NBSIR 75-706

Calculations of Radiant Heat Flux in the Proposed Floor Covering Flame Spread Test Apparatus

James Quintiere and Kevin Bromberg

Center for Fire Research
Institute for Applied Technology
National Bureau of Standards
Washington, D. C. 20234

December 1975

Final Report

DEPARTMENT OF COMMERCE * NATIONAL BUREAU OF STANDARDS *

U S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

NBSIR 75-706

CALCULATIONS OF RADIANT HEAT FLUX IN THE PROPOSED FLOOR COVERING FLAME SPREAD TEST APPARATUS

James Quintiere and Kevin Bromberg

Center for Fire Research
Institute for Applied Technology
National Bureau of Standards
Washington, D. C. 20234

December 1975

Final Report

CONTENTS

LIST OF FIGURES

CALCULATIONS OF RADIANT HEAT FLUX IN THE PROPOSED FLOOR COVERING FLAME SPREAD TEST APPARATUS

James Quintiere and Kevin Bromberg

Calculations have been made to determine the radiant heat flux distribution to the test specimen in the proposed radiant panel flame spread test for floor covering materials. Comparison with measured heat flux indicates a significant heat transfer contribution from the enclosure of the test apparatus. Also, nonuniformities in the temperature of the radiant panel affect the resultant flux distribution. Based on these results, it is expected that two similar test apparatuses would not have identical heat flux profiles along the specimen. Additional calculations were made to illustrate possible heat flux profiles capable with the present apparatus under various panel temperatures and orientations.

Key words: Floor covering; heat flux; radiant panel test method.

1. INTRODUCTION

The purpose of this report is to analyze the radiant heat transfer characteristics of the proposed radiant panel test for measuring floor covering flammability [1,2][1]. In the test apparatus, a gas-fired porous refractory burner is enclosed in a rectagular chamber. The burner is oriented at an angle to the horizontal and faces downward. A test specimen is mounted in a horizontal plane below the burner. The analysis considered in this report will be directed at the radiant heat exchange between the radiant panel, specimen, and the surrounding surfaces of the enclosure. This analysis does not consider heat transfer effects associated with flame spread along the specimen. It is primarily concerned with the initial radiant heat flux distribution to the specimen.

The specific objectives of this analysis are: (1) to identify and quantify the sources of radiant heat flux to the specimen, (2) to determine the relative importance of the different factors which influence the incident radiant flux, and (3) to compare the theoretically determined radiant heat fluxes with measured results.

---

[1] Numbers in brackets correspond with the literature references listed at the end of this paper.

By accomplishing these objectives, the resultant information should be helpful in the development and interpretation of the proposed test method.

2. ANALYSIS AND RESULTS

The primary source of radiant heat transfer to the specimen plane is the gas-fired panel. Several factors influence the magnitude of this flux and will be considered in the analysis to follow. Radiation from the panel depends on the temperature distribution over its face. The face of the burner consists of a porous burner region which is heated by the combustion process, and an "inactive" perimeter which is heated basically by conduction. The temperature distribution over the combustion zone of the panel and its edges will influence the emitted radiant heat transfer.

A secondary source of radiant heat transfer which is expected to contribute to the heat flux on the specimen plane originates from the heated walls and ceiling of the enclosure. This contribution depends on the temperature distribution along the enclosure surfaces. This contribution will not be directly predicted since it would involve a more complex analysis than is required to meet the objectives of this analysis. However, the magnitude of the enclosure heat flux contribution will be determined by comparison of measured specimen fluxes with and without enclosure walls.

2.1. Radiant Heat Flux from Panel to Specimen Plane

The incident radiative heat flux on the specimen due to the panel is determined by

$$\dot{q}''_{SP} = F_{SP}\ \sigma T_P^4 \qquad (1)$$

where F_{SP} is the configuration factor from a differential specimen area to the panel,

σ is the Stefan-Boltzmann constant,

and T_P is the effective blackbody temperature of the panel burner.

The configuration factor is a function of orientation and geometry. The arrangement of the panel with respect to the specimen plane is shown in figure 1. The constraints on the NBS apparatus are such that height of the specimen plane can be varied, and the panel inclination can be varied about the lower edge as an axis of rotation. The active burner area of the panel is 30.5 cm wide (b = 15.3 cm) and 45.7 cm long ($a_2 - a_1$ = 45.7 cm). The inactive perimeter of the panel face is 1.9 cm in width. The configuration factor between an element dA_S on the centerline of the specimen and the panel face, P, is determined from the configuration factor relationship for the basic arrangement shown in figure 2 [3]

where $$F_{12} = \frac{1}{2\Pi}\left\{\tan^{-1}\left(\frac{1}{L}\right) + V\left(N\cos\phi - L\right)\tan^{-1} V + \frac{\cos\phi}{W}\left[\tan^{-1}\left(\frac{N-L\cos\phi}{W}\right) + \tan^{-1}\left(\frac{L\cos\phi}{W}\right)\right]\right\} \tag{2}$$

where $$V = \left(N^2 + L^2 - 2NL\cos\phi\right)^{-1/2}$$

$$W = \left(1 + L^2 \sin^2 \phi\right)^{1/2}$$

$$N = {}^a/_b$$

and $$L = {}^c/_b$$

Configuration factor algebra [3] is then used to determine F_{SP}. The basic configuration factor F_{12} can be considered as a function of a, b, and c. It can be shown that

$$F_{SP} = 2\left[F_{12}\left(a_2, b, H\cot\phi + 8.9\text{ cm} + x\right) - F_{12}\left(a_1, b, H\cot\phi + 8.9\text{ cm} + x\right)\right] \tag{3}$$

where $F_{12} = F_{12}\ (a,b,c)$ is given by equation (2).

Two test conditions have been used extensively with this apparatus and have been referred to as conditions C and D [1]. The parameters defining these conditions are listed in table 1. These conditions will be referred to in the following discussion.

