EXPERIMENTAL ASPECTS OF VALIDATING A COMPARTMENT WALL FIRE MODEL

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ABSTRACT

The advent of computer modeling has opened new ways to assess fire risks of intricate systems. Several models are available for calculating burning rates of objects and smoke transport in a given system. However, modeling capability is limited when fires extend to walls and ceiling. This paper summarizes the research progress made by the Forest Products Laboratory and the National Forest Products Association to develop and validate algorithm for wall and corner fires within the compartment of fire origin. The approach includes bench-scale and full-scale experiments. The bench-scale tests are for establishing material thermophysical and fire properties such as ignition, flame spread rate, and rate of heat and smoke production. A wide range of scenarios of full-scale tests were conducted to establish a data base that would be suitable for validating a model. Steady-state experiments were conducted to characterize the source flame in particular configurations such as against a wall or in a corner of walls. The paper describes some highlights of bench-scale and full-scale test results, as well as empirical correlations between bench-scale and full-scale data. A philosophy of validation for an "idealized" two-zone model is proposed.

INTRODUCTION

In a joint effort to develop a validated model for compartment fire growth, the Forest Products Laboratory (FPL) and the National Forest Products Association (NFPA) initiated a fire growth research program. In this study, bench-scale tests provide input data for the model and full-scale test data are used to verify model predictions. A materials bank has also been stored at FPL as part of the NFPA program to provide materials to the fire research participants and to establish a data base for these wood products. A subset of six materials having a range of different flame spread indices according to the ASTM E84 test method (1) have been used throughout the study.

To develop algorithms that describe the source (burner), steady-state experiments are being conducted to characterize the flame and fire plume both against a wall or in a corner of walls.

1The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin. This article was written and prepared by U.S. Government employees on official time, and it is therefore in the public domain and not subject to copyright.
This paper describes some experimental aspects of the fire growth research program, highlights some research findings, and reports on progress of the compartment wall fire model under development.

**EXPERIMENTAL**

**Materials**

The six wood materials being used in this study are Douglas-fir (DF) plywood, redwood, Southern Pine (SP) plywood, particleboard, oriented strandboard (OSB), and fire-retardant-treated (FRT) SP plywood. The DF plywood is five-ply CD grade, 32/16, PS1-83, all DF veneer; redwood, tongue and groove lumber; and SP plywood, four-ply CD grade, 32/16. PS1-83, all SP veneer. Particleboard is urea bonded for interior use. The OSB primarily consists of aspen flakes, bonded by phenolic resins. The FRT plywood is from the same stock as the SP plywood, treated with a proprietary treatment by Kopper’s Company.\(^1\) Material thickness, density, and equilibrium moisture content in the conditioning chamber are given in Table 1.

The materials were selected according to their relative flame spread classification in the ASTM E84 test.\(^1\) Materials were classified into three classes based on flame spread index (FSI): class I, FSI 0–25; class II, FSI 26–75; and class III, FSI 76–200. The FRT plywood is class I. Redwood with a FSI of 70 is class II. The DF and SP plywood have an FSI of about 115 to 130 and are in the low range of class III. The FSI of the test particleboard is estimated to be 150. The OSB has an FSI of 137 to 175 depending on the type of additive and is in the high range of class III; the material used in our study has an FSI of 175. The materials were conditioned at 23°C and 50 percent relative humidity prior to testing.

**Bench-Scale Tests**

The equipment used for the bench-scale tests consists of two heat release rate calorimeters, the Ohio State University (OSU) apparatus (2) and the National Institute of Standards and Technology (NIST) cone calorimeter (3). For flame spread properties, a lateral ignition and flame spread test (LIFT) apparatus (4) at NIST is used to obtain the data suitable for modeling. The OSU apparatus at FPL has been modified to obtain piloted ignition data and heat release rate data by the oxygen consumption method so that results can be compared with the cone calorimeter. Piloted ignition data were obtained with all three apparatuses.

