NIST Sponsored Research in Sprinkler Performance Modeling

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Introduction

Rapidly changing building designs, uses, materials, contents, fire protection and the general intermix of industrial/commercial and residential occupancies has created a need to understand the potential hazards and losses from fires and the performance of fire protection systems under conditions that may not be specifically addressed by historic fire testing and codes. In the absence of an accurate understanding of potential fire events, excessively conservative decisions are made, usually increasing costs and creating barriers to innovation. It is impractical, and in many cases too hazardous, to physically test all fire scenarios of interest.

In cooperation with industry, a numerical fire model, Fire Dynamics Simulator, is being developed at NIST to evaluate the performance of fire protection systems in buildings. The model has been used to generate predictions of fires in industrial facilities protected entirely or in part by automatic fire sprinklers. The heart of the model is a Large Eddy Simulation (LES) based fire model with the capability of simulating large scale industrial fires. Because the model provides far more detailed simulations than zone models can, it requires more detailed information about the fuels, building materials and fire protection systems. The Building and Fire Research Laboratory at NIST has supported efforts, both internally and through its grants program, to develop measurement techniques to generate this information. These measurements include droplet size distributions, spray patterns, droplet trajectories, and heat transfer coefficients. The results of these studies will be used as input to the model so that realistic sprinklers systems can be evaluated.

Fire Dynamics Simulator

To date, three distinct approaches to the simulation of fires have emerged. The first to reach maturity, the "zone" models, describe compartment fires. Each compartment is divided into two spatially homogeneous volumes, a hot upper layer and a cool lower layer. Mass and energy balances are enforced for each layer, with additional models describing other physical processes appended as differential or algebraic equations as appropriate. An excellent description of the physical and mathematical assumptions behind the zone modeling concept is given by Quintiere [1], who chronicles developments through 1983. Model development since then has progressed to the point where documented and supported software implementing these models are widely available [2].

The relative physical and computational simplicity of the zone models has led to their widespread use in the analysis of fire scenarios. So long as detailed spatial distributions of physical properties are not required, and the two layer description reasonably approximates reality, these models are quite reliable. However, by their very nature, there is no way to systematically improve them. The rapid growth of computing power and the corresponding maturing of computational fluid dynamics (CFD), has led to the development of CFD based "field" models applied to fire research problems.

Virtually all this work is based on the conceptual framework provided by the Reynolds-averaged form of the governing equations, in particular the $k-\epsilon$ turbulence model pioneered by Patankar and Spalding [3]. The use of CFD models has allowed the description of fires in complex geometries, and the incorporation of a wide variety of physical phenomena. However, these models have a fundamental limitation for fire applications – the averaging procedure at the root of the model equations. The $k-\epsilon$ model was developed as a time-averaged approximation to the conservation equations of fluid dynamics. While the precise nature of the averaging time is not specified, it is clearly long enough to require the introduction of large eddy transport coefficients to describe the unresolved fluxes of mass, momentum and energy. This is the root cause of the smoothed appearance of the results of even the most highly resolved fire simulations.

Unfortunately, the evolution of large eddy structures characteristic of most fire plumes is lost with such an approach, as is the prediction of local transient events. This is especially true for simulations involving the activation of sprinklers. The activation of an industrial sprinkler instantaneously transforms the fire-driven flow field by driving the hot gases of ceiling jet downwards. Flow solvers that average the governing equations over several seconds cannot capture this rapid transformation of the flow field. The application of "Large Eddy Simulation" (LES) techniques to fire is aimed at extracting greater temporal and spatial fidelity from simulations of fire performed on the more finely meshed grids allowed by ever faster computers. The basic idea behind the LES technique is that the eddies that account for most of the mixing are large enough to be calculated with reasonable accuracy from the equations of fluid dynamics. Present day desktop computers limit the number of such cells to at most a few million. This means that the ratio of largest to smallest eddy length scales that can be resolved by the computation (the "dynamic range" of the simulation) is roughly 100. In other words, a fire in a space of characteristic length 10 m can be simulated at a resolution of about 10 cm.

