categorizations of smoke from varying type fire sources in a test program, one must treat smoke density as a continum so that all test can be included. Nevertheless, in trials of human subjects, only one value of dense smoke can be used so that the evacuation test will be statistically significant.

Also plotted in figure 18 is the relationship between temperature increase and optical density per meter as derived earlier from the full-scale test data. For a given optical density, one can use the temperature correlation curve to find the corresponding temperature increase associated with this smoke density or use the visibility correlation to find the distance at which a self-illuminated sign is barely visible through smoke of a given optical density. Note that the temperature/optical density correlation was taken for the upper zone as described earlier in the discussion of the zonal variation of optical density.

CABIN EMERGENCY ILLUMINATION.

Two photometers with remote probes equipped with cosine receptors were used to determine the decay of illumination in the cabin area at the armrest height (FAR 25.812(c)) due to smoke from an external fuel fire. The emergency interior cabin illumination was initially adjusted to provide 0.07 foot-candle height (the minimum value of 0.05 foot-candle was not attainable). During the light smoke conditions produced in test 28 (figure 19), the armrest illumination increased from 0.07 foot-candle to greater than 1.2 foot-candles, approximately 30 seconds after the external fuel fire was ignited. The increase in illumination was a result of light emitted by the fuel-fire flames penetrating the cabin environment. Although light transmission near the ceiling was eventually reduced to less than 40 percent, the fire provided illumination greater than the required 0.05 foot-candle at the armrest height, apparently, the smoke layer was not deep enough to obscure the flames from the external fuel fire.

Figure 20 contains data recorded during a much smokier test (test 72) where visual observations indicated "a very black smoke condition" at 52 seconds after the fuel fire was ignited and zero visibility at the 60-inch level at 120 seconds. Because it was closer to the fire, the forward photometer measured higher cabin illumination than the aft photometer. During this test the smoke in the cabin area became dense enough to obscure the external fuel-fire flames, and the photometers readings decreased steadily to zero. Thus, during a survivable postcrash external fuel fire, emergency interior cabin lighting may be overpowered by the illumination emitted from the flames, but eventually illumination from the fire will be blocked out by smoke accumulation.

EXIT SIGN LOCATION/BRIGHTNESS.

Five identical lights were used to evaluate the effectiveness of increased brightness and the importance of vertical height location in a cabin smoke environment. To examine the effectiveness of brightness, three lights were positioned in a horizontal plane with the centerline of the lamps 61 1/2 inches above the cabin floor (figure 3). To examine the effectiveness of changing the vertical location of illumination sources, three lights were positioned 78 inches, 61 1/2 inches (one of the horizontal lights) and 38 inches above the cabin floor. Each light was enclosed in a metal box with a 1/4-inch thick Pyrex™ window for protection against heat and smoke (figure 21). This array of lights was located directly across from the forward observation booth, which also had a 24 by 60 by 1/4 inch Pyrex viewing window. Three spotmeters with a 1/2° viewing angle were located in the booth and provided a 5-meter viewing distance to the lights. This distance complies with FAR 25.811(b), which states that the "signs (emergency exit) must be recognizable from a distance equal to the width of the cabin." Spotmeter measurements from the booth indicated an 18.1 percent light reduction through the Pyrex windows in both the metal boxes and viewing window. This fact did not affect comparison of test data, since all the tests were conducted under the same viewing conditions and the glass was cleaned on both sides prior to each test. The data were not corrected for this reduction in light transmission.

