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FIRE GROWTH EXPERIMENTS - TOWARD A STANDARD ROOM FIRE TEST

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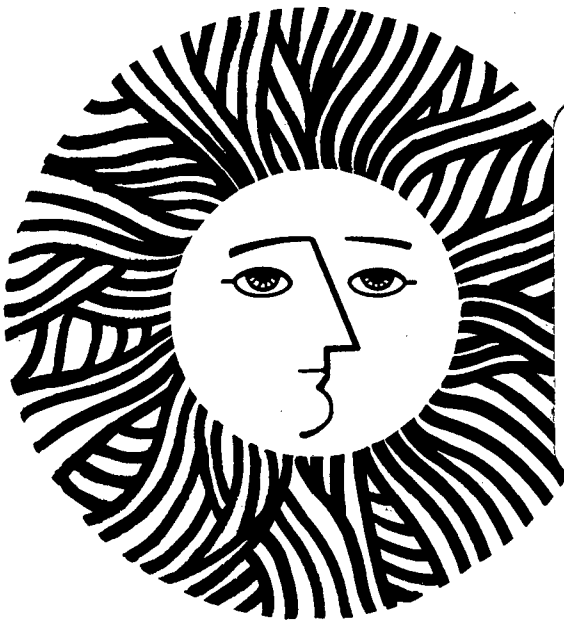

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ABSTRACT

This paper briefly reviews the use of full-scale room fire experiments and the development of a standard room fire test. A series of room fire experiments with a gas burner ignition source, and gypsum wallboard, glass fiber insulation and plywood linings are described in detail. The results of the experiments are discussed in the context of a standard room fire test.

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1.0 INTRODUCTION

There is a growing trend to use full-scale room fire experiments for evaluation of the fire growth characteristics of materials and building systems. Yet, in spite of this, there is still no standard version of a room fire test. The exact details of a standard room fire test are presently being debated by working groups within the American Society of Testing and Materials (ASTM). Their place of departure is the ASTM E603-77 Guide for Room Fire Experiments (1) which discusses the choices available for such parameters as compartment design, ignition source, instrumentation, test procedure, analysis of data and reporting of results. The current thinking favors a test compartment with a single door and the ignition source placed in one corner of the interior, away from the door.

The purpose of a large-scale standard test would be to evaluate the fire performance of materials or objects under actual in-use situations. The contribution of a specimen to the rate of fire growth, within a previously calibrated compartment, has been evaluated by many different research programs. For example, a "corner-wall" room fire test was one of the comparative tests used at the Forest Products Laboratory (2) to relate the 8-foot tunnel furnace to realistic fire situations. More recently, Lee and Parker (3) used both full-scale and quarter-scale compartments to study the contribution of furnishing and lining materials to fire growth. These and other similar research programs have found that compartment or room-like experiments were necessary in order to realistically predict the behavior of a specimen when subjected to a pre-flashover fire environment.

The principal small-scale, or laboratory-scale, fire tests in the United States for fire growth are ASTM E84 and E162 (1). Both of these tests have simplistic data reduction schemes which mask much of the true test specimen performance. In addition, many plastic specimens give little indication of how they will behave under end-use conditions. Presently, a series of small-scale tests are being developed, but there is a need for full-scale test data to support the validity of these tests. It is the authors' view that a standard room fire test could be used both as a development tool, and a performance

evaluation method until such time as a series of smaller, less expensive tests have been proven. Even then, new materials and systems which are different in principle from those already validated for small-scale fire tests would still require the full-scale test to show the applicability of small-scale tests.

This paper describes a series of fire growth experiments which have been directed toward answering several questions concerning a standard room fire test. First, can a room fire test be expected to be a repeatable, scientific experiment and supply information on which to base a prediction of the contribution of materials to fire growth? Second, what details have to be fixed to insure a meaningful standard test and what values should be chosen for such important parameters as the ignition source? Finally, what is the contribution of a thin cellulosic wall panel to fire growth under the standard test conditions? The dissemination of the test results for the experiments described in this paper will enable all parties involved in the concensus process to put the proposed test method into a proper perspective and to acquire an appreciation for the fire characteristics of cellulosic materials.

The importance of the ignition source and its placement was emphasized in Benjamin's review (4) of the history of room fire testing. For instance, whether or not the ignition source flames hit the ceiling during an experiment will drastically affect the fire development with combustible ceiling materials. If the ignition source does not put flames to the ceiling, then the fire can only reach the ceiling by traveling up the wall lining. One of the objectives of the experiments described below was to explicitly explore this point.

The ignition source is perhaps the most critical element in determining standard room fire test criteria since it should represent a realistic fire exposure for the test specimen and at the same time not bring the test compartment to flashover by itself (5). The ignition source currently under study is a .095 m^2 (1 ft^2), methane fed, porous ceramic burner which is located in one corner of the test compartment.

2.0 EXPERIMENTAL PROCEDURE

2.1 Experimental Compartment

The compartment experiments described in this paper have been conducted in a laboratory test bay having a total volume of approximately 1894 m^3 (65,000 ft^3). The test compartment was placed under a vent so that the combustion products generated in the compartment would flow by natural convection out of the test bay. The vent system used in experiments C-165 through C-172 is shown in Figures 1(a) and (b)*[1]. The vent system consisted of a sheet metal hood measuring 3.1 m X 3.1 m (10' X 10') in plan which connects to a 0.62 m X 0.62 m (2' X 2') square vent. A 0.9 m (3') deep skirt of 13 mm (1/2") thick gypsum wallboard was used to extend the depth of the hood to a point approximately .62 m (2') below the ceiling line of the compartment. The vent stack was open to the atmosphere above the laboratory roof and thus the flow was driven by natural convection from the experimental fires. The test bay itself was vented at ground level during each experiment in order to provide adequate "make-up" air.

The test compartment as shown in Figure 1(a) and (b) has inside dimensions of 2.44 m X 3.66 m X 2.44 m (8' X 12' X 8') with an open doorway of 2.05 m X 0.92 m (80" X 36"). The test compartment was constructed of a heavy steel frame which defines the vertical corners of the walls and the horizontal edges of the floor and ceiling. The walls and ceiling can then be considered to consist of panels which are attached to the steel frame.

In all tests, the composite wall and ceiling construction remained constant with respect to all components except the lining materials. The ceiling was composed of construction grade 38 mm X 89 mm Douglas Fir joists spaced on 0.406 m (16") centers. The exterior of the ceiling was sheathed in 13 mm (1/2") non-fire rated gypsum wallboard. All joist cavities were filled with R-11 glass fiber insulation without vapor barrier. In the tests in which the ceiling did not contain

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*[1]The vent system used in experiments C-162 through C-164 was different and will be discussed later.

**[2]Heretofore, all lumber dimensions are "nominal" where a 2 X 4 is actually 1.5" X 3.5" (38 mm X 89 mm)

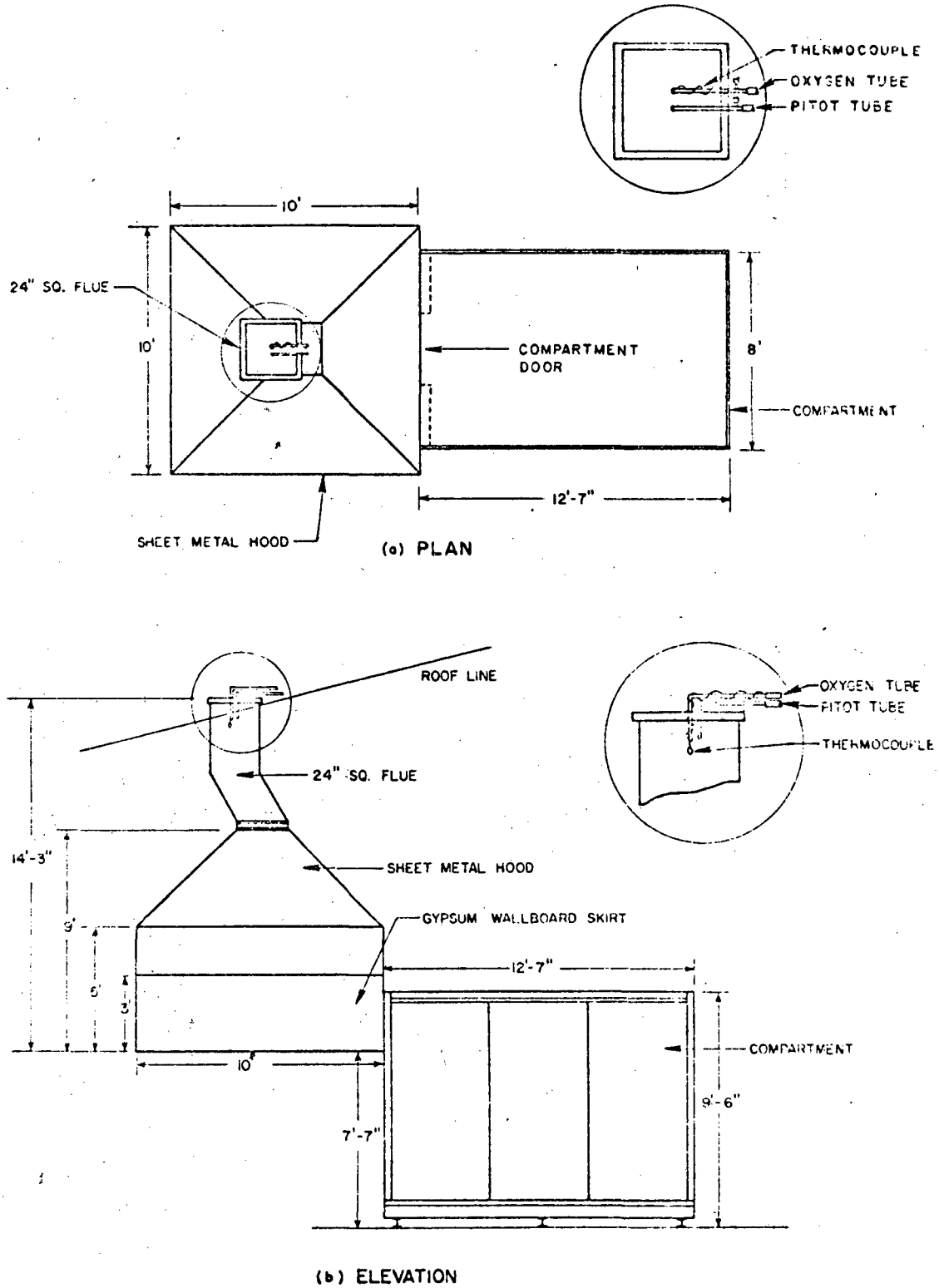


FIGURE 1: The Experimental Compartment and Vent System as Shown in Plan (a) and Elevation (b). This arrangement was used in Experiments C-165 through 172.