The Building and Fire Research Laboratory at NIST has recently released version 1.0 of the Fire Dynamics Simulator (FDS). Previous versions of the model were referred to as LES, LES3D and most recently IFS (Industrial Fire Simulator). The name Fire Dynamics Simulator was chosen because model development is heading in a number of different directions; some of which are not necessarily "industrial" in nature. More information about the model and its applications can be found on the website http://fire.nist.gov.

Sprinklers

Accurate prediction of the activation and spray characteristics of automatic sprinklers is crucial in predicting the growth or suppression of fires. There are presently standard tests to determine some of the necessary parameters needed by the numerical model to predict sprinkler activation, but as yet no standard test methods for obtaining a given sprinkler's droplet size distribution and initial spray characteristics. Following is a brief description of some of the areas of active interest.

Activation

In the FDS model, the temperature of the sensing element of a given sprinkler is estimated from the differential equation put forth by Heskestad and Bill [4], with the addition of a term to account for evaporative cooling by water droplets in the gas stream from previously activated sprinklers

$$\frac{dT_l}{dt} = \frac{\sqrt{|\mathbf{u}|}}{\mathrm{RTI}}(T_g - T_l) - \frac{C}{\mathrm{RTI}}(T_l - T_m) - \frac{C_2}{\mathrm{RTI}}\beta|\mathbf{u}| \qquad (1)$$

Here T_l is the link temperature, T_g is the gas temperature in the neighborhood of the link, T_m is the temperature of the sprinkler mount, β is the volume fraction of (liquid) water in the **gas** stream, and $|\mathbf{u}|$ is the velocity of the air streaming by the sprinkler. The sensitivity of the link is indicated by the RTI (Response Time Index) and the amount of heat conducted away from the link by the mount is indicated by the "C-Factor", C.

The third term on the right hand side has been put forth based on the experimental work of DiMarzo and his collaborators at the University of Maryland [5]. The product $\beta\,|\mathbf{u}|$ is the flux of water impinging on the thermally active link. The constant C_2 has been empirically determined to be 6×10^6 K/(m/s)$^{\frac{1}{2}}$, and its value is relatively constant for different types of sprinklers. This is an important result because it allows the same expression to be used for any sprinkler. The inclusion of the third term in **Eq.** 1 is important in considering how small droplets introduced into the ceiling jet by activated sprinklers can delay or inhibit second or third row sprinklers from activating.

Droplet Size

Because the cooling efficiency of a misting sprinkler is very sensitive to small droplets of water that may be carried aloft by the fire plume, it is vital for accurate prediction of this phenomenon that the droplet size distribution from a given sprinkler be characterized. There are several techniques used to measure water droplets from sprinklers. Researchers at NIST and Factory Mutual have used an optical array probe (OAP) to measure the droplet size distribution for a variety of sprinklers [6, 7]. The instrument consists of an elliptical ribbon of helium-neon laser light that illuminates a photodiode detector array. Droplets pass between the laser and detectors, and a maximum horizontal drop width (diameter) is determined for each droplet from its shadowing pattern on the photodiodes. The shadows are formed by droplet diffraction, refraction, and absorption. The droplet diameter determined by the OAP is equal to the sum of the widths of the blocked diodes; a diode is considered blocked if its incident laser light intensity is reduced by a given fraction.

Underwriters Laboratories has purchased a Phase Doppler Particle Analyzer (PDPA). This method is based upon the principles of light scattering interferometry. Measurements are made at a small, non-intrusive optical probe defined by the intersection of two laser beams. **As** a droplet passes through the probe volume, it scatters light from the beams and creates an interference fringe pattern. A receiving lens located at an off-axis collection angle projects a portion of this fringe pattern onto several detectors. Each detector produces a Doppler burst signal with a frequency proportional to the droplet velocity. The phase shift between the Doppler burst signals from the different detectors is proportional to the size of the spherical droplets.

NIST possesses both types of instruments and is presently evaluating both techniques. The goal of the research is to better quantify the uncertainty inherent in both types of measurements. The performance of the instruments may depend on the size distribution of the droplets. To date, there have been some attempts to measure the droplets from industrial scale sprinklers with both devices [7, 8], but not enough to fully understand the uncertainty. An obvious first step is to measure the droplets from the same sprinkler with the two devices, and that work is being done at NIST this year.