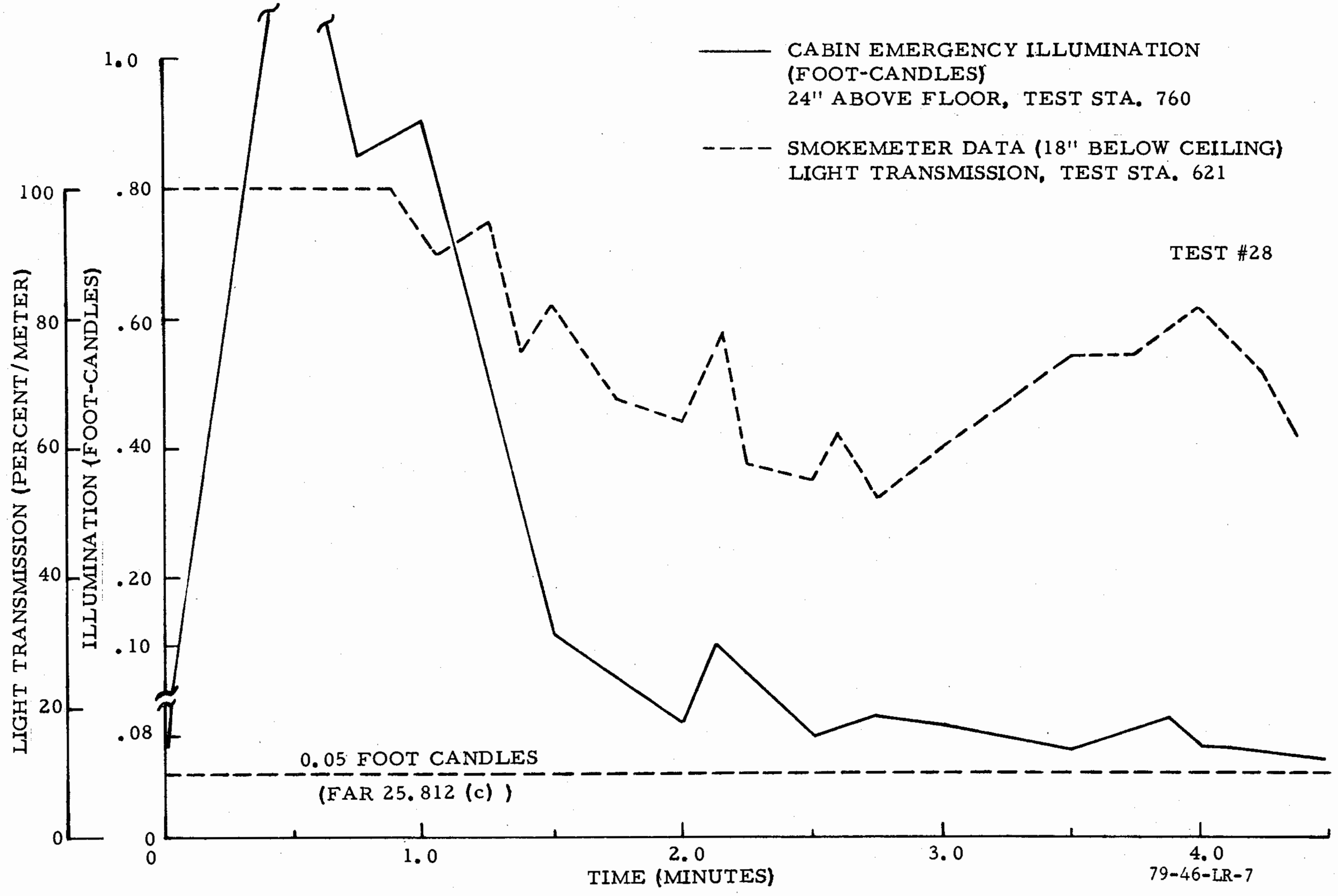

FIGURE 19. EFFECTS OF FIRE/SMOKE ON CABIN EMERGENCY ILLUMINATION, TEST 28

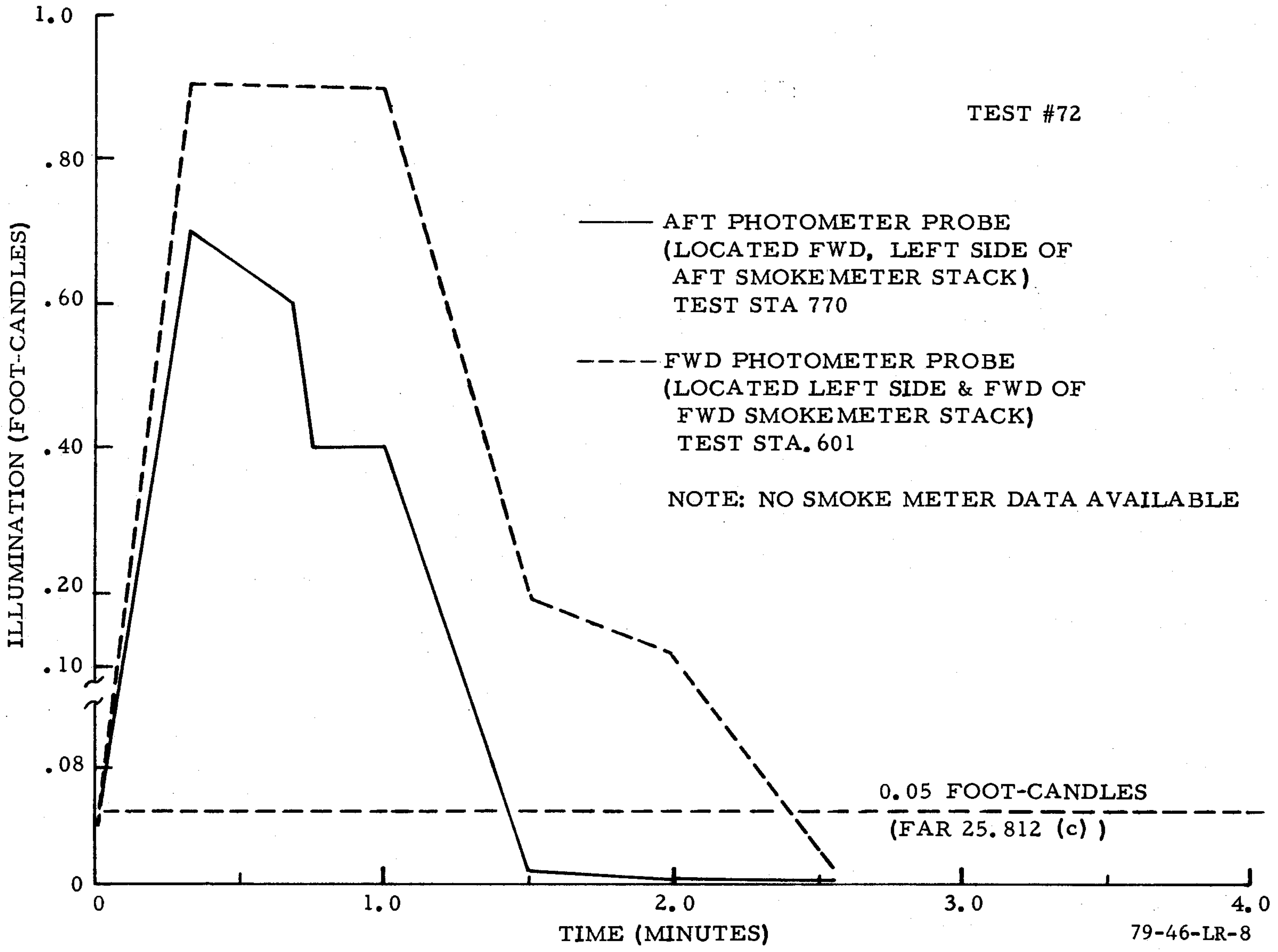

FIGURE 20. EFFECTS OF FIRE/SMOKE ON CABIN EMERGENCY ILLUMINATION, TEST 72

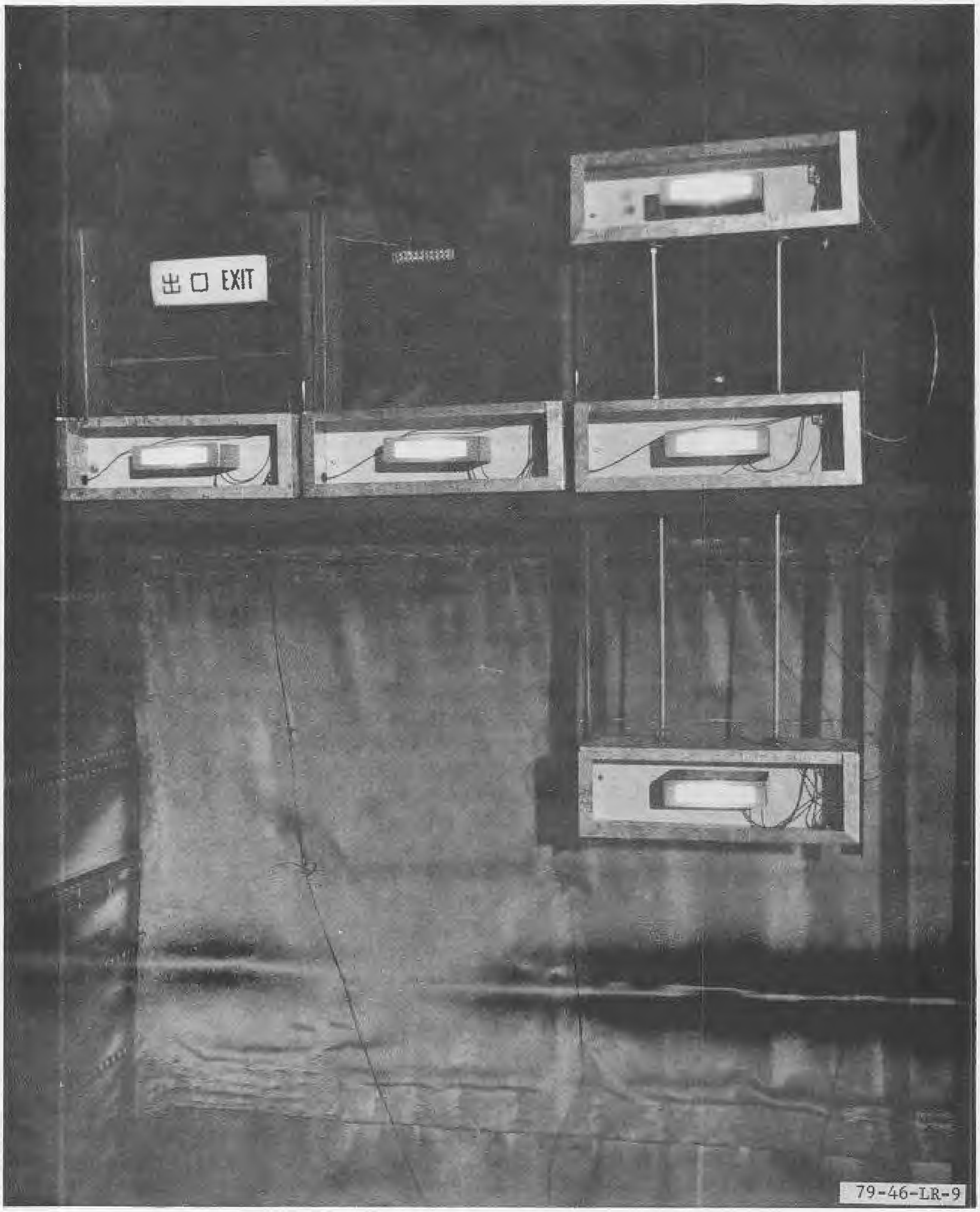

FIGURE 21. HORIZONTAL AND VERTICAL LIGHT CONFIGURATION

EFFECT OF BRIGHTNESS.

To determine the effect of brightness, the three horizontal lights were adjusted to provide illumination values of 25, 50, and 75 foot-lamberts (figure 22). These values were selected to provide a factor of 2 and 3 times the illumination value specified in FAR 25.812 (i) for emergency exit sign(s). The three spotmeters located in the forward observation booth were focused on the lights, and the viewing angle of the spotmeters provided identical viewing areas for each of the lights. The viewing height of each spotmeter was 61 1/2 inches above the cabin floor (average value of centerline height of passengers eyes while standing).

During test 46, the smoke conditions within the cabin were dense. Figure 22 indicates that the bright lights (50- and 75 foot-lamberts) provided illumination values higher than the required 25 foot-lamberts for only a short period of time beyond that provided by a "standard" light of 25 foot-lamberts — approximately 10 and 15 seconds, respectively. The data indicates that the different luminance values all reach a minimum value at approximately the same time. The smokemeter data recorded at the same elevation as the spotmeters exhibited the same behavior as the spotmeter data. Thus, heavy smoke accumulations can, and did, mask out any major benefits from increased brightness.

EFFECT OF VERTICAL LOCATION.

The three vertical lights were adjusted as closely as possible to the same luminance. The three spotmeters were focused on the three lights, with the spotmeter viewing height fixed at 61 1/2 inches, as in the horizontal tests. Figure 23 presents data from test 66, which produced dense smoke conditions in the cabin area and indicate that lowering the