This paper focuses on a series of room fire experiments that have been conducted in a 2.44 m X 3.66 m X 2.44 m (8' X 12' X 8') test compartment with the following lining materials on all walls and ceilings:

TESTS NO.	WALL	CEILING
C-162	Glass Fiber Insulation	Glass Fiber Insulation
C-163,171,172	Gypsum Wallboard	Gypsum Wallboard
C-164	Plywood	Gypsum Wallboard
C-169	Plywood	Gypsum Wallboard
C-165-168	Glass Fiber Insulation	Plywood
C-170	Plywood	Plywood

The experimental conditions were chosen to be consistent with an early version of the standard room fire test method under consideration by ASTM except, a gas flow of 0.139 m^3/min (4.9 ft^3/min) of CH_4, 50% of of that in the current draft standard,*[1] was used. Measurements were made of:

(i) the oxygen depletion in the exhaust gases leaving the room,

(ii) the air temperature at a number of locations,

(iii) the pressure profile from floor to ceiling at the wall and at a single location in the center of the room,

(iv) the air flow and temperature at the doorway, and

(v) heat fluxes at several locations.

The experimental procedures will be described first, to be followed by the data, and finally, by a discussion of the results relevant to the above questions.

---

*[1]The current draft standard calls for propane and therefore a different flow rate.

a lining material (i.e., tests C-162 and C-169) the glass fiber insulation was supported with No. 20 B & S gage soft iron wire oriented perpendicular to the joists and spaced on 0.61 m (24") centers. Wherever the glass fiber insulation was exposed, the faces of the 2 X 4 lumber were covered with strips of gypsum wallboard in order to maintain an essentially noncombustible surface.

The walls were fabricated from construction grade 38 mm X 89 mm (2 X 4) Douglas Fir studs spaced on 0.61 m (24") centers and connected to single top and bottom plates. The walls were fabricated in 1.23 m (4') wide sections. The exterior of each panel was sheathed in 13 mm (1/2") non-fire rated gypsum wallboard. The wall panels were secured to the steel frame of the compartment by clips at the top, bottom and sides.

The gypsum wallboard used as an interior finish material in tests C-163 and C-164 consisted of a 13 mm (1/2") thick non-fire rated board measuring 1.23 m X 2.45 m (4' X 8') and having an average weight of 8.1 kgs/m^2 (1.66 lbs/ft^2). The unfinished plywood used in tests C-164, 168, 169 and 170 was 6.4 mm (1/4") A-D*[1] weighing approximately 3.66 kg/m^2 (0.75 lbs/ft^2). The moisture content**[2] of the plywood.

---

*[1]A-D refers to the grade of veneer used in the face plies of plywood panels. In all of these experiments the "A" face was exposed to fire.

A = Smooth and paintable ply. Neat repairs are permissible. Also used for natural finish in less demanding applications.

D = Permits knots and knotholes to 2-1/2" wide and 1/2" larger under certain specified limits. Limited splits are permitted.

REF: Ramsey and Sleeper, Architectural Graphic Standards, 6th Ed., John Wiley & Sons, 1970.

**[2]Moisture contents were calculated according to the procedure typically utilized by the wood products industry, given as follows:

$$\% \text{ Moisture Content} = \frac{W_T - W_D}{W_D} \times 100$$

where W_T = weight at test

W_D = oven dry weight

was determined at the time of each test and is presented with the data. All interior finish materials were attached to the 50 mm X 100 mm (2 X 4) studs and joists using type "S" screws spaced at approximately .305 m (12") on center.

2.2 Instrumentation

The instrumentation employed in these experiments evolved during the course of this research. Refinements were made in the hood used to trap combustion products, the oxygen monitoring system and the data acquisition system. The data obtained during experiments C-162 through C-164 indicated inadequacies and thus dictated certain changes which were implemented prior to the execution of experiments C-165 through C-170. The instrumentation employed and the modifications which were made are outlined below.

2.2.1 Temperature Measurements

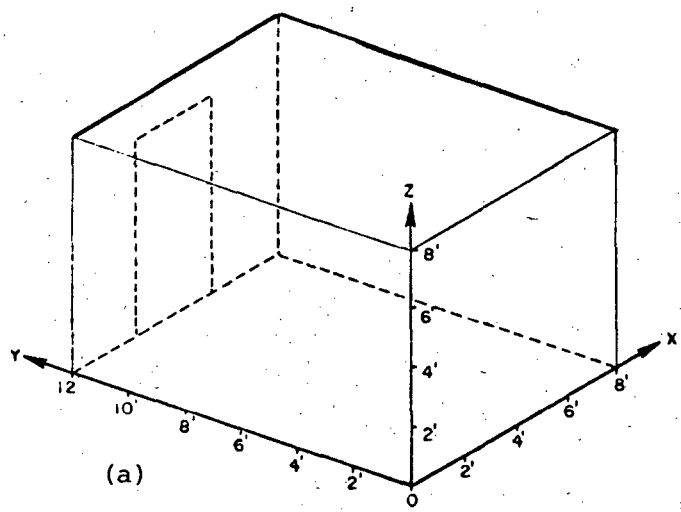
Temperatures were measured using Type K thermocouples fabricated from 24 AWG wire and having a bead diameter of approximately 0.5 mm. A complete listing of the thermocouple locations is presented in Table I. This table lists each thermocouple location using a right-hand rectangular coordinate system in which the origin is located at the floor level in the corner containing the ignition source.

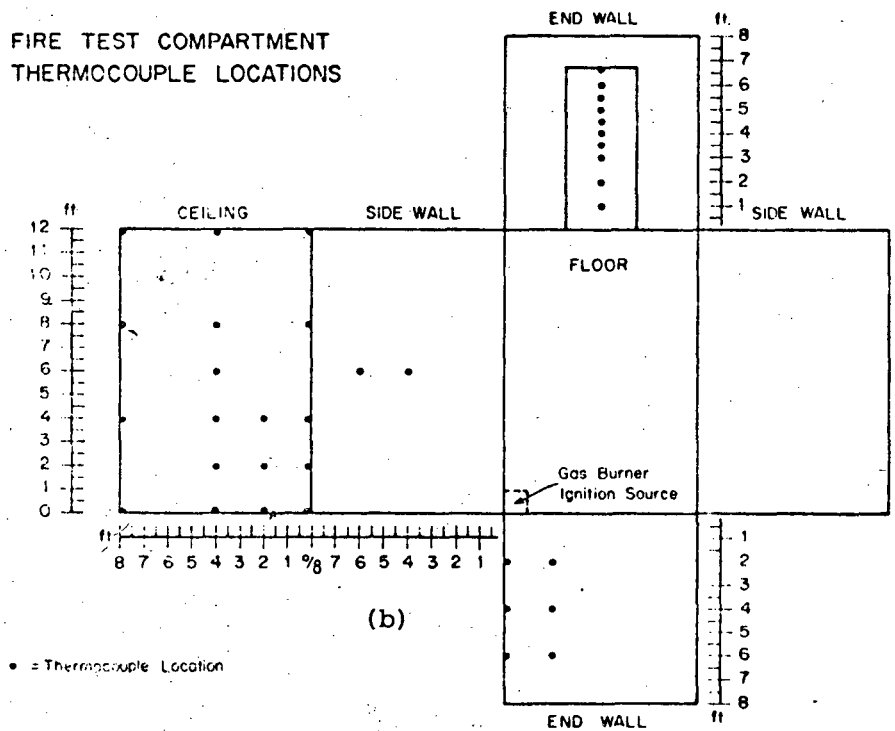
2.2.2 Heat Flux Measurements

Measurements of heat flux within the experimental compartment were taken at two locations; at the center of the ceiling and at the center of the floor. In both locations the heat flux gauges were mounted flush with the surface on which they were contained. The heat flux gauges were of the water cooled Gardon type and had a 180° view angle. The surfaces of the calorimeters were coated with a flat black finish and thus had an emissivity approximately equal to one. The heat flux gauges were cooled using a cold water source. This practice caused problems of water condensation on the calorimeter face during some of the experiments. In future experiments, use will be made of a hot water supply at a temperature of approximately 65°C (150°F) in order to decrease this problem.

TABLE I: List of Thermocouple Locations in Test Compartment (The location of thermocouples in the compartment is given in a coordinate system [x,y,z] shown in the schematic diagrams (a) and (b) below).

Ceiling Gas Thermocouples Ignition Corner[1]	Ceiling Gas Thermocouples Away from Ignition Corner	Door Thermocouples	Left Wall Thermocouples	Middle of Room	Right Wall Thermocouples
(0,0, 7'-11")	(4,6, 7'-11")	(4,12,1)	(0,6,4)	(4,6,4)	(0,0,2)
(2,0, 7'-11")	(8,0, 7'-11")	(4,12,2)	(0,6,6)		(0,0,4)
(4,0, 7'-11")	(8,4, 7'-11")	(4,12,3)			(0,0,6)
(0,2, 7'-11")	(8,8, 7'-11")	(4,12, 3'-6")			(2,0,2)
(2,2, 7'-11")	(4,8, 7'-11")	(4,12, 4'-0")			(2,0,4)
(4,2, 7'-11")	(0,8, 7'-11")	(4,12, 4'-6")			(2,0,6)
(0,4, 7'-11")	(8,12, 7'-11")	(4,12, 5'-0")			
(2,4, 7'-11")	(4,12, 7'-11")	(4,12, 5'-6")			
(4,4, 7'-11")	(0,12, 7'-11")	(4,12, 6'-0")			
		(4,12, 6'-8")			





[1]Ceiling Thermocouples are 25 mm Below Ceiling

2.2.3 Oxygen Monitoring System

The oxygen monitoring system consisted of a membrane-diffusion type of oxygen sensor, Bacarach Model #514-010, coupled to various filtering elements. Experiments C-162 through C-164 utilized a system in which a single large volume glass fiber filter was used ahead of the oxygen cell. This system proved inadequate in that water and CO_2 were not removed from the sample stream and thus adversely affected oxygen cell performance. Starting with experiment C-165 the system was modified to include a glass fiber filter cooled in an alcohol dry-ice bath, two ascarite filters and one perchlorate filter. The glass fiber filter was used to remove particulates and water. The ascarite filters removed carbon dioxide and the perchlorate filter removed residual water vapor not trapped by the glass fiber filter. The total empty volume of the inlet probe and filter elements was approximately 2.3ℓ. The volume displaced by the filter agents was estimated to be about 0.63ℓ resulting in a void volume of 1.67ℓ. This system proved capable of adequately conditioning the sample stream prior to entry into the oxygen cell; however, further modifications will be made to decrease the volume of the filtering system.

