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Heat Release Rates from Wall Assemblies

Oxygen Consumption and Other Methods Compared

John J. Brenden
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The rate of heat release is increasingly used to assess the overall fire performance of both individual materials and assemblies. In this study, wall assemblies containing either fire-retardant-treated wood members or steel members were exposed to fire using American Society for Testing and Materials (ASTM) Method E 119

(1) to obtain additional information on the performance of fire-retardant-treated wood-based structural assemblies exposed to fire;

(2) to extend methods of measuring the rate of heat release in individual construction materials to full-scale structural assemblies;

(3) to compare heat release rates obtained by the oxygen consumption, substitution, and weight of material/heat of combustion methods;

(4) to determine if heat release rate measurements can be incorporated into ASTM Method E 119.

Fire-retardant-treated wood had a low heat release rate under ASTM E 119 exposure conditions. The onset of active heat release occurred at least 23 minutes after initial fire exposure.

The oxygen consumption method was shown to be the most advantageous way of measuring the heat release rate since only one test was required and the rate of heat release could be measured over time. However, this method requires careful monitoring of temperature, oxygen, and mass velocity in the exhaust gases as well as monitoring of the exhaust concentrations of carbon dioxide and water vapor.

The experiments described in this paper also demonstrated how heat release measurement methodology can be extended from single materials to assemblies. However, construction details of individual furnaces limit the kinds of exhaust gas measurements possible and, therefore, the extent to which these techniques can generally be incorporated into ASTM E 119.

Keywords: Heat release, heat release rate, wall assemblies, fire-retardant-treated wood, ASTM Method E 119, oxygen consumption, fire-test furnace operation.

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	<i>Page</i>
Introduction and Objectives	1
Background	1
Experimental Methods	2
Wall Assembly Construction	2
Furnace Design and Fire Exposure	3
Test Design	3
Substitution Method	4
Oxygen Consumption Method	4
Weight of Material/Heat of Combustion Method ...	7
Results and Discussion	10
Conclusions	11
Literature Cited	11
Nomenclature	12
Appendix A—Calculation of Heat Release Rate by the Substitution Method	13
Appendix B—Oxygen Consumption Calculations in Detail	14
Appendix C—Stack Gas Velocity Measurements ...	19
Appendix D—Combustion Calculations	20

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Introduction and Objectives

In recent years, the concept known as rate of heat release (RHR) or heat release rate (HRR) has been increasingly used to assess the overall fire performance of both individual construction materials and combinations of materials (assemblies). The HRR is a comparative measurement of the heat contributed by a material or an assembly to its surroundings during fire exposure. HRR data can be applied to mathematical models that describe fire growth in rooms, enclosures, and compartments.

This report describes a cooperative effort among the National Forest Products Association (NFPA), Washington, DC; Forest Products Laboratory (FPL), Madison, WI; and the Center for Fire Research at the National Bureau of Standards (NBS), Gaithersburg, MD. The objectives were: (1) to obtain additional information on the performance of fire-retardant-treated wood-based structural assemblies exposed to fire; (2) to extend methods of measuring HRR in individual materials to full-scale structural assemblies; (3) to compare HRR obtained by the substitution, oxygen consumption, and weight of material/heat of combustion methods; and (4) to determine if HRR measurements can be incorporated into American Society for Testing and Materials (ASTM) Method E 119.

¹Retired, 1982.

Background

Considerable effort has been expended in developing instruments and techniques for measuring HRR. Parker and Long (1972) at the National Bureau of Standards, Brenden (1975) at FPL, and Smith (1971) at Ohio State University each developed a different type of calorimeter. Chamberlain (1982,1983) described several methods for determining HRR of lumber and wood products. Only a few studies have measured the HRR of full-scale assemblies of construction materials (ASTM 1982, Fang 1982, Fitzgerald 1978).

Three methods of measuring HRR have been developed: the substitution method, the oxygen consumption method, and the weight of material/heat of combustion method. In the substitution method, the amount of fuel supplied to the exposure furnace during the test of a "reference" (noncontributing) wall assembly is compared to the amount of fuel supplied during a test of a combustible test wall. The difference in fuel consumption required to maintain the ASTM temperature-time (T/t) curve is, in principle, equivalent to the heat released by the test wall. Chamberlain² adapted the substitution method of Thompson and Cousins (1959) to measure HRR during an ASTM E 119 standard test (ASTM 1978) for fire endurance of full-scale wall assemblies. Two successive fire exposures were performed. One exposure was made using a "reference" or noncontributing gypsum wallboard wall assembly containing steel studs and plates.

²Chamberlain, D. L. Heat release rates of construction assemblies. I. The substitution method. Washington, DC: National Forest Products Assoc. Manuscript in preparation.

Experimental Methods

The other exposure was made with a "test" wall assembly, identical to the reference except that the studs and plates were of nominal 2- by 4-inch fire-retardant-treated southern pine lumber. Chamberlain's work formed the basis for the study reported here.

The recently developed oxygen consumption technique for measuring HRR is based on the observation that heats of combustion per unit mass of oxygen reacted (consumed) are approximately the same for most fuels. As demonstrated by the work of Huggett (1980), Parker (1977, 1982), and Thornton (1917), the advantages of the oxygen consumption technique are that HRR values may be obtained from a single exposure (reference assembly not required) and that HRR is independent of heat loss from the specimen or furnace. The oxygen consumption method requires knowledge of the furnace fuel composition and mass flow rate and accurate measurement of the mass flow of air into and out of the exposure apparatus. Complete combustion is assumed (with end products of carbon dioxide and water vapor). Chamberlain's attempt to use the oxygen consumption method in ASTM E 119 tests failed because the geometry of the particular exhaust duct from the furnace prevented accurate measurement of exhaust velocity (manuscript in preparation).

The weight of material/heat of combustion method of measuring HRR consists of comparing the heat available for release before and after a test. The difference between the two end-point values is regarded as the heat released during the test. The heat available for release before a test is the weight of wood multiplied by its heat of combustion per unit weight. The heat available after a test is the sum of the weights of unburned wood and char, each multiplied by their respective heats of combustion.

Wall Assembly Construction

The wall assemblies used in our experiments were designed to simulate nonload-bearing interior walls without insulation in the stud cavities. The 8-foot-high by 10-foot-wide assemblies contained either fire-retardant-treated wood members or steel members and were fabricated with 5/8-inch-thick gypsum wallboard commonly used for fire-resistant construction. The wallboard, furnished in 4- by 8-foot sheets, was fastened to both the exposed (fire) and unexposed (room) sides of each wall assembly. Figure 1 shows an assembly, mounted in a masonry frame, shortly after joint-sealing compound had been applied to the seams and fastening points. At least 12 hours of drying were allowed before exposure to fire. The kraft paper surface of the gypsum wallboard was left in the unfinished condition as-received, and no insulation was placed in the stud cavities of the walls. A Chromel-Alumel (20 gauge, type K) thermocouple was mounted at the midpoint of the center stud cavity for recording the stud-cavity temperature.

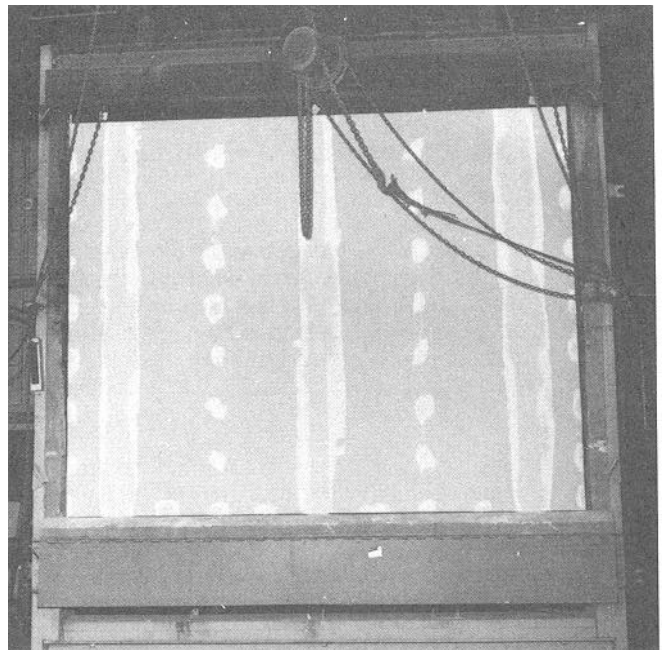


Figure 1.—Typical wall assembly after application of joint-sealing compound. Assembly is mounted in a moveable frame. (M 150394-7)

Figure 2 show construction details for the wall assemblies made with fire-retardant-treated members. The vertical members were braced at 5 feet. The nominal 2- by 4-inch studs were representative of commercially available fire-retardant-treated wood. This pressure-treated product, designated FR-S, is intended for interior use. The reported chemical retention is in the range of 3 to 4 pounds per cubic foot (lb/ft^3). When conditioned to equilibrium at 80°F and 30 percent relative humidity, the moisture content of the wood ranged from 7 to 9 percent, based on the oven-dry weight of the treated wood. The wallboard was fastened to the wood stud members with nails placed 7 inches on center. Glass fiber insulation was used to seal the wall assemblies into the frame (fig. 1) on the top, bottom, and both vertical ends.

Figure 3 illustrates construction details for the wall assemblies made with steel members. The 3-5/8-inch by 8-foot-long, 25-gauge galvanized steel studs were representative of those in common usage. The studs were anchored at the top and bottom by galvanized steel track fastened with 3/8-inch panhead screws. The wallboard was attached with screws at intervals of 8 inches on center along the horizontal track and 12 inches on center along the vertical studs. To furnish a smooth surface, joints in both types of assembly were covered with paper tape and two applications of joint-sealing compound; screws and nails were covered with two applications of compound alone.

Furnace Design and Fire Exposure

The assemblies were exposed to fire in the vertical wall furnace shown in figure 4. This furnace, originally designed to accommodate 10- by 10-foot wall sections, was modified to accept 8- by 10-foot specimens through the addition of concrete blocks along the bottom front edge. It is a gas-fired furnace which burns a mixture (approximately 1/10 ratio) of natural gas and (primary) air in 60 stainless-steel nozzles of 0.75-inch diameter. Supplemental (secondary) air enters the furnace around the burner mounting holes and through eight 3-inch-diameter openings at the bottom of the rear wall. The supply of air (both primary and secondary) and the fuel-air mixture were adjusted to give a soft, luminous flame. Eickner (1975) has described the furnace in detail.

Furnace operation and all test exposures were conducted according to the ASTM E 119 standard (ASTM 1978). The furnace temperature was programmed to follow the E 119 temperature-time curve (fig. 5).

Test Design

Three "runs" (runs I, II, and III) were made in the study. Each run consisted of two tests: one test with a steel reference assembly (A) and the other test with a fire-retardant-treated wood assembly (B). Accordingly, the six assemblies are designated I-A, I-B; II-A, II-B; and III-A, III-B. Tests were conducted on the second and fourth days of the same week, and exposure conditions for each run were held as constant and uniform as possible.

