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EXPERIMENTAL VALIDATION OF RELIEF— A ZONE MODEL TO PREDICT FIRE BEHAVIOR IN ENCLOSURES WITH WALL LININGS

RAJIV KUMAR

SUNIL K. SHARMA

Central Building Research Institute, Roorkee
(Council of Scientific and Industrial Research), India

ABSTRACT

A simple and user-friendly mathematical zone model named RELIEF (Risk Estimation due to Linings In Enclosure Fires) [1] has been developed to predict the temperature of upper gas layer in the enclosure with wall and ceiling linings when lining materials along with source fuel burns and contributes in the fire spread and its growth. The model has been validated with the help of experimental data due to Kokkala et al. [2]. The upper hot gas layer temperature and layer heights predicted by RELIEF were compared with these observed data. The predictions are very close to the experimental data.

INTRODUCTION

Nowadays, there is an increase in the use of predictive fire models for fire engineering design instead of performance based codes. Computer models are like "black boxes"—we put something in and we get something else back out [3]. In order to understand the important and fundamental principles involved and have confidence on the models, there is a need to validate the model. The developed model must be rigorously tested to make sure that the model yields acceptable results, regardless of its simplicity or complexity. The testing of

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developed model is commonly referred to as *model validation or model verification.* Model validation refers to the determination of the appropriateness of the fundamental equations used in the development of the model and the numerical solution technique employed to solve them. Watts Jr. [3] defined validation as a process for determining that the outputs of a model conform to reality. However, according to Beard [4], "validation" means "comparisons with experiments." Once the experimental data are available, a comparison between model predictions and experimental results is to be conducted to provide an indication of the accuracy of the model. Comparisons with experiments give confidence among the modeler and user.

The most commonly used procedure for comparing experimental data and model predictions is through graphical methods. Two variables are plotted against each other for both experimental and model results. Time—temperature and time—interface locations are the most widely used plots. There are three methods to analyze the predictive capacity of the model: *A priori*, *Blind*, and *Open* comparison between prediction and experiment [5]. It is desirable for all three kinds of comparisons to be made. *A priori* comparisons are carried out without the prior knowledge of experimental results of the parameter to be predicted. Also input data can be specified rather than calculated from the experimental data. For *blind* or *open* comparisons, the experimental results are known to the modelers. For *blind,* input is decided before running the model and not adjusted after comparing with experiment. For *open,* input parameters may be adjusted after comparing the predictions with experiment. The input in both types of comparison are calculated from measured experimental data. For example, in *a priori* comparisons heat release rate (HRR) to be used as input can be estimated by knowing the fire size and fuel rather than finding it from the measured mass loss rate. Using the measured mass loss rate from an experiment being used for comparison make it a *blind* or *open* comparison.

The comparison in this article has been carried out by *open* method. Heat release rate (HRR) from both source as well as from lining materials, are taken as input parameters. The HRR due to source fuel has been calculated with the help of measured burning rate of fuel in the experiment while HRR due to lining material is measured directly by oxygen consumption method.

The present article is an attempt in this direction to make RELIEF (Risk Estimation due to Lining In Enclosure Fires) a valuable fire model, so that it can play a vital role in fire safety decision making. RELIEF is a simple two layer pre-flashover model [1]. It has been developed to predict dynamic environment generated by fires in an enclosure with lining material on wall and ceiling. The detailed description including mathematical representation in the form of time dependant conservation equations of mass and energy have been described in Kumar and Sharma [1]. Simulation has been done with the experimental data available in the literature. Internationally, a number of studies have been conducted with internal lining material developed in those countries. Some of them have been conducted with a view to study the role of wall lining materials and their contribution to the room fire development. One of these studies, entitled "Fire Hazard–Fire Growth in Compartments in the Early Stages of Development (Pre-flashover)," was conducted in Sweden under a joint research program by Lund University, the Swedish National Testing and Research Institute, and the Swedish Institute for Wood Technology Research [6]. Another study was carried out within the Nordic research program "EUREFIC—EUropean REaction to FIre Classification." It was a collaborative program among Dantest, Denmark; VTT, Technical Research Centre of Finland; SINTEF NBL, Norwegian Fire Research Laboratory; and SP Swedish National Testing and Research Institute. Experimental data of the study carried out under this program [2] have been used for validation of model "RELIEF" developed in the present study.

RELIEF is validated with the experimental data of one of the EUREFIC studies reported by Kokkala et al. [2]. It has been shown that RELIEF has provided satisfactory simulations. The experimental details and comparison of the experimental and the predicted data are reported in the following paragraphs.

Experimental Details

Kokkala et al. [2] reported the five large scale room fire experiments conducted under EUREFIC fire research program. A large room of size 9.0 m wide × 6.75 m deep with a height of 4.9 m, as shown in Figure 1, was used for the experiments. The room was constructed with walls and ceiling of 200 mm thick light weight concrete (density 600 kg/m^3). There is door size opening of 2.0 m wide and 2.0 m high on the longer wall. Five experiments with different lining materials were conducted with propane burner placed in one corner, opposite to door for ignition. Fire retarded particle board B1 (630 kg/m^3), PVC wall covering on a gypsum board (800 kg/m^3), textile wall covering on a gypsum board (800 kg/m^3), ordinary birch plywood (600 kg/m^3), and combustible facing on a mineral wool (87 kg/m^3) were used as lining materials and fixed on the inner surface of wall and ceiling. The propane flow was controlled so that heat release rate (HRR) was 100 kW for first 10 minutes which was raised to 300 kW for next 10 minutes. Thereafter, heat release rate (HRR) was raised to 900 kW. The experiments in the above room were conducted as per procedure prescribed in ISO 9705 [7] Room/Corner Method in which a room of size 3.6 m × 2.4 m × 2.4 m is used for experiments.

Temperatures at 50 locations, heat flux on floor and walls, and heat release rate of ignition source as well as that of lining and ignition source combined, were measured. Smoke generation rate along with the CO concentration was also measured.

