Room Fire Test for Fire Growth Modeling–A Sensitivity Study

HAO C. TRAN

Research Forest Products Technologist
U.S. Department of Agriculture
Forest Service
Forest Products Laboratory *
One Gifford Pinchot Drive
Madison, WI 53705-2398

MARC L. JANSSENS

Research Associate
National Forest Products Association
1250 Connecticut Avenue, NW
Washington, DC 20036

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ABSTRACT: A room test designed according to the ASTM draft standard was used to investigate the effect of various parameters on the contribution of wall and corner fires to compartment fire growth. Location of the burner (against a wall or in a corner), power program of the gas burner ignition source, and combination of wall linings were varied, An initial series of calibration tests were conducted on ceramic fiber blanket and gypsum board. These tests showed satisfactory instrumentation, good repeatability, and reliable data reduction techniques. The second series were wall and corner tests with Douglas-fir plywood on the walls in contact with the burner and either ceramic fiber or gypsum on the ceiling and remaining walls. Notably, fire growth was much faster in the tests with ceramic fiber. We conclude from the data analysis that at least for corner tests, gypsum board should be used for the ceiling and remaining walls as specified in standardized procedures. A burner program of 40 kW for 5 min followed by 160 kW for the next 5 min was the most informative program; it will be used for wall and corner tests in subsequent steps of this ongoing study.

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INTRODUCTION

FLASHOVER IN THE compartment of fire origin is a very important turning point in the development of a fire in a building. Suddenly, the threat to people and property increases dramatically, potentially affecting the whole building. Thus, an appropriate fire protection system should be able to delay the time to flashover. This delay will increase the likelihood of early fire detection, occupant escape, and early intervention by fire fighters. The fire protection system should also incorporate measures to constrain the fire and to ensure structural stability in the event the fire indeed grows beyond flashover. This paper does not deal with structural issues but addresses only the pre-flashover phase. It is during this phase that early detection and intervention play an important role in reducing the hazards of fire.

To regulate the use of interior finish materials for their possible contribution to the growth of a pre-flashover fire, North American building codes refer to the ASTM E-84 test [1]. This test, also known as the "Steiner Tunnel" test, evaluates the performance of materials in one specific standardized pre-flashover fire environment. The test results are expressed in terms of a flame spread index (FSI). According to the FSI, building codes classify the materials into three classes, A, B, and C. Gypsum board and fire-retardant-treated wood represent class A material, whereas most untreated wood products represent class C. This approach has several problems:

1. Little information on correlation between performance in the ASTM E-84 test and real fires is available. The correlation that exists [2], which is based on one room fire scenario, was not conclusive.
2. The ASTM E-84 test standard applies only to interior finish and not to the contents of a building. Contents are now virtually unregulated because they are not considered an integral part of the building. However, in many real fires the contents prove to be the main or even only contributor.

Technically, the ideal solution for assessing fire performance of a material would be to test the material in a number of full-scale fire scenarios. The test conditions should be chosen to represent the most realistic fire situations in which the material is likely to be involved. Unfortunately, this approach is not feasible, mainly for economic reasons. Indeed, full-scale fire tests are expensive and time consuming. Moreover, more than one test scenario will probably be needed to represent the real world.

The advent of mathematical fire modeling opens new ways to assess performance of materials in real fire situations, including the contribution of contents in compartment fires. Substitution for the full-scale tests by model simulations is becoming feasible and makes economic sense. Expensive full-scale experiments are being replaced by relatively inexpensive bench-scale tests and a series of computer model runs. The bench-scale tests are required to obtain basic material property data that are used as input to the models.

Currently, a number of models are available that can predict compartment fire growth for cases where only contents (such as furniture and mattresses) are burning [3,4]. Predictions can be made with sufficient accuracy for engineering purposes. Also, movement of smoke and toxic gases from the compartment of fire origin through the building can be calculated [5,6,7]. However, these models are unable to accurately predict fire development in scenarios in which fire extends to combustible wall and ceiling materials. One model that can handle this kind of situation is available [8]. Although the results of this model seem to agree well with some real test data, some physical algorithms in the model are approximations that need further improvement and validation.

Once an adequate model is available to describe fire development in a room with any type of wall and ceiling material, this model can be merged with existing models for burning contents and for smoke transport. The result will be a complete mathematical model that can handle any real fire scenario relevant to the type of occupancy currently addressed by the building codes. The model will also be able to evaluate the critical contribution of contents. The evaluation of fire growth within the compartment can be extremely useful in the determination of fire load and fire exposure to assemblies.