lights will extend the time the lights provide passenger awareness information in contrast to previously described tests. Light transmissions data for this test were obtained from smoke meters developed and built at the Technical Center. These meters incorporated a light beam projected over a 1-foot distance onto a photosensitive device to measure light transmission, (reference 7). The data were converted to optical density per meter to keep values consistant throughout the report. The data indicates that lowering the light from the 78-inch level to the 61-1/2 inch level would only extend the time to attain total obscuration by 15 seconds, but if the light source were lowered from the 78-inch level to the 38-inch level, the time required to attain total obscuration would be extended approximately 45 seconds. The smoke optical density data in figure 23 indicate that the 78-inch and possibly the 61-1/2 inch light sources become covered by the layer of smoke near the ceiling; however, the lower light source (38 inches) would have remained visible if viewed from a height closer to its elevation. Thus, lights located closer to the floor would be highly beneficial to crouched individuals during evacuation of a smoke filled cabin. Figure 24 pictorially shows the value of locating lights below the 61 1/2-inch level used extensively for measurements in the study. Under the smoke conditions studied in the C-133, it is very difficult for the eye to receive any information from a sign or light located in the ceiling or above the door at the 78-inch level. A horizontal path of vision at the 61 1/2-inch level passes through less smoke, but the lower levels present the best location, since now the "eye" is only looking through the "corners" of the more dense smoke levels. During the evacuation stuides at CAMI (reference 4) lights and signs located in a normal configuration were of little or no value to evacuating passengers when the cabin was filled with smoke. A stooped position, looking down almost at the heels of the preceding passenger,

