Scale Modeling in Fire

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ABSTRACT

Following Ref. [17], a review is made of work on scale modeling in fire is presented from the experience of the author. Primarily scale modeling in air is discussed but there is a brief discussion of 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 are made for the partial scaling of specific fire scenarios. Studies have been motivated by basic research interests as well as for fire investigation. The dynamics 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 its design flaws. The challenge to develop a water mist system to pass a fire test designed to insure safety on transport ferries was systematically done using a scale model, and confirmed at full-scale. Scaling was examined for a fire development in a furnished bedroom pushing the limited of modeling to its utmost, but finding some success in illustrating very similar overall behavior.

KEYWORDS: Dimensionless groups, fire, scale modeling.

INTRODUCTION

Analysis and design in fire safety and investigation have used computer models or formulas as tools. Phenomena scale smaller than the 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 are then subject to an analysis using some theory and dimensionless parameters that extend 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 formulated 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 somehow widespread is the use of scale modeling as seen by these past symposia [1]. Thomas [2] wrote a

Proceedings of the Ninth International Seminar on Fire and Explosion Hazards (ISFEH9), pp. 49-64
Edited by Snegirev A., Liu N.A., Tamanini F., Bradley D., Molkov V., and Chaumeix N.
Published by St. Petersburg Polytechnic University Press
ISBN: 978-5-7422-6496-5 DOI: 10.18720/spbpu/2/k19-138

telling paper on scale model referring to its execution as “a magic art”. The complex world of fire cannot be brought to perfect similitude as that of subsonic flight that relies only on the Reynolds number as its basis. Scaling in fire may not be perfect in preserving all dimensionless groups, but with an understanding of their role the main 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 rely on the Froude number but ignores the Reynolds number.

The art of scale modeling in fire is demonstrated by the multitude of phenomena that apply and the resulting dimensionless groups to be preserved are overwhelming. Williams [4] list these groups as 29! Table 1 displays 22 Pi-groups that include phenomena including 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.

The paper is primarily based on this author’s experience using physical scale modeling. The omission of other work is not to slight it, as the paper is not meant as a review. Indeed, the reader is encouraged to seek out further examples in the field and of course 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 thesis 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 details may be obscured by brevity. A range of problem will be illustrated from somewhere scaling is nearly perfect to others where perfect scaling is impossible, yet the results can still be invaluable.

MAIN FEATURES OF FIRE SCALE MODELING

Many dimensionless parameters are shown in Table 1. As Thomas said there is a “magic art” to the process. Only a few groups can be preserved in scaling. As in the scaling of ship dynamics, in fire scaling the Reynolds number is not preserved but as full-scale flows are turbulent, the size of the model must be big enough to ensure turbulent flow. This 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. The ability to perfectly scale fire growth is impossible, as too many groups are required for preservation, and they cannot be controlled. 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 there will not be complete scaling of all variables. Indeed, the ultimate key is to preserve enough groups, first principally Q^*, so that the scale model data yield at least the dependent variables: temperature, velocity, and species concentrations. To get the species right, 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, 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 have advantage. 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 simulate it.

Although this paper is not a review, it would be remiss not to mention some key pioneering works. G. Heskestad’s works 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 ¼ the geometric scale model is impressive [7]. These works inspired me 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. The scaling symposia 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.