Recognizing the lack of knowledge in predicting wall contribution, a joint fire growth study was initiated between the Forest Products Laboratory (FPL) and the National Forest Products Association (NFPA). First, an extensive review of the literature was undertaken [9-26]. Then, a five-step experimental program was designed to ultimately develop a validated mathematical model able to accurately describe fires extending to walls and ceilings. Data pertinent to the first step of this program are discussed in this paper.

The FPL-NFPA Study Plan

A room/corner test facility was built at FPL for the study of fire growth. The facility was built in accordance with the specifications of the American Society for Testing and Materials (ASTM) proposed standard [27]. The test procedure is about to be published as an ASTM standard. A similar method is published as a draft International Standards Organization (ISO) standard [28].

The study plan consists of five distinct steps. Step 1, which forms the subject of this paper, is a sensitivity study. The effects of different parameters in the test conditions are investigated with the objective of finding the optimum protocol for the subsequent steps. This protocol may be different in some respects from the protocols presently proposed by ASTM and ISO. In step 2, a set of five different materials having a range of FSI are to be tested using the developed protocol. In the remaining steps of the experimental program, data will be generated to validate several algorithms for the model.

Objectives of Sensitivity Analysis

The overall objective of step 1 is to investigate how three major factors affect the result of a room burn test. These factors are burner location, burner power output program, and selected materials. From different combinations of these factors, and with additional instrumentation of the test facility, the test data will be useful for:

1. Obtaining information on the repeatability of room fire tests
2. Defining, analyzing, and comparing criteria for performance of a material
3. Providing information for model validation

EXPERIMENTAL PROGRAM

Experimental Arrangement and Instrumentation

Figure 1 shows the geometry of the room and location of the measuring transducers for the data reported in this paper. All temperatures in the room are measured with 0.25-mm wire type-K thermocouples. The heat flux meters are of the Schmidt-Boelter type, have a 180°0 view angle, and have an exposed area of 25 mm in diameter.

For all tests, the ignition source was the standard ASTM square propane diffusion burner. Two burner positions were used to study two types of fire: wall and corner fires. Fuel supply to the burner was measured and controlled with an electronic mass-flow controller.

Figure 2 shows a cross-sectional view of the room, the hood, and the exhaust system. Flow rate in the duct is calculated on the basis of dif-

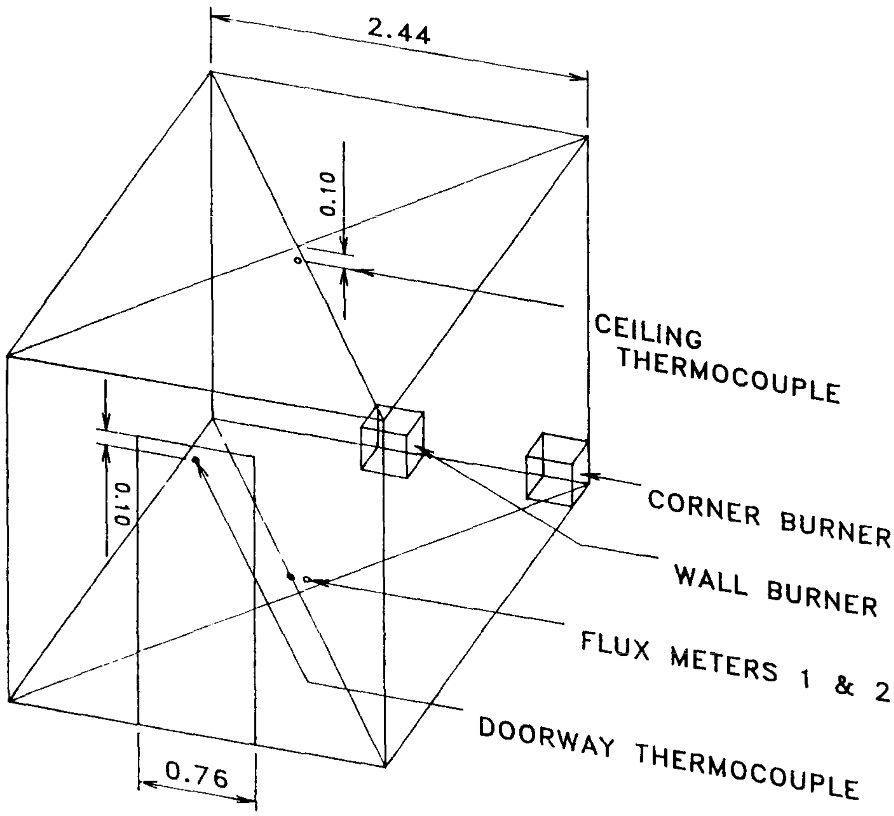

Figure 1. Three-dimensional view of burn room.

ferential pressure across a bidirectional probe [29] and gas temperature at the location of the probe. An exhaust gas sample is drawn through a sampling probe and analyzed for O_2 and other species.