2.2.4 Gas Flow Measurement

Gas flows into and out of the compartment were monitored at three locations. The air inflow into the compartment was measured at a point 50 mm (~2") above the bottom of the door at its horizontal centerline. The gas velocity exiting the doorway was measured at its horizontal centerline 50 mm (~2") below the door top. Gas velocity was measured in the exhaust duct at the location shown in Figures 1(a) and (b). These flows were measured using pitot tubes whose static and dynamic pressure heads were measured using electronic pressure transducers (MKS Type 220A, 133 pascals full-scale). Conversion of the pressures to flow data was made using the relationships described by Bernouli's equations and the ideal gas law.

2.2.5 Data Acquisition System

The data acquisition system employed for experiments C-162 through C-164 consisted of a (FET switched) data logger capable of measuring

100 individual data channels of both thermocouples and millivolt inputs, at the rate of approximately 2 channels/second. This rate of data acquisition proved to be too slow to adequately document the events occurring during these experiments, particularly at the inception of flashover. The data on this system was recorded through the use of a high speed paper tape punch and a printed tape.

The experience gained during the first three experiments indicated that an increased rate of data acquisition was necessary. As a result, another data acquisition system was utilized for experiments C-165 through 170. The second system was centered around a minicomputer in which thermocouple inputs were multiplexed to the minicomputer by a 100 channel reed switched scanner. The minicomputer operating program and the experimental data were stored on a dual floppy disk system. This system of data acquisition enabled scanning of all of the thermocouples once each second. The millivolt outputs of the oxygen cell, pressure transducers and calorimeters were recorded by other means. The oxygen cell and heat flux gages were recorded using the older data logger while the outputs of the pressure transducers were continuously monitored using a chart recorder. This resulted in the oxygen cell and heat flux gages being read once each 15 seconds and in a continuous recording of the pressure transducers attached to the pitot tubes.

2.2.6 Photographic Documentation

Each of the experiments was documented using 35 mm color film and super 8 mm color movies. The frequency of photographs was dependent upon the state of fire growth within the compartment but, in general, photographs were taken at intervals of 30 seconds. The time was depicted on a digital clock which was driven by the data system.

2.3 Experimental Conduct

Each experiment was started by first igniting the gas burner ignition source at a very low gas flow rate. The data acquisition system was then activated and a 10 second countdown began. At time zero the gas flow was increased to its prescribed rate of 0.139 m^3/min

(4.9 ft^3/min) and all recording instruments were started. Photographs were taken at intervals of 30 seconds or less and visual observations were recorded throughout the duration of the experiment. The experiments were allowed to continue for a period of 15 minutes or until postflashover conditions were reached in which flames were no longer contained within the hood system and thus posed danger to the laboratory facilities. After the experiment reached flashover, the gas burner was shut off and the fire was allowed to continue burning. Extinguishment of the test fires was accomplished using a 38 mm (1-1/2") hoseline fitted with an adjustible nozzle able to produce a single stream or a fine spray.

During the experiments the fuel gas flow to the ignition source was measured with a turbine flow meter which produced a pulse output which was recorded by the data acquisition system. A pressure transducer was mounted on the outlet of the flow meter and its output was also recorded by the data acquisition system. The flow was adjusted to give 0.117 m^3/min (4.9 ft^3/min) of methane which translates into 1,260 Kcal/min (87.8 kW).

3.0 EXPERIMENTAL RESULTS

3.1 Overview

Eleven separate experiments which fall into four categories are summarized in Table II. Experiments C-162, 163, 171, and 172 are essentially calibration experiments in which the ignition source releases the only significant energy within the compartment. The second category is a pair of duplicate experiments, C-164 and C-169. which had plywood on the walls. These two experiments are particularly interesting since they took approximately the same time-to-flashover (within 15 seconds), and thereby illustrate the repeatability of these experiments. They also are useful in discussing the State Transition Model (STM) which was used in Table II to give more details about the experiments. That discussion will appear below. The four experiments, C-165, 166, 167, and 168 fall into a third category in which it was found that the plywood ceiling was not ignited unless the flame from the ignition source played directly on its surface. The ignition source was raised in experiment C-168 so that the flames would reach the ceiling and the compartment reached flashover in 6 minutes, 13 seconds. The fourth category, experiment C-170, was the fastest and most intense fire with plywood on both the walls and ceiling.

The summary in Table II uses the STM described by Williamson (6) in order to differentiate the fire growth in the experiments. Fire growth in the STM has been divided into three "states", J, K, and L, and are defined as follows:

J ≡ The period of time from the beginning of the experiment to ignition,

K ≡ The period of time from ignition of the specimen until flames touch the ceiling, and

L ≡ The period of time from when the flames first touch the ceiling until full involvement (flashover) occurs.

The use of STM allows beneficial comparison between fire growth experiments (6). The two experiments C-164 and C-169, both using plywood walls, one having gypsum wallboard ceiling and the other glass fiber insulation ceiling, are good examples illustrating the usefulness of STM. The state J for C-164 is 45 seconds as compared to 30 seconds

TABLE IIA: Summary of Fire Test - The states are discussed in text and ref. (6), flashover assumed when flames first emerge from door.

TEST NUMBER	MATERIAL		DURATION OF STATES			TIME TO FLAMES OUT THE DOOR	EXTINGUISH TIME	NOTES
	WALL	CEILING	J	K	L			
			min:sec	min:sec	min:sec	(J+K+L)	min:sec	
C-162	Glass Fiber Insulation	Glass Fiber Insulation	-	-	-	-	15:00	A
C-163	Gypsum Wallboard	Gypsum Wallboard	0:33	-	-	-	15:00	A
C-164	Plywood	Gypsum Wallboard	0:45	0:51	2:09	3:45	4:42	B MC = 6.16%
C-165	Glass Fiber Insulation	Plywood	-	-	-	-	10:00	B, D MC = 8.54%
C-166	Glass Fiber Insulation*	Plywood	-	-	-	-	1:00	B, D MC = 7.32%
C-167	Glass Fiber Insulation*	Plywood	-	-	-	-	10:00	A, D
C-168	Glass Fiber Insulation*	Plywood	-	3:42**	2:31	6:13	9:20	C MC = 7.23%
C-169	Plywood	Glass Fiber Insulation	0:30	0:50	2:40	4:00	5:13	A MC = 8.13%
C-170	Plywood	Plywood	0:16	0:39	1:56	2:51	4:10	A MC = 10.71%
C-171-2	Gypsum Wallboard	Gypsum Wallboard	-	-	-	-	15:00	A, E

NOTES

A - Surface of burner is 12" above the floor, against the wall

B - Surface of burner is 12" above the floor, 1" away from wall

C - Surface of burner is 34" above floor, against the wall

D - No ignition of the plywood occurred

MC - Moisture content of plywood at time of test

E - Calibration tests done with Gypsum Wallboard on the corner walls and ceiling. The remaining inside surface area of the compartment consisted of exposed glass fiber insulation

* - Gypsum Wallboard in corner on both walls behind ignition source

** - Ignition of ceiling

TABLE IIB: Comparison of total time of States J, K and L (i.e., "Time-to-Flashover") with the measurement of temperature, heat flux or the observation of flames out the doorway.

TEST NUMBER	TIME TO FLASHOVER (MIN) AS DETERMINED BY TIME TO REACH		
	650°C Ave. Gas Temp. 25 mm Below Ceiling	Flames Out of Compartment Door	$2w/cm^2$ at Floor Level (Center of Compartment)
C-162	-	-	-
C-163	-	-	-
C-164	3.2	3.5	NO DATA
C-165	-	-	-
C-166	-	-	-
C-167	-	-	-
C-168	5.6	6.2	6.5
C-169	3.3	4.0	4.0
C-170	2.1	2.9	3.1
C-171-2	-	-	-

for C-169 even though the moisture content of the latter was almost 2% higher. The probable origin of this delay is due to a 2.54 cm (1") spacing of the burner away from the wall in C-164 (see note B of Table IIA) as compared to the close spacing in C-169 (see note A of Table II-A). A review of the photographs shows that the ignition flame did not "attach" itself to the wall in C-164 as it did in C-169 and this lack of attachment delayed the ignition. It is also interesting to note from the photographs that the area of plywood which first ignited is approximately 10 cm above the plane of the burner. However, once the plywood wall was ignited the two experiments show essentially identical K states when the flame is spreading to the ceiling. Finally, the duration of state L is approximately 30 seconds shorter for experiment C-164 using the gypsum wallboard ceiling. The moisture content of the plywood in C-164 is the probable cause of the shorter state L, although the paper surface on the wallboard may also have contributed to the more rapid fire spread. Thus, on closer examination these almost identical experiments have differences. The significance of this example is that the division into three states allows a more detailed comparison than the frequently used time-to-flashover approach which was within 15 seconds for the two experiments.

Table IIB indicates the values of three criteria commonly used to determine flashover: 650°C average gas temperature 25 mm (~1") below the ceiling; flames emerging from the doorway; and, heat flux of $2W/cm^2$ at the floor of the compartment. Although these values are only available for experiments C-168 through C-170 they do indicate a close correlation between the projection of flames from the compartment door and the $2W/cm^2$ heat flux at the floor level. The time an average ceiling gas temperature of 650°C is reached appears to occur well before the remaining two criteria are reached, especially the floor heat flux.

