NATIONAL BUREAU OF STANDARDS REPORT

FIRE GROWTH AND FLASHOVER
IN MODEL ENCLOSURES
SIMULATING AIRPLANE CABINS

Progress Report No. 2

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

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NBS PROJECT		NBS REPORT
4212427	September 11, 1969	10 083

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by

D. Gross

For
Federal Aviation Administration
Project No. 510-001-11X
Agreement No. FA67NF-AP-21

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1.0 INTRODUCTION

A previous report [1] described preliminary experiments on laboratory models of fire development in enclosed spaces. Using a 20 x 20 x 40 inch chamber it was found that within certain ventilation and physical property limits flaming ignition of a wall lining specimen by radiant heating would occur; and outside these limits flaming ignition would not occur.

This report summarizes additional tests performed in this chamber using small cubes of polyurethane cushioning foam, similar to that used in seat cushions. A larger chamber, 24 x 24 x 192 inch long, was constructed to examine the conditions under which flames would propagate down a long chamber. The polyurethane foam was exposed in a variety of ways, viz. open flame ignition, radiant heating, and internal heating using an embedded electrical heater.

At this time only a summary of the experimental work is being presented. The analysis of the data and a projection of the findings will be presented in a later report.

2.0 MATERIALS IN TEST

Three types of polyurethane foam were used as listed below:

Designation	Type	Source	Nominal Thickness in	Measured Density pcf
A	Polyether urethane B. F. Goodrich untreated airplane seat cushioning	NAFEC	4	1.3
B	Polyether urethane B. F. Goodrich fire-retardant treated airplane seat cushioning	NAFEC	4	1.3
C	Urethane bed foam	Local	1	1.3

The wall lining materials used were as follows:

FBD	Unfinished fiberboard	Storeroom	1/2	25
HBD	Unfinished, oil-tempered hardboard	Commercial	3/16	60

3.0 EXPERIMENTAL RESULTS

3.1 Small Chamber Tests

Except as noted, all tests were conducted using the insulated asbestos lined 20 x 20 x 40 inch chamber. These tests were made using cubes assembled from one-inch thick layers of polyurethane foam which is normally used in bed mattresses, and was purchased locally. Small cubes of polyurethane foam were placed within the chamber to simulate the principal fuel load (seat cushions) in airplane cabins. Table 1 is a summary of test results.

Using two-inch polyurethane cubes, with a glowing electrical ignitor placed on top of one cube, fire spread to all cubes only when corners touched. When spaced apart one-quarter inch or more, only the ingited cube burned.

Using nine three-inch polyurethane cubes subject to radiation from Calrod heaters, flaming occurred with vent openings between one-quarter inch and four inches but not at six inches. A minimum time to initial flaming (14 and one-half minutes) occurred with an opening of one inch, although repeat tests produced active flaming at times up to twenty-one and one-half minutes. (See Figure 1.) At a fixed vent opening of two inches, the same or shorter times to initial flashing were observed with only three, four, or five cubes. Usually, flaming occurred initially near the electrical Calrod heater, although flashing occasionally involved all the cubes.

In Test 28, using a fiberboard lined wall opposite the Calrod heaters, the fiberboard did not affect the ignition time of the polyurethane cubes and did not ignite by itself.

Test No. 30 employed foam from standard airplane cushions; Tests 31 to 33 foam from retardant-treated airplane cushions received from NAFEC. The cubes were trimmed to three inches from the standard four-inch thickness.

Whereas the regular (untreated) foam ignited at one and four inch vent openings, the fire retardant-treated foam did not ignite at these same vent openings.

In every case, the temperature of the air close to the ceiling at the center of the unlined box reached a value between 270 and 290 °C (520 to 550 °F) just prior to ignition. The temperature of the air near the floor was approximately 100 °C lower.

3.2 Large Chamber Tests

A larger and longer insulated asbestos board chamber was constructed and used for all subsequent tests. Figure 2 shows the vent end of the 24 x 24 x 192 inch chamber and instrumentation for gas analysis alongside. The electrical Calrod heating elements are mounted on one wall of the chamber and are shown in Figure 3. The principal test results are summarized in Table 2.

An exploratory series of tests was conducted in the uninsulated asbestos-wall chamber (Tests 5 to 13). All subsequent tests were conducted with the chamber insulated with a one-inch layer of glass fiber batting, comparable to that covering the small chamber. Ceiling temperatures were generally lower and ignition times generally shorter compared to tests in the small chamber; but the radiant heater supply, the urethane fuel, and the spatial separations were not similar.

Tests 28 to 32 were made without any foam using combustible hardboard or fiberboard wall linings opposite the Calrod heating elements in a manner similar to that employed in previous tests in the smaller chamber. With the hardboard wall lining and vent openings of one-half and two inches, flames were noted at 58 and one-quarter and 65 minutes respectively. No ignition was obtained using an eight-inch vent opening, although the hardboard reached a glowing state after 80 minutes. In a test in a small chamber with a two-inch vent, (data reported previously [1]) flames were noted at the specimen after 34 minutes. Using a fiberboard wall lining and vent openings of one-half and two inches in the large chamber, flames were noted in approximately 55 minutes compared to about 20 minutes in the small chamber.

During Tests 14 and 15 measurements were made of the combustion gas concentration above the polyurethane cubes. The CO content reached two percent and the oxygen content dropped to a minimum of nine percent in Test No. 14. The readings in Test No. 15 were CO 0.6 percent maximum, CO_2 0.2 percent maximum, and O_2 20.5 percent minimum. No comparative gas concentration measurements are available for the other tests.

