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A Simple Correlation for Predicting Temperature in a Room Fire

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TABLE OF CONTENTS

List of Tables

TABLE OF CONTENTS

List of Tables

List of Figures

Nomenclature

A	surface area of enclosure
A_o	area of vent
c	specific heat of solid
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
g	gravitational acceleration
h	effective heat transfer coefficient
h_k	effective enclosure conductance
H_o	vertical vent dimension
k	thermal conductivity
m	mass
$\dot{m}$	mass rate of fuel supply
$\dot{m}_o$	rate of mass flow out of vent
Q	rate of energy release
T	temperature of upper gas
T_o	initial or ambient air temperature
t	time
t_p	thermal penetration time, eq. (6)
W_o	width of vent
X_1, X_2	dimensionless groups, eq. (7)
δ	enclosure material thickness
ΔH	heat of reaction
ΔT	temperature rise of upper gas
ρ	density
ρ_o	density of ambient air

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The use of a simple formula for predicting upper compartment gas temperature in a fire is demonstrated. The formula is given in terms of energy release rate, vent geometry, and compartment lining material properties. It treats discrete fires within the room. Several examples are considered to show the versatility of the formula and its general level of accuracy.

Keywords: Compartment fires; energy release rate; modeling; prediction temperature; vent effects, wall effects.

1. INTRODUCTION

The gas temperatures within a compartment which result from fire in that compartment depend on many factors. Temperatures within the flame zone will be very high, approaching theoretical flame temperatures at most. In contrast, air entering openings will be at ambient temperature and will be heated slightly as it flows towards the flame. Also, combustion products flowing away from the fire will cool due to mixing with colder gases and heat transfer to surfaces. Despite this extreme range of spatially varying gas temperatures in a compartment fire, a simplified description is reasonably adequate for the process. This description is based on a zone model which assumes a uniform temperature upper gas region within the compartment, a lower region at ambient (air) temperature, and the fire plume represented as a localized heat source. It is a good description for small fires in conventional size rooms. For larger fires (fully involved room fires) and for fires in large compartments, temperature variations in this upper zone could be large. Nevertheless, the estimation of an average upper gas temperature could still have some utility in characterizing the severity of the compartment fire. In general, buoyancy and recirculation promote a distinct uniform temperature zone while heat transfer and combustion effects promote temperature variations in this upper region.

The concept of a zone model for compartment fires has been used by several investigators [e.g., 1-4] to predict various aspects of fire growth. These include flame spread and burning of various materials and even the computation of the fire effects on other rooms of the building. These studies predict many variables in the fire growth process, and consequently require a computer solution for the many coupled governing equations. For a complete understanding of the contribution by materials to fire growth and of the impact of fire on its surroundings, these computer solutions will be necessary. In some cases, a more easily implemented solution may be possible. Indeed, the purpose of the current study is to explore the use of a simple solution for upper gas temperature in a room fire. Its accuracy and applicability will be demonstrated by illustrative examples for various fire conditions.

Before proceeding with the details of this simple solution, some background will be presented to explain its development. McCaffrey [2,5] discovered that the gas temperatures measured in the upper part of the room could be correlated in a power law relationship involving the energy release rate of the fire (Q), the ventilation factor for the opening ($A_o\sqrt{H_o}$), and a room geometric scale factor. These data applied to steady gas burner fires and to the peak burning conditions for wood or plastic crib fires. The correlation was so successful that it inspired a further study of its application. The results of that study by McCaffrey, Quintiere and Harkleroad [6] led to a more general correlation which included the additional parameters of room surface area and its thermal properties. This more comprehensive result was developed from an analysis of over 100 data sets for a wide range of fires. That development will be reviewed here and examples will be presented to illustrate applications of the correlation.

2. DEVELOPMENT OF CORRELATION

The problem being addressed is shown schematically in figure 1 along with the significant variables that apply. The fire is considered to be in the lower portion of the room such that it has direct access to the air flowing into the compartment. Ceiling fires would not be within the scope of this analysis. The objective is to predict the upper gas temperature rise (ΔT) in terms of the variables listed in figure 1. The rate of energy release (Q) is an important input variable, but is not known a priori under fire growth conditions. To make a complete prediction, Q as well as T would have to be derived. Alternatively, Q will have to be estimated or derived from experimental results to predict T in this problem. These aspects will be discussed further in the examples to follow. The other variables in figure 1 should be consistent with a general view of the problem. They involve room geometry, opening dimensions and thermal properties of the materials of construction. All of these variables can be easily determined.

The variables used in the ΔT correlation were derived by applying the conservation of energy equation to the flame and upper gas region shown in figure 1.

$$Q = c_v \frac{d(mT)}{dt} + \dot{m}_o c_p \Delta T + hA\Delta T \tag{1}$$

$$\begin{bmatrix}\text{Rate of}\\ \text{energy}\\ \text{released}\end{bmatrix} = \begin{bmatrix}\text{Rate of}\\ \text{energy}\\ \text{stored in}\\ \text{the gas}\end{bmatrix} + \begin{bmatrix}\text{Rate of}\\ \text{enthalpy}\\ \text{flow out}\\ \text{of the}\\ \text{openings}\end{bmatrix} + \begin{bmatrix}\text{Rate of}\\ \text{heat lost}\\ \text{by the gas}\end{bmatrix}$$

The terms are defined below.

Q = rate of energy release within the compartment by the fire

m = mass of the heated gases within the compartment

T = temperature of the heated gases within the compartment

ΔT = temperature rise above the initial or ambient temperature, T_o

t = time

c_v, c_p = specific heats for the gas at constant volume and constant pressure, respectively

$\dot{m}_o$ = gas flow rate out of the opening

h = an effective heat transfer coefficient for the enclosure walls, ceiling and floor

and A = the corresponding wall, ceiling and floor areas for heat transfer.

The rate of energy stored in the gas is small compared to the other terms in eq. (1) for most fire situations. By neglecting it, eq. (1) can be solved for ΔT to yield

$$\frac{\Delta T}{T_o} = \frac{Q/(c_p T_o \dot{m}_o)}{1 + hA/(c_p \dot{m}_o)} \tag{2}$$

The intention is to formulate the dependence of $\Delta T/T_o$ into easily computed dimensionless variables. The quantities $\dot{m}_o$ and h need to be transformed into workable expressions to achieve this objective. It can be shown that the gas flow rate can be represented as

$$\dot{m}_o = \rho_o \sqrt{g}\, A_o \sqrt{H_o} \cdot \phi(T, Q, A_o, H_o) \tag{3}$$

where ϕ is a dimensionless function of T, Q, A_o and H_o [1,6]. For small A_o, $\dot{m}_o$ is nearly directly proportional to $A_o\sqrt{H_o}$ (the ventilation factor), but in general ϕ must be known to compute $\dot{m}_o$. The effective heat transfer coefficient, h, involves many heat transfer processes. Radiation and convective heat transfer occur at the enclosure solid boundaries (walls, etc.) followed by conduction into these surfaces; also radiative heat loss occurs at openings. The convective and radiative processes will depend on T, Q and geometric factors; while the "wall" conduction depends on its thickness (δ) and thermal properties (k, conductivity; c, specific heat; and ρ, density). The effective heat transfer coefficient will therefore be represented as follows:

$$h = h_k \cdot \psi(T, Q, A_o, \ldots) \tag{4}$$

where ψ represents the radiative and convective effects and will depend on a number of variables in the problem,

and h_k represents the "wall" or enclosure conductance.

This "wall" conductance term is given by a convenient approximate expression [1,6]:

$$h_k = \begin{cases} \sqrt{k\rho c/t}, & t \leq t_p \\ k/\delta, & t \geq t_p \end{cases} \tag{5}$$

where the solid thermal penetration time, t_p, is given by

$$t_p = \left(\frac{\rho c}{k}\right)\left(\frac{\delta}{2}\right)^2 . \tag{6}$$

Equation (5) combines the initial heating solution of an infinitely thick wall with the steady-state heat conduction result for a wall of thickness δ.

By substituting eqs. (3) and (4) into eq. (2) it can be seen that functionally $\Delta T/T_o$ can be expressed in terms of easily determined quantities. However, the functions ϕ and ψ are not generally known; and even if they were, an explicit solution for ΔT would not be possible. Nevertheless, it can be said that the functional form of the solution would be

$$\Delta T/T_o = f(X_1, X_2) \tag{7}$$

where

$$X_1 = Q/(\sqrt{g}\ \rho_o\ c_p\ T_o\ A_o\sqrt{H_o}),$$

and

$$X_2 = h_k A/(\sqrt{g}\ \rho_o\ c_p\ A_o\sqrt{H_o}).$$

Thus, through this analysis the relevant dimensionless groups, X_1 and X_2, have been derived. This result could have been developed by other methods, but perhaps the analysis used here has revealed more of their physical significance. Moreover, a solution in the form of eq. (7) should account for phenomena not explicitly described, such as gas flow rate through the opening, and radiative and convective heat transfer processes. The objective now is to develop an explicit relationship for the function of X_1 and X_2, and establish its accuracy. This was done by McCaffrey et al. [6] and their result will be described.

The strategy for seeking a relationship for $f(X_1, X_2)$ was to consider a power law variation in the form of

$$\Delta T/T_o = C\ X_1^n\ X_2^m\ . \tag{8}$$

The values for C, n and m were determined a best-fit with experimental results. The source of that data was eight experiments which are summarized in table 1 [6]. In most cases the peak (or nearly steady) burning conditions were used. For Data Set 6, data were analyzed during the fire spread period. Judgment was used in the interpretation of the most representative measure of the average upper gas temperature; however, it is not uncommon to find temperature variations in the layer to be within 20% of the temperature rise at a single location. Another uncertainty is the determination of Q. All of the data considered were estimated to lie within the fuel-controlled burning regime in which sufficient air flow entered the compartment to burn all of the fuel released. The flow rate of fuel was monitored by flowmeters for gaseous fuels and by continuous weight sensors for solid fuels. Therefore, the instantaneous mass rate of fuel supplied $\dot{m}(t)$ times the heat of reaction for the fuel (ΔH) gives Q:

$$Q(t) = \dot{m}(t)\ \Delta H\ . \tag{9}$$

For solid fuels, WH in the flaming state is generally less than the theoretical heat of combustion for complete burning. The values of WH used in this analysis were the best available estimates and are listed in table 1. Uncertainties, of the order of 20%, are possible for the solid fuels listed there.