Table 1.
Parameters Defining Condition C and D

Condition	T_p (°C)	H (cm)	ϕ (deg.)
C	490	14.0	30
D	670	8.6	30

2.2. Effect of Panel Edge Surface on Heat Flux

A calculation was made to determine the effect of the inert perimeter region of the panel which is heated by conduction. The inert region was assumed to be at the same temperature as the combustion zone of the panel. That is, the radiating area was increased to include the edge region. In this manner, equation (1) was used to evaluate the edge effect. It was found that for both conditions C and D, the edge contribution could be, at most, between 4% at x = 0 and 18% at x = 90 cm, where x is the position along the test sample. Since this edge temperature is expected to be lower than the effective panel temperature T_p in practice, it was concluded that its effect on heat transfer is small; and consequently, will be neglected in all subsequent calculations. (In effect, this influence can be absorbed into the enclosure influence discussed in 2.5.)

2.3. Effect of Panel Temperature on Heat Flux

It has been recognized that two factors influence the temperature, T_p, of the radiant panel [4]. In one case, the nature of the porous burner is such that a nonuniform surface temperature is likely to occur. In fact, Adams has found that a "hot spot" existed over the lower left corner of the burner used in the NBS apparatus [4]. Based on these temperature measurements, this hot spot effect was included in our calculations by dividing the panel surface into two zones of uniform temperature. This is shown in figure 3. The temperature of the "hot spot" was taken as 35 °C above the average panel temperature in condition D. The incident radiant flux on dA_S from the panel with a "hot spot" is given as

$$\dot{q}''_{SP} = F'_{SP}\,\sigma T_P^4 + F_{SH}\,\sigma\left(T_P + \Delta T_H\right)^4 \qquad (4)$$

where F'_{SP} is the configuration factor between dA_S and the panel face minus the hot spot region,

F_{SH} is the configuration factor between dA_S and the hot spot region,

and ΔT_H is the increase in temperature of the hot region above the average panel temperature, T_P.

The configuration factors F'_{SP} and F_{SH} can be found by using equation (2) and configuration factor algebra.

Before presenting the result of this calculation, one other effect on panel temperature, which was accounted for in the calculations, should be discussed. The panel temperatures given in table 1 are nominal values, initially measured with a pyrometer viewing the panel through the open bottom of the enclosure. After the bottom of the enclosure is closed with the specimen holder, it has been found that the average panel temperature increases [4]. The increase was measured to be about 12 °C for condition C and 18 °C for condition D. Hence, when the heat flux distribution is measured with the specimen holder in place, the water cooled heat flux sensor views a panel which is hotter than that seen by the pyrometer initially.

In comparing calculations with measured heat flux, it was then necessary to use the increased panel temperature in equation (4).

2.4. Comparison of Calculated Heat Flux with Measured Flux

Figures 4 and 5 illustrate a comparison of the calculated radiative heat flux distributions with measured values for conditions C and D, respectively. The calculated values are based on equation (4) with two results shown; one for the initial panel temperature, and one for the increased panel temperature after it has reached a new equilibrium, due to closing the bottom of the enclosure. The measured values were determined using a total heat flux sensor which is water cooled and hence is a cold target relative to its hot surroundings. Since a total heat flux meter was used, convective heating to the sensor cannot be precluded. However, measurements with a radiometer indicated that convective heating is likely insignificant [4]. The deviation between calculated fluxes and measured values must be due to the added radiation received from the heated walls of the enclosure.

In order to determine that the walls were responsible for the difference between calculated and measured values, a profile of heat flux was determined with the walls and ceiling removed from the apparatus. The measurements are included for comparison in figures 6 and 7. Two calculated curves are shown, one at the initial panel temperature and the other at the increased panel temperature after it would come to equilibrium with the enclosure and specimen in its test position. It was estimated that the specimen surface has the dominant influence on increasing the panel temperature. Hence, the curves calculated for the increased temperature are more appropriate for comparing results with the measured values even for the case where the walls were removed. Except for specimen positions close to the radiant panel for condition D, the calculated flux from the panel agrees well with the measured heat flux with the enclosure removed. The inability of the calculation to predict the measured flux in D could be due to a convective heating effect or a temperature variation effect of the panel unique to condition D.

2.5. Effect of Enclosure on Heat Flux

As shown above, the enclosure accounts for a significant portion of the heat flux to the specimen. For example, under flux conditions C and D, 40% or more of the total incident flux to the sample comes from the heated enclosure for distances beyond 60 cm (see figs. 6 and 7). This contribution increases relative to the flux from the panel with increasing distance from the panel. In order to predict the radiative heat flux component due to the heated enclosure, the temperature distribution must be known. If the enclosure temperature is assumed to be uniform, T_W, then the incident heat flux to the specimen element dA_S would be given as

$$\dot{q}'' = \sigma\, F_{SP}\, T_P^4 + \sigma\, (1 - F_{SP})\, T_W^4 \qquad (5)$$

If the measured heat flux is substituted into equation (5), an effective enclosure temperature can be calculated corresponding to each specimen position x. This was done and yielded effective enclosure temperatures which decreased from 200 °C at x = 10 cm to 80 °C at x = 90 cm for condition C. Measurements of side wall temperatures for conditon C indicated 154 °C at x = 40 cm and 99 °C at x = 70 cm. These measurements were made with thermocouples located on the side wall midway between the specimen plane and the ceiling. The corresponding calculated effective temperatures were 139 °C and 93 °C. Thus, these calculations yield results which confirm the effect of enclosure walls on heat flux to the specimen.

