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Scaling realistic fire scenarios

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Category

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Keywords

dimensionless groups, fire, models, scaling, smoke movement, structures, world trade center fire

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Scaling realistic fire scenarios

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Abstract

A review is made of work on scale modeling in fire and presented from the experience of the author. Primarily, scale modeling in air is discussed but there is a brief discussion of a scale model with salt and fresh water for smoke movement. A complete set of dimensionless groups is presented for fire, then it is illustrated how selections were made for the partial scaling of specific fire scenarios. Studies have been motivated by basic research interests as well as for fire investigations. The dynamics of floorcovering fire spread in a corridor is studied to reveal many features of fire behavior and validation is made with full-scale. Smoke movement in a department store atrium is studied to reveal flaws in the fire suppression system. The challenge was to develop a water mist system that passed fire testing, and was systematically done using a scale model and confirmed at full-scale. Fire effects on steel structures were studied at various scales, and a related classroom project examined one floor of the World Trade Center collapse on September 11, 2001. Finally, scaling was examined for a fire development in a furnished bedroom, pushing the limits of modeling to its utmost but finding some success in illustrating very similar overall behavior.

Keywords: Dimensionless groups; Fire; Models; Scaling; Smoke movement; Structures; World Trade Center fire

Introduction

Analysis and design in fire safety and investigation have used computer models or formulas as tools. However, phenomena scales smaller than a computer grid spacing limits the accuracy of computer models. Moreover, many phenomena, such as the formation of soot, the unraveling of veneer wood paneling in flame spread, or water droplet breakup in suppression—not to mention turbulent combustion—cannot be represented by fundamental formulations. On the other hand, formulas for specific phenomena are usually grounded in data. The data have generally been taken in the laboratory with some variation in scale, and over a range of relevant parameters. These data were then subjected to an analysis using some theory and dimensionless parameters that extended the resulting correlation. Many such correlating formulas have found consensus by their widespread testing and adoption. For a singular phenomenon these formulas are usually accurate to ±25 % and many serve as benchmark tests for a computer. The formulas have generally been expressed in dimensionless groups that can extend their accuracy to larger than laboratory scales. This is a form of scale modeling with particular attention to the dominant controlling variables of the phenomena; it is *partial scaling*. While formulas might address a particular phenomenon, a physical scale model can address multiple phenomena through its data; this is the field of scale modeling. It is rarely used in fire applications, but here an array of problems will be presented to illustrate its approach and potential.

Other fields use physical scale modeling, most notably the design of aircraft in a wind tunnel. Even the Wright brothers used this technique to their advantage. It might be surprising to some people how widespread is the use of scale modeling, as seen by these past symposia [1]. Thomas [2] wrote a telling paper on scale modeling, referring to its execution as "a magic art". The complex world of fire cannot be brought to perfect similitude as that of subsonic flight which relies only on the Reynolds numbers as its basis. Scaling in fire may not be perfect in preserving all dimensionless groups, but with an understanding of their role the main

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Table 1. Dimensionless variables and scaling in fire.

Variable/Group	Dimensionless	Scaling/Comment
Dependent		
Velocity, u	$\hat{u} = u/\sqrt{gl}$	$u \sim l^{1/2}$
Temperature, T	$\hat{T} = T/T_\infty$	$T \sim l^0$
Pressure, p	$\hat{p} = p/\rho_\infty g l$	$p \sim l$
Concentration, Y_i	$Y_i/Y_{i,\infty}$	$Y_i \sim l^0$
Droplet number, n	n/n_{ref}	$n \sim l^{3/2}$
Droplet diameter, D_l	D_l/l	$\Pi_{12} \rightarrow D_l \sim l^{1/2}$
Burning rate per area, $\dot{m}''_F$	$\dot{m}''_F l/\mu$	$\dot{m}''_F \sim \frac{h_c l}{\mu c_p} = \frac{\mathrm{Nu}}{\mathrm{Pr}}$
Independent		
Coordinates, x, y, z	x_i/l	$x_i \sim l$
Time, t	$t/\sqrt{l/g}$	$t \sim l^{1/2}$
Pi groups		
$\Pi_1 \left(\frac{\text{inertia}}{\text{viscous}}\right)$, Re	$\mathrm{Re} = \frac{\rho_\infty \sqrt{g} l^{3/2}}{\mu}$	Usually ignored $(u \sim l^{-1})$
$\Pi_2 \left(\frac{\text{firepower}}{\text{enthalpy rate}}\right)$, Q^*	$\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g} l^{5/2}}$	Significant in combustion
$\Pi_3 \left(\frac{\text{radiant emission}}{\text{ideal emission}}\right)$	κl	$\kappa \sim l^{-1}$, when gas is important
$\Pi_4 \left(\frac{\text{radiant loss}}{\text{firepower}}\right)$, X_r	$X_r = \dot{q}_r/\dot{Q}$	$X_r \sim l^0$, important for free burning
$\Pi_5 \left(\frac{\text{conduction}}{\text{enthalpy}}\right)$, Q_k^*	$\frac{(k\rho c)_w^{1/2}}{\rho_w c_p g^{1/4} l^{3/4}}$	$k_w \sim \rho_w \sim l^{3/4}$, conduction important
$\Pi_6 \left(\frac{\text{convection}}{\text{enthalpy}}\right)$, Q_c^*	$\frac{h_c}{\rho_\infty c_p \sqrt{gl}}$	$h_c \sim l^{1/2}$, convection important
$\Pi_7 \left(\frac{\text{radiation}}{\text{enthalpy}}\right)$, Q_r^*	$\frac{\sigma T_\infty^3}{\rho_\infty c_p \sqrt{gl}}$	$T_\infty = l^{1/6}$, inconsistent with others
$\Pi_8 \left(\frac{\text{thickness}}{\text{thermal length}}\right)$	$\left(\frac{\rho c}{k}\right)_w^{1/2} \left(\frac{g}{l}\right)^{1/4}$	$\delta_w \sim l^{1/4}$, thickness of boundaries

phenomena can be addressed. As with formulas for specific phenomena, this "art" is partial scaling. It is used very effectively to design the hulls of boats that relies on the Froude number but ignores the Reynolds number.

The art of scale modeling in fire is demonstrated by the multitude of phenomena to which it can be applied; the resulting dimensionless groups to be preserved are overwhelming. Williams [4] lists these groups as 29! Table 1 displays 22 Pi-groups that include the phenomena of combustion, material fluid properties, water droplets, and forced and natural convection. Geometric scaling is mostly used with the scale length designated as *l*. Groups pertaining to structural scaling in fire are not shown in the table, but this aspect will be discussed.

This paper is primarily based on the author's experiences using physical scale modeling. The omission of other work is not to slight it, as this paper is not meant to be a review. Indeed, the reader is encouraged to seek out further examples in the field and, of course, in the past symposia of this distinguished conference. Neither is this paper intended as a treatise for scale modeling. In that regard the reader is referred to the list of references, and perhaps my chapter on scale modeling [3]. Most of this work with done in association with the fire program of NIST and with many graduate students at the Department of Fire Protection Engineering, University of Maryland; and the reader is referred to those sources for more detailed information. Here the nature of the results will be illustrated and, in some cases, details may be obscured by brevity. A range of problems will be illustrated where scaling is nearly perfect to others where perfect scaling is impossible, yet the results can still be invaluable.

Although this paper is not a review, it would be remiss not to mention some key pioneering works. G. Heskestad's work on compartment fire modeling [5] and on suppression by water droplets [6] are illustrations of excellence. Moreover, the work by Parker and Lee to predict flashover in the burning of lining materials in a room using a 1/4 geometric scale model is impressive [7]; these manuscripts inspired me

Table 1. (Continued)

Π_9 $\left(\frac{\text{fan flow}}{\text{advection}}\right), m^*_{Fan}$	$\frac{\dot{m}_{Fan}}{\rho_\infty \sqrt{g} l^{5/2}}$	$\dot{m}_{Fan} \sim l^{5/2}$, forced flows
Π_{10} $\left(\frac{\text{fuel flow}}{\text{advection}}\right), m^*_F$	$\frac{\dot{m}_F}{\rho_\infty \sqrt{g} l^{5/2}}$	Fuel mass flux depends on B, Gr, Re,
Π_{11} $\left(\frac{\text{sensible}}{\text{latent}}\right), \tau_o$	$c_p(T_v - T_\infty)/L$	Burning rate term
Π_{12} $\left(\frac{\text{available } O_2}{\text{stoichiometric } O_2}\right), r_o$	$Y_{O_2,\infty}/rY_{F,o}$	Burning rate term
Π_{13} $\left(\frac{\text{evaporation energy}}{\text{sensible energy}}\right)$	$M_g h_{fg}/RT_i$	"Activation" of vaporization
Π_{14} $\left(\frac{\text{collision loss}}{\text{initial particles}}\right)$	$\hat{n}_{col} = \dot{n}_{col}/\left(\frac{\dot{V}_{l,o}}{D^3_{l,o}}\right)$	$\dot{n}_{col} \sim l$, collision number rate
Π_{15} $\left(\frac{\text{spray thrust}}{\text{jet momentum}}\right)$	$F_o/\left(\frac{\dot{V}_{l,o}}{D_o}\right)^2$	$F_o \sim l^3$, D_o nozzle diameter, $D_o \sim l$
Π_{16} $\left(\frac{\text{evaporation rate}}{\text{droplet mass loss}}\right)$	$\dot{m}''_g/\rho_l D_l \sqrt{gl}$	$\dot{m}''_g \sim l^0$
Π_{17} $\left(\frac{\text{weight of droplet}}{\text{drag force}}\right), \hat{D}_\mu$	$\hat{D}_\mu = D_l Re_l^{1/3}$	$D_l \sim l^{1/2}$
Π_{18} $\left(\frac{\text{advection}}{\text{mass transfer}}\right)$	$\mathrm{Pr}^{2/3}\hat{D}_l^{1/2}\mathrm{Re}_l^{1/2}$	$D_l \sim l^{1/4}$, inconsistent with Π_{17}
Π_{19} $\left(\frac{i^{\text{th}} \text{ enthalpy}}{\text{chemical energy}}\right)$	$y_i c_p T_\infty/\Delta h_c$	$y_i \sim l^0$
Π_{20} $\left(\frac{\text{droplet momentum}}{\text{surface tension}}\right)$	$\mathrm{We} = \rho_l u_l^2 D_l/\sigma_3$	$D_l \sim l^{-1}$, inconsistent with Π_{17}
Π_{21} $\left(\frac{\text{enthalpy}}{\text{combustion energy}}\right)$	$rc_p T_\infty/A h_k$	Nearly always constant
Π_{22} $\left(\frac{\text{convection}}{\text{conduction}}\right)$	$\mathrm{Nu} = h_c l/k$	$h_c \sim l^{-1}$

to explore scale modeling in a variety of applications.

