

# **ANALYSIS OF LARGE-SCALE FIRE TEST DATA**

by

**Richard D. Peacock and Vytenis Babrauskas  
Building and Fire Research Laboratory  
National Institute of Standards and Technology  
Gaithersburg, MD 20899 USA**

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## Analysis of Large-scale Fire Test Data\*

Richard D. Peacock & Vytenis Babrauskas

Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, USA

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### ABSTRACT

*Large-scale room fire testing has evolved from simple fire performance measurements such as intensity and duration of 'room fires' to sophisticated measurements to understand the properties which cause the fire. This paper provides an overview of typical calculations, based upon published research results, that are used at the Center for Fire Research and elsewhere for the analysis of a large-scale room fire test. Analysis of large-scale fire test data requires the development of a series of algorithms that combine individual measurements to produce the desired physical quantity. A set of algorithms for the analysis of fire test data based upon published research results is described. Included are fire-specific calculations such as smoke and gas analysis, layer temperature and interface position, mass loss and flows, and rate of heat release. Examples of the application of the calculations are provided.*

### NOTATION

- $C$  Opening flow coefficient (-) (typical values are 0.73 for out-flow and 0.68 for inflow)  
 $C_N$  Empirically determined value (typical value is 0.2)  
 $E$  Net heat released by complete combustion per unit of oxygen consumed (kJ/kg of  $O_2$ ) (typical values are 13100 kJ/kg for organics, 17600 kJ/kg for combustion of CO to  $CO_2$ )

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$f$	Yield of species as determined from cone calorimeter measurements (kg/kg of fuel)
$g$	Gravitational constant (9.81 m/s <sup>2</sup> )
$h$	Height (m)
$I$	Beam intensity
$k$	Smoke extinction coefficient (m <sup>-1</sup> )
$L$	Measurement path length for the smoke (m)
$m$	Mass (kg)
$\dot{m}$	Mass flow rate or mass loss rate (kg/s)
$M$	Molecular weight (kg/kmol) (typical value for air is 28.95 kg/kmol)
$\dot{q}$	Rate of heat released from the fire room (kW)
$p$	Pressure (Pa) (ambient value is 101325 Pa)
$\Delta p$	Pressure difference (Pa)
$P$	Total smoke production (m <sup>3</sup> )
$R$	Universal gas constant (8314 J/kmol K)
$t$	Time (s)
$T$	Gas temperature (K)
$v$	Gas velocity (m/s)
$\dot{V}$	Volume flow rate (m <sup>3</sup> /s)
$W$	Opening width (m)
$X$	Measured concentration (mole fraction)
$\gamma$	Molar C/H ratio, as measured in the cone calorimeter (-)
$\rho$	Gas density (kg/m <sup>3</sup> )
$\sigma$	Average specific extinction area (m <sup>2</sup> /kg)

#### Subscripts

a	Air
b	Bottom
CO	Carbon monoxide
CO <sub>2</sub>	Carbon dioxide
d	Doorway
dry	Dry air
e	Exhaust duct
f	Fuel
h	Horizontal
H <sub>2</sub> O	Water
i	Inside room
l	Lower
max	Maximum
N	At neutral plane or layer interface height

o	Outside room or initial value
O <sub>2</sub>	Oxygen
s	In the exhaust stack
soot	Soot in the exhaust stack
u	Upper
v	Vertical
z	Of species z
∞	Final value

#### *Superscripts*

A	In the exhaust stack analyzer
o	Ambient

## INTRODUCTION

From the earliest days of organized fire safety research, large-scale fire testing has played an integral role in advancing the understanding of fire behavior. Over the years, the understanding of the fundamental physics and chemistry behind fire phenomena has increased dramatically. Has this level of sophistication carried over to large-scale fire testing, or is it a craft practiced by experienced artisans? This paper provides an overview of typical calculations, based upon published research results, that are used at the Center for Fire Research and elsewhere for the analysis of a large-scale room fire test. Examples of the application of the calculations are provided. In the process, an understanding of the evolution of large-scale fire testing paralleling the advancement of fire science begins to emerge.

For the present purposes, large-scale fire testing can be defined as studies of products and assemblies in sizes and configurations existing in actual end-use configurations. Within this definition, the discussion in this paper is limited to full-size, single or multiple room fire tests. Large-scale fire testing of products and assemblies has distinct advantages over the plethora of bench-scale test methods available. Often, the smaller-scale tests characterize only a few aspects of the materials' fire performance under laboratory conditions without regard to the end use within a building.<sup>1</sup> Large-scale testing of the materials in realistic scale and surroundings overcomes this limitation by affording an assessment of the overall fire behavior of the products as well as providing this evaluation in a realistic end-use setting. Even recent attempts in predicting large-scale burning behavior of materials from bench-scale test results have met with only limited success for items of furniture<sup>2</sup> and with less success for other, more generic materials.<sup>3</sup>

Testing in full size is not without disadvantages, however. Large-scale tests of room assemblies are often prohibitively expensive. A single, fully furnished room fire test can cost from \$10 000 to \$50 000. In addition, the advantage of providing an overall assessment of the fire behavior of a material can also represent a disadvantage. By quantifying the outcome of the fire without a knowledge of the factors leading to the resulting fire and without relating the observed fire behavior to basic material properties, little insight into the intrinsic performance of the materials may result.

### EARLY DEVELOPMENTS

Prior to the mid-1970s there was not much need to make experimental studies of the details of room fires. Room fire experiments were typically conducted as an adjunct to studying fire endurance.<sup>4,5</sup> For such purposes, it was necessary to track the average room temperature, since this temperature was viewed as the boundary condition determining what the wall, floor, column, etc., was exposed to. Neither the heat release rate, nor other aspects of the room fire such as gas production rates were of major interest. While as early as 1950, some investigators, in conducting full-scale house burns, did try to study the gas production rates as a means of determining how early untenable environments might exist,<sup>6</sup> there was no great incentive to pursue the topic quantitatively. That incentive, in fact, came with the development of the mathematical theories of room fires. Post-flashover room fire theories were being developed throughout the 1950s, 1960s and 1970s. The more detailed understanding necessary for the pre-flashover portion of room fires was becoming achievable by around 1975.

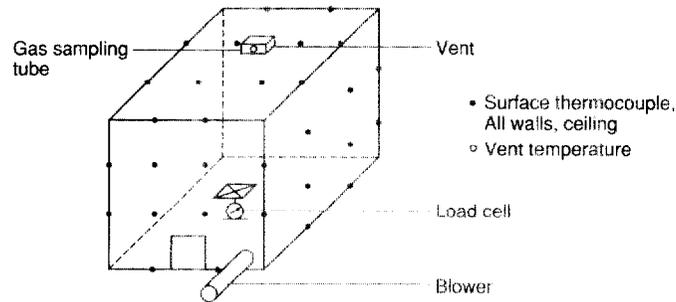
During the 1970s, however, empirical room fire tests were regularly being conducted at many fire research and testing facilities throughout the world. Instrumentation typically comprised a multiplicity of thermocouples; several probes where gas samples were extracted; smoke meters, typically located at several heights along an open burn room doorway; heat flux gages located in the walls of the burn room; and, possibly, a load platform. The load platform might register the weight of a single burning item, but was of little use when fully furnished rooms were tested. Despite the fundamental role of heat release rate in the room fire, there was no technique available to measure that. Since neither the burning item's mass loss rate nor the air and gas flow rates could, in most instances, be determined, the measurements of gas and smoke concentrations at isolated measuring stations were not of much use in tracking evolution rates.