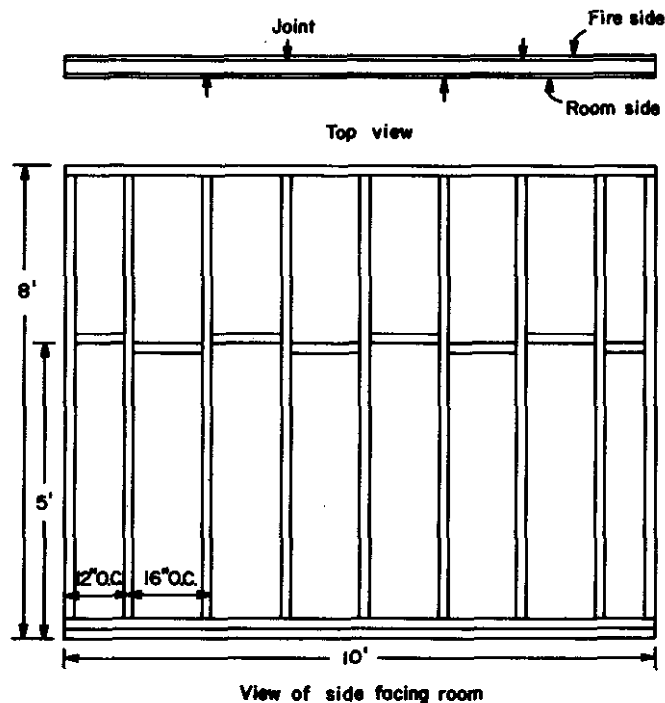


Figure 2.—Construction details for wall assemblies made using fire-retardant-treated wood. (ML85 5572)

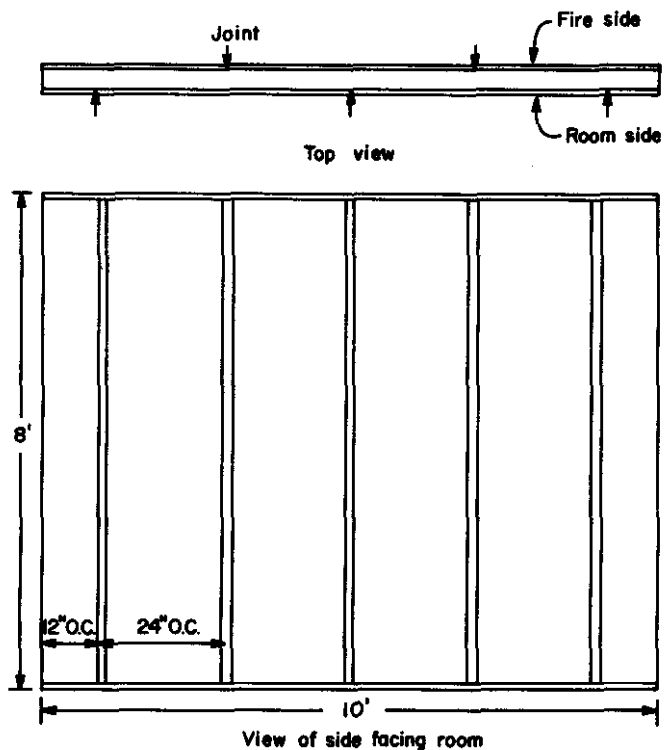


Figure 3.—Construction details for wall assemblies made using steel members. (ML85 5573)

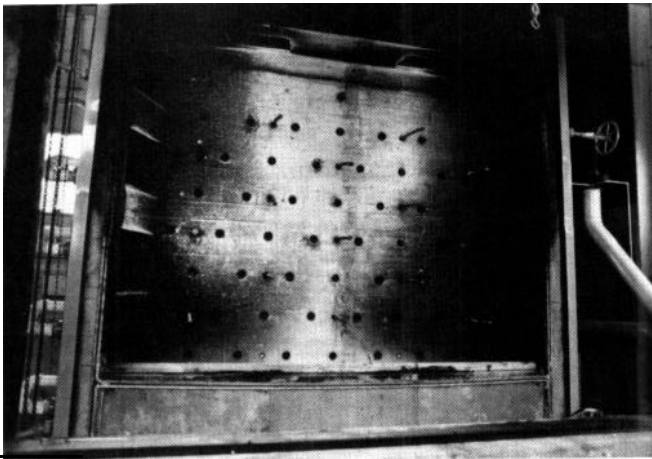


Figure 4.—Fire exposure furnace. (M 141060-18)

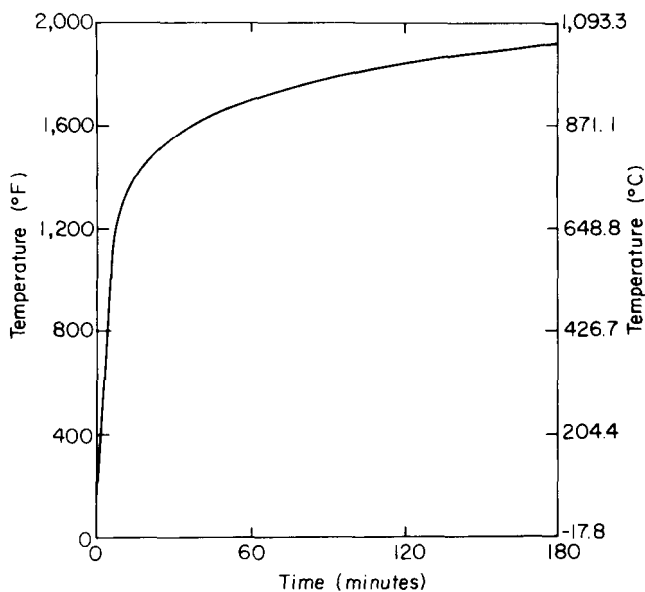


Figure 5.—Temperature-time curve for ASTM standard E 119. (ML85 5530)

Substitution Method

Substitution method calculations are based on the fuel gas input to the furnace during two successive tests (a steel-membered assembly test paired with a wood-membered assembly test). An integrating, bellows-type, positive displacement meter (described under oxygen consumption method measurements) was used to obtain readings. To correct for moisture content (Appendix A), the wood members in each assembly were weighed and their moisture content determined by oven-drying representative samples.

Assumptions inherent to the substitution method are as follows:

- (1) Thermal characteristics of the exposure furnace do not change over the time period of interest.
- (2) Heating value of the fuel supplied to the exposure furnace is known and constant.
- (3) Changes in the relative humidity of the air supplied to the furnace will have a negligible effect on HRR.
- (4) Small temperature variations in ambient air are negligible (the fire laboratory at FPL is temperature controlled within comfortable limits).
- (5) The effect of temperature variations of incoming fuel gas is negligible.
- (6) The difference in the total heat release between the test and reference assemblies is due only to the difference in total heat of combustion of the framing members of the respective assemblies.

The major disadvantages of the substitution method are the necessity for two separate exposures and the uncertainty of the assumption that the furnace performance will be identical for the two tests.

To minimize the effect of inaccurate assumptions, particularly (1) above, HRR calculations (Appendix A) were based on the period of active heat contribution from the treated wood specimen. This basis disregards the heat necessary to bring the furnace apparatus and assembly temperature to the conditions where the combustible specimen begins to release heat to the surroundings; it helps eliminate variability in the early part of the test. The time at which active heat contribution began for each treated wood assembly was determined from its corresponding HRR versus time curve calculated by the oxygen consumption method (Appendix B). The actual fuel meter readings used for the substitution method HRR calculations are given in tables 1 and 2. When figures of fuel consumption during the first 60 minutes or after the entire test (63-67 min) are used (table 1), calculation of heat release from the treated wood can be obscured by different starting points for the tests (different room temperatures, for example). Thus, in some cases, 60-minute data or end-of-test data show more fuel consumed during exposure of treated wood assemblies than during exposure of steel-membered assemblies.

HRR calculations by the substitution method are discussed in more detail in Appendix A.

Oxygen Consumption Method

Temperature, velocity, and oxygen concentration in the exhaust gases were measured at a point near the top of the 12- by 20-inch rectangular furnace stack. Measurements were initiated at the beginning of fire exposure and continued for a period long enough to include at least 60 minutes of related calculations.

Temperature was measured with a 20-gauge, Type K (Chromel-Alumel) thermocouple positioned about 9 inches below the top of the stack, 3 inches from one 20-inch stack face, and midway between the two adjacent 12-inch faces.

Table 1.—Consumption of natural gas fuel during period of active heat release, first 60 minutes, and entire test

Run Timepoint	Time of meter reading	Wall assembly		
		Steel members	Treated wood members	
	<i>Min</i>	----- <i>SCF</i> ¹ -----		
PERIOD OF ACTIVE HEAT RELEASE				
I	End of test	65	66,410	74,020
	Initial	24	64,300	71,980
	Difference	41	2,110	2,040
II	End of test	66	84,120	87,540
	Initial	34	82,440	85,900
	Difference	32	1,680	1,640
III	End of test	63	92,820	96,050
	Initial	39	90,790	94,070
	Difference	24	2,030	1,980
FIRST 60 MINUTES				
I	End of test	60	66,160	73,780
	Initial	0	63,070	70,760
	Difference	60	3,090	3,020
II	End of test	60	83,800	87,240
	Initial	0	80,980	84,170
	Difference	60	2,820	3,070
III	End of test	60	92,670	95,920
	Initial	0	89,630	92,840
	Difference	60	3,040	3,080
ENTIRE TEST				
I	End of test		66,410 (65 min)	74,030 (66 min)
	Initial	0	63,070	70,760
	Difference		3,340	3,270
II	End of test		84,120 (66 min)	87,054 (66 min)
	Initial	0	80,980	84,170
	Difference		3,140	3,370
III	End of test		92,820 (63 min)	96,230 (67 min)
	Initial	0	89,630	92,840
	Difference		3,190	3,390

¹Standard cubic feet.

Table 2.—Consumption of natural gas fuel at 15-minute intervals

Run Timepoint	Time of meter reading	Wall assembly		
		Steel members	Treated wood members	
	<i>Min</i>	----- <i>SCF</i> ¹ -----		
I		15	63,830	75,510
		0	63,070	70,760
	Difference	15	760	750
II		30	64,590	72,290
		15	63,830	71,510
	Difference	15	760	780
III		45	65,360	73,040
		30	64,590	72,290
	Difference	15	770	750
I		60	66,160	73,780
		45	65,360	73,040
	Difference	15	800	740
II		15	81,550	84,910
		0	80,980	84,170
	Difference	15	570	740
III		30	82,230	85,690
		15	81,550	84,910
	Difference	15	680	780
I		45	83,020	86,480
		30	82,230	85,690
	Difference	15	790	790
II		60	83,800	87,240
		45	83,020	86,480
	Difference	15	780	760
III		15	90,320	93,600
		0	89,630	92,840
	Difference	15	690	760
I		30	91,100	94,380
		15	90,320	93,600
	Difference	15	780	780
II		45	91,890	95,160
		30	91,100	94,380
	Difference	15	790	780
III		60	92,670	95,920
		45	91,890	95,160
	Difference	15	780	760

¹Standard cubic feet.