Figure 4 shows typical vertical profiles of gas temperature at the quarter-point locations shortly before the first indication of fire. The high temperature noted at six inches below the ceiling in Position A is due to the heat produced by the polyurethane cubes which were mounted eighteen inches above the floor.

In Tests 33 to 41, with the heaters placed on the floor, four-inch polyurethane cubes placed two inches above the heaters; and using a bottom end vent of two inches ignition occurred either near the cubes or at the heaters in times ranging from 6:50 to 8:00 minutes. In this case, ignition occurred at ceiling temperatures from 110 to 126 °C (210 to 250 °F). Placing the cubes at six and nine inches above the heater resulted in no ignition or very much delayed ignition.

Tests 52 to 64, using a 2,150 watt electrical barbecue heater sandwiched between layers of polyurethane foam produced ignition in every case. The temperature in the middle of the sandwich reached 400 to 500 °C when flame broke out. Usually the onset of flaming was accompanied by a sudden pressure rise which simultaneously blew out a twelve-inch square plug at the far end of the chamber. Active flaming then continued in the polyurethane stack until it was consumed. In one instance where a row of urethane cubes was lined up adjacent to the stack, the flames did not propagate to

these cubes. The simultaneous ignition and plug blowout occurred with conventional foam and with untreated and fire retardant treated airplane cushioning foam in times ranging from one and one-half to six minutes. The quantity of foam, as measured by the height of the stack, appeared to have a slight affect upon the time to initial fire for two types of polyurethane foam (See Figure 5). The shortest times were obtained with the thinnest stack (one inch). The air temperature near the ceiling (above the stack) was generally below 50 °C (120 °F) at the time of ignition and was somewhat lower elsewhere in the chamber. After ignition occurred, temperatures rose rapidly to over 500 °C above the polyurethane stack. In several tests, temperatures in excess of 400 °C and sometimes over 500 °C were recorded two to four feet down the box, indicating the passage of flame or hot gases. Temperature profiles during the peak burning stage in two tests is shown in Figure 6. The elevated temperature toward the vent end (thirteen feet from the polyurethane) may have been due to a pocket of high temperature products, a likely condition, since the chamber was tilted up toward the vent end for this series of tests. The slight reversal of temperatures between two and four feet from the polyurethane is so far unexplained.

In Tests 47 to 51, several open flame sources (a candle, a bunsen burner, and a pan of heptane) were used to examine whether flame propagation with a space above a 4 x 12 x 12 inch urethane stack would occur. For the given test conditions, there was no indication of flames extending along the chamber beyond the burning polyurethane.

4.0 DISCUSSION

The test series covered by this report have shown that flaming would not propagate readily between small polyurethane cubes within a model enclosure. Whether ignition was initiated indirectly by thermal radiation, directly by contact with an electrically-heated ignitor, or by an open flame source, flames did not involve the entire chamber and did not spread to adjacent polyurethane cubes spaced one-quarter inch or more apart. (In these tests, the simplest cabin geometry was used; no attempt was made to simulate actual cabin conditions of rounded cross-section; the presence of seat backs, hat racks, and other space-defining components; or of the use of curtains, upholstery and other materials capable of igniting and spreading flame.) Where thermal radiation was used to initiate decomposition, flaming occurred principally in the gaseous products near the glowing electrical heaters. The gasification and accumulation of combustible products under these heating conditions and fuel element size was apparently insufficient to produce a propagating self-sustaining flame. For most hydrocarbon

vapors at room temperature, the lower limit of flammability is approximately 45 to 50 mg of combustible vapor per liter (0.045 to 0.050 oz/ft^3) of air at standard conditions [2].

An electrical heater sandwiched between layers of polyurethane foam produced a more rapid local concentration of combustible products and resulted in ignition in every case. Usually the onset of flaming was preceded by a sudden pressure rise which blew out a plug at the far end of the chamber. Here again the flaming intensity was apparently insufficient to increase the mean concentration of CO or other combustible gases to permit flaming over an extensive area or to involve adjacent polyurethane cubes. The limits of flammability for mixtures containing CO is shown in Figure 7. The limited number and accuracy of gas measurements to date has precluded any judgment as to whether sufficient CO and/or other products were being accumulated for flame propagation to be possible.

5.0 FUTURE TESTS

Additional tests are planned in the large chamber, and will include the following conditions:

- Materials (e.g., vinyl cloth) mounted along the ceiling.
- Horizontal and vertical spatial separators to more closely simulate airplane cabin configurations.
- More accurate measurements of CO concentrations using a recently purchased infrared analyzer with 0 to 2 percent range.

6.0 REFERENCES

[1] Gross, D., "Fire Growth and Flashover in Model Enclosures Simulating Airplane Cabins", NBS Report No. 9931, October 4, 1968.

[2] Zabetakis, M. G., "Flammability Characteristics of Combustible Gases and Vapors", Bureau of Mines Bulletin No. 627, 1965.

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Table 1

Summary of Test Results
20 x 20 x 40 in Chamber

Test	Cubes			Vent Opening	Time to Ignition	Ceiling Air Temperature Prior to Ignition	Notes
	No.	Size in	Spacing in	in	min:sec	°C	
				Ignition by Electrical Wire			
Foam Type C							
							ignited
Foam Type A							
30	9	3	1/2	1	20:10	289	All cubes ignited
Foam Type B							
31	9	3	1/2	1	----	---	No ignition; 60 min.
32	9	3	1/2	4	----	---	No ignition; 45 min.
33	9	3	1/2	10	----	---	No ignition; 45 min.

