Modeling of Sprinkler, Vent and Draft Curtain Interaction

K.B. McGrattan, A. Hamins and G.P. Forney
National Institute of Standards and Technology
Gaithersburg, Maryland, USA

ABSTRACT

The International Fire Sprinkler, Smoke & Heat Vent, Draft Curtain Fire Test Project organized by the National Fire Protection Research Foundation (NFPRF) brought together a group of industrial sponsors to support and plan a series of large scale tests to study the interaction of sprinklers, roof vents and draft curtains of the type found in large warehouses, manufacturing facilities, and warehouse-like retail stores. In conjunction with the large scale tests, NIST developed a numerical model based on large eddy simulation techniques, the Industrial Fire Simulator (IFS), that could be used to plan, analyze and supplement the test results. A series of bench scale experiments was conducted to develop necessary input data for the model. These experiments generated data describing the burning rate and flame spread behavior of the cartoned plastic commodity, thermal response parameters and spray pattern of the sprinkler, and the effect of the water spray on the burning commodity.

KEY WORDS: Draft Curtains, Numerical Modeling, Sprinklers, Vents

INTRODUCTION

A group of industrial sponsors was brought together by the National Fire Protection Research Foundation (NFPRF) to support and plan a series of large scale experiments using both a heptane spray burner and cartoned polystyrene cups (Group A plastic) as fire sources. The objective of the project was to investigate the effect of roof vents and draft curtains on the time, number, and location of sprinkler activations; and also the effect of sprinklers and draft curtains on the activation time, number, and discharge rates of roof vents. Thirty-nine tests were conducted in the Large Scale Fire Test Facility at Underwriters Laboratories (UL) in Northbrook, Illinois. The experiments were divided into three series: an initial set of 22 heptane spray burner tests (Heptane Series I) [1], 12 additional heptane spray burner tests (Heptane Series II) [2], and 5 cartoned plastic commodity tests (Plastic Series) [2].

In parallel with the large scale fire tests, a program was conducted at NIST to develop a numerical field model, the Industrial Fire Simulator (IFS), that incorporated the physical phenomena of the experiments [3]. A series of bench scale experiments was conducted to develop necessary input data for the model. These experiments generated data describing the burning rate and flame spread behavior of the cartoned plastic commodity, thermal response parameters and spray pattern of the sprinkler, and the effect of the water spray on the burning commodity. Simulations were first performed for the heptane spray burner tests, where they were shown to be in good *quantitative* agreement in terms of both predicting sprinkler activation times and near-ceiling gas temperature rise. Next, simulations were performed and compared with unsprinklered calorimetry burns of the cartoned plastic commodity. Simulations of the 5 cartoned plastic commodity fire tests were then performed. The goal of these simulations was to be able to differentiate between those experiments that activated a large number of sprinklers, and those that activated a small number.

NUMERICAL MODEL

The numerical model developed for this project is based on large eddy simulation (LES) techniques. The idea behind this approach is to divide the test space into as many control volumes as possible (in this case, hundreds of thousands to over a million) to resolve as much of the convective motion of the gases (air, smoke) as possible. In this way, much of the mixing of the hot gases from the fire with the cool surrounding air can be captured directly, reducing the dependence on empirical entrainment or turbulence parameters that are often subject to much debate and uncertainty. The heart of the numerical model is an algorithm that solves the set of partial differential equations describing the transport of smoke and hot gases from the fire and its subsequent mixing with the surrounding air. This is often referred to as the hydrodynamic model, and it is described in Ref. [4]. The fire and the sprinkler spray are represented by source terms in the governing equations. These are the focus of the present discussion.

The Fire

The fire is represented by a large number of Lagrangian, or thermal, elements that release heat as they are transported by the thermally-induced motion. Since the fluid motion determines where the heat is actually released, and the heat release determines the motion, the large scale features of the coupling between the fire and the smoke transport are retained. The heat release rate per unit mass of burning fuel is determined from experiment. The spread of the fire through the fuel array is predicted by the calculation. The thermal elements originate at solid (burning) surfaces. In the case of polystyrene cups in corrugated paper boxes, the paper heats up due to both convective and radiative heat transfer from the surrounding gas. When the paper heats up to its measured ignition temperature, thermal elements are ejected from the surface and burned at a prescribed rate. Charring effects are neglected. The corrugated paper is assumed to be thermally-thin, and the rate at which it heats up depends on the product of its density ρ_s, specific heat c_s and characteristic thickness δ