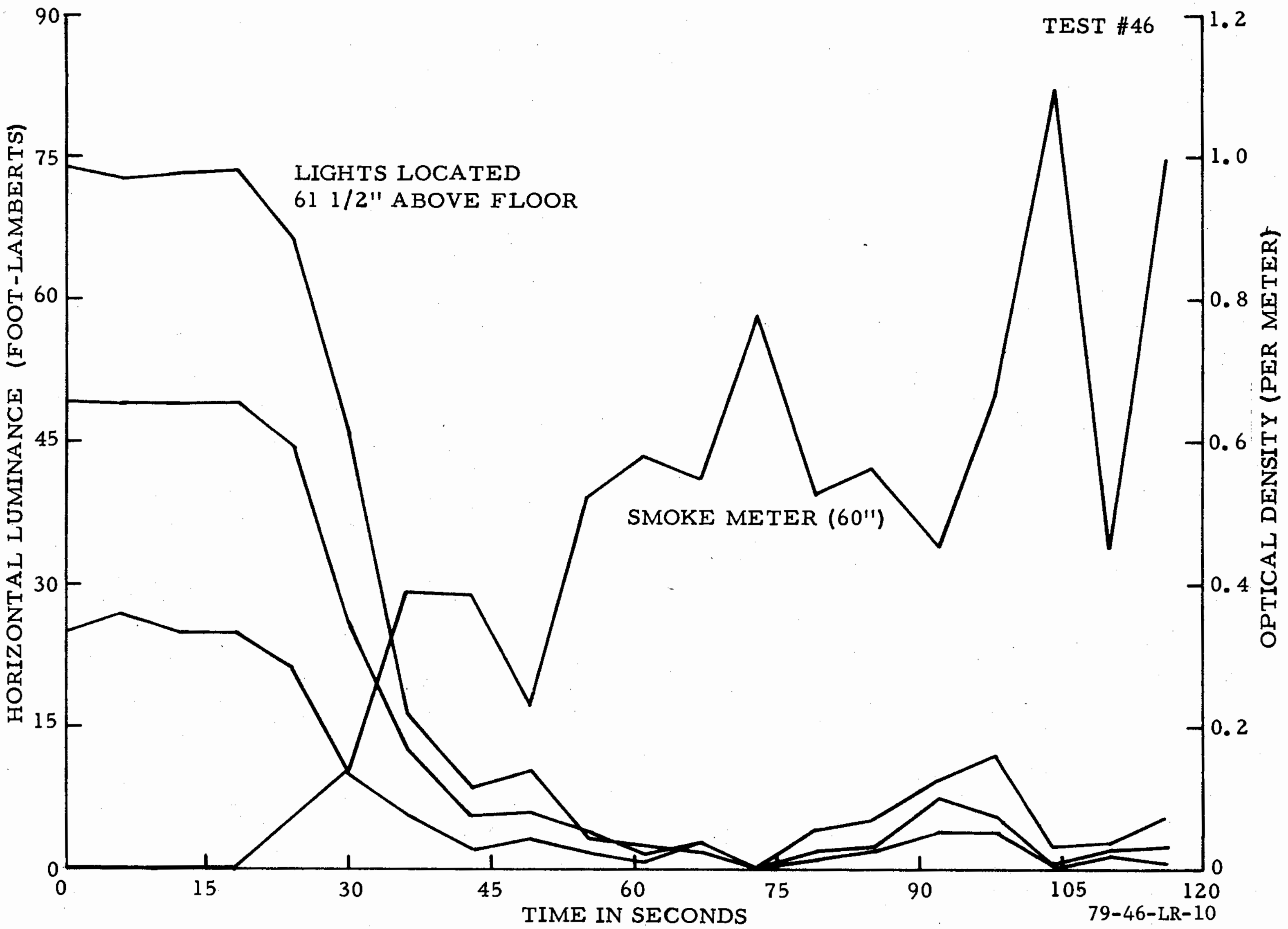

FIGURE 22. HORIZONTAL ILLUMINATION PROFILE VERSUS OPTICAL DENSITY

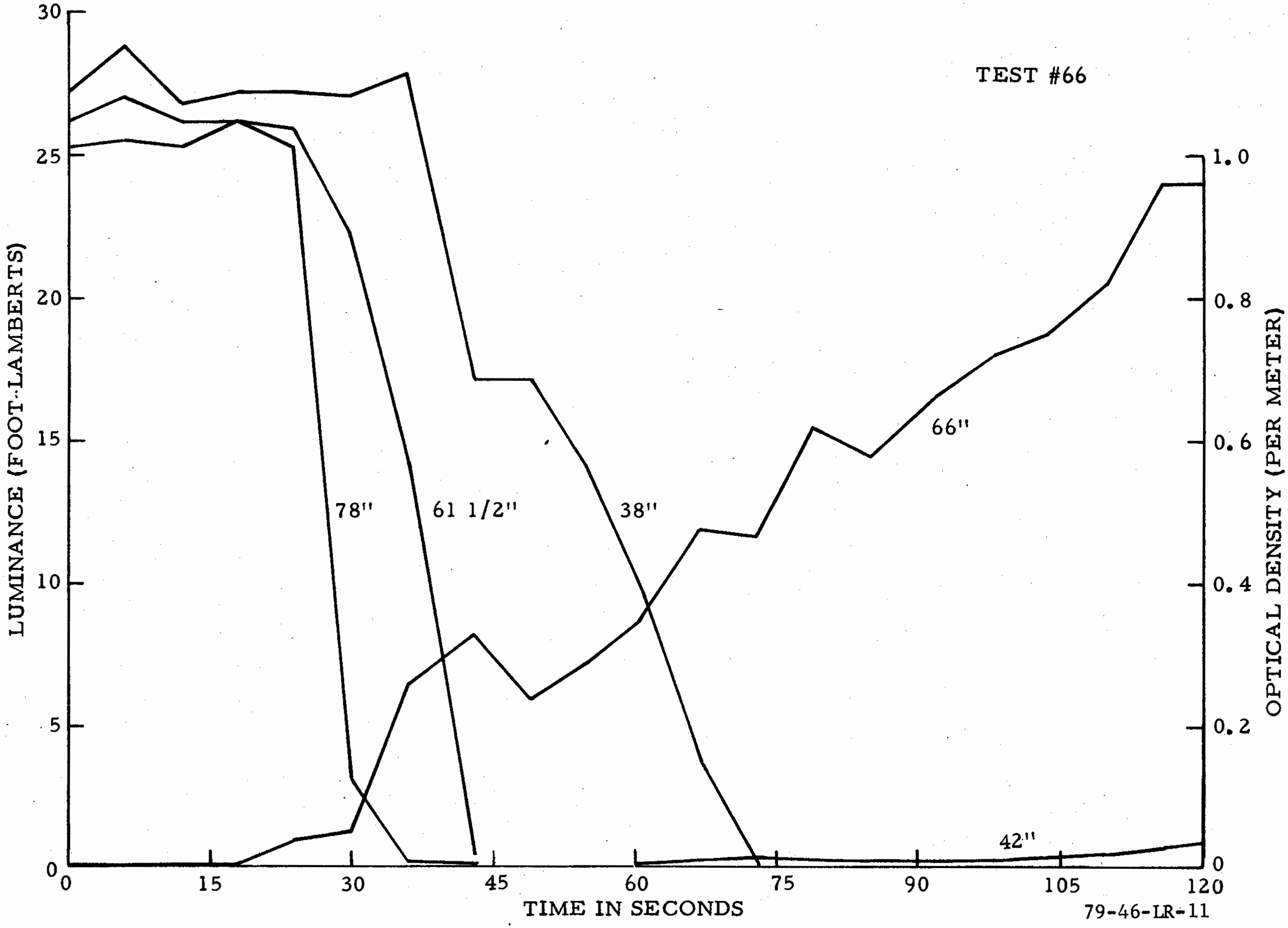

FIGURE 23. VERTICAL LIGHT ILLUMINATION PROFILE VERSUS OPTICAL DENSITY

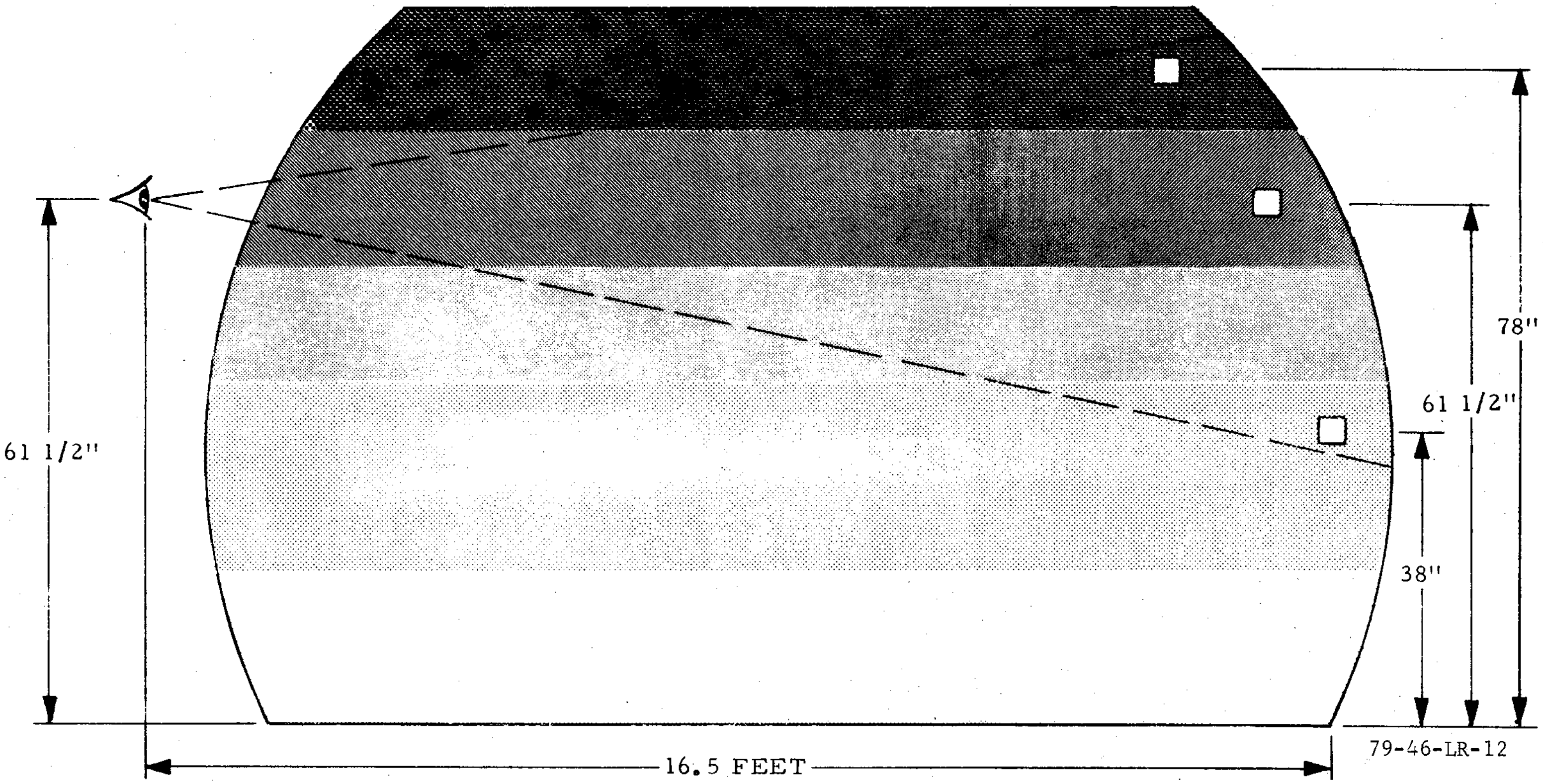

FIGURE 24. SMOKE LAYERING VERSUS "EYE LEVEL" OBSERVATION

was a common escape behavior among the subjects. Armrest lights or light sources located nearer the floor were most beneficial and were instrumental in decreasing the evacuation time.

EFFECT OF SMOKE FROM BURNING INTERIOR MATERIALS ON EMERGENCY LIGHTING.

The forward portion of the C-133 aircraft was fitted with wide-body ceiling panels, side panels, luggage bins, seats and carpet to conduct tests where the interior materials become involved in postcrash fire.

Interior materials became thermally involved within 10 seconds after the fuel fire was ignited. Visual observation indicated traces of smoke along the ceiling at station 780 within 40 seconds. The 78 inch light became partially obscured at 68 seconds and totally obscured at 83 seconds. The decay of illumination values shown in figure 25 indicate that lights at the 61 1/2-inch and 38-inch location will extend passenger awareness time approximately 18 and 29 seconds, respectively.

A millicandela probe with a cosine receptor was located inside the viewing booth, 24 inches above the floor and against the viewing window. This last minute decision to use the millicandela probe did not allow installation as per previous tests. The cosine receptor was parallel to the floor and a general cabin illumination value of 0.014 foot-candles was recorded. This value decreased to zero at 104 seconds after the fire was initiated. There was no initial increase in illumination level in the aft cabin as observed in previous tests without materials. This is due to the installation of a galley island at station 548 for this series of tests. This galley island was 8 feet high 6 feet wide and 4 feet deep, with aisles on each side of the cabin. The blackened interior, from previous tests, also decreased the amount of fire brightness in the aft cabin.

Finally, the presence of seats would decrease the amount of light passing through the lower levels of the cabin.

Light reduction versus temperature increase is plotted in figure 4 from data collected during the test with interior materials (test No. 34) described earlier in this section. These several data points indicate that the relationship between cabin smoke and heat appear to be comparable for exterior fuel-fires and interior materials fires.

EMERGENCY EXIT SIGNS (INSTRUMENTATION AND TEST EQUIPMENT)

The failure of an exit awareness sign, due to elevated thermal conditions during the test program, brought about the need to conduct a modest in-house study of other wide-body exit signs, as listed in table 3.

To evaluate the behavior of wide-body exit signs at elevated air temperatures, an electric oven was utilized to provide a controlled thermal environment. A suitable stand was fabricated for each sign and the holes designed for aircraft mounting were utilized for securing the light to the stand.