This paper gives an overview of these applications, and the interested reader might wish to seek out the details in references given here and in theses by graduate students in fire protection engineering and the University of Maryland. Also of interest might be to explore how scale modeling is used in other fields. This scaling symposium, founded by Professor R.I. Emori [8] and carried on by Professor K. Saito [9], contain a vast array of scaling in many fields of engineering.

Main features of fire scale modeling

A listing of dimensionless parameters is given in Table 1. As Thomas said, there is a "magic art" to the process. Only a few groups can be preserved in scaling. Similar to the scaling of ship dynamics, in fire scaling the Reynolds number is not preserved but, because full-scale flows are turbulent, the size of the model must be big enough to ensure turbulent flow. This limit is generally about 0.3 m (1 ft.) in height as a minimum. The key parameter is to preserve Π_2 or Q^*, the Zukoski number. As is often the case in computer modeling, this requires that the firepower (or more commonly the heat release rate) must be known for the full-scale. Thereby, the ability to perfectly scale fire growth is impossible because too many groups are required for preservation and they cannot be controlled; it seems they have a mind of their own. Yet by understanding how they might behave, a scale model with fire growth can still be revealing and useful although complete scaling of all variables is not possible. Indeed, the ultimate key is to preserve enough groups, first principally Q^*, so that the scale model data yield at least the dependent variables of temperature, velocity and species concentrations. To get the species correct, the same fuel must be used in the model and full-scale. These dependent variables are then related at corresponding dimensionless position and time. The geometry is fully scaled by the scaling factor of length of model-to-length of full scale. Time is often scaled by the "flow time", as displayed in Table 1, but other characteristic times might also be advantageous. Often it is common to avoid the flow time and not satisfy that aspect, and use the burning time as a key parameter. At times in scaling the firepower is formed in the model by the same fuel but a liquid pool fire or a gas burner might also be satisfactory for simulation.

The next set of parameters that require considera-

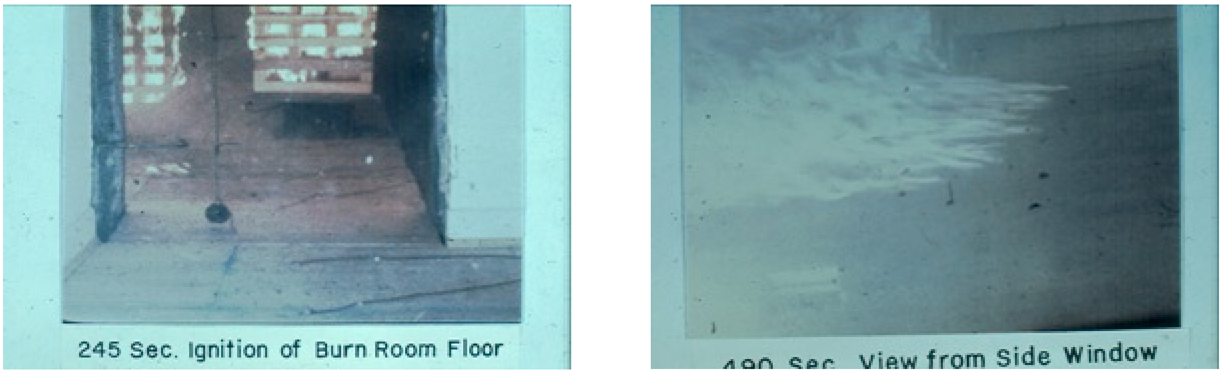

Fig. 1. Fire spread into a corridor on a wood floor.

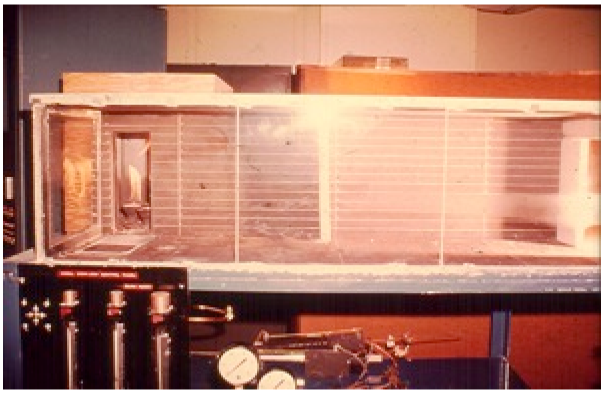

Fig. 2. Scale model of corridor fires.

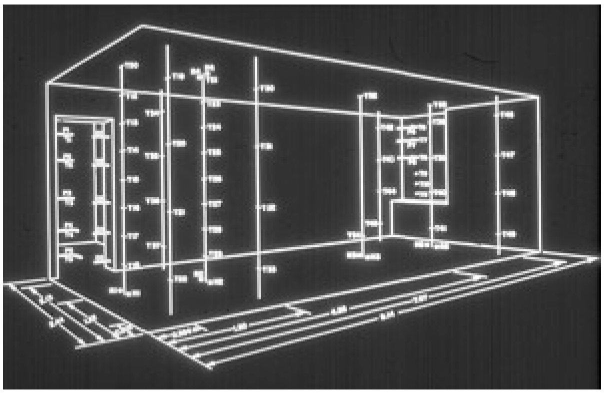

Fig. 3. Full-scale corridor.

tion for obtaining correct heat losses for construction materials are groups Π_5 to Π_8 . However, the confluence of radiation, convection and conduction make it impossible to preserve all of these groups. Consequently, some compromises have to occur, such as eliminating radiation when the application is a small fire with emphasis on smoke movement and detection, or alternatively, convection can be sacrificed when the application is a large fire and radiation becomes dominant.

To go beyond the above constraints in compartment fires, the application of suppression or structural fire behavior demand the addition of new groups. Again, all of them will not be preserved and the "magic art" comes into play, along with the common sense of science.

Advantages of fire scaling

Although scaling can never be perfectly complete, some distinct advantages exist in using it. First, for a specific phenomenon, such as the average layer temperature of smoke in a room, the key dimensionless groups can be identified and then a correlation can emerge that encompasses many scales. Reference 3 discusses this aspect and the role scaling has had in establishing many formulas used in fire research. These correlations provide formulas in complex areas where turbulent flows are problematic to model.

Second, scale models that aim to emulate, like studies of geometric models in a wind tunnel, possess inherent flow physics. Turbulence is manifested in the model as it would in full-scale. There is no need for a special sub-grid model in the computer code. In addition, for fire, combustion occurs as it would in nature, soot is formed and species emerge as the flame develops.

Third, observing a scale model by eye directly and by using enhancing visualization techniques reveals many aspects for learning, understanding and discovery. Indeed, it is likely scale modeling contributed to the concept of the zone model, or specifically the discrete well-mixed upper layer in a room fire.

Finally, the use of a scale model has the advantage of size. It is less expensive to construct and operate; it allows ease of adding instrumentation and observing overall fire behavior. It can be a convenient benchmark for computer modeling.

Examples of scale modeling in fire

Three basic applications of scaling with models will be presented. The first deals principally with the early behavior of fire in an enclosure, the second addresses suppression, and the third considers fully developed fires including the effect on steel structures. In most cases the firepower is known and can easily be modeled, but fire growth effects of thermally enhanced burning and spread, and the mitigation by the reduction in oxygen, will also be considered.

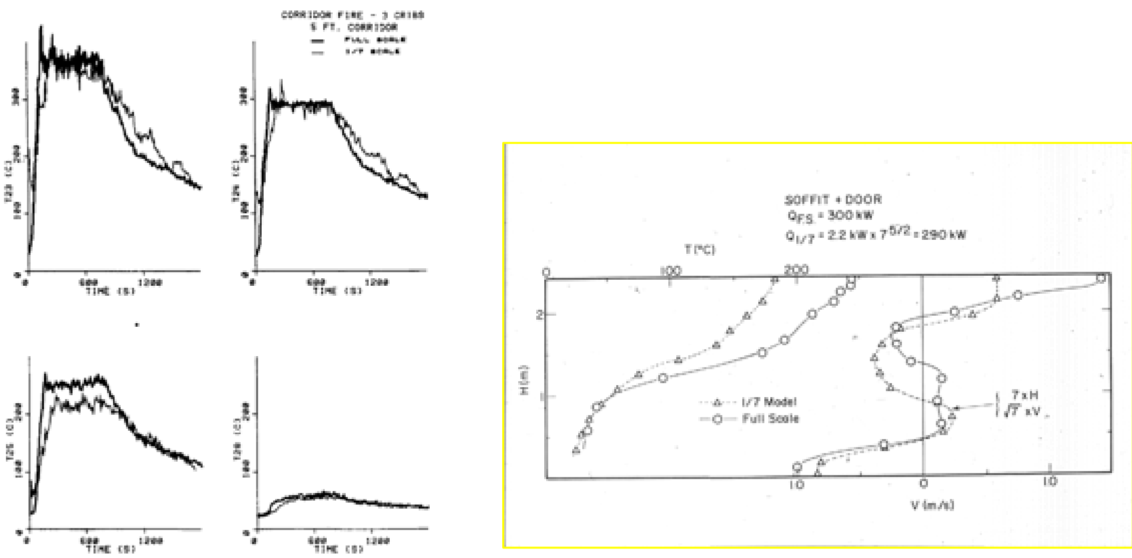

Fig. 4. Temperatures and scaled corridor velocities.