The sequence of experiment C-165 through C-168 has important implications for a standard room fire test. The flame from the ignition source in its normal position did not reach the ceiling and experiments C-165 through C-167 produced no ignition of the exposed plywood ceiling. In experiment C-168 the plane of the burner was raised to 0.87 m (34") above the floor with the resulting regular impingement of flames on the

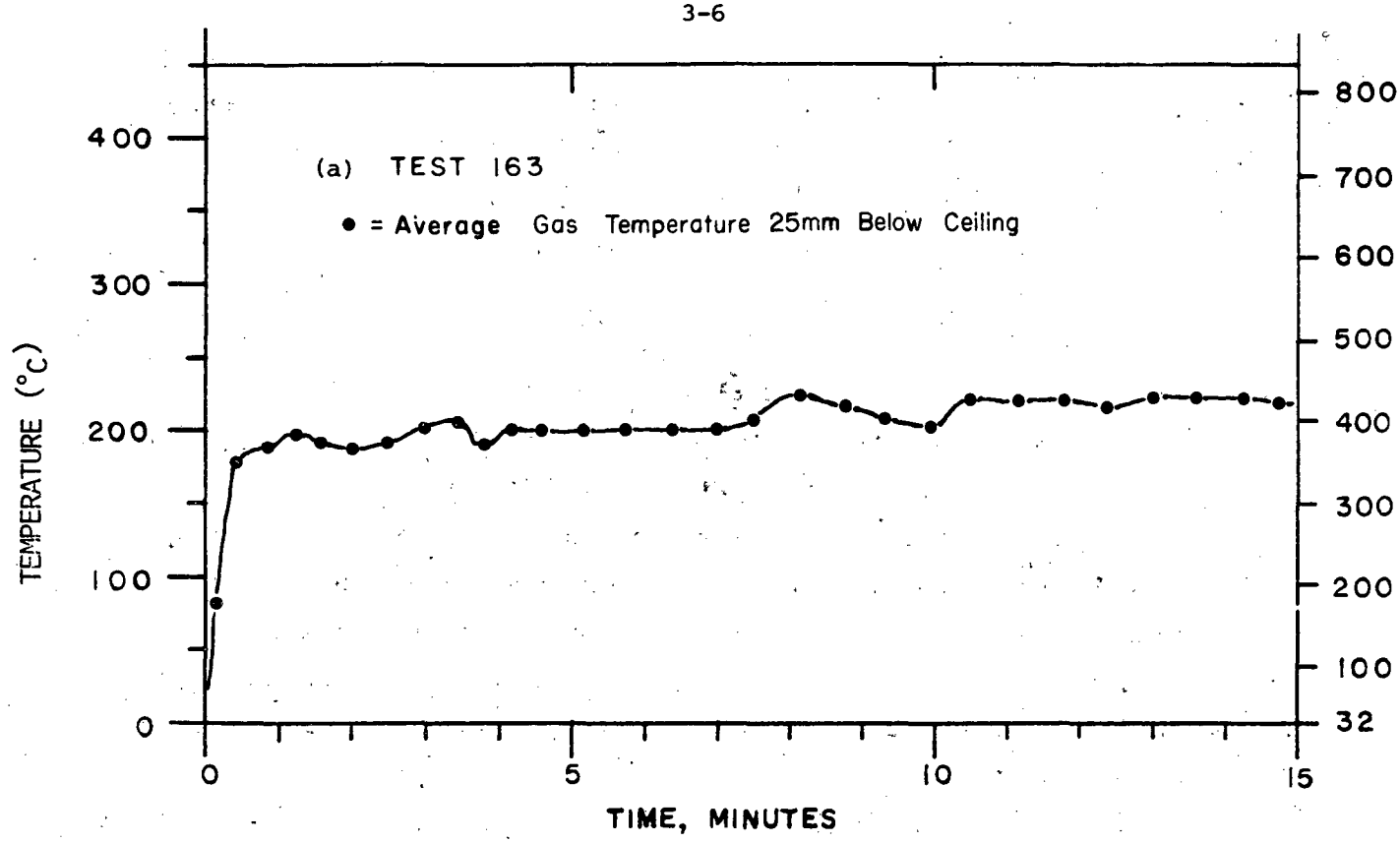
plywood ceiling. This led to ignition of the ceiling after 3 minutes, 43, seconds, and flames emerged from the door 2 minutes, 21 seconds later to signal flashover or full-involvement. If ceiling materials are to be tested alone, the standard room test will have to have an ignition source which reaches the ceiling. This will be discussed below.

3.2 Temperature and Heat Flux Measurements

The average temperatures 25 mm (1") below the ceiling for experiments C-163 and 172 are shown in Figures 2(a) and (b), respectively, and they are approximately 200°C from the beginning to the end of the experiments. These experiments can be considered calibration runs for the compartment. A different flow of gas to the ignition source or a change in the composition of the ignition gas would lead to a different average temperature. This type of measurement is essential for validating a standard test apparatus.

The average temperature 25 mm (1") below the ceiling for experiment C-164 is shown in Figure 3 and that for experiment C-169 in Figure 4. Both of these experiments had plywood on the walls and their average temperature 25 mm below the ceiling followed almost the same pattern. The slightly higher temperature for C-169 when flames emerged from the door may have been due to the lower $K\rho c$ of the exposed glass fiber insulation on the ceiling. The average ceiling temperature for experiment C-168, which had a plywood ceiling, is shown in Figure 5. In that experiment there was a steady period with an average ceiling temperature of approximately 250°C and then once the ceiling ignited, it rapidly rose to approximately 700°C where it remained for several minutes. During this period, flames steadily emerged from the door. Finally, the most rapidly developing fire was seen in experiment C-170 where the average ceiling temperature history, shown in Figure 6, was similar to that of the other experiments except that the time scale was compressed.

Each plot of average temperatures 25 mm (1") below the ceiling has certain features which reflect specific effects observed during the particular experiment. For example, experiment C-164 shows an initial shoulder at approximately 200°C which reflects the delayed ignition due to the gap between the ignition source and the wall. Other features of the



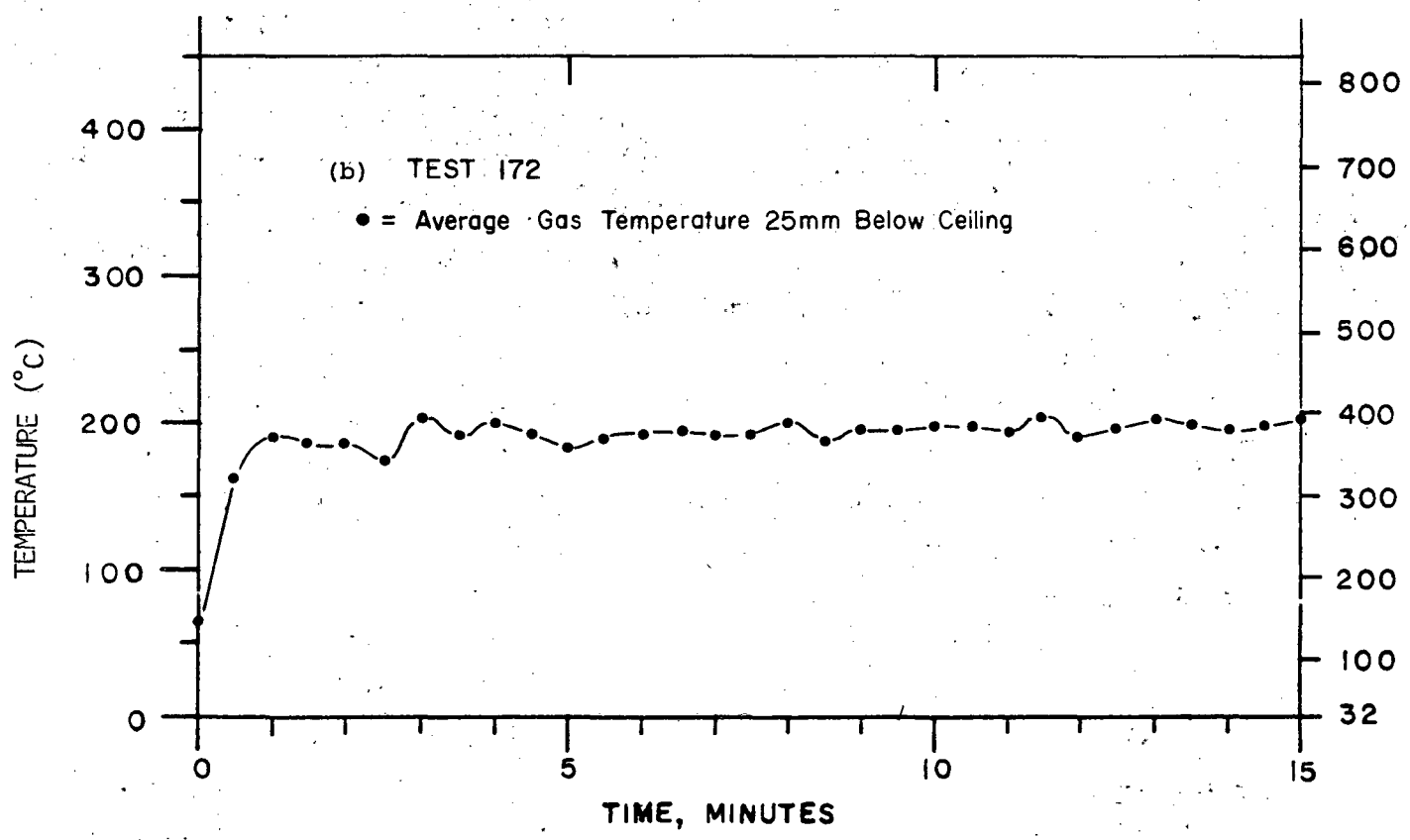


FIGURE 2: Average Temperature 25 mm Below Ceiling for Experiments with Gypsum Wallboard on Walls and Ceiling of Test Compartment (a) - Test C-163, (b) Test C-172.