The exhaust rate can be adjusted by a blower having a capacity of 1 to 3 m^3/s. For all tests, the exhaust rate was set at the lowest setting and increased after flashover to remove all exhaust gases.

Test Series

The tests can be subdivided into two series. The first series is referred to as calibration tests because the gas burner was the only significant source of heat in the room. The second series involved Douglas-fir plywood.

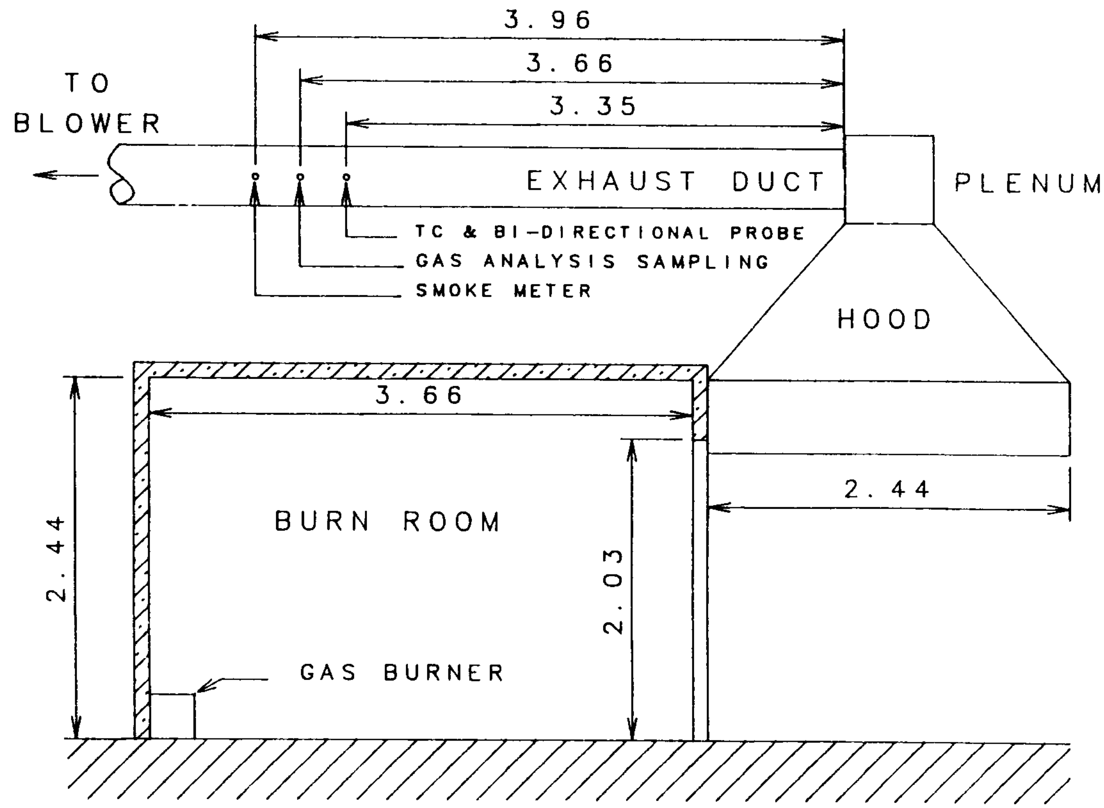

Figure 2. *Cross section of room and exhaust system.*

Calibration Tests

Calibration tests are described in Table 1. The test number indicates the order in which these tests were carried out. Some tests are out of sequence because they were repeated when we discovered a systematic error in the mass flow controller calibration. The three parameters were burner location, burner output program, and lining material.

Burner Location

Two locations were considered. In the wall location, the burner was placed at the centerline of the rear wall. In the corner location, the burner was placed in the right rear corner. The edge or edges of the burner were flush with the adjacent wall or walls.