Velocity was measured with a bidirectional differential-pressure probe (fig. C-1, Appendix C) located 9 inches below the top of the vertical axis of the stack. Use of this probe is described in detail in Appendix C.

Oxygen concentrations were measured with two paramagnetic oxygen analyzers connected in series. Details of the sampling and analysis train are shown in figure 6. The instruments were calibrated before each test at 0, 10.8, and 20.9 percent oxygen. The first analyzer measured oxygen in the sample from which only particulates had been removed (fig. 6). At the inlet to the first analyzer, the sample was saturated with water vapor at room temperature (see Appendix B). The sample was then passed through two successive scrubbers containing 25 percent potassium hydroxide solution at 0° C. Scrubbing removed carbon dioxide and maintained the water vapor pressure at 4.5- to 5-mm Hg.

Oxygen concentration with and without carbon dioxide was measured to compare two different methods of calculating HRR. If carbon dioxide is removed from the exhaust gas sample, the number of components in the sample is reduced from four (CO₂, N₂, O₂, H₂O) to three. A slightly simpler calculation scheme, involving ratios of oxygen to oxygen plus nitrogen can then be used. In addition, removal or measurement of carbon dioxide and/or water vapor expands the range of possible HRR measurements because, under these conditions, it is no longer necessary to assume that the sample's contribution to the exhaust (flue) gases is small or negligible.

Exhaust gases were occasionally sampled for carbon monoxide (which would indicate incomplete combustion) using a conventional colorimetric gas analyzer kit. Carbon monoxide concentrations of 0.01 to 0.1 percent were measurable. Samples (0.5 liter) were drawn through indicator tubes by a handheld pump. No indication of carbon monoxide was found in any of the tests.

The natural gas fuel supplied to the test furnace was analyzed using an especially calibrated, automatic sampling gas chromatograph. One to three gas analyses made during the day of a test provided sufficient data to establish the fuel gas composition. Analytical data accumulated during a period of several months showed that the natural gas composition was essentially stable over the 2 or 3 days of a particular run; therefore, the heat of combustion of the fuel gas was the same for both tests of a given run. Results of fuel gas analyses and calculated heats of combustion are given in table 3.

An integrating, bellows-type, positive displacement meter was used to measure natural gas consumption. This meter mechanism was calibrated and compensated to read standard cubic feet (SCF) at 60° F and 30 inches of mercury. Meter readings were taken visually at 1-minute intervals and recorded manually.

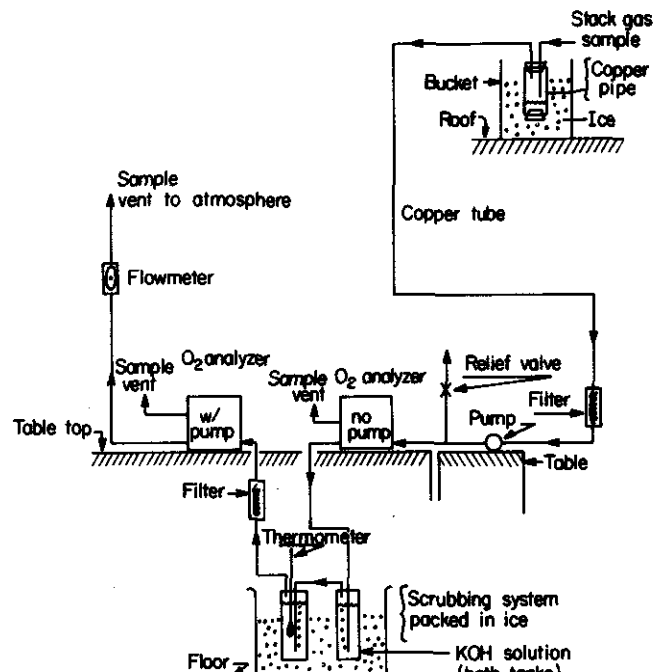


Figure 6.—Schematic of stack gas sampling analysis system. (ML85 5531)

Assumptions inherent in the oxygen consumption method are as follow:

- (1) The quantity of heat released per unit of oxygen consumed is approximately constant for all the combustion reactions.
- (2) Combustion is complete (i.e. the combustion products are carbon dioxide and water vapor).
- (3) Oxygen is used only for combustion reactions and not in any other way.
- (4) The composition of the natural gas fuel is constant, so that the oxygen required for fuel combustion can be calculated from the fuel flow rate.

To calculate HRR using the oxygen consumption method, it is first necessary to determine the total oxygen consumed and then to deduct from this total the oxygen required for combustion of the natural gas fuel. The rate of oxygen consumption can be calculated for steel and wood assemblies using the following equations:

(a) Steel member assembly

$$\text{Rate of oxygen consumption} = \text{Rate of oxygen needed to burn fuel} + \text{Rate of oxygen needed to burn paper on wallboard} \quad (1)$$

(b) Wood member assembly

$$\text{Rate of oxygen consumption} = \text{Rate of oxygen needed to burn fuel} + \text{Rate of oxygen needed to burn wood} + \text{Rate of oxygen needed to burn paper on wallboard} \quad (2)$$

The fire exposures were run in pairs, each pair consisting of a test assembly made from treated wood members and a reference assembly made from steel members. The tests on steel-membered assemblies served to check for measurement errors by comparing the oxygen consumed with the oxygen required for fuel combustion (eq. (1)). The HRR from wood test assemblies could then be obtained from equation (2). In using equations (1) and (2) the heat contributed by the pacer on the gypsum wallboard can be neglected (Appendix B). Figure 7 shows the flow chart used for oxygen consumption calculations; the chart is discussed and illustrated in Appendix B. HRR calculations by oxygen consumption for the three assemblies containing treated wood are summarized in figure 8. Oxygen consumption HRR and substitution HRR, both at 15-minute intervals, are given in table 4.

Weight of Material/Heat of Combustion Method

This method is based on the difference between the heat available for release before a test and the heat remaining unreleased after a test. Total weight and moisture content of the lumber in each wood-containing assembly were determined prior to fire exposure. Following exposure, the assembly was carefully dismantled and the char, along with any unburned wood, was recovered. Unburned wood and char were separated, weighed, and their moisture content determined prior to heat of combustion measurements.

In the weight of material/heat of combustion method, the total heat available in the treated wood is calculated before the test, and the unreleased heat is deducted from this total at the end of the test. Assumptions inherent in this method are as follow:

- (1) Combustion is complete (only carbon dioxide and water vapor are formed).
- (2) Wood that remains unburned after a test has the same net heat of combustion as the original treated wood from which the wall assembly was made.
- (3) Residual material from the wood members is either char or unburned wood.
- (4) Composition of the char residue is uniform.

Table 3.—Natural gas composition and heat of combustion

Component	Test I	Test II	Test III
MOLE FRACTION OF COMPONENT			
Methane (CH ₄)	0.9149	0.897	0.8988
Ethane (C ₂ H ₆)	.0314	.0325	.0328
Propane (C ₃ H ₈)	.0056	.0040	.0045
Butanes (C ₄ H ₁₀)	.0030	.0007	.0008
Carbon dioxide (CO ₂)	.0057	.0048	.0054
Nitrogen/Argon (N ₂ + Ar)	.0394	.061	.0577
HEAT OF COMBUSTION			
<i>BTU/SCF¹</i>			
Gross	1004	976	980
Net	906	881	883

¹BTU per standard cubic foot.

Table 4.—Fuel gas consumption and wood assembly heat release at 15-minute intervals

Run	Assembly type	Interval			
		0-15	15-30	30-45	45-60
FUEL GAS CONSUMPTION					
-----SCF ¹ -----					
Run I					
	Steel-membered assembly	760	760	770	800
	Wood-membered assembly	750	780	750	740
	Difference	10		20	60
Run II					
	Steel-membered assembly	570	680	790	780
	Wood-membered assembly	740	780	790	760
	Difference				20
Run III					
	Steel-membered assembly	690	780	790	780
	Wood-membered assembly	760	780	780	760
	Difference			10	20
WOOD ASSEMBLY HEAT RELEASE					
--- BTU·MIN ⁻¹ ·FT ⁻² ---					
Substitution method²					
	Run I	8	—	15	45
	Run II	—	—	—	15
	Run III	—	—	7	15
Oxygen consumption method³					
	Run I	—	8	12	61
	Run II	—	—	22	68
	Run III	—	3	14	57

¹Standard cubic feet.

²From eq. (A-5): HR_g/15 (i.e. apparent heat release, uncorrected for moisture).

³Arithmetic mean of minute-to-minute calculations (fig. 8) over 15-min intervals.

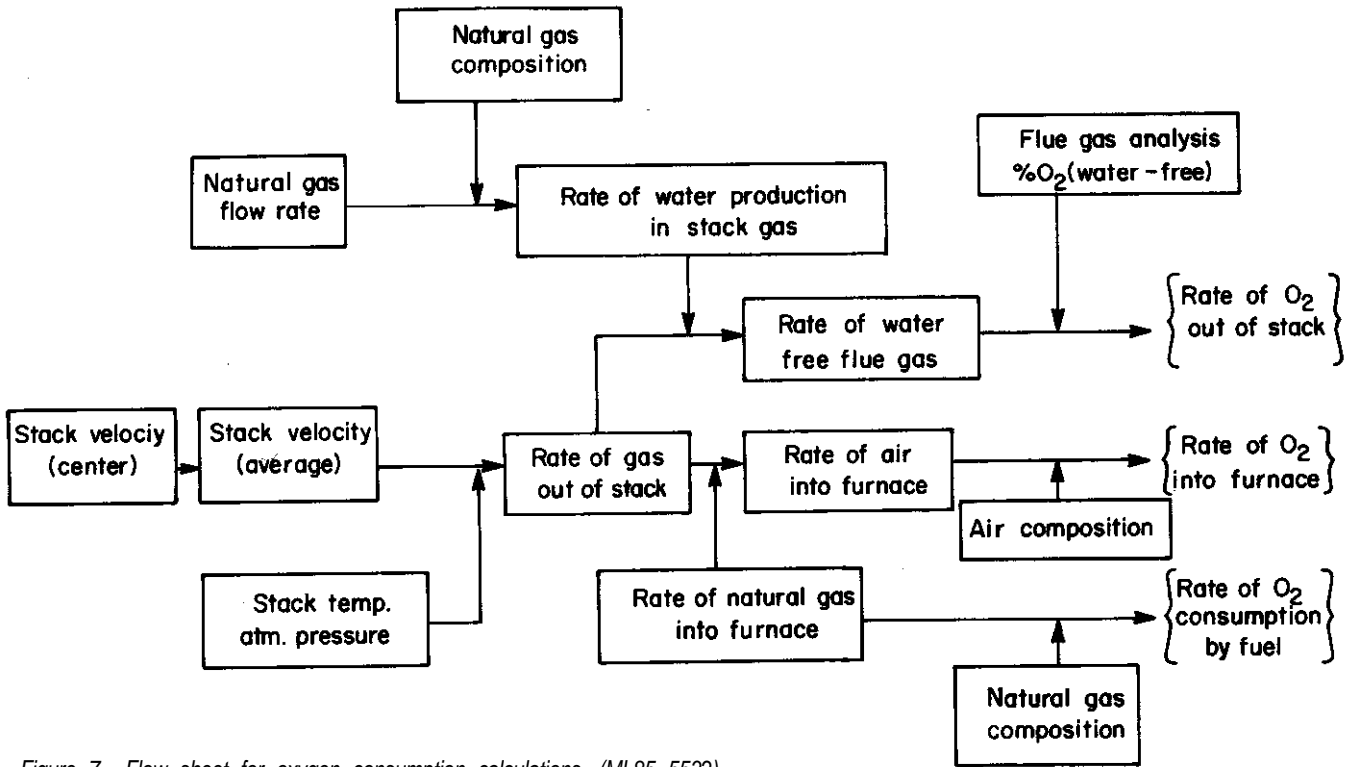


Figure 7.—Flow sheet for oxygen consumption calculations. (ML85 5532)