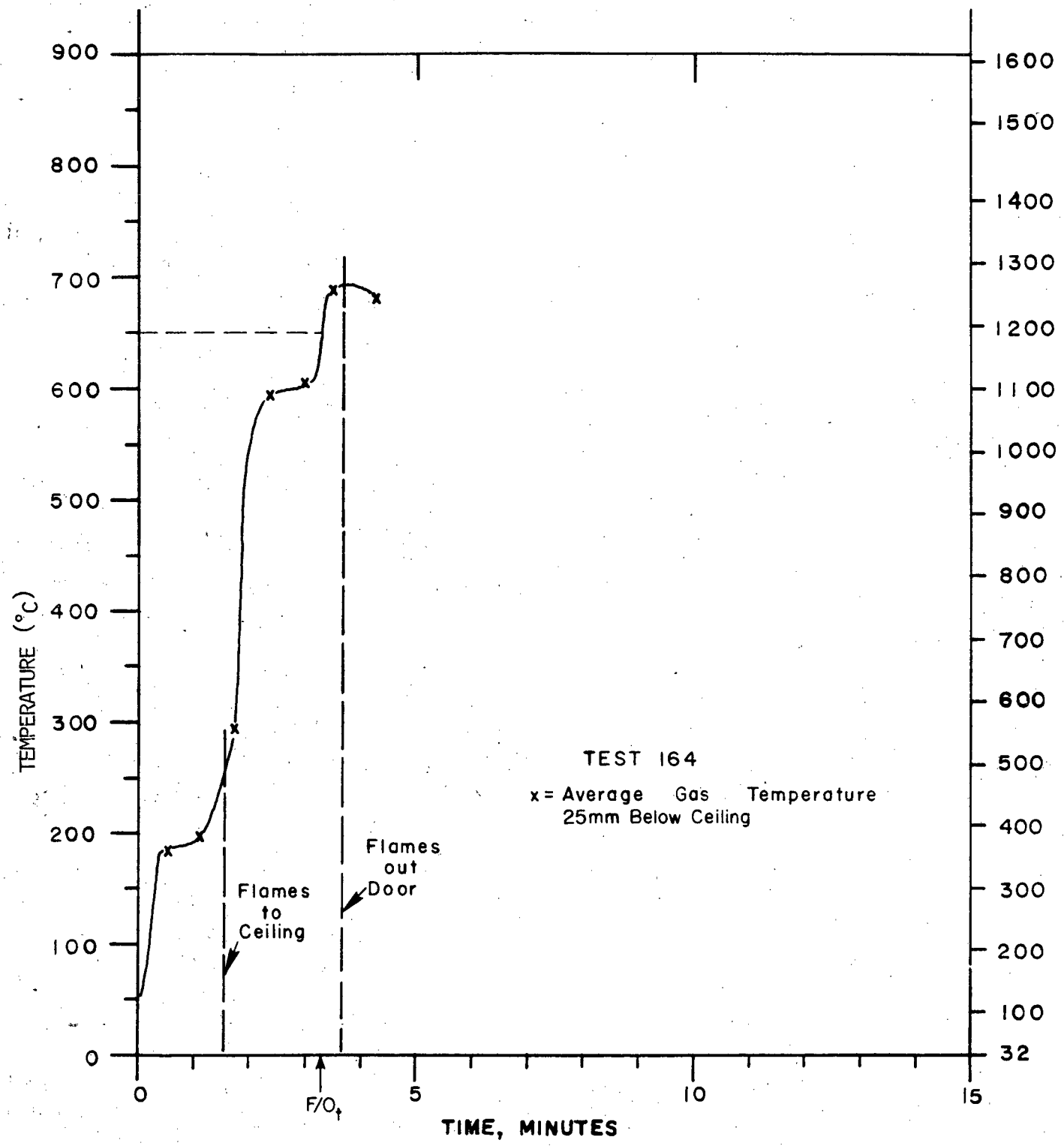


FIGURE 3: Average Temperature 25 mm Below Ceiling for Experiment C-164 which had 6.4 mm (1/4") Unfinished A-D Plywood on Walls and Gypsum Wallboard on Ceiling. There was a 2.5 cm (1") gap between the ignition source and the wall. F/O$_t$ denotes the time of flashover if a temperature criterion of 650°C is used.

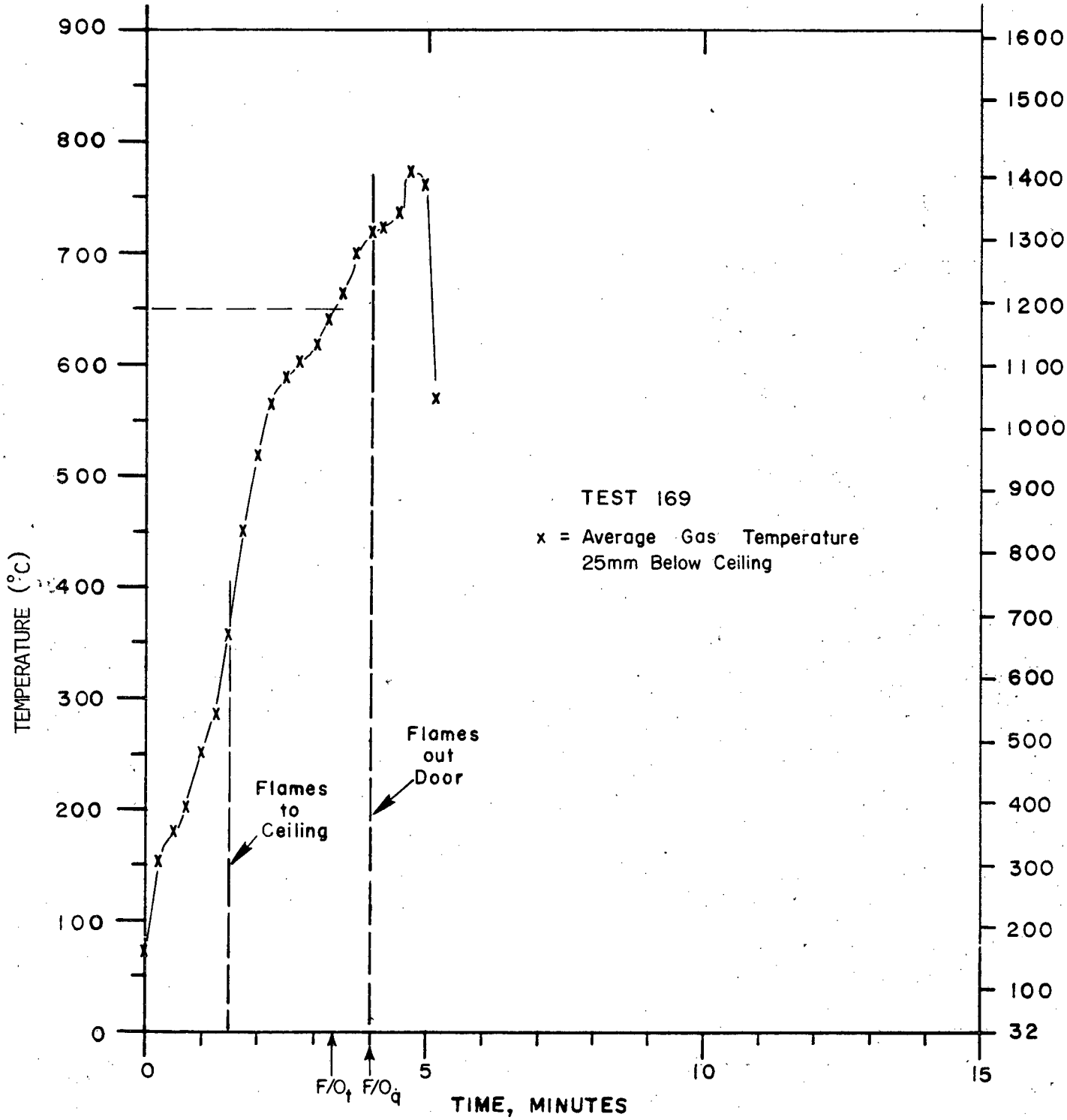


FIGURE 4: Average Temperature 25 mm Below Ceiling for Experiment C-169 which had 6.4 mm (1/4") Unfinished A-D Plywood on Walls and Exposed Glass Fiber Insulation on Ceiling. The ignition source was in contact with the wall. F/O_t denotes the time of flashover if a temperature criterion of 650°C is used. $F/O_{\dot{q}}$ denotes the time of flashover if a heat flux criterion of $2W/cm^2$ at the floor is used.

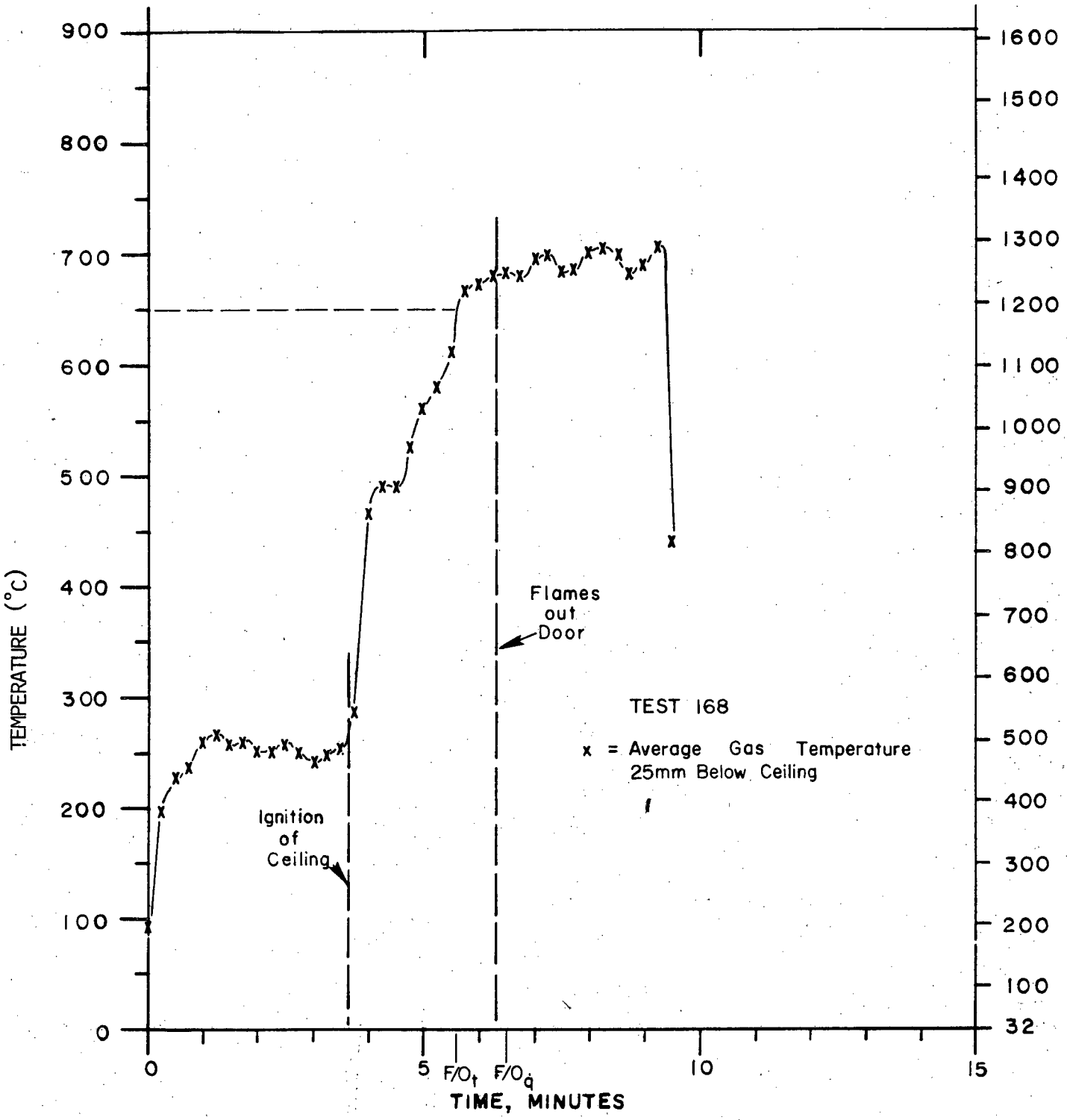


FIGURE 5: Average Temperature 25 mm Below Ceiling for Experiment C-168 which had Exposed Glass Fiber Insulation on Walls (except in the ignition corner which was covered with gypsum wallboard) and 6.4 mm (1/4") Unfinished A-D Plywood on Ceiling. It should be noted that the ignition source was raised 0.87 m (34") above the compartment floor. F/O_t denotes the time of flashover if a temperature criterion of 650°C is used. $F/O_{\dot{q}}$ denotes the time of flashover if a heat flux criterion of $2W/cm^2$ at the floor is used.