Spray Dynamics

Once a sprinkler has activated, a sampled set of water droplets are tracked by the numerical model. Even when the size distribution of the droplets has been determined, there still remains the task of prescribing the initial speed and direction, *i.e.* the velocity, of the droplets. **A** very promising technique for measuring these initial conditions is being explored by David Sheppard of Underwriters Laboratories who is pursuing a doctorate in mechanical engineering at Northwestern University under the direction of Prof. Richard Lueptow with support from the Building and Fire Research Laboratory at NIST. In what is referred to as Particle Image Velocimetry (PIV), a sheet of high-intensity laser light illuminates a vertical cross section of the sprinkler spray. **A** camera aligned perpendicular to the sheet images droplets within the illuminated field in quick succession, the result being two images with the droplets a short distance apart so that their velocity is known because the time between photographs is known. Figure 1 shows one such photograph, plus the velocity vectors inferred from like pairs.

To confirm the accuracy of the PIV measurements, Sheppard calculated the resulting water flux at the floor by computing the trajectories of the water droplets in accordance with the initial conditions measured. The agreement with actual pan data is excellent. More on these measurements is included in these proceedings [9].

Fire Suppression by Water

The above discussion describes efforts to predict where the water from sprinklers will go, but there remains the problem of predicting how that water will effect the heat release rate of the fire. When the water droplets encounter burning surfaces, simple heat transfer correlations are difficult to apply. The reason for this is that the water is not only cooling the surface and the surrounding gas, but it is also changing the pyrolysis rate of the fuel. If the surface of the fuel is planar, it is possible to characterize the decrease in the pyrolysis rate as a function of the decrease in the total heat feedback to the surface. Unfortunately, most fuels of interest in fire applications are multi-component solids with complex geometry at scales unresolvable by the computational grid.

To date, most of the work in this area has been performed at Factory Mutual. An important paper on the subject is by Yu *et al.* [10]. The authors consider dozens of rack storage commodity fires of different geometries and water application rates, and characterize the suppression rates in terms of a few global parameters. Their analysis yields an expression for the total heat release rate from a rack storage fire after sprinkler activation

$$\dot{Q} = \dot{Q}_0 \, e^{-k(t-t_0)} \tag{2}$$

where $\dot{Q}_0$ is the total heat release rate at the time of application t_0, and k is a fuel-dependent function of the water application rate. For example, the value of k for the FMRC Standard Plastic commodity is given as

$$k = 0.716\, \dot{m}_w'' - 0.0131 \quad \mathrm{s}^{-1} \tag{3}$$

where $\dot{m}_w''$ is the flow rate of water impinging on the box tops, divided by the area of exposed surface (top and sides). It is expressed in units of kg/m^2/s.

Unfortunately, this analysis is based on global water flow and burning rates. Equation (2) accounts for both the cooling of non-burning surfaces as well as the decrease in heat release rate of burning surfaces. In the FDS model, the cooling of unburned surfaces and the reduction in the heat release rate are computed locally, thus it is awkward to apply a global suppression rule. However,