Table 1

Summary of Test Results
20 x 20 x 40 in Chamber

Test	Cubes			Vent Opening	Time to Ignition	Ceiling Air Temperature Prior to Ignition	Notes
	No.	Size in	Spacing in	in	min:sec	°C	
Ignition by Electrical Wire							
Foam Type C							
2,3,4	11	2	1	2			No spread between cubes
5	11	2	1/2	1/2			No spread between cubes
6	11	2	1/4	1/2			No spread between cubes
7	11	2	Corners touching	1/2	4:00		All cubes burned
Radiant Heating - 2 Calrod Units							
Foam Type C							
19	9	3	1/2	1/4	17:35	280	Flash from Calrod heater to ceiling; occasional flashing until 18:10 when all cubes ignited; intermittent flashing to 27 min.
15	9	3	1/2	1/2	20:27	289	Sudden flash preceded by pulsation.
16	9	3	1/2	1	14:30	270	Flash at Calrod heater; cubes ignited at 15:04 min.
27	9	3	1/2	1	18:27	290	All cubes ignited
29	9	3	1/2	1	21:34	288	All cubes ignited
14	9	3	1/2	2	17:37	271	All cubes ignited
17	9	3	1/2	4	21:50	285	Flash from heater top down; all cubes ignited
18	9	3	1/2	6	----	---	50 min. test
28	9	3	1/2	1	17:21	298	Homasote wall opposite Calrod units did not ignite; cubes ignited
21	3	3	1/2	2	15:45	278	Flash across ceiling; intermittent to 16:15; cubes not ignited
22	4	3	1/2	2	16:38	288	Sudden flash; all cubes ignited
20	5	3	1/2	2	14:25	283	Flash across ceiling; cubes ignited
Foam Type A							
30	9	3	1/2	1	20:10	289	All cubes ignited
Foam Type B							
31	9	3	1/2	1	----	---	No ignition; 60 min.
32	9	3	1/2	4	----	---	No ignition; 45 min.
33	9	3	1/2	10	----	---	No ignition; 45 min.

Table 2A

Summary of Test Results

								ignition
32	1/2	None		55:15		58:32	307	Homasote (did not ignite)
				Heaters (4) on Floor				
Foam Type C								
33	9	20	9	33:50	35:15	35:18	200	Intermittent flaming; cubes--50% burned, 50% melted
34	2	20	6					Melting of cubes only; test terminated at 35 min.
35	2	20	2	7:55		7:48	110	Intermittent flaming; cubes--50% burned, 50% melted
36	2	20	2	8:00		7:58	120	Intermittent flaming; cubes--50% burned, 50% melted
37	2	12	2	6:50		6:48	116	Electrical ignitor at ceiling used at 30 sec. intervals. No significant difference noted. Cubes--50% burned
38	2	6	2					Two heaters only. No ignition; cubes--25% melted
40	2	8	2	8:20				Single slight momentary flame only
41	2	10	2	7:35		7:38	126	Intermittent burning; cubes--80% burned

Table 2A

Summary of Test Results
24 x 24 x 192 in Chamber

Test	Vent in	4" Cubes No.	4" Cubes Distance to Heater in	4" Cubes Height Above Floor in	Ignition Time, min:sec Flash	Ignition Time, min:sec Sustained Fire	Ignition Time, min:sec Sudden Temp Rise	Ceiling Air Temperature Prior to Ignition °C	Remarks
Foam Type C									
					Asbestos-Wall Chamber				
5	2	7	3	18		12:10		187	Spark ignition (10 sec)
6	2	7	3	18		14:10		180	Spark ignition
7	2	7	3	18		13:45	13:40	152	
8	2	7	10	18				---	
9	2	7	8	12				---	
10	10	7	3	18	10:20		10:24	144	
11	6	7	3	18		11:25	10:48	150	
12	4	7	3	18		10:30	10:00	150	
13	4	7	3	18		10:40	10:48	153	
					Chamber Insulated				
14	4	7	3	18		10:55	11:06	121	
15	4	8	3	12				---	
16	4	12	3	18	10:50		12:30	159	
17	15	12	3	18		18:10	18:08	150	
18	1/2	12	3	18		12:00	12:04	150	
19	0	12	3	18	14:26	-----	-----	---	Momentary flash
20	23+	12	3	18				---	
21	1/4	12	3	18		12:00	12:00	130	
22	8	12	3	18		10:50	10:52	139	Momentary flash
23	1	12	2	6	12:20			---	
24	8	40	2.5 to 17.5	18	83:00	95:00	94:26		Flash (from Homasote) down Homasote wall from ceiling to floor
25	8	20	3	18					No ignition
26	8	26	3	18	11:05	-----	-----	---	Momentary flash; cubes 90% melted
27	2	33	3	18		12:30	12:46	147	12 cubes entirely burned; remainder melted
28	2	None				65:00	65:00	300	Hardboard wall only; 276 °C prior to ignition
29	1/2	None			57:15	58:15	58:30	295	Hardboard wall; 291 °C prior to ignition
30	8	None							Hardboard split apart at 77 min; glowing at 80 min
31	2	None			54:10	56:55	54:54	310	Homasote 320 °C prior to ignition
32	1/2	None			55:15		58:32	307	Homasote (did not ignite)
					Heaters (4) on Floor				
Foam Type C									
33	9	20		9	33:50	35:15	35:18	200	Intermittent flaming; cubes--50% burned, 50% melted
34	2	20		6					Melting of cubes only; test terminated at 35 min.
35	2	20		2	7:55		7:48	110	Intermittent flaming; cubes--50% burned, 50% melted
36	2	20		2	8:00		7:58	120	Intermittent flaming; cubes--50% burned, 50% melted
37	2	12		2	6:50		6:48	116	Electrical ignitor at ceiling used at 30 sec. intervals. No significant difference noted. Cubes--50% burned
38	2	6		2					Two heaters only. No ignition; cubes--25% melted
40	2	8		2	8:20				Single slight momentary flame only
41	2	10		2	7:35		7:38	126	Intermittent burning; cubes--80% burned