From these experiments, numerical results for 112 data groups were derived in order to determine the power law constants. It was felt that the variations in the experimental conditions were sufficiently broad to provide a basis for a fairly general correlation. Fuel ranged from gas, to wood, to plastics. Scale ranged from conventional room sizes down to nearly 1/8 of that. Both door and window openings were included. The construction materials used for the compartments were all essentially noncombustible and had a wide range of properties. Table 2 lists these properties (k, p, c, a = k/pc and kpc) for the construction materials in table 1 and other representative room lining materials. It should be noted that the computation of $h_k A$ in X_2 must account for all of the materials used in the floor, walls and ceiling. The following procedure should be used for computing $h_k A$:

(1) Each area of enclosure lining having a different construction must be considered separately, then summed.

$$h_k A = \underset{i}{S} (h_k A)_i \qquad (10)$$

where A_i is the surface area of that region; e.g., it could be the wall, ceiling or floor area.

(2) $h_{k,i}$ is computed for the ith region consistent with eqs. (5) and (6). If it is a single material, this is exactly as given. If it is a composite construction, then eqs. (5) and (6) should be applied as appropriate for a series of thermal conductors. For a composite consisting of j-layers:

$$h_k = 1/\underset{j}{S} \frac{1}{h_{k,j}} \qquad (11)$$

where

$$\frac{1}{h_{k,1}} = \begin{cases} \sqrt{t/(k\rho c)_1} & , \quad 0 \le t \le t_{p,1} \\ (\delta/k)_1 & , \quad t \ge t_{p,1} \end{cases}$$

$$\frac{1}{h_{k,2}} = \begin{cases} 0 & , \quad 0 \le t \le t_{p,1} \\ \sqrt{t/(k\rho c)_2} & , \quad t_{p,1} \le t \le (t_{p,1} + t_{p,2}) \\ (\delta/k)_2 & , \quad t \ge (t_{p,1} + t_{p,2}) \end{cases} \tag{12}$$

$$\vdots$$

and $h_{k,j}$ can be found accordingly. Thus, the $h_k A$ values were computed for each of the 112 data groups analyzed in reference [6]. The specific analysis derived for each experiment is described in that reference. Once those computations were completed, values for $\Delta T/T_o$, X_1 and X_2 were substituted into eq. (8) and the constants C, n and m were determined by regression analysis.

A correlation was developed for two cases. In one case the floor was ignored as a heat transfer region, and in the second case it was included along with the walls and ceiling. The motivation for this is that in the early stage of fire growth at low upper gas temperature, there would be little heat transfer to the floor; in the later period of fire development, at high temperatures, floor heat transfer would become significant. Figure 2 shows the result of the regression analysis for the case of floor heat loss; the other case yields a similar result. The corresponding equations are, for no floor heat loss:

$$\Delta T/T_o = 1.32\ X_1^{0.624}\ X_2^{-0.315} \tag{13}$$

and for the floor included:

$$\Delta T/T_o = 1.52\ X_1^{0.650}\ X_2^{-0.387}\ . \tag{14}$$

An alternative form of these equations, motivated by results from plume theory is

$$\Delta T/T_o = 1.63\ X_1^{2/3}\ X_2^{-1/3} \tag{15}$$

Equation (15) will be used throughout the remainder of this presentation, and will be interpreted to include the floor heat loss. A more convenient form of eq. (15) in specific units is given by

$$\Delta T = 6.85 \left[\frac{Q^2}{(A_o\sqrt{H_o})(h_k A)} \right]^{1/3} \text{ in } {}^0\mathrm{C} \tag{16}$$

where Q is in kW,
A_o, A are in m^2,
H_o is in m,
h_k is in kW/m^2-K,

and the constant quantities have been taken as $g = 9.8$ m/s^2, $\rho_o = 1.2$ kg/m^3, $T_o = 295$ K, and $c_p = 1.05$ kJ/kg-K. This will be the working equation for the subsequent examples. It should be applied as follows:

(1) $Q(t)$ represents the instantaneous rate of energy release within the compartment at time t.

(2) $A_o\sqrt{H_o}$ is the sum for all openings in the walls to the ambient at T_o under natural ventilation conditions.

(3) h_kA is the appropriate sum of the wall, ceiling and floor effects based on eqs. (10-12).

A series of examples illustrating the application and accuracy of eq. (16) will now be presented. In each case the example is based on experimental results or results derived from mathematical models. No absolute measure of accuracy will be possible to ascribe to eq. (16) from these comparisons since uncertainties exist relative to the experiments and the mathematical models. But favorable agreements in these comparisons will give more confidence in the general applicability of the empirical correlation (eq. (16)). This should follow since all of the examples to be considered have new or different features from the data base which established the correlation. Hence, this exercise could be viewed as a test of its validity; not just an explanation of its application. A summary description of the examples along with a distinguishing feature for each is given below:

Examples 1 and 2 - These examples display the application of the formula to a spreading fire on a bed. The room fire configuration is similar to those experiments considered in the development of the correlation. However, the formula will be used to predict the temperature response over time, in contrast to peak or steady-state temperature data used in the derivation of the formula.

Example 3 - This is an exercise to examine the results from applying the correlation formula to a spreading fire within a room having both an open door and window.

Example 4 - In this example the fire consists of a fixed diameter pool of polymethyl methacrylate beads which is uniformly ignited. Therefore changes in the burning rate are only due to transient effects of the fuel bed and room thermal feedback.

Example 5 - The formula is applied to predict the transient temperature response due to a room fire consisting of four wood cribs. The results are compared to both experimental data and results from a computer-based zone method fire growth model.

Example 6 - This example is an extension of the previous example. Here the peak results are examined for a series of experiments involving plastic crib fires and room door widths, both of which varies in size. The formula is used to estimate the temperature at the ventilation limit condition. This corresponds to the point for which the air supply to the room is equal to that required to burn all the available fuel.

Example 7 - Some investigators have suggested that the achievement of a critical temperature rise (500-600°C) can be used to indicate the onset of flashover or potential full-involvement of the remaining fuel in the room. The formula is applied in order to determine the relationship between the corresponding critical energy release rate and room geometric parameters. Results from a specific example are compared with results derived from using the Harvard Room Fire Code.

2.1 Example 1: Factory Mutual Bedroom Fire (1973) [7]

The experiment [7] consisted of a typically furnished bedroom with a closet and a single doorway open to the surroundings. The fire was initiated on the bed, consuming initially the mattress. A decay in the growth then briefly occurred, followed by involvement of other items near the bed leading to full-involvement of the room furnishings. The floor material was plywood, and the walls and ceiling were sheetrock on studs and joists. These investigators [7] performed an energy balance from their measurements in order to estimate the energy release by the fire Q(t). This is a difficult estimation to perform accurately, and some negative values computed at the start of the fire demonstrate that uncertainty. Nevertheless, their positive values will be considered valid for the purpose of estimating ΔT. This computed temperature will then be compared to two measured temperatures--0.24 m from the ceiling, between the bed and the doorway, and 0.13 m from the top of the doorway. The computations are summarized below:

<u>Ventilation Factor</u>

$$H_o = 2.03 \text{ m}$$
$$W_o = 0.74 \text{ m}$$
$$A_o\sqrt{H_o} = W_o H_o^{3/2} = 2.13 \text{ m}^{5/2}$$

Heat Loss Factor

1. Wall/ceiling material - sheetrock

Area of walls and ceiling including closet, $A_1 = 47.7\ m^2$

Thickness, $\delta_1 = 0.0159$ m

$(k/\rho c)_1 = 0.16 \times 10^{-6}\ m^2/s$

$\therefore\ t_{p,1} = 395$ s

$$h_1 = \left\{ \begin{array}{l} \sqrt{(k\rho c)_1/t} = \sqrt{0.18/t}\ , \ t < 395 \text{ s} \\ \\ k_1/\delta_1 = 0.17 \times 10^{-2}/0.0159 = 1.07 \times 10^{-2},\ t > 395 \text{ s} \end{array} \right\} kW/m^2K$$

2. Floor material - plywood

Area of floor including closet, $A_2 = 9.38\ m^2$

Thickness, $\delta_2 = 0.0159$ m

$(k/\rho c)_2 = 0.089 \times 10^{-6}\ m^2/s$

$\therefore\ t_{p,2} = 710$ s

$$h_2 = \left\{ \begin{array}{l} \sqrt{0.16/t}\ , \ t < 710 \text{ s} \\ \\ 0.12 \times 10^{-3}/0.0159 = 0.75 \times 10^{-2}\ , \ t > 710 \text{ s} \end{array} \right\} kW/m^2\text{-}K$$

Finally, from eq. (10)

$$h_k A = (hA)_1 + (hA)_2$$

From the values of Q estimated by these experimenters [7] and the values of $A_o\sqrt{H_o}$ and $h_k A$ given above, ΔT can be computed using eq. (16). These results are tabulated in table 3 along with the selected measured room and doorway temperature rises. The temperature rise is plotted as a function of time in figure 3. The computed results are connected by a smooth curve for ease in illustrating the trend. Although a sharp temperature rise occurs just after 16 minutes, flashover was defined to occur at 17 min. 40 s. in this experiment. It is significant, for the purposes of estimating Q(t), that they [7] estimated that the heat flux to the burning fuel did not exceed 20% of its free burn value before flashover. That means that the mass loss rate ($\dot{m}(t)$, eq. (9)) of the bed until flashover, was nearly at a value that could have been determined from burning it outside of the room. The general establishment of this fuel response characteristic would enable a practical method for estimating $\dot{m}(t)$ and then $Q(t)$ for complex fuel arrangements in order to predict room temperature. After flashover occurs, and a fully-developed fire results, room heat transfer can enhance the mass loss rate many times over its free burn value, or ventilation limited conditions can reduce the mass loss rate relative to free burn levels. Mass loss rate will depend directly on surface heat transfer rate and air supply rate or oxygen concentration. Qualitatively, this can be expressed for a given fuel as

$$\dot{m} = \dot{m}_\infty + f_1(O_2) + f_2(\dot{q}'') \qquad (17)$$

where $\dot{m}_\infty$ is the free burn value,

f_1 is the effect of O_2

and f_2 is the effect of heat flux to the fuel.

The functions f_1 and f_2 are not completely understood, and more research is needed to formulate them completely. Nevertheless, since $f_1(O_2)$ will have a negative effect as $A_o\sqrt{H_o}$ is reduced or the fire grows,

$$\dot{m} \leq \dot{m}_\infty(t) \qquad (18)$$

during the growth period to flashover provided $f_2(\dot{q}'')$ is not a significant value before flashover. Complete resolution of this issue has not yet been made. A lesser, but non-trivial, issue is the estimation that $Q = \dot{m}\Delta H$. If eq. (18) holds, then $Q = \dot{m}_\infty \Delta H$ is an upper limit if ΔH is taken as the theoretical heat of combustion for the fuel. Better accuracy will undoubtedly require the determination of an "effective" ΔH consistent with the actual fire process. Perhaps this digression on computing Q has given some insight on how best to make that estimate for the intended application of eq. (16).