Burner Program

To investigate the effect of the exposure, four burner programs were used in this study:

Program A The burner was programmed to produce 40 kW of net heat release for a duration of 15 min

Program B 40 kW for 5 min, followed by 160 kW for an additional 5 min

Program C 40 kW for 30 s, 80 kW for 30s, 120 kW for 30 s, and maintenance at 160 kW for a total test time of 10 min

Program D 40 kW for 5 min, 100 kW for 5 min, and 160 kW for 5 min

The burner programs are shown in Figure 3. Program A was a constant exposure and represented a small ignition source, such as a burn-

Table 1. Description of calibration tests.

Test No.	Lining Material	Burner Location	Burner Program
2	Gypsum board	Corner	B
7	Ceramic fiber	Corner	A
21	Ceramic fiber	Corner	B
22	Ceramic fiber	Corner	C
23	Ceramic fiber	Corner	D
12	Ceramic fiber	Wall	A
24R	Ceramic fiber	Wall	B
25R	Ceramic fiber	Wall	C

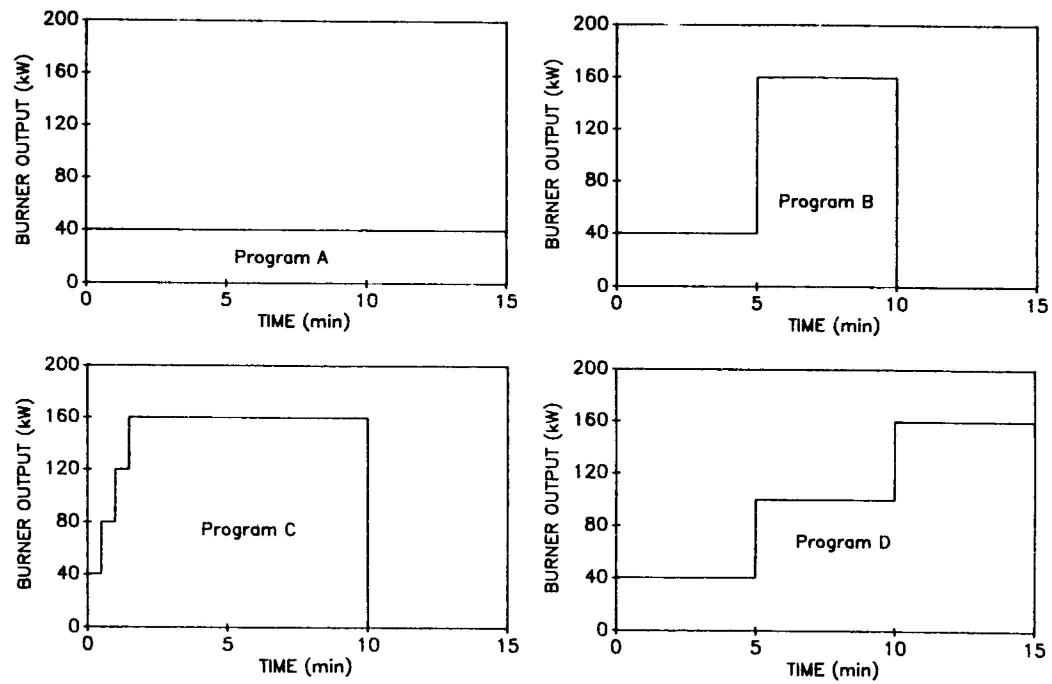

Figure 3. Burner programs A, B, C, and D.

ing waste basket. Program B had a preheat period of 5 min at 40 kW as in program A, but this period was followed by a 5 min exposure at 160 kW. This exposure has been proposed by the ASTM task group for calibration tests and for a series of round-robin tests. It was also used in previous works [2,31]. Program C was the previously proposed ASTM standard exposure that simulates the initial burning rate of wood cribs, but it was maintained for 10 min in our study. Program D had a preheat period of 40 kW followed by a moderate exposure of 100 kW before the 160 kW level, as needed.

Lining Material

The two materials used in the calibration tests were gypsum wallboard and ceramic fiber. The gypsum was type X, fire rated, 16 mm thick. The ceramic fiber was a high temperature insulation material, 12.7 mm thick, density 100 kg/m^3. We chose ceramic fiber over gypsum for most tests for several reasons:

1. Because gypsum calcines and disintegrates during exposure to heat, it has to be replaced after every test. Time and money are saved by using the ceramic fiber blanket, which survives a great number of tests.
2. The changes in thermal properties of gypsum must be taken into account in the model. With ceramic fiber blanket, the thermal properties are known as a function of temperature and do not change much from test to test. Thus, model validation is easier and more accurate.
3. A nearly steady state can be reached in calibration tests with ceramic fiber, which is not possible with gypsum.