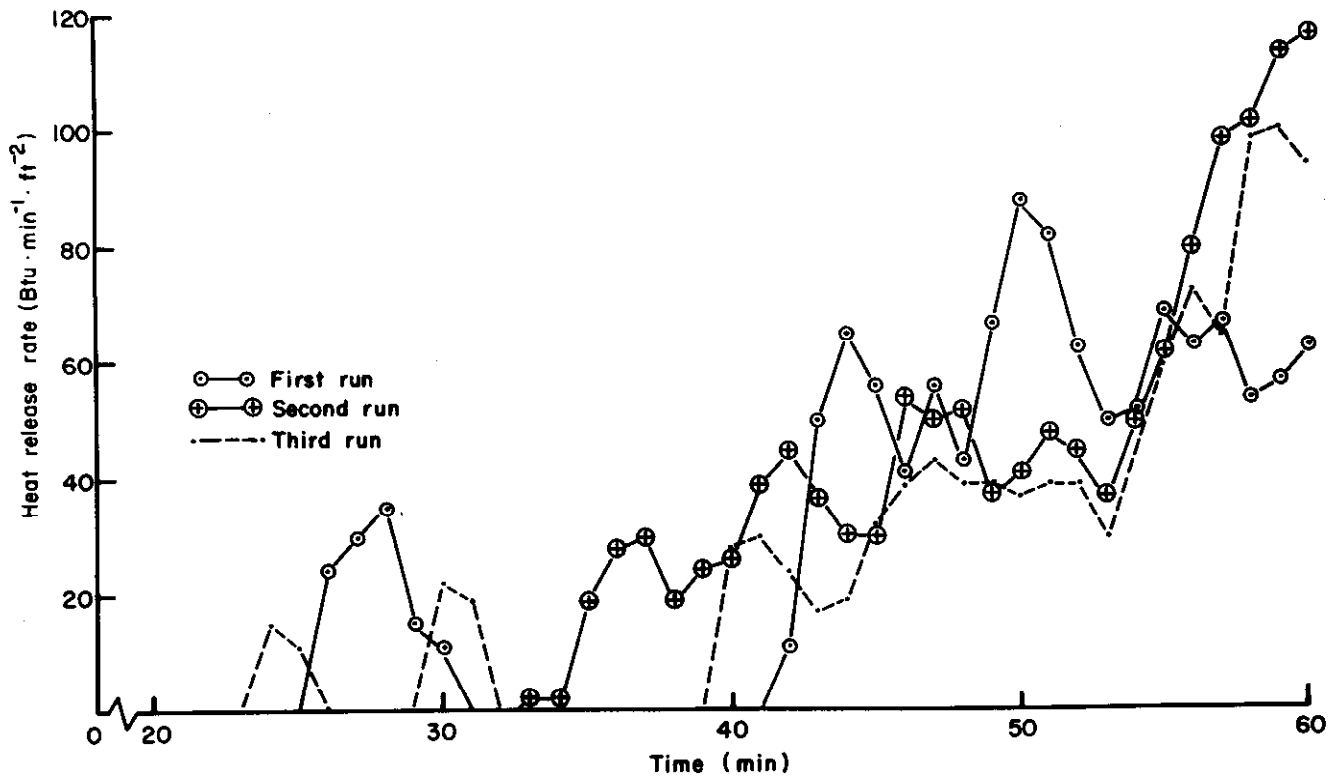


Figure 8.—Heat release rate based on oxygen consumption. (ML85 5585)

At the end of the test, unreleased heat is in the form of the heats of combustion of residual char and unburned wood. Thus, using the notations

W = dry weight of material (lb)

DH_c = net heat of combustion (Btu/dry lb)

= 7,485 Btu per pound dry, treated wood

= 11,337 Btu per pound dry char

and the subscripts wo for original treated wood, ch for char, and wb for unburned wood (after test), these ideas can be expressed as

$$DH_1 = W_{wo} (DH_c)_w = \text{original heat available} \quad (3)$$

$$DH_{ch} = W_{ch} (DH_c)_{ch} = \text{heat remaining in char} \quad (4)$$

$$DH_{wo} = W_{wb} (DH_c)_w = \text{heat remaining in unburned wood.} \quad (5)$$

Noting that the exposed surface area is 80 ft²

$$HR_3 = \frac{\Delta H_1 - \Delta H_{ch} - \Delta H_{wb}}{80} \quad (6)$$

= total heat release (Btu/ft²)

These calculations are summarized in table 5.

The estimates based on wood weight and heat of combustion use measurements made before and after a test; the total heat release is estimated. If the total heat release (in Btu/ft²) is divided by the "period of active heat release," then an "average" release rate can be calculated. "Quench time" is the period between fuel gas cutoff (solenoid valve actuated) and the time at which combustion of the wall assembly is essentially halted. Approximately 6 minutes were needed to (1) disconnect laboratory apparatus and move appropriate items to a safe location, (2) separate the test assembly in its frame from the furnace, and (3) carefully apply fire-suppressing agents (carbon dioxide and water) while minimizing physical damage to the assembly.

Table 5.—Summary of weight of material/heat of combustion HRR calculations of fire-retardant-treated wood assemblies (DH_1 and DH_{wb} based on 7,485 Btu/lb of dry treated wood; DH_{ch} based on 11,387 Btu/lb of dry char with residual treatment chemicals)¹

Run	W_{wo}	DH_1	W_{ch}	DH_{ch}	W_{wb}	DH_{wb}	² HR_3
	<i>Lb</i>	<i>Btu</i>	<i>Lb</i>	<i>Btu</i>	<i>Lb</i>	<i>Btu</i>	<i>Btu/ft²</i>
I-B	132.8	993,000	45.5	518,100	28.6	214,200	3,270
II-B	138.4	1,036,600	44.0	501,000	49.1	367,800	2,098
III-B	133.2	997,300	52.2	594,400	34.9	261,400	1,769

¹ W_{wo} = dry weight of material.

DH_1 = net heat of combustion.

ch = char.

wb = unburned wood after test.

² HR_3 = total heat release by the weight of material—heat of combustion method (eq. (6)).

The active period of heat release of walls containing treated wood is shown below.

	Run I-B	Run II-B	Run III-B
	-----	<i>min</i>	-----
Fuel gas cut-off time	65.3	66.5	67.7
Plus quench time	<u>6.0</u>	<u>6.0</u>	<u>6.0</u>
Equals total time	71.3	72.5	73.7
Minus time heat release started	<u>24.0</u>	<u>34.0</u>	<u>24.0</u>
Equals total active period	47.3	38.5	49.7

For the first test, the beginning of the active period was determined by visual observation. The onset of heat release in the second and third runs was determined using oxygen consumption data (Appendix B).

The active period of heat release was used to calculate the HRR as shown below.

Run	Total heat release (Btu/ft ²)	Active period of heat release (min)	Heat release rate (Btu·min ⁻¹ ·ft ⁻²)
I-B	3,270	47.3	69
II-B	2,098	36.5	54
III-B	1,769	49.7	36

Results and Discussion

The rates of heat release obtained by the substitution, oxygen consumption, and weight of material/heat of combustion methods are compared in table 6. Data for the substitution method are taken directly from tables A-1 and A-2 (Appendix A). Average HRR by the oxygen consumption method was calculated as the arithmetic mean of the 1-minute interval data over a period beginning at the first detectable heat contribution and ending at 60 minutes of test time. Wood assembly heat release by the oxygen consumption and substitution methods is compared at 15-minute intervals in table 4.

During the period of active heat release, the furnace consumed fuel at a rate equivalent to around 45,000 to 46,000 Btu/mjn. Assembly heat release rates of 100 Btu·min⁻¹·ft⁻² were 8,000 Btu/min, based on 80 square feet of surface area. Thus, the release rates under study were about 16 to 17 percent of the natural gas fuel or about 15 percent of the total heat required to maintain the standard fire exposure. When the test assembly released relatively small amounts of heat, the HRR varied considerably. The estimated variability associated with the mean rates shown in table 5 was as follows: weight of material/heat of combustion—20 percent; oxygen consumption—20 percent; and substitution—25 percent.

Table 6.—Heat release rates (HRRs) of wall assemblies containing fire-retardant-treated members

Run	Rate of heat release ¹		
	substitution method (fuel consumption)	Oxygen consumption method	Weight of material/heat of combustion method
	----- Btu·min ⁻¹ ·ft ⁻² -----		
I	22(11-33) ²	50	69
II	21(7-35)	47	54
III	17(6-29)	42	36

¹Averages were calculated over slightly different periods:

	Run I (min)	Run II (min)	Run III (min)
Substitution method	24-65	34-66	24-63
Oxygen consumption method	26-60	33-60	24-60
Weight of material/heat of combustion method	24-71	34-73	24-74

²Numbers in parentheses indicate the result of a slight change in gas-meter readings before and after the fire tests (Appendix A).

It was not always possible to track the released heat in the oxygen consumption and the weight of material/heat of combustion methods, we presumably measured only heat generated by wood combustion. Whether or not the released heat returned into the furnace is not known. On the other hand, the substitution method measures heat contributed by the assembly to the furnace, as indicated by reduced furnace fuel demand. Correction is made for wood moisture content. If the assembly's contribution of heat to the furnace is of primary interest, then only fuel reduction needs to be considered (table 4). The lower HRR found by the substitution method might be explained on the basis that this method measures only heat flowing into the exposure furnace. However, if the moisture content of the wood were not taken into account, the results of tests with the substitution method would be less useful. Incorporation of a correction for moisture into the oxygen consumption data would require some subjective judgements and assumptions about the time at which moisture is released.

Agreement between the methods is fairly good. The effect of changing the gas meter reading by one digit (10 SCF of natural gas fuel) in each of the tests in which the substitution method was used is shown in table A-2 and table 6. Errors in meter reading tend to be much less significant when natural gas flow rates are calculated for the oxygen consumption method.