It should be clear now that an assessment of the accuracy of eq. (16), as displayed by the comparisons in figure 3, is not straight forward. The inability to reconcile the concept of a computed average upper gas temperature with point-wise varying temperature measurements, and the uncertain accuracy of $Q(t)$ preclude a precise assessment. Nevertheless, general agreement of these temperatures in this example and those to follow will provide some perspective on this question. Only in this way can the confidence in the validity of approximate fire models be developed. The remaining examples will be presented in decreasing illustrative detail. The reader is encouraged to complete the steps in order to gain an appreciation and understanding of the analysis. High precision was not maintained in these illustrations so that alternative computations may lead to slightly different numerical results.

2.2 Example 2: Factory Mutual Second Bedroom Fire (1974) [8]

This experiment [8] had an arrangement similar to that of Example 1. A bed was the item ignited as previously, but the spread was more rapid in this case. This, of course, underscores our inability to accurately predict $\dot{Q}(t)$. Fortunately, the determination of $Q(t)$ in this test appears to have yielded more accurate results based on the quantity and consistency of the data displayed [8]. Since the test conditions were the same as in Example 1, the same values of $h_k A$ and $A_o\sqrt{H_o}$ should be used with the new values for Q. However, since the plywood floor area is small relative to the area of the walls and ceiling, and since the sheetrock properties are similar to the plywood, a reasonable approximate is to use the sheetrock properties throughout. It can be shown that the results are as follows:

$$\Delta T = 1.85\,[Q^2\sqrt{t}]^{1/3},\ t < 395\ \text{s}$$

and

$$\Delta T = 6.05\,Q^{2/3},\ t > 395\ \text{s}$$

in the units of eq. (16) (T in ^{0}C, Q in kW). The results of the computations and the measured temperatures are listed in table 4 and shown in figure 4. The same measurement positions as in Example 1 were selected. In contrast to Example 1, flashover occurred earlier and the fire was extinguished after 7.5 minutes. The agreement between results compared up to that time is seen to be, remarkably, excellent.

2.3 Example 3: FM Room Test No. 4 - Open Door and Window [9]

This example is taken from a series of room fire tests conducted jointly by FMRC and Harvard University [9]. The room structure (Marinite XL*, δ = 0.0254 m) and size (2.4 x 3.7 x 2.4 m high) remained fixed throughout the series. In this test, the primary fuel consisted of a polyurethane slab located 0.6 m above the floor and a smaller remote "target" of the same material located 0.25 m above the slab height. The slab was ignited at the center and fire spread over its surface. The target would become involved later by spontaneous ignition under sufficient radiative heating. This target ignition could be construed as the inception of "flashover". The distinguishing feature of Test No. 4 is that both an open doorway (0.775 m x 2.04 m high) and window (0.76 m x 0.97 m high) were incorporated. The computation proceeds as follows based on the data available [9]:

$$A_o\sqrt{H_o} = (0.775)(2.04)^{3/2} + (0.76)(0.97)^{3/2} = 299 \text{ m}^{5/2}$$
$$\delta = 0.0254 \text{ m}$$
$$k/\rho c = 0.16 \times 10^{-6} \text{ m}^2/\text{s}$$

From eq. (6), t_p = 1008 s.

Since $t \leq 362$ s in this example, then from eq. (5),

$$h_k = \sqrt{k\rho c/t} \text{ with } k\rho c = 0.098\left(\frac{\text{kW}}{\text{m}^2\text{K}}\right)^2 \text{s}$$

or

$$h_k A = 14.7/\sqrt{t} \text{ kW/K for } t < 1008 \text{ s.}$$

The value for Q was estimated by eq. (9) where ΔH was given [9] as 18.7 kJ/g and $\dot{m}$ was determined from continuous mass loss measurements of both the primary fuel slab and the target. It can be shown that on substitution of the above information into eq. (16)

$$\Delta T = 13.7\ (\dot{m}^2\sqrt{t})^{1/3},\ (^0\text{C})$$

*The use of trade names does not constitute an endorsement by NBS.

where $\dot{m}$ is in g/s and t is in s. The variables are listed in table 5 along with the defined [9] average upper gas temperature based on measurements 0.72 m below the ceiling. The results are plotted in figure 5.

It is interesting to note that the mass loss rate of the primary fuel dropped after the target became involved. Eventually the total mass loss rate dropped and a sprinkler extinguished the fire at 384 s.

2.4 Example 4: FM Room Test No. 5 - Steady PMMA Fire [10]

This test [10] is another in the series described in the previous example. In this case, the differences from Test No. 4 are that only the door was open, and the primary fire element was a 0.73 m diameter pool of polymethyl methacrylate (PMMA) beads which were uniformly ignited. The objective was to consider a non-spreading fire which would tend to reach a steady burning level. Steady-state occurred in approximately 1000 s. In order to compute the temperature rise the following calculations are made:

$$A_o\sqrt{H_o} = 0.775(2.04)^{3/2} = 2.26 \text{ m}^{5/2}$$

$$h_k A = 14.7/\sqrt{t} \text{ for } t \leq 1008 \text{ s}$$

From eq. (5), $$h_k A = \frac{k}{\delta} A = \frac{(0.125 \times 10^{-3} \text{ kW/m-K})}{(0.0254 \text{ m})} (47 \text{ m}^2)$$

$$= 0.230 \text{ kW/K for } t > 1008 \text{ s.}$$

From eq. (9), $Q = \dot{m}(t)\Delta H$

where $\dot{m}$ is in g/s as given [10] and ΔH was taken as 24.2 kJ/g for PMMA [11]. Therefore, eq. (16) yields

$$\Delta T = \begin{cases} 17.8(\dot{m}^2\sqrt{t})^{1/3}, & t \leq 1008 \text{ s} \\ 71.3\ \dot{m}^{2/3}, & t > 1008 \text{ s} \end{cases}$$

The results are compared to the average measured upper layer gas temperature in table 6 and figure 6.

A sprinkler was activated at 1780 s and terminated the fire. The target did not ignite for the PMMA primary fuel; and in the free burning condition, the mass loss rate achieved 8.5 g/s [12]. Hence, the room enhancement effect was approximately

$$(m - m_\infty)/m_\infty = (10 - 8.5)/8.5 = 0.176$$

or roughly 18%. Thus, computations based on a free burn mass loss rate would have given slightly lower values of ΔT. Another point to consider is the "discontinuity" in the ΔT prediction at 1008 s. This, of course, comes from the change in h_k inherent in its approximate form. Despite that effect, the overall results do not appear to suffer much.

2.5 Example 5: NBS/PRC Room Test W-4-1 - Four Wood Cribs [2,13]

This example is based on a series of room fire experiments involving wood (sugar pine) or plastic (rigid polyurethane) of nearly the same density. They were conducted at the National Bureau of Standards [13] and sponsored by the Products Research Committee. The room had a single door opening whose width (W_o) was varied. The room size was 2.18 x 2.18 x 2.41 m high and lined on the walls and ceiling with calcium silicate board of 0.019 m thickness, the floor was concrete. The peak burning condition results were used to generate the correlation, eqns. (13-15) [6] whereas computations over time will be made here. The case of four wood cribs with the standard (largest) door width will be considered. The mass loss rate of the cribs was determined from the measurements. Here, a heat of reaction was selected as 13 kJ/g compared with 15 kJ/g used in the previous analysis [6]. This reflects the uncertainty in this value [2], and the lower value is consistent with more recent computations performed by a more complete computer-based model [2,13]. The nature of this problem and the results for ΔT are summarized in figure 7. The required steps in the computation are shown below.

$$A_o\sqrt{H_o} = W_o\, H_o^{3/2} = (0.79)(1.83)^{3/2} = 1.96\ m^{5/2}$$

For these enclosure materials, it can be shown that t_p will be greater than or equal to the limit of these calculations--t = 600 s. Hence, from eqs. (5) and (10) and for enclosure parameters of

(1) calcium silicate walls and ceiling:

$$A_1 = 26.2 \text{ m}^2$$

$$(k\rho c)_1 = 0.098 \text{ (kW/m}^2\text{-K)}^2\text{-s}$$

(2) concrete floor:

$$A_2 = 4.75 \text{ m}^2$$

$$(k\rho c)_2 = 2.9 \text{ (kW/m}^2\text{-K)}^2\text{-s}$$

it follows that

$$h_k A = 26.2\sqrt{0.098/t} + 4.75\sqrt{2.9/t}$$

$$h_k A = 16.3/\sqrt{t} \text{ kW/K with t in s.}$$

From eqs. (9) and (16) with $T_o = 21^0$C

$$T = 21 + 11.9(\dot{m}^2\sqrt{t})^{1/3} \ {}^0\text{C}$$

with $\dot{m}$ in g/s and t in s. The results of this computation ("estimate") are plotted in figure 8 along with experimental results and results from a more complete model [13]. The experimental results [2] show the temperature variation of equally spaced ceiling to floor (9-23) thermocouples, numbered 9-23, and surface thermocouples numbered as 8 and 25. Down to thermocouple 13 (0.75 m from the ceiling) and above the floor to thermocouple 19 (0.75 m from the floor) the variation is slight. Thus, two distinct gas layers (zones) are revealed in room fires with a transition zone in between. The more complete model [2,13] is based on a two zone characterization for the gases in the enclosure and those predicted temperatures ($T_{g,u}$, $T_{g,\ell}$) along with their corresponding solid boundary surface temperatures ($T_{w,u}$, $T_{w,\ell}$) have been plotted in figure 8. The estimated results are too low as computed by eq. (16). The computer model predictions are in better agreement with the measurements and give a more complete thermal characterization.