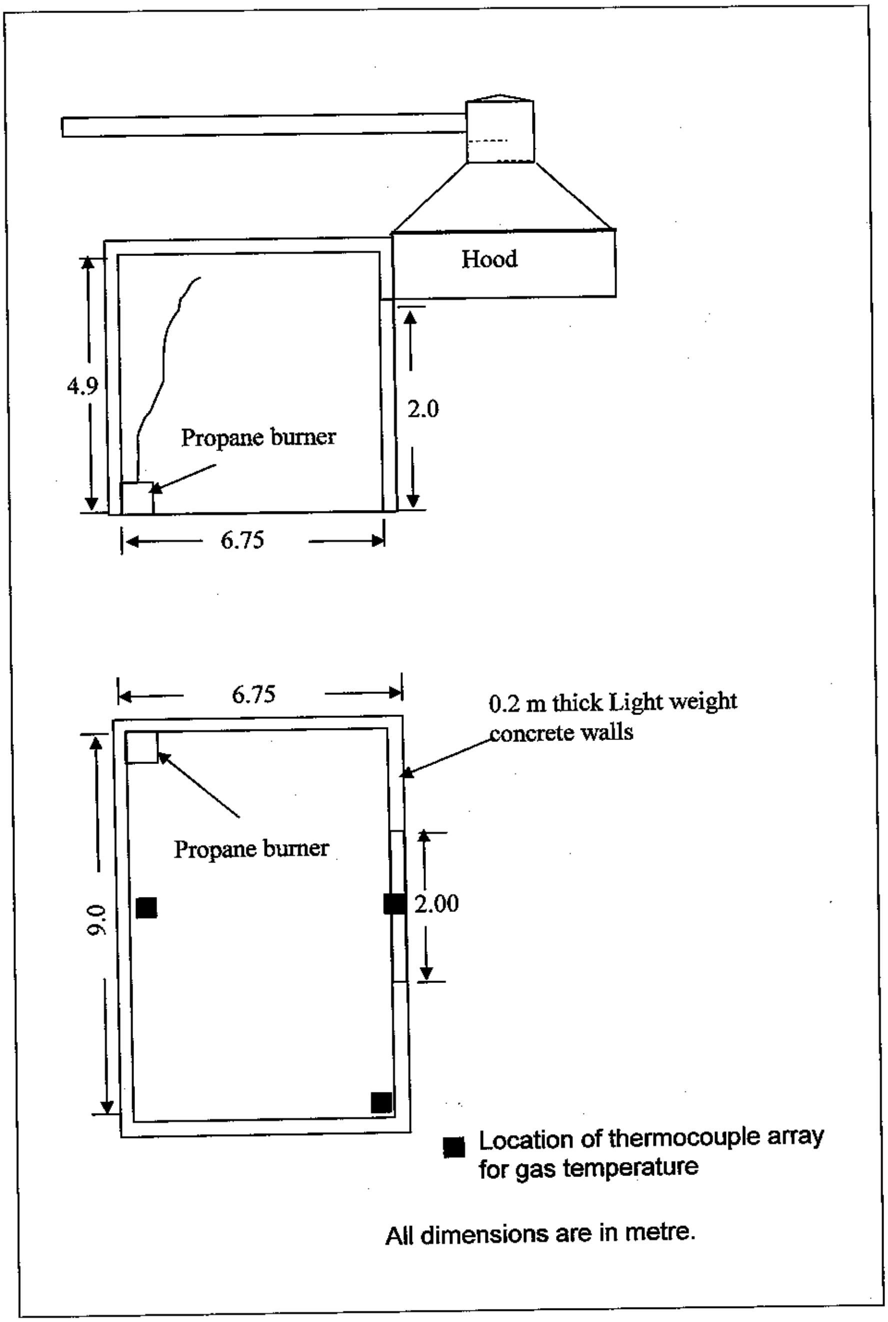

Figure 1. Experimental room in study of Kokkala et al. [2].

Temperatures

Following temperatures were measured at 50 locations by thermocouples.

1. The surface temperatures were measured:
   (a) at 12 locations on the diagonal on the ceiling of the room; and
   (b) at 10 locations on the vertical centre line of the wall opposite to the door.
2. The gas temperatures were measured by 0.05 mm thermocouples at the following locations:
   (a) at eight different heights by a vertical array of eight thermocouple placed in the corner opposite to the burner;
   (b) in case of textile wall covering on gypsum board used as lining, temperatures were measured at eight different heights by a vertical array of eight thermocouples located at 0.25 m from the wall opposite to the door and the top most thermocouple of the vertical array was placed 0.32 m below the ceiling; in case of all the other lining materials, the thermocouples were located at 0.30 m from the wall opposite to the door and the top most thermocouple of the vertical array was placed 0.34 m below the ceiling; and
   (c) at 12 different heights by vertical thermocouple array placed in and above the doorway inside the room.

Heat Release Rates

Hood method and exhaust duct method were used to measure the rate of heat release by the wall linings and the ignition burner. Hood was located over the door opening and outgoing combustion gases were collected in the hood. The gases were discharged through a duct which was instrumented for oxygen consumption calorimetry.

The propane burner placed in corner is used to ignite the lining material. As soon as the surface lining is ignited, it starts contributing heat energy to the enclosure in addition to heat energy already released by the burner. By oxygen consumption calorimetry, total heat released by surface linings and burner is determined. Thus there are two types of heat released determined in the experiments:

1. *Heat released by the ignition source (i.e., propane burner):* The heat released by the burner is controlled by flow of propane. It is 100 kW for first 10 minutes, raised to 300 kW for next 10 minutes, and finally to 900 kW.
2. *Total heat release rate:* It is measured by oxygen consumption calorimetry method by measuring the oxygen concentration in the combustion products at the exhaust duct. It consists of the total heat released both by the lining materials and ignition source. It will be referred as measured heat release rate further in the text.

The contribution by the surface lining is calculated by deducting the burner heat release rate from the total heat release rate. Both the heat release rates, i.e. heat released by burner only and measured heat release rate which includes heat released by burner as well as by surface linings, are taken as input to RELIEF.

COMPARISONS WITH EXPERIMENTAL DATA OF EUREFIC STUDY [2]

The results of one of EUREFIC [2] study were used for the validation of the RELIEF. The study reported the temperatures measured at various locations. However, the gas temperatures are measured with the help of vertical array at three locations inside the room. So there is a need to determine the average experimental temperature and layer heights of upper hot gas layer as RELIEF predicts average temperatures of hot gas layer formed below the ceiling. This is because of our assumption that temperature in the upper hot zone is uniform, which is assumed to simplify the conservation equation formulation. To determine average layer temperature and layer height the following procedure has been used.

Determination of Average Experimental Layer Temperature and Layer Heights

It is observed from the analysis of vertical gas temperature variations with time, measured by three vertical arrays of thermocouples placed at three locations in the room, that the horizontal temperature distribution in the room is quite homogenous. Vertically also, the temperature is almost uniform up to a certain distance below the ceiling. However, if the distance from ceiling increases beyond it, the temperature decreases sharply. The hot gas layer interface may lie between these two distances. The height of the locations where there is sudden decrease in temperature, is taken as the layer interface height and average of the temperatures measured at locations above these height is taken as the experimental average temperature of the upper hot gas layer. These determined average values of temperatures and layer heights have been used for validation of the predictions of RELIEF.

INPUTS REQUIRED FOR VALIDATION

The data required as input to RELIEF have been given in Table 1. Thermal conductivity (k), density (ρ), and thermal capacity (C) of the ordinary birch plywood and thickness of all lining materials used in experiments [2] have been supplied by researchers at VTT Technical Research Centre of Finland [8]. Thermal conductivity (k), density (ρ), and thermal capacity (C) of other lining materials were not measured by them. These properties are required for calculating the convective heat loss fraction through boundaries (λ_c) by equation (39) given in

Table 1. Input Data to RELIEF

Input parameter	Value
Room size	6.75 m × 9.0 m × 4.9 m high
Door size	2 m × 2 m on 9.0 m long wall
Fire height	0.145 m
Fire diameter	0.19 m (100 kW, 0.27 m (300 kW), 0.31 (900 kW)
Radiative loss fraction (λr)	0.27
Heat release rate of ignition source (propane)	As per Figures 2, 3, 4, and 5
Total heat release rate measured	As per Figures 2, 3, 4, and 5
Heat of combustion of propane	46.4 MJ/kg

Properties of lining material	Textile wall covered gypsum board	PVC covered gypsum board	Fire retarded particle board B1	Ordinary birch plywood
Heat of combustion of lining material (MJ/kg)	13	13	14	40
Thickness (mm)	12.6	13	16	12
Thermal conductivity (k), kW/m-K	NA	NA	NA	0.0002
Density (ρ), kg/m^3	800	800	630	600
Thermal capacity (C), kJ/kg-K	NA	NA	NA	1.5
$k\rho C$, (kW/m-K)^{2}s	0.570	0.208	0.626	0.18
Ignition temperature (°C)	406	410	405	363
Boundary loss fraction (λ_c)	0.5	0.5	0.5	Calculated
$\dot{q}_i''$, kW/m^2	30	30	30	30

NA – Values are not available.

Kumar and Sharma [1]. Convective heat loss fraction through boundaries (λ_c) for the comparisons with experimental data with ordinary birch plywood as lining materials has been calculated by equation (39) given in Kumar and Sharma [1], while for remaining linings materials, losses through boundaries have been assumed ($\lambda_c = 0.5$) as per the criterion specified by Cooper [9]. The value of product of these properties ($k\rho C$), ignition temperature (T_i), and heat flux ($\dot{q}''_f$) to ignite the lining are required as input to calculate ignition time by equation (2) given in Kumar and Sharma [1]. The value of $k\rho C$ has been taken from literature [10]. Since this value is available only for three lining materials (viz. textile wall covering on a gypsum board, fire retarded particle board B1, and PVC wall covering on a gypsum board) in literature [10], the experimental data for combustible faced mineral wool is not used for validation purposes. The values of ignition temperature of the lining materials (T_i) are taken from Karlsson [6]. Thomas [11] recommended for 25 to 30 kW/m^2 to be taken as the value of Heat flux ($\dot{q}''_f$) for smaller fire size (less than 1 m). So the value of Heat flux ($\dot{q}''_f$) has been taken as 30 kW/m^2 as has also been used in Cleary and Quintiere [12]. The value of the radiative heat loss fraction (λ_r) is taken as 0.27. Cooper [13] has indicated that the flaming fires exhibit a radiative heat λ_r. values between 0 and 0.6, smaller values for small transparent fires and higher values for large sooty fires.