What may be difficult to comprehend in hindsight is that during the early 1970s the concept of measuring heat release rates in room fires was not appreciated! Today the heat release rate (i.e. energy output) of a room fire is viewed as its single most important characteristic; such appreciation, however, is a very new phenomenon. Part of the reason comes from the fact that tools of adequate quality for measuring the heat release rates in room fires were not available at that time.

Even before the era of heat-release-rate focused studies could begin, there were several series of notably thorough room fire experiments; two were conducted at Factory Mutual Research Corporation, while a third one was at NBS (former name of NIST). The first series at FMRC,<sup>7-9</sup> which served as a basis for the Harvard Computer Fire Code, are a prime example. Three replicate full-scale bedroom fire tests in which the fire grew from an ignition in the middle of a polyurethane mattress to flashover were studied in enough detail to define the fire as a series of loosely coupled events. As the component parts of the fire became better understood, a model of the entire fire growth process as a series of quantitative calculations was developed.<sup>10</sup> To make these tests most useful for a scientific study of fire, several hundred measurements of temperature, radiation level, gas composition, gas velocity and weight loss were made. The mechanism of fire spread from the initial burning mattress to other room furnishings, estimates of the flow of the gases through room openings, and estimates of the energy balance of the system were all quantified. The largest distinction between these tests and earlier test series was the carefully defined purpose; to understand the underlying principles of fire growth to be able to predict the progress of a fire in a generic building. A second series of tests at FMRC<sup>11</sup> extended this work by reporting on a simpler test configuration—single slabs of polyurethane foam in the room, instead of fully furnished bedrooms. A similarly fundamental series of experiments was also conducted at NBS by Quintiere & McCaffrey,<sup>12</sup> who examined wood and polyurethane cribs burning in well-instrumented rooms.

### **The Monsanto room calorimeter**

The first attempt to develop a technique for measuring rate of heat release in room fires was in 1978, by Warren Fitzgerald, at Monsanto Chemicals.<sup>13</sup> He constructed a small room ( $2.7 \times 2.7 \times 2.7$  m) instrumented with a large number of thermocouples, located in the gas space, the walls and the exhaust duct (Fig. 1). The room had a forced air supply of  $0.19 \text{ m}^3/\text{s}$ , from a small  $0.15 \times 0.15$  m supply duct (later raised



**Fig. 1.** The Monsanto room calorimeter.

to  $0.26 \text{ m}^3/\text{s}^{14}$ ), with another duct used to let out the combustion products. The room was also equipped with a load cell and a port for extracting gas samples. Fitzgerald realized that a simple measurement of temperatures in the exhaust duct would not be sufficient to determine the heat release rate. Instead, he developed a purely statistical method—a correlation was sought between contributions from the various temperature measurements to the heat release rate. The stated capacity was 140 kW, which would not nowadays be considered to be full-scale. This system has been sporadically in use at the Southwest Research Institute, in San Antonio, Texas. The approach however, has not been pursued by any other laboratories due to its empirical nature, its limited heat handling capacity, and due to concerns about errors due to varying radiative fractions.

### **New instrumentation and techniques**

A sensible-enthalpy calorimeter, such as the Monsanto one, was not judged by the profession to be adequate for present needs. Instead, it was necessary to await the development of two things: a robust instrument for measuring the flow rates of air and gas in a soot-laden environment; and a measurement technique which did not depend on direct measurement of heat flow in inevitably loss-prone systems. The first was developed by Heskestad at FMRC in 1974.<sup>15</sup> Conventional velocity measurement devices are normally precluded from use in fire applications due to several problems. These include clogging of small orifices (an issue with pitot/static probes) and the inability to properly calibrate for high-temperature use (hot wire or disc anemometers). The new 'bi-directional velocity probe' (Fig. 2) solved these problems of measuring air flow rates in rooms, in corridors and in smoke extraction systems.

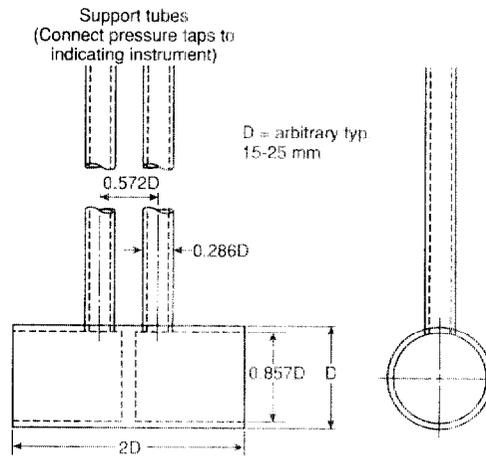


Fig. 2. Bi-directional velocity probe.

By far the most important development which was needed, however, was the principle of oxygen consumption. The principles have been covered in detail by Huggett<sup>16</sup> and Parker.<sup>17</sup> The application of this principle to room fires literally revolutionized the field. Prior to that, the focus was on point measurements. It is adequate to use measurements of temperatures and other quantities at individual locations in a room as a means of verifying a model *if* a near-ideal model is already available. Such point measurements, however, were of limited use in developing and extending the models. With the availability of oxygen consumption-based rate of heat release measurements, for the first time quantitative descriptions of fire output could be made.

### The ASTM room fire test

During the late 1970s and early 1980s a number of laboratories decided on the need for developing a standardized method for measuring heat release rates in rooms, based on oxygen consumption. Unlike the Monsanto test, the concern here was in measuring the burning rate of combustible room linings (i.e. wall, ceiling or floor coverings), and not furniture or other free-standing combustibles.

The original development was at the University of California by Fisher & Williamson.<sup>18</sup> Later, extensive development was also done at the laboratories of the Weyerhaeuser Company and at NBS.<sup>19</sup> The method, in its simplest form, consisted primarily of adding oxygen consumption measurements into the exhaust system attached to a room very similar to that originally used by Castino and coworkers at

Underwriters Laboratories,<sup>20</sup> who, however, did not measure heat release rates at all. The room was 2.4 by 3.7 m in size and 2.4 m high, with a single doorway opening in one wall, 0.76 m wide by 2.03 m high (Fig. 3). The original studies at the University of California led to ASTM issuing in 1977 a Standard Guide for Room Fire Experiments.<sup>21</sup> The Guide did not contain prescriptive details on room size, ignition source, etc., but was simply a guide to good practice in designing room fire tests of various sorts. The Guide being completed, ASTM then turned to consideration of an actual prescriptive test method. Such a test was published as a 'Proposed Method' in 1982.<sup>22</sup> The 1982 document mandated the above-mentioned room size and also a standard ignition source, which was a gas burner, placed in a rear corner of the room, giving an output of 176 kW. Since the development work at the University of California with a natural convection exhaust system uncovered problems with it, the actual test specification entailed a requirement to 'establish an initial volumetric flow rate of 0.47 m<sup>3</sup>/s through the duct if a forced ventilation system is used, and increase the volume flow rate through the duct to 2.36 m<sup>3</sup>/s when the oxygen content falls below 14%'. This specification required a complex exhaust arrangement, and it is not clear that there were many laboratories prepared to meet it. The proposed method was withdrawn by ASTM; however, variants of this method continue to be used by a number of laboratories. Very recently, an international round robin on this activity has been organized by ASTM.<sup>23</sup>