$$\frac{dT_s}{dt} = \frac{\dot{q}_c'' + \dot{q}_r'' - \dot{q}_e''}{\rho_s c_s \delta} \tag{1}$$

where $\dot{q}_c''$, $\dot{q}_r''$ and $\dot{q}_e''$ represent heat fluxes due to convection, radiative absorption, and radiative emission. The individual values of the parameters ρ_s, c_s and δ are not relevant here; rather it is their product that is determined experimentally, and this product is referred to as the lumped thermal capacitance of the fuel. For a vertical sample of the corrugated paper used in the tests, $\rho_s c_s \delta$ was determined from the LIFT (Lateral Ignition and Flame spread Test) apparatus at NIST to be 1.5±0.4 kJ/m^2·K [5]. Note that the data analysis was based on a thermally-thin assumption, following the method outlined by Ohlemiller [6]. The ignition temperature of the sample was determined to be 370°C (700°F). The convective heat flux to the surface, $\dot{q}_c''$, is estimated from a correlation of the form

$$\dot{q}_c'' = C \Delta T^{\frac{1}{3}} \Delta T \quad \text{W/m}^2 \tag{2}$$

where ΔT (K) is the difference between the wall and gas temperature, and C is an empirical constant of value 1.43 for a horizontal surface and 0.95 for a vertical surface [7]. The radiative heat flux to the surface, $\dot{q}_r''$, is calculated based on the assumption that a prescribed fraction of the heat released from a thermal element is radiated away, and this energy is absorbed by the surrounding surfaces without attenuation by the surrounding gas. Usually, the fraction of energy radiated away from the fire is obtained by comparing the total heat release rate with the convective heat release rate. For a given point $\mathbf{x}_s$ on a wall or surface, the radiative flux is given as

$$\dot{q}_r'' = \sum_{i=1} \cos(\phi_i) \frac{\chi_r \dot{q}_i}{4\pi |\mathbf{x}_i - \mathbf{x}_s|^2} \tag{3}$$

where $\mathbf{x}_i$ is the position of the ith thermal element, χ_r is the fraction of the heat release rate of the ith element, $\dot{q}_i$, converted into radiative energy (50% in this case, based on full scale calorimetry burns where both the total and convective heat release rates were measured), and ϕ_i is the angle formed by the normal to the surface and the vector $\mathbf{x}_p - \mathbf{x}_s$. Since there are hundreds of thousands of thermal elements in a typical calculation, the above summation is made over a sampling of the elements.

Once the fuel surface reaches its ignition temperature, thermal elements are ejected at a rate of $\dot{n}''$ elements per unit time per unit area (about 1,000 elements/m^2·s) with a small normal velocity ($\approx$0.20 m/s) into the flow domain. The heat release rate for the fire at a given time t is then expressed by summing over all of the thermal elements in the flow field

$$\dot{q}(t) = \sum \frac{\dot{q}''}{\dot{n}''} \frac{1}{\tau} \qquad (t - t_0 < \tau) \tag{4}$$

where the $\dot{q}''$ is a prescribed rate of heat release per unit area, τ is a characteristic element burn-out time, and t_0 is the time that a given particle leaves a solid surface. The heat release rate per unit area $\dot{q}''$ for the cartoned plastic commodity was determined from small scale cone calorimeter measurements [8] to be about 500 kW/m^2, but this value had to be adjusted to about 600 kW/m^2 to match full scale calorimeter measurements. The burn-out time was established empirically by comparing the length of the flames in the simulations with those from the experiments. Oxygen transport and consumption was included in the calculations, as well. It was assumed that 1 kg of oxygen was consumed for every 13,100 kJ of energy released. When the oxygen mass fraction Y_{O_2} fell to a certain prescribed lower limit (about 12%), combustion was assumed to stop, and the unburned fuel associated with the thermal elements remained unburned until more oxygen was available [3].