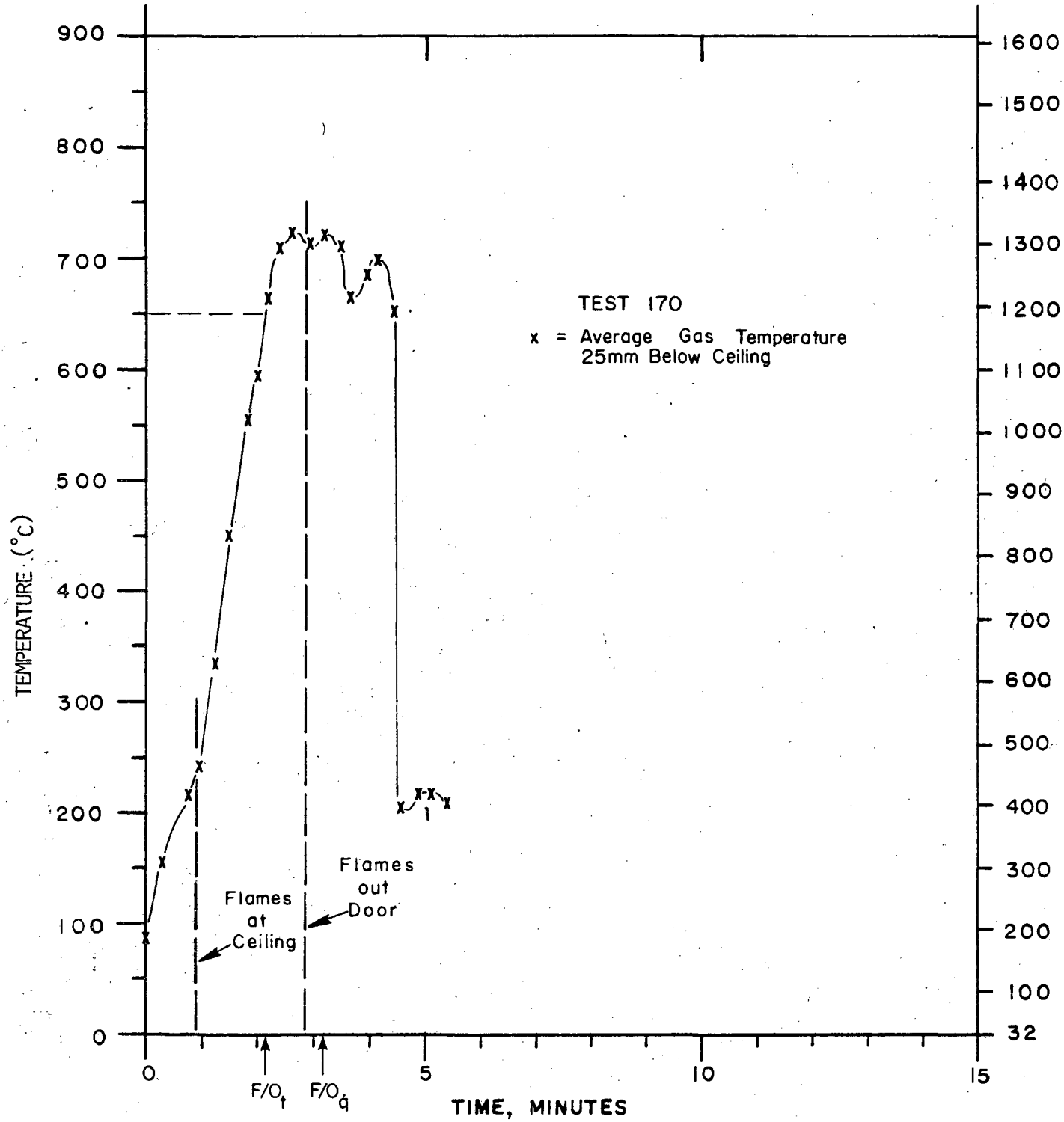


FIGURE 6: Average Temperature 25 mm Below Ceiling for Experiment C-170 which had 6.4 mm (1/4") Unfinished Plywood on both Walls and Ceiling. The ignition source was in contact with the wall. F/O_t denotes the time of flashover if a temperature criterion of 650°C is used. F/O_q denotes the time of flashover if a heat flux criterion of $2W/cm^2$ at the floor is used.

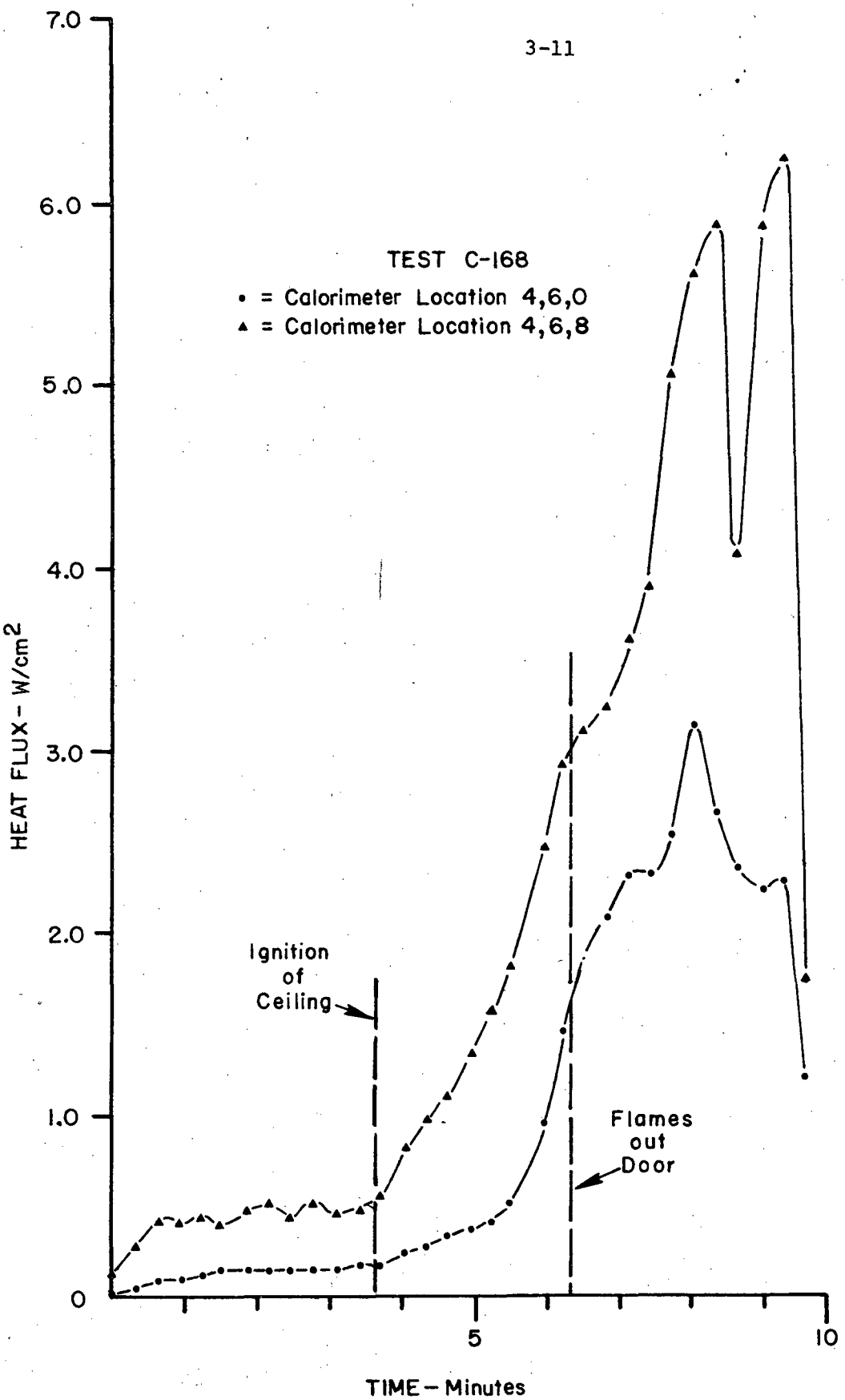


FIGURE 7: Total Heat Flux to the Center of the Floor (Location 4,6,0) and to the Center of the Ceiling (Location 4,6,8) for Experiment C-168.

average ceiling temperature plots are remarkably similar. The average ceiling temperature at the time flames emerge from the door is approximately 700°C. The same fuel and ventilation conditions would be expected to yield the same temperatures.

A typical measurement of the total heat flux during one of the experiments is shown in Figure 7. The heat flux gauge located at 4,6,8 was at the center of the ceiling and that at 4,6,0 at the center of the floor. It should be noted that there is a considerable differential between the ceiling and the floor heat flux; the heat flux at the floor is just under $2W/cm^2$ at the same time the flames emerge from the door. This will be discussed further below.

3.3 Oxygen Depletion and Flow Measurements

The heat release during a room fire test can be calculated from the oxygen depletion measured in the exhaust gases if the volume flow of those gases is measured. The measured oxygen depletion factor, ϕ, is given by:

$$\bar{\phi} = \frac{O_{2_i} - O_{2_t}}{O_{2_i}} \qquad (1)$$

where:

O_{2_i} = stabilized oxygen cell reading prior to the fire test.

O_{2_t} = oxygen cell reading at a particular time during the fire test (CO^2 removed).

This can then be translated into the actual oxygen depletion factor, $\bar{\phi}$, by the relation:

$$\phi = \bar{\phi}\,\frac{(1 + \chi)}{(1 + \chi\bar{\phi})} \qquad (2)$$

where:

$$\chi = \frac{\chi_{O_2}}{\chi_{N_2}} = 0.266$$

where χ_{O_2} and χ_{N_2} are the volume fraction of oxygen and nitrogen in the ambient air.

The corrected volume flow rate, V, was shown by Parker (7) to be given by:

$$V = \frac{\bar{V}}{[1 + (\alpha - 1)\phi]} \qquad (3)$$

where:

$\bar{V}$ = volume flow rate, corrected to STP, recorded from pitot tube in vent stack, and

α = expansion factor for the fraction of air that is depleted of its oxygen. It can be expressed as:

$$\alpha = 0.79 + 0.21\beta$$

Typical values of α: $\alpha_{wood} = 1.175$

$\alpha_{methane} = 1.105$

β = ratio of the moles of combustion products produced to the moles of oxygen consumed for a given fuel undergoing stoichiometric combustion (e.g., $\beta_{wood} = 1.83$, $\beta_{methane} = 1.5$).

Then the rate of heat release in the experiment, $\dot{Q}$, is given by:

$$\dot{Q} = 0.21\ V\phi E \qquad (4)$$

where

E = heat produced from the stoichiometric combustion of a given fuel with one unit volume of oxygen.

A sample calculation from experiment C-168 is shown on the next page to illustrate the magnitude of the depletion, flows, and finally, the heat release.

