NISTIR 6030

THIRTEENTH MEETING OF THE UJNR PANEL ON FIRE RESEARCH AND SAFETY, MARCH 13-20, 1996

VOLUME 1

Kellie Ann Beall, Editor

June 1997
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

U.S. Department of Commerce
William M. Daley, *Secretary*
Technology Administration
Gary R. Bachula, *Acting Under Secretary for Technology*
National Institute of Standards and Technology
Robert E. Hebner, *Acting Director*

UPWARD FLAME SPREAD ON VERTICAL SURFACES

Craig L. Beyler, Sean P. Hunt, and Naeem Iqbal
Hughes Associates Inc.
3610 Commerce Drive, Suite 817
Baltimore, Maryland, 21227, USA

Frederick W. Williams
Naval Research Laboratory
Washington, DC 20375, USA

ABSTRACT

A model which describes the physical processes of upward flame spread and fire growth on wall materials has been developed and implemented as a computer program. The computer based flame spread model simulates the fire growth along a vertical combustible wall. The vertical wall material may be heated by an imposed external heat flux and is ignited at its bottom edge with a flame from a line burner of user specified strength. The model predicts the flame spread rate, the heat release rate of the fire, the flame height, the net heat flux to the wall surface and the time varying surface temperature. The model uses inputs developed from cone calorimeter data. The results from the model compare favorably to upward flame spread experimental results for PMMA and plywood found in the literature.

1.0 INTRODUCTION

In this paper a vertical flame spread model is developed and validated against literature data. This work is a part of U.S. Navy Passive Fire Protection (PFP) Program and designed to provide a technique for specifying the performance required for the U.S. Navy material applications in terms of small-scale tests. The PFP program will result in known fire performance of material applications and will allow manufacturers/developers to provide cost-effective materials with the required performance, leading to cost saving and known performance.

The upward flame spread model on vertical surfaces is the first part of the modeling effort designed to develop a general modeling framework which will assess performance of materials in Navy fire scenarios from small-scale test data. This model is formulated on the basis of a review of the fire dynamics literature relevant to fire growth presented by Williams and Beyler (1994).

A computer model has been developed which calculates the flame spread on a vertical wall subject to a line ignition source. Flame spread is calculated using sub-models derived from the literature from inputs determined from cone calorimeter tests. The model is formulated based on existing sub-models of (1) ignition, (2) material heating, pyrolysis, and burning rate, (3) flame spread, and (4) flame and surface heat transfer. The details for each component of the analysis will be described in the following sections.

2.0 THEORY AND DESCRIPTION OF THE MODEL

The computer model calculates the flame spread on a vertical surface by breaking up the surface into a large number of elements. The conditions of each element are independently computed. The centroid of an element is assumed to be representative of the entire element. There are a number of global conditions that are calculated by summing the contributions from each element: the heat release rate, the height of the pyrolysis, the flame height along the wall and, the height of burnout front along the wall.

Each element is in one of four states: (1) preheat (above the flame), (2) preheat (exposed to the flame), (3) burning, and (4) consumed. The model keeps track of these conditions for each element, and the model stops when either the user entered simulation time is reached, the fuel is entirely consumed, or the flame propagation ceases.

In the present model, the wall can be heated by three sources: (1) an imposed external heat flux, (2) a line fire placed against the base of the wall (the ignitor), and (3) the wall flame itself. It has been shown that the heat flux to the wall from line fires against the wall and the wall itself can be correlated in the same manner. Heat fluxes distributions are prescribed based on prior work available in the literature which summarized by Quintiere (1988).

Prior to ignition, the wall surface is assumed to be a semi-infinite one-dimensional slab with a time dependent surface heat flux determined from the wall flame and external sources as described above. The conduction model used in this computer model is an approximate solution to the semi-infinite slab problem using an assumed cubic temperature profile and an integral solution [Eckert and Drake (1972)]. This method was selected based on its excellent predictive performance and computational efficiency.

Once an element has reached the ignition temperature, it is allowed to pyrolyze, burn and contribute energy to the wall fire. The heat release rate of the wall is determined by summing up the heat release rates of each burning element.

The material properties required by the model are determined using the cone calorimeter ASTM standard test method E-1354. These properties are as follows:

(1) Ignition temperature, T_{ig}, (K)
(2) Thermal inertia, $k\rho c$, $(kW/m^2\text{-}K)^2$ sec
(3) Effective heat of gasification, Δh_g (kJ/kg); and
(4) Heat of combustion, ΔH_c (kJ/kg).

The detailed method for determining these properties is described in a Naval Research Laboratory (NRL) forthcoming report.