3. OTHER CALCULATED HEAT FLUX PROFILES

In the development of the test apparatus, it is likely that the present flux conditions (C and D) may be modified. Several considerations are likely to affect this decision. Among these considerations is that the flux should span a range of values that are relevant to real fire conditions. Also, the flux should decrease slowly with x initially and gradually decrease more rapidly as x is increased. This feature is desirable in order to minimize transient effects associated with ignition and a relatively high rate of flame spread at the start of the test, and to minimize test time. In anticipation of a modification of the flux distribution, some calculations were made to estimate the flux distribution for several conditions. These results are shown in figure 8. They were determined using equation (1) for the configurations without a surrounding enclosure, and equation (5) for the configurations with an enclosure. The wall temperature distribution was approximated by an effective wall temperature distribution similar to that determined for condition D.

4. CONCLUSIONS

Calculations and measurements indicate that the enclosure can produce a significant contribution to the specimen heat flux. About 10 to 60% of the incident heat flux in conditions C and D originates from the heated enclosure. Hence, for test apparatuses with differing enclosure materials or geometry, it is expected that the heat flux distribution on the specimen will differ accordingly for the same panel temperature and orientation. In addition, nonuniformity of temperature over the burner face will perturb the heat flux distribution to specimen. Consequently, in the specification of a test method, it is important to require a record of the flux distribution for each apparatus. It is not likely, nor should it be expected for the current state of the apparatus, that the heat flux profiles would be the same for all apparatuses.

The implication of these conclusions bears on the case concerned with flame spread along a specimen in the test. Ideally, during a test, the externally applied radiative heat flux to the specimen should remain constant, and the only additional specimen heating should result directly from the spreading flame on the specimen. The results of this report have shown that the initial external heat flux is sensitive to the enclosure surface temperature, and that the panel temperature can increase due to radiative exchange with hot surfaces. Thus, during flame spread it is expected that the panel temperature will change and the enclosure surface will become hotter. Specimen smoke production, flame height impingement on the panel, and energy release rate will influence the extent of these changes. It is noted that for a similar gas-fired radiant panel, used in a vertical flame spread test, Buschman [5] found a significant increase (about 20%) in panel emitted radiative heat flux due to the presence of an adjacent burning specimen. Hartzell [1] found in his study of the floor covering test, that panel temperature could increase or decrease during a flame spread test. These factors indicate a need for experiments to determine the influence of specimen flame spread on the initially applied external radiative heat flux.

5. REFERENCES

[1] Hartzell, L.G., Developing of a Radiant Panel Test for Flooring Materials, Nat. Bur. Stand. (U.S.), NBSIR 74-495 (May 1974).

[2] Quintiere, J. and Huggett, C., An Evaluation of Flame Spread Test Methods for Floor Covering Materials, Fire Safety Research, Proceedings of a Symposium held at the National Bureau of Standards, Aug. 22, 1973, Nat. Bur. Stand. (U.S.), SP-411 (Nov. 1974).

[3] Hamilton, D. C. and Morgan, W. R., Radiant Interchange Configuration Factors, NACA Tech. Note 2836 (Dec. 1952).

[4] Adams, C.H., Private Communications, National Bureau of Standards, 1974.

[5] Buschman, A. J., Ignition of Some Woods Exposed to Low Level Radiation, Second Progress Report, Nat. Bur. Stand. (U.S.) NBS Report 7848 (Apr. 1963).