The interval used for calculating HRR (table 6) was longest for the weight of material/heat of combustion method and shortest for the oxygen consumption method. Since HRR was usually higher near the end of the test, reducing the interval of measurement would tend to lower the observed HRR mean values. Adjusting the results to an equivalent-time basis (60 min) would slightly reduce the HRR calculated by the substitution method and would greatly reduce the HRR calculated by the weight of material/heat combustion method.

At the National Bureau of Standards (NBS), Fang (1982) used the oxygen consumption technique to measure the HRR of fire-exposed ceiling-floor assemblies. He determined the total oxygen consumption rate and deducted the oxygen required for burning the natural gas fuel in order to arrive at the oxygen consumed by the test assembly (eq. (2)). When only fuel was being consumed, the oxygen consumption measurements agreed within 3 percent with the stoichiometric oxygen required for fuel combustion. Using oxygen consumption, Fang was also able to establish the time at which the combustible assemblies began to contribute heat to the fire-exposure furnace system. The results of Fang's study cannot be directly compared to our results since the composition of the assemblies differ.

Conclusions

The results of this study provide information about the fire performance of fire-retardant-treated wood assemblies in terms of the HRR. At least 23 minutes elapsed from the start of the ASTM Standard E 119 test to the time when wall assemblies containing treated wood began to contribute heat. Two factors may have contributed to the time delay: the thermal barrier effect of the gypsum wallboard and the fire-retardant treatment of the wood members. Heat contributions were in the range of up to 80 to 100 Btu per square foot per minute near the end of the test. Average HRR for the assemblies containing treated wood were 20 to 70 Btu per square foot per minute over the active period of heat release.

Results of this study demonstrate that current methods used to measure HRR in individual construction materials can be extended to full-scale wall assemblies. The three methods of HRR measurement used in conjunction with ASTM E 119 were

- (1) The substitution method, by which the amount of natural gas fuel required to burn a noncombustible wall assembly was compared to the amount of fuel required to burn a combustible assembly.
- (2) The oxygen consumption method, by which the HRR was related to the amount of oxygen consumed in burning of the combustible material.
- (3) The weight of material/heat of combustion method, by which the heat of combustion of the original (unexposed) material was compared to the residual heat of combustion of any unburned material at the end of the test.

The oxygen consumption method was shown to be the most advantageous way of measuring HRR. First, only one test was required, compared to two replicate tests needed by the substitution method. Second, HRR could be measured over time. However, the technique requires accurate monitoring of temperature, oxygen concentration, and mass flow in the furnace exhaust gas stream as well as measurement of the mass flow in the inlet air stream. Measurements of the exhaust gas velocity used to calculate mass flows are critically dependent upon the geometry of the duct where the measurements are made. Therefore, it may not be economically feasible to use oxygen consumption measurements for fire-exposure tests in some ASTM E 119 test facilities. Moreover, as HRR increases, the specimen contributes greater amounts of carbon dioxide and water vapor to the exhaust gas stream. When HRR is high, calculations show that it is wrong to assume that all carbon dioxide and water vapor in the stack originate from fuel combustion. Therefore, at an HRR estimated at approximately 350 Btu per square foot per minute, flue gas composition must be analytically monitored with respect to carbon dioxide and water vapor.

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Nomenclature

- A = cross-sectional area of exhaust stack (ft^2) (eq. (B-2)).
 D = difference in gas flow-meter reading (after test minus before test) (ft^3) (eq. (A-1)).
 ρ = gas density (lb/ft^3) (eq. (C-1)).
 D_1 = natural gas equivalent of heat contributed by wood (ft^3) (eq. (A-1)).
 D_s = fuel consumed during test–steel-membered assembly (ft^3) (eq. (A-1)).
 D_w = fuel consumed during test–treated-wood assembly (ft^3) (eq. (A-1)).
 ΔH_1 = original heat available as heat of combustion of treated wood (Btu/lb) (eq. (3)).
 ΔH_c = heat of combustion (Btu/lb) (eq. 3, 4, 5, etc.).
 (ΔH_c) = heat of combustion of residual char (Btu/lb) (eq. (4)).
 $(\Delta H_{c,f})$ = heat of combustion of natural gas fuel (Btu/SCF) (eq. (A-2)).
 $(\Delta H_{c,w})$ = heat of combustion of original treated wood (Btu/lb) (eq. (3)).
 $(\Delta H_{c, ch})$ = heat remaining as heat of combustion of char (Btu/lb) (eq. (4)).
 $(\Delta H)_r$ = heat of vaporization of water (Btu/lb) (eq. (A-2)).
 $(\Delta H)_{wb}$ = heat remaining in unburned wood (Btu/lb) (eq. (5)).
 HRR = heat release rate from oxygen consumption ($\text{Btu}\cdot\text{min}^{-1}\cdot\text{ft}^{-2}$) (eq. (B-15)).
 HR_2 = total heat release, expressed in terms of standard cubic feet of natural gas, corrected for moisture content of treated wood (SCF) (eq. (A-3)).
 HR_3 = total heat release by the weight of material-heat of combustion method (Btu/ft^2) (eq. (6)).
 HR_s = apparent heat release by substitution (without moisture correction) ($\text{Btu}\cdot\text{min}^{-1}\cdot\text{ft}^{-2}$) (eq. (A-5)).
 HRR_s = rate of heat release by substitution ($\text{Btu}\cdot\text{min}^{-1}\cdot\text{ft}^{-2}$) (eq. (A-4)).
 k_o, k_w = combustion constants (lb moles oxygen or water per standard ft^3 of fuel gas) (Appendix B).
 M = moisture content of treated wood (lb water/lb wet wood) (eq. (A-2)).
 m = period of active heat release (min) (eq. (A-4)).
 N_{Ai} = air input to furnace (lb moles/min) (eqs. (D-3),
 N_{Na} = natural gas fuel input to furnace (lb moles/min) (eqs. (D-3), (B-3)).
 N_{Ow} = oxygen required for combustion of treated wood (lb moles/min) (eq. (B-12)).
 N_{Ox} = oxygen required for stoichiometric combustion of natural gas fuel (lb moles/min) (eqs. (D-1), (B-11)).
 N'_{O_x} = oxygen input to furnace (lb moles/min) (eq. (B-5)).
 N_{O_x} = oxygen flow in exhaust stack (lb moles/min) (eq. (B-9)).
 N_{Ox-c} = total oxygen consumed in furnace (lb moles/min) (eq. (B-10)).
 N_{st} = stack (exhaust) flow (lb moles/min) (eqs. (D-3) (B-2)).
 N'_{st} = stack (exhaust) flow (lb moles/min) (water-free basis) (eq. (B-8)).
 N_{Wa} = water formed during stoichiometric combustion of natural gas fuel (lb moles/min) (eqs. (D-2) (B-7)).
 $\%O_2$ = measured oxygen concentration in exhaust gas (pct) (eq. (B-6)).
 $\%O'_2$ = measured oxygen concentration (water-free basis) (pct) (eq. (B-6)).
 P, P_B = atmospheric pressure (in. Hg) (eq. (C-2) Appendix B, Appendix D).
 P_H = vapor pressure of water (in. Hg) (eq. (B-6)).
 P_v = velocity pressure-bidirectional probe (in. water) (eq. (C-1)).
 R = gas constant ($\text{ft}^3\cdot\text{in. Hg}/\text{lb mole}\cdot\text{degree R}$) (Appendix B, Appendix D).
 SCFM = standard cubic feet per minute of natural gas fuel (eq. (D-1), etc.).
 $(\text{SCF})_H$ = natural gas equivalent of wood moisture content (ft^3) (eq. (A-2)).
 T = temperature ($^{\circ}\text{F}$ or $^{\circ}\text{R}$) (eq. (C-1), Appendix B, Appendix D).
 V = air velocity in furnace stack (ft/min) (eq. (C-1), etc.).
 V_{av} = average stack velocity (ft/min) (eqs. (B-2) (C-4)).
 V_{cen} = center stack velocity (ft/min) (eq. (C-4)).
 W_{ch} = weight of char after test (lb) (eq. (4)).
 W_{wb} = weight of unburned wood after test (lb) (eq. (5)).
 W_o, W_{wo} = weight of treated wood in test assembly prior to fire exposure (lb) (eqs. (A-2) and (3) table 5).

Appendix A

Calculation of Heat Release Rate by the Substitution Method

The heat contributed by the treated wood members can be estimated from fuel meter readings (table 2) as

$$D_1 = D_s - D_w \quad (A-1)$$

where

- D_1 = estimated heat contribution from wood (SCF)
- D_s = fuel consumed during test: assembly with steel members (SCF)
- D_w = fuel consumed during test: assembly with treated-wood members (SCF).

Some of the heat released by the wood members is used to evaporate the water present as the moisture content of the wood. The natural gas equivalent of this portion of the heat release is

$$SCF_H = \frac{W_o M (\Delta H)_r}{(\Delta H_{c,f})} \quad (A-2)$$

where

- SCF_H = natural gas fuel equivalent of wood moisture content (SCF)
- $(\Delta H)_r$ = heat of vaporization (Btu/lb water) = 970 Btu/lb
- $(\Delta H_{c,f})$ = net (low) heat of combustion of natural gas fuel (Btu/SCF) (see table 3)
- M = moisture content of wood (weight fraction, in lb water/lb wet wood)
- W_o = weight of wet wood.

The corrected heat release is then

$$HR_2 = D_1 + SCF_H = D_1 + \frac{W_o M (\Delta H)_r}{(\Delta H_{c,f})} \quad (A-3)$$

where

- HR_2 = total heat release expressed in terms of standard cubic feet of natural gas.

The heat required to remove water from the gypsum wallboard need not be considered in substitution calculations because the same quantity of heat is presumably required for both wood-membered and steel-membered assemblies. Given a fire-exposed surface area of 80 ft², the heat release can be calculated as

$$HRR_s = \frac{(HR_2)(\Delta H_{c,f})}{80m} = \frac{(\Delta H_{c,f})}{80m} D_1 + \left[\frac{W_o(\Delta H)_r M}{(\Delta H_{c,f})} \right] \quad (A-4)$$

or

$$HR_s = \frac{D_1(\Delta H_{c,f})}{80m} \quad (A-5)$$

where

- HRR_s = rate of heat release by substitution (with moisture correction) (Btu·min⁻¹·ft⁻²)
- HR_s = apparent heat release (without moisture correction) (Btu·min⁻¹·ft⁻²)
- m = time (min).

Using data from tables 1 and 2 and table A-1 for the first run, these calculations are

$$\text{Equation (A-1): } D_1 = 2,110 - 2,040 = 70 \text{ SCF of fuel gas}$$

$$\text{Equation (A-2): } SCF_H = \frac{(143)(0.0715)(970)}{906} = 10.95 \text{ SCF of fuel gas}$$

$$\text{Equation (A-3): } HR_2 = 70 + 11 = 81 \text{ SCF of fuel gas}$$

$$\text{Equation (A-4): } HRR_s = \frac{(81)(906)}{(65 - 24)(80)} = 22 \text{ Btu} \cdot \text{min}^{-1} \cdot \text{ft}^{-2}$$

Data for the three runs, based on the "period active heat release" (Appendix B), are summarized in table A-1.