Table 2B

Various Ignition Sources

Test	Vent	Type	Urethane			Ignition Source & Location	Remarks
			No.	Size in	Distance Above Floor in		
47	Removable 12" plug	A	1	4 x 12 x 12	5	Candle at corner	No flash fire beyond stack
48	Removable 12" plug	A	1	4 x 12 x 12	9-1/2	Bunsen burner at bottom center	No flash fire beyond stack
49	Removable 12" plug	A	1	4 x 12 x 12	9-1/2	20 ml heptane in pan	No flash fire beyond stack. Chamber sloped 1 ft/16 ft. Heptane burned 1:40 min. Flames to 2:15 min.
50	Removable 12" plug	A	1	4 x 12 x 12	9-1/2	100 ml heptane in pan	No flash fire beyond stack. Chamber sloped 1 ft/16 ft. Heptane burned 1:25 min. Flames to 2:00 min.
51	2	A	1	4 x 12 x 12	9-1/2	100 ml heptane in pan	No flash fire beyond stack. Chamber sloped 1 ft/16 ft. Heptane burned 1:10 min (70% remained). No continuing flames from urethane (40% remained).

Table 2C

Electric Barbecue Heater in Sandwich

Test	Vent	Urethane				Ignition Time, min:sec			Ceiling Air Temperature Prior to Ignition °C	Remarks
		Type	No.	Size in	Distance Above Floor in	Flash	Sustained Flaming	Sudden Temp Rise		
Small Barbecue Heater										
44	See Remarks	C	1	2 x 12 x 12	4		4:45	4:50	38	Vent closed with 12 in. square plug; plug
60	See Remarks	C	*	(1 x 8 x 16)*	4		1:30	1:36	50	*Urethane pieces matched to heater element.
61	See Remarks	C	*	(1 x 12 x 16)*	4		1:30	1:36	54	*Urethane pieces matched to heater element. Fire; plug blew out
62	See Remarks	A	*	(1 x 12 x 16)*	4		1:33	1:36	48	*Fire; plug blew out. Same as above.
63	See Remarks	A	1	16 x 16 x 16	2		2:15	2:18	48	Fire; plug blew out
64	See Remarks	C	1	16 x 16 x 16	2		2:55	2:56	48	Fire; plug blew out

Table 2C

Electric Barbecue Heater in Sandwich

Test	Vent	Urethane				Ignition Time, min:sec			Ceiling Air Temperature Prior to Ignition	Remarks
		Type	No.	Size in	Distance Above Floor in	Flash	Sustained Flaming	Sudden Temp Rise	°C	
Small Barbecue Heater										
44	See Remarks	C	1	2 x 12 x 12	4		4:45	4:50	38	Vent closed with 12 in. square plug; plug removed at 6:00 min. Flames out at 6:15 min.
45	See Remarks	C	1	4 x 12 x 12	4		6:00	6:02	41	Vent plug blew out. Seven 4" cubes placed in line near sandwich did not ignite.
46	See Remarks	A	1	4 x 12 x 12	4		4:45	4:50	56	Vent plug blew out. Seven 4" cubes placed in line near sandwich did not ignite.
Large Barbecue Heater (2150 Watts)										
52	See Remarks	A	1	4 x 16 x 16	9-1/2		4:30			Plug opened slightly
53	See Remarks	A	1	4 x 16 x 16	12		2:30	2:24		Plug blew out. Urethane burned completely
54	See Remarks	B	1	4 x 16 x 16	12		3:05	3:12		Plug blew out. Urethane burned completely
55	See Remarks	A	1	8 x 16 x 16	12		2:00	2:02		Plug blew out. Urethane burned completely. Flames for 1 min. then out. Urethane 50% consumed.
56	See Remarks	C	1	8 x 16 x 16	12		2:10	2:12		Plug blew out; (new) urethane 100% consumed
		(New TC set-up)								
57	See Remarks	C	1	4 x 16 x 16	4		1:57	2:00	36	Plug blew out. Urethane 100% consumed.
58	See Remarks	C	1	2 x 16 x 16	4		1:50	1:54	48	Plug blew out. Urethane 100% consumed.
59	See Remarks	C	1	1 x 16 x 16	4		1:30	1:36	45	Plug blew out.
60	See Remarks	C	*	(1 x 8 x 16)*	4		1:30	1:36	50	*Urethane pieces matched to heater element.
61	See Remarks	C	*	(1 x 12 x 16)*	4		1:30	1:36	54	*Urethane pieces matched to heater element. Fire; plug blew out
62	See Remarks	A	*	(1 x 12 x 16)*	4		1:33	1:36	48	*Fire; plug blew out. Same as above.
63	See Remarks	A	1	16 x 16 x 16	2		2:15	2:18	48	Fire; plug blew out
64	See Remarks	C	1	16 x 16 x 16	2		2:55	2:56	48	Fire; plug blew out