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\(^1\) The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.
Full-Scale Room Test

The FPL room test facility was constructed to conform with the specifications of the proposed ASTM standard method for room fire test (5). Although this test method is presently a proposed standard, several research and testing laboratories have already followed its specifications. In addition to the basic measurements required by the proposed standard, many thermocouples were placed at selected locations to monitor the temperature profile development in the room. Several differential pressure probes were placed at selected heights on the front wall to monitor pressure drops across the doorway. These pressure drops combined with the temperature profile in the doorway and within the room provide the information for calculating mass flow in and out of the room. These additional measurements are needed to check the accuracy of the model.

The gas burner is a square sand burner as specified in the proposed ASTM standard. Propane (cp grade, at least 99 percent purity) was metered in via an electronic mass flow controller. Figure 1 shows features of the exhaust hood and duct system, which is crucial in the measurement of heat and smoke release rate.

In the first step of this research program, a sensitivity study was conducted. Three factors were varied: location of the burner, burner output program, and lining materials. The burner was located at either the centerline of the rear wall or a rear corner. Four burner output programs represented the range of exposures. The DF plywood was used in combination with either gypsum board or a ceramic fiber blanket for the ceiling and the walls not covered with plywood. Ceramic
fiber blanket was considered a candidate for these tests because it has several advantages over gypsum board, such as well-known thermal properties and survivability from test to test.

From this study, we concluded that the burner program consisting of 40 kW exposure for 5 min followed by 160 kW for an additional 5 min was the most informative. Consequently, this program was used for the testing of the six materials in the study reported here. A similar burner program is now used in the round-robin testing procedures of the ASTM rom test. The ceramic fiber blanket used to line the ceiling and walls not coveted with plywood has greater insulting ability than the gypsum board and resulted in faster flashover in the sensitivity study. Therefore, in the subsequent corner tests reported here, gypsum board was used to line the ceiling and the uncovered walls. For the wall tests, which are primarily of academic interest, ceramic fiber was used. The results of this sensitivity study were documented (6).

**Steady-State Experiments for Characterizing Source Flame**

The characteristics of axisymmetric flames are well understood. However, many assumptions are made about the source flame when it is against a wall or in a corner of walls. The presence of the wall or walls affects the turbulent diffusion nature of the source flame and plume. Steady-state experiments are being conducted to provide the data needed. The square burner is used as the source flame. Two heat output levels are considered—40 and 160 kW: two fuel types—natural gas and a mixture of natural gas with toluene: and two burner positions—against wall and in a corner of 25-mm calcium silicate walls. The measurements include

a. heat flux to the wall at incremental heights.

b. temperature drops across the wall at incremental heights.

c. temperature, velocity, and gas species Concentration profiles at incremental heights, and

d. soot concentration profile at different heights.

The data obtained from these measurements can be used to derive entrainment and several aspects of heat transfer for modeling purposes.

**HIGHLIGHTS OF TEST RESULTS**

**Bench-Scale Tests**

Ignition data from all three bench-scale apparatuses were compared. By plotting ignition time raised to the power of $-0.547$ against heat flux as proposed by Janssens (7), a linear relationship was found. The factor $-0.547$ was found to be the best empirical fit to the solution of the mathematical formulation of the piloted ignition problem. A typical plot is shown for DF plywood (Fig. 2). Fairly good agreement between the three apparatuses was obtained. Table 2 summarizes the ignition data expressed in this form for the six test materials with data pooled from the three apparatuses. Critical ignition flux and ignition temperature can be calculated from such data. Critical ignition flux is the Intercept with the abscissa; ignition temperature is calculated based on the critical flux being equal to surface heat losses at equilibrium. Thermal inertia is calculated from the slope of the line (7). Poor correlation was obtained for FRT plywood mainly because ignition was difficult to determine visually with this material.

Gardner and Thomson (8) compared measurement of heat release rate by the cone calorimeter and the OSU apparatus modified for the oxygen consumption method. Samples were tested in vertical orientation in all cases. Reasonable agreement between the two calorimeters was found for the first and second peaks of heat release. However, the OSU apparatus yielded higher heat
Figure 2—Ignition data for OSU, cone calorimeter, and LIFT apparatus for bench-scale tests of 12.7-mm Douglas-fir plywood.