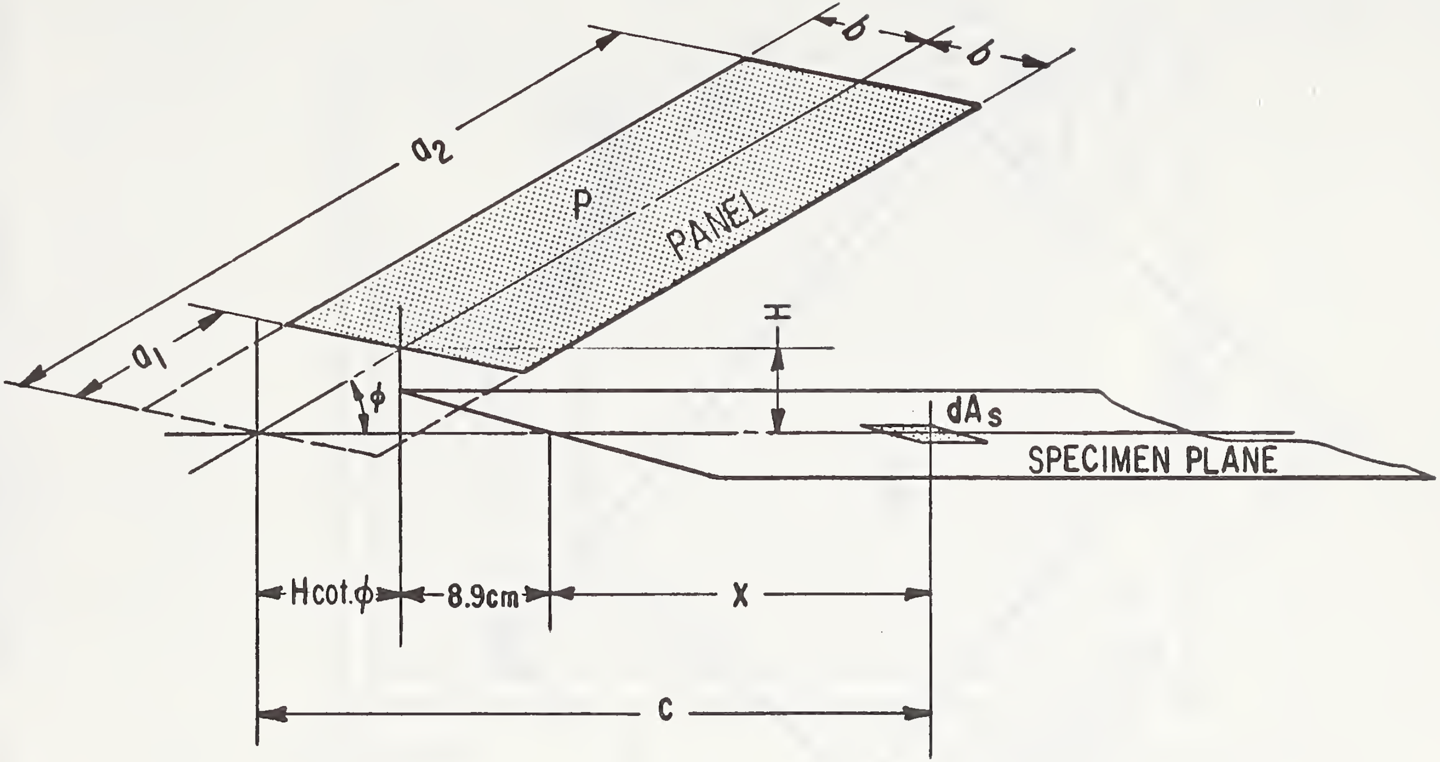

Figure 1. Panel geometry and orientation with respect to the specimen plane.

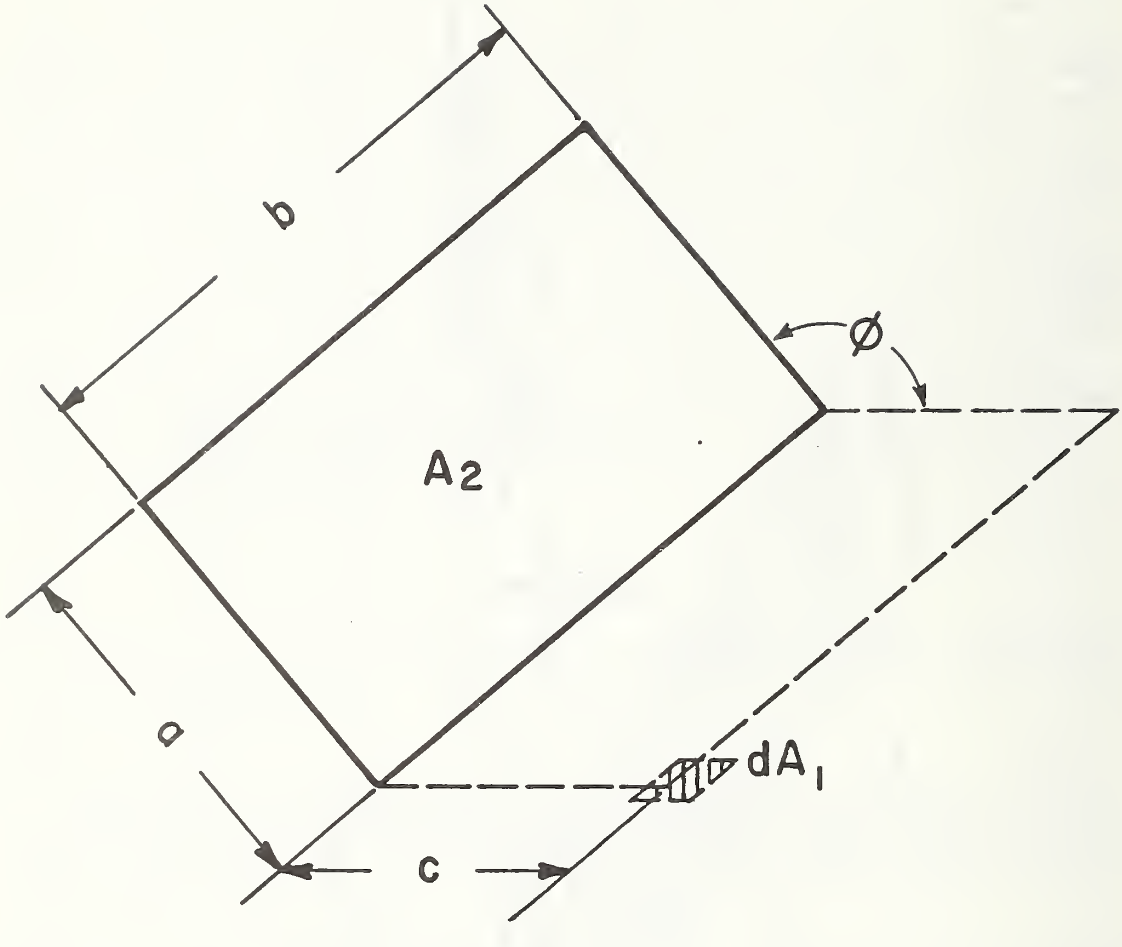

Figure 2. Basic configuration (applies to eq. [2]).