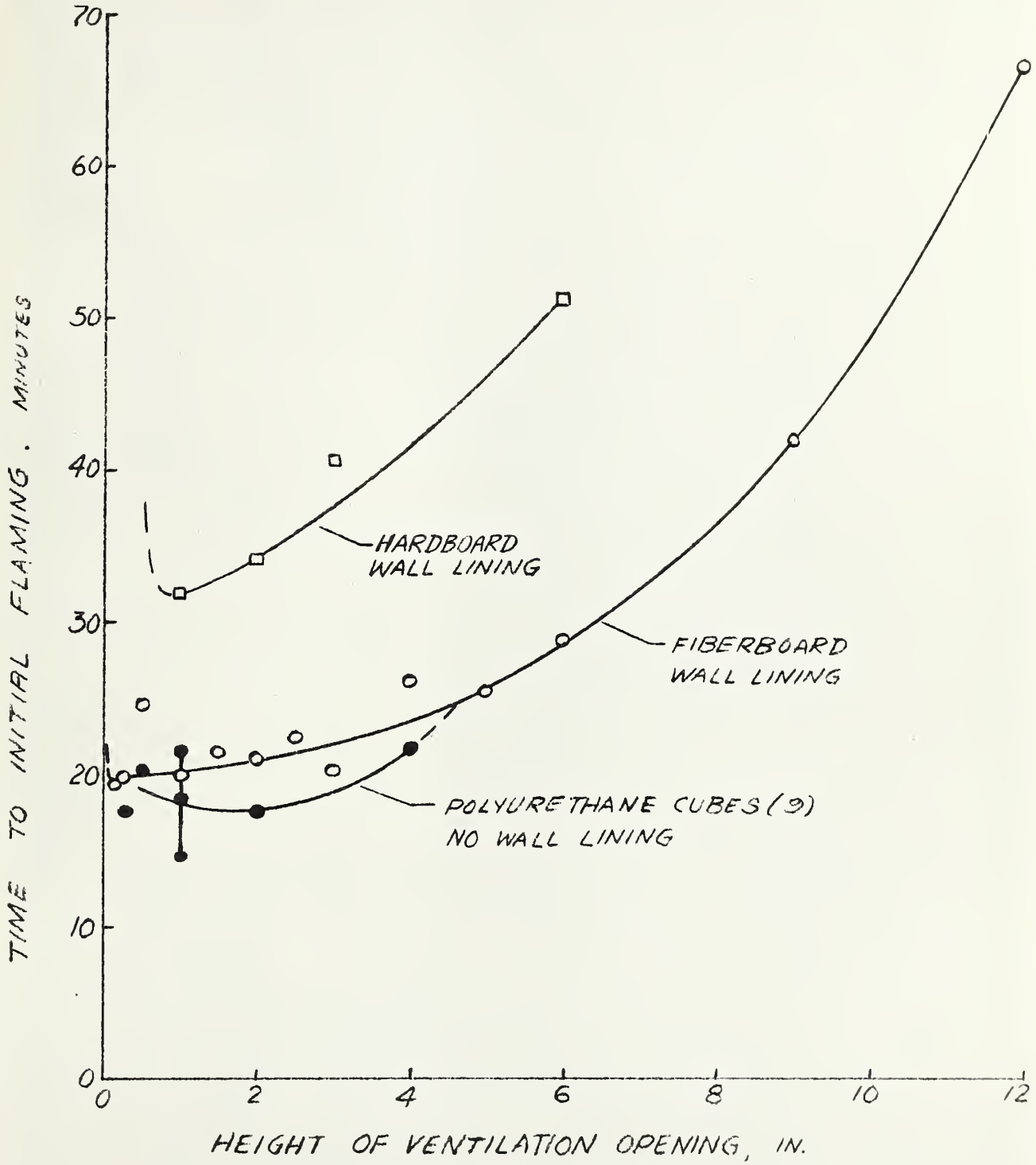


FIG. 1 -- FLAMING TIME FOR POLYURETHANE CUBES IN 20 x 20 x 40 INCH CHAMBER

Previous Results with Wall Linings For Comparison

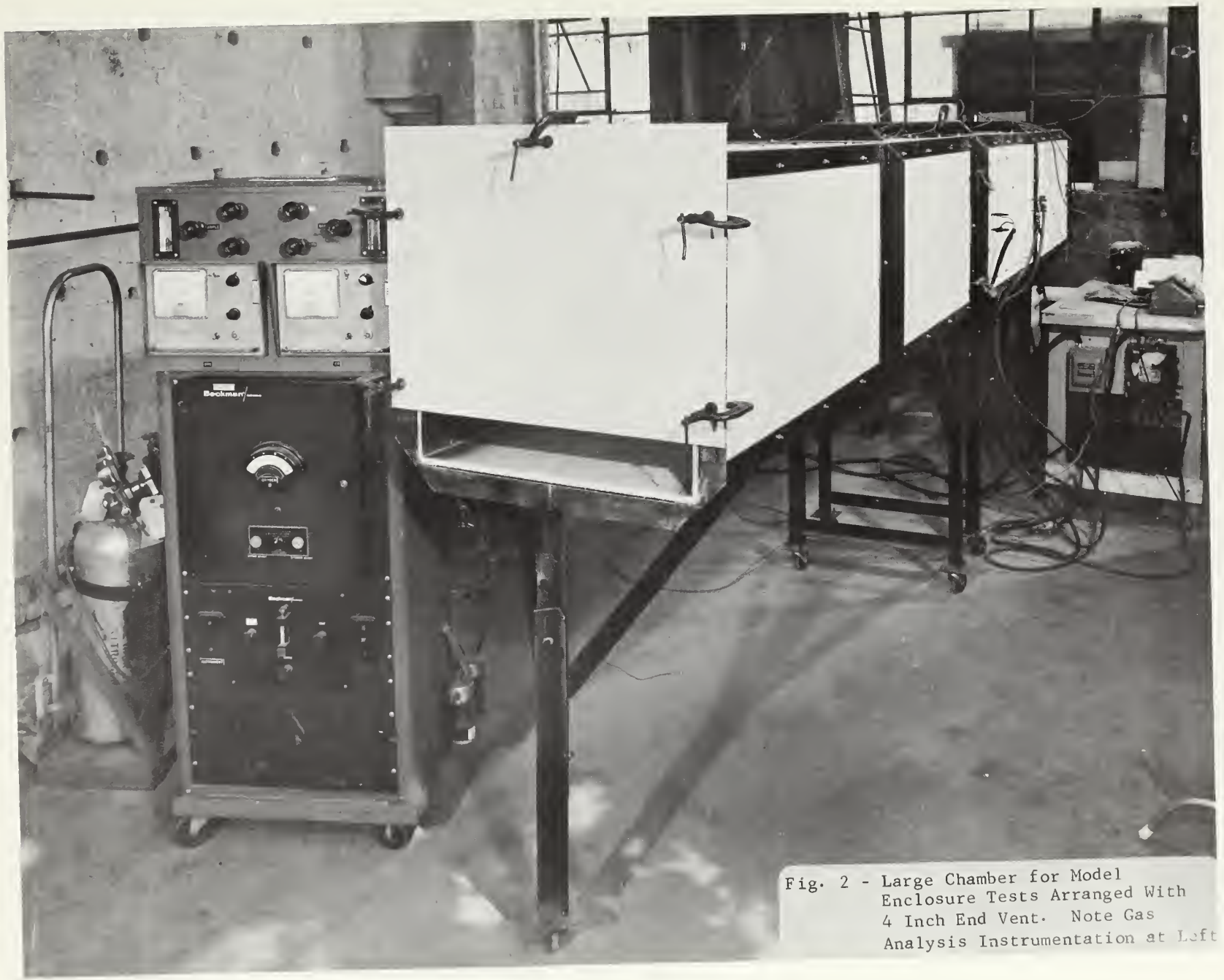


Fig. 2 - Large Chamber for Model Enclosure Tests Arranged With 4 Inch End Vent. Note Gas Analysis Instrumentation at Left