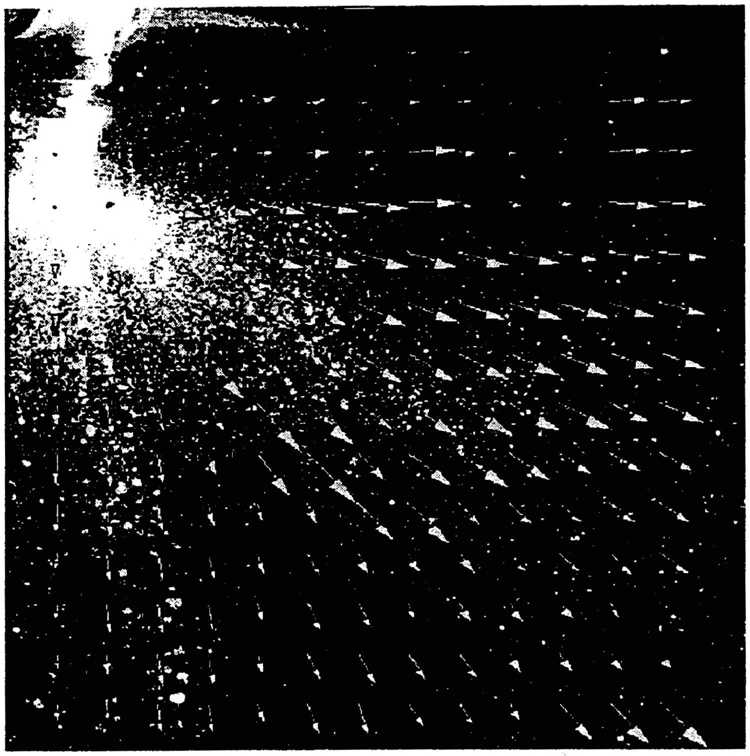

FIGURE 1: PIV image of a pendant sprinkler, showing the velocity vectors of the droplets. Reprinted courtesy of David Sheppard, Underwriters Laboratories and Richard Lueptow, Northwestern University.

the exponential nature of suppression by water is observed both locally and globally, thus it is assumed that the local heat release rate of the fuel can be expressed in the form [11]

$$\dot{q}''_f(t) = \dot{q}''_{f,0}(t) \left(e^{-\int k_1 \, dt} + k_2 (t - t_0) \right) \tag{4}$$

Here $\dot{q}''_{f,0}(t)$ is the heat release rate per unit area of the fuel when no water is appliedand k_1 and k_2 are functions of the local water mass per unit area, m''_w, expressed in units of kg/m^2.

$$\begin{aligned} k_1 &= a_1 \, m''_w \quad \mathrm{s}^{-1} && (5) \\ k_2 &= a_2 \, m''_w + b_2 \quad \mathrm{s}^{-1} && (6) \end{aligned}$$

The linear term in **Eq.** (4) is based on the observation that for a boxed commodity, it is possible for the local heat release rate to increase as the fire burns into the box and is protected from the water droplets by material overhead, thus often a gradual increase in the heat release rate is observed following the initial decrease after water is applied.

To develop the suppression model for the FMRC Standard Plastic commodity, 19 experiments were conducted at UL under a 2 MW calorimeter [11]. These experiments were designed as small-scale RDD (Required Delivered Density) tests. The fuel/sprinkler arrangement consisted of four boxes of the FMRC Plastic Commodity. The boxes were stacked two high. The two stacks were positioned 15 cm (6 in) apart, the same separation that is commonly used in full-scale tests. **A** water applicator was positioned above the boxes to deliver a uniform water flux onto the tops of the boxes. The applicator consisted of four nozzles that were 60 cm **(2** ft) apart and 30 cm (1 ft) above the plane of the box tops. Several nozzle sizes were used, depending on the desired water flow. Table 1 lists the average water application rate per unit area and the time of water application. The time of water application was varied from 30 s to 200 s. The water **flux** at the box top was varied from 0.03 kg/m^2/s (0.05 gpm/ft^2) to 0.66 kg/m^2/s (0.97 gpm/ft^2). The ignition source was a propane igniter that consisted of two parallel 12.5 mm diameter copper tubes each 30 cm long.

The heat release rate histories for the experiments and the simulations are given in Figs. 2–4. The decay, and in some cases re-growth, of the fire is captured reasonably well by the simulations. **A** weakness of the suppression algorithm, however, is its reliance on 5 empirical coefficients that are not easily measured. It is hoped that further work in this area will provide more insight into fire suppression, and the numerical algorithm will reflect this improved understanding.

Test No.	Application Time (s)	Total Water Flow		Average Water **Flux**	
		(L/s)	(gpm)	($L/m^2/s$)	(gpm/ft^2)
1	380	0.98	15.5	0.66	0.97
2	470	0.57	9.0	0.38	0.56
3	65	0.41	6.5	0.28	0.41
4	106	0.41	6.5	0.28	0.41
5	115	0.11	1.8	0.074	0.11
6	122	0.11	1.8	0.074	0.11
7	150	0.079	1.3	0.053	0.08
8	93	0.11	1.8	0.074	0.11
9	93	0.21	3.3	0.14	0.20
10	110	0.21	3.3	0.14	0.20
11	205	0.21	3.3	0.14	0.20
12	116	0.16	2.5	0.11	0.16
13	63	0.16	2.5	0.11	0.16
14	64	0.28	4.5	0.19	0.28
15	71	0.079	1.3	0.053	0.08
16	62	0.047	0.9	0.032	0.05
17	104	0.047	0.9	0.032	0.05
18	58	0.079	1.3	0.053	0.08
19	30	0.079	1.3	0.053	0.08