3.0 RESULTS OF THE MODEL

The model results were compared with full-scale tests to evaluate the capabilities of the computer program in predicting vertical spread. Heat release rates, surface temperatures, and flame heights were compared with data available in the literature. No tests were found that described in adequate detail all of the potential characteristics for comparison. In addition, the test conditions were not adequately described in terms of the ignition temperature, material properties, and heat flux conditions. Comparisons were made using values or data from other literature sources.

Validation of the numerical solution for upward flame spread was made by comparing with full-scale experimental results using material properties from bench-scale data available in the literature. Full-scale data was available for vertical flame spread on Polymethylmethacrylate (PMMA) and plywood. The present numerical solution was compared to the experimental measurement of flame spread over a vertical PMMA surface by Wu, Delichatsios, and de Ris (1993), the experimental measurements of flame spread over a vertical surface of plywood with externally applied radiation flux by Delichatsios et al., (1994).

The ignition and flame spread properties and dimensions (input for model) are based on the bench-scale test data available in the literature.

3.1 Comparison of Predicted Results with Experimental Results for Non-charring Polymethylmethacrylate (PMMA)

Wu, Delichatsios, and de Ris (1993) conducted experiments to measured heat release rate for bench-scale and full-scale PMMA wall fires. In the bench-scale tests, a vertical PMMA slab measuring 0.90 m high, 0.2 m wide and 25 mm thick was ignited at the bottom of the panel by 20 ml of methanol and cotton balls in an aluminum dish (0.025 m x 0.20 m x 0.01 m high). The full-scale flame spread experiments were carried out with a 25 mm thick PMMA slab, 0.58 m wide x 5 m high. The ignition source was 35 ml of heptane in a copper dish (0.025 m x 0.6 m x 0.025 m high) at the bottom of the wall. This was simulated in the model as a 1 kW/m line fire source.

Figure 1 shows a comparison of heat release rate during upward flame spread over 0.90 m x 0.20 m vertical PMMA surface. The solid line is the model prediction while dash line is the experimental data of Wu, Delichatsios, and de Ris (1993). Due to the sensitivity of the computer model to the heat flux and flame height correlations, several simulations of the test were performed in order to determine the optimum combination. The flame heat flux in the burning region used was 21 kW/m^2. Since exact value of flame heat flux after ignition were not described in the test conducted by Wu, Delichatsios, and de Ris (1993), after several runs of the model a value of 21 kW/m^2 heat flux after ignition was found to yield the most adequate results.

3.2 Comparison of Predicted Results with Experimental Results for Plywood

Delichatsios et al., (1994) have conducted theoretical and experimental analysis of upward fire spread along 2.4 m high, 0.61 m wide and 12.7 mm thick vertical wall made of plywood. Five full-scale flame spread experiments were conducted. The samples were exposed to a specified heat flux from a large-scale radiant panel. The following measurements were made:

(1) Rate of heat release,
(2) Total heat flux to the specimen surface,
(3) Surface temperature, and
(4) Propagation of the pyrolysis front.

The full-scale test results demonstrated the sensitivity of the flame rate to the external heat flux. The samples of plywood in the experiments were ignited by a red-hot nichrome wire. The wire was preheated using a welder power supply set to provide a 40 Amp current through the wire. After preheating, the wire was brought into direct contact with the specimen at a location approximately 25 mm above the base of the specimen. A thin spacer located between specimen holder and the center of the specimen was used to make the specimen slightly convex at the base and ensure good contact for the ignition wire over the entire width of the specimen.

Comparison of PFP upward flame spread model predictions to the full-scale experimental results [Delichatsios et al. (1994)] is shown in Figure 2. The predictions and experimental propagation of pyrolysis front (determined using surface thermocouples) are shown in Figure 2. In general, there is a reasonable agreement between predicted and measured propagation of the pyrolysis zone.

4.0 CONCLUSIONS

A computer model has been developed that successfully addressed upward fire growth on vertical surfaces. The agreement with experimental results is good. Assumptions have been made based on the limited information for flame heat transfer rates to cause burning and spread, and more complete experimental results are needed.

It is the intent of this work to present a simple flame spread model that integrates many of the features and capabilities of those described and that requires a minimum of input data and accurately predicts the fire growth along vertical walls subject to ignition sources. Ultimately, the model will be generalized so that two and three dimensional geometries may be modelled. The ultimate goal of these modeling efforts is to predict and evaluate the fire performance of U.S. Navy materials, products, and assemblies and to provide a link between small-scale ignition and heat release rate measurements in the cone calorimeter with the full-scale fire performance to ensure an environment safe from destructive fires.