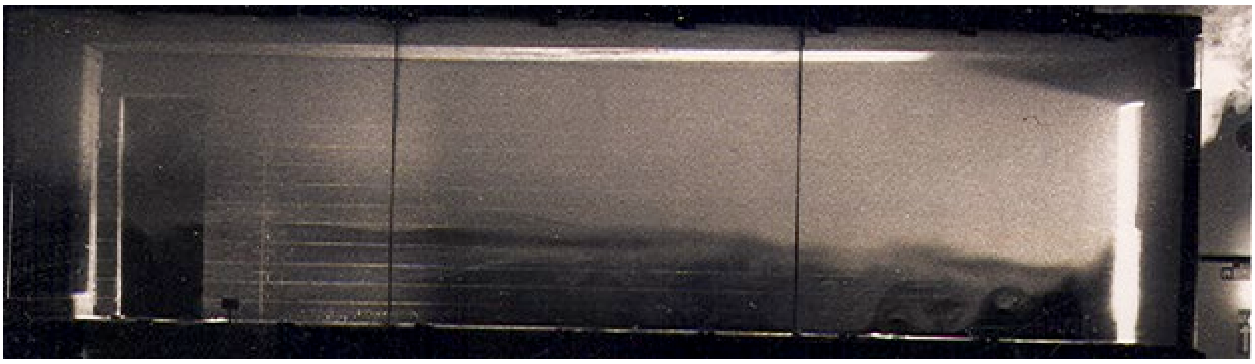

Fig. 5. Smoke layer in a corridor from a room fire.

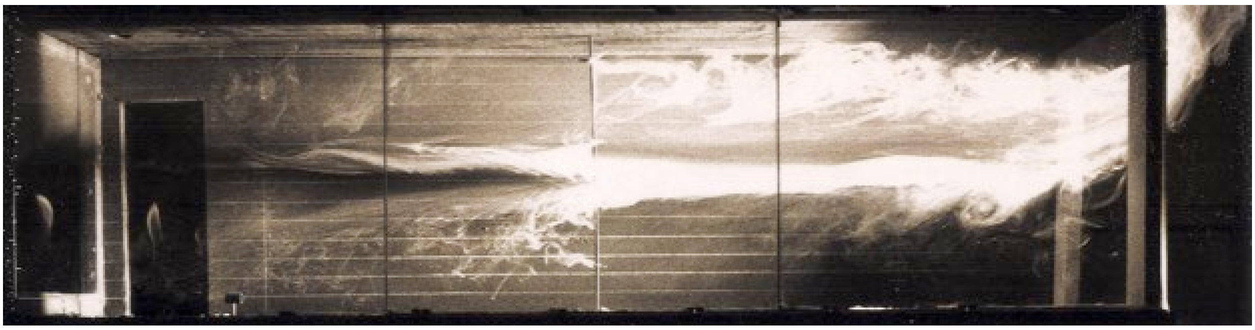

Fig. 6 Recirculating layer flows and mixing at the right vent.

Enclosure fire dynamics

Corridor fires

This study was prompted by full-scale experiments to investigate the spread of fire from a room over a floorcovering of a corridor in which the dramatic rapid fire spread along the corridor could not be fully understood. The fire progressed slowly out of a room with opposed flow flame spread on the floor, and then into turned into the corridor. As the fire became larger on the corridor floor its buoyancy began to interfere with the induced airflow from a window at the end of the corridor (Fig. 1).

The many questions raised by these floorcovering corridor experiments prompted the use of a scale model along with full-scale tests of the same corridor configuration without fire growth. The scale model used gas burners in place of wood cribs (Fig. 2). The model incorporated walls that simulated gypsum board construction of the full-scale corridor, and was

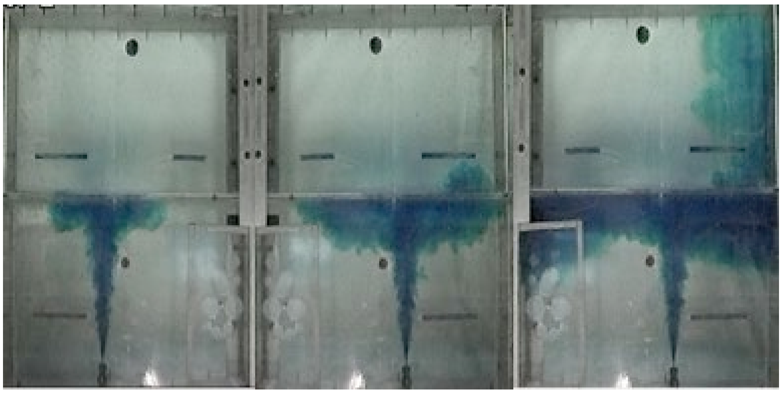

Fig. 7. Saltwater modeling (inverted) [14].

Fig. 8. Hart Albin department store in Billings, Montana.

separately outfitted with glass walls to allow for visualization studies.

The 9 m long corridor was geometrically scaled by 1/7th in an attempt to conserve turbulence and maintain a convenient laboratory scale (Fig. 3)—it seemed to work. The scaling hypotheses considered temperatures and flow velocities dependent on Π_2 (Q^*), Π_5, Π_6 and Π_8. In this study, time was scaled with the burning time of the wood cribs and the scale model used gas burners to simulate the cribs. Fig. 4 shows the agreement for temperature and scaled velocity.

Visualization of the smoke in the upper layer showed homogeneity characteristic of compartment fire behavior (Fig. 5). However, by using smoke traces, as in Fig. 6, the flow within the upper and lower layers was revealed to be more complex with recirculation into four layers with turbulent ceiling and floor jets but laminar inner layers. In addition, at the right flow exit the large eddies displayed the mixing between the upper and lower layers at the window vent. More information on these corridor studies can be found in references [11] and [12].

Saltwater modeling

This paper highlights scaling with fire conditions, but the fluid dynamics of buoyancy flows due to fire can be modeled by an analog system, i.e. saltwater into fresh water in an upside-down geometric rendition. In saltwater simulation, Q^* is maintained through the flow rate of dyed saltwater and concentration differences correspond to temperature differences [13]. For systems of negligible heat transfer to the boundaries, the analog equations are identical between energy and salt. Visualization in saltwater modeling of complex smoke filling of two rooms connected by a

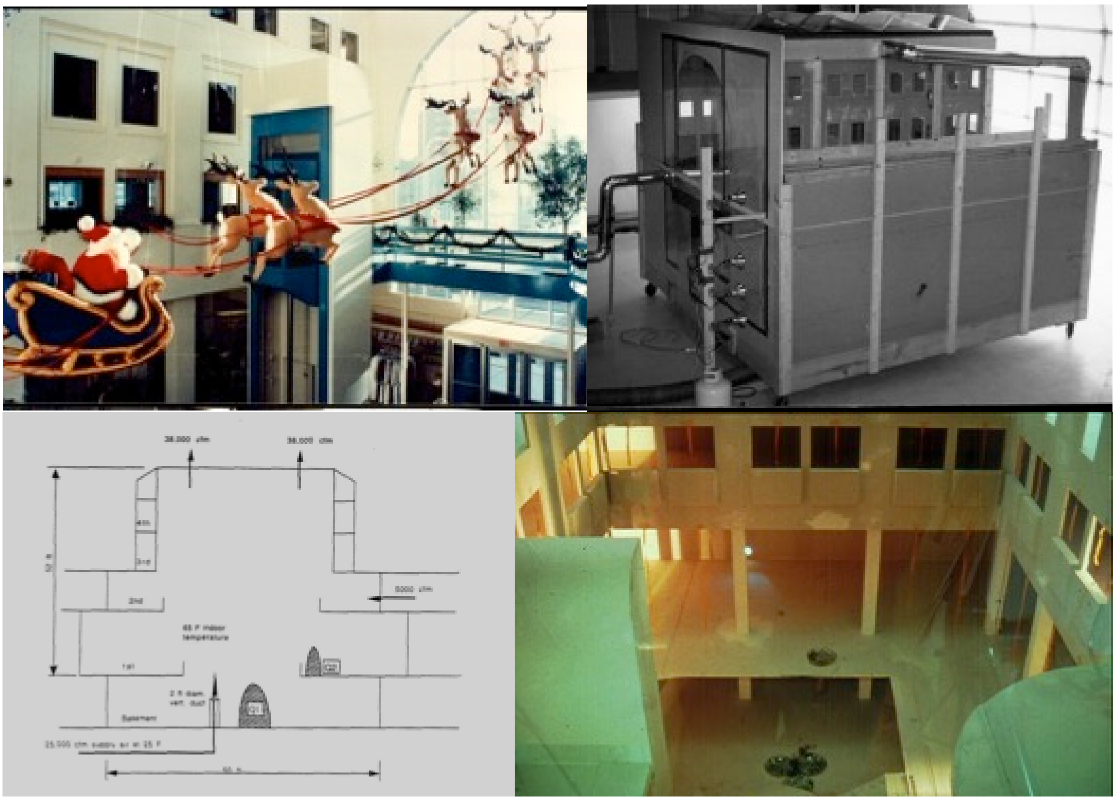

Fig. 9. Fire origin and scale model of the Hart Albin atrium and smoke control system.

Fig. 10. Full scale with 4.5 m complex baffled ceiling, and 1/8th scale model.

single ceiling vent is an example (Fig. 7) [14].

Smoke control in an atrium

Shortly before 6:45 am on December 17, 1988, a fire occurred in the atrium of the historic Hart Albin department store in Billings, Montana (Fig. 8). The fire occurred on a polystyrene and wood Santa Claus and sleigh display suspended in the atrium, as shown in Fig. 9. The burning display fell to the basement and first floor landings, as shown in the schematic of the atrium in Fig. 9. As a consequence, the smoke control system was automatically initiated. It consisted of two 38,000 cfm fans mounted at the roof of the atrium and two supplies. The primary supply fan injected 25°F ambient air through a 2 ft. diameter vertical duct at 25,000 cfm from the basement level of the atrium. A secondary supply diffusely injected 5000 cfm at the 2nd floor level. Smoke accumulated throughout the atrium and the adjoining store levels. This Christmas fire forced the Hart-Albin Department storeowners into bankruptcy in 1990.