The experimental heat release rates (both burner's heat release rates and measured heat release rates), as reported in Figures 2 through 5, are taken as input to RELIEF. When measured HRR (heat release rate) is larger than the burner output, it is given as input to the RELIEF for total heat release rate. In case measured HRR (heat release rate) are lower than the burner output, it means that there is no significant contributions by the lining material, burner output is given as input to RELIEF for ignition source's heat release as well as for total heat release rate (which includes HRR of lining and ignition source).

Heat Release Rates for the Enclosure with Fire Retarded Particle Board Used as Lining Material

The variation of heat release rate with time for enclosure with fire retarded particle board used as lining material, is shown in Figure 2. In this case, the contribution of the lining material to fire growth was insignificant. When heat release rate of the burner was 100 kW for the first 600 s, it is observed that the 4 m high flames from the linings appears to hit the ceiling at 120 s in the test. The predicted ignition time is 81.8 s as reported in Table 2. However, the contribution by lining was very small. Only smoke was produced resulting in the poor visibility in the upper zone. It can be observed from Figure 2 that the measured heat release rate at exhaust duct are lower than the burner output, indicating that contribution of lining was negligible. When heat release rate of the

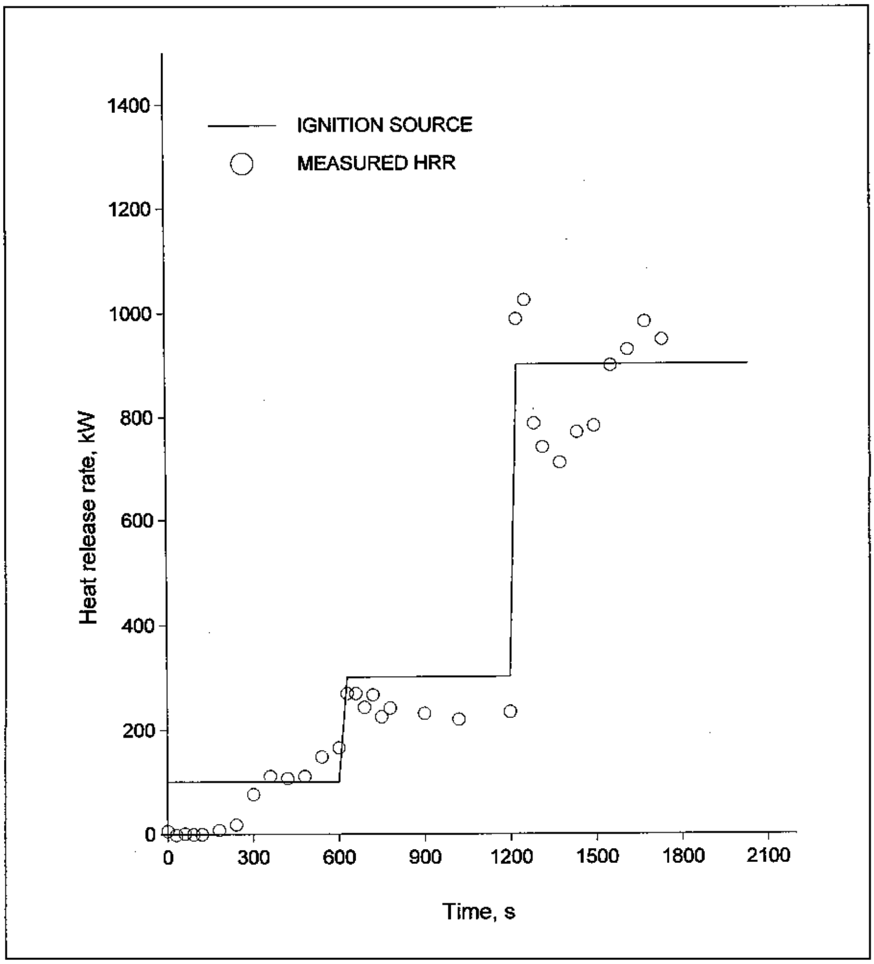

Figure 2. Heat release curve for the enclosure with fire retarded particle board used as lining material.

burner was raised to 300 kW, smoke production increased and contribution of lining in growth of fire was still negligible. When the heat release rate by burner was increased to 900 kW after 1200 s, the measured heat release was practically only due to the burner and increased up to 1023 kW at 1260 s. Later on, no contribution of the lining was observed and flashover conditions were neither observed nor predicted by RELIEF. However, the rate of production of smoke increased intensively. The charred pieces of particle board started falling at 1680 s and no spread of fire was observed.

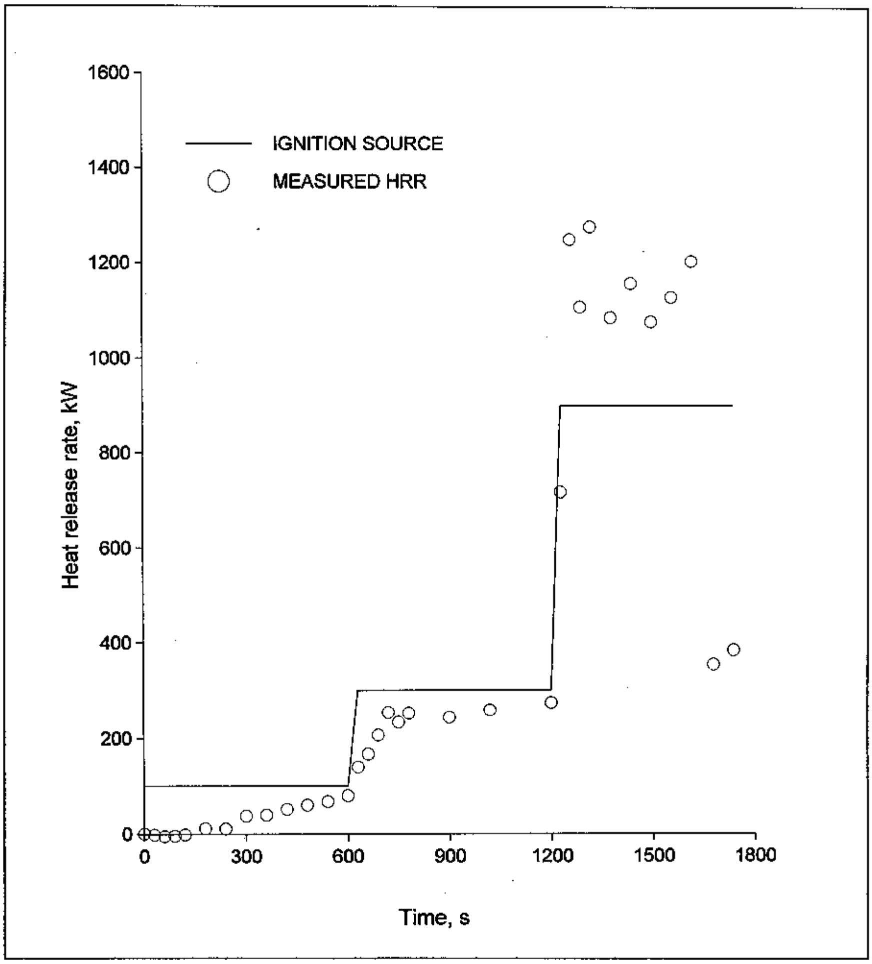

Figure 3. Heat release curve for the enclosure with PVC wall covering on gypsum board used as lining material.