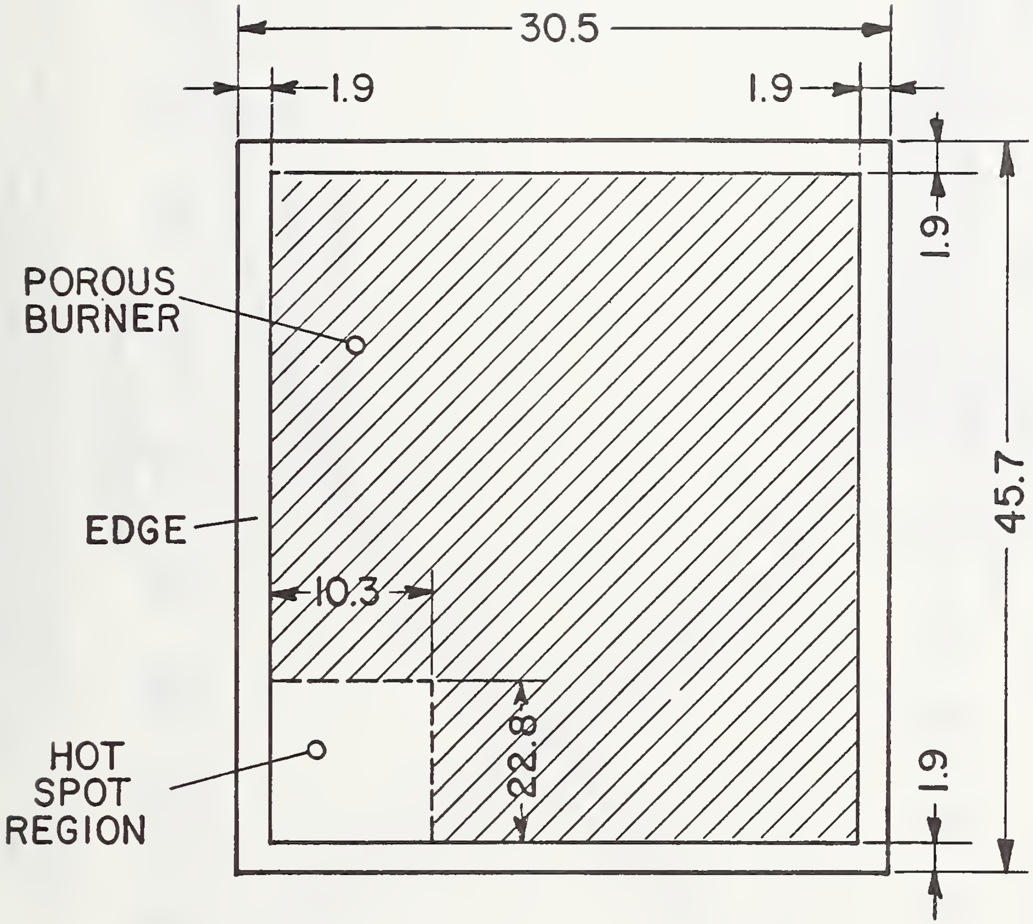

Figure 3. Schematic of radiant panel showing hot spot region as approximated in calculations. (Dimensions are in cm)

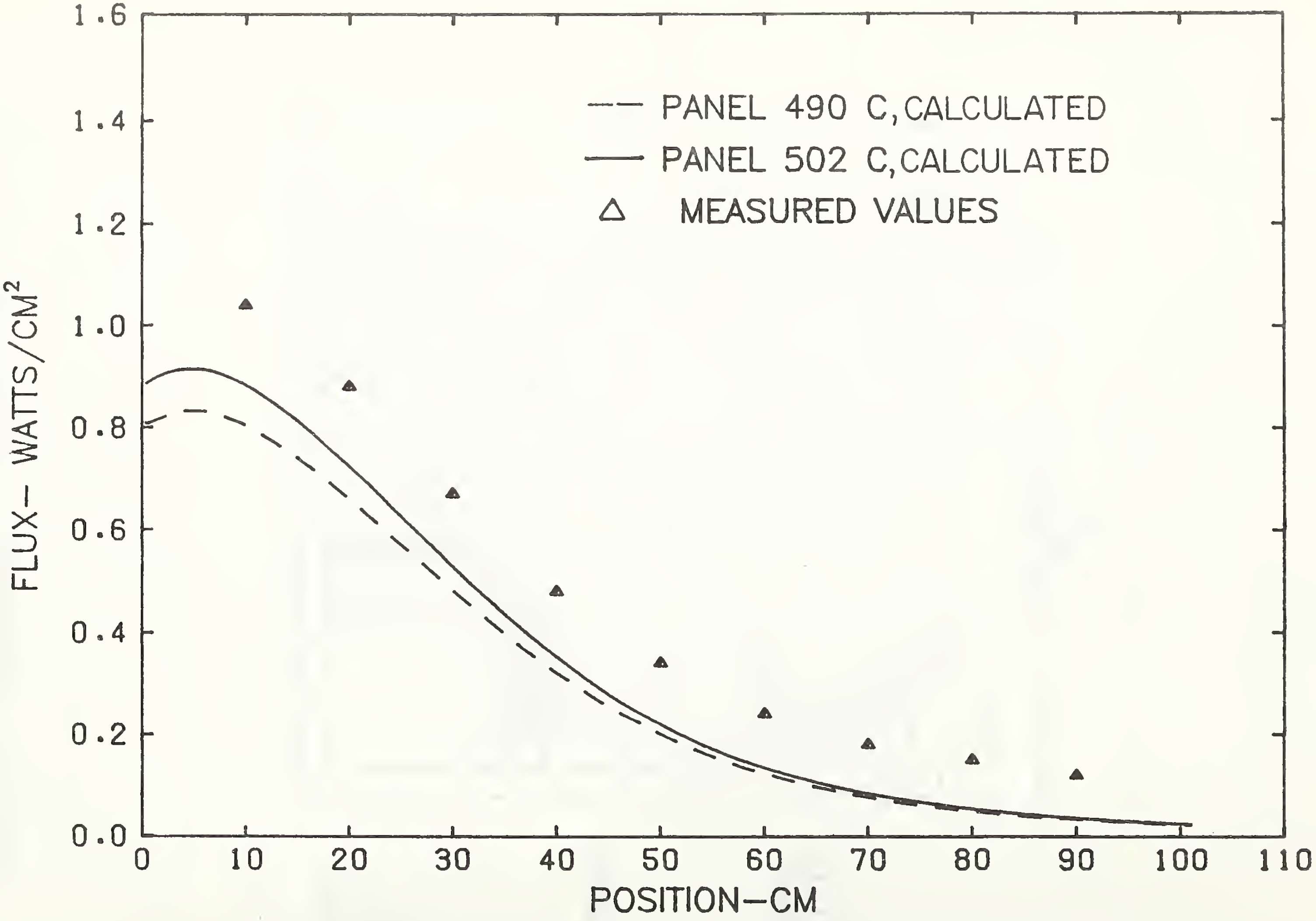

Figure 4. Comparison of calculated and measured heat flux distributions for condition C.