To validate the fire spread algorithm, calculations were compared with experimental burns of the cartoned plastic commodity that were performed at UL. Two, three and four tier configurations were tested. Figure 1 shows the convective heat release rates for the UL burns compared

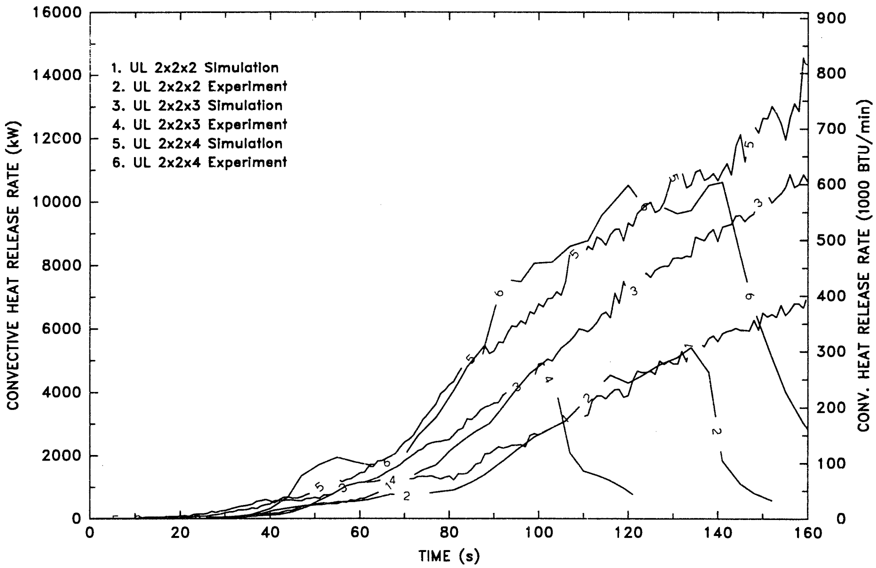

FIGURE 1: Comparison of experimental and simulated convective heat release rates for the two, three and four tier cartoned plastic calorimetry burns. Water was applied to the fire at 130 s in the two tier test, and 95 s in the three tier test. The simulations were performed with no water application.

with those computed by the numerical model. For the period of time before water application, the simulation heat release rate is within 20% of the experiment.

The Sprinkler Spray

The temperature of the sensing element of an automatic sprinkler is estimated from the differential equation presented by Heskestad and Bill [9]

$$\frac{dT_l}{dt} = \frac{\sqrt{u}}{\mathrm{RTI}}(T_g - T_l) - \frac{C}{\mathrm{RTI}}(T_l - T_m) \tag{5}$$

where 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, and u is the gas velocity. Once a sprinkler has activated, the sizes, temperatures and trajectories of a representative sample of the water droplets are computed. The initial conditions are deduced from measurements of droplet sizes and density patterns of sprays not subjected to a fire plume. Note that tracking every droplet is prohibitively expensive, and unnecessary. The sampling of droplets has been referred to as the "superdrop" concept [10]. Each droplet that is tracked in the calculation is assumed to represent many others of similar size and trajectory. The major assumption is that the drops do not interact with each other, only the hot gas. In the calculations that will be discussed below, typically five to ten thousand droplets from each active sprinkler interact with the gas at any given time. This number of droplets ensures that an accurate spatial distribution of the water is obtained.

In order to compute the droplet trajectories, the initial size and velocity of each droplet must be prescribed. This is done in terms of random distributions. The initial droplet size distribution of the sprinkler spray is expressed in terms of its Cumulative Volume Fraction (CVF), a function that relates the fraction of the water volume transported by droplets less than a given diameter. This function can be approximated by a combination of log-normal and Rosin-Rammler distributions [11]

$$F(d) = \begin{cases} \frac{1}{\sqrt{2\pi}} \int_0^d \frac{1}{\sigma\delta} e^{-\frac{[\ln(\delta/d_m)]^2}{2\sigma^2}} \, d\delta & (d \leq d_m) \\ 1 - e^{-0.693\left(\frac{d}{d_m}\right)^\gamma} & (d_m < d) \end{cases} \tag{6}$$

where d_m is the median droplet diameter (*i.e.* half the mass is carried by droplets d_m or smaller in diameter), and γ and σ are empirical constants equal to about 2.4 and 0.58, respectively. The median diameter varies from sprinkler to sprinkler, and it also varies with the pressure applied. In the numerical algorithm, the sizes of the sprinkler droplets are chosen to mimic the Rosin-Rammler/log-normal distribution. A Probability Density Function (PDF) for the droplet diameter is defined

$$f(d) = \frac{F'(d)}{d^3} \Big/ \int_0^\infty \frac{F'(\delta)}{\delta^3} \, d\delta \tag{7}$$

Note that $F'(d)$ denotes the first derivative of the function $F(d)$. Droplet diameters are randomly selected by equating the Cumulative Number Fraction of the droplet distribution with a uniformly distributed random variable. Once the sprinkler droplet size distribution is measured, the initial spray angle and droplet velocities are estimated from spray density measurements made at the floor. This is a trial-and-error process where various initial conditions are prescribed and the resulting spray pattern is compared with measurements. The droplet trajectories are calculated based on force balance arguments. Heat and mass transfer between the the droplets and the gas is computed using standard correlations [7].