Table 2. Ignition data^a

<table>
<thead>
<tr>
<th>Material</th>
<th>a</th>
<th>b</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF plywood</td>
<td>0.006006</td>
<td>−0.0789</td>
<td>0.97</td>
</tr>
<tr>
<td>Redwood</td>
<td>0.006587</td>
<td>−0.0883</td>
<td>0.89</td>
</tr>
<tr>
<td>SP plywood</td>
<td>0.006330</td>
<td>−0.0843</td>
<td>0.89</td>
</tr>
<tr>
<td>Particleboard</td>
<td>0.003752</td>
<td>−0.0316</td>
<td>0.86</td>
</tr>
<tr>
<td>OSB</td>
<td>0.005928</td>
<td>−0.0736</td>
<td>0.97</td>
</tr>
<tr>
<td>FRT plywood</td>
<td>0.001854</td>
<td>−0.0099</td>
<td>0.34</td>
</tr>
</tbody>
</table>

^ Linear regression of the form $Y = aX + b$, where $Y$ is $(t_{ig})^{-547}$ and $X$ is heat flux (kW/m²).

release in the steady period between the peaks. The heat release rate for DF plywood exposed to 35 kW/m² is shown as an example in Figure 3. The difference between the results from the different apparatuses is most likely due to the heating environment of the OSU calorimeter. Attempts to reconcile the difference are not trivial. Average heat release data over 5 min were found to be a linear function of heat flux (8). The linear regression data for the materials for both the OSU modified for oxygen consumption and the cone calorimeter are summarized in Table 3. Poor correlation in the case of FRT plywood was tied to the same difficulty in determining ignition time encountered in the bench-scale tests.

Full-Scale Room Tests

Table 4 shows flashover time using different criteria and heat release rate measured when floor flux exceeded 20 kW/m². In the wall tests in which ceramic fiber blanket lined the ceiling and uncovered walls, the heat release rate was low during the first 5 min at the 40-kW exposure.
Figure 3–Comparison between OSU and cone calorimeter for Douglas-fir plywood exposed to 35 kW/m².

Table 3. Average heat release rate over a 5-min period

<table>
<thead>
<tr>
<th>Material</th>
<th>OSU</th>
<th>Cone calorimeter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>DF plywood</td>
<td>1.6789</td>
<td>40.85</td>
</tr>
<tr>
<td>Redwood</td>
<td>1.5037</td>
<td>21.41</td>
</tr>
<tr>
<td>SP plywood</td>
<td>1.2226</td>
<td>75.74</td>
</tr>
<tr>
<td>Particleboard</td>
<td>1.6493</td>
<td>79.94</td>
</tr>
<tr>
<td>OSB</td>
<td>1.2512</td>
<td>103.2</td>
</tr>
<tr>
<td>FRT plywood</td>
<td>2.3075</td>
<td>-42.7</td>
</tr>
</tbody>
</table>

* Linear regression of the form $Y = aX + b$, where
  $Y$ is heat release rate (kW/m²) and $X$ is heat flux (kW/m²).
  + Ohio State University apparatus modified to obtain piloted ignition data and heat release data by the oxygen consumption method.

When the burner was increased to 160 kW, the heat release rate accelerated in all tests, except for the test with FRT plywood, which did not cause flashover (Fig. 4). In the corner tents with gypsum wall board ceiling (Fig. 5), the separation between materials was more pronounced. The DF plywood and redwood had similar fire growth patterns. Heat release rates were low during the first 5 min of 40-kW exposure. They accelerated after the increase to 160 kW. The heat release rate of SP plywood and particleboard steadily increased during the first 5 min and reached flashover conditions after the burner increase. The OSB had the steepest heat release rate curve during the first 5 min and reached flashover before the burner increase. The FRT plywood did not release sufficient heat to cause flashover.
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Table 4. Flashover information for full-scale tests