Table 2. Description of tests with Douglas-fir plywood.

Test No.	Lining Material	Burner Location	Burner Program
5	Gypsum board	Corner	B
15	Ceramic fiber	Wall	A
16	Ceramic fiber	Wall	B
16R	Ceramic fiber	Wall	B
17	Ceramic fiber	Wall	C
18	Ceramic fiber	Corner	A
19	Ceramic fiber	Corner	B
20	Ceramic fiber	Corner	C
26	Ceramic fiber	Corner	D

Tests with Douglas-Fir Plywood

The second series of tests were with Douglas-fir plywood mounted on at least one wall of the compartment. The tests are described in Table 2. Douglas-fir plywood was chosen because of its availability and because several bench-scale and large-scale tests have been conducted with this material. Thus, we could compare our results with data in the literature.

The plywood was a 12.7-mm, 5-ply CD grade, 32/16, PS1-83, all Douglas-fir veneer. Average ovendry density was 465 kg/m^3. Prior to the tests, the plywood was conditioned at 23° C and 50 percent relative humidity, leading to an average moisture content of 9.6 percent. The same parameters were varied as for the calibration tests.

The same two burner locations (wall and corner) and the same burner programs (A through D) were used for the Douglas-fir plywood tests that had been used for the calibration tests. In the plywood tests, the burner was terminated and the fire extinguished as soon as flashover conditions were reached to minimize damage to the instruments within the room. We later found that in two wall tests, 16 and 17, the burner output was 150 kW instead of 160 kW because of an error associated with the calibration of the mass-flow controller. Test 16R was a repeat of test 16 with the proper heat output of 160 kW.

In the wall tests, only the rear wall was lined with plywood, the rest with ceramic fiber. In the corner tests, the two walls adjacent to the burner were lined with plywood, the rest with ceramic fiber. The exception was test 5, in which the ceiling and remaining walls were lined with gypsum. The use of ceramic fiber blanket was investigated mainly for the reasons mentioned for the calibration tests.

RESULTS

The data reported in this paper include the following:

1. Rate of heat release, which was calculated on the basis of the oxygen-depletion principle following equations given by Parker [30]
2. Temperature, 0.1 m below ceiling at centerline of room and 0.1 m below sill at centerline of doorway
3. Heat flux to center of floor (meters 1 and 2)
4. Visual observation of flames outside doorway

These are the most important measurements. However, many more data were taken. Detailed analysis of heat and smoke release, mass flow in and out of doorway, and modes of flame spread will be reported in a future paper.

Table 3. Severity of exposure in calibration tests.

Burner Location	Test No.	Heat Release Rate (kW)	Heat Flux (kW/m^2) Meter No. 1	Meter No. 2	Temperature (°c) Ceiling	Door
Corner	2	40	0.14	0.14	127	105
		160	2.64	2.49	331	261
	7	40	0.68	0.64	160	142
	21	40	0.50	0.62	158	133
		160	5.31	5.73	387	299
	22	160	5.05	5.49	383	293
	23	40	0.53	0.65	158	133
		100	2.48	2.72	285	231
		160	5.39	5.83	383	300
Wall	12	40	0.46	0.57	127	114
	24R	40	0.38	0.56	119	106
		160	4.05	4.56	314	281
	25R	160	3.96	4.56	313	284

Calibration Tests

The calibration tests with gypsum wallboard and ceramic fiber linings were designed to obtain baseline data and to calibrate the system. Some heat flux measurements and selected temperature data showed the severity of the ignition source and the effects of the environment. The flux meters (1 and 2) at the center of the floor showed mainly radiative heat flux from the flames and the heated ceiling and upper layer. Temperature near the center of the ceiling (0.1 m from ceiling) and near the top of the doorway (0.1 m from sill) indicated the degree of heat buildup. The results of the calibration tests are summarized in Table 3. The flux and temperature values are time averaged over 1 min; that is, over the period between minutes 4 and 5 at 40 kW and over the last minute at 100 kW and 160 kW.

As the heat release from the walls is negligible, the oxygen consumption measurement should agree with the theoretical rate of heat release from the burner. Agreement was excellent for all tests (apart from some lag in the oxygen consumption measurement), as illustrated for test 23 in Figure 4. Total heat release integrated over a number of calibration tests agreed to within 5 percent of the value calculated from the total mass loss from the propane tank.