The motivation of this department store study was a civil litigation by the insurer against the installers of the air ventilation system. It was alleged that the smoke dampers were not activated and this caused smoke to progress throughout the entire store. Alternatively, the smoke control system design, which was in compliance with a California code, could have been faulty. The

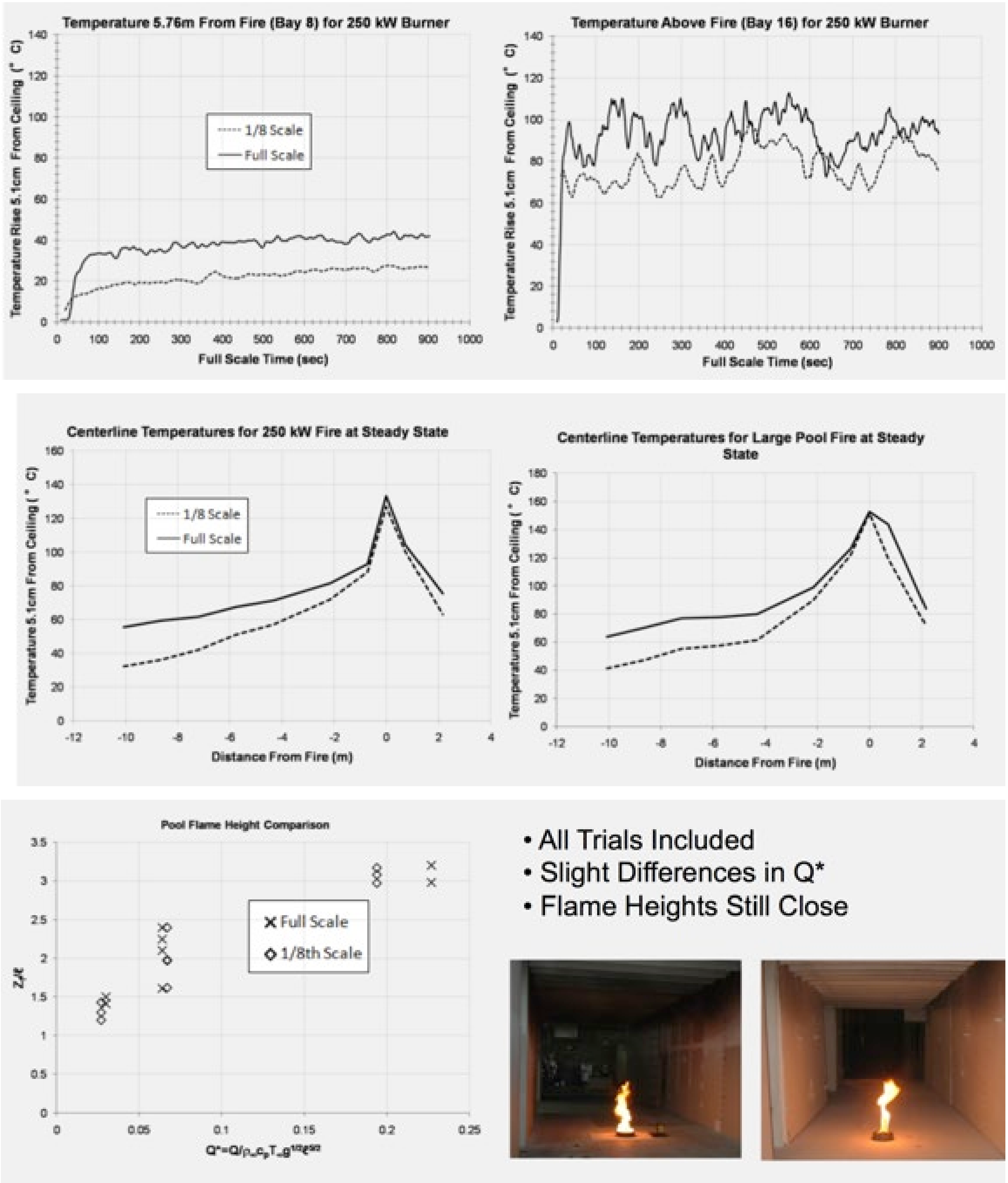

Fig. 11. Comparison of temperatures, and scaled flame heights for various fires.

vertical intake of outside air directed upwards into the atrium had been intended to assist the rise of smoke to the exhaust fans at the atrium roof. Instead it helped to mix and overturn the smoke layer and carried smoke throughout the building. A scale model, using burners for the two fires, (Fig. 9) proved this point [10].

The court decided that the smoke vent defendants were not liable, the model results could not be used by any of the other defendants, and the model would be returned for our use after the litigation. The model was built in a warehouse outside of Billings MT, and the experiments were run outside under a cold night sky in March to assuage the owners of the warehouse on safety. The model was made available to us following this case, but no funding could be secured to continue the study of smoke control in an atrium. Evidently to some, scale modeling is not convincing.

Some scaling equations are presented in the following for the atrium fire. These are indicative of the equations used for developing or static fires where radiation is ignored and early fire dynamics and smoke movement is the study aim. The Π-groups can be related to Table 1 with some combination of groups. Flow time is scaled here as $(l/g)^{1/2}$.

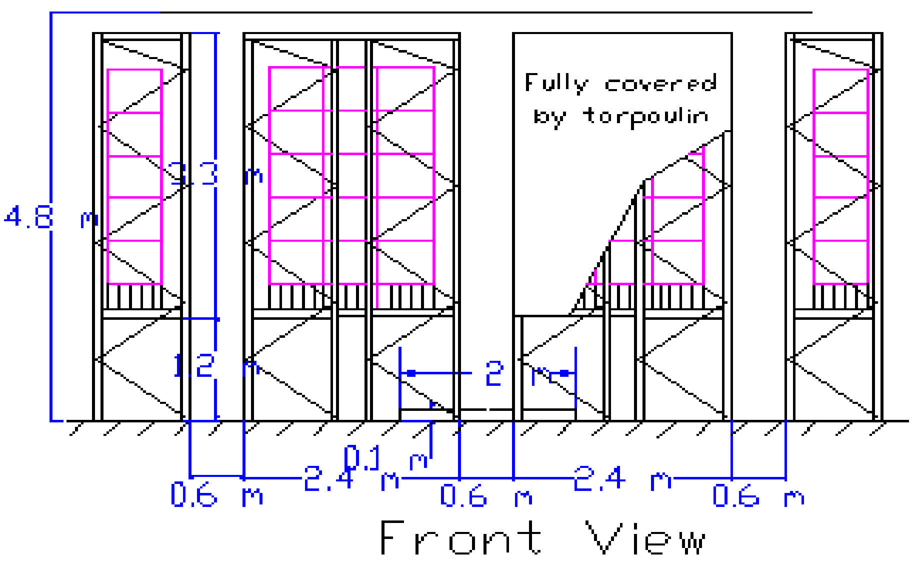

Fig. 12. MSC 914 full scale test arrangement with heptane pool and truck bed commodities.

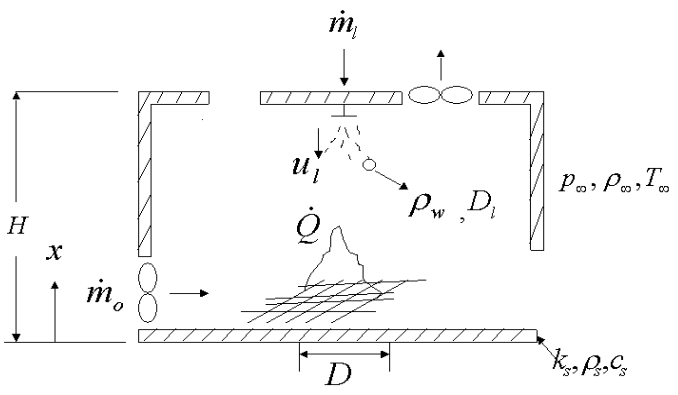

Fig. 13. Phenomena to be scaled.

$$\begin{Bmatrix} \dfrac{T}{T_o} \\ \dfrac{v}{\sqrt{gl}} \\ \dfrac{p}{\rho_o g l} \\ \dfrac{T_w}{T_o} \end{Bmatrix} = f\left(\frac{x}{l},\frac{y}{l},\frac{z}{l},\frac{t}{\sqrt{(l/g)}},\pi_Q,\pi_w,\pi_{fan}\right)$$

$$\pi_Q = Q_l^* = \frac{\dot{Q}}{\rho_o c_p T_o g^{1/2} l^{5/2}}$$

$$\pi_{fan} = \frac{\dot{V}}{g^{1/2} l^{5/2}}$$

$$\pi_w = g^{0.3} v^{1.6} k^2 (k\rho c)_w^{-1} l^{0.9}$$

Complex corridor ceiling

Another study involved a complex corridor arrangement that had been used for a forensic investigation at the ATF Fire Laboratory (Fig. 10); the National Institute of Justice (NIJ) funded the work to demonstrate the use of scale modeling for fire investigation [16]. The scale model was rendered as 1/8th geometric scale with dimensions 2.2 m long × 0.97 m wide × 0.56 m high, and both model and prototype are shown in Fig. 10; Allison Carey crawled inside to instrument it, details of which and more can be found in her thesis [17]. Gas burners and heptane pool fires were considered; results are shown in Fig. 11.

Scaling with suppression

Several years ago a problem arose to see if water suppression could extinguish or control a large test fire established to qualify suppression systems for ferry ships in Europe (Maritime Safety Committee Circular MSC 914). An attempt to pass the test, invented at SP (the Swedish national laboratory in Boras), failed with sprinklers. Vtec secured funding from the Office of Naval Research (ONR) under a Small Business

Innovative Research (SBIR) grant to develop a successful water-mist type sprinkler design to pass the MSC 914 test.