Heat Release Rates for the Enclosure with PVC Wall Covering on Gypsum Plaster Board Used as Lining Material

Figure 3 shows the variation of measured and burner's heat release rates for enclosure with PVC lining material. Ignition time of linings could not be observed but 4 m to 4.5 m flames were seen between 55 s to 75 s. The predicted time of ignition is 28 s as shown in Table 2. It can be observed from Figure 3 that for the first 20 minutes, the measured heat release rates are lower or equal to the burner

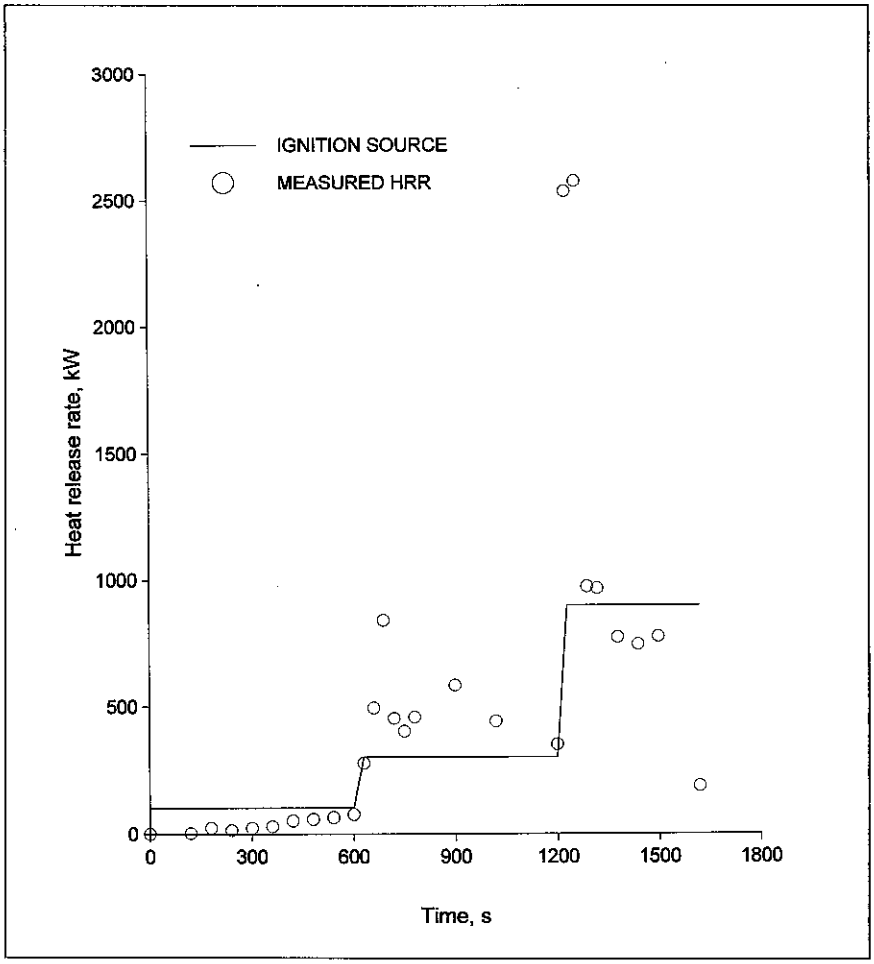

Figure 4. Heat release curve for the enclosure with textile wall covering on gypsum board used as lining material.

heat release rates. It means that there is no significant contribution of lining material. The temperature rise in enclosure is mainly due to heat released by the source of ignition. However, the small pieces of wall covering started falling and giving smoke. When the HRR of burner is increased to 900 kW after 1200 s, more and more pieces of wall covering began to fall from the ceiling and spread on all of the floor. The enclosure is filled with smoke. Even burner is not visible. However, some flames are seen near to the ceiling at 1240 s and maximum value of measured heat release rate is 1276 kW at 1320 s. Then the fire decay started.

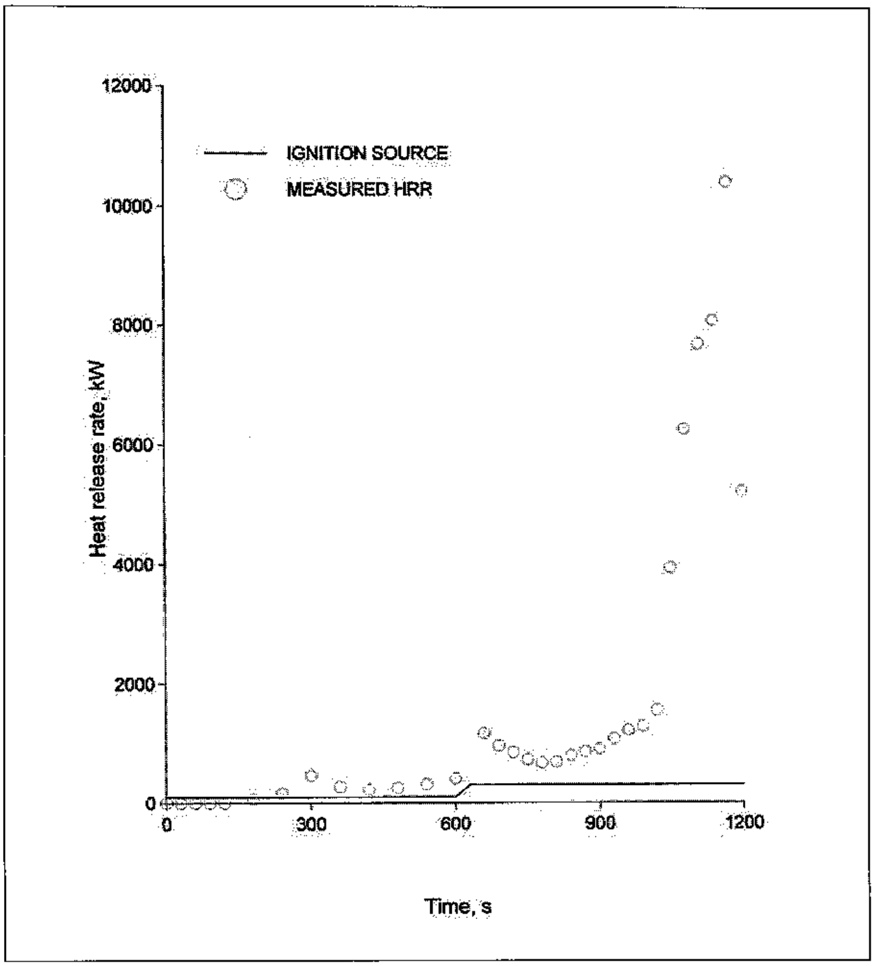

Figure 5. Heat release curve for the enclosure with ordinary birch plywood used as lining material.

No flashover conditions were observed in the test. RELIEF also predicts that temperature were not so high as to reach flashover conditions.

Heat Release Rates for the Enclosure with Textile Wall Covering on Gypsum Plaster Board Used as Lining Material

The variation of measured and burner's heat release rates for enclosure with Textile wall covering on gypsum plaster board used as lining material, is plotted in Figure 4. It is found in the experiment that at 75 s, the flames hit the ceiling after

Table 2. Predicted Values of Ignition Time of Lining, Heights of Upper Hot Gas Layer and Neutral Plane, Mass Flow Rate of Outgoing Combustion Gases and Air Entering into the Room

S. No.	Lining materials	Time to ignition (s)	Ignition source heat release rate (kW)	Neutral plane height (m)	Mass flow of outgoing gases (kg/s)	Mass flow of air entering (kg/s)
1.	Fire retarded particle board	81	100	1.56	0.5752	0.5745
			300	1.50	0.8087	0.8173
			900	1.34	1.3005	1.2897
2.	PVC wall covering on gypsum plaster board	28	100	1.57 (1.9)*	0.5073	0.5150
			300	1.50	0.8114	0.8183
			900	1.34	1.2027	1.1998
3.	Textile wall covering on gypsum plaster board	76	100	1.58	0.5083	0.5198
			300	1.54 (1.8)*	0.7643	0.7625
			900	1.35	1.2989	1.2803
4.	Ordinary birch plywood board	18.8	100	1.57	0.6716	0.6873
			300	1.25	1.4160	1.3416
			900	—	—	—

*In brackets, experimental layer height is given. For other experiments this value is not available.

ignition of the linings. RELIEF predicts that the wall lining behind the burner are ignited at 76 s as reported in Table 2. It can be observed from Figure 4 that for the first 240 s the measured heat release rate which includes the heat release from propane burner, is zero as combustion gases could not reach the hood and exhaust duct. When burner output is 100 kW, even after 240 s, the measured values are lower than the burner output. It clearly indicates that there is no significant contribution from the linings.