A check of the numerical model is how well it predicted sprinkler activation times. Examination of the activation times of nearby sprinklers was also important, especially in cases where several sprinklers were at equal distances from the fire and, in theory, should have activated at the same time. Table 1 presents a summary of the numerical simulations, comparing the number and time of sprinkler activations and the average peak temperatures near the fire. In most of the tests, the numerical model predicted the activation of the first four sprinklers surrounding the fire to within about 5 or 10 s. For the next ring of sprinklers, the model underpredicted the activation times by 15 to 30 s, on average. This difference probably was due to the uncertainty in the droplet size distribution. Work is still underway to more accurately measure the droplet size distribution. A sensitivity analysis was performed to determine what parameters had the most impact on the results of the calculations, and droplet size was shown to be one of the more important. The reason for this is because the heat transfer between the hot gases and the

Heptane Spray Burner Test Series I Simulations										
Test No.	Burner Pos.	Vent Operation	Avg. Act. Time First Ring		No. of Sprinklers		Avg. Peak Temp. (C)		Draft Curtains	Heat Release Rate MW @ s
			Exp.	Sim.	Exp.	Sim	Exp.	Sim.		
I-1	B	Closed	1:09	1:08	11	12	137	148	Yes	4.4 @ 50
I-2	B	Manual (0:40)	1:10	1:12	12	9	134	137	Yes	4.4 @ 50
I-3	B	Manual (1:30)	1:09	1:12	12	10	138	141	Yes	4.4 @ 50
I-4	C	Closed	1:05	1:09	10	10	136	142	Yes	4.4 @ 50
I-5	C	Manual (0:40)	1:16	1:10	9	8	125	132	Yes	4.4 @ 50
I-6	C	Manual (1:30)	1:24	1:13	8	8	137	134	Yes	4.4 @ 50
I-7	C	74°C link (DNO)	1:13	1:09	10	10	133	142	Yes	4.4 @ 50
I-8	B	74°C link (9:26)	1:09	1:09	11	12	125	148	Yes	4.4 @ 50
I-9	D	74°C link (DNO)	1:18	1:12	12	12	134	143	Yes	4.4 @ 50
I-10	D	Manual (0:40)	1:22	1:16	13	12	133	136	Yes	4.4 @ 50
I-11	D	74°C link (4:48)	N/A	N/A	N/A	N/A	196	152	Yes	4.4 @ 50
I-12	A	Closed	1:13	1:22	14	12	138	148	Yes	4.4 @ 50
I-13	A	74°C link (1:04)	1:29	1:48	5	4	119	114	Yes	6.0 @ 60
I-14	A	Manual (0:40)	1:58	2:14	7	4	116	108	Yes	5.8 @ 60
I-15	A	Manual (1:30)	1:08	1:19	5	4	143	153	Yes	5.8 @ 60
I-16	A	74°C link (1:46)	2:03	2:56	4	4	110	106	Yes	5.0 @ 110
I-17	B	100°C link (DNO)	1:06	1:01	4	10	105	122	No	4.6 @ 50
I-18	C	100°C link (DNO)	1:06	1:05	4	9	98	113	No	3.7 @ 50
I-19	A	100°C link (10:00)	1:06	1:15	10	12	110	127	No	4.6 @ 50
I-20	A	74°C link (1:20)	1:50	1:25	4	4	104	117	No	4.2 @ 50
I-21	C	74°C link (7:00)	1:05	1:03	10	10	119	125	No	4.6 @ 50
I-22	D	100°C link (DNO)	1:04	1:00	6	12	115	131	No	4.6 @ 50

TABLE 1: Results of the heptane spray burner Series I simulations. Note that "Avg. Peak Temp." in this table refers to the average peak temperature of the nearest 16 sprinkler-mounted thermocouples. The "Avg. Act. Time First Ring" is the average activation time of the nearest 4 sprinklers.

droplet is directly proportional to the surface area of the droplet. Thus doubling the size of the droplets reduces the number of droplets by a factor of 8 and reduces the heat transferred from the gas by a factor of 2.