SAMPLE CALCULATION OF RATE OF HEAT RELEASE FROM MEASURED OXYGEN DEPLETION

Test C-168

Time of Calculation: 6 minutes, 29 seconds

$\chi = 0.266 \qquad O_{2_i} = 91.32 \qquad \bar{V} = 99.77\ m^3/min$

$\gamma = 1.175 \qquad O_{2_t} = 85.15 \qquad E \cong 4{,}021\ Kcal/m^3 O_2^*$

$$\bar{\phi} = \frac{O_{2_i} - O_{2_t}}{O_{2_i}} = \frac{91.32 \quad 85.14}{91.32} = \boxed{0.068}$$

$$\phi = \bar{\phi}\left[\frac{(1+\chi)}{1+(\chi\,\bar{\phi})}\right] = 0.068\left[\frac{1+0.266}{1+\ [\ (0.266)0.068]}\right] = \boxed{0.085}$$

$$V = \frac{\bar{V}}{[1+(\gamma-1)\phi]} = \frac{99.77\ m^3/min}{[1+(0.175)\ 0.085]}$$

$$= \frac{99.77\ m^3/min}{1.015}$$

$$= \boxed{98.31\ m^3/min}$$

$$\dot{Q} = (0.21)\ (98.31\ m^3/min)\ (0.085)\ \ (4{,}021\ Kcal/m^3)$$

$$\dot{Q} = 7{,}056\ Kcal/min = 492\ kW = 28{,}000\ Btu/min$$

*Values taken from reference (8)

Figure 8 shows the oxygen depletion as a function of time measured in experiments C-168 through C-172. It is readily apparent that experiments C-169 and C-170 gave only partial data because of their rapid fire growth and early extinguishment. On the other hand, experiments C-168 and C-172 were slow and long enough to give relatively complete data.

The volume flow of exhaust gases for experiments C-168 through C-172 are shown in Figure 9. These measurements are quite sensitive to fire conditions and do not have the appreciable time delay shown in the oxygen depletion measurements.

The calculation of heat release for experiment C-168 is shown in Figure 10 as a function of time. Initially, the value calculated from the volume flow and the oxygen depletion rate did not match the one calculated just from the burning of the ignition source, $\dot{Q}_B$. But after two minutes, these values matched fairly well. Then, after the ceiling ignited, there was another delay of one or more minutes before the total heat release rate, $\dot{Q}_T$, rose appreciably above $\dot{Q}_B$. The contribution of the specimen, $\dot{Q}_S$, is plotted in Figure 10 and it is apparent that it represents a major factor in the growth of the fire.

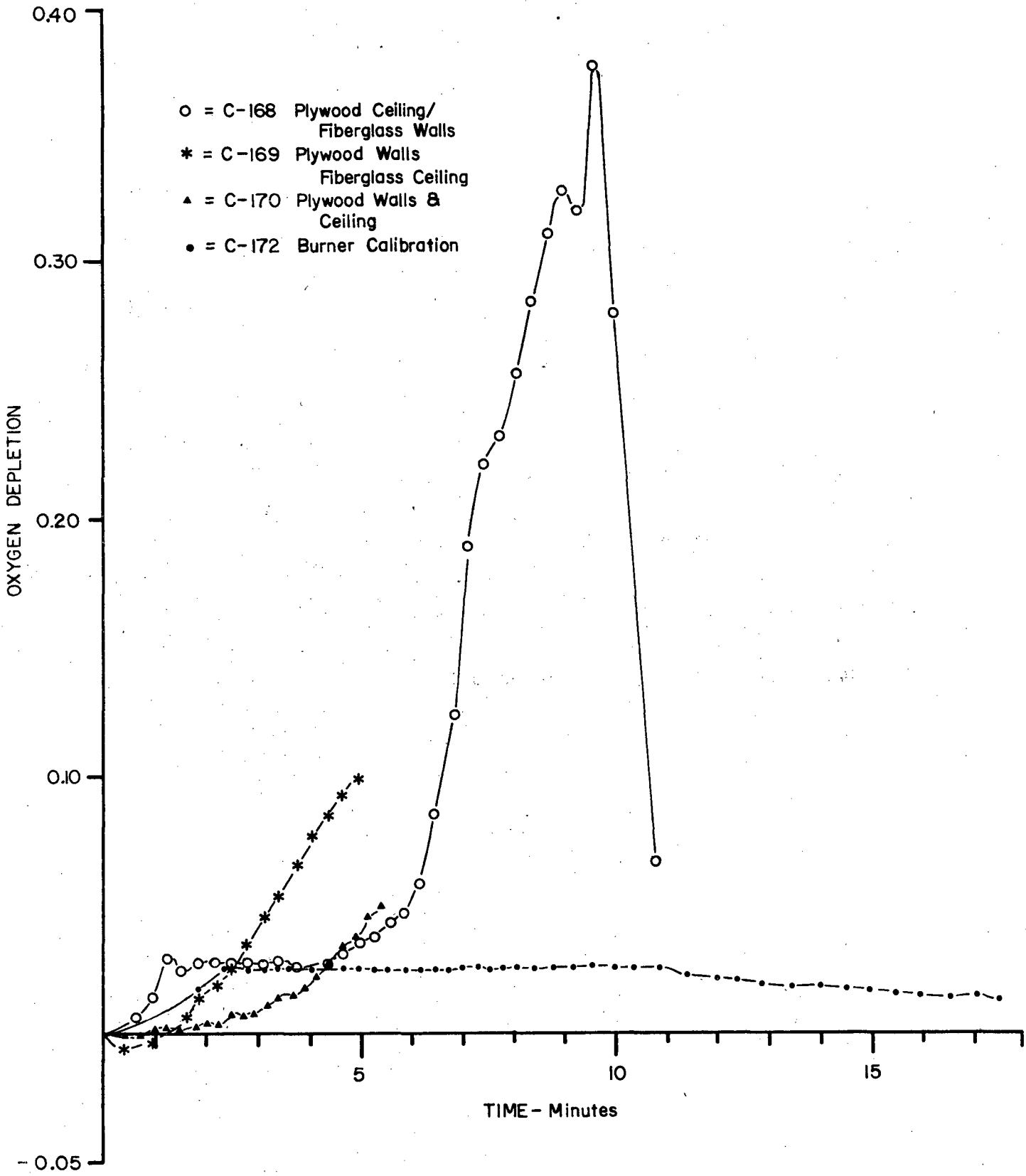


FIGURE 8: Oxygen Depletion from Four Experiments as Measured at the Top of the Exhaust Stack Shown Here as a Function of Time.

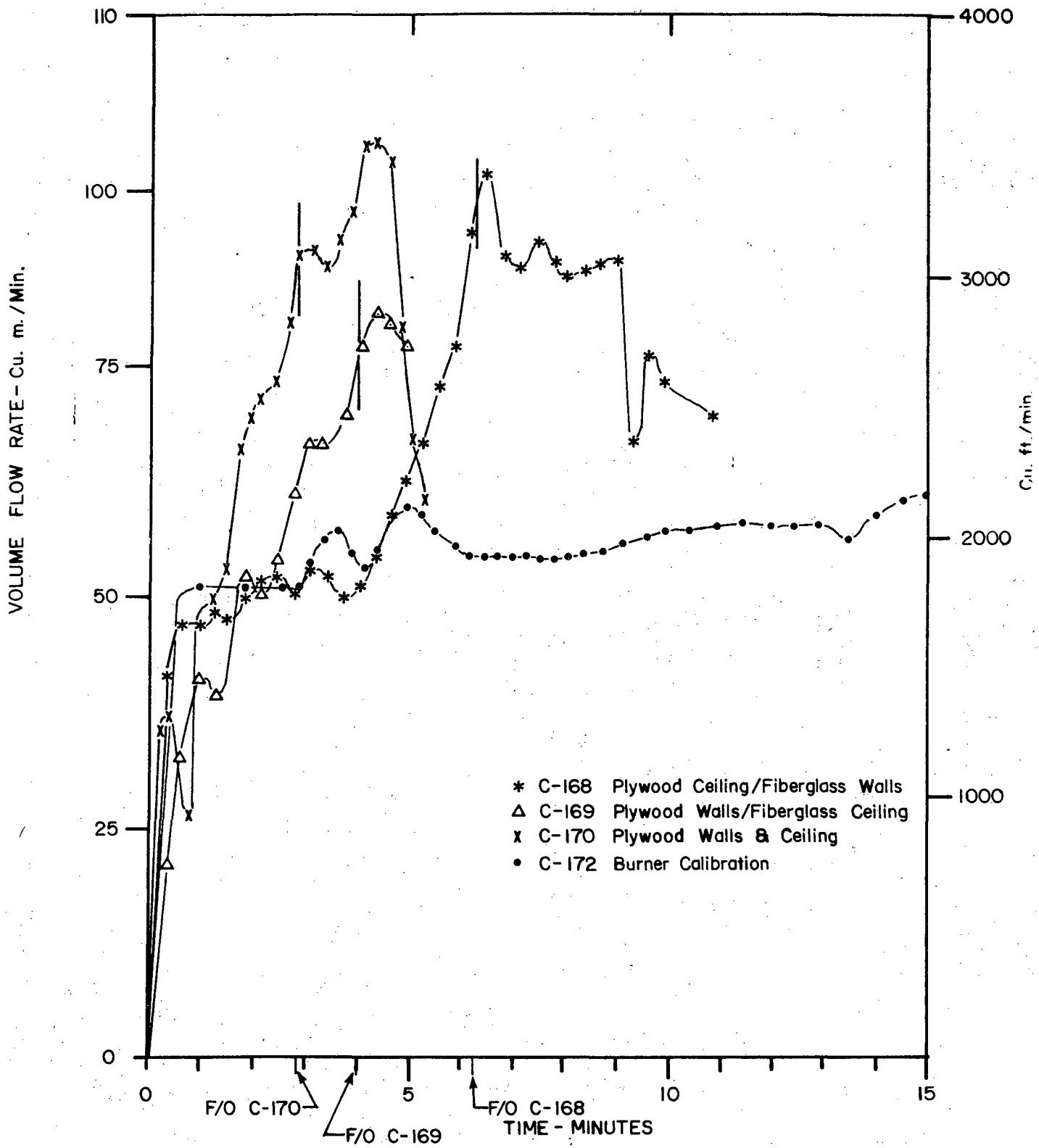


FIGURE 9: The Flow or Exhaust Gases at the Top of the Exhaust Stack is Shown Here for Four Experiments. Note: the rapid rise in volume flow as flames emerged from the compartment (marked F/O on the time scale).

*Volumes are corrected to a base of 60°F (16°C) and 1 atmosphere.