When burner output is increased to 300 kW, measured heat release is higher than the burner output. It reaches to maximum value of 841 kW at 690 s. It shows that contribution from the lining is significant. But after 900 s, contribution from lining again becomes insignificant.

When output of the burner is increased to 900 kW, ceiling linings were ignited at 1210 s and start contributing, fire appears to be close to flashover and measured heat release rate increases up to a maximum value of 2576 kW at 1260 s. However, later on the contribution of lining decreases and fire stabilizes and measured heat release rate becomes equal to or less than the burner output. RELIEF predicts the flashover conditions as has been observed in the test.

Heat Release Rates for the Enclosure with Ordinary Birch Plywood Used as Lining Material

Figure 5 shows the heat release variation for the experiments conducted in enclosure with ordinary birch plywood used as lining material. In this experiment, wall behind the burner is ignited at 45 s. Ceiling is also ignited at 160 s when flame reaches the ceiling. However, burning of the ceiling stops at 360 s and charring takes place. The ceiling is re-ignited at 570 s. It can be observed from the Figure 5 that heat released by the lining material starts contributing significantly when the burner releases heat at the rate of 100 kW as measured heat release rates at exhaust duct (total heat release rate of the enclosure) is more than the heat released by the burner. The maximum heat release rate measured at exhaust duct is 457 kW at 300 s when the burner output was 100 kW.

Similarly, when the burner releases heat at the rate of 300 kW after 600 s, there is an increase in the burning of plywood boards and very high T-flames are developed. At 660 s, the contribution by the lining is substantial and measured heat release rate is 1158.06 and, thereafter, it starts decreasing and at 710 s, contribution by the ceiling lining becomes zero. It can be observed in Figure 5 that measured heat release rate, when rate of heat released by the burner is 300 kW, is minimum at 780 s, although it is more than the output of the propane burner. At about 870 s, the pieces of charred plywood began to fall on the floor close to burner and start burning. At the end of the test, there is fierce burning outside the door and heat release increases rapidly at a maximum rate of more than 100 kW/s, thus resulting in a maximum value of measured heat release rate equal to 10.6 MW. At 1185 s, the fire is extinguished. Fire growth toward flashover was observed in the experiment. RELIEF also predicts the flashover stage.

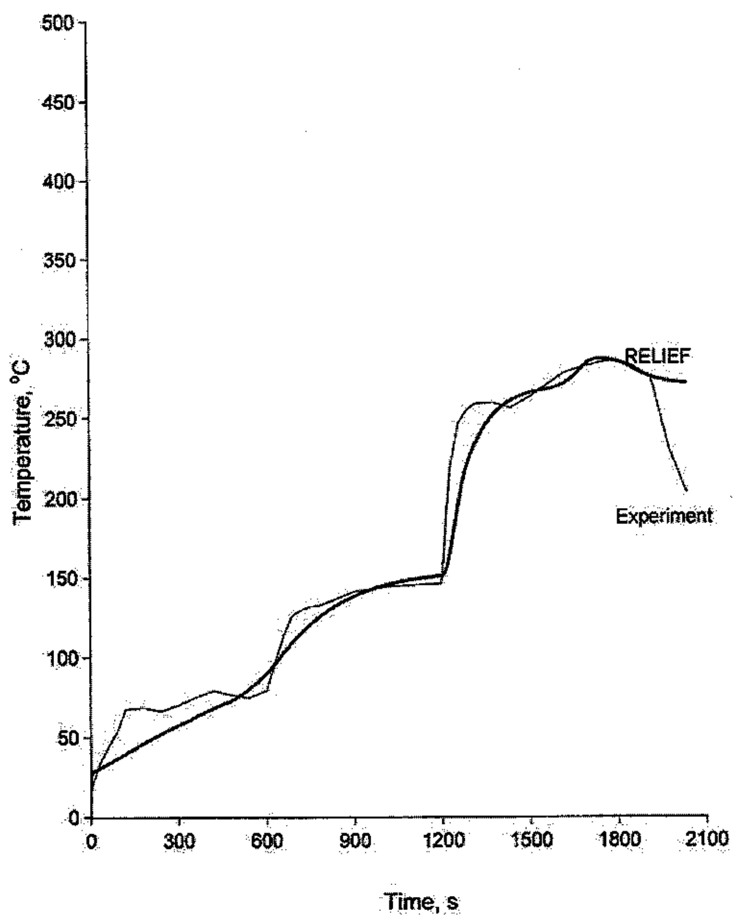

Figure 6. Comparison of RELIEF's predictions with the experimental temperatures observed in the enclosure with fire retarded particle board used as lining material.

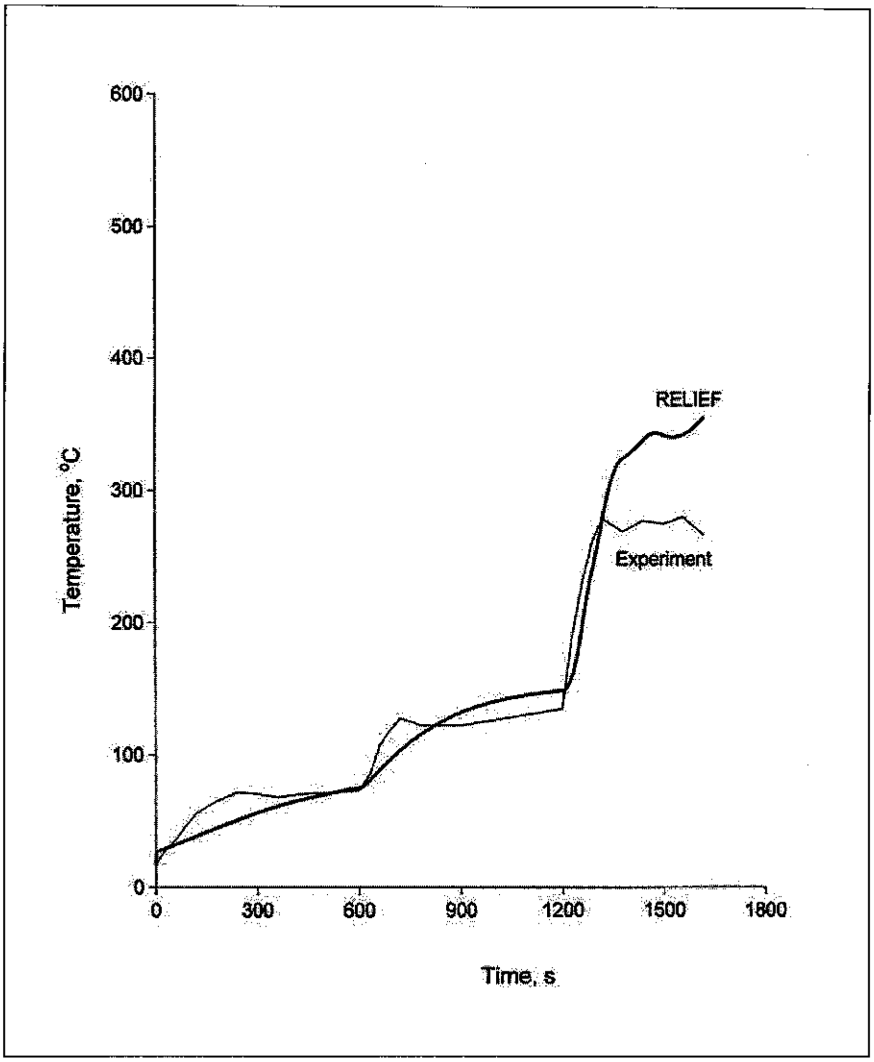

Figure 7. Comparison of RELIEF's predictions with the experimental temperatures observed in the enclosure with PVC wall covering on gypsum board used as lining material.