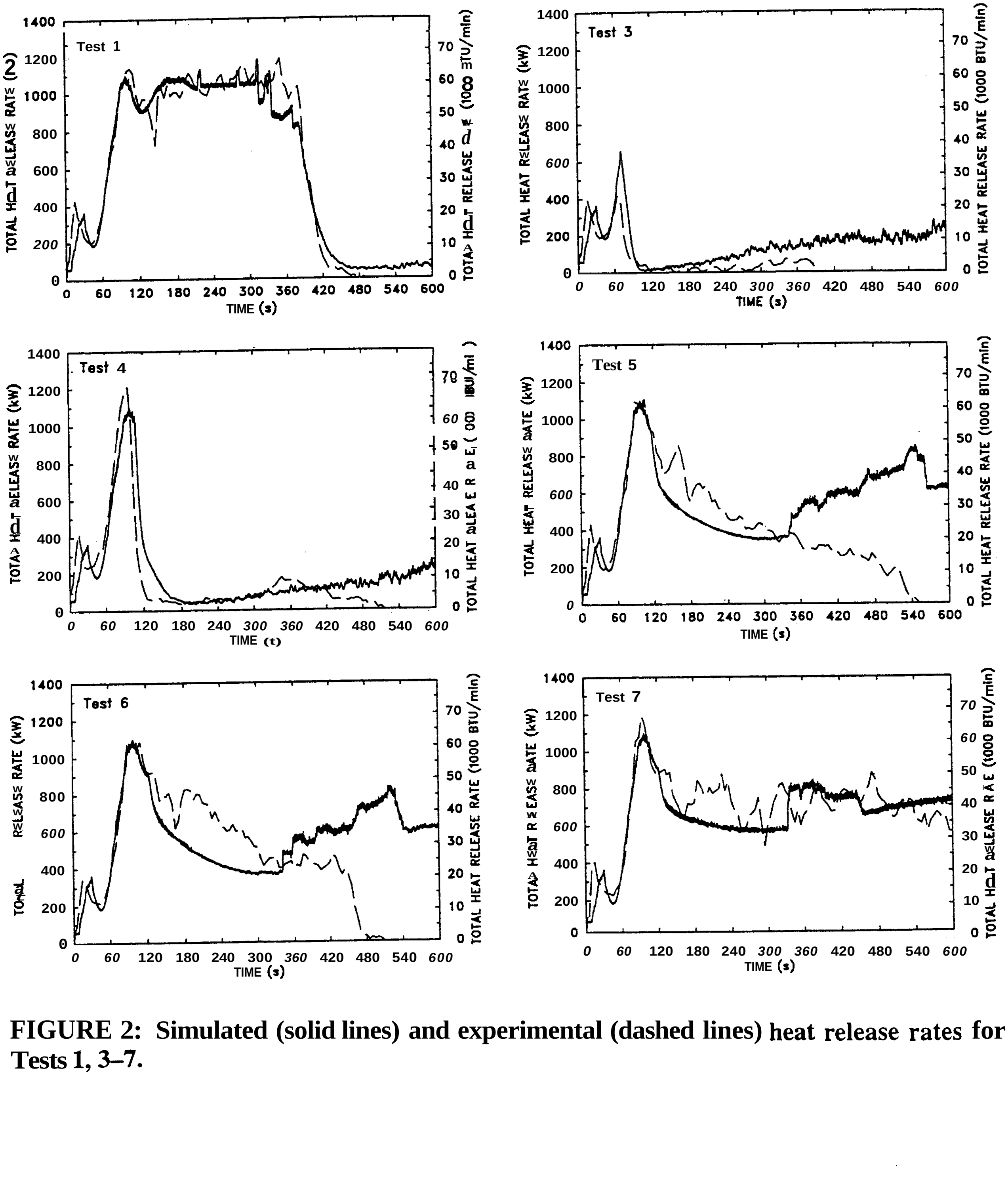

FIGURE 2: Simulated (solid lines) and experimental (dashed lines) heat release rates for Tests 1, 3–7.