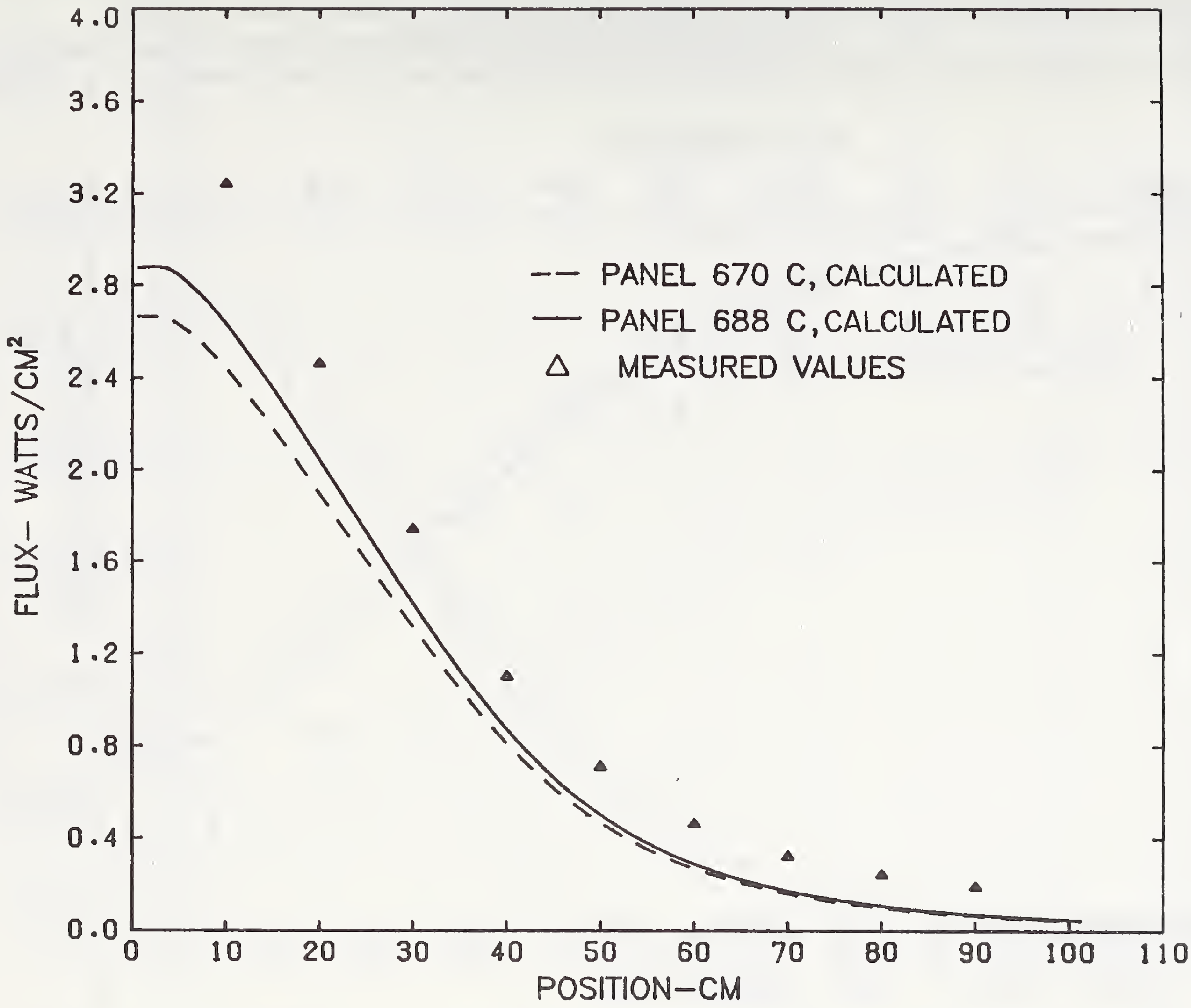

Figure 5. Comparison of calculated and measured heat flux distributions for condition D.