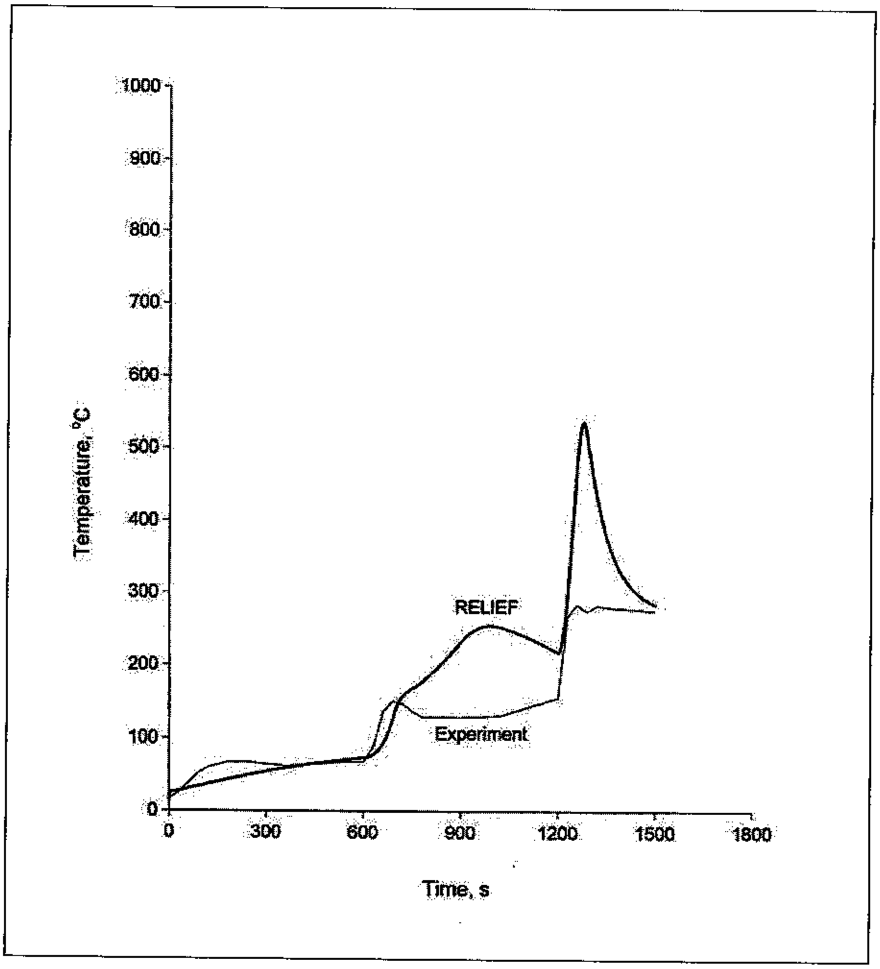

Figure 8. Comparison of RELIEF's predictions with the experimental temperatures observed in the enclosure with textile wall covering on gypsum board used as lining material.

RESULTS AND DISCUSSION

The results of comparison of the predictions of RELIEF with experimental data have been presented graphically in Figures 6-13. Comparison of temperature predictions are given in Figures 6 through 9.

Figure 6 relates to comparison of RELIEF's predictions with the experimental temperatures observed in the enclosure with Fire Retarded Particle Board used as lining material. Figure 7 shows the comparison of RELIEF's predictions with

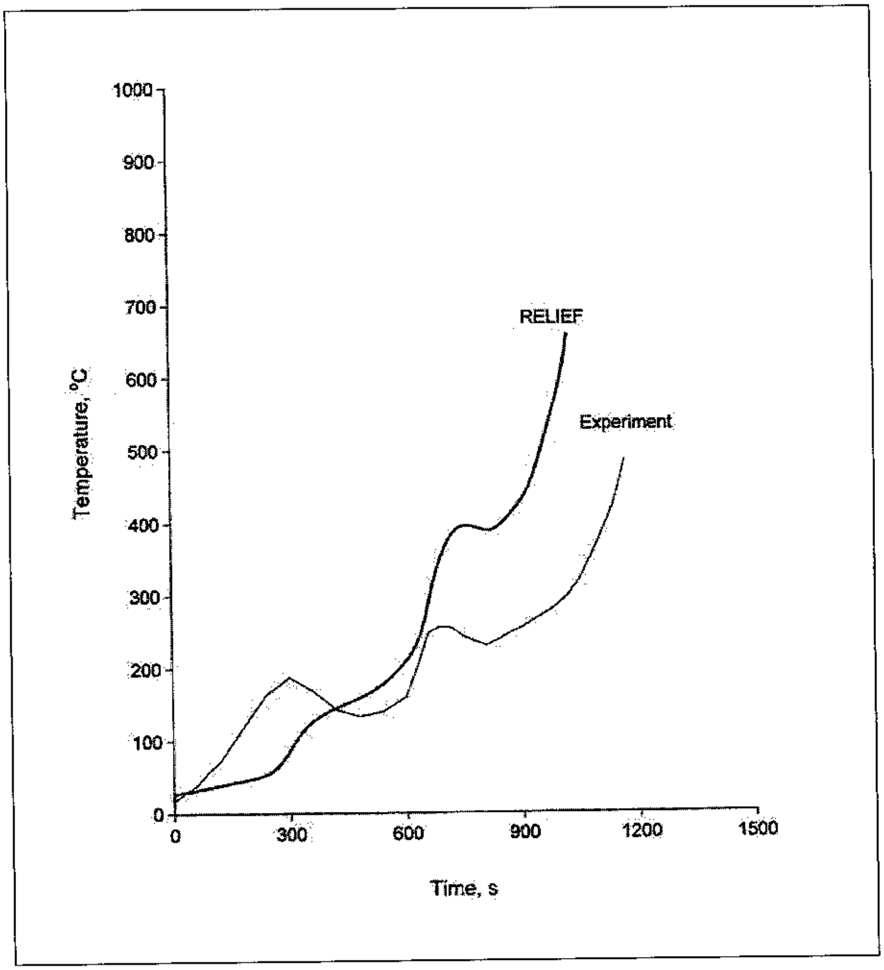

Figure 9. Comparison of RELIEF's predictions with the experimental temperatures observed in the enclosure with ordinary birch plywood used as lining material.

the experimental temperatures observed in the enclosure with PVC Wall covering on gypsum board used as lining material. In Figure 8, comparison of RELIEF's predictions with the experimental temperatures observed in the enclosure with Textile Wall covering on gypsum board used as lining material has been presented. Figure 9 compares predictions of RELIEF with the experimental temperatures observed in the enclosure with ordinary birch plywood used as lining material.

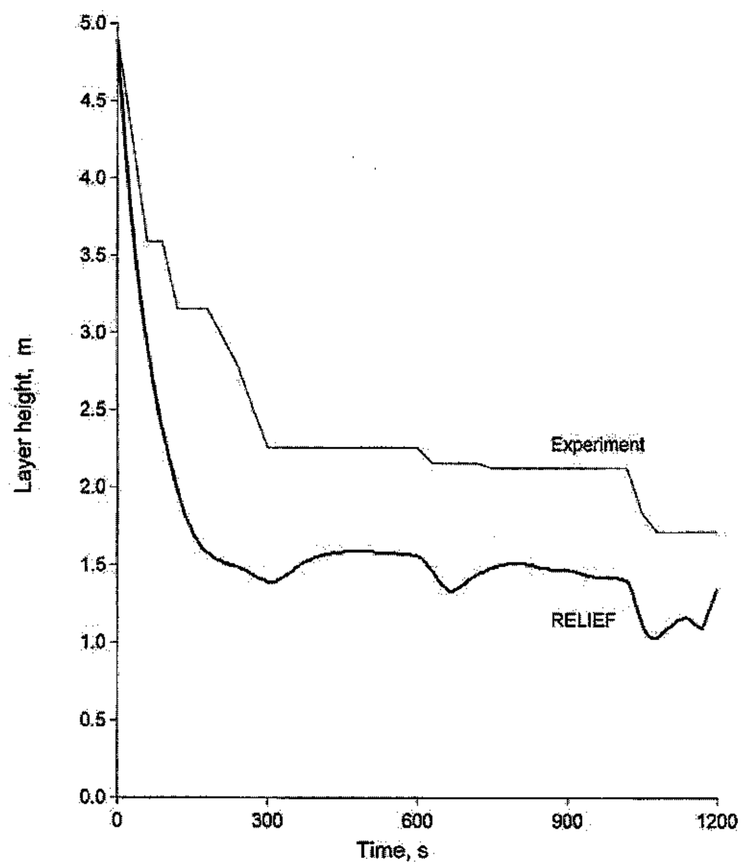

Figure 10. Comparison of RELIEF's predictions with the experimental heights of upper hot gas layer observed in the enclosure with fire retarded particle board used as lining material.