In general, heat of combustion calculations are based on sufficient oxygen being present for complete combustion (i.e., the end products are carbon dioxide gas and water vapor). Inside the stud cavity, the oxygen requirement may not always be satisfied and carbon monoxide could possibly be formed, particularly if the gypsum wallboard acts as a barrier to movement of gases. It is assumed, however, that all products of wood pyrolysis eventually find their way into the furnace itself, where an excess of oxygen is present. Thus, any carbon monoxide formed in a stud cavity is converted to carbon dioxide. Intermittent flow of pyrolysis products from the stud cavities to the furnace interior could help explain some features of later data (the time from about 20 min to about 42 min in fig. 8).

Using tables 1, 2 and A-1, it is possible to estimate how slight changes in meter readings affect the heat release calculations. If the readings had changed by one significant digit (10 SCF) (run I, active period, high side),

	Steel members	Treated-wood members
End of test	66,420 SCF	74,010 SCF
Initial	64,290 SCF	71,990 SCF
Difference	2,130 SCF	2,020 SCF

then the heat release calculations would be

$$\text{Equation (A-1): } D_1 = 2,130 - 2,020 = 110 \text{ SCF}$$

$$\text{Equation (A-3): } HR_2 = 110 + 11 = 121 \text{ SCF}$$

$$\text{Equation (A-4): } HRR_s = \frac{(121)(906)}{(80)(65 - 24)} = 33 \text{ Btu} \cdot \text{min}^{-1} \cdot \text{ft}^{-2}$$

Table A-2 shows the results of similar calculations for all three runs. The table indicates that slight changes in gas-meter readings can introduce uncertainty in HRR calculations using the substitution method.

Appendix B Oxygen Consumption Calculations in Detail

Table A-1.—Heat release rate (HRR) calculations using the substitution method

Run	D ₁	W _o	M (water/ wet wood)	(ΔH _c) _f	(SCF) _H ¹	Time	HRR ²
	SCF	LB		Btu/SCF		Min	Btu·min ⁻¹ ·ft ⁻²
I	70	143.0	0.0715	906	11	41	22
II	40	157.2	.119	881	21	32	21
III	50	143.4	.0706	883	11	39	17

¹Standard cubic feet (fuel equivalent of moisture content; see eq. A-2).

²Heat release rate (averaged over the active period of each run) (see eq. A-4): Run I, 24-65 min; Run II, 34-66 min; Run III, 24-63 min.

Table A-2.—Effect on heat release rate (HRR) of a one-digit change in gas-meter readings

Run	HRR	HRR ¹
	Btu·min ⁻¹ ·ft ⁻²	
I	22	11-33
II	21	7-35
III	17	6-29

¹Reading changed by one digit.

Details of combustion chemistry are given in Appendix D using the fuel gas compositions shown in table 3. The calculations in Appendix D for run II are typical of all three runs. When the fuel flow rate and composition have been established, the oxygen required to burn the fuel can be calculated as

$$N_{O_x} = (\text{SCFM}) k_o \quad (\text{B-1})$$

where

N_{O_x} = oxygen required for fuel consumption (moles/min)
 SCFM = natural gas flow rate (standard ft³/min)
 $k_o = 0.005113$ (run II, see Appendix D, eq. (D-1))
 = oxygen required for 1 SCF based on gas composition (table 3).

The air and oxygen flow into the furnace system is calculated next. It is important to note that the entry point of the Inlet air is unspecified throughout the following development. First

$$N_{St} = \frac{(V_{av})(A)(P)}{RT} \quad (\text{B-2})$$

where

N_{St} = total exhaust gas (moles/min)
 V_{av} = average stack velocity (ft/min)
 A = cross-sectional area of stack (ft²).
 P = atmospheric pressure (in. Hg)
 R = gas constant (in. Hg·ft³/°R)
 T = absolute temperature (°F + 460)(°R).

From Appendix D, the natural gas fuel input rate (N_{Na} in moles/min) is

$$N_{Na} = (\text{SCFM})(0.00265) \quad (\text{B-3})$$

so that, as given in Appendix D, equation (D-4) is

$$N_{Ai} = N_{St} - N_{Na} = \frac{(V_{av})(A)(P)}{RT} - \text{SCFM}(0.00265) \quad (\text{B-4})$$

where

N_{Ai} = total air input to the furnace (moles/min).

The oxygen input with this air is

$$N'_{O_x} = 0.209 N_{Ai} \quad (\text{B-5})$$

where

N'_{O_x} = oxygen input to furnace (moles/min).

The final step in making oxygen balances is to calculate the oxygen content of the flue (exhaust) gases. Because the sample system shown in figure 6 removes an unknown quantity of water from the flue gas sample before measuring the oxygen concentration, both the sample stream itself and the flue gas must be converted to a water-free basis. The oxygen concentration of the flue gas sample stream can be reduced to a water-free basis by noting the temperature when the sample is saturated with water vapor. During the tests, we observed that the filter located just above the table (fig. 6) was moist with condensate; therefore the sample stream entering the oxygen analyzer system could be assumed to be saturated with water vapor at room temperature.

Oxygen concentrations in the unscrubbed flue gas sample (fig. 6) were most suitable for calculating oxygen consumption. For an unknown reason, oxygen concentrations in the scrubbed samples were lower than corresponding concentrations in the unscrubbed samples. Presumably, scrubbed values should have been higher due to the removal of a component (carbon dioxide) of the flue gas sample stream. The data shown in table B-1 (from run II-B) are typical. In general, oxygen concentrations measured in scrubbed samples were approximately 1.5 to 3.0 percent oxygen below the corresponding concentrations in unscrubbed samples. Using erroneously low oxygen concentrations in the flue gas leads to erroneously high calculations of oxygen consumed. The calculations described below refer to the analysis using unscrubbed gas samples assuming a small contribution of material from the wood members.

Then

$$\%O_2' = \%O_2 \frac{P}{(P - P_H)} \quad (B-6)$$

where

$\%O_2'$ = water-free oxygen concentration (pct)

$\%O_2$ = measured oxygen concentration (pct)

P = atmospheric pressure (in. Hg)

P_H = vapor pressure of water (in. Hg).

Assuming the water released by wood combustion or as wood moisture content is small, the water present in the exhaust gases can be calculated using equations similar to equation (D-2) in Appendix D. For example,

$$N_{Wa} = (\text{SCFM}) k_w \quad (B-7)$$

where

N_{Wa} = water in flue gas (moles/min)

k_w = 0.00506 (run II, see Appendix D) = water formed during combustion of 1 SCF based on gas composition.

The water-free flue gas is then given by

$$N_{St}' = N_{St} - N_{Wa} = \frac{(V_{av})(A)(P)}{RT} - (\text{SCFM}) k_w \quad (B-8)$$

where

N_{St}' = water-free flue gas (moles/min).

Table B-1.—Flue gas oxygen concentrations (scrubbed and unscrubbed)¹—Run II-B

Time	O ₂ concentration		Time	O ₂ concentration	
	Scrubbed	Unscrubbed		Scrubbed	Unscrubbed
Min	pct		Min	pct	
0					
1			31	6.14	8.26
2			32	6.12	8.26
3	4.78	6.60	33	6.02	8.19
4	7.43	9.05	34	6.04	8.14
5	7.50	9.38	35	6.04	8.02
6	7.63	9.38	36	6.09	7.96
7	7.80	9.48	37	5.99	8.02
8	7.05	8.87	38	5.99	8.09
9	7.25	8.93	39	5.97	7.96
10	7.95	9.73	40	5.99	7.75
11	7.55	9.57	41	5.66	7.70
12	7.12	9.00	42	5.54	7.62
13	7.17	8.93	43	5.54	7.63
14	7.22	8.93	44	5.49	7.58
15	7.60	9.18	45	5.36	7.58
16	7.12	9.05	46	4.98	7.24
17	7.12	9.05	47	5.24	7.45
18	7.05	8.93	48	5.11	7.24
19	7.00	9.05	49	5.03	7.23
20	7.00	8.93	50	4.96	7.22
21	6.87	8.80	51	4.91	7.25
22	6.80	8.80	52	4.86	7.25
23	6.77	8.67	53	4.78	7.46
24	6.62	8.67	54	4.76	7.07
25	6.42	8.54	55	4.58	6.99
26	6.29	8.53	56	4.58	6.99
27	6.24	8.40	57	4.35	6.81
28	6.22	8.40	58	4.23	6.73
29	6.24	8.35	59	4.08	6.58
30	6.24	8.35	60	3.98	6.60

¹Water-free basis (see eq. (B-6)).

The oxygen in the flue (stack) gases can then be calculated as

$$N''_{O_x} = \frac{\%O_2}{100} N_{St} \quad (B-9)$$

where

N''_{O_x} = oxygen present in flue gas (moles/min).

The oxygen consumed is then

$$N_{O_x-c} = N'_{O_x} - N''_{O_x} \quad (B-10)$$

where

N_{O_x-c} = oxygen consumed in furnace (moles/min).

Equations (1) and (2) can be restated using this notation as follows:

For a steel-membered assembly,

$$N_{O_x-c} = N'_{O_x} - N''_{O_x} = N_{O_x} = (\text{SCFM}) k_o \quad (B-11)$$

where

$k_o = 0.00511$ (run II, see Appendix D).

For a wood-membered assembly,

$$N_{O_x-c} = N'_{O_x} - N''_{O_x} = N_{O_x} + N_{O_w} \quad (B-12)$$

and

$$N_{O_w} = N_{O_x-c} - N_{O_x} = N_{O_x-c} - (\text{SCFM}) k_o \quad (B-13)$$

where

N_{O_w} = oxygen required to burn wood (moles/min).

These calculations are based on the assumption that little water and carbon dioxide is contributed by the burning wood compared to that contributed by the burning fuel gas. Trial and error calculations, taking the weight of gases (CO_2 and H_2O) contributed by the specimen into account, show that the assumption used in this present work is justified up to an HRR of about $360 \text{ Btu} \cdot \text{min}^{-1} \cdot \text{ft}^{-2}$.

Using the methodology outlined above, it was possible to calculate oxygen balances at 1-minute intervals for all the experimental runs. Typical calculations are shown in table B-2 (run II-A, steel-membered assembly) and table B-3 (run II-B, treated-wood assembly). Oxygen balance data are summarized for the runs in figure B-1. The illustration data and calculations shown in tables B-2 and B-3 appear in figure B-1 (II-A, II-B), respectively.