Fig. 3 - Electrical Calrod Heating Element Mounted Along Wall of Large Chamber

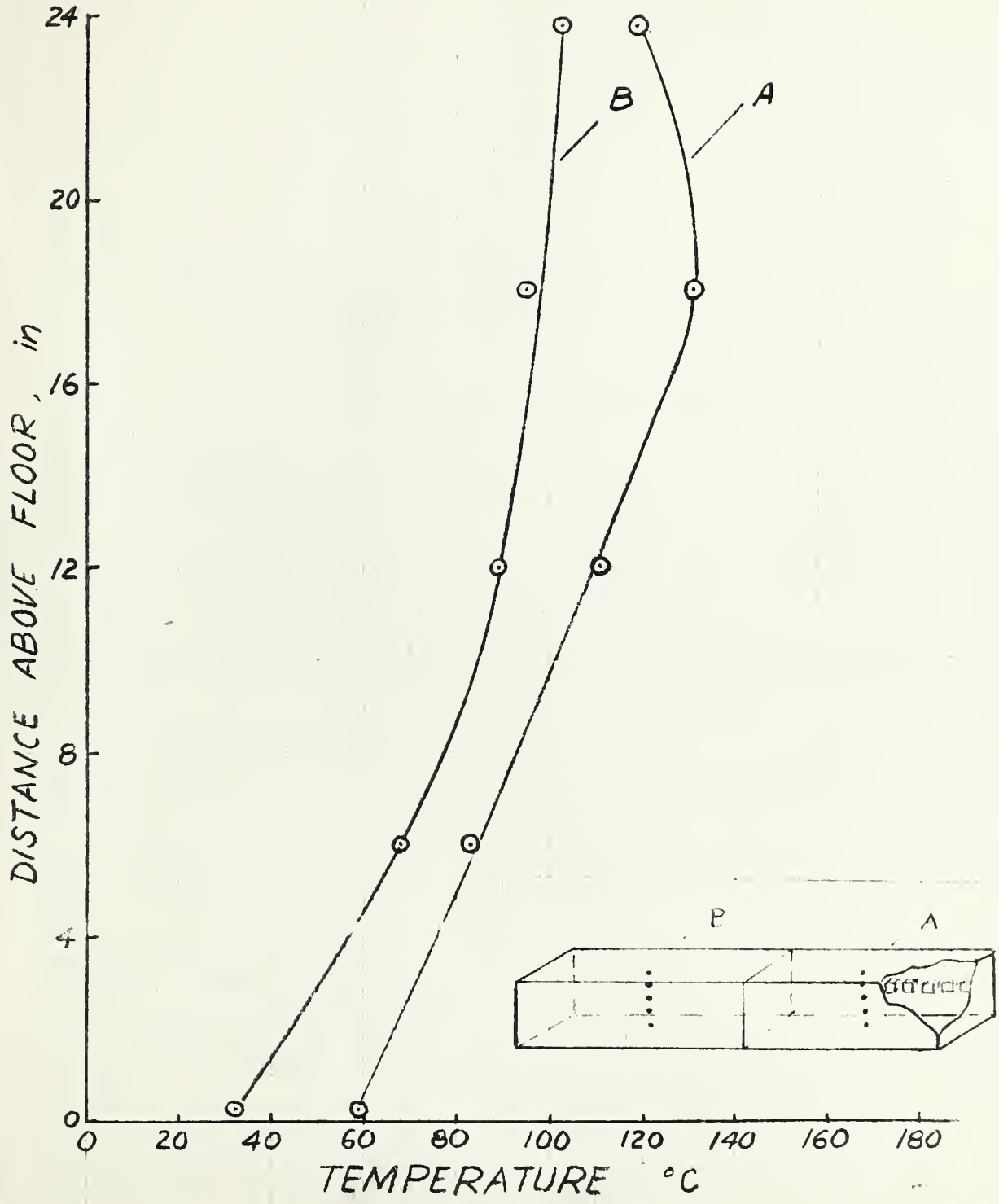