Extinguishment

When a water droplet hits a solid horizontal surface, it is assigned a random horizontal direction and moves at a fixed velocity until it reaches the edge, at which point it drops straight down the side of the carton at a constant speed. This terminal velocity was determined by injecting a colored dye into a stream of water that cascaded down the side of a carton. It was roughly 0.55 m/s. Both the heating of unburned surfaces and the heat release rates from burning surfaces are affected by the droplets. The heat transfer coefficient between the surface and the water film is calculated based on an empirical correlation for forced flow past a flat plate [7]

$$\mathrm{Nu} = \frac{h_L L}{k_w} = 0.664\,\mathrm{Re}^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}} \approx 450 \quad \text{for water flowing at 0.55 m/s} \tag{8}$$

The characteristic length L is assumed to be the size of the fuel package. For computational convenience, the water continues to be tracked in the form of droplets, but the heat transfer coefficient between the water droplets and their surroundings is written in terms of an equivalent heat transfer coefficient between the thin film of water and the surface. By doing this, the same thermodynamic formulae may be applied to the droplet whether it is airborne or not. This is a numerical convenience because the transport of water is much easier to describe in terms of Lagrangian droplets rather than sheets of liquid. If the water formed a thin sheet, its temperature T_w would be governed by

$$\frac{dT_w}{dt} = \frac{h_L (T_s - T_w)}{c_w m''_w} \tag{9}$$

On the other hand, as a droplet the water temperature T_d would be governed by

$$\frac{dT_d}{dt} = \frac{3h_d}{c_w r_d \rho_d}(T_g - T_d) \tag{10}$$

Equating dT_w/dt with dT_d/dt and taking $T_g = T_s$, an effective heat transfer coefficient is derived

$$h_d = \frac{h_L r_d \rho_d}{m''_w} \tag{11}$$

Here, r_d is an arbitrarily chosen droplet radius, and m''_w is the mass of water per unit area.

Extinguishment of the fire is the single most difficult component of the numerical model. To date, most of the work in this area has been performed at Factory Mutual Research Corporation (FMRC). An important paper on the subject is by Yu *et al.* [12]. Their analysis yields an expression for the total heat release rate from a rack storage fire after sprinkler activation

$$\dot{Q} = \dot{Q}_0 e^{-k(t-t_0)} \tag{12}$$

where $\dot{Q}_0$ is the total heat release rate at the time of application t_0, and k is a fuel-dependent constant that for the FMRC Standard Plastic test commodity is given as

$$k = 0.176\dot{m}_w'' - 0.0131 \quad s^{-1} \tag{13}$$

The quantity $\dot{m}_w''$ 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 fluxes and burning rates. The numerical model requires more detail about the burning rate as a function of the local water flux. Until better models can be developed, the present extinguishment model consists of an empirical rule that decreases the local heat release rate as more water is applied

$$\dot{q}'' = \left(1 - \left(\frac{m_w''}{m_{w_0}''}\right)^2\right) \dot{q}_0'' \tag{14}$$

The critical water density m_{w_0}'' is estimated from small scale calorimeter burns of the commodity by choosing a value that best fits the data. The external radiation used in these experiments was 75 kW/m^2, typical of the heat flux measured in large scale calorimetry burns.

RESULTS

A very useful application of the numerical model has been to simulate the five cartoned plastic commodity tests performed during the project. The benefit of the numerical model in this application is that it provides a consistent means of varying test parameters. In other words, if two calculations are performed in which only one input parameter is different, then the difference in the results of the two calculations can safely be attributed to the difference in the input parameter. A drawback of large scale testing is that this type of sensitivity analysis usually requires more tests than can be afforded. If a sufficient number of replicates cannot be performed, then the outcomes of the experiments are often subject to debate as to whether differences in test results were due to changes in test parameters or due to random variations.

Experimental Description

The Large Scale Fire Test Facility at UL contains a 37 m by 37 m (120 ft by 120 ft) main fire test cell, equipped with a 30.5 m by 30.5 m (100 ft by 100 ft) adjustable height ceiling, which for these tests was set at 8.2 m (27 ft). The exhaust flow rate in the test facility was set to its maximum of 28 m^3/s (60,000 ft^3/min). Four 1.5 m (5 ft) diameter inlet ducts provided make up air and were located at the walls 3 m (10 ft) above the test floor to minimize any induced drafts during the tests. Draft curtains 1.8 m (6 ft) deep were installed for 3 out of the 5 tests.