Table B-2.—Summary of calculations for run II-A (steel reference assembly)

Experimental parameters	One-minute interval during run II-A			
	44	45	46	47
Fuel gas flow rate (SCFM)	52.67	52.67	52.33	52.33
Oxygen required to burn fuel, N_{O_x} (moles/min) (eq. (B-1))	.269	.269	.268	.268
Stack temperature (°F)	1198	1218	1209	1212
Velocity (average) (ft/min)	1677	1664	1671	1661
Exhaust gas, N_{St} (moles/min) (eq. (B-2))	2.250	2.206	2.228	2.210
Natural gas flow, N_{Na} (moles/min) (eq. (B-3))	.139	.139	.138	.138
Air into furnace, N_{Ai} (moles/min) (eq. (B-4))	2.111	2.067	2.090	2.072
Oxygen input to furnace, N'_{O_x} (moles/min) (eq. (B-5))	.441	.432	.437	.433
Percent oxygen in stack (pct, water-free) (eq. (B-6))	8.57	8.44	8.52	8.31
Water in flue gas, N_{Wa} (moles/min) (eq. (B-7))	.266	.266	.265	.265
Water-free flue gas, N'_{St} (moles/min) (eq. (B-8))	1.984	1.940	1.963	1.945
Oxygen flow in stack of furnace, N''_{O_x} (moles/min) (eq. (B-9))	.170	.164	.167	.162
Oxygen consumed, N_{O_x-c} (moles/min) (eq. (B-10))	.271	.268	.269	.271

(Note: These data are shown as part of fig. B-1 (II-A). Eqs. (B-1) to (B-10) are found in Appendix B.)

Table B3.—Summary of calculations for run II-B (fire-retardant-treated wood test assembly)

Experimental parameters	One-minute interval during run II-B			
	44	45	46	47
Fuel gas flow rate (SCFM)	52.67	52.67	51.67	51.33
Oxygen required to burn fuel, N_{Ox} (moles/min) (eq. (B-1))	.269	.269	.264	.263
Stack temperature (°F)	1298	1303	1305	1300
Velocity (average) (ft/min)	1727	1731	1731	1728
Exhaust gas, N_{St} (moles/min) (eq. (B-2))	2.194	2.190	2.190	2.193
Natural gas flow, N_{Na} (moles/min) (eq. (B-3))	.139	.139	.137	.136
Air input to furnace, N_{Ai} (moles/min) (eq. (B-4))	2.055	2.051	2.053	2.057
Oxygen input to furnace, N_{Ox} (moles/min) (eq. (B-5))	.430	.429	.429	.430
Percent oxygen in stack (pct, water-free) (eq. (B-6))	7.58	7.58	7.24	7.45
Water in flue gas, N_{Wa} (moles/min) (eq. (B-7))	.266	.266	.261	.260
Water-free flue gas, N'_{St} (moles/min) (eq. (B-8))	1.928	1.924	1.929	1.933
Oxygen flow in stack of furnace, N''_{Ox} (moles/min) (eq. (B-9))	.146	.146	.140	.144
Oxygen consumed in furnace, N_{Ox-c} (moles/min) (eq. (B-10))	.283	.283	.289	.286
Oxygen consumed by wood, N_{Ow} (moles/min) (eq. (B-13))	.013	.013	.025	.023
Heat release rate, HRR (Btu·min ⁻¹ ·ft ²) (eq. (B-15))	30	30	54	50

(Note: These data are shown as part of fig. 8 and fig. B-1 (II-B). Eqs. (B-1) to (B-15) are found in Appendix B.)

In figure B-1 it is important to note that the oxygen consumption curves were experimentally determined from the air input and the exhaust gas output of the exposure furnace. In contrast, the oxygen required for fuel combustion was calculated from the fuel input rate and fuel composition. Close agreement between experimental oxygen consumption data and the calculated fuel requirement (fig. B-1; I-A, II-A, III-A) shows that very little oxygen was used in burning the paper on the gypsum wallboard. Further, calculations show that the net heat of combustion of the paper on each wallboard face was about 23,900 Btu, an amount of heat equivalent to about 30 seconds of fuel flow. Although the temperature at midheight in the center stud cavity (fig. B-2) reached 400° in about 20 minutes, much of the paper on the two inner wallboard faces remained carbonized but not completely burned after the tests. A substantial portion of the heat of combustion of the carbonized paper was not released. The gypsum wallboard fastened to the assembly members probably had the effect of creating virtual "compartments" or cells within the assembly, each compartment receiving its own time-temperature exposure. Because temperature was measured in only one "compartment," it is difficult to say what the fire exposure in the others might have been. For these reasons, in figure B-1 (I-B, II-B, III-B), the differences between calculated and observed oxygen consumption are attributed to only the oxygen used in combustion of the treated-wood members.

Heat release *per unit of oxygen consumed* is approximately constant for many substances. Taking the constant as

$$\text{heat release} = 440 \text{ Btu/ft}^3 \text{ of oxygen at 1 atm and } 25^\circ\text{C (77}^\circ\text{ F)},$$

the molar content of 1 ft³ is

$$\frac{(14.7)(1)}{(10.73)(460 + 77)} = 2.551 \times 10^{-3}$$

moles of oxygen. The assemblies had 80 ft² of exposed surface area; therefore

$$\frac{440 \text{ Btu}}{2.551 \times 10^{-3} \text{ moles O}_2} \cdot \frac{1}{80 \text{ ft}^2} = 2,160 \frac{\text{Btu}}{(\text{ft}^2)(\text{mole O}_2)} \quad (\text{B-14})$$

Combining this with equation (B-13) the heat release can be calculated as

$$\text{HRR} = 2160 N_{Ow} \quad (\text{B-15})$$

where

HRR = heat release rate from oxygen consumption (Btu·min⁻¹·ft²).

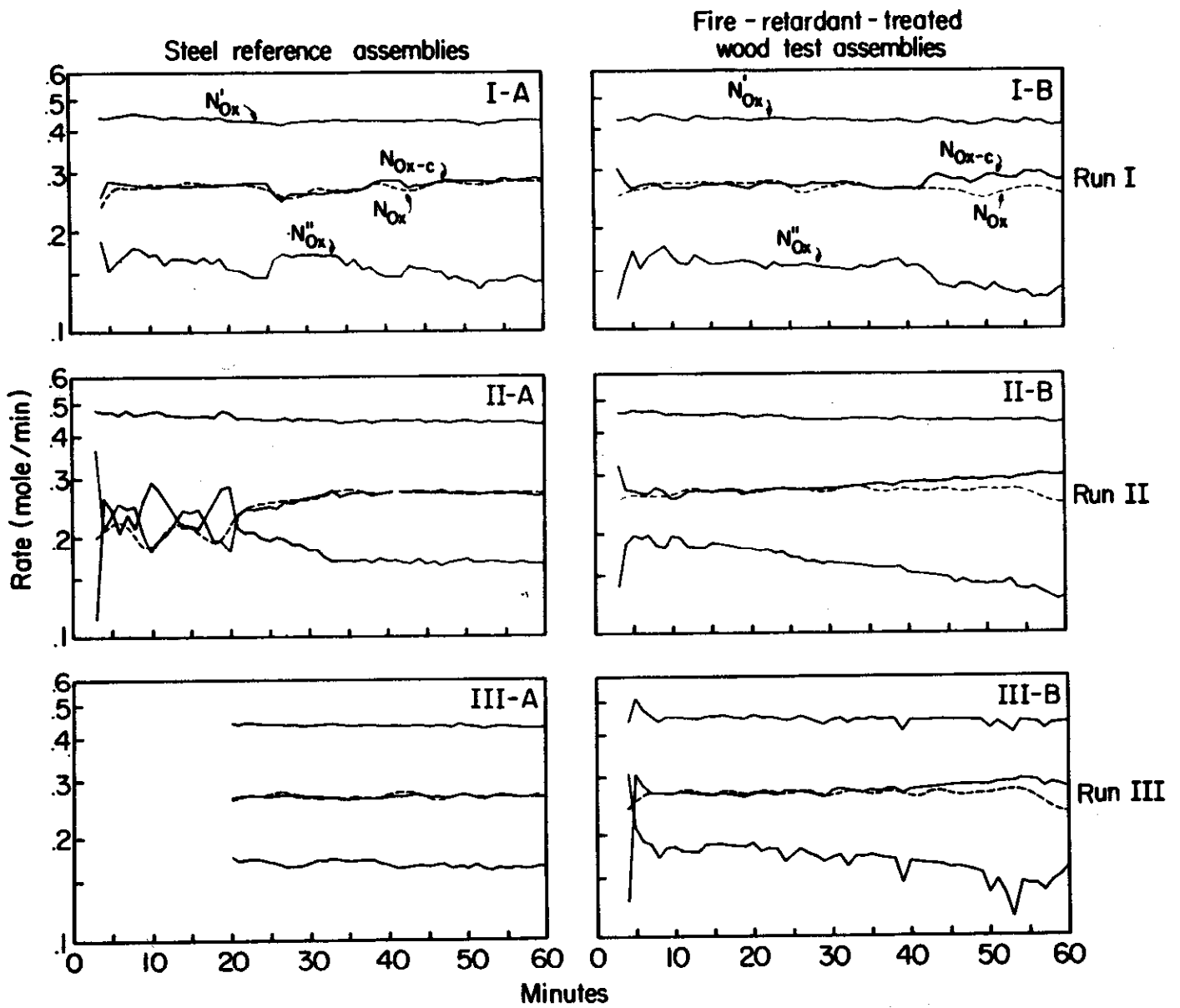


Figure B-1.—Oxygen flow rates of steel reference (A) and fire-retardant-treated wood (B) test assemblies in runs I, II, and III. (ML85 5584)

Appendix C Stack Gas Velocity Measurements

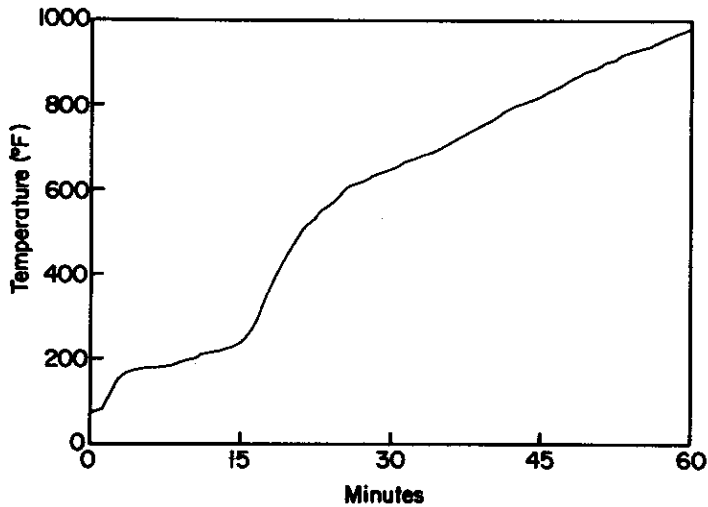


Figure B-2.—Stud cavity temperatures (center cavity, below brace, run II-B). (ML85 5586)

For calculating HRRs by oxygen consumption, the assembly made with steel members in each run was used to check the process measurements using equation (1) in the form of equation (B-11). Heat release rates for the corresponding fire-retardant treated wood assemblies were calculated from equation (2) in the form of equation (B-13), in conjunction with equation (B-15). RHR calculations by oxygen consumption for the three assemblies containing treated wood are summarized in figure 8.