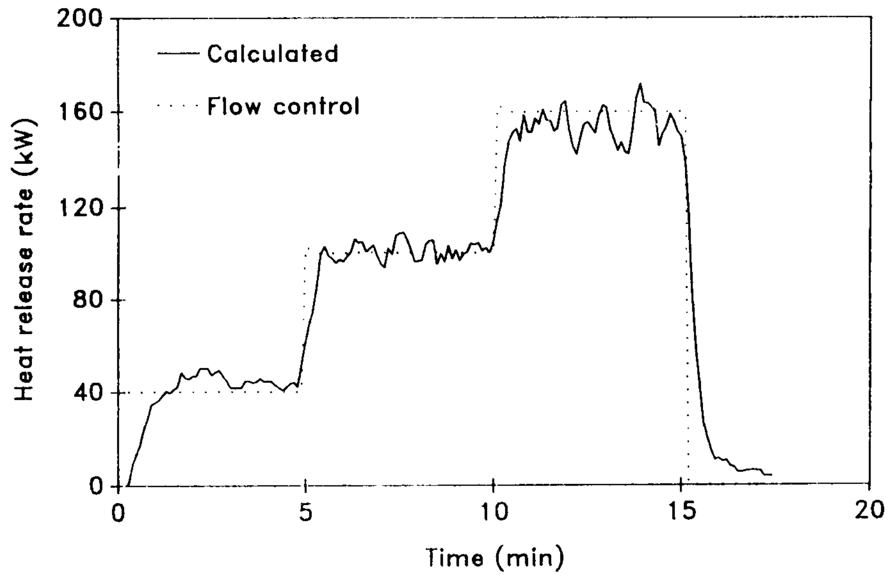

Figure 4. Calibration test no. 23, program D.

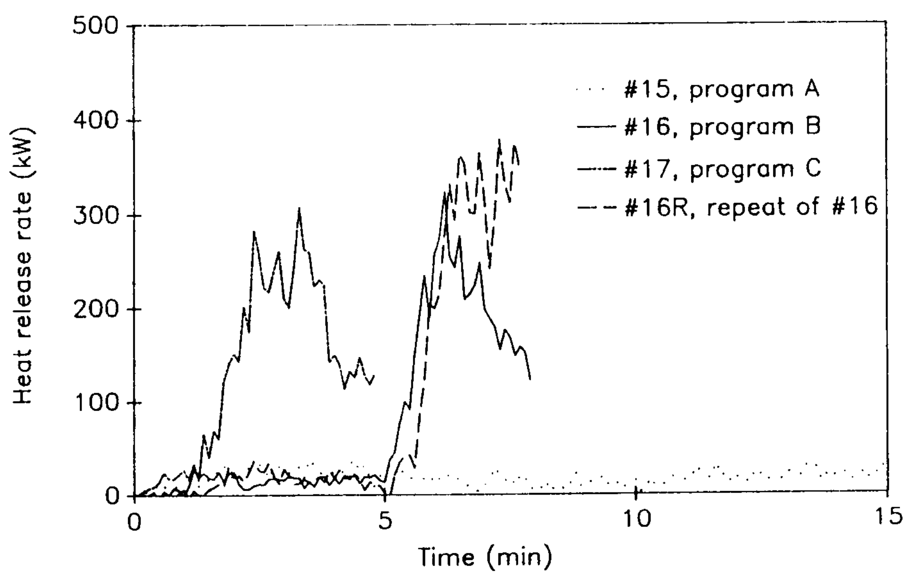

Figure 5. Rate of heat release in wall tests.