The sprinklers used in all the tests were Central ELO-231 (Extra Large Orifice) uprights. The orifice diameter of this sprinkler was reported by the manufacturer to be nominally 0.64 in, the reference actuation temperature was reported by the manufacturer to be 74°C (165°F). The RTI (Response Time Index) and C-factor (Conductivity factor) were reported by UL to be 148 $(m \cdot s)^{\frac{1}{2}}$ (268 $(ft \cdot s)^{\frac{1}{2}}$) and 0.7 $(m/s)^{\frac{1}{2}}$ (1.3 $(ft/s)^{\frac{1}{2}}$), respectively [1]. When installed, the sprinkler deflector was located 8 cm (3 in) below the ceiling. The thermal element of the sprinkler was located 11 cm (4.25 in) below the ceiling. The sprinklers were installed with 3 m by 3 m (10 ft by 10 ft) spacing in a system designed to deliver a constant 0.34 L/(s·m^2) (0.50 gpm/ft^2) discharge density when supplied by a 131 kPa (19 psi) discharge pressure. Unlike an actual sprinkler system, this pressure is held constant no matter how many sprinklers have activated.

UL-listed double leaf fire vents with steel covers and steel curb were installed in the adjustable height ceiling in the positions shown in Fig. 2. The vent doors were recessed into the ceiling about 0.3 m (1 ft). The vent was designed to open manually or automatically. In tests where automatic operation of the vents was desired, UL-listed fusible links rated at 74°C (165°F) were installed.

The Factory Mutual Research Corporation (FMRC) Standard Plastic test commodity, a Cartoned Group A Unexpanded Plastic, served as the fuel for the cartoned plastic commodity series. This commodity has been used extensively for testing since 1971 [13]. It consisted of rigid crystalline polystyrene cups (empty, 0.47 L (16 fl oz) size) packaged in compartmented, single-wall, corrugated paper cartons. The cups were arranged open end down in five layers, 25 per layer for a total of 125 per carton. Each carton, or box, was a cube 0.53 m (21 in) on a side. Eight boxes comprised a pallet load. Two-way, 1.06 m by 1.06 m by 0.13 m (42 in by 42 in by 5 in) slatted deck hardwood pallets supported the loads.

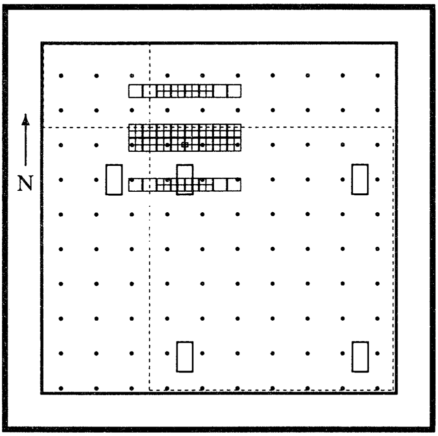

FIGURE 2: Layout of Plastic Test P-3.

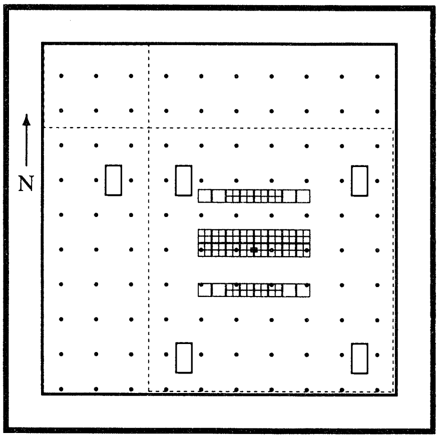

FIGURE 3: Layout of Plastic Test P-4.

The layouts for two of the cartoned plastic commodity tests are shown in Figs. 2–3. Each storage array consisted of a main (ignition) double-row rack at the center, flanked on two sides by single row target racks. The rows were separated by 8 ft wide aisles. Each of the two rows of the main array consisted of four 2.4 m (8 ft) long bays; a 0.15 m (6 in) flue separated the rows. Longitudinal flues of 0.2 m (7.5 in) were used to separate the pallets within a row. The overall loaded area of the double-row rack measured approximately 2.3 m (7.5 ft) wide by 10 m (33 ft) long. The racks were divided vertically into 4 tiers; the overall loaded height was 5.8 m (19 ft). A similar configuration was used in a series of FMRC burns documented in Ref. [14].

Sample Numerical Simulations

Simulations of all the cartoned commodity tests were performed on a grid with 20 cm resolution spanning the volume under the largest curtained area in Figs. 2 and 3. The grid size was 100 by 108 by 40 (432,000 cells). A 5 min simulation required about 50 h CPU time on an IBM RISC/6000 workstation. About half of this time was devoted to the radiation calculation and the sprinkler droplet tracking.