2.6 Example 6: NBS/PRC Room Tests - Peak Burning of Plastic Cribs [2,13]

These results are taken from the same series of experiments described in Example 5. In this case, the plastic (rigid polyurethane, 340 kg/m^3) fires will be examined at their peak burning conditions in each test. The computed results for ΔT (T_o = 21^{0}C) will be compared with both the experimental results and the results of the more complex zone model described earlier [2,13]. That zone model incorporates a specific pyrolysis (burning) rate expression, as given by eq. (17). It accounts for heating effects between adjacent cribs, radiative heat flux to the crib surfaces, and reduced pyrolysis due to a lowering of oxygen concentration in the vitiated air flowing into the base of the cribs. Fortunately, for items which burn like cribs (internal channel dominated pyrolysis), the free burn rate ($\dot{m}_\infty$) is a good approximation to the pyrolysis rate in a compartment provided the ventilation (air-controlled) limit is not reached. Eq. (16) can still be used until the ventilation limit is reached with $\dot{m}_\infty$ taken as nominally 8 g/s per crib. The limit condition which gives the maximum temperature for a fixed $A_o\sqrt{H_o}$ and corresponding fuel load (n-cribs) can be estimated as follows:

The maximum air flow rate ($\dot{m}_a$) for small openings or fully-involved enclosure fires was shown by Kawagoe [1] to be

$$\dot{m}_a = k_o A_o \sqrt{H_o}; \; k_o = 0.5 \text{ kg/m}^{5/2}\text{-s.} \qquad (19)$$

The maximum possible energy release rate within the compartment is therefore

$$Q_{max} = \dot{m}_a \Delta H_a \qquad (20)$$

where ΔH_a = 3 kJ/g air consumed, approximately. This number is fairly constant for the range of combustibles in fires. Substituting eq. (19) and (20) in eq. (16), the limit temperature is estimated for the boundary between ventilation-limited and fuel-limited fires. For the same fuel load, the ΔT for either larger or smaller openings ($A_o\sqrt{H}$ values) will be lower. Hence,

$$\Delta T_{limit} = 896[A_o\sqrt{H_o}/(h_k A)]^{1/3} \; (^0\text{C}) \qquad (21)$$

with (S.I.) units as used in eq. (16).

The fuel-controlled (non-air-limited) temperatures are calculated as usually. For this example, the following is done:

(1) The height (H_o) of the opening was fixed at 1.83 m, and the door width (W_o) was varied.

(2) The heat of reaction was taken as $\Delta H = 19$ kJ/g.

(3) The mass loss rate was taken as $\dot{m} = 8n$(g/s) where n is the number of cribs.

(4) Peak burning conditions were nominally reached at t = 250 s, therefore $h_k A = 16.3/\sqrt{t}$ kW/K was computed at this peak time condition.

Substituting all of the above into eq. (16) yields

$$\Delta T = 142(n^2/W_o)^{1/3} \; (^0C)$$

where W_o is in m. Correspondingly, the limit temperature rise was computed from eq. (21) so

$$\Delta T_{limit} = 1190 \; W_o^{1/3}.$$

Hence, for each W_o, there is some number of cribs which correspond to the maximum possible ΔT rise for that opening.

The results of these estimates are compared to the data [2] and computer model results [13] in figure 9. The lower (ventilation) limit temperatures found by the more complete zone model reflect the reduction in the pyrolysis rate due to local vitiation of the crib air; this likely occurs before the estimated limit eq. (21) is reached. Although deviations exist among all the values, the estimated results appear reasonably consistent.

2.7 Example 7: "Flashover" Conditions by Peacock [14] using the Harvard Computer Fire Code V

Although this example is entitled "flashover," the term can not be precisely defined, but is based on the subjective "eye of the beholder." Having seen a dramatic eruption of fire in a room, an observer shouts "flashover." To define this event in operational terms requires a complete understanding of the fire growth mechanisms responsible for its cause. Nevertheless, despite this lack of complete understanding, expedient investigators seek simple operational measurements to signify flashover. Recently, Thomas [15] tried to give some basis for using an upper gas temperature rise as an indicator of "flashover." Table 7 summarizes these estimates for several potentially promoting mechanisms--"others" are also listed to leave the issue open. In this context, Peacock [14] decided to define $\Delta T = 500^0C$ as the point of flashover. He proceeded to compute conditions which would yield this temperature for an impulsively initiated, constant energy release rate fire. He selected the following configuration for his computations:

(1) Room height fixed at 2.4 m, but total room surface area (A) ranged from 48 to 323 m^2.

(2) Lining material was gypsum board with $\delta = 0.0127$ m and $k = 0.17 \times 10^{-3}$ kW/m-K.

(3) Door height (H_o) was fixed at 2.03 m, but the width (W_o) was varied.

Since a steady fire was considered and the maximum ΔT sought, it follows that

$$h_k = k/\delta = 0.0134 \text{ kW/m}^2\text{-K}.$$

Hence, from eq. (16) with $\Delta T = 500^0C$ the corresponding Q values are found by

$$Q_{500} = 0.0721 \, (A \, A_o \sqrt{H_o})^{1/2} \text{ in MW}.$$

The limit curve (i.e. $\Delta T_{limit} = 500^0C$) was also computed from eq. (21). These estimated values are compared in Figure 10 with the results given by Peacock [14] based on the Harvard Code V. It is interesting to note that Peacock computed down to the estimated ventilation limit line without any explicit recognition of it; however, the Code should have dealt with it properly depending on its input information. Agreement between the two computations seems fair for conventional room sizes, i.e., 48-85 m^2. The empirical result (Eq. (16)) springs from data taken in such rooms. The Harvard code also gives higher Q_{500} values, especially for "small" $A_o\sqrt{H_o}$ (note, a typical door or window has an $A_o\sqrt{H_o}$ of 2-3 $m^{5/2}$). This may result because that model considers the lower room space to remain at its initial temperature, thereby becoming an excessive heat sink as enclosure temperatures increase. For the "large" wall area compartment and "large" $A_o\sqrt{H_o}$ values, no experimental data are available to provide credibility to each of these computed results. Overall, both show similar trends and their utility is clear for design purposes.

Another view of this type of analysis has been made by Thomas [15]. He compared several formulae to predict the Q required to achieve an upper gas temperature of 600^0C in the experiments of Hagglund et al. [16]. Babrauskas [17] derived an expression for this Q as a function primarily of $A_o\sqrt{H_o}$, and subsequently a modified expression involving the surface area (A or A_w). Thomas [15] developed an independent analysis and found Q for T = 600^0C to be

$$Q_{(T=600^0C)} = 7.8\ A + 378\ A_o\sqrt{H_o}\ (kW)$$

with the dimensions in m. While not explicit in the Thomas formula, since he particularized it to the Hagglund experiments, is the enclosure material properties. Taking the present result in eq. (16) for the Hagglund experiments it can be shown that

$$Q_{(T=600^0C)}/A_o\sqrt{H_o} = 144\ (A/A_o\sqrt{H_o})^{1/2}$$

in units of kW and m. As A → 0 (or more physically meaningful, $h_k \rightarrow 0$) this result is not valid; its behavior is an artifact of the correlation. A comparison between all of these formulae and the data of Hagglund et al. [16] that just achieved T = 600^0C is shown in figure 11. As in figure 10, it is interesting to note that all of the results in figure 11 are within the fuel-controlled (non-ventilation-limited) fire regime since from eqs. (19) and (20)

$$Q_{max}/A_o\sqrt{H_o} = 1500\ \mathrm{kW/m^{5/2}}\ .$$

3. SUMMARY OF RESULTS

An assessment and demonstration of using the empirically based formula for upper gas enclosure temperature rise,

$$\frac{\Delta T}{T_o} = 1.6\left(\frac{Q}{\sqrt{g}\ c_p\rho_o T_o A_o\sqrt{H_o}}\right)^{2/3}\left(\frac{h_k A}{\sqrt{g}\ c_p\rho_o A_o\sqrt{H_o}}\right)^{-1/3}$$

has been presented. An impression of the initial correlation (Fig. 2) and the results of the various examples suggests it predicts experimental results within 100^0C (at worst). The uncertainties in selecting Q and the lack of one-to-one correspondence between an average bulk computed temperature and pointwise measurements mitigate that evaluation. The need to specify Q is a critical one. It may be resolved by using free burn data, but a complete generalization of this approach needs to address enclosure radiative feedback effects on fire growth. A thorough assessment of this issue is key to using eq. (16). Nevertheless, estimates for Q from experiments have led to good predictions of temperature in those experiments. And it has been illustrated that these predictions appear to account well for the effects of vents, material properties, time and scale. More complete models are certainly needed to address the wide range of interest in fire safety; however, this empirical formula could provide a simply derived estimate of thermal effects.

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TABLE 1: DATA SOURCES USED IN DEVELOPING THE CORRELATION

Data Set	Fuel	$\Delta H \times 10^{-3}$ kJ/kg	Enclosure H (m)	Enclosure W (m)	Enclosure L (m)	Opening H (m)	Opening W (m)	Material/Thickness (m) Ceiling and Walls	Floor	Reference
1	Polymethyl methacrylate sheets	18	.30	.30	.56	.225	.015-.285	Alumina-silica/.025 block	Same	1
2	Sugar pine cribs Polyurethane cribs	15 23	2.41	2.18	2.18	1.83	.20-.79	Calcium silicate board/.019	Concrete/.13	2
3	Natural gas	50	2.44	3.40	3.52	2.13	.91	Cement-asbestos board/.013 over type X gypsum/.016	Cement-asbestos board/.013 over concrete/.13	3
4	Propane	46	2.3	3.0	3.0	1.93	.73	Fibrous glass insulation/ .025 over aluminum alloy/ .0064 (insulation faced with glass cloth)	Painted aluminum sheet/.0032 over concrete/.13	4
5	Natural gas	50	.41	.39	.37	.29	.11	Alumina-silica block/.025 over plywood/.013	Asbestos-cement board/.025	4
6	Fir wood cribs	15	2.7	2.9	3.75	1.3	.15-1.2	Walls: aerated concrete	Floor and ceiling: concrete	5
7	Polyurethane foam slabs (spreading fire)	18.7	2.4	2.4	3.6	2.0 1.0	.194,.775 .775(W)	Calcium silicate board/.025	Calcium silicate board/.032	6
8	Methane	50	2.13	2.8	2.8	1.83 .457-1.83	.235-.991 .737(W)	Alumina silicate/.013 over aluminum/.00066	Calcium silicate board/.019 over plywood/.013	7

Note:
1. (W) - Window
2. Table taken from ref. 6.