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	$\hat{p} = p/(\rho_\infty g l)$	$p \sim l^1$
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, m''_F	$m''_F l/\mu$	$m''_F \sim h_c l/(\mu c_p) = \mathrm{Nu}/\mathrm{Pr}$
	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	
$\Pi_1 = \dfrac{\text{inetrtia}}{\text{viscous}}$, Re	$\mathrm{Re} = \rho_\infty \sqrt{g} l^{3/2}/\mu$	Usually ignored ($u \sim l^{-1}$)
$\Pi_2 = \dfrac{\text{fire power}}{\text{enthalpy rate}}$, Q^*	$\dot{Q}/(\rho_\infty c_p T_\infty \sqrt{g} l^{5/2})$	Significant in combustion
$\Pi_3 = \dfrac{\text{radiant emission}}{\text{ideal emission}}$,	κl	$\kappa \sim l^{-1}$, when gas is important
$\Pi_4 = \dfrac{\text{radiant loss}}{\text{fire power}}$, χ_r	$\chi_r = \dot{Q}_r/\dot{Q}$	$\chi_r \sim l^0$, important for free burning
$\Pi_5 = \dfrac{\text{conduction}}{\text{enthalpy}}$, Q^*_k	$(k_w \rho_w c_w)^{1/2}/(\rho_\infty c_p g^{1/4} l^{3/4})$	$k_w \sim \rho_w \sim l^{3/4}$, conduction important
$\Pi_6 = \dfrac{\text{convection}}{\text{enthalpy}}$, Q^*_c	$h_c/(\rho_\infty c_p \sqrt{gl})$	$h_c \sim l^{1/2}$, convection important
$\Pi_7 = \dfrac{\text{radiation}}{\text{enthalpy}}$, Q^*_r	$\sigma T^3_\infty/(\rho_\infty c_p \sqrt{gl})$	$T_\infty \sim l^{1/6}$
$\Pi_8 = \dfrac{\text{thickness}}{\text{thermal length}}$	$(\rho_w c_w/k_w)^{1/2}(g/l)^{1/4}$	$\delta_w \sim l^{1/4}$

$\Pi_9 = \dfrac{\text{fan flow}}{\text{advection}}$, m_{Fan}^*	$\dot{m}_{Fan} \big/ \left(\rho_\infty \sqrt{g} l^{5/2}\right)$	$\dot{m}_{Fan} \sim l^{5/2}$, forced flows
$\Pi_{10} = \dfrac{\text{fuel flow}}{\text{advection}}$, m_F^*	$\dot{m}_F \big/ \left(\rho_\infty \sqrt{g} l^{5/2}\right)$	Fuel mass flux depends on B, Gr, Re
$\Pi_{11} = \dfrac{\text{sensible}}{\text{latent}}$, τ_0	$c_p \left(T_v - T_\infty\right) \big/ L$	Burning rate term
$\Pi_{12} = \dfrac{\text{available } O_2}{\text{stoichiometric } O_2}$, r_0	$Y_{O_2,\infty} \big/ r Y_{F,0}$	Burning rate term
$\Pi_{13} = \dfrac{\text{evaporation energy}}{\text{sensible energy}}$	$M_g h_{fg} \big/ \left(R T_i\right)$	"Activation" of vaporization
$\Pi_{14} = \dfrac{\text{collision loss}}{\text{initial particles}}$	$\hat{n}_{col} = \dot{n}_{col} \big/ \left(\dot{V}_{l,0} \big/ D_0^3\right)$	$\dot{n}_{col} \sim l^1$, collision number rate
$\Pi_{15} = \dfrac{\text{spray thrust}}{\text{jet momentum}}$	$F_0 \big/ \left(\dot{V}_{l,0} \big/ D_0\right)^2$	$F_0 \sim l^3$, D_0 nozzle diameter, $D_0 \sim l^1$
$\Pi_{16} = \dfrac{\text{evaporation rate}}{\text{droplet mass loss}}$	$\dot{m}_g'' \big/ \left(\rho_l D_l \sqrt{g l}\right)$	$\dot{m}_g'' \sim l^0$
$\Pi_{17} = \dfrac{\text{weight of droplet}}{\text{drag force}}$, $\hat{D}_\mu$	$\hat{D}_\mu = D_l \, \mathrm{Re}_l^{1/3}$	$D_l \sim l^{1/2}$
$\Pi_{18} = \dfrac{\text{advection}}{\text{mass transfer}}$	$\mathrm{Pr}^{2/3} \hat{D}_l^{1/2} \mathrm{Re}_l^{1/2}$	$D_l \sim l^{-1/4}$, inconsistent with Π_{17}
$\Pi_{19} = \dfrac{\text{i}^{\text{th}} \text{ enthalpy}}{\text{chemical energy}}$	$Y_i c_p T_\infty \big/ \Delta h_c$	$Y_i \sim l^0$
$\Pi_{20} = \dfrac{\text{droplet momentum}}{\text{surface tension}}$	$\mathrm{We} = \rho_l u_l^2 D_l \big/ \sigma_l$	$D_l \sim l^{-1}$, inconsistent with Π_{17}
$\Pi_{21} = \dfrac{\text{enthalpy}}{\text{combustion energy}}$	$r c_p