### **The ISO/NORDTEST room fire test**

Following ASTM's disengagement from the development of a standard room fire test, activity was accelerated in the Nordic countries. Development was principally pursued in Sweden, at the Statens Provningsanstalt, by Sundström.<sup>24</sup> The NORDTEST method,<sup>25,26</sup> as eventually published in 1986, uses a room of essentially the ASTM dimensions, 2.4 by 3.6 m by 2.4 m high, with an 0.8 by 2.0 m doorway opening (Fig. 4). The exhaust system flow rate capability was raised to a required value of 4.0 kg/s, with the capability to go down to 0.5 kg/s mandated to be available during the early part of the test in order to increase the resolution.

A special concern in the Nordic countries has been the effect of the igniting burner. A parallel project at the Valtion Teknillinen Tutkimuskeskus (VTT) in Espoo, Finland by Ahonen and coworkers<sup>27</sup> developed data on three burner sizes and three burner outputs. The

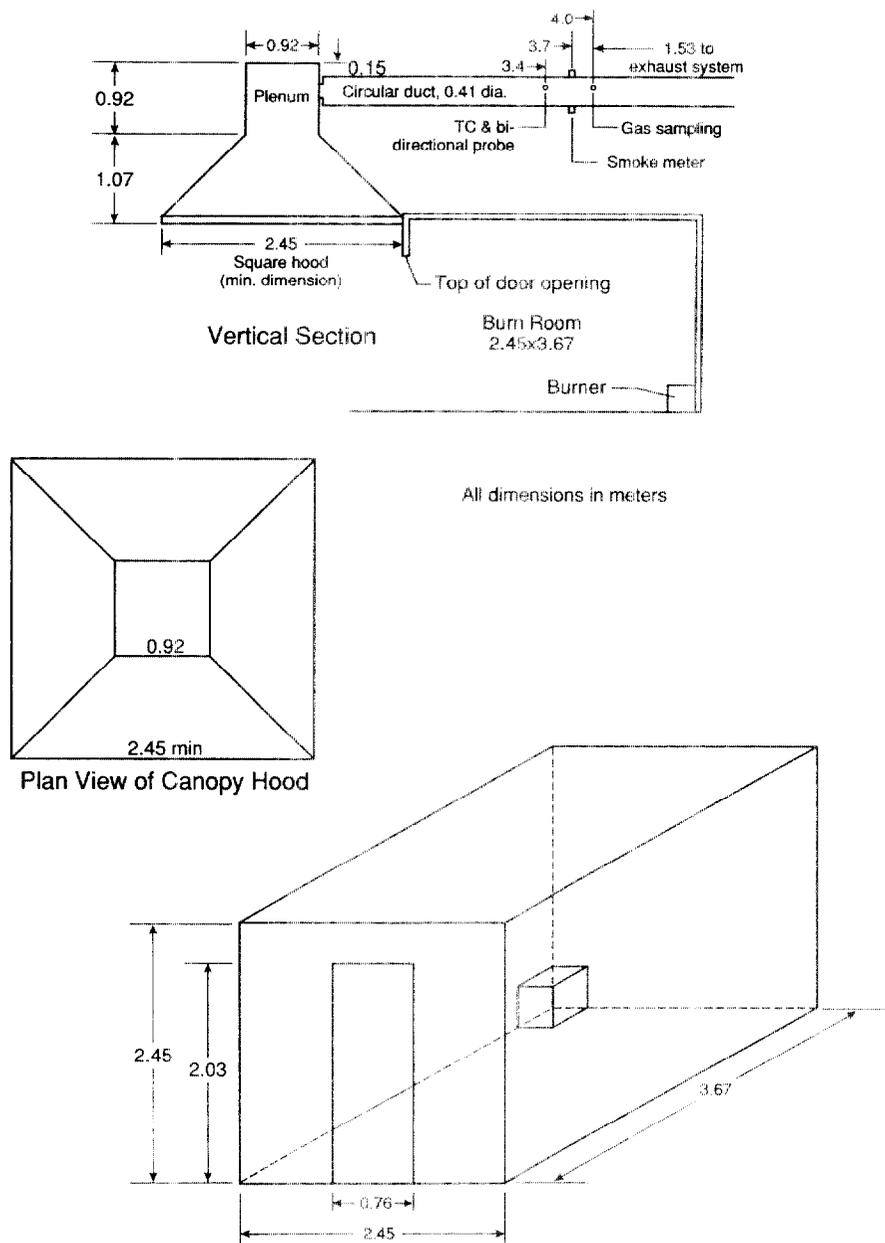
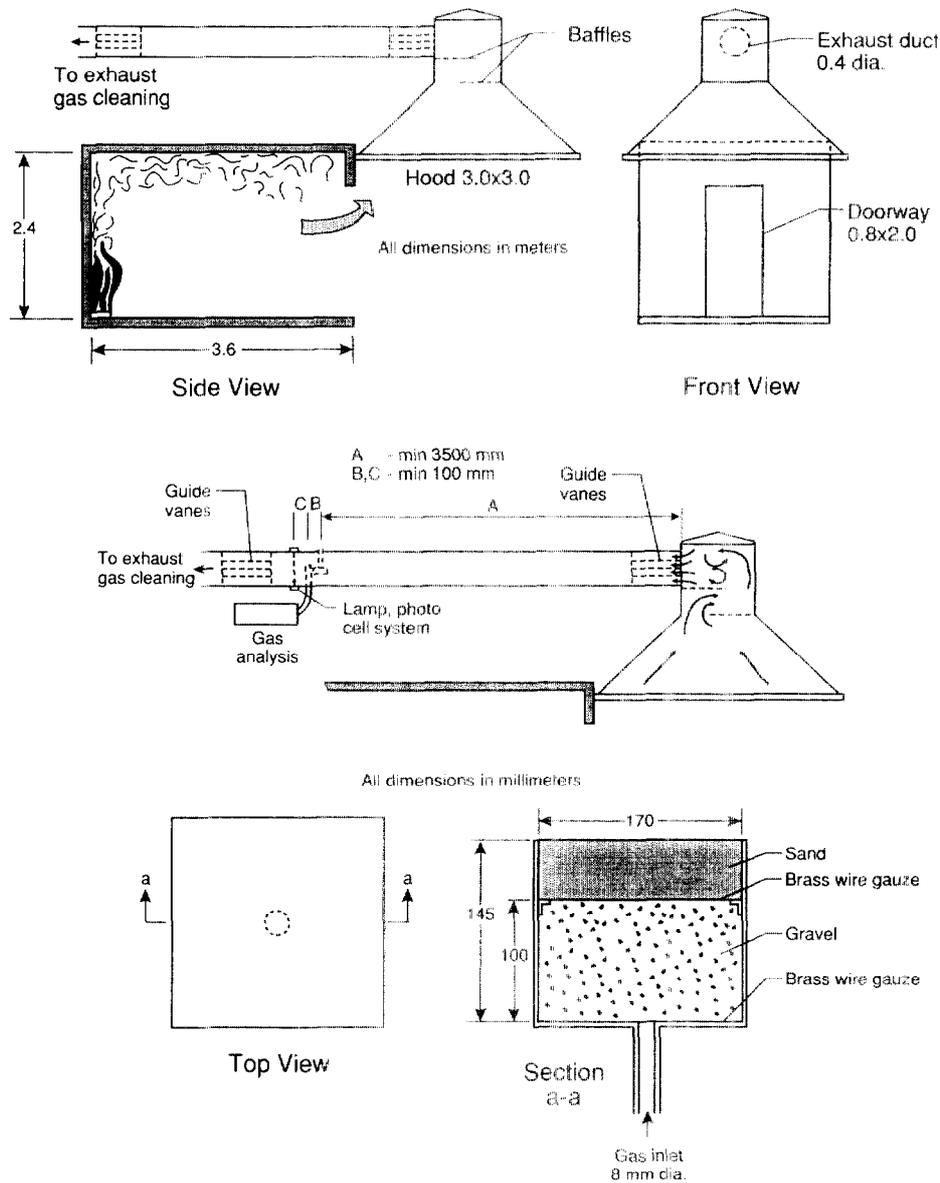