Our approach, working with Vtec Laboratories, was to scale the test, and then select a variety of nozzle types, configurations, and flow rates to suppress the scaled-fire [17,18]. When an appropriate type was confirmed, scale up of the nozzle configuration and flow rates would begin to test fire suppression at full-scale. As a spoiler, the scale modeling approach would lead us to a successful sprinkler design.

The MSC 914 suppression scenario is a large heptane pool fire of 3 m² attacking combustible cargo of stacked cardboard boxes containing FM Global polystyrene cups on two covered open-bed full-scale trailer-trucks. We conducted a successful full-scale suppression control test, but not without difficulty. The test was done in a building open at two ends in near freezing weather. In our first test, the sprinklers opened and began to engage the fire but suddenly the facility water supply failed, and the building was nearly destroyed before the fire fighters could react. After much finger pointing, we were removed from the site. Later, cooler heads allowed us to conduct one more test with a now operational water supply system. The dramatic failure of the water system, and resulting large fire that threatened the building, took several firefighters some time to control and protect the building, demonstrated the potential fire growth hazard capacity of the heptane and trailer truck commodity. The second test with the designed sprinkler system was sufficient to control the fire.

Fig. 12 shows aspects of the MSC 914 full-scale features; the geometric scaling for the model was 1/4. In this work, the flow rate, water droplets, pool fire, commodities and thrust of the spray were scaled. It is not likely that a design nozzle configuration could have been efficiently found without using a scaling strategy.

A full-scale MSC 914 fire test without automatic suppression determined the fire to be very difficult to extinguish. Just 1 minute after ignition, manual suppression was begun and it took several hours to completely extinguish the fire because once the flames spread into the cargo they were shielded from the water. Hence, the design criterion for a small droplet sprinkler system to be successful controlling the fire was deemed to be within 1½ minutes, at most.

Some details of the scaling are presented in the following; Fig. 13 displays a general description of the problem and the variables involved (in this case no fans were present). The geometry, the fire, water spray and construction materials needed to be modeled for scaling, and the approach to select the scaling parameters used the governing conservation equations [17, 18]. The fluid and water parameters were a function of geometry, time and many other variables, as illustrated in the functional equation below. The objective was to select the most significant dimensionless variables that could be practically controlled, and then to test the performance of the system at the reduced scale with known nozzle properties. More complete details can be found in [17, 18] where analyses are presented in establishing the "best" choices for scaling.

The variables in suppression modeling with significant flame radiation are:

$$\left(\frac{\rho}{\rho_\infty}, \frac{u}{\sqrt{gH}}, \frac{p'}{\rho_\infty gH}, \frac{T}{T_\infty}, \frac{T_s}{T_\infty}, \frac{\dot{m}_w}{\rho_\infty\sqrt{gH}}, \frac{D_l}{H}, \frac{n}{H^3}, \frac{\bar{\rho}_l}{\rho_\infty}, \frac{u_l}{\sqrt{gH}}\right)$$

These variables are a function of:

$$\left(\begin{array}{c} \frac{x}{H}, \frac{t\sqrt{g}}{\sqrt{H}}, P_r, \frac{c_p T_\infty}{h_{fg}}, \frac{\rho_\infty}{\rho_l}, \frac{c_p T_\infty}{gH}, \frac{c_p}{c_v}, \frac{\rho_\infty\sqrt{gH}H}{\mu}, \\ \frac{\sigma T_\infty^3 \kappa H}{\rho_\infty c_p\sqrt{gH}}, \frac{\dot{Q}}{\rho_\infty c_p T_\infty\sqrt{g}H^{5/2}}, \frac{\dot{m}_o}{\rho_\infty\sqrt{gH}H^2}, \\ \frac{D_o}{H}, \frac{\dot{m}_{l,o}}{\rho_\infty\sqrt{gH}H^2}, \frac{D_{l,o}}{H}\left(\frac{\rho_\infty\sqrt{gH}H}{\mu}\right)^{1/3}, \\ \frac{x_s}{\left(\left(\frac{k}{\rho c}\right)_s\sqrt{gH}H\right)^{1/2}}, \frac{n_o}{H^3}, \\ \frac{k}{\left((k\rho c)_s\sqrt{gH}H\right)^{1/2}}\left(\frac{\rho_\infty\sqrt{gH}H}{\mu}\right)_r^{0.8}\mathrm{Pr}^{1/3}, \\ \frac{\sigma T_\infty^3}{\left(k\rho c\sqrt{g/H}\right)^{1/2}} \end{array}\right)$$

The following scaling choices were selected for control.

1. Fuel:

Heat release rate:

$$\frac{\dot{Q}}{\rho_\infty c_p T_\infty\sqrt{g}H^{5/2}} \Longrightarrow \dot{Q} \propto H^{5/2}$$

Radiation absorption coefficient:

$$\frac{\sigma T_\infty^3 \kappa H}{\rho_\infty c_p\sqrt{gH}} \Longrightarrow \kappa \propto H^{-1/2}$$

2. Water spray:

Thrust of spray, F:

$$\hat{F} = \frac{F}{\rho_\infty (gH)^2 H} \Longrightarrow F \propto H^3$$

Droplet diameter, D_l:

$$\hat{D}_\mu = \frac{D_l}{H/\mathrm{Re}_H^{1/3}} = \frac{D_l}{H}\left(\frac{\rho_\infty\sqrt{gH}H}{\mu}\right)^{1/3} \Longrightarrow D_l \propto H^{1/2}$$

Droplet evaporation rate per unit area per droplet:

$$\hat{\dot{m}}_\mu = \frac{\dot{m}_w}{\rho_\infty\sqrt{gH}/\mathrm{Re}_H^{1/3}} \Longrightarrow \dot{m}_w \propto H^0$$

Number of droplets per unit volume, n:

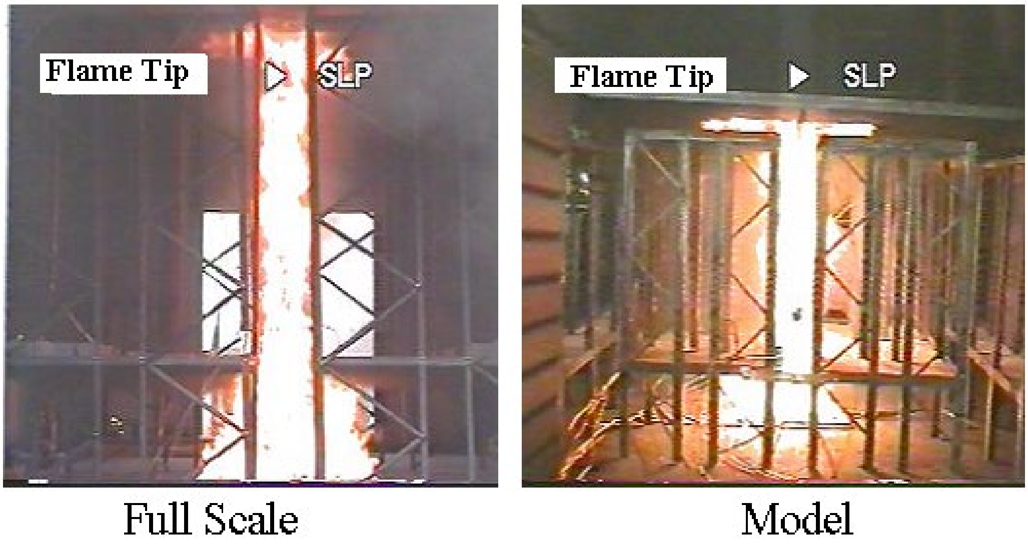

Fig. 14. Full and 1/4 scale of heptane pool fire between truck trailer faces.

Table 2. Scaled conditions that resulted in extinction between the trailers.

Nozzle	Orifice diameter (in. / mm)	Extinction in slot (gpm)
P54	0.054 / 1.37	> 1.16
P80	0.080 / 2.03	1.84–2.22
L66	0.066 / 1.68	1.02–1.19
L120	0.120 / 3.05	2.7–3.32

Table 3. Pool fire fuel scaling.

	Full-scale	Model gas	Model liquid
Fuel	Heptane	Propylene	0.65 methanol + 0.35 toluene
Heat of combustion, kJ/g	41.2	40.5	0.65(19.1) + 0.35(27.7) = 22.1
Firepower, kW$\sim H^{5/2}$	9,250	289	289
Absorption coef., $\mathrm{m}^{-1} \sim H^{-1/2}$	15	24	0.65(6.5) + 0.35(54) = 23
Fuel pan, x_1 by x_2, $x \sim H^1$	1.5×2.0	0.38×0.5	0.55×0.73
Duration of fire, $t \sim H^{1/2}$	80	50	50
Firepower with commodities (60 s after ignition in FS)	10,400	325	325
Sprinkler activation after ignition, s	60	40	20
Fire duration in water tests, s	NA	160	80

$$\hat{n} = n\frac{H^3}{\mathrm{Re}_H} = \frac{n}{\mathrm{Re}_H/H^3} \Longrightarrow n \propto H^{3/2}n$$

Water flow rate:

$$\widehat{\dot{m}}_{l,0} = \frac{\dot{m}_{l,0}}{\rho_\infty\sqrt{gH}H^2} \Longrightarrow \dot{m}_{l,0} \propto H^{5/2}$$

3. Construction material:
Thermal inertia of solids:

$$\frac{\sigma T_\infty^3}{\left((k\rho c)_s\sqrt{g/H}\right)^{1/2}} \Longrightarrow (k\rho c)_s \propto H^{1/2}$$

Thickness:

$$\frac{x_s}{\left(\left(\frac{k}{\rho c}\right)_s\sqrt{\frac{H}{g}}\right)^{1/2}} \Longrightarrow \frac{x_s}{\left(\frac{H^{1/2}}{H^{1/2}}H^{1/2}\right)^{1/2}} \Longrightarrow x_s \propto H^{1/4}$$