The cartoned plastic burn that caused the most fire damage was Test P-3. In this test, the ignition point was placed close to the intersection of two draft curtains (Fig. 2). An estimated 184 boxes were consumed during the test, compared to 103 and 81 in Tests P-4 and P-5, the other two Plastic tests conducted with draft curtains in place. Figures 4 and 5 present the results of the simulations of Tests P-3 and P-4. The vent nearest the ignition point in Test P-3 opened at 4:11, and no vents opened in Test P-4, thus venting did not have any impact on the results in either case, at least for the first 4 min. Clearly, the draft curtains had an effect on the performance of the sprinkler system. The draft curtains delayed the opening of the two sprinklers directly north of the first two sprinklers to activate. Less obvious, the draft curtains changed the near-ceiling flow pattern of both the sprinkler spray and the fire plume. Regardless of the sub-model used to simulate the burning of the cartoned plastic commodity, the calculation showed that less water reached the north side of the central array when the draft curtains were installed. In Test P-3, the fire has spread to the north face of the array, whereas in Test P-4 the sprinklers in the north aisle prevent the spread to the north face.

CONCLUSION

The Industrial Fire Simulator (IFS) developed in conjunction with the test program was shown to be in good *quantitative* agreement with the heptane spray burner tests in terms of both predicting sprinkler activation times and near-ceiling gas temperatures. The sprinkler activation times were predicted to within about 15% of the experiments for the first ring, 25% for the second. The gas temperatures near the ceiling were predicted to within about 15%. Simulations were performed and compared with unsprinklered calorimetry burns of the cartoned plastic commodity. The heat release rates of the growing fires were predicted to within about 20%.Simulations of the 5 cartoned plastic commodity fire tests were then performed. The goal of these simulations was to be able to differentiate between those experiments that activated a large number of sprinklers, and those that activated a small number. This goal has been met. The model also provided valuable insight into what occurred in the experiments, and also what would have occurred in the event of various changes of test parameters.

ACKNOWLEDGMENTS

The authors would like to thank the following for their assistance in this project: Fred Mulhaupt and Doug Brown at the NFPA Research Foundation for providing us the opportunity to participate in the International Fire Sprinkler, Smoke & Heat Vent, Draft Curtain Fire Test Project; Dave Sheppard and Dan Steppan at UL and Joe Hankins at FMRC for contributing test data; and Stephen DiGiovanni of the University of Maryland, Jukka Hietaniemi of VTT Finland, and Roy McLane of NIST for their work on the plastic commodity used in the tests.

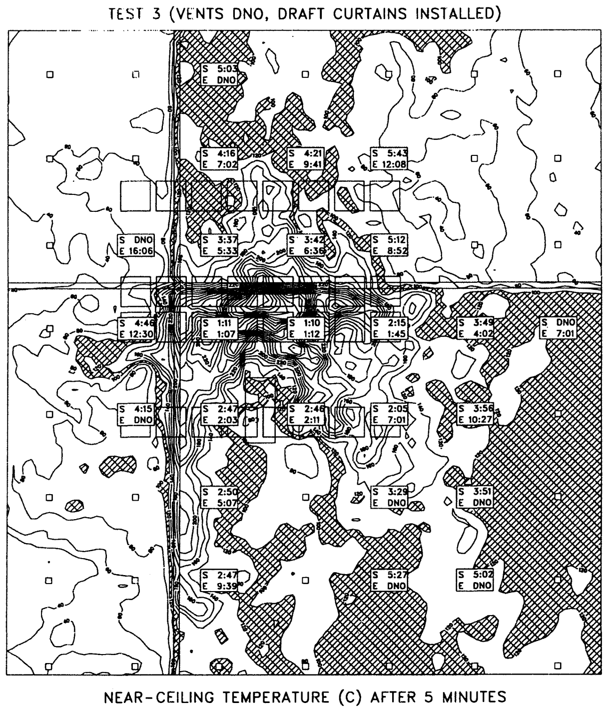

FIGURE 4: Results of Plastic Test P-3 simulation. “S” denotes simulation sprinkler activation time, “E” experiment. The cross-hatched area indicates temperatures between 100 and 120°C.