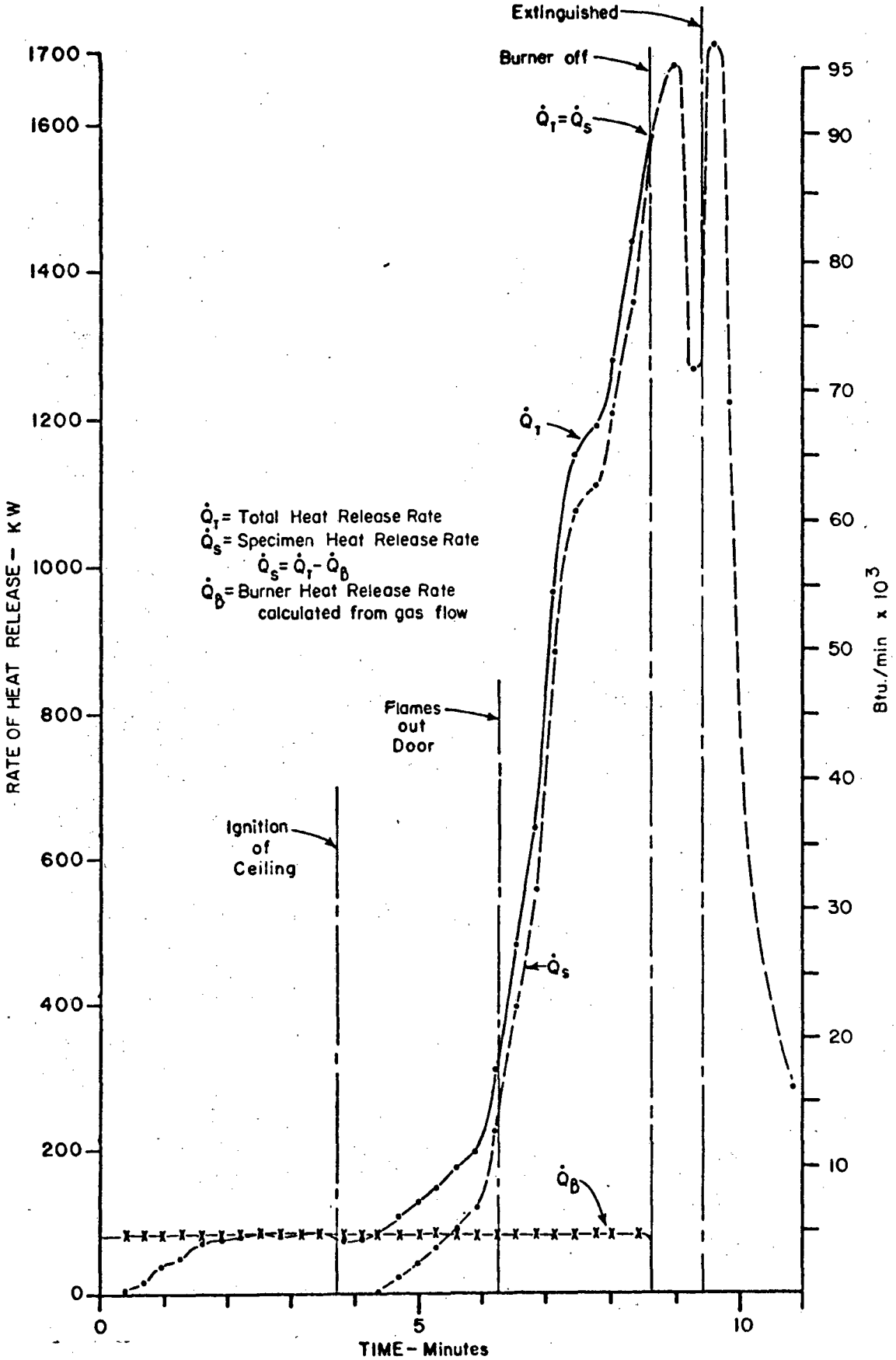


FIGURE 10: The Heat Release Rate for Experiment C-168 is Shown Here as a Function of Time. This was calculated from the oxygen depletion and exhaust flow data shown in Figures 8 and 9, respectively.

4.0 DISCUSSION

4.1 Contribution of Materials to Fire Growth - Possible Criteria

The ignition and spread of the fire on the plywood was clearly documented in the experiments described in this paper. The average gas temperature 25 mm below the ceiling, heat flux, visual observations, and the flow of oxygen depleted exhaust gases all reflected the contribution of the plywood to the growth of the fire within the compartment. The contribution of the specimen material in the standard room fire test would be documented in a similar fashion but there would be an additional imposition of pass-fail criteria to rank the tested material with other materials. The criteria might be based on the average gas temperature 25 mm below the ceiling, time-to-flashover, heat flux at the floor, heat release rate or other data from the test. The authors would like to suggest that the issue of criteria should remain fluid at this time, since a considerable amount of further research is required to establish such criteria.

Several points can be made on the basis of the experiments reported here. A definition of flashover needs to be established in the context of these experiments and the standard room test geometry. Parker (7) suggests that rather than defining flashover as the moment when flames emerge from the door it would be better to base flashover on fire conditions which are severe enough to ignite all of the combustibles in the room. Obviously, the ignition of isolated cellulosic indicator panels at the floor level would be a direct simulation of this basic fire condition. Furthermore, he suggests that flashover defined in this way correlates well with an average air temperature of 600-700°C 25-100 mm below the ceiling of the fire compartment and a radiant flux of $2W/cm^2$ at the floor level. All of these criteria are consistent with the measurements reported in this paper. One of the ultimate objectives of the standard room fire test would be to establish a classification of materials which would not cause flashover in the standard test.

It is the authors' opinion that the criteria finally chosen to determine flashover should be independent of visual observations. The reason for this is that visual observations (e.g., flames projecting from the doorway, ignition of target fuels on the compartment floor, etc.)

are dependent upon the judgement of the observer; as such they are more subjective than are the measurements made by some form of transducer (e.g., radiometers, thermocouples, etc.). Additionally, accurate visual observations can be hindered by the presence of large quantities of smoke, a condition which will certainly be encountered during tests of certain types of synthetic polymers. However, we believe that visual observations form an important part of the overall test record and that they can be useful as a secondary indication of flashover.

4.2 Ignition Source

The ignition source utilized in this study proved to be a reliable, repeatable device, yet there are some problems in utilizing it in a standard room fire test. First, it is the authors' opinion that the flames should reach the ceiling from its standard location without the walls contributing to the flame spread. This is necessary if ceiling and walls are to be evaluated separately. The three experiments C-165, 166 and 167 showed the futility of testing a ceiling when flames from the ignition source do not reach it.

As mentioned in the introduction, the gas flow in these experiments was less than the draft standard currently under consideration by ASTM. Preliminary experiments show that if the gas flow is increased to the burner to achieve 176 kW (10^4 BTU/min [gross]), the flames reach the ceiling. This is true for either methane or propane. The current ASTM draft standard specified propane because it has higher radiation which more closely approximates some actual ignition sources. The oxygen depletion measurements shown in Figure 8 and the resulting heat release rate shown in Figure 10 indicate that the proposed increase in heat release rate of the ignition source would not have been excessive. Figure 10 shows that the specimen contribution increased from approximately 211 kW to approximately 845 kW in the one minute following 6:13 when the flames emerged from the door. Because of the time delay in the measurement system, this increase probably occurred prior to the flames emerging from the door and it illustrates that the increased heat release rate from the proposed ignition source is well below the heat release rate required for flashover.

The spacing between the ignition source and the wall is another

critical parameter which must be fixed in the standard test method. There were photographs presented earlier (5) of the differences between a corner, side-wall, or open placement of a diffusion burner, but the differences noted in experiments C-164 and C-169 show that even a small distance can make a difference.

4.3 Oxygen Depletion and Determination of Heat Release

It is reasonable that the heat release rate determined from the oxygen depletion of the exhaust gases from a standard room fire test could be used as one measure of the contribution of the test specimen to fire growth, and the results shown in Figure 10 are encouraging. Unfortunately, the simple oxygen measuring cell utilized in these experiments does not appear adequate. The major problem encountered in the use of this type of cell was baseline drift. The cell was operated at a sample flow rate of 1 ℓ/min (2.12 ft^3/hr). Such a sample flow rate caused significant (on the order to 1-2 minutes) time delays in the overall system. Attempts to decrease response time consisted of decreasing the total volume of the filtering system as well as increasing the sample flow rate. Increases in sample flow rate had the effect of increasing the baseline drift to an intolerable level.

If this cell is to be used to measure oxygen depletion in the standard room test, it will be necessary to specify a filter system and a flow rate through the filter system which will significantly decrease the sample transit time. Parker (7) has suggested that the sample transit time could be significantly decreased by employing a high flow velocity through the filtering system and using a low velocity tap at the exit of the filter system for input to the cell. This method should decrease transit time without introducing a large baseline drift in the cell output. The main advantage of using this type of oxygen cell is its low cost (~$150/cell); however, before it can be specified for use in the standard test it must be demonstrated that the problems encountered to date can be solved.

Perhaps a solution to this problem is apparent in Figure 9 which shows the volume flow rate for exhaust gases in four different experiments. Note that for experiments C-168, 169 and 170 there was a rapid rise in flow just prior to the emergence of flames from the door. It

may be practical to simply establish a criteria based on this exhaust flow in the standard room test. Again, as discussed with respect to flashover, the analytical models of fire growth could give some scientific basis to this criterion.

The use of a large duct as shown in Figure 1 is essential to capture the exhaust gases from any room fire experiments which approache flashover. The earlier duct shown schematically by Van Volkinburg et al (5) was not adequate for flashover conditions. Additionally, the use of forced ventilation in the flue may present a problem under standard room fire test conditions and it should be investigated. Certainly the natural ventilation of the flue in these experiments allowed the measurements of the fire generated flow without a correction for mechanical assistance.

4.4 Toward a Standard Room Fire Test - Conclusion

The fire growth experiments described above have been directed toward answering the questions posed in the introduction. The results of these experiments cause the authors to believe that it is indeed possible to evolve a standard room fire test which is a repeatable, scientific experiment able to supply the information allowing a prediction of the contribution of materials to fire growth. Much of the previous discussion addresses this question. In establishing a standard test many details will have to be fixed to prevent undesirable scatter in the results. There are a number of observations in the experiments reported above which need to be considered in the standard test. There are other items, such as criteria and size of the ignition source, which are more than mere details; they are major components of a standard test method. This presents a further area where these experiments provide a better understanding of major parameters.

Finally, the experimental results described here provide information on the question of the contribution of a thin cellulosic material to fire growth under the standard test conditions. It has long been recognized that thin cellulosic materials, such as the plywood used in these experiments, can contribute to a rapid fire growth and the dissemination of these experimental results will enable all parties

involved in the concensus standard process to put the proposed test method into perspective. It is the authors' view that the standard room test would be utilized on materials which contribute considerably less to fire growth, but these experiments represent a bench mark for comparison with other materials.

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