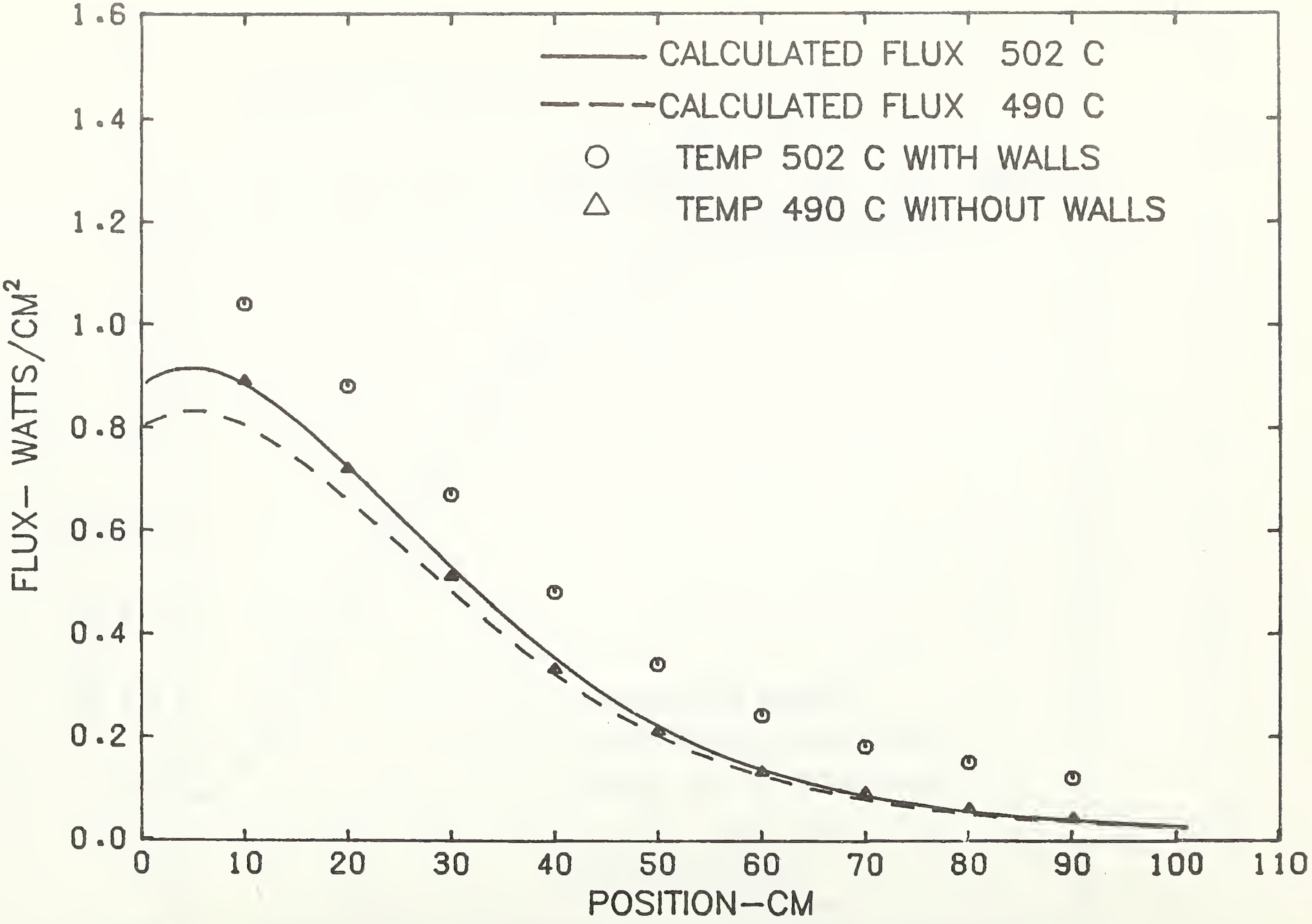

Figure 6. Comparison of calculated and measured heat flux distributions with the enclosure surfaces removed for condition C.

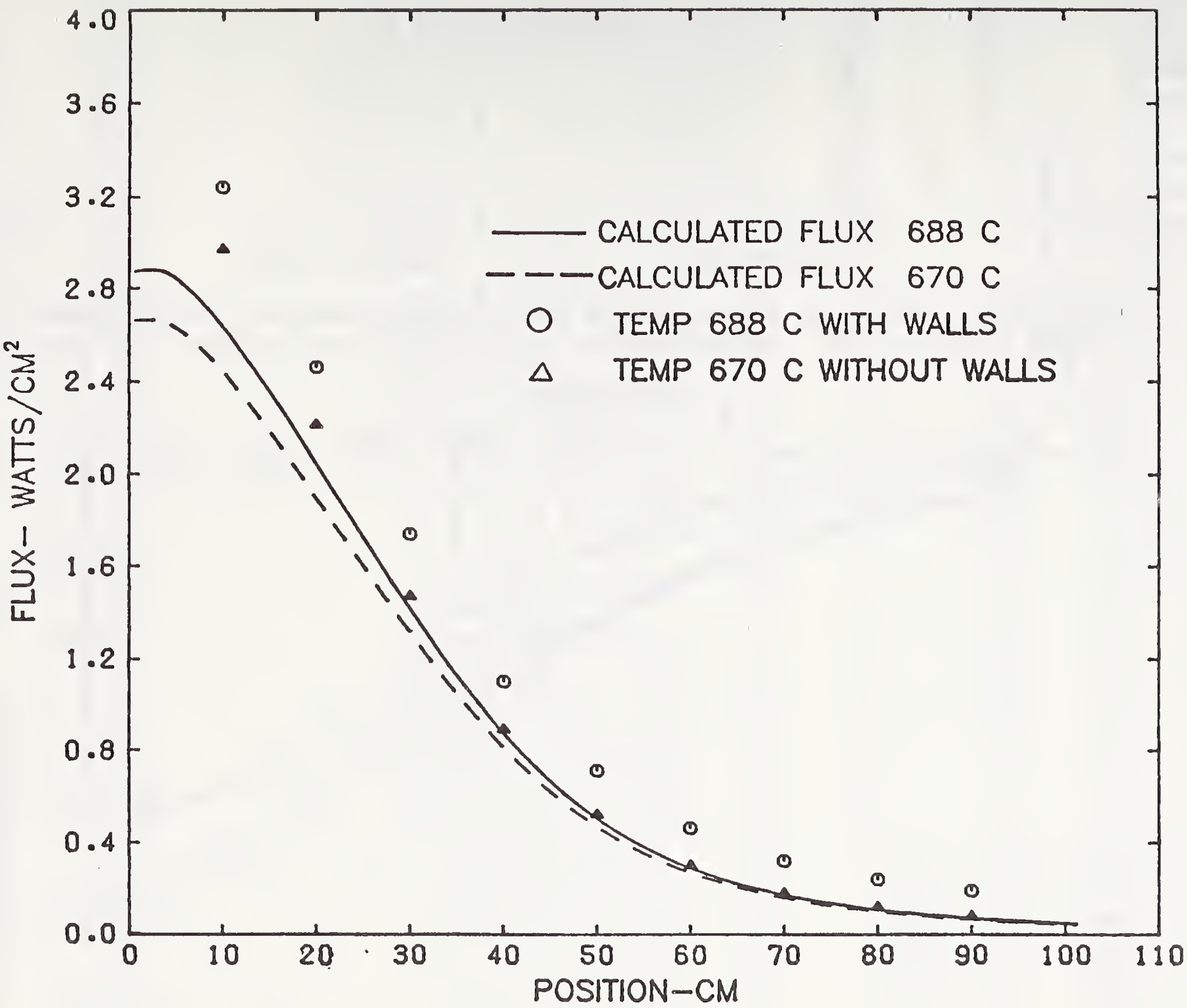

Figure 7. Comparison of calculated and measured heat flux distributions with the enclosure surfaces removed for condition D.