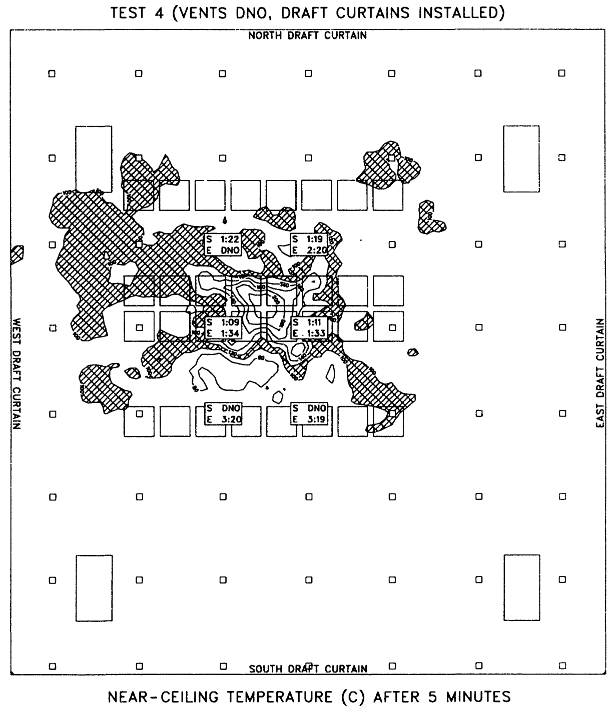

FIGURE 5: Results of Plastic Test P-4 simulation. “S” denotes simulation sprinkler activation time, “E” experiment. The cross-hatched area indicates temperatures between 100 and 120°C.

REFERENCES

[1] D.T. Sheppard and D.R. Steppan. Sprinkler, Heat & Smoke Vent, Draft Curtain Project – Phase 1 Scoping Tests. Technical report, Underwriters Laboratories, Inc., Northbrook, Illinois, May 1997.

[2] D.T. Sheppard. International Fire Sprinkler, Heat & Smoke Vent, Draft Curtain Fire Test Project – Test Report. Technical report, Underwriters Laboratories, Inc., Northbrook, Illinois, 1998. NC987-96NK37863.

[3] K.B. McGrattan, A. Hamins, and D. Stroup. Sprinkler, Smoke & Heat Vent, Draft Curtain Interaction — Large Scale Experiments and Model Development. Technical Report NISTIR 6196-1, National Institute of Standards and Technology, Gaithersburg, Maryland, September 1998.

[4] K.B. McGrattan, H.R. Baum, and R.G. Rehm. Large Eddy Simulations of Smoke Movement. *Fire Safety Journal*, 30:161–178, 1998.

[5] American National Standards Institute. *ASTM E-1321, Lateral Ignition and Flame Spread Test*, 1994.

[6] T.J. Ohlemiller and K.M. Villa. Material Flammability Test Assessment for Space Station Freedom. Technical Report NISTIR 4591, National Institute of Standards and Technology, Gaithersburg, Maryland, June 1991.

[7] F.P. Incropera and D.P. De Witt. *Fundamentals of Heat and Mass Transfer*. John Wiley and Sons, New York, 3rd edition, 1990.

[8] American National Standards Institute. *ASTM E-1354, Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Combustion Calorimeter*, 1994.

[9] G. Heskestad and R.G. Bill. Quantification of Thermal Responsiveness of Automatic Sprinklers Including Conduction Effects. *Fire Safety Journal*, 14:113–125, 1988.

[10] S. Kumar, G.M. Heywood, S.K. Liew, and W.S. Atkins. JASMINE Sprinkler Model - Some Validation Studies. In *Proceedings of the First European Symposium on Fire Safety Science*, 1995. ETH, Zurich.

[11] T.S. Chan. Measurements of Water Density and Droplet Size Distributions of Selected ESFR Sprinklers. *Journal of Fire Protection Engineering*, 6(2):79–87, 1994.

[12] H.Z. Yu, J.L. Lee, and H.C. Kung. Suppression of Rack-Storage Fires by Water. In *Fire Safety Science – Proceedings of the Fourth International Symposium, International Association For Fire Safety Science*, pages 901–912, 1994.

[13] R.K. Dean. Stored Plastics Test Program. Technical Report FMRC J.I. 202069, Factory Mutual Research Corporation, Norwood, Massachusetts, June 1975.

[14] J.M.A Troup. Large-Scale Fire Tests of Rack Stored Group A Plastics in Retail Operation Scenarios Protected by Extra Large Orifice (ELO) Sprinklers. Technical Report FMRC J.I. 0X1R0.RR, Factory Mutual Research Corporation, Norwood, Massachusetts, November 1994. Prepared for Group A Plastics Committee, Lansdale, Pennsylvania.