FIG. 4 GAS TEMPERATURE VERTICAL PROFILES
TEST NO. 14 10 MINUTES

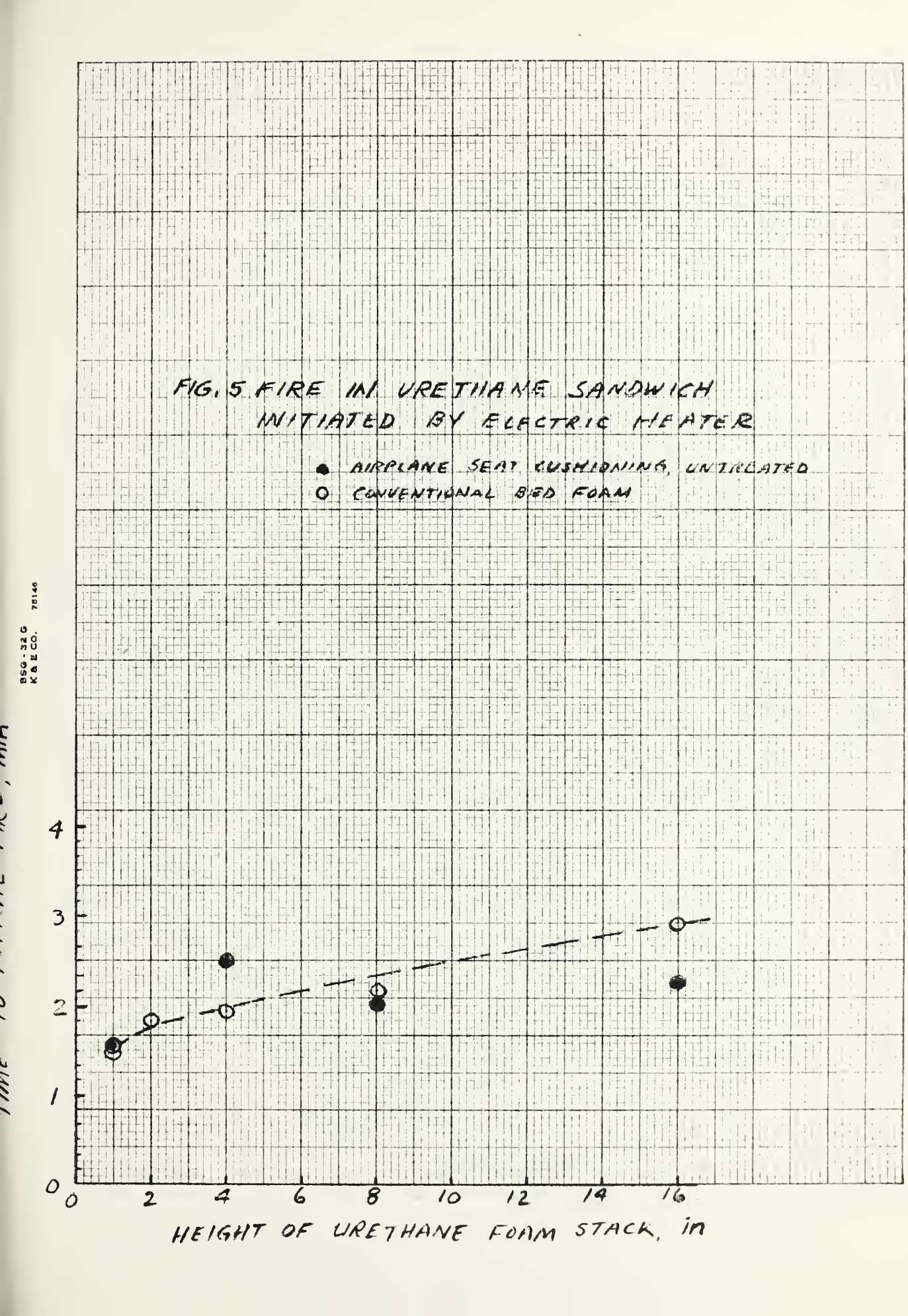
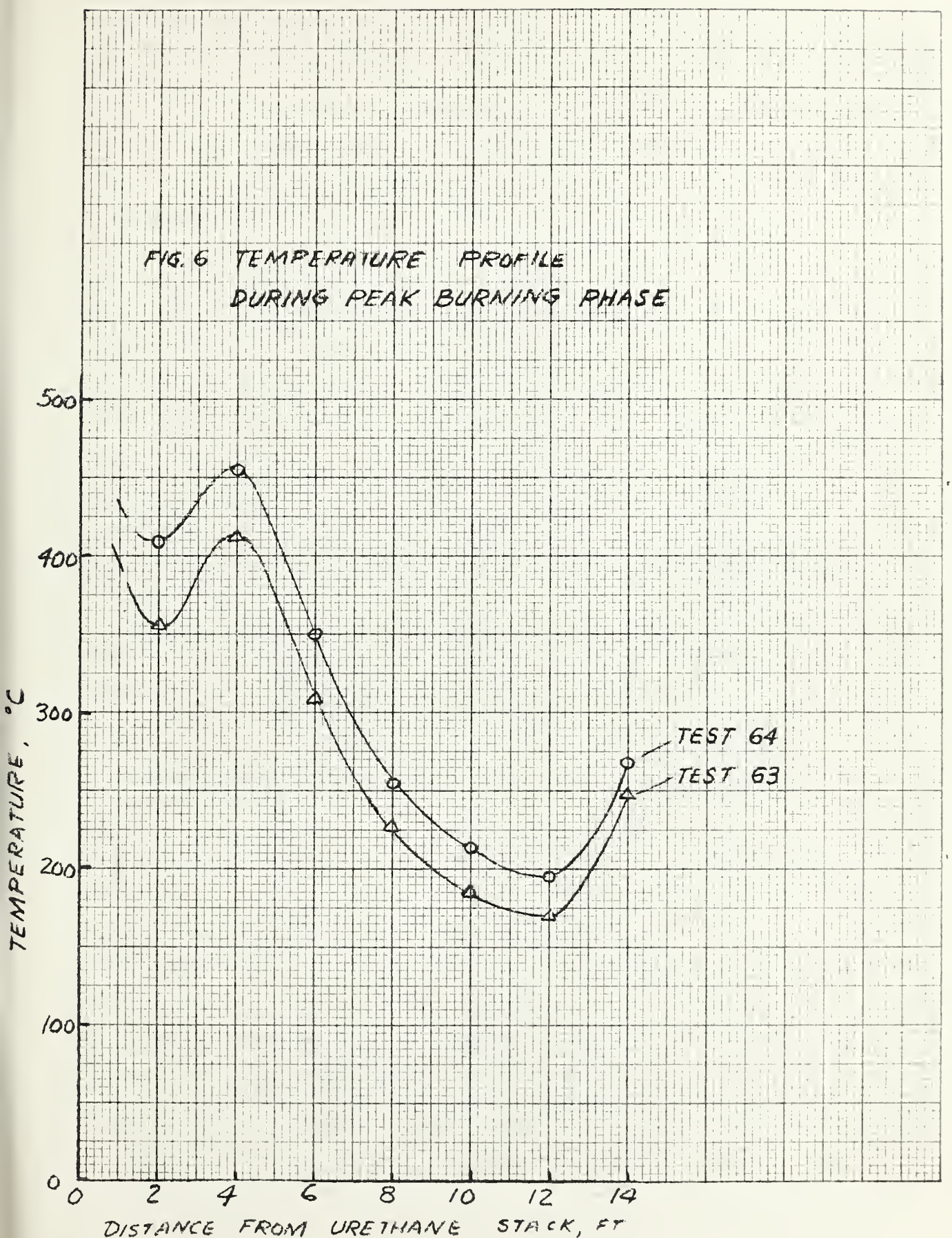