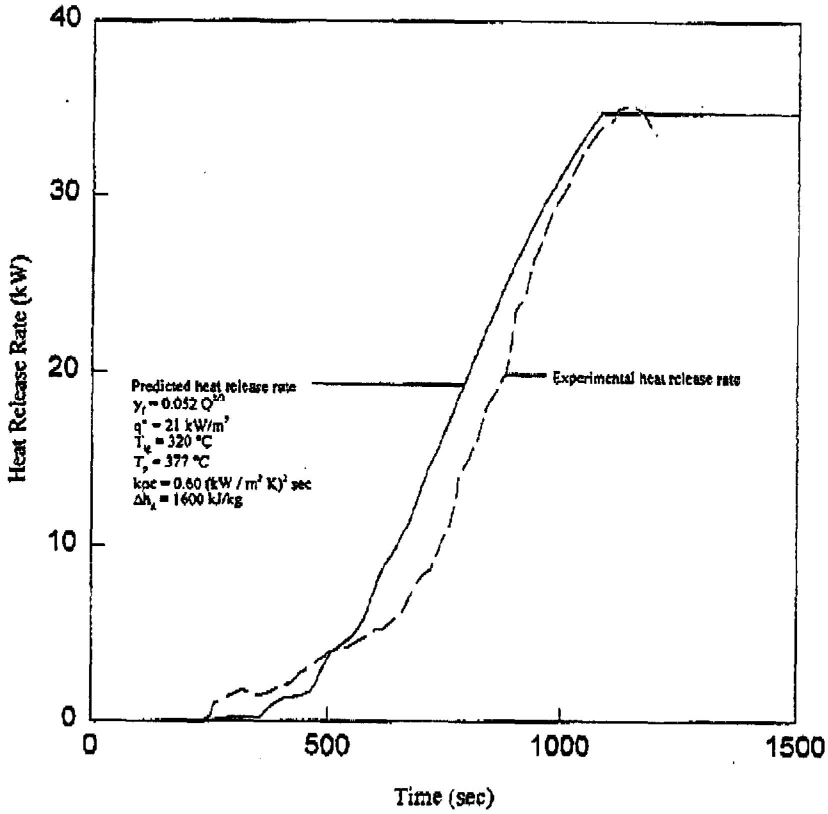

Figure 1 Comparison of heat release rate predictions for a 0.90 m x 0.20 m vertical PMMA surface with Wu, Delichatsios, and de Ris. 1993 data

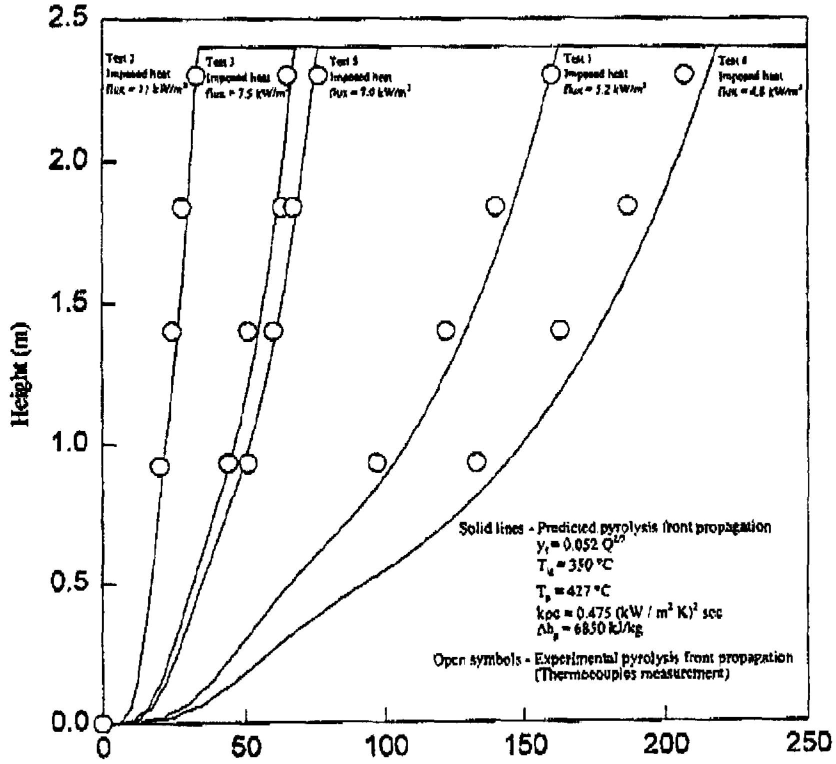

Figure 2 Comparsion of pyrolysis front propagation predictions for a 2.4 m x 0.61 m vertical plywood surface with Delichatsios et al. 1994 data

REFERENCES

Delichatsios, M. M., Wu, P-K., Delichatsios, M. A., Lougheed, G. H., Crampton, G. P., Qian, C., Ishida, H., and Satio, K., 1994, "Effects of External Radiant Heat Flux on Upward Fire Spread: Measurements on Plywood and Numerical Predications", *Fire Safety Science-Proceeding of the Fourth International Symposium*, International Association of Fire Safety Science, Kashiwagi, Editor, 1994, pp. 421-432.