Fig. 3. The original (1982) ASTM proposed room fire test.



**Fig. 4.** The NORDTEST room fire test.

three burners had top surface sizes of 170 mm by 170 mm, 305 by 305 mm and 500 by 500 mm respectively. The fuel flow rates were 40, 160 and 300 kW respectively. The results that the VTI reported were on chipboard room linings. They found no significant differences at all between the burner sizes. The burner output did, of course, make a difference; however, the difference between 40 and 160 kW was much

larger than between 160 and 300 kW. The VTT conclusion was that either the 160 or the 300 kW level was acceptable. The NORDTEST method itself has taken an ignition source to be at the 100 kW level. If no ignition is achieved in 10 min, the heat output is then raised to 300 kW.

ISO (the International Organization for Standardization) has adopted the NORDTEST room fire test for its use and is in the process of finalizing the standard.<sup>28</sup>

### **Contemporary large-scale fire testing**

Contemporary large-scale fire testing is used for a variety of purposes and in varying complexities:

- Understanding the burning behavior of materials in realistic end-use settings;
- correlating the fire hazards of materials tested in bench-scale apparatuses to their full-scale burning behavior;
- exploring the underlying phenomena in the growth of the fire (such as flame spread, rate of heat release, smoke production, and combustion product generation); and
- verifying the predictive capabilities of fire growth and spread models.

As this level of sophistication has been obtained, the process of large-scale fire testing has evolved beyond the early 'build and burn' mentality. This is evident in the characteristics of modern large-scale fire testing:

- A sound experimental design utilizing knowledge of fire modeling and fire phenomenology can maximize the information gathered in what must be a limited number of experiments;
- quantitative results can be obtained from complex experiments in a form which allows ready comparison to results of other experiments or predictive models; and
- key physical variables can be extracted and translated into fire safety performance criteria paralleling similar measurements made in modern bench-scale tests.

## **DESIGN OF LARGE-SCALE ROOM FIRE TESTS**

The choice of data to be collected during the experimental phase depends upon the stated purpose of the study. The test design simulates as varied a set of conditions (i.e. enclosure configuration, fuel loading,

fuel type, ignition mechanism) as are suitable for the study. Due to the high cost of individual large-scale fire tests, a true parametric experimental design is rarely possible. However, fractional factorial designs<sup>29</sup> and more recently, predictive fire models have been used to reduce the number of tests to a minimum.<sup>30</sup> The ASTM Guide<sup>21</sup> should be consulted by the novice for some general advice in setting up of room fire tests. The Guide, however, is now well over a decade old and no longer represents the best or latest research findings.

The experimentalist develops the instrumentation design by starting with the purpose of the study and determining suitable algorithms for generating the necessary data output from the large-scale tests. These define the instrumentation requirements, and experience is used to define instrument placement. Typical instrumentation for a contemporary large-scale fire test is shown in Fig. 5. Instrumentation for a single test will include continuous monitoring of the following types of

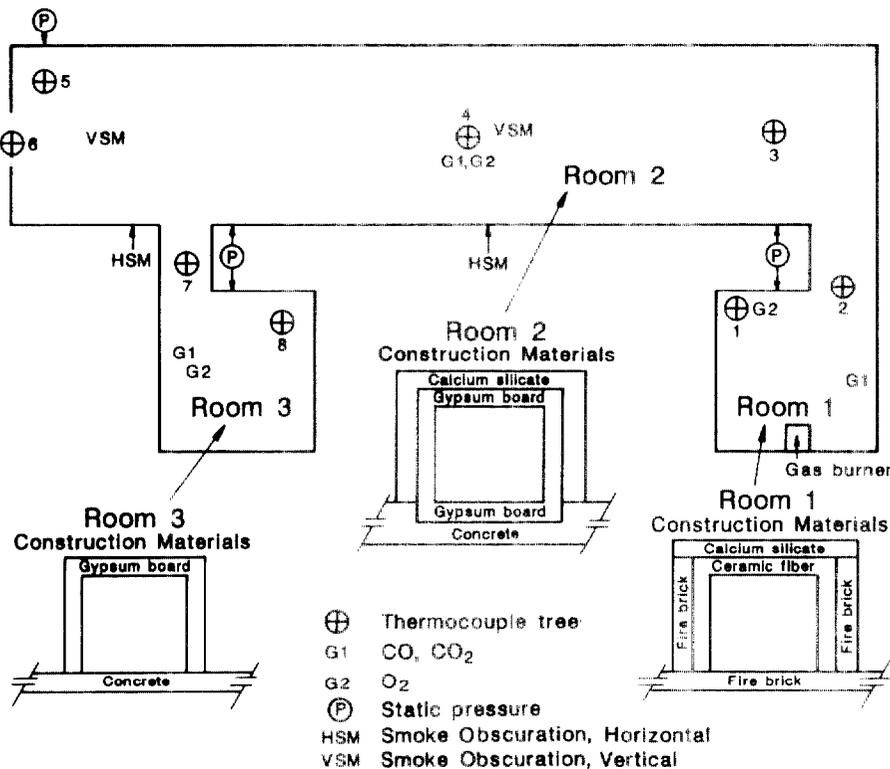


Fig. 5. Typical instrumentation for a contemporary large-scale fire test.

measurements:

- Temperature measurements (either gas or material surface), typically profiles along the vertical or horizontal axis in a room or room doorway;
- pressure measurements or profiles across a doorway or window to estimate gas flow through openings;
- light transmission measurements to estimate smoke obscuration/density within a room, again typically in vertical or horizontal profiles;
- gas concentration measurements, typically O<sub>2</sub>, CO<sub>2</sub> and CO and possibly other gases such as H<sub>2</sub>O, HCN and particulates.