Figures 10 through 13 compare the predictions of height of upper hot gas layer. Figure 10 compares predictions of RELIEF with the experimental heights of upper hot gas layer observed in the enclosure with Fire Retarded Particle Board used as lining material. Figure 11 shows the comparison of RELIEF's predictions with the experimental heights of upper hot gas layer observed in the enclosure with PVC Wall covering on gypsum board used as lining material. Comparison of RELIEF's predictions with the experimental heights of upper

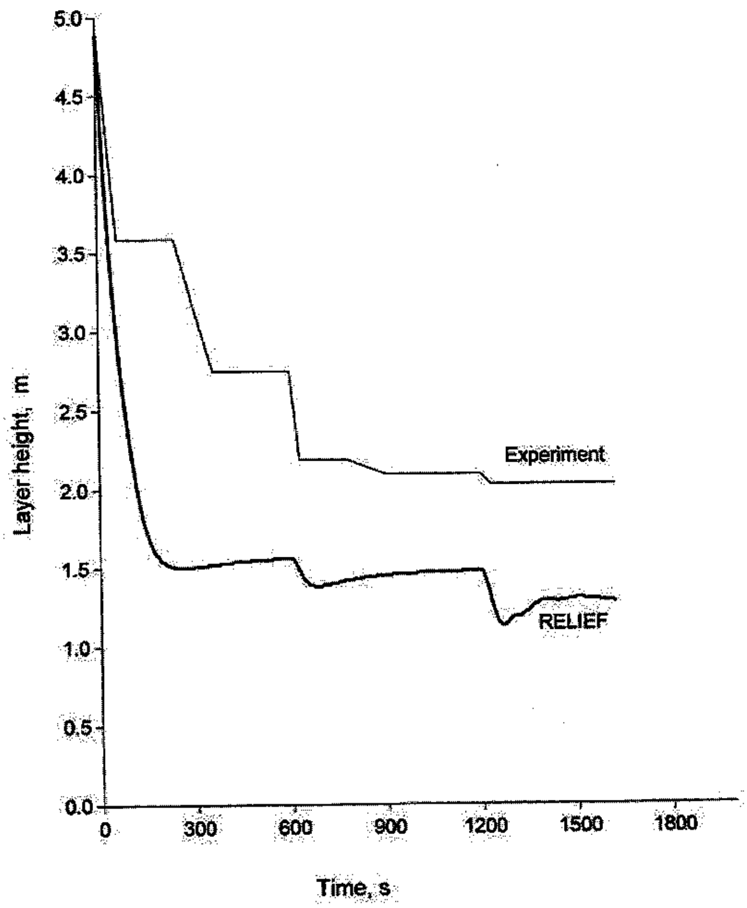

Figure 11. Comparison of RELIEF's predictions with the experimental heights of upper hot gas layer observed in the enclosure with PVC wall covering on gypsum board used as lining material.

hot gas layer observed in the enclosure with Textile Wall covering on gypsum board used as lining material is shown in Figure 12. In Figure 13 comparison of RELIEF's predictions with the experimental height of upper hot gas layer observed in the enclosure with ordinary birch plywood used as lining material are shown.

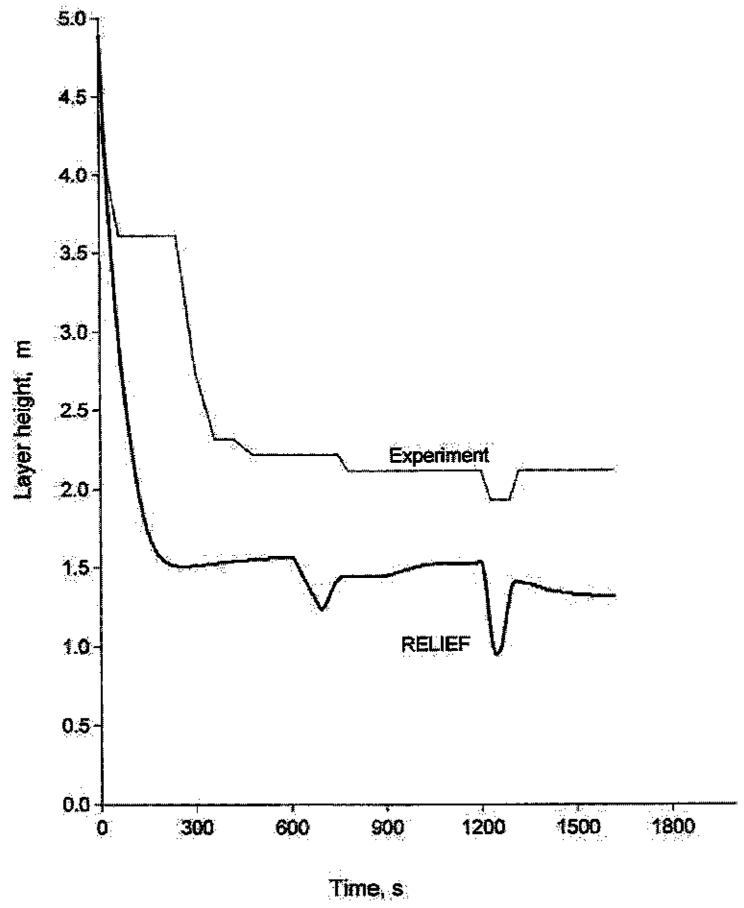

Figure 12. Comparison of RELIEF's predictions with the experimental heights of upper hot gas layer observed in the enclosure with textile wall covering on gypsum board used as lining material.

Comparison of Experimental Data with the Prediction of RELIEF

1. Fire Retarded Particle Board

Comparison of temperatures predicted by RELIEF with the average of experimental gas layer temperature data generated when Fire Retarded Particle Board

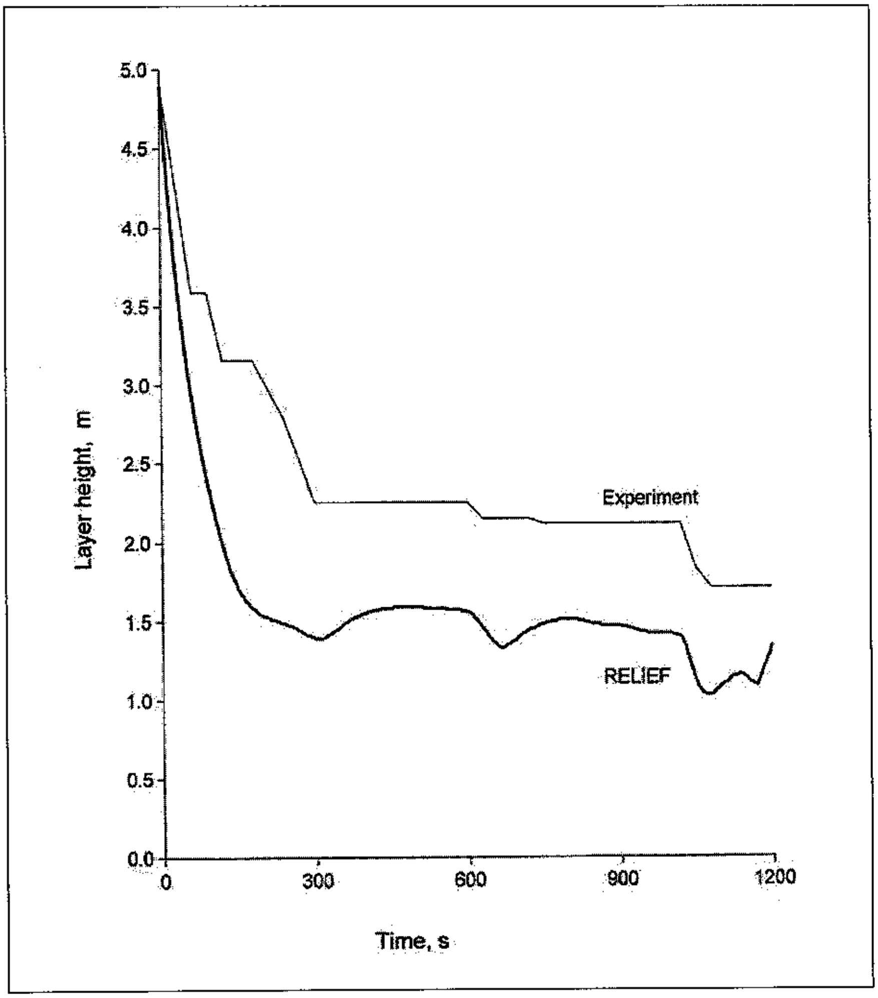

Figure 13. Comparison of RELIEF's predictions with the experimental temperatures observed in the enclosure with ordinary birch plywood used as lining material.

was used as lining material is shown in Figure 6. The predicted values are very close to the experimental ones for all the three heat release rates of the ignition source.