4. Heat flux to surface:
Radiant heat flux:

$$\dot{q}''_{rad} = (1 - e^{-x})T^4 - T_s^4 \propto H^0$$

Convective heat flux:

$$\dot{q}''_{conv} = h_s(T - T_s) \propto \frac{k}{H}\left(\frac{\rho\sqrt{gH}H}{\mu}\right)^{4/5} \propto H^{1/5}$$

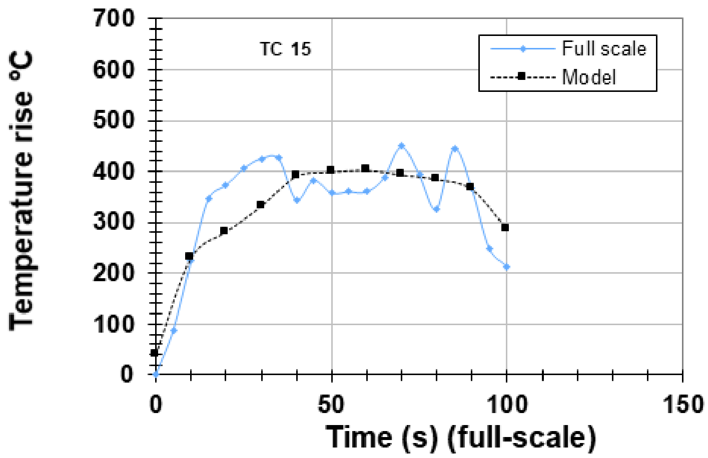

Fig. 15a. Temperature comparison for pool fire alone.

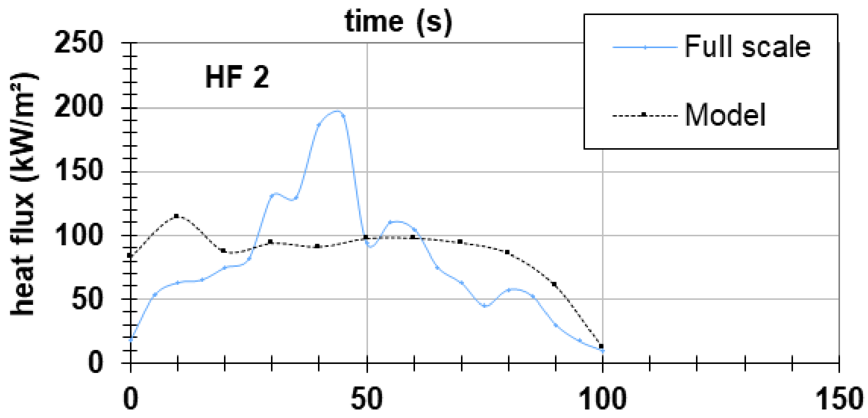

Fig. 15b. Heat flux comparison for pool fire alone.

Table 4. Material selection in scaling, 1/4 scale.

Material	Thickness $\delta \sim H^{1/4}$ mm		Density $\rho_s \sim H^{1/4}$ g/cm3		Thickness Scaling ratio (M/FS)		Density Scaling ratio (M/FS)	
	FS	M	FS	M	Actual	Required	Actual	Required
Cardboard	3	2	0.67	1.0	0.67	0.71	1.5	0.71
PS cups	1	0.8	0,80	0.71	0.80	0.71	0.75	0.71
Steel structure	4.7	1.3	0.67	0.5	0.67	0.5	1	1
Ceiling	15	15	1	0.71	1	0.71	1	0.71

Total heat flux to surface:

$$\dot{q}_s'' = \dot{q}_{rad}'' + \dot{q}_{conv}'' \propto H^0 + H^{1/5} \approx H^0$$

Modeling the fire

First, how well the heptane pool fire could be modeled at 1/4-scale was examined; this was a big fire and radiation was a consideration. Also control in the scale test was a factor, so a gas burner was used with propylene. The absorption coefficient of the propylene needed to be $\kappa \sim \kappa_{\text{heptane}}(1/4)^{-1/2} = 15\ \text{m}^{-1}(2) = 30\ \text{m}^{-1}$ while its reported value is $24.1\ \text{m}^{-1}$—good enough. The heptane pool fire was modeled as a 9.2 MW fire for 80 s. A comparison of the full-scale heptane fire between the two truck trailers and the 1/4-scale is shown in Fig. 14; the flame shapes should be geometrically identical for good scaling. Fig. 15 shows temperature and heat flux comparisons for these tests.

Scaled water suppression tests

It was decided to continue to use a gas burner for the 1/4-scaled tests to establish the small-scale sprinkler specifications; this was done by estimating the full-scale energy release rate one minute into the full-scale

Fig. 16. Scaled MSC 914 tests: cartons, configuration and suppression of fire.

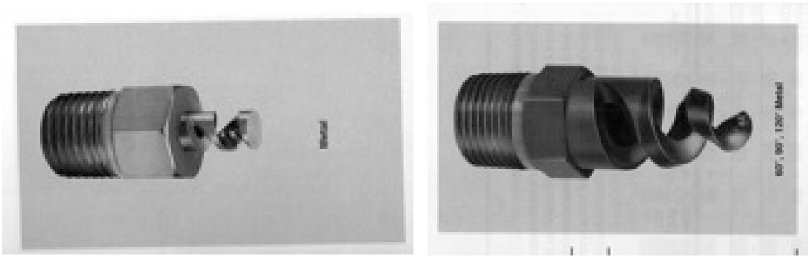

Fig. 17. L66 1/4 scale nozzle (left) and TF18 full-scale nozzle (right).

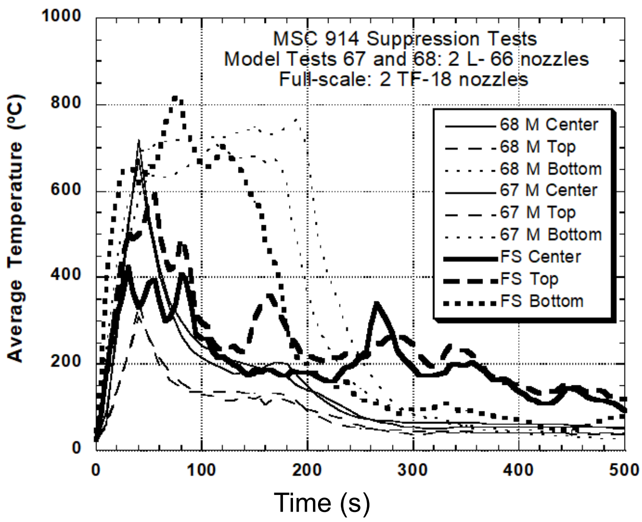

Fig. 18. MSC 914 suppression in 1/4 and full-scale.

Table 5. Scale-up nozzle design.

Parameter		1/4-model L-66 nozzle	Full-scale required	TF18 Specs.
Nozzle diameter,	in	0.066	0.264	0.281
$D \sim H$	mm	1.7	6.7	7.1
Droplet diameter,				
$D_{l,o} \sim H^{1/2}$	mm	80	160	170
Pressure,	psi	150	600	496
$p \sim H$	MPa	1.04	4.14	3.42
Water flow rate	gpm	1.46	46.7	47.2
(per nozzle)$\sim H^{5/2}$	L/s	0.092	2.94	2.97

MC 914 test, at which point the fire was out of control.

The full-scale heptane fire initially contributed 9.2 MW and the commodity fire grew to 10.4 MW after one minute; thus, the criterion for successful control was that it must begin within 1 minute after start of the fire. The gas burner simulated the heptane and growing fire up to 1 minute and the scaled test used sheet metal boxes to simulate the geometry of the trailer cargo

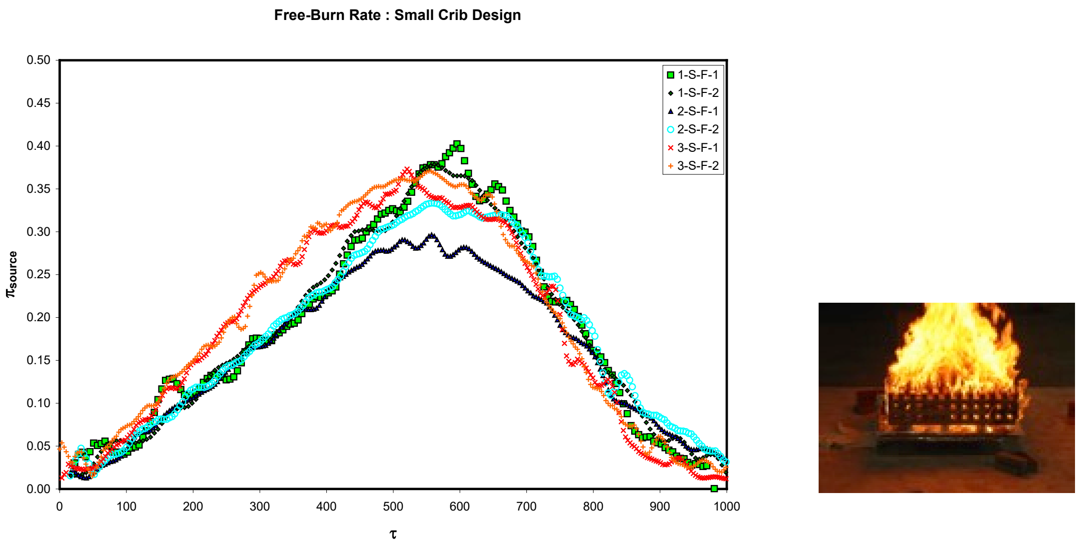

Fig. 19. Dimensionless burn rate and time for wood cribs.