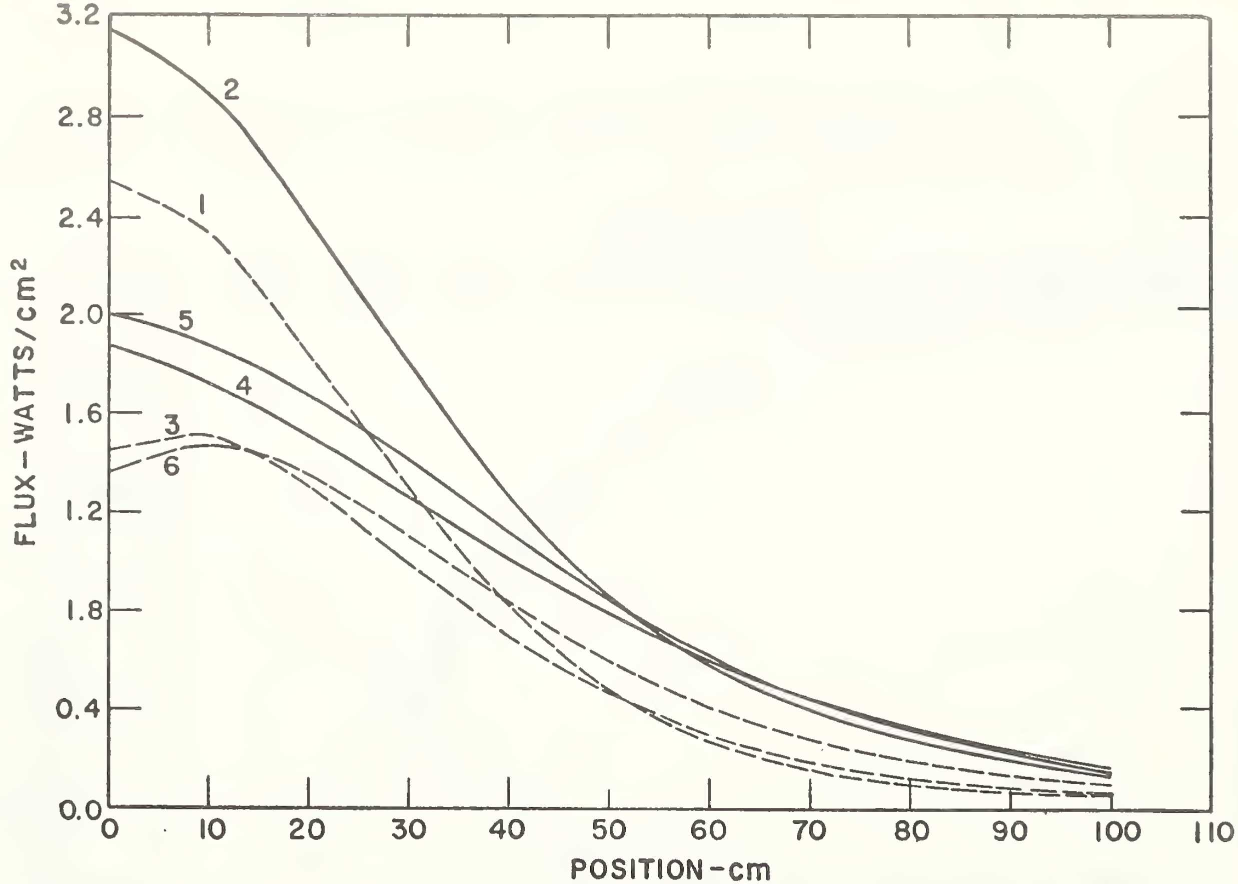

Figure 8. Calculated heat flux distributions for various panel temperature, orientations, and presence of enclosure surfaces.

Curve	Panel Temp. T (°C)	Orientation H (cm)	Orientation ϕ (deg)	Enclosure
1	670	8.6	30	no
2	670	8.6	30	yes
3	670	17.8	30	no
4	670	33.0	30	yes
5	670	33.0	15	yes
6	750	25.4	30	no

NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBSIR 75-706	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE Calculations of Radiant Heat Flux in the Proposed Floor Covering Flame Spread Test Apparatus			5. Publication Date December 1975 6. Performing Organization Code
7. AUTHOR(S) James Quintiere and Kevin Bromberg			8. Performing Organ. Report No.
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234			10. Project/Task/Work Unit No. 4915676 11. Contract/Grant No.
12. Sponsoring Organization Name and Complete Address (Street, City, State, ZIP) same as No. 9			13. Type of Report & Period Covered Final Report 14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

Calculations have been made to determine the radiant heat flux distribution to the test specimen in the proposed radiant panel flame spread test for floor covering materials. Comparison with measured heat flux indicates a significant heat transfer contribution from the enclosure of the test apparatus. Also, nonuniformities in the temperature of the radiant panel affect the resultant flux distribution. Based on these results, it is expected that two similar test apparatuses would not have identical heat flux profiles along the specimen. Additional calculations were made to illustrate possible heat flux profiles capable with the present apparatus under various panel temperatures and orientations.

17. KEY WORDS (six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons) Floor covering; heat flux; radiant panel test method.

18. AVAILABILITY	19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
[x] Unlimited [ ] For Official Distribution. Do Not Release to NTIS [ ] Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13 [x] Order From National Technical Information Service (NTIS) Springfield, Virginia 22151	UNCLASSIFIED	20
	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. Price $3.50

USCOMM-DC 29042-P74

AMERICAN REVOLUTION BICENTENNIAL
1776-1976