TABLE 2: THERMAL PROPERTIES OF LINING MATERIALS

	ρ $\left[\frac{kg}{m^3}\right]$	c $\left[\frac{kJ}{kg.K}\right]$	k x 10^3 $\left[\frac{kW}{m.K}\right]$	α x 10^6 $\left[\frac{m^2}{s}\right]$	ρck $\left(\frac{kW}{m^2K}\right)^2 s$	Reference
Aluminum (pure)	2710	.895	206	85	500	H
Concrete	2400	.75	1.6	.91	2.9	H
Asbestos-cement board (heavy)	2100	1.0	1.1	.52	2.3	[13]
Brick	2600	0.8	0.8	.38	1.7	[15]
Brick/concrete block	1900	.84	.73	.46	1.2	[13]
Gypsum board	960	1.1	.17	.16	0.18	[2], [13]
Plasterboard	950	.84	.16	.20	0.13	[15]
			.20			[3]
Plywood	540	2.5	.12	.089	0.16	[13]
Chipboard	800	1.25	.15	.15	0.15	[15]
Aerated concrete	500	.96	.26	.54	0.13	H
Cement-asbestos board	658	1.06	.14	.20	.098	
Calcium silicate board (Marinite XL)*	700	1.12	.11-.14	.14-.18	.086-.11	[2]
Fibre insulation board	240	1.25	.053	.18	.015	[15]
Alumina silicate block (kaowool)*	260	<1>	.14	.54	.036	[1]
Glass fibre insulation	60	.8	.037	.77	.0018	[14]
Expanded polystyrene	20	1.5	.034	1.13	.0010	[15]

Note:
(1) *Trade name - implies no endorsement by NBS.
(2) H - Handbook values (concretes based on density).
(3) Table taken from ref. 6.

Table 3

Results for Example 1: FM Bedroom Fire (1973)

t min	h_1 (kW/m^2-K)	h_2 (kW/m^2-K)	h_kA (kW/K)	Q (kW)	ΔT (^{0}C)	Experimental Values ΔT_3 (door) (^{0}C)	ΔT_{44} (room) (^{0}C)
2	0.0387	0.0365	2.16	99.9	88.6	9	0
4	0.0274	0.0258	1.53	264	190	82	51
5	0.0245	0.0231	1.37	331	229	120	98
6	0.0224	0.0211	1.25	538	326	185	161
7	0.0107	0.0195	0.687	711	481	235	219
8	0.0107	0.0183	0.676	694	475	465	327
10	0.0107	0.0163	0.657	360	307	255	275
11	0.0107	0.0155	0.650	347	300	217	242
13	0.0107	0.0075	0.574	50	87	143	167
16	0.0107	0.0075	0.574	145	177	220	194
17	0.0107	0.0075	0.574	1199	723	699	445

Table 4

Results for Example 2: FM Second Bedroom Fire 1974 [8]

t (min)	Q (kW)	ΔT (^{0}C)	Experimental Values ΔT_{51} (door) (^{0}C)	ΔT_{77} (room) (^{0}C)
0.5	-0.50	---	0	0
1.0	0.15	1.0	0	0
1.5	1.09	4.2	2	2
2.0	0.88	3.8	3	2
2.5	1.80	6.3	5	4
3.0	3.50	10.1	8	7
3.5	7.70	17.6	12	12
4.0	15.70	28.9	21	19
4.5	42.20	57.0	43	39
5.0	82.40	90.6	71	72
5.5	176.30	153.0	137	147
6.0	218.70	179.0	139	162
6.5	953.00	484.0	467	452
7.0	2185.00	852.0	723	749
7.5	2342.00	903.0	777	833

Table 5

Results for Example 3: FM Room Test No. 4 - Open Door and Window [9]

t (s)	$\dot{m}$ (g/s)	ΔT (^0C)	$\overline{\Delta T}_{measured}$ (^0C)
10	0.012	1.0	0.5
100	0.328	14.0	2.0
200	3.040	69.5	42.6
300	44.000	442.0	316.0
320	63.600	571.0	563.0
362	52.7 (65.7)*	514 (595)	595.0

*Corresponds to contribution by the target item following its ignition at 350 s.

Table 6

Results for Example 4: FM Test No. 5 - PMMA Steady Pool Fire

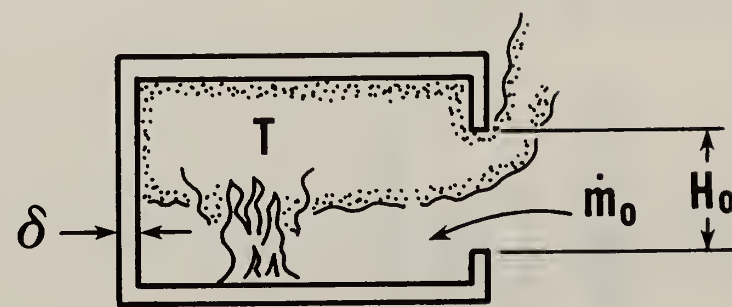
t (s)	$\dot{m}$ (g/s)	ΔT (^{0}C)	$\overline{\Delta T}_{(measured)}$ (^{0}C)
100	3.17	83	124
200	6.01	142	169
300	7.21	172	204
400	8.48	201	219
600	9.06	225	244
1000	9.85	259	273
1200	10.03	332	288
1400	10.09	333	294
1600	9.74	325	297

Table 7

"Flashover" criteria by Thomas [15]

Mechanism	Critical ΔT (°C)
• Thermal feedback/Instability	300 - 650
• Ignition threshold of solids	$\sim$ 600
• Gas phase ignition	$\geq$ 400 - 500
(others)	

PROBLEM



Q, rate of energy release

ΔT, gas temperature rise

A_0, area of opening

H_0, height of opening

A, enclosure surface area

h_k, effective heat transfer coefficient

Fig. 1. Problem definition

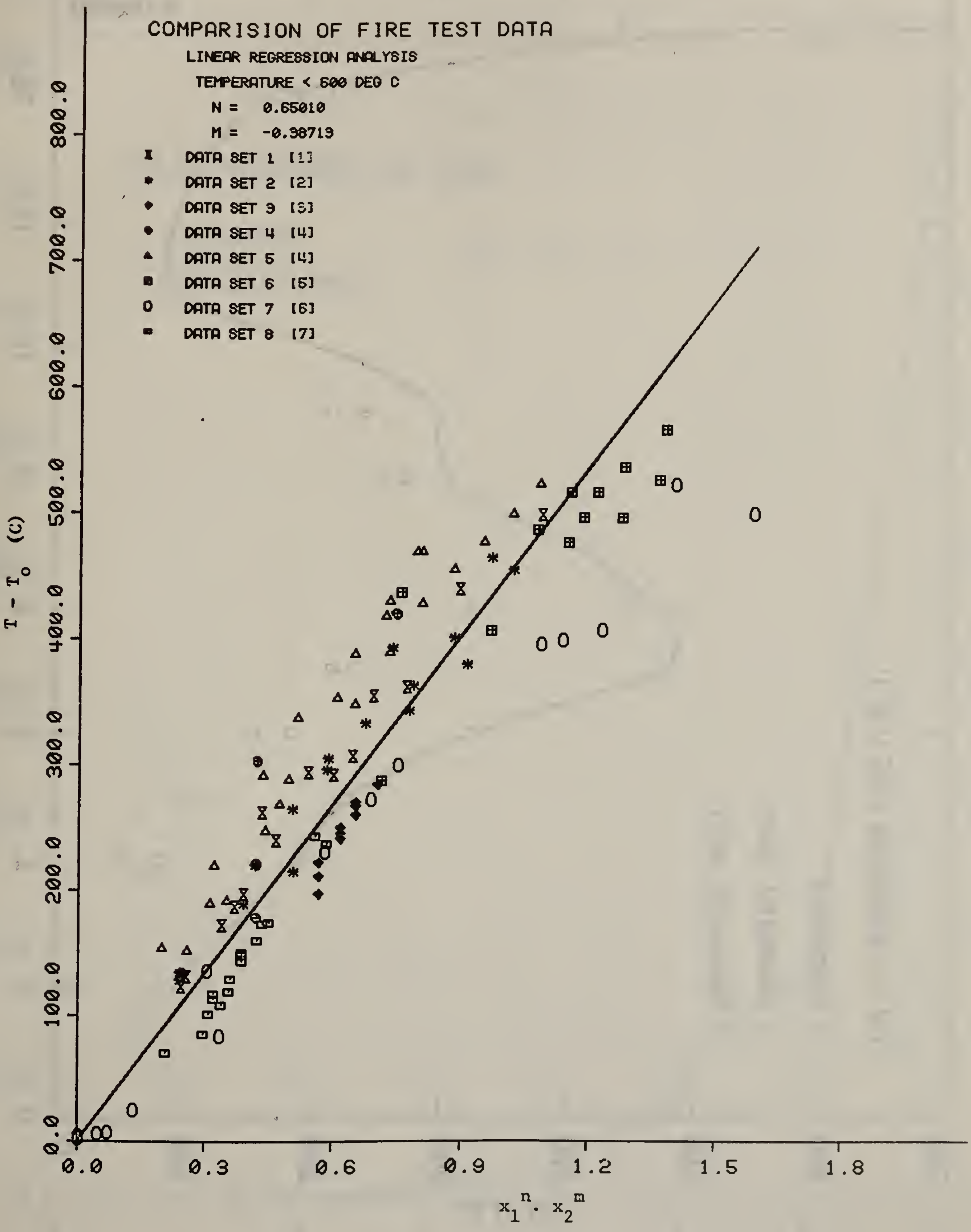


Fig. 2. ΔT correlation with floor heat loss taken from Ref. [6], X_1 and X_2 given in eq. (7)