The individual transducers of which there may be several hundred, have to be carefully installed, calibrated, and documented as to what they measure and where they are located. Since it is rare to find an individual raw data observation that provides a measurement of a desired property, single data elements are often combined to produce 'derived' data in engineering units. Using data collection techniques appropriate to the testing needs (e.g. scan rates, noise rejection, etc.), the individual data points are collected and typically processed by computer to provide the desired outputs.

## DATA ANALYSIS

Data analysis requires the development of a series of algorithms that combine individual data elements to produce the desired output parameter. Peacock *et al.*<sup>31</sup> have prepared a specially designed computer program for the reduction of full-scale fire test data. In addition to easing the burden of repetitive and similar calculations, the program provides a standard set of algorithms for the analysis of fire test data based upon published research results and a standard form for detailing the calculations to be performed and for examining the results of the calculations. The program combines automated instrument calibrations with more complex, fire-specific calculations such as

- smoke and gas analysis,
- layer temperature and interface position,
- mass loss and flows, and
- rate of heat release.

A description of these algorithms applicable to the analysis of large-scale fire test data is presented below.

### Smoke and gas analysis

In the recent past, optical smoke measurements in room fires have been made in several ways:

- Vertical or horizontal beams within the room,<sup>32</sup>
- vertical or horizontal beams in the doorway,<sup>33</sup>
- vertical or horizontal beams in the corridor,<sup>34</sup> and
- a diagonal, 45° beam across the doorway plume.<sup>35</sup>

The actual measurement is typically made with a collimated light source and directly opposed photometer receiver. This provides a measure of the percentage of the light output by the source that reaches the photometer, and is typically expressed in terms of an extinction coefficient,  $k$ , as follows:

$$k = \ln \left( \frac{I_0}{I} \right) \quad (1)$$

Bukowski<sup>36</sup> has published a recommendation for a widely used design of photometer using an incandescent lamp source. Newer designs<sup>37</sup> are available, however, which are based on a laser source and which are, therefore, free of certain measurement errors.<sup>38</sup>

Smoke measurements have been reported in a multitude of ways. Many reporting variables suffer from the drawback that the values are dependent as much on geometric or flow details of the apparatus, as they are on properties of the combustible being burned. Thus, it was important to arrive at a set of variables from which the apparatus influence is divided out. There are two such variables. The first is the total smoke *production* for the duration of the test,  $P$  (m<sup>2</sup>). The second is the *yield* of smoke, per kg of specimen mass lost (m<sup>2</sup>/kg). The latter has come to be called the *specific extinction area*,  $\sigma_t$ . None of the measurement geometries mentioned above, however, are at all useful in characterizing these variables. Such information **can** be obtained by providing a photometer in the exhaust collection system,<sup>39</sup> as, for instance, is done with the ISO/NORDTEST standard (Fig. 4).

The specific extinction area is the true measure of the smoke-producing tendency of a material which can be described on a per-mass basis, for instance, wall covering materials. If a fully furnished room is being tested, or some other configuration is examined where mass loss records are not available, then the smoke production serves to

characterize the results. The total smoke production is computed as

$$P = \int k \dot{V} dt \quad (2)$$

where  $\dot{V}$  is the *actual* volume flow rate at the smoke measuring location.

The average specific extinction area is then computed as

$$\sigma_t = \frac{P}{m_o - m_s} \quad (3)$$

One of primary applications of the yield is in comparing results on the same material conducted in different test apparatus or geometries. Since the effects of specimen size, flow rate, etc., have been normalized out in this expression, the variable permits actual material properties to be compared. In some cases it is also of interest to derive the instantaneous, time-varying expression for  $\sigma_t$ . Its definition is analogous the one given in eqn (3).

Gas measurements in the 1970s were typically made by installing probes for CO, CO<sub>2</sub>, or other gas analyzers in several places in the room or in the doorway. Data from such measurements had the same limitations as point measurements of temperature: only the behaviour at one point was characterized, and no measurement of total fire output was available. Once measurement systems, such as the ISO/NORDTEST room fire test have been adopted which collect all of the combustion products in an exhaust hood, it became a simple manner to instrument that exhaust system for combustion gases.

Old data for gas measurements are typically reported as ppm of a particular gas. Similarly to smoke, such measurements depend strongly on the test environment and are not very useful for describing the fuel itself. The appropriate units are very similar to those for smoke. The **production** of a particular gas is simply the total kg of that gas which flowed through the exhaust duct for the duration of the entire test. The **yield** of a particular gas (kg/kg) is the production, divided by the total specimen mass lost. As for smoke, unless there are scale effects applicable to a particular gas, the yield of a given gas might be expected to be similar for various apparatuses and experiments where the specimen was burned under similar combustion conditions.<sup>40</sup>

### Layer interface and temperature

Cooper *et al.*<sup>41</sup> have presented a method for defining the height of the interface between the relatively hot upper layer and cooler lower layer induced by a fire. Since the calculation depends upon a continuous

temperature profile, and a limited number of pointwise measurements are practical, linear interpolation is used to determine temperatures between measured points. The equivalent two-zone layer height is the height where the measured air temperature is equal to the temperature  $T_N$ , determined by examination of the measured temperature profile from  $T_b$  up to  $T_{max}$  with the relationship:

$$T_N = C_N(T_{max} - T_b) + T_b \quad (4)$$

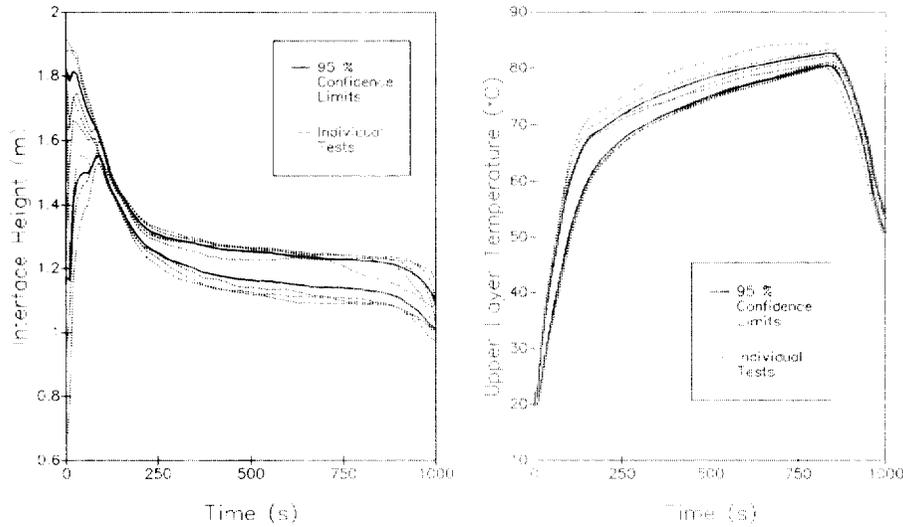
$C_N$  is determined empirically and typically ranges from 0.15 to 0.2. Once the location of the interface has been determined, it is a simple matter to determine an average temperature of the hot and cold layers within the rooms as:

$$T_u = \int_{h_N}^{h_u} \frac{T(h)}{h_u - h_N} dh \quad (5)$$

$$T_l = \int_{h_l}^{h_N} \frac{T(h)}{h_N - h_l} dh$$

With a discrete vertical profile of temperatures at a given location, the integral can be evaluated numerically. The average layer temperature (either of the lower layer or the upper layer),  $T_{avg}$ , is thus simply an average over the height of the layer from the lower bound,  $z_l$ , to the upper bound,  $z_u$  for either the upper or lower layers. Figure 6 shows the results of such a calculation of layer height and layer temperature for a set of eight replicate experiments.<sup>42</sup> Although systematic errors are apparent in the data (two distinct subsets of the data are apparent which may relate to seasonal temperature variations over the testing period) and the limitations inherent in two-zone fire models are equally applicable to these layer height and temperature calculations, the reproducibility of the calculation is good. For a series of large-scale test measurements in a multiple room facility, the uncertainty between 95% confidence limits averaged under 16%.<sup>42</sup>

While the in-room smoke measurement schemes are not useful in quantifying the smoke production or yield, they can be used to deduce the location of the interface in a buoyantly stratified compartment.<sup>43</sup> In this method, if a two-zone model is assumed (a smoke-filled upper zone and a clear lower zone), the use of a paired vertical (floor to ceiling) smoke meter and horizontal (near the ceiling) smoke meter can be used to determine the smoke layer thickness. If the smoke layer is homogeneous,  $k_v/L_v = k_h/L_h$ ; and the height of the smoke layer,  $L_v$ ,



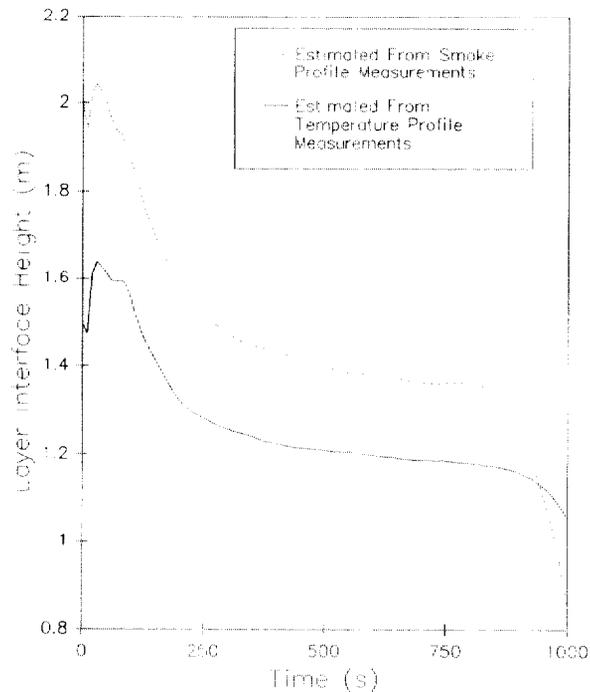
**Fig. 6.** An example of layer interface position and layer temperature calculated from temperature profiles measured during several tests along with estimated repeatability of the measurement.<sup>42</sup>

can be given as a simple ratio:

$$L_v = h_t - \left( \frac{\ln(L_v/L_t)}{\ln(L_v/L_h)} \right) L_h \quad (6)$$

where the subscripts v and h refer to the vertical and horizontal measurements, respectively.

Figure 7 presents a comparison of the smoke layer height calculated from smoke measurements and from temperature measurements for one series of tests.<sup>42</sup> Within experimental uncertainty, the two methods may be equivalent. However, small systematic differences exist. Firstly, the smoke measurement estimates are typically higher than the temperature-based calculations. This is consistent with the observations of others, notably Zukoski & Kubota,<sup>44</sup> who measured temperature profiles in detail in a scale 'room' measuring 0.58 m square with a doorway in one wall measuring 0.43 m by 0.18 m. A smoke tracer was used to allow visual observation of the smoke layer thickness along with the temperature profile measurements. They concluded that, since the lower boundary layer is not steady and induces distinct waves along the boundary, the smoke measurements produce a less steep boundary than would be measured from instantaneous profiles at a given instant of time. Since the smoke measurements presented were averaged electronically to smooth noise in the data (with a time constant of roughly 10 s), the thermocouple data can be expected to produce a sharper and



**Fig. 7.** A comparison of hot/cold layer interface position estimated from temperature profiles and from smoke obscuration in one test series (an average of nine individual tests).<sup>42</sup>

more distinct layer than the smoke measurements. Within the assumption of a uniform smoke layer, this results in a higher estimated layer interface due to the nonuniform layer near the interface. For tests where the interface height reaches the floor, the temperature-based method falters since it is based upon interpolation between adjacent measurement points. Without extensive instrumentation near the floor, a bottom limit at the level of the lowest thermocouple is evident in the temperature-based calculations. However, with the typically higher uncertainty of the smoke-based measurements, the significance of any perceived difference between the two different techniques must be questioned.

### Mass flows

Computation of mass flows through openings can be accomplished through a knowledge of the velocity profile in the opening:<sup>45,46</sup>

$$\begin{aligned} \dot{m}_u &= C \int_{h_N}^{h_1} \rho v W \, dh \\ \dot{m}_l &= C \int_{h_b}^{h_N} \rho v W \, dh \end{aligned} \quad (7)$$

The velocity profile can be determined in a number of ways. In some experiments, the bi-directional velocity probes described earlier can be used to directly measure velocity in a room doorway. This is usually done by locating 6 to 12 such probes vertically along the centerline of the doorway. Mass flow rates can be computed by eqn (7) and can give adequate results for steady-state fires, especially if the opening is much taller than it is broad.<sup>47</sup> Use of such a straightforward technique in non-steady-state fires, and especially when the opening is broader than it is tall, has been shown to give nonsensical results.<sup>48</sup> Lee<sup>47</sup> exploits this method to calculate the mass flow using the pressure drop across the doorway to calculate the velocity. Since the pressure drop across an opening passes through zero as the flow changes direction at the height of the neutral plane, measurement of the pressure profile in a doorway is particularly difficult. Estimation of the pressure in the extreme lower resolution of the instrumentation (as the pressure drop approaches zero) yields an inherently noisy measurement. As such, these measurements are used only as an alternative to the temperature method, to provide an assessment of the consistency of the data collected. With the realization of the lesser importance of these measurements, combined with dramatically higher instrumentation costs (several orders of magnitude higher than the temperature measurements), a less detailed profile of measurement points can be used for the pressure profile.