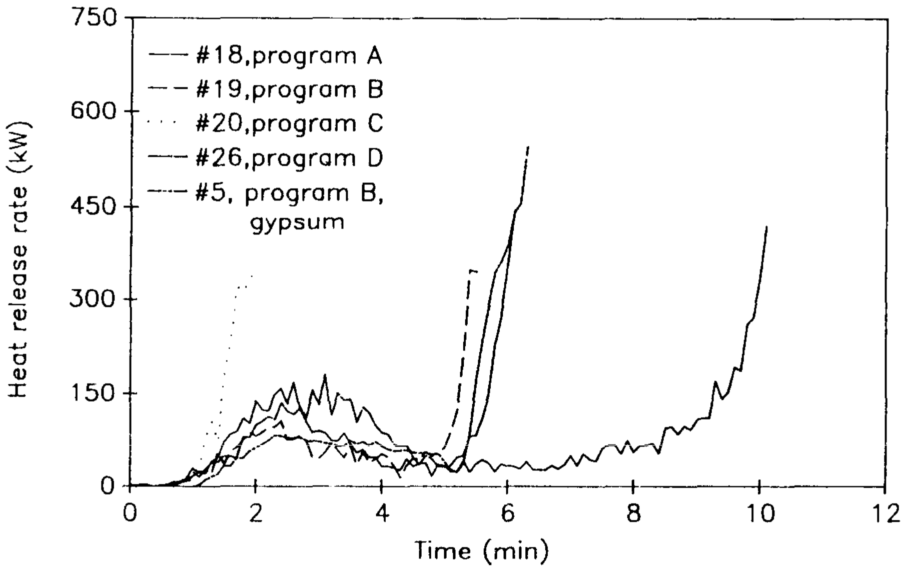

Figure 6. *Rate of heat release in corner tests.*

Douglas-Fir Plywood Tests

Figure 5 shows rate of heat release data for the wall tests. Figure 6 shows the same for the corner tests (including test 5), but the heat release rate is cut off at flashover. In both figures, rate of heat release from the burner is subtracted from total heat release. Thus, only the contribution from the wall lining is shown.

Table 4 shows temperature, heat flux, and some heat release data for

Table 4. Repeatability of Douglas-fir plywood tests.

Test No.	Heat Release Rate (kW)	Heat Flux (kW/m^2)		Temperature (°C)	
		Meter No. 1	Meter No. 2	Ceiling	Door
5	54	0.72	0.65	234	190
15	25	0.69	0.77	163	151
16	18	0.72	0.73	145	130
16R	15	0.67	0.91	155	139
18	32	—	1.24	214	195
19	44	1.18	1.35	226	199
26	55	1.64	1.79	242	218

all Douglas-fir plywood tests. All values are l-rein averages obtained in the same way as the values obtained for the calibration tests.

Tables 5 and 6 give some data for the tests in which flashover occurred. Flashover times are reported according to three widely used criteria: (1) flameover-flame observed outside door, (2) heat flux to floor exceeds 20 kW/m^2, and (3) temperature at top of door reaches 600° C.

All temperatures, heat fluxes, and rate of heat release values in Table 6 are averages over three scans (18 s) taken close to the time of flashover. The rate of heat release values at flashover includes both burner output and contribution from the walls.

DISCUSSION

Test Repeatability

Although no complete tests were repeated, several tests can nevertheless be compared because they had some period in common. For instance, calibration tests 7, 21, and 23 all started with an initial 40-kW exposure with the burner in the corner. Agreement between ceiling and doorway temperature measurements is excellent. Values of heat flux to the floor are also close, considering their very low level. The situation is very similar for the wall tests 12 and 24R.

In calibration tests with ceramic fiber lining, the walls did not contribute to the fire and steady-state conditions were quickly approached. Thus, the 160-kW data of tests 21, 22, and 23 should also be comparable, which is confirmed by the data in Table 3. Such a comparison is also valid for wall tests 24R and 25R.

For the tests with Douglas-fir plywood, data obtained at the end of the initial 5-min exposure to a 40 kW burner can be compared (tests 15, 16, and 16R for the wall configuration and tests 18, 19, and 26 for the corner configuration). Agreement of temperature and heat flux data is reasonable, as indicated in Table 4. Rate of heat release (excluding the burner output) for the wall tests appears to be very repeatable, as indicated in Figure 5. Furthermore, rate of heat release in test 16 can be regarded as close to that measured in test 17 but delayed by 5 min. The values for peak rate of heat release in both cases are very close (about 300 kW). As indicated in Figure 6, agreement of rate of heat release over the first 5 min in corner tests 18, 19, and 26 is not as good.

Finally, tests similar to No. 5 were done earlier by Lee [31] and Gardner and Thomson [2]. Both studies reported flashover times that are very close to ours: 380 s (Lee) and 390 s (Gardner and Thomson). Thus, agreement between laboratories is good in spite of deviations in the

Table 5. Flashover times.

Test No.	t_{flame} (s)	t_{flux} (s)	t_{door} (s)
5	380	378	372
16R	—	384	450
18	604	606	612
19	335	330	336
20	123	120	126
26	370	366	378

Table 6. Floor heat flux, temperature, and heat release rate at flashover.