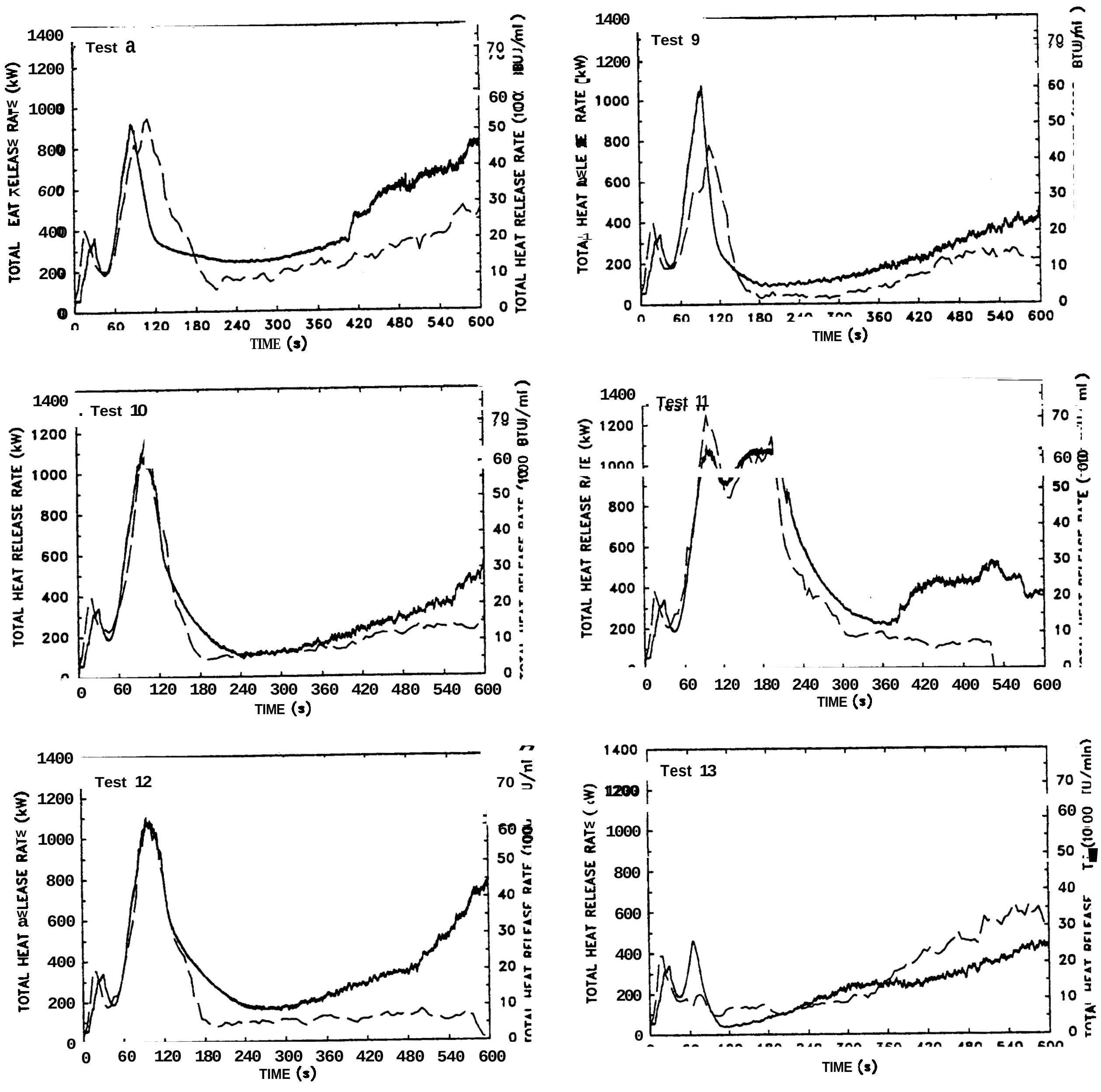

FIGURE 3: Simulated (solid lines) and experimental (dashed lines) heat release rates for Tests 8–13.