Two 28 AWG Chromel/Alumel thermocouples were installed in the interior of each sign except the Symbolic Display sign. The construction of this sign would not permit installation of an internal thermocouple. Two 28 AWG Chromel/Alumel thermocouples

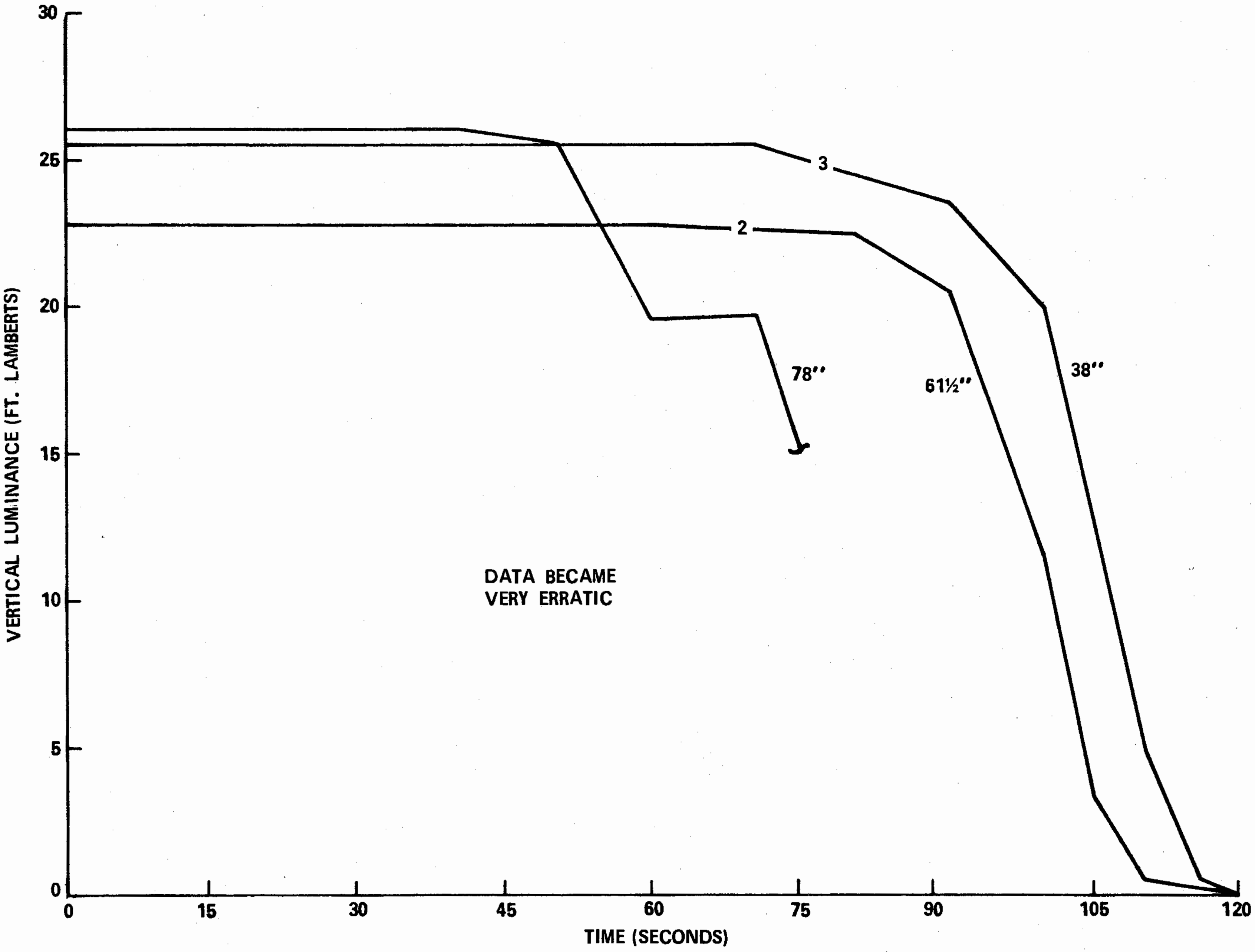

FIGURE 25. VERTICAL LUMINANCE PROFILE

TABLE 3. WIDE-BODY EXIT SIGNS

Manufacturer: Midland Ross-Grimes Division

Part Number: 10-0705-1 and 10-0705-13

Use: Over Exit Door-Threshold Illumination

Aircraft: Command Post B-747

Description: 2-"Hard Wired" Lamps for Threshold Illumination 12-Minature Lamps for "Exit" Illumination

Test Number: 2 and 3

Manufacturer: Symbolic Displays

Part Number: 700311-1 Serial Number 074

Use: Over Exit Door

Aircraft: Boeing 747

Description: 7PR. Minature Lamps for "Exit" Illumination-(7 Reg. and 7 Emerg.)

Test Number: 2

Manufacturer: Luminator

Part Number: Unknown (A) Test Purpose Only

Use: Over Aisle: Exit Locator

Aircraft: Douglas DC-10

Description: 6 Lamps for "Exit" Illumination
1 Lamp for Threshold Illumination

Test Number: 1

Manufacturer: Luminator

Part Number: L20482 Serial Number 788621 Test Purpose Only

Use: Exit Identification

Aircraft: Douglas DC-10

Description: 3 Lamps for Exit Illumination

Test Number: 1

Manufacturer: Midland Ross-Grimes Division

Part Number: 10-0482-3

Use: Exit Identification

Aircraft: Lockheed L1011

Description: 8 Lamps for "Exit" Illumination
4-Normal — 4Emergency Use

Test Number: 1

were installed in the test oven to measure the oven temperature. These theromocouples were connected to an Esterline Angus 2020 digital recorder and the temperature data was recorded at 20-second intervals throughout the test. The electric oven (HEAVY DUTY, FA-10333) used for these tests has internal dimensions of 13-inches wide, 13-inches high, and 29 1/2-inches deep. The oven door was replaced with a Pyrex window, allowing observation and photographic coverage during the test. Prior to subjecting the signs to the elevated temperature environment, the oven was calibrated and various time/temperature data were generated. The determination was made to raise the oven temperature from ambient to 350° F in 20° F increments. This upper limit is the temperature for human collapse in approximately three minutes (reference 9). The oven was equipped with an automatic controller which was utilized to raise the oven temperature. Using this procedure, approximately 20 minutes was required to raise the oven temperature from ambient to 350° F. Due to the limited volume of the oven chamber, it was necessary to perform 3 tests to examine the six types of signs. The manufacturers recommended rated voltage was provided to the direct current (d.c.) power supply and this was visually monitored with a d.c. voltmeter. Three of the four signs remained illuminated through the test. The fourth sign lost only partial illumination due to lamp contact failure very near the upper temperature limit. Although the plastic covers failed and/or distorted, the ability of the lamps or bulbs to remain lighted was not affected. A complete description of the exit signs and test results is contained in reference 3.