Eckert, E. R., and Drake, R. M., 1972, "*Analysis of Heat and Mass Transfer*", Chapter 4 - Unsteady Heat Conduction, McGraw-Hill Book Company, 1972, pp. 138-221.

Quintiere, J. G., 1988, The Application of Flame Spread Theory to Predict Material Performance", *Journal of Research of the National Bureau of Standards*, **93** (1), January/February 1988, pp. 61-70.

Williams, F. W., and Beyler, C. L., 1994, "Passive Fire Protection (PFP) Modeling Literature Review", NRL Letter Report Serial 6180/0221A, 13 July 1994.

Williams, F. W., Beyler, C. L., Hunt, S. P., and Iqbal, N., 1995, "Upward Flame Spread on Vertical Surfaces", NRL Memorandum Report 1995 in publication.

Wu, P-K, Delichatsios, M. M., and de Ris, J., 1993, "Upward Fire Spread Over PMMA Walls-A Model/Experiment Comparison", *1993 Annual Conference on Fire Research: Book of Abstract*, NISTIR - 5280, U.S. National Institute of Standard and Technology, Gaithersburg, Maryland, 1993, pp. 7-10.

Discussion

Richard Gann: Craig, for what types of walls are you intending to model to be used?

Craig Beyler: The most immediate interest with the Navy is for thin covering type of materials. Not paint, as much as coverings over insulating materials, just a couple millimeters thick type coatings as opposed to a coat of paint.

Richard Gann: For those kinds of layered materials, will your heat and flame spread model, which is appropriate for simple materials, work?

Craig Beyler: On a good day, yes. I think the thermal underlying material tends to dominate the behavior there. And of course, things like ignition temperatures and pyrolysis are dominated by the coating material. I think there are undoubtedly situations where that won't be true, but I think there are non-trivial cases where I think that will work.

Henri Mitler: First, where did you obtain your $\kappa\rho c$ data?

Craig Beyler: Basically, we deduced the properties from the Cone Calorimeter data, and I should have addressed that more. We did ignition experiments and used known ignition temperatures from direct measurement to fit the ignition temperature. We then took the ignition time as a function of flux and determined the $\kappa\rho c$ which would reproduce that ignition behavior.

Henri Mitler: My second question is more philosophical. There are at least four existing upward spread models available, and you obviously decided that another attack was worth doing. I'm curious as to what inadequacies you found in the earlier models that led you to that.

Craig Beyler: I wouldn't say it was the inadequacies of the existing models that motivated us to start over. Certainly, we were standing on the shoulders of the existing models. We could well have done this part of the work by taking your model or other models and using them and adjusting them if necessary. Our ultimate goal here was to do something that was going to be able to do walls, corners, lateral spread, a more generalized kind of prediction than the ones that were available. The infrastructure we think we created in the code is one that can grow into these other applications.

Yuji Hasemi: When you observe fire spread, if radiation is very high, the flame velocity becomes very fast, and that would make measurement difficult. When the heating is weak, then the heat release rate is difficult to measure. There is some difficulty in getting reproducible results. I would like to hear your opinion as to at what level we should try to start.

Craig Beyler: If I understand your question, it relates to levels of the heat fluxes in the Cone Calorimeter vs. Full scale and that at high fluxes, ignition times are very quick and at low fluxes, it's difficult to get good burning rate data. It certainly is. With regard to ignition, I haven't seen much problem inasmuch as the heat fluxes in a wall flame are something on the order of zero to fifty kW/m^2 and the Cone Calorimeter has no particular difficulty in resolving ignition behavior.

Discussion cont.

So in that regard, I haven't seen a problem. Clearly in the Cone Calorimeter, low heat release rates are less accurately measured than very vigorous burning items. We often find it necessary to not use standard Cone Calorimeter methods for thin materials and low heat release to improve the resolution of the data.

Mark Janssens: Your model relies on experimental correlations for the heat flux, which is based on incident heat flux measurements, using the heat of gasification concept. How does your model account for losses?

Craig Beyler: You've almost given the answer yourself. Basically, the model, as we use it, has a constant heat gasification and a specified surface temperature. So the losses are simply due to black-body radiation and the net flux is a constant. We did assume a constant temperature and that is the weakness.