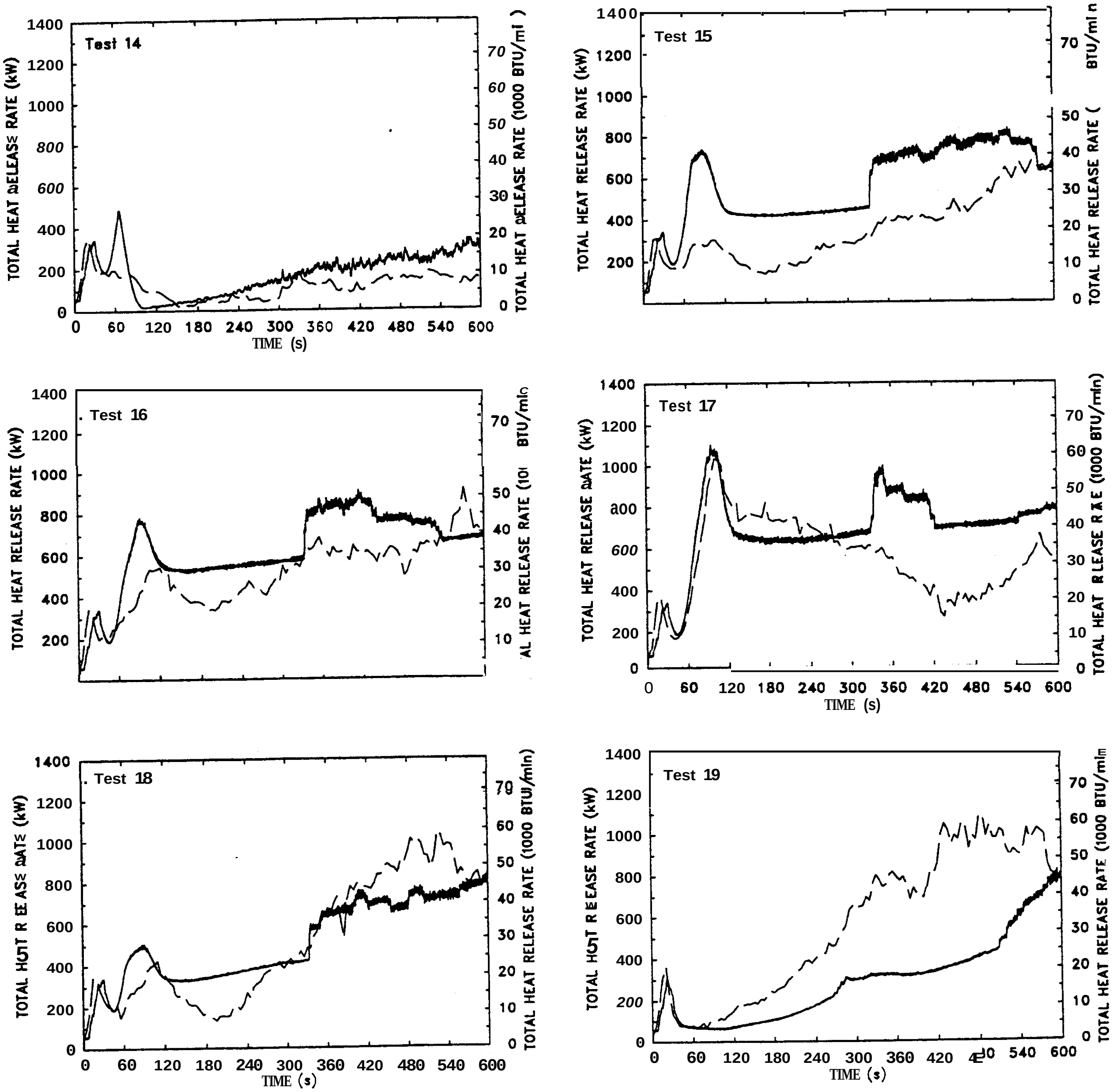

FIGURE 4: Simulated (solid lines) and experimental (dashed lines) heat release rates for Tests 14–19.

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