NEW LIGHTING SYSTEMS

Three new or prototype systems were evaluated during the initial phase of the test program: the Plumly™ armrest light, the sequence flashing light system, and the electroluminescent or Capsul light system. Betalight, self-powered illumination markers for aisle identification, was evaluated during tests conducted in the final phase of the test program. The armrest light was designed to be installed in the aisle-side armrest of the passenger seat. (Tests conducted at CAMI (reference 4) indicated that armrest lights, alternating each row on the right and left side of the aisle, provided more than adequate illumination for evacuating passengers from a smoke filled cabin.) The light tested provided an exit direction arrow as well as illumination of the floor directly below it (the aisle area). There was no attempt to measure the illuminance of the light during a test, and the evaluation consisted of observer comments during the tests which indicated the light/sign provided more passenger awareness information than conventional systems. Since the height of the light was 2 feet above the cabin floor, the smoke/light transmission data at the 2-foot level gave an indication of the extended use of this light to provide passenger exit information as well as additional illumination to the floor level. Examination of data from the initial 2-minute period of 45 tests indicated there was very little or no smoke accumulation at the 2-foot level during 35 tests. Light obscuration of 50 percent or less occurred during 10 tests, and total light obscuration occurred during five tests.

The sequence flashing light system was designed to orient an evacuating passenger to a specific direction and was installed on the floor of the aft cabin, extending from the aft observation booth window to the right rear exit door. The short flash duration prevented the measurement of the illumination output of the lights during the test. On the basis of video and motion picture coverage and voice recorded descriptions by observers in the booth, this lighting system provided passenger awareness throughout the most severe smoke environment. Only when the visibility in the cabin reached zero near the floor was this awareness lost, and then, by stooping, the time for usefulness was extended, making it apparent that a passenger would still be oriented to a direction of escape.

The electroluminescent or Capsul light system was designed to be secured to the cabin floor, out lining the aisle and the cross-aisle leading to an exit. This lighting system (a supplement to the main emergency lighting) provided passenger awareness of the aisle configuration. This floor-mounted system continued to provide information throughout the duration of most tests when set at a constant illumination level. Attempts to sequence the long lighting segments of the system proved to be confusing to an observer. As with the sequencing light system, it was only at the point of almost total obscuration near the floor that the Capsul light system ceased to provide evacuation information. Again, this time would be extended when an individual stooped over or dropped to a crawling position. It should be noted that these floor-mounted systems were tested in a bare fuselage interior. The Betalight self-powered illumination markers were utilized to outline a portion of the aisle/cross-aisle area in the aft cabin. Figure 2 shows the outlining effect in partial darkness (0.05-0.10 foot lamberts). As viewed from a standing height, test 33 was used to evaluate the selfpowered illumination markers. Data shown in figures 25 and 26 indicated approximately 68 seconds after the external fuel fire was started, a layer of dense black smoke, 10 to 14 inches thick, obscured the ceiling-mounted emergency lights. The marker lights were providing aisle identification and passenger evacuation awareness for approximately 120 seconds. Total cabin light obscuration occurred rapidly and further observed evaluation of the marker lights was not possible. The last observer comments that at lapsed time of 156 seconds indicated absolute obscuration from even a stooped position.

CONCLUSIONS

1. Smoke entering a transport cabin from an external fuel fire, or generated by burning interior materials, will rapidly obscure ceiling-mounted lights/signs and significantly decrease cabin illumination when cabin temperatures are still at a survivable level.

2. Lowering exit/cabin illumination sources below the 61 1/2-inch level will significantly increase their effectiveness in a cabin smoke environment.

3. Under most smoke conditions studied, increasing the luminance of lights/signs does not substantially increase the time they remain visible.

4. Lights located in the aisle-side armrests of passenger seats provide both passenger awareness, exit information, and cabin illumination (especially of the floor area) for a period of time substantially longer than any of the ceiling or bulkhead mounted lights/signs.

5. Floor-mounted electroluminescent lights provide the maximum visibility in smoke for passenger awareness.

6. Self-powered Betalights provided aisle outline identification when viewed from below the horizontal smoke layer and in a darkened environment.