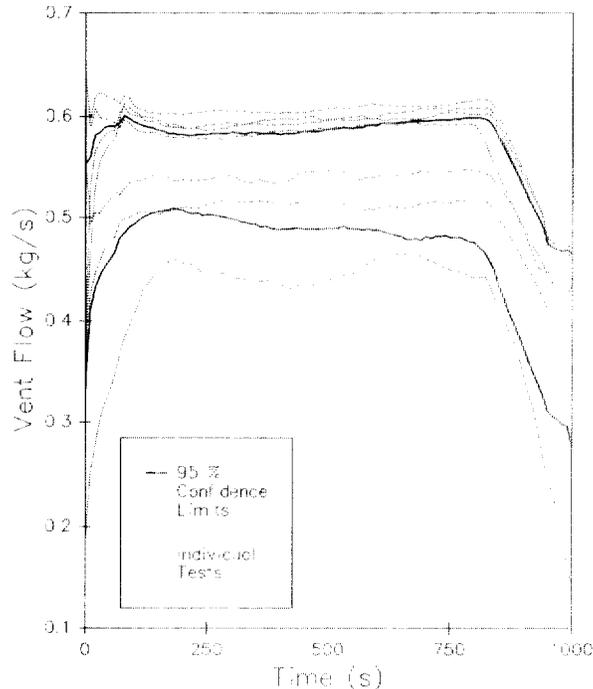
Steckler *et al.*<sup>49</sup> used an integral function of the temperature profile within the opening to calculate the mass flow. Their equations may be cast in the form that can be used directly to calculate the velocity profile for use in eqn (7):

$$v_h = \sqrt{2gT_0 \int_{h_N}^h \left( \frac{1}{T_i} - \frac{1}{T_0} \right) dh} \quad (8)$$

The temperature profile may also be used with a single pressure measurement to determine the neutral plane height,  $h_N$ , required in eqn (8). The neutral plane is obtained by solving for  $h_N$  in the equation:<sup>47</sup>

$$\Delta p_b + \frac{M_a p_a g}{R} \int_{h_0}^{h_N} \left( \frac{1}{T_0} - \frac{1}{T_i} \right) dh = 0 \quad (9)$$

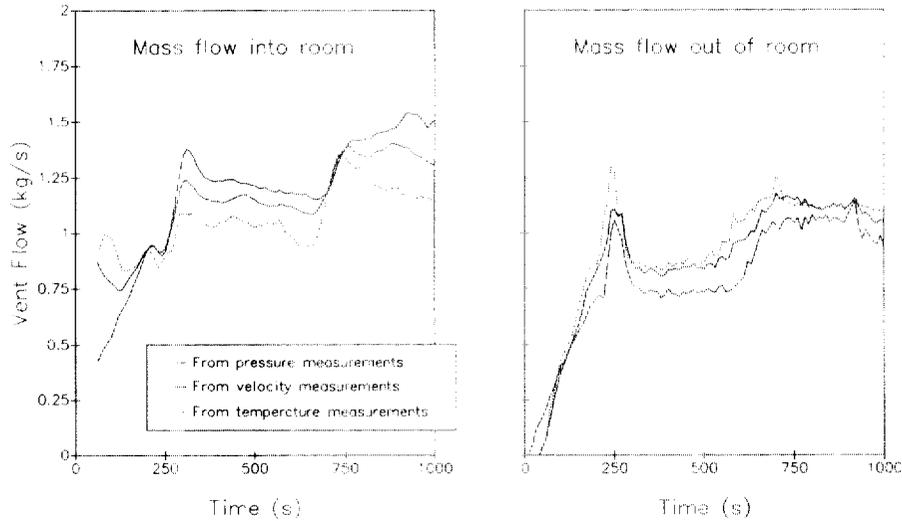
Figure 8 shows the results of such a mass flow calculation for a set of eight replicate experiments. For the same set of experiments, the reproducibility of the mass flow calculation is lower than for the layer height and temperature calculations, averaging 35%.<sup>42</sup> The reasons for this are at least two-fold. The technique used, as described by Steckler *et al.*<sup>49</sup> was developed for a single room exhausting into an infinite reservoir of ambient air. An extension of the technique for flow



**Fig. 8.** An example of mass flow calculated from temperature profiles measured during several tests along with estimated repeatability of the measurement.<sup>42</sup>

between rooms is available.<sup>50</sup> Note that the technique utilizes temperature changes from the neutral plane to the edges of the opening to calculate the flow. Because the smaller temperature change from the neutral plane is in the lower, cooler region, a small variation in temperature should cause more uncertainty in mass flow than in the upper, hotter region where the temperature gradient is larger. However, in general, the integral could be evaluated from either edge of the opening.

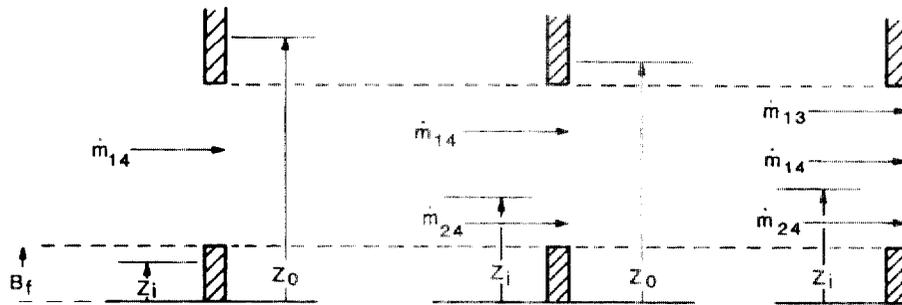
Figure 9 shows a comparison of the mass flow through a typical doorway calculated from pressure measurements, from temperature measurements, and from velocity measurements made in the doorway for a large-scale room fire test.<sup>51</sup> Comparing the mass flow calculations, it is apparent that the temperature-based calculations result in a slightly lower mass flow into a room and correspondingly higher mass flow out of a room than for the pressure-based calculations. This is consistent with the difference in calculated neutral plane height for the two methods. As previously discussed, measurement of flows using commercially available pressure transducers is difficult due to the extremely



**Fig. 9.** A comparison of calculated mass flow based upon temperature, pressure and velocity profiles measured during a large-scale fire test.<sup>51</sup>

low pressures involved. Compounding the problem for the measurement of the neutral plane height is the desire to know where the flow changes direction. Thus, the most important measurement points are those with the smallest magnitude, just on either side of the neutral plane. Since the neutral plane calculation from pressure measurements searches for the point of zero pressure from the floor up, the calculated point of zero pressure is consistently low.

The potential for multiple neutral planes within an opening further complicates the measurement of flow with pressure-based measurements. Jones & Bodart<sup>52</sup> have described an improved fluid transport model with up to three neutral planes within a single opening to incorporate in predictive models (see Fig. 10). With potentially



**Fig. 10.** Flow possibilities in a single vent connected to two rooms with different layer boundaries in the rooms.<sup>52</sup>

different layer boundaries in the two rooms connected to the opening, cross flows are possible between the layers, leading to flow reversals depending upon the relative positions of the two layer boundaries.

Since the temperature-based measurements rely on only one pressure measurement, near the bottom (or top) of the opening where the pressure gradient is highest, the temperature-based measurements have far less dependency on the low flow region of the opening.