		Heat Flux (kW/m²)		Temperature (°"C)	
Test No.	Heat Release Rate* (kW)	Meter No. 1	Meter No.2	Ceiling	Door
5	707	21.6	22.0	861	617
16R	483	20.7	20.9	620	529
18	466	—	22.2	694	553
19	471	21.3	23.0	723	565
20	512	21.5	23.4	745	591
26	542	21.4	22.0	678	520

*Heat release rate includes burner

Table 7. Effect of preheat period. *

			Heat Flux (kW/m²)		Temperature (°C)	
Burner Location	Test No.	Heat Release Rate* * (kW)	Meter No. 1	Meter No. 2	Ceiling	Door
16	372	440	16.8	17.3	557	519
17	198	424	16.8	16.9	530	513

*All data are three scan averages at time of maximum heat release
**Heat release rate includes burner

test procedure and probable differences in the Douglas-fir plywood materials tested.

Flashover Criteria

Flashover times according to the test criteria are shown in Table 5 for corner tests 5, 18, 19, 20, and 26. In all these tests, agreement between the three criteria is very good. For practical purposes, the flameover criterion was the easiest to use beta use it can be readily observed during a test. For model validation, however, either of the other criteria is a more appropriate choice.

Agreement between the criteria is not good for the only wall test in which flashover occurred (No. 16R). Flameover did not occur and the other criteria were met at quite different times.

Ceramic Fiber or Gypsum Board

The question whether the ceiling and walls not in contact with the burner should be lined with ceramic fiber blanket or gypsum board can be resolved by comparing tests 5 and 19. The use of ceramic fiber evidently led to a dramatic reduction in flashover time (test 19). This was clearly due to the higher thermal insulating properties of ceramic fiber compared to gypsum board. At flashover, the rate of heat release was much smaller in test 19 compared with test 5.

We can explain the behavior of ceramic fiber on the basis of differences in $k\varrho c$ (thermal inertia) of this material and gypsum board. The $k\varrho c$ is the product of thermal conductivity, density, and heat capacity of a material, and it is a good indication of the thermal properties of the material. Thomas and others [32] showed that flashover times in a compartment fire are proportional to $k\varrho c$ of the wall lining raised to a power of 0.5 or less. In our study, we assumed the fire started at the step increase of the burner to 160 kW because only a small amount of material was consumed prior to this. With this reference, flashover times were 80s for test 5 and 35 s for test 19. The major part of conduction heat loss was through the ceiling, so that we took only the $k\varrho c$ of the ceiling lining into account. The power is calculated as 0.34 with $k\varrho c$ = 0.096 kJ^{2}K-2m-4s-1 for gypsum board [33] and $k\varrho c$ = 0.008 kJ^{2}K-2m-4s-1 for ceramic fiber blanket [34], both evaluated at 300°C.

Flashover times depended strongly on the burner program (Figures 5 and 6). At 40 kW exposure, the corner test finally flashed over whereas the wall test did not. In all other corner tests, flashover happened after the burner had been increased to 160 kW or 100 kW.

Burner Program

Test 18 eventually led to flashover after more than 10 min. This indicates that some materials will produce flashover during exposure to a 40 kW burner. In fact, one material tested in a similar scenario did just that during the first 5 min of exposure [2]. Consequently, an initial exposure at 40 kW is justified and will result in more information than program C, which prescribes an almost step-increase of the burner to 160 kW at the start of the test. Moreover, in comparing the rate of heat release curves for tests 16 and 17, the initial 40-kW period apparently resulted in a 5-min delay for materials that needed 160 kW to flash over the room. Thus, no information was lost due to the preheat, as illustrated in Table 7. The data reported in this table are averages taken over three scans around the time of maximum heat release rate.

CONCLUDING REMARKS

The calibration tests show that the instrumentation and data acquisition-reduction software work adequately and that repeatability of tests is very good.

Use of ceramic fiber blanket instead of gypsum board to cover the ceiling and walls not in contact with the ignition source results in a much faster-growing fire. With ceramic fiber blanket, rate of heat release curves and flashover times (provided flashover occurs) for different materials will be much closer than with gypsum board. Thus, the distinction between materials becomes more diflicult. Also, ceramic fiber certainly does not typify the material generally used in construction. The insulation effect from the ceramic fiber was more dramatic in the corner tests than in the wall tests. Consequently, we suggest using gypsum board at least for corner tests.

A burner program of 40 kW for 5 min followed by 160 kW was the most informative of all programs investigated. This program will be used for wall and corner tests in subsequent steps of the study.

The three flashover criteria used agree very well. Flameover is the most practical criterion during tests because it can be observed without sophisticated instrumentation. Either of the other criteria–heat flux to floor and temperature at top of door-is recommended for model validation.

A large amount of data was generated for model validation. Much of these data are not discussed in this paper but will be covered in detail in a future report.

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