Fig. 3. Example 1, FM first bedroom fire

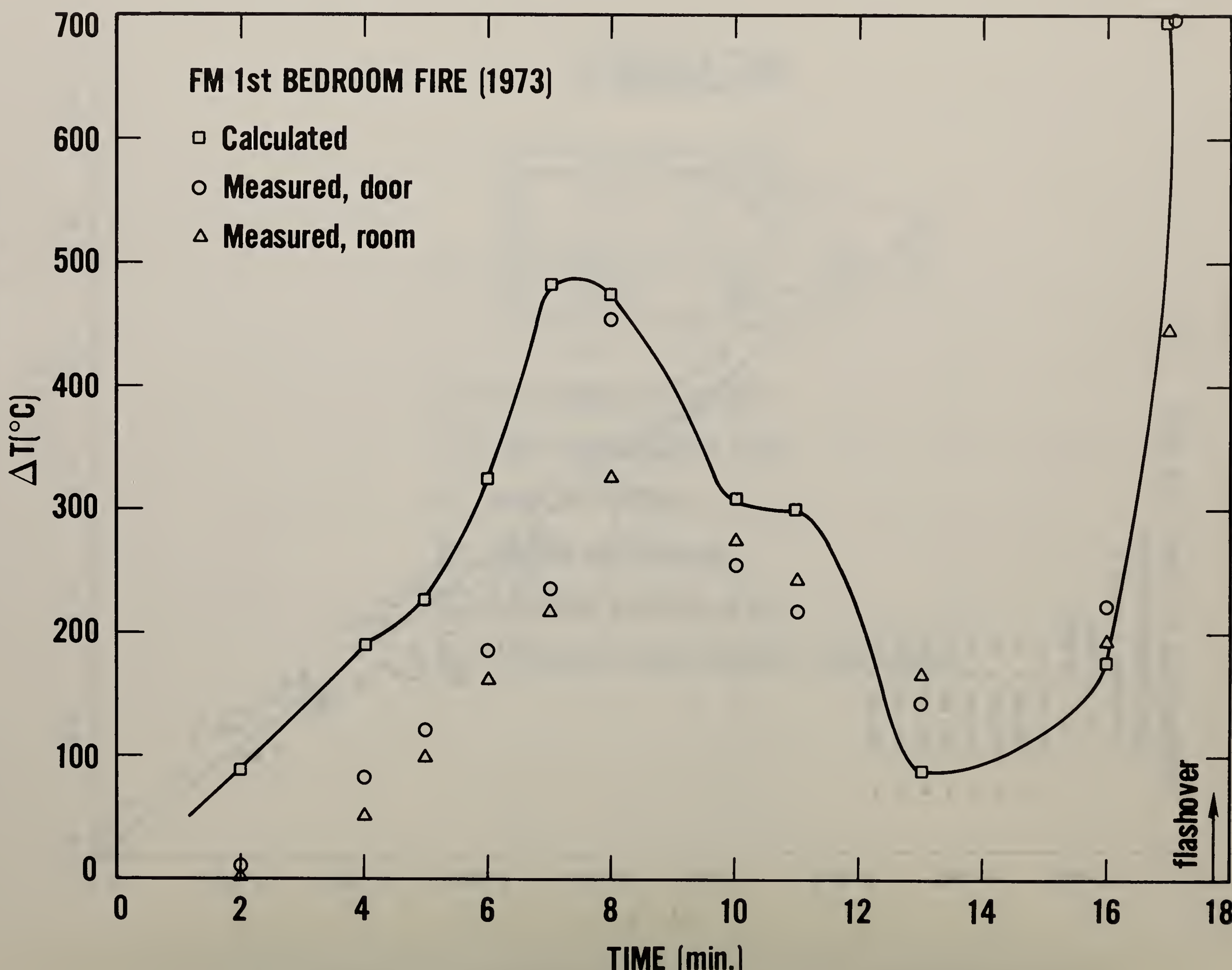
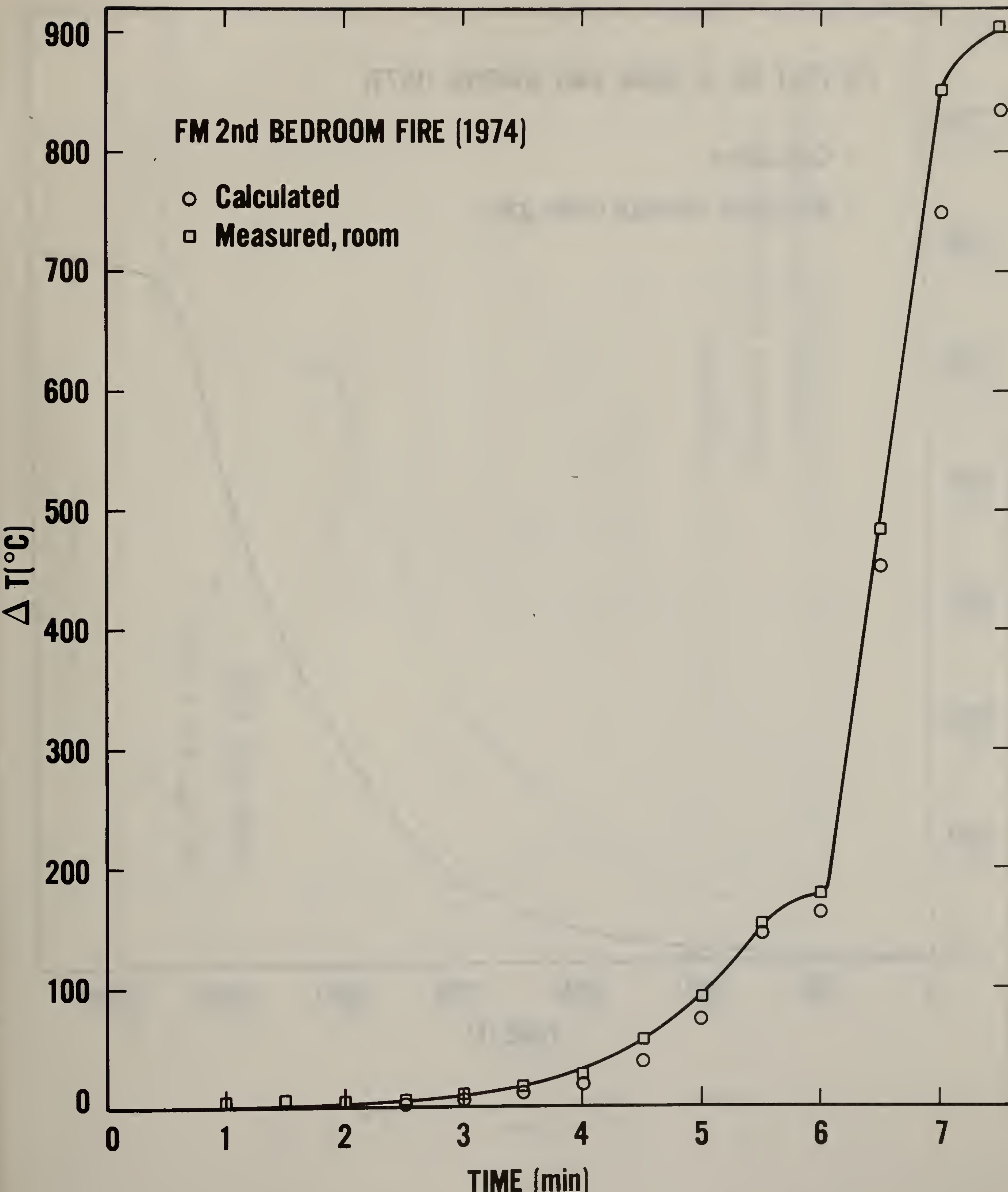