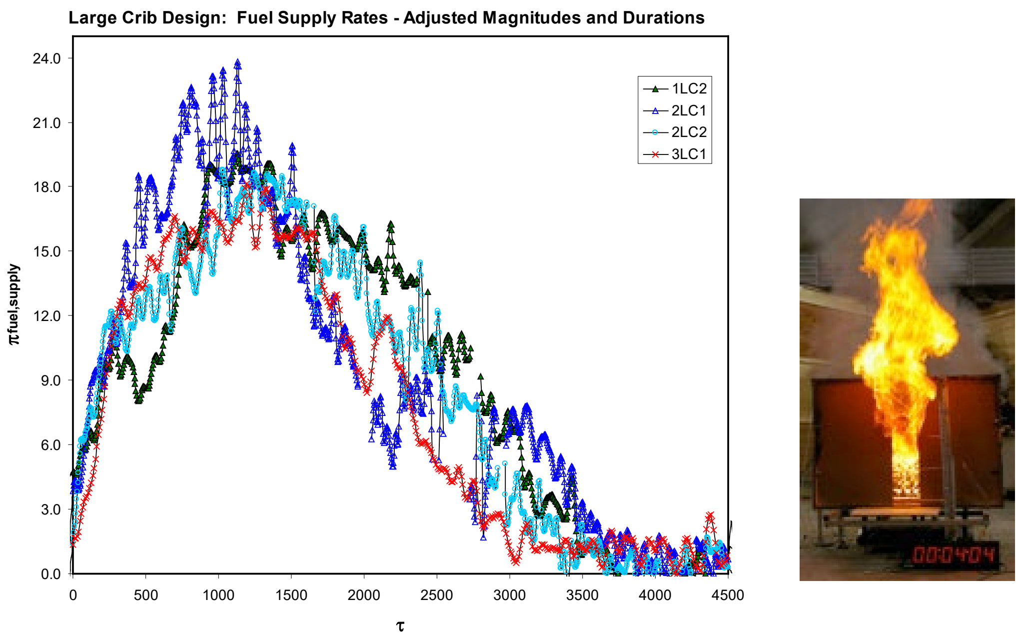

Fig. 20. Dimensionless burning rate within compartments.

commodity. Several candidate nozzles were selected for testing, and their flow rates, droplet sizes and thrusts were varied until satisfactory fire control was achieved. The suppression condition for each nozzle is presented in Table 2.

After the inert commodity tests were completed and a candidate design nozzle configuration was selected, actual 1/4-scale commodity tests were performed using a liquid fuel; pool fire simulation data are summarized in Table 3, and the commodities and structure were scaled, as shown in Table 4. Two L66 nozzles, 91 cm apart in the slot between the trailers, were selected for the scaled liquid pool and commodities fire (Table 5). The scaled tests are indicated in Fig. 16 with suppression indicated by the "knockdown" for fire in the slot.

Scale-up test

After two L66 nozzles were found to be effective in suppression during the scaled MSC 914 test, an appropriate scaled-up nozzle was identified for the full-scale test. The nozzles were of a swirl-type and are shown in Fig. 17; the required and actual conditions for scaling up are given in Table 5.

Fig. 18 shows the results for the temperatures in the central slot between the trailers at the top, mid-height and bottom. The nozzles were manually opened 45 seconds after beginning of the fire in the full-scale test.

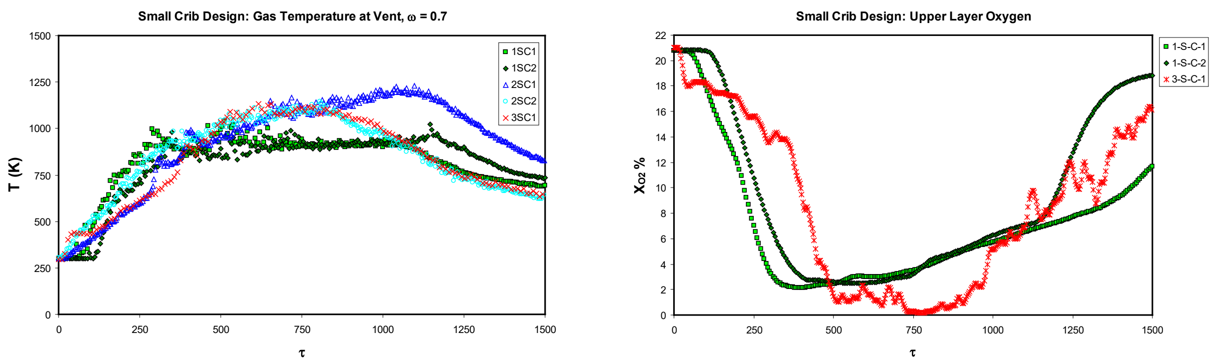

Fig. 21. Compartment temperature and oxygen concentrations at three scales.

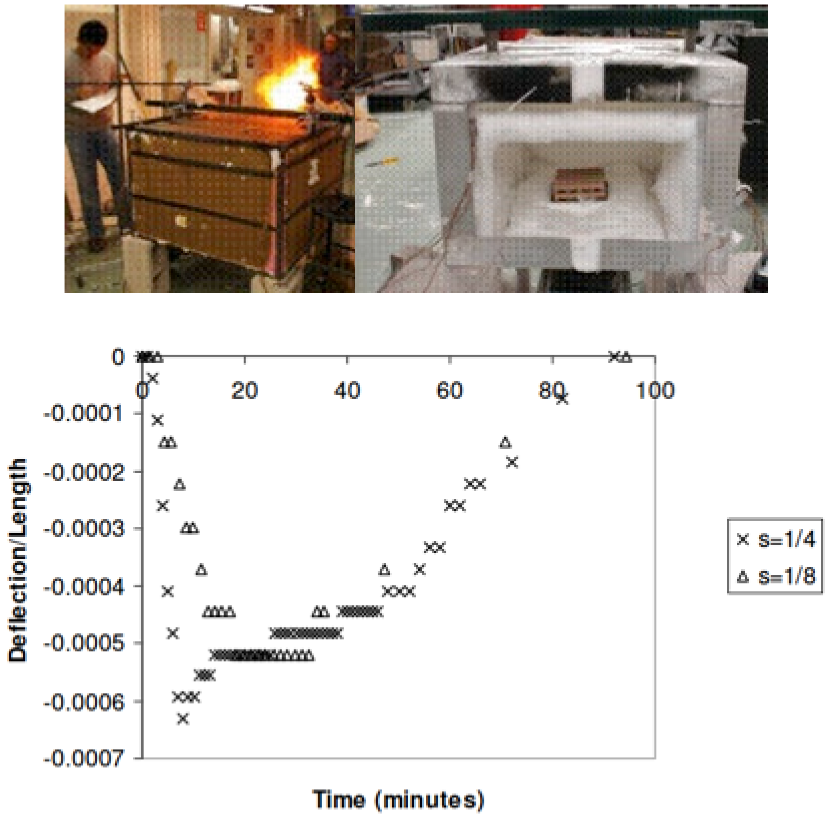

Fig. 22. Deflection of an insulated steel frame at two scales.

Also, two repeated, small-scale results are shown for the L66 nozzles used in Tests 67 and 68 that indicate reproducibility, and the full-scale test with Nozzles TF18 indicate good scaling results. In all cases, the fire was suppressed in the slot and pushed down.

Fully developed fire and structures

Following the collapse of the World Trade Center (WTC) caused by a terrorist attack on September 11, 2001, a proposal was made to study the fire and its collapse by scale modeling. It was common for structural engineers to use scale modeling as a tool before about 1960; indeed, even impact on structures could be modeled, so the effect of an aircraft impact could be simulated. The advantage to such an approach is that it would provide data with respect to a real event where no data existed and then mathematical modeling could be validated against the scaled simulations. Moreover, the scaled experiments would offer insight, repeatability and parameter variations during tests. Although this testing was not done in the official investigation, it prompted a NSF grant that allowed generic enclosure testing of the effects of fire on insulated loaded steel structures. The study examined the scaling of wood crib burning freely and within compartments and insulated steel loaded structures [20–23]. The work by Perricone [20] presents a

Fig. 23. Aspects of scaling a floor of the North WTC Tower fire.

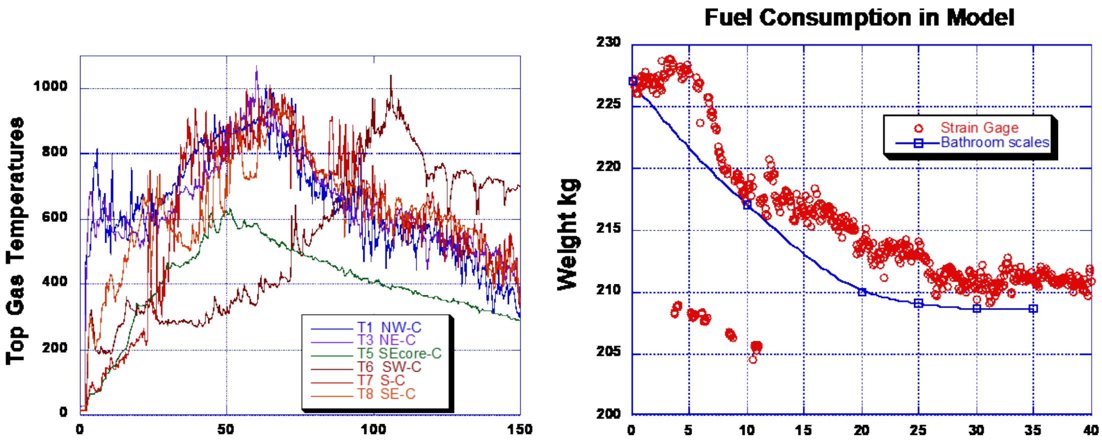

Fig. 24. WTC model temperatures versus real time and fuel weight versus time in the model. (Real time $= (20)^{1/2} \times$ Model time).

detailed analysis of wood cribs burning in compartments of scales of 1, 2 and 3/8th relative to typical full-scale rooms. Some examples of this work on enclosure fires and structures will be presented.

Fig. 19 shows the dimensionless burning rate for freely burning wood cribs of three scales with scaled time:

$$\pi_{source} = \frac{\dot{m}_{crib}}{\rho_\infty \sqrt{g} H^{5/2}}, \tau = \frac{t}{\sqrt{H/g}}$$

Fig. 20 shows the dimensionless burning rate for the three scales within the scaled compartments. Fig. 21 shows corresponding examples of compartment temperature and oxygen concentration for three scales. Fig. 22 shows dimensionless deflection over scaled time for two scales. Details of all the scaling have not been elucidated here but aspects of the steel insulation, structure, compartment and crib construction have been considered and the reader is referred to the references for more information. It would appear that scale modeling for aspects of the WTC tower fires and collapse could have been studied at reduced scale.