When heat release of the burner is kept at 100 kW up to 600 s, the predicted temperatures are near to the average gas temperatures, but slightly lower than the gas temperatures measured near to fire source. The possible reason may be that fire retarded particle board is not contributing in terms of heat but may reduce the losses through the boundaries so it appears that assumed value of heat loss through boundaries (λ_c =0.5) is on higher side so predicted temperatures are lower. However, the predicted temperatures in the hot layer reaches close to the stabilized gas temperatures of 100°C.

Similar trend has been observed when the burner output is increased to 300 kW and 900 kW. The predicted temperatures are very near to experimental average temperature but lower than stabilized gas temperatures of 210°C and 400°C in both the cases.

It is also observed that variation of the predicted temperatures with respect to time is following a similar pattern as has been observed in experiments. No flashover is predicted by RELIEF as well observed in experiment.

2. *PVC Wall Covering on Gypsum Board*

It can be observed from Figure 7 that during the first 600 s, when heat release rate is 100 kW, the predicted temperatures are very close but lower than the average value of the hot gas layer temperature data observed experimentally. The reason of predicted temperatures being lower may be that the lining is thermally insulated, so losses are less. The assumed value of convective losses through boundary (λ_c = 0.5) is on higher size. The predicted temperatures reach very close to the stabilized gas layer temperature which is 95°C.

Similarly, when heat release rate is raised to 300 kW for the next 600 s (i.e., predicted temperatures are very close to the experimental average gas temperatures), the predicted temperatures reach near to stabilized hot gas layer temperatures of 180°C.

However, when the burner heat release rate is increased to 900 kW after 1200 s, predicted temperatures by RELIEF are higher than the experimental average temperatures. The possible reason for this behavior may be that for higher heat release rates of ignition source, more and more pieces of the lining began to fall and smoke production is intense. Fall of lining material results in loss of insulation lining from the wall and ceiling. It causes increased convective heat losses from the boundaries which may be higher than the assumed value of convective heat loss through boundaries (λ_c = 0.5) for prediction by RELIEF. Another possible cause of lower temperatures observed in experiments may be due to leakage of hot gases through the ceiling joints. As mentioned by Kokkala et al. [2], the leakage through the ceiling joints was observed despite the fact that it was minimized by filling the joints but never disappeared completely. Due to high heat flux and intense smoke production during the period, the pressure differential through these leaks increased which would have resulted in the increased rate of hot gas flow through these leaks. So observed average temperatures of the upper gases are lower as compared to predicted values by RELIEF.

3. *Textile Wall Covering on Gypsum Board*

The comparison of predicted temperatures with experimental average temperatures is plotted in Figure 8. It is observed that the predicted gas temperatures are very close but slightly less than the experimental gas temperatures for first 600 s when HRR of burner is 100 kW. Also, no contribution of lining material was observed during first 600 s. The temperature stabilized up to 85°C in experiments. Predicted temperatures reach near to the stabilized temperature with time.

As the heat release rate of ignition source is increased to 300 kW, the predicted temperatures become higher than the experimental gas temperatures. It is also observed in the experiment that linings burn and contribute up to 300 s after the heat release rate of ignition source was increased to 300 kW. It has resulted in the loss of lining material and convective heat losses through the boundaries would have increased and are on higher side than the assumed values ($\lambda_c = 0.5$) used as input to RELIEF for predictions. Also, as mentioned by Kokkala et al. [2], there was leakage of hot gases observed through the ceiling joints which was substantial so hot gases, reaching the ceiling, would have not stayed below the ceiling to form hot upper layer and this may be another reason for the lower average temperatures observed in experiment. The experimental temperatures stabilized to 190°C are lower than the predicted values.

Similarly, when the burner output was increased to 900 kW after 1200 s, there is instantaneous and tremendous increase in predicted temperatures due to rise in measured heat release rate due to re-ignition of ceiling lining and sudden increase of flames in the enclosure which stopped at 1260 s. The observed average temperatures are much lower than the predicted value. The possible reason for this phenomenon may be the leakage through ceiling joints in experiment which would have resulted in higher loss of hot combustion gases just near ceiling through these leaks without contributing much to increase the average temperatures of the hot upper layer. Similarly, due to burning of the lining material, the convective losses through boundaries would have increased as compared to the assumed values ($\lambda_c = 0.5$) used for predicting temperatures by RELIEF.

4. *Ordinary Birch Plywood*

Figure 9 shows the comparison of temperatures predicted by RELIEF with the data obtained in this experiment. When heat release of the burner is 100 kW, the predicted temperatures are lower than average temperature of hot layer in experiment, the possible cause of lower initial predicted temperatures may be that the calculated convective losses are larger than the actual losses, as minimum limit for losses (λ_c) in RELIEF has been kept equal to 0.5. But after 360 s, the predicted temperatures are slightly higher than those observed in experiment. During this period, lining material starts contributing and a part of hot combustion products leaks out through the ceiling joints without substantial increase of temperature of hot layer formed below the ceiling.

After 600 s when heat release rate of burner is increased to 300 kW, contribution of the lining becomes high and plywood also starts falling on the floor thus removing the lining material from the wall and ceiling resulting in higher losses from the boundaries. RELIEF does not take this phenomenon into account while calculating losses. So calculated loss by RELIEF may be lower than the actual losses, thus resulting in much higher predicted temperatures in the range of up to 4500°C as compared to the experimental observations. Another reason for higher predicted temperatures may be that the lower temperatures are observed inside the room. Although fire was intense and flashover conditions are observed, but due to burning and extension of flame out of the door, the bigger part of energy generated by the fire is lost to atmosphere out of the room through the door. Leakage through joints in ceiling may also increase due to higher pressure differentials between inside and outside because of intense fire in the room. Lower temperatures below 800°C are observed inside the room are thus explained. RELIEF also predicts flashover to take place at 1002 s.

It is to be noted that temperatures in the experiments are not stabilized for each fire strength, and increase continuously. Same trend has been predicted by RELIEF.

Comparison of the Predicted Layer Heights with Experimental Data

The comparison of predicted layer heights with experimental heights have been shown in Figures 10 through 13 for all the four experiments. It can be observed that variation of predicted layer heights with time is following the same pattern as has been observed in experiments; however, the predicted layer heights are lower than the experimental values for all the tests. The possible reason for higher experimental layer heights are observed due to the leakage of combustion gases through the ceiling joints. As observed in the experiments, 10-20% of combustion products were lost due to leaks through ceiling, thus increasing the observed layer heights. Had there been no leakage through the ceiling joints, the combustion gases generated due to fire would have spread below the ceiling and would have descended resulting in increased layer thickness (i.e., lower layer heights above the floor).

CONCLUSIONS

Study shows that RELIEF has provided satisfactory comparison with the experimental results of experimental study of Kokkala et al. [2]. RELIEF predicts neutral plane heights, mass of outgoing gases, and mass of air entering into the enclosure through the ventilation opening as shown in Table 2.

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Direct reprint requests to:

Rajiv Kumar, Ph.D.
Fire Research Division
Central Building Research Institute
Roorkee, India
e-mail: rajivkgoel@gmail.com