FIG. 5 FIRE IN URETHANE SANDWICH
INITIATED BY ELECTRIC HEATER
● AIRPLANE SEAT CUSHIONING, UNTREATED
○ CONVENTIONAL BED FOAM
TIME TO FLAME, MIN
0
1
2
3
4
0
2
4
6
8
10
12
14
16
HEIGHT OF URETHANE FOAM STACK, in
BSG-32G
K & E CO.
78146

FIG. 6 TEMPERATURE PROFILE
DURING PEAK BURNING PHASE



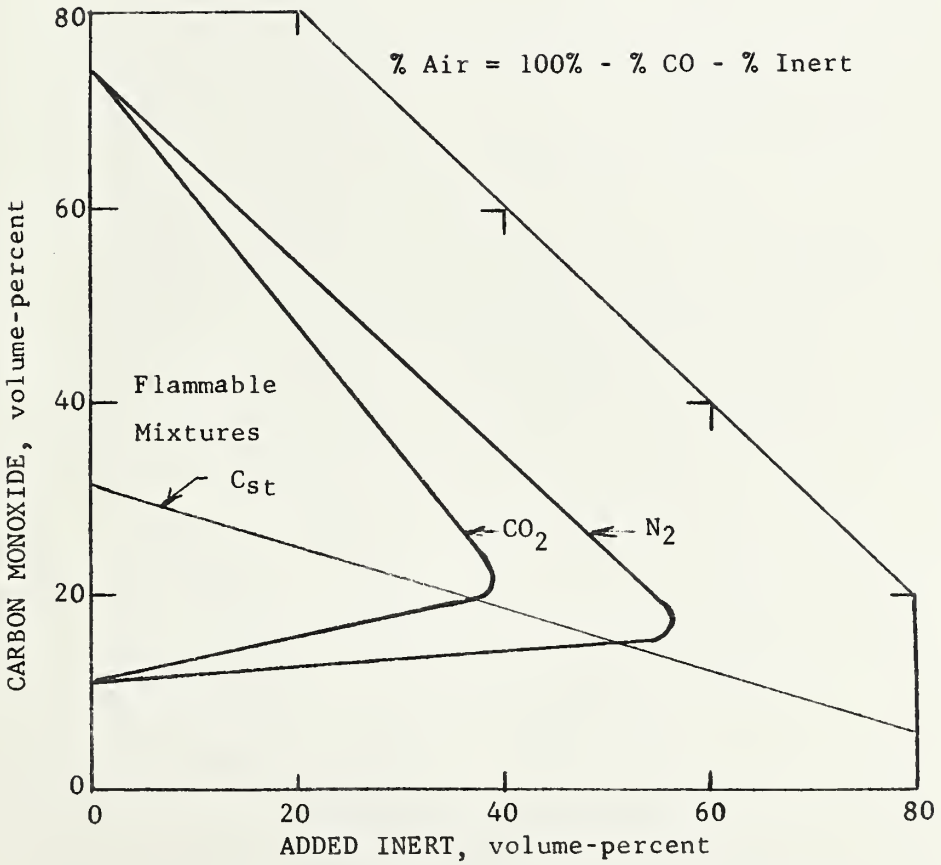


Fig. 7 Limits of Flammability of Carbon Monoxide-Carbon Dioxide-Air and Carbon Monoxide-Nitrogen-Air Mixtures at Atmospheric Pressure and 26°C [Ref. 2, Fig 126]


DEPARTMENT OF COMMERCE
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