Scale model of a floor of the WTC fire

A student class at the University of Maryland scaled an aspect of the WTC fire by examining the fire aspects and geometry of the 96th floor of the North WTC Tower. They reconstructed a 1/20th geometric model of the event. In groups, they established the vented area

Fig. 25. Scale modeling of a bedroom fire.

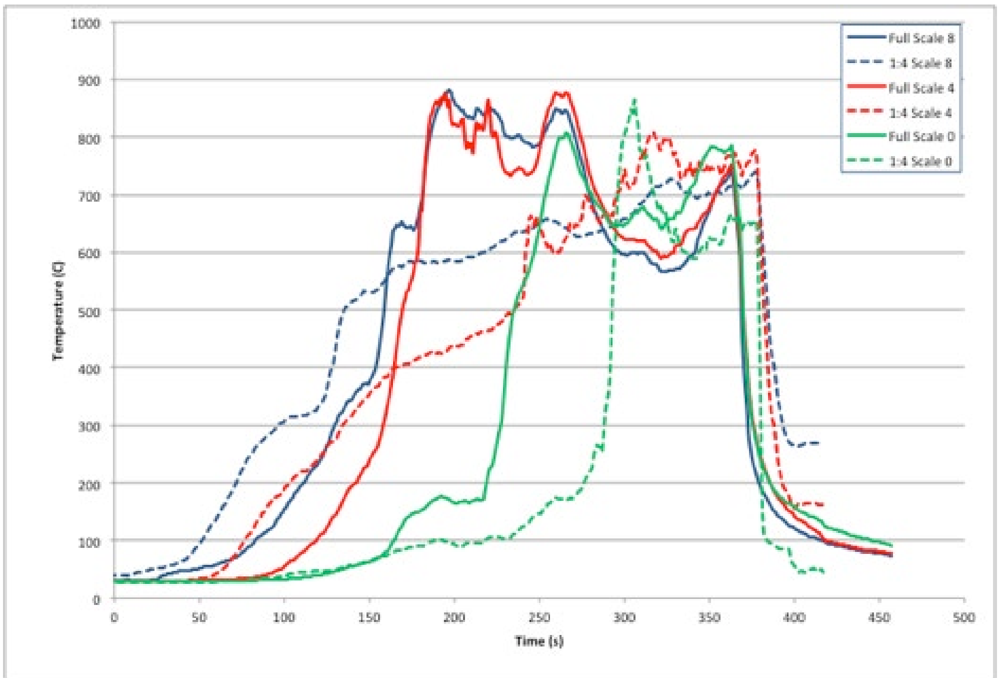

Fig. 26. Temperature at the center of the room full and 1/4 scale.

caused by the aircraft and window breakage due to fire movement, the fuel load in the office space, the fuel burned by the aircraft, and the construction of the floor. A graduate student even added a scaled insulated floor truss and an external column. All of these aspects were taken into account in the scaling; Marshall, et. al. detail the work done by the students [24].

The students also designed and built many of the instruments needed to measure temperature, mass loss and smoke concentration over time. Vent openings were timed to the actual event times for window breakage on each wall. Fig. 23 shows some aspects of this scaling project. The class, the layout of the fuel load as wood cribs, the damage, the flames through vented areas on each side, and the structural damage to a floor truss were examined. The components of the experiment were assembled the Monday after the Fall Thanksgiving break, and an experiment was run on Tuesday to an invited assembly.

Fig. 24 displays the measured upper smoke temperatures as the fire moved through the floor. The fire was ventilation-limited and, as such, all of the simulated office fuel load (wood cribs) burned over a portion as the fire progressed around the floor. Fig. 24 also displays the mass of the fuel, as measured by two techniques: (1) a strain gauge of student design and (2) bathroom scales at each support. In the actual event, the North Tower collapsed in 102 minutes.

Fire growth of a bedroom to flashover and full development

This last example stretches the ability of scaling. It is not possible to maintain all of the key dimensionless groups in fire growth on real furnishings, but we wished to see how far the abilities of scaling could take us; the results are yet to be published [25]. The hypothesis for scaling was to construct all room dimensions and overall furniture elements to a geometric scaling of 1/4. All materials between the full-scale and model were the same and had identical thicknesses; in other words, for scaling of a mattress,

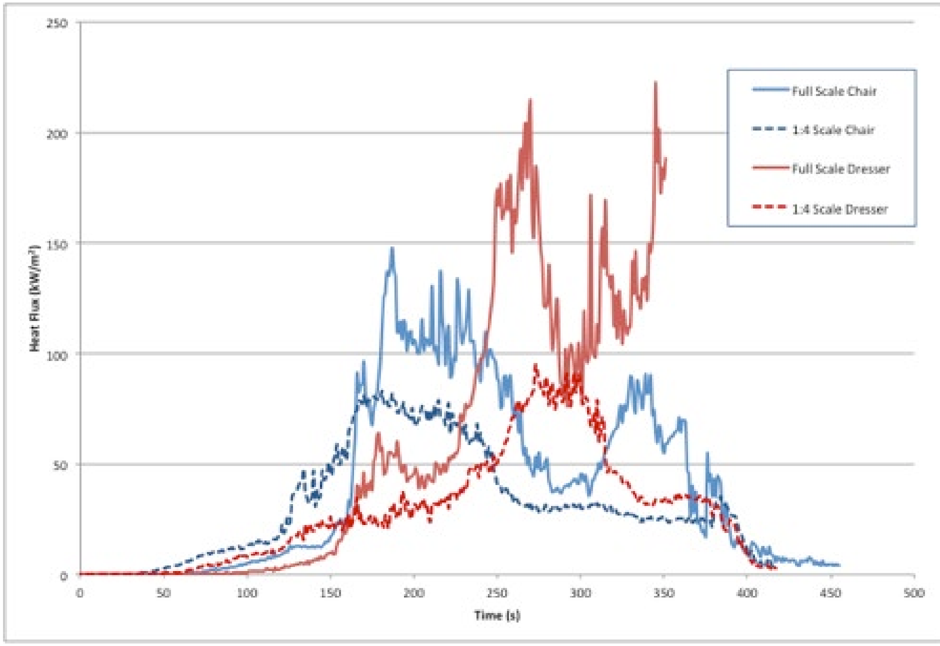

Fig. 27. Heat flux at the two locations in the room full and 1/4 scale.

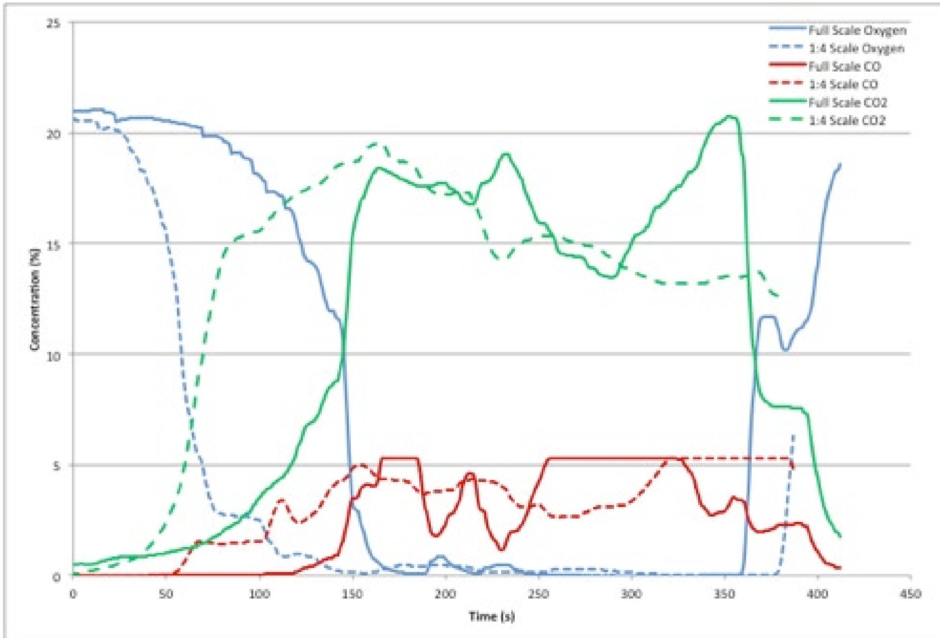

Fig. 28. Gas concentrations in the smoke for the full and 1/4 scale room.

the overall object was ¼ scale but the foam and coverings were of the same thickness in the full-scale and model. This work was part of a grant from NIJ and a cooperative study with the ATF Fire Laboratory; L. Reeves, an ATF agent, contributed as part of his certification for fire investigations. Because he liked to make his own furniture, he built all of the models according to their exact composition in the full-scale test. Analysis of the scaling indicated that the early growth of the fire would be faster in the model due to flame spread moving proportionately more, but later the full-scale growth would go faster; after the smoke layer got above 300 °C, radiation in the full-scale dominated and made it grow faster. However, surprisingly the phenomena of growth were the same, carbon monoxide levels comparable and the overall results proved potentially useful for both design and investigation. Fig. 25 shows some of these results; Figs. 26 – 28 show, accordingly, the temperatures in the center of the room, the heat fluxes and the gas concentrations plotted for the full-scale and model with a full-scale time axis. The results were consistent with expectation, and remarkably showed a similar progression of the fire, although not perfect in time.

Conclusions

This paper has tried to illustrate my experience with the use of scale modeling. It is a neglected technique that could play a useful role in performance based-design and fire investigation. It is a tool that requires understanding of the phenomena to be scaled so that all dimensionless variables are preserved. It can provide a source of valuable insight and a validity check on mathematical modeling.

Acknowledgements

This presentation could not be made without the contributions of colleagues and students.

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