<table>
<thead>
<tr>
<th>Series no.</th>
<th>Test Material</th>
<th>$t_{\text{flame}}$ (s)</th>
<th>$t_{\text{flux}}$ (s)</th>
<th>$t_{\text{door}}$ (s)</th>
<th>Heat release rate $^a$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall 16R</td>
<td>DF plywood</td>
<td>384</td>
<td>450</td>
<td>447</td>
<td>447</td>
</tr>
<tr>
<td>27 Redwood</td>
<td>—</td>
<td>348</td>
<td>378</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>28 SP plywood</td>
<td>—</td>
<td>366</td>
<td>390</td>
<td>497</td>
<td></td>
</tr>
<tr>
<td>29 Particleboard</td>
<td>—</td>
<td>360</td>
<td>372</td>
<td>547</td>
<td></td>
</tr>
<tr>
<td>30 OSB</td>
<td>—</td>
<td>336</td>
<td>342</td>
<td>534</td>
<td></td>
</tr>
<tr>
<td>31 FRT plywood</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Corner 5</td>
<td>DF plywood</td>
<td>380</td>
<td>378</td>
<td>372</td>
<td>707</td>
</tr>
<tr>
<td>32 Redwood</td>
<td>378</td>
<td>378</td>
<td>Malfunction</td>
<td>719</td>
<td></td>
</tr>
<tr>
<td>33 SP plywood</td>
<td>344</td>
<td>348</td>
<td>336</td>
<td>725</td>
<td></td>
</tr>
<tr>
<td>34 Particleboard</td>
<td>336</td>
<td>342</td>
<td>390$^b$</td>
<td>705</td>
<td></td>
</tr>
<tr>
<td>35 OSB</td>
<td>266</td>
<td>270</td>
<td>312</td>
<td>676</td>
<td></td>
</tr>
<tr>
<td>36 FRT plywood</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>NA</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Includes burner.

$^b$ Maximum 592°C.

Figure 4—Heat release rate of wall tests with no burner contribution.

Correlation of Room Test and ASTM E84 Data

The overall objective of this study is to generate large-scale test data to validate algorithms or models using data from bench-scale tests. Research has shown that simple correlations can be established, although the correlations are not entirely plausible. One such attempt was carried
out by Gardner and Thomson (8), who showed a correlation between FSI (ASTM E84) and the logarithmic values of time to flashover. The room test in this study was similar to the corner tests performed in our study.

Our results in the cornet tests are similar to those of Gardner and Thomson (8) (Fig. 6). With respect to FSI, the corner test could distinguish class I materials (no flashover) and high-range class-III materials (flashover during the first 5 min at 40 kW). However, the performance of class II and low-range class-III materials in the corner test was mixed, indicating factors other than those controlling performance in the ASTM E84 test affect overall fire growth.

Linear regression of the pooled data (Fig. 6) is of the form

\[ t_{\text{flashover}} = 446.6 - 0.922 \text{ FSI} \]

\[ R^2 = 0.78 \]

The scatter of data is significant in this correlation although it appears less so in the log-linear plot presented by Gardner and Thomson (8). Although the correlation may be reasonable with wood products, earlier experiments (10) with a variety of materials could not predict room fires based on ASTM E84 data. Therefore, we must caution the reader that correlations of this type are only applicable in a familiar range of products.

Correlation of Room Test and Bench-Scale Data

Other empirical correlations involving several factors have been proposed. For example, Ostman and Nussbaum (11) suggest a correlation between time to flashover, time to ignition in bench-scale tests at 25 kW/m², density of the lining material, and heat release at peak period at
Figure 6–Correlation between room corner tests and ASTM E 84 test method for class I, II, and III materials.

50 kW/m². However, the conditions of these tests were different from those used in our study. The room fire test had the same dimensions as those used in the proposed ASTM standard. However, the burner and its output are specified by the ISO standard (100 kW for 10 min and an increase to 300 kW if flashover does not occur). Most materials would result in flashover during the 100-kW exposure, except for gypsum board.