### Rate of heat release

The large-scale measurement which has benefitted the most from the emergence of science in large-scale fire testing is the measurement of the rate of heat released by a fire. With few exceptions,<sup>53,54</sup> this is calculated by the use of the oxygen consumption principle. If all the exhaust from a room fire test is collected, measurement of temperature and velocity, oxygen, carbon dioxide, carbon monoxide and water vapor concentrations in the exhaust collection hood can be used to estimate the rate of energy production of the fire. With these measurements, the total rate of heat release from the room can be determined from:<sup>55</sup>

$$\dot{q} = \left( E\phi - (E_{CO} - E) \frac{1 - \phi X_{CO}^A}{2 X_{O_2}^A} \right) \frac{M_{O_2}}{M_a} \dot{m}_a (1 - X_{H_2O}^o) X_{O_2}^{A''} \quad (10)$$

where

$$M_e = (1 - X_{H_2O})(X_{O_2} + 4X_{CO_2} + 2.5)4 + 18 \quad (11)$$

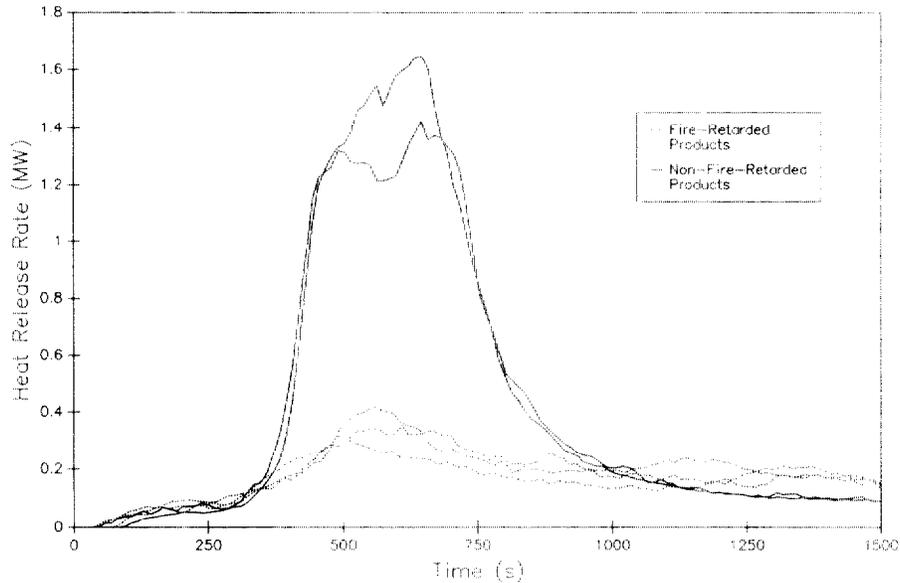
$$\dot{m}_c = C \sqrt{\frac{M_{dry} \Delta p}{M_e T_c}} \quad (12)$$

$$\frac{\dot{m}_a}{M_a} = \frac{\dot{m}_c (1 - X_{H_2O})(1 - X_{O_2}^A - X_{CO_2}^A - X_{CO}^A)}{M_e (1 - X_{H_2O}^o)(1 - X_{O_2}^{A''} - X_{CO_2}^{A''})} \quad (13)$$

$$\phi = \frac{X_{O_2}^{A''}(1 - X_{CO_2}^A - X_{CO}^A) - X_{O_2}^A(1 - X_{CO_2}^{A''})}{X_{O_2}^A(1 - X_{O_2}^A - X_{CO_2}^A - X_{CO}^A)} \quad (14)$$

Simplifications are available, with some loss of precision, if concentrations of some of the gas species are not measured.

Figure 11 shows an example of calculated heat release rate from several large scale fire tests.<sup>30</sup> Measurement errors in rate of heat release measurements can be higher than in other measurements, especially for smaller fires. In one study,<sup>42</sup> coefficients of variation ranged from 4 to 52%. With an oxygen depletion for a 100 kW fire of only 0.26%, the calculation of heat release rate suffers the same fate as



**Fig. 11.** An example of heat release rate calculated from oxygen consumption calorimetry in several large-scale fire tests.<sup>30</sup>

the calculation of mass flows with pressure probes described previously, with much of the uncertainty in the heat release calculations attributable to noise in the underlying measurements.

This technique has been used extensively in both small- and large-scale testing.<sup>26,30,48,56,57</sup> Babrauskas,<sup>48</sup> for instance, has demonstrated the validity of the measurements in a study of upholstered furniture fires. He provides comparisons between replicate tests in the open and enclosed in a room. He notes precision to within 15% for fires of 2.5 MW and consistent comparisons of heat release rate expected from mass loss measurements of those measured by oxygen consumption calorimetry.

A corollary of this calculation technique can be used to indirectly estimate specimen mass loss rate. Babrauskas *et al.*<sup>58</sup> developed a method whereby the specimen mass loss rate is calculated based on  $X_{CO_2}$ ,  $X_{CO}$  and smoke measurements in the exhaust duct. This could be determined in a straightforward manner if concentrations of CO, CO<sub>2</sub>, O<sub>2</sub>, H<sub>2</sub>O, HCl, HCN and soot are measured in the exhaust stack. Since H<sub>2</sub>O, HCl, HCN and soot are not typically measured in the real-scale exhaust stack, indirect information from the cone calorimeter must be used. In order to determine the H<sub>2</sub>O concentration in the exhaust duct, a C/H ratio is derived from the measurements of CO, CO<sub>2</sub> and H<sub>2</sub>O in the cone calorimeter. The yields of HCl and HCN are assumed to be

the same in the real-scale test as those measured in the cone calorimeter. To derive the real-scale soot yields, reliance is placed on a real-time smoke photometer. The soot yield and the smoke specific extinction area are related by a constant of 10 000–12 000 m<sup>2</sup> extinction area per kg of soot.<sup>59</sup> The specimen mass loss rate is computed on the basis of having information about the molecular composition of the fuel pyrolysates and on being able to measure flow rates of certain products of combustion:

$$\dot{m} = \frac{\frac{2\dot{V}}{22 \cdot 4} \left( \frac{T_o}{T_s} \right) \left[ \frac{(44\gamma + 9)X_{CO_2}^A + (28\gamma + 9)X_{CO}^A}{X_{CO_2}^A + X_{CO}^A + 2\gamma} \right] + \frac{k\dot{V}}{\sigma_{soot}} - \frac{\dot{q}}{13100}}{1 - f_{HCl} - f_{HCN}} \quad (15)$$

where

$$\gamma = \frac{9 \left( \frac{1}{11} f_{CO_2} + \frac{1}{7} f_{CO} \right)}{4 f_{H_2O}} \quad (16)$$

Since this technique is based upon the same oxygen depletion principle as the rate of heat release, similar precision can be expected in the measurements.

## CONCLUSIONS

Large-scale room fire testing has evolved from simple fire performance measurements such as intensity and duration of 'room fires' to sophisticated measurements to understand the properties which cause the fire. The development and verification of complex fire growth and spread models will close the loop and bring us back to assessing the results of a fire as seen in early large-scale fire tests; but this time the results of the fire are seen with a scientifically based understanding of the underlying phenomena leading to the fire development.

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