Fig. 4. Example 2, FM second bedroom fire



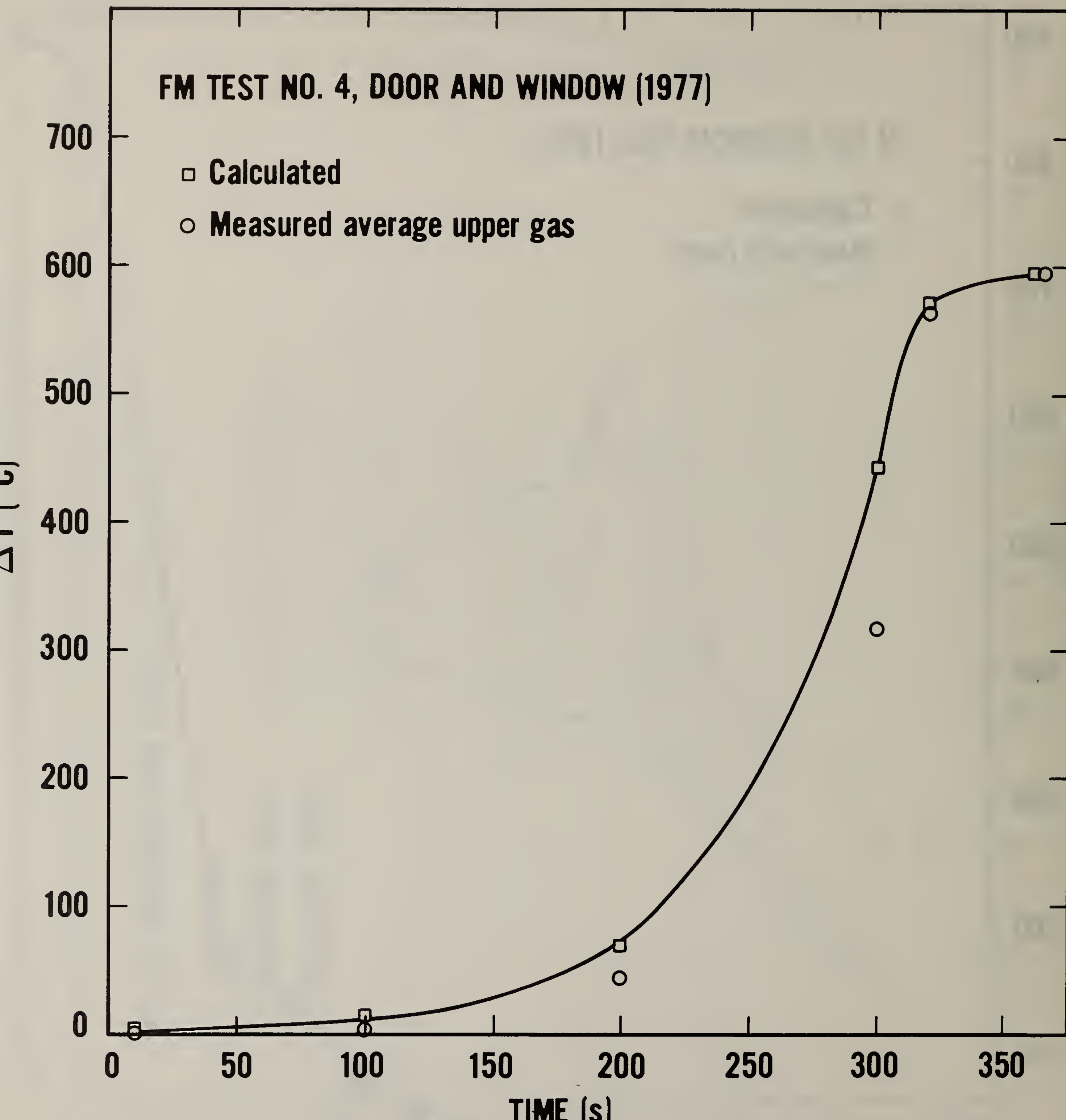


Figure 5. Example 3, room with an open door and window

Figure 6. Example 4, pool fire fuel source

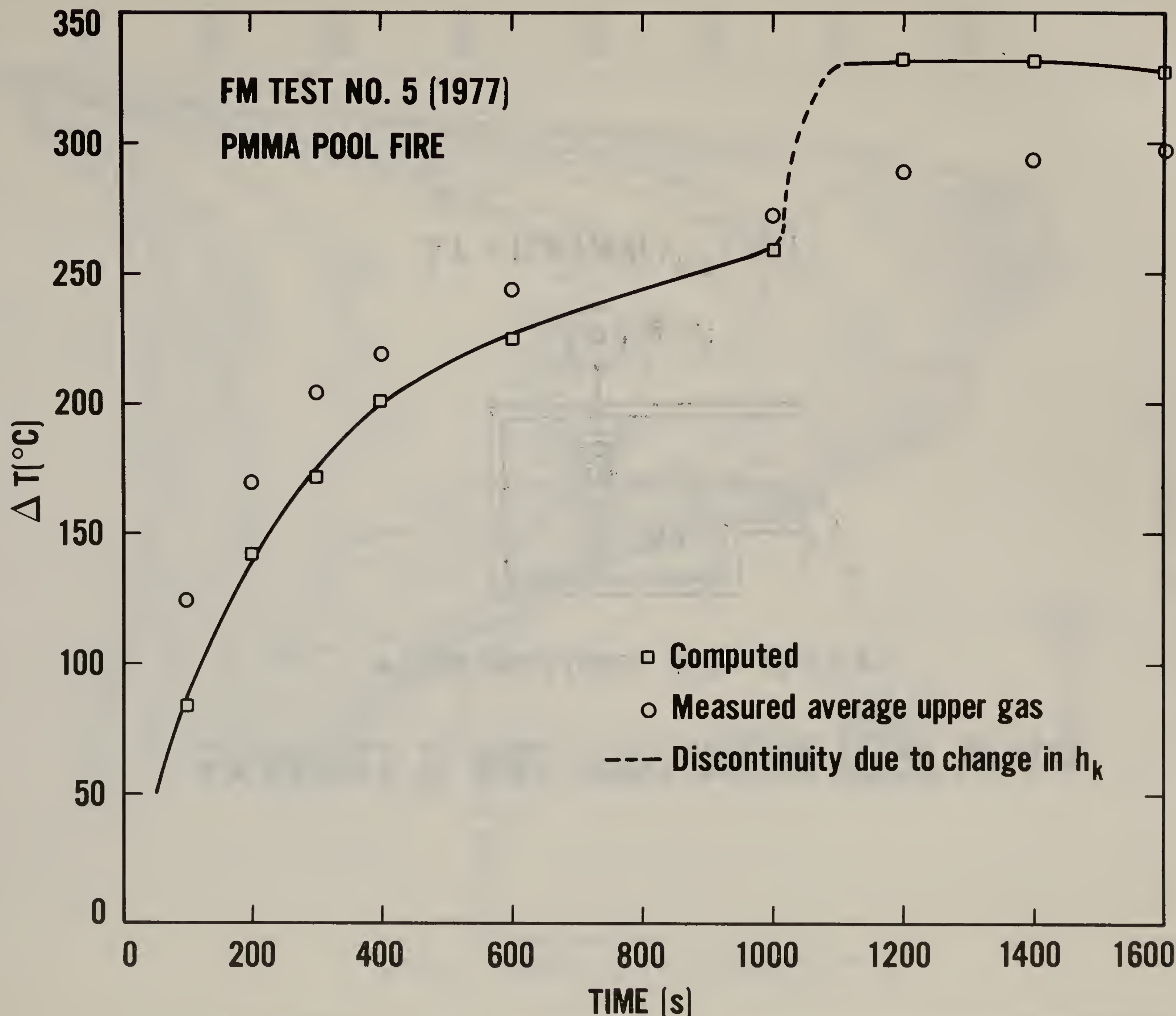
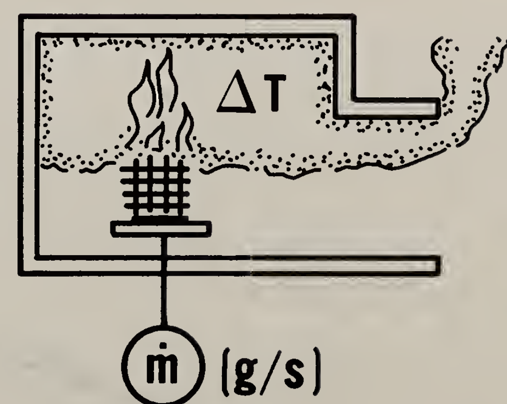


Figure 7. Example 5, fire conditions and configuration

EXAMPLE 5: NBS/PRC ROOM TEST W-4-1

- Four wood cribs, $\Delta H = 13\ kJ/g$



$$\Delta T = 11.9\,(\dot{m}\sqrt{t})^{1/3} \quad (K)$$

Figure 8. Example 5, temperature distribution - wood cribs (measured values apply to positions from ceiling to floor, 9-23; calculated values from Ref. [13] for upper and lower layers; estimated result from eq. (16)

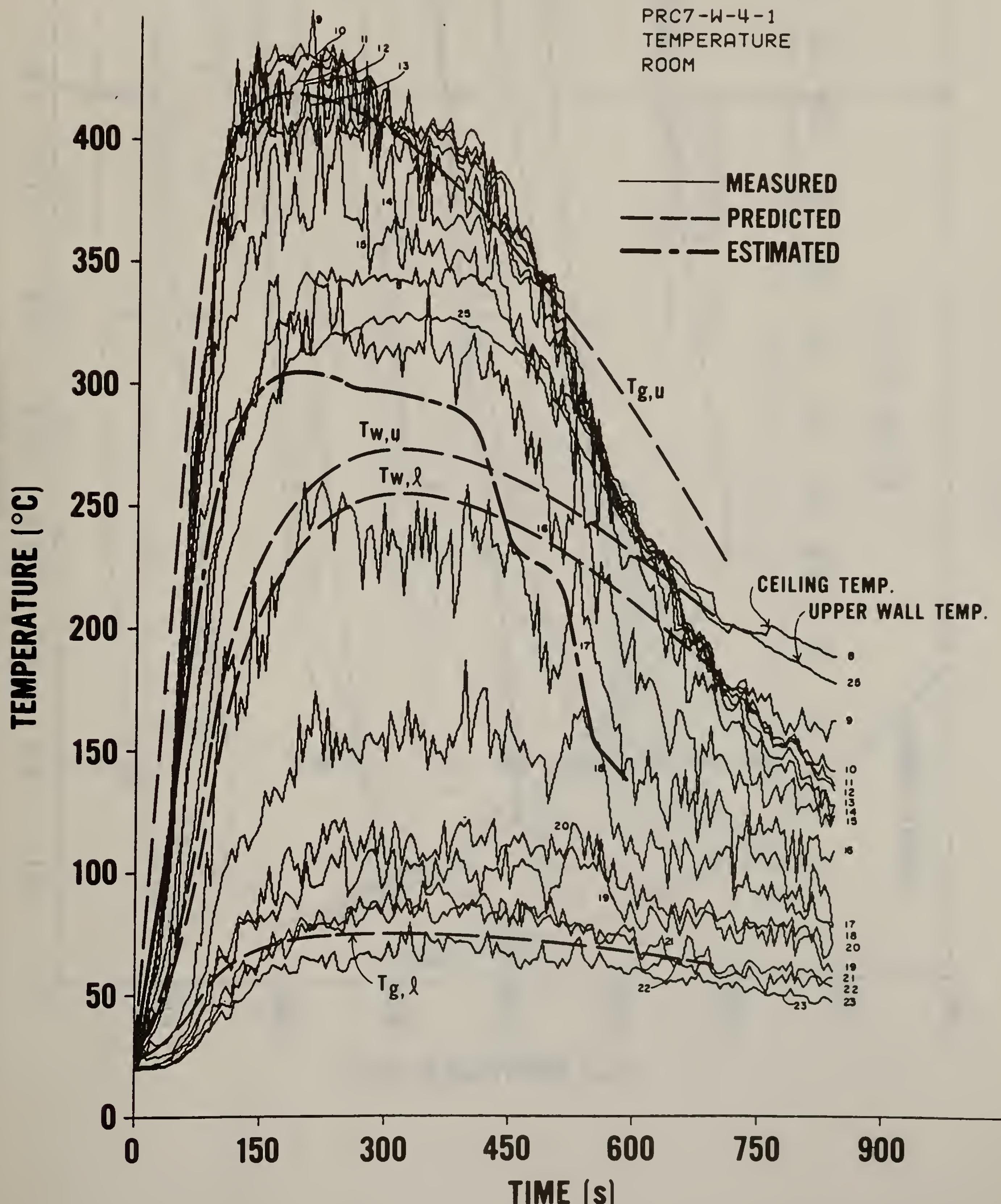


Figure 9. Example 6, peak temperatures as a function of door width - plastic crib fires
0 = 4, ⬡ = 3, Δ = 2, □ = 1 crib