The data plotted in figure 8 show an initial period, up to about 24 or 25 minutes, when no heat was released. This initial period probably resulted from the protection given the wood members by the attached gypsum wallboard and possibly from the fire-retardant treatment given the members. The period from the first-observed heat release until the end of the test has been designated the "period of active heat release." The time at which heat release began and the "period of active heat release" were used to calculate comparative HRRs by the substitution and the weight of material/heat of combustion methods.

Measurement of HRR by the oxygen consumption method requires knowledge of the mass flow rate of air into and out of the furnace. The bidirectional probe (fig. C-1), a very useful modification (McCaffrey and Heskestad 1976) of the Pitot tube, was chosen as the most useful instrument for determining velocity as a means for calculating mass flows in the exhaust stack. Average velocities could be combined with the cross-sectional area to give the required volumetric flow rates. A conventional Pitot tube for measuring velocities under similar conditions is very prone to soot deposition, especially in the static pressure holes. The modified probe is much less susceptible to plugging and also less sensitive to alignment with the flow direction. Its major disadvantage is lower sensitivity at low Reynolds number conditions (based on the probe dimensions); however, flow rates in the stack were sufficiently high so that lower sensitivity was not a problem. At moderate-to-high Reynolds numbers (based on the probe), the bidirectional probe yields velocities about 1.08 times greater than the Pitot tube, requiring a conversion factor of $1/1.08 = 0.926$ in order that the conventional Pitot tube equations can be used.

For our experiments, the bidirectional probe was used in the same manner as a Pitot tube. Differential pressure was measured with a sensitive electronic pressure transducer, and velocity values were calculated from the following equations (which apply to Pitot tubes):

$$\text{Air velocity} = V = 1.096.2 \quad \text{in feet per minute} \quad (\text{C-1})$$

where

$$P_v = \text{velocity pressure (differential pressure) in inches of water}$$

$$\rho = \text{air density in pounds per cubic foot}$$

$$\text{Air density} = \rho = 1.325 \times P_B/T \quad (\text{C-2})$$

where

$$P_B = \text{barometric pressure in inches of mercury}$$

$$T = \text{absolute temperature, } ^\circ\text{R} (^\circ\text{F} + 460)$$

Finally,

$$V = 1,096.2 \times 0.926 \sqrt{P_v T / 1.325 P_B} = 881.8 \sqrt{P_v T / P_B}$$

$$\text{Flow in cubic feet per minute} = \frac{\text{duct area (in square feet)} \times \text{air velocity in feet per minute}}{\text{velocity in feet per minute}} \quad (\text{C-3})$$

The pressure transducer was located 50 feet from and 20 feet below the bidirectional probe. A standard double-hose oxygen-acetylene line was used to connect the probe and transducer as a convenient and acceptable substitute for the usual copper tubing connections. It was assumed that the temperature profile in the descending section of the hose was the same in both tubes so that spurious differential pressures were not generated.

The geometry of the exhaust stack required "mapping" to obtain a calibration constant that would relate the axial (center) velocity to the average overall stack velocity. The calibration procedure consisted of locating the bidirectional probe in each of the positions shown by the map in figure

Appendix D Combustion Calculations

C-2 and waiting until a stable (more or less equilibrium) reading could be obtained. After the series of nine readings was completed, the measurement was repeated at position 5, the axis of the stack. Exhaust gas temperatures were measured and recorded at each position using a Chromel-Alumel (type K) thermocouple mounted near the probe, but not close enough to disturb the flow patterns.

Several mapping sequences were made; these yielded calibration constants in the range of 0.83 to 0.86. For the later calculations, a value of 0.83 was used because this value had been obtained under the best experimental conditions. Thus,

$$V_{av}/V_{cen} = 0.83 \quad (C-4)$$

where

V_{av} = average stack velocity (ft/min)
 V_{cen} = velocity at geometric center (ft/min).

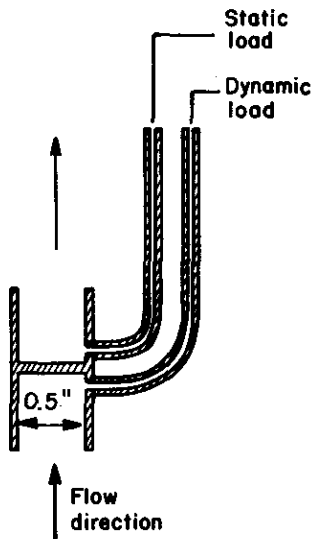


Figure C-1.—Bidirectional probe (cross section). (ML85 5587)

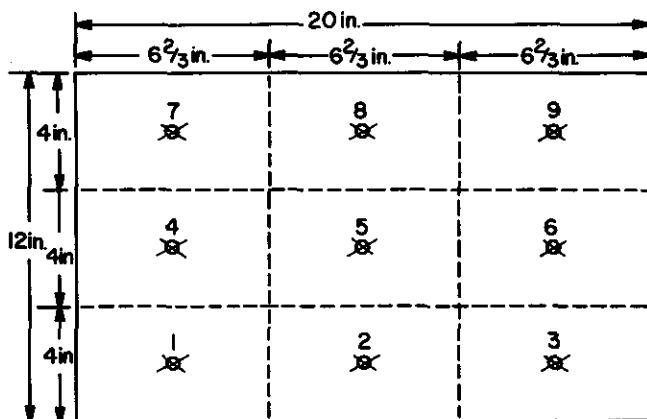
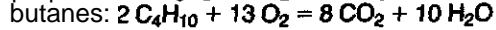
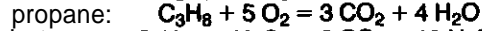
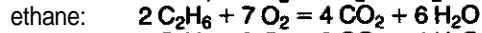
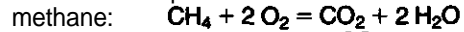


Figure C-2.—Map for velocity measurements in furnace stack (ML85 5574)

Calculations illustrating the combustion stoichiometry for the natural gas fuel used in run II are given below:

Combustion equations:



Calculations:

Basis: 100 cubic feet of natural gas at 30 inches Hg pressure and 60° F (i.e., 100 SCF)

$$\begin{aligned} \text{Moles natural gas} &= \frac{PV}{RT} = \frac{(30.00)(100)}{(21.8)(460+60)} \\ &= 0.2646 \text{ mole}^* \end{aligned}$$

(P, V, and T are the standard pressure, volume, and temperature, respectively; R is the standard gas constant.)

Example:

Stoichiometry-ethane component of fuel, run II:

$$\text{Oxygen required} = (0.2646)(0.0325)\left(\frac{7}{2}\right) = 0.0301 \text{ mole}$$

$$\text{CO}_2 \text{ produced} = (0.2646)(0.0325)(2) = 0.0172 \text{ mole}$$

$$\text{H}_2\text{O produced} = (0.2646)(0.0325)(3) = 0.0258 \text{ mole}$$

Results of all calculations are summarized in table D-1.

$$\text{Air required (per 100 SCF)}: \frac{0.5113}{0.209} = 2.446 \text{ moles.}$$

Material balance (per 100 SCF of natural gas):

	Moles
Air into furnace	2.446
Natural gas into furnace	.265
Material into furnace	<u>2.711</u>
Water in exhaust ^{a,b}	0.506
Carbon dioxide in exhaust ^a	.260
Nitrogen (from air) = (2.466) (0.791) =	1.935
Nitrogen (in fuel) ^a = (0.2646) (0.061) =	.016
	<u>2.717</u>

Notes:

a. From summary.

b. The assumption is made that the water vapor content of the inlet air can be neglected.

Discussion:

1. The oxygen required for combustion of this natural gas is

$$N_{Ox} = \text{SCFM} (0.005113) \quad (D-1)$$

*i.e., lb mole.

where

N_{Ox} = oxygen required for fuel combustion (moles/min)
 SCFM = natural gas flow rate in standard cubic feet per minute.

2. The water formed as a result of combustion is

$$N_{Wa} = \text{SCFM} (0.005056) \quad (D-2)$$

where

N_{Wa} = water in flue gas (moles/min).

Note: Water entering the system as inlet air humidity is about 1 to 2 percent of the water formed as a by product of combustion. Errors associated with the use of equation (D-2) are expected to be in the range of about 5 percent. Therefore, corrections which might result from inlet air humidity calculations have been omitted.

3. Thus, approximately

$$N_{Ai} + N_{Na} \doteq N_{St} \quad (D-3)$$

where

N_{Ai} = air required (moles/min)
 N_{Na} = natural gas fuel rate (moles/min)
 N_{St} = stack (exhaust) gas (moles/min).

Equation (D-3) can be rearranged so that

$$N_{Ai} = N_{St} - N_{Na} \quad (D-4)$$

This means that if (1) N_{St} is measured (stack velocity, temperature, and pressure), and (2) N_{Na} is measured (from the fuel flow rate),

then the air input to the furnace can be calculated using equation (D-4).

4. Applying equation (D-4) to the material balance data above, the air input is calculated as

$$N_{Ai} = 2.717 - 0.265 = 2.452 \text{ moles (compares to } 2.446 \text{ calculated from the natural gas composition)}$$

The error, amounting to 0.006 mole, can be expressed as $(0.006/2.446)(100) = 0.25$ percent based on the stoichiometric air requirement. If 10 percent excess air were used, then $N_{Ai} = (2.452)(1.10) = 2.697$ moles. The error proportion would be $(0.006/2.697)(100) = 0.22$ percent. In general, the use of excess air, over and above the stoichiometric requirements, tends to reduce the error fraction incurred through the use of the equation (D-4).

Because fuel consumption was recorded manually at 1-minute intervals, it was necessary to construct flow rate data. Constructed flow rates were obtained by averaging five successive 1-minute readings using the linear regression method taken at two 1-minute intervals before and two 1-minute intervals after the minute of interest. These five readings were plotted against time and fitted with a straight line correlation; the slope of the correlation line is the desired flow rate. In practice, the "coefficient of correlation" (γ^2) was never less than $\gamma^2 = 0.98$ for all runs.

Table D-1.—Summary of combustion calculations per 100 SCF of natural gas

Component	Fuel Run II	Oxygen required	CO ₂ formed	H ₂ O formed	Heat of combustion	
					Gross	Net
		----- Moles -----			---- Btu ----	
Methane	0.2373	0.4747	0.2373	0.4747	90,600	81,700
Ethane	.0086	.0301	.0172	.0258	5,800	5,300
Propane	.0011	.0053	.0032	.0042	1,000	900
Butanes	.0002	.0012	.0007	.0009	200	200
CO ₂ (in fuel)	.0013	--	.0013	--	--	--
N ₂ (in fuel)	.0161	--	--	--	--	--
Totals	0.2646	0.5113	0.2597	0.5056	97,600	88,100