The same approach is not applicable in our study because of the step function in the burner output. Time to flashover depends a great deal on the exposure, which in our study was not constant. Correlation between flashover time to combinations of the factors used by Ostman and Nussbaum (11) was found to be poor ($R^2 < 0.3$). A fairly good correlation, however, was found between bench-scale heat release rate obtained in both the OSU apparatus and the cone calorimeter and the average rate of heat release in the room corner tests (Fig. 7). The bench-scale data are 5-min averages of heat release rate calculated from regression data (Table 3) for 50-kW/m² heat flux. The full-scale data are average global rate of heat release (excluding the burner) during either the 40- or 160-kW burner setting. The $R^2$ value for these regression plots is 0.80 or better.

There are definitely two regimes of fire growth depending on the burner exposure. Within each regime, correlation between bench-scale and full-scale heat release rates is undoubtedly good. This is consistent with the findings by Oatman and Nussbaum (11) and also those of Wickstrom and Goransson (12) using cone colorimeter data and room data with the ISO burner (100-kW regime). A more sophisticated approach was used by Karlsson and Magnuson (13) for the ISO room corner scenarios. Similar to the approach used by Wickstrom and Goransson (12), certain assumptions had to be made about the ignition and burning of the areas behind the burner source. The good agreement between predicted and experimental data is encouraging and indicates that modeling for predicting fire growth based on bench-scale data is possible.
DEVELOPMENT OF COMPARTMENT WALL FIRE MODEL

Simple correlations like those described perhaps can adequately predict some aspects of fire growth. However, they are valid only in limited conditions, namely fixed exposures, compartment configurations, and properties of materials used in the tests. Flexibility is needed in models that take these factors into account. In the present state of development, our model will be validated for wall fires using the conditions of the proposed ASTM room fire test. As of this writing, the experimental work is complete. The model being developed follows the classical two-zone approach: a hot upper layer and a lower layer at a temperature slightly above ambient. The model development and validation process will consist of the following components:

1. Using data from the steady-state experiments, an algorithm to describe the source flame can be well defined. This algorithm will accurately describe the source flame in terms of heat transfer to the wall and entrainment of air into the plume, both against a wall and in a corner of walls. The algorithm will provide the means to calculate ignition and burning characteristics of the wall segments adjacent to the source. The burning of these areas are presently assumed (12,13).

2. Surface flame spread in two modes—wind-aided (upward and along the interface between wall and ceiling) and opposed flow (downward and lateral)—can be calculated from the exposure and fundamental properties data obtained from LIFT and the heat release calorimeters. Research has shown that wind-aided flame spread depends on the rate of heat release whereas opposed-flow flame spread is controlled by thermal inertia of the material. In both ISO and ASTM room scenarios, flame spread along the wall-ceiling interface followed by downward flame spread controls the acceleration of fire growth to flashover. In simplified models, assumptions are made that fire will grow exponentially once certain criteria are met. Although these assumptions may be good for the scenarios considered, the model can be made more flexible through calculations based on our experimental data on flame spread.
3. Global heat release can be tracked from the burning surface using heat release rate data either from the OSU apparatus or cone calorimeters. As shown in Figure 7, a fairly good prediction of full-scale rate of heat release can be made with a crude correlation. In the model, the heat release history of each burning segment is taken into account and should provide more rigorous derivation of global heat release.

4. An orifice model is used to calculate flows through the doorway. The physics of buoyancy-driven Row of smoke through vent or vents is well developed. With the additional instrumentation, the FPL room test facility provides ample data to make this calculation possible.

5. The model must be able to track fire growth within the compartment. Heat release, temperature development, mass flow in and out of the system, and heat flux to selected locations are normally used as criteria for validation. However, it is difficult to have a complete set of either experimental data or rigorous data reduction to compare with model prediction. There now exists a data base of 36 full-scale tests over a wide range of variables such as burner location, burner output program, and different materials that cover walls and ceiling. An extensive data reduction program is being carried out to calculate global rate of heat release, mass flow of individual species through the vent, idealized temperature (mass averaged) in the upper and lower layers in the room, and interface height between the layers and neutral plane height in the doorway. These reduced data can then be compared with the calculations of the two-zone model.

The model must be able to take into account the fundamental properties that are determined by bench-scale experiments and use rigorous laws of physics without introducing arbitrary factors. Progress so far indicates that prediction of wall and corner fires is within our reach.

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REFERENCES