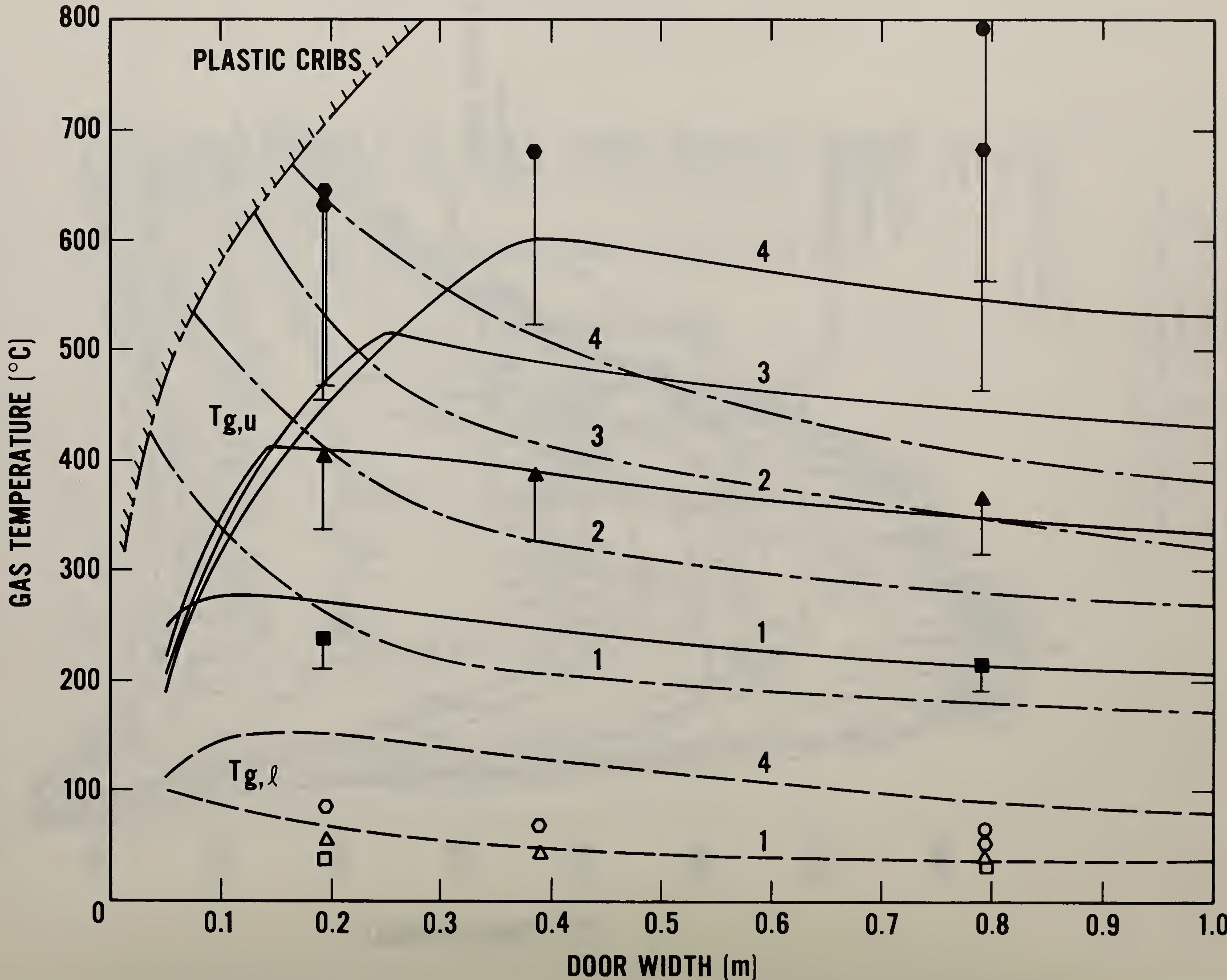


Fig. 10. Example 7, conditions for $\Delta T = 500°C$

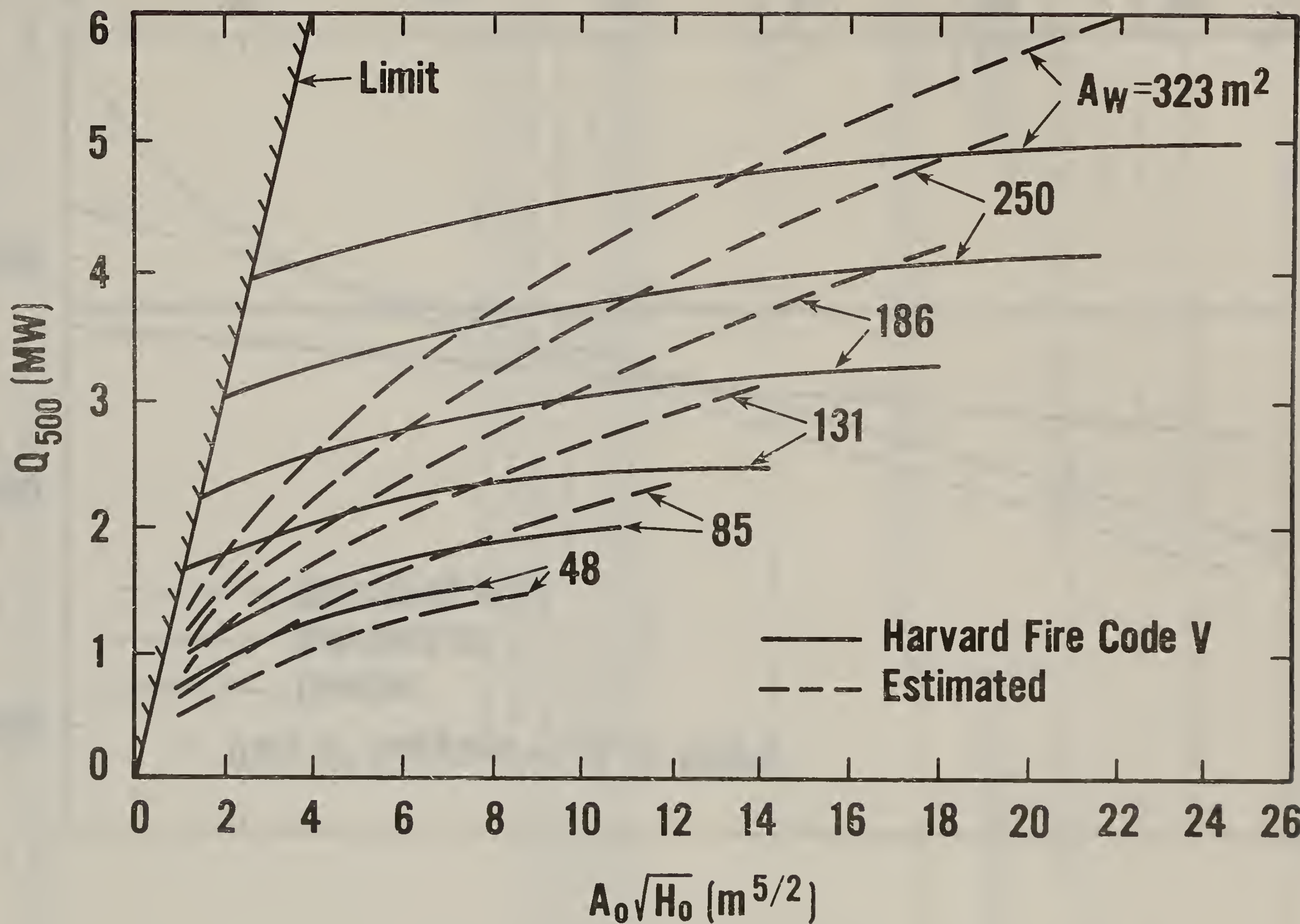
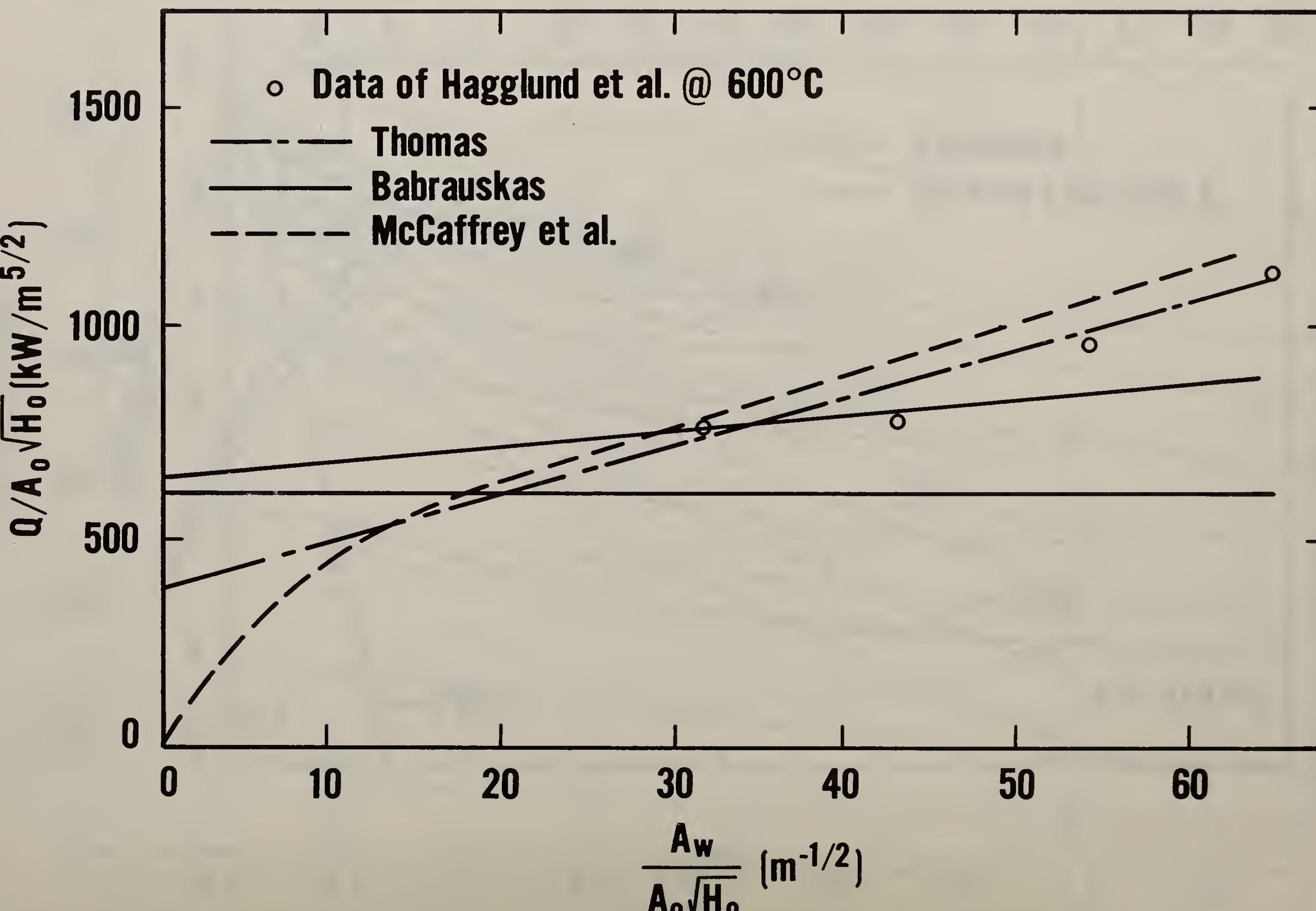


Fig. 11. Comparison of "flashover" ($\Delta T = 600°C$) predictions



NBS-114A (REV. 2-80)

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4. TITLE AND SUBTITLE

A Simple Correlation for Predicting Temperature in a Room Fire

5. AUTHOR(S)
James G. Quintiere

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9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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

The use of a simple formula for predicting upper compartment gas temperature in a fire is demonstrated. The formula is given in terms of energy release rate, vent geometry, and compartment lining material properties. It treats discrete fires within the room. Several examples are considered to show the versatility of the formula and its general level of accuracy.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Compartment fires; energy release rate; modeling; prediction temperature; vent effects; wall effects

13. AVAILABILITY	14. NO. OF PRINTED PAGES
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