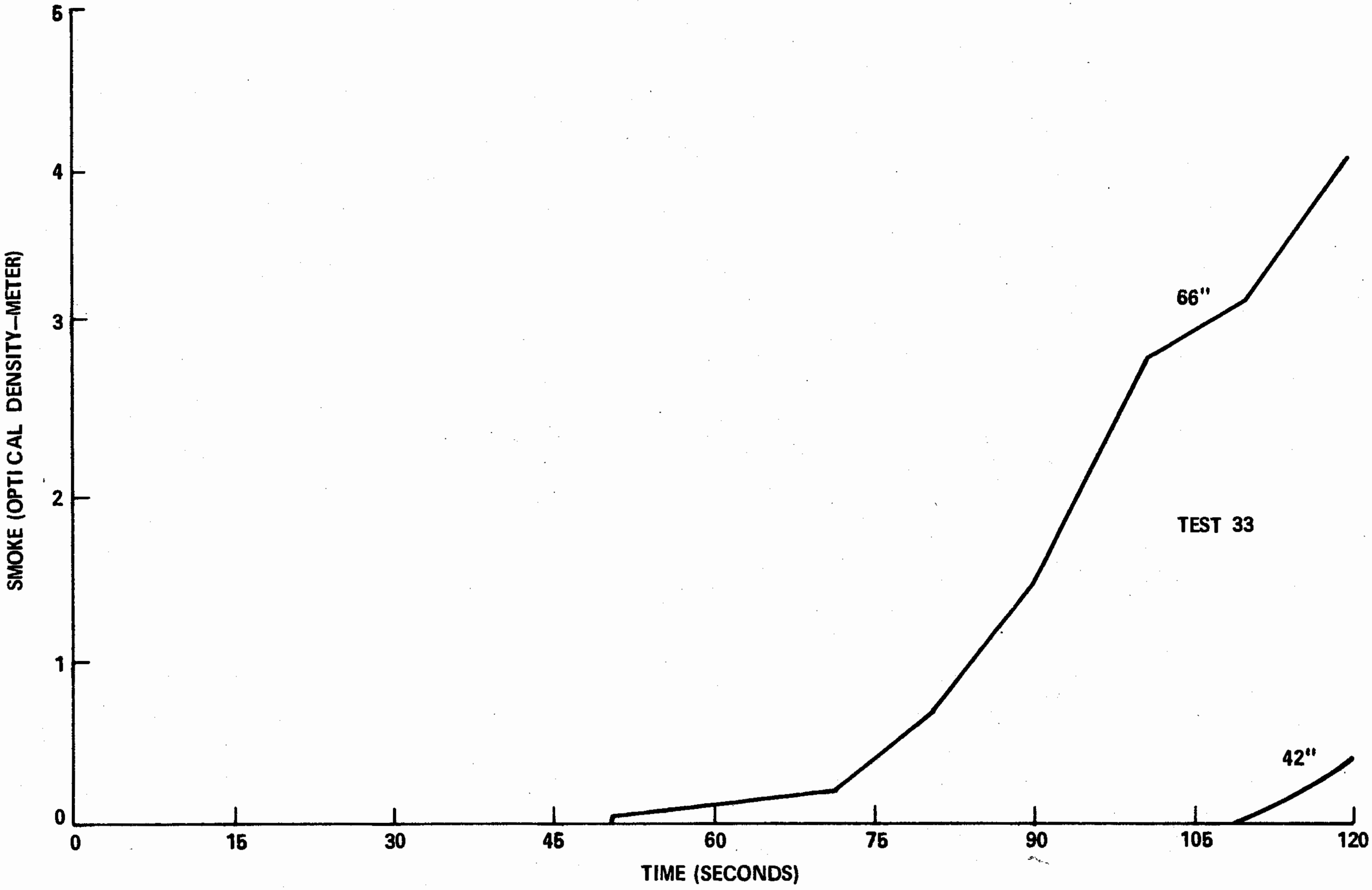

FIGURE 26. LIGHT TRANSMISSION (SMOKEMETER) VERSUS OPTICAL DENSITY

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GLOSSARY

ILLUMINATION or ILLUMINANCE: The value of light (falling) on a surface and a typical unit of measurement of the foot-candle.

LUMINANCE: The brightness of the illuminated surface.

FOOT-CANDLE: The measurement unit of illumination at a point (A) on a surface which is one foot from and perpendicular to a uniform point source of one candela.

CANDELA: The candela is the international basic physical quality in all measurements of light; all other units are derived from it. Its value is determined by the light emitted by a laboratory device called a blackbody, operating at a specific temperature.

APPENDIX A

FEDERAL AIR REGULATIONS 25.811 — EMERGENCY EXIT MARKING

§ 25.811 Emergency exit marking.

(a) Each passenger emergency exit, its means of access, and its means of opening must be conspicuously marked.

(b) The identity and location of each passenger emergency exit must be recognizable from a distance equal to the width of the cabin.

(c) Means must be provided to assist the occupants in locating the exits in conditions of dense smoke.

(d) The location of each passenger emergency exit must be indicated by a sign visible to occupants approaching along the main passenger aisle (or aisles). There must be—

(1) A passenger emergency exit locator sign above the aisle (or aisles) near each passenger emergency exit, or at another overhead location if it is more practical because of low headroom, except that one sign may serve more than one exit if each exit can be seen readily from the sign;

(2) A passenger emergency exit marking sign next to each passenger emergency exit, except that one sign may serve two such exits if they both can be seen readily from the sign; and

(3) A sign on each bulkhead or divider that prevents fore and aft vision along the passenger cabin to indicate emergency exits beyond and obscured by the bulkhead or divider, except that if this is not possible the sign may be placed at another appropriate location.

[(e) The location of the operating handle and instructions for opening the exit from the inside must be shown as follows:

[(1) For each passenger emergency exit, by a marking on or near the exit that is readable from a distance of 30 inches. In addition, the operating handle for each Type III passenger emergency exit must be self-illuminated with an initial brightness of at least 160 microlamberts. If the operating handle is covered, self-illuminated cover removal instructions having an initial brightness of at least 160 microlamberts must also be provided.]

APPENDIX B

FEDERAL AIR REGULATIONS 25.812 — EMERGENCY LIGHTING

§ 25.812 Emergency lighting.

[(a) An emergency lighting system, independent of the main lighting system, must be installed. However, the sources of general cabin illumination may be common to both the emergency and the main lighting systems if the power supply to the emergency lighting system is independent of the power supply to the main lighting system. The emergency lighting system must include:]

(1) Illuminated emergency exit marking and locating signs, sources of general cabin illumination, and interior lighting in emergency exit areas.

(2) Exterior emergency lighting.

[(b) Emergency exit signs—

[(1) For airplanes that have a passenger seating configuration, excluding pilot seats, of 10 seats or more must meet the following requirements:

[(i) Each passenger emergency exit locator sign required by § 25.811(d)(1) and each passenger emergency exit marking sign required by § 25.811(d)(2) must have red letters at least 1½ inches high on an illuminated white background, and must have an area of at least 21 square inches excluding the letters. The lighted background-to-letter contrast must be at least 10:1. The letter height to stroke-width ratio may not be more than 7:1 nor less than 6:1. These signs must be internally electrically illuminated with a background brightness of at least 25 foot-lamberts and a high-to-low background contrast no greater than 3:1.

[(ii) Each passenger emergency exit sign required by § 25.811(d)(3) must have red letters at least 1½ inches high on a white background having an area of at least 21 square inches excluding the letters. These signs must be internally electrically illuminated or self-illuminated by other than electrical means and must have an initial brightness of at least 400 microlamberts. The colors may be reversed in the case of a sign that is self-illuminated by other than electrical means.

[(2) For airplanes that have a passenger seating configuration, excluding pilot seats, of nine seats or less, that are required by § 25.811(d) (1), (2), and (3) must have red letters at least 1 inch high on a white background at least 2 inches high. These signs may be internally electrically illuminated, or self-illuminated by other than electrical means, with an initial brightness of at least 160 microlamberts. The colors may be reversed in the case of a sign that is self-illuminated by other than electrical means.

[(c) General illumination in the passenger cabin must be provided so that when measured along the centerline of main passenger aisle(s), and cross aisle(s) between main aisles, at seat armrest height and at 40-inch intervals, the average illumination is not less than 0.05 foot-candle and the illumination at each 40-inch interval is not less than 0.01 foot-candle. A main passenger aisle(s) is considered to extend along the fuselage from the most forward passenger emergency exit or cabin occupant seat, whichever is farther forward, to the most rearward passenger emergency exit or cabin occupant seat, whichever is farther aft.

[(d) The floor of the passageway leading to each floor-level passenger emergency exit, between the main aisles and the exit openings, must be provided with illumination that is not less than 0.02 foot-candle measured along a line that is within six inches of and parallel to the floor and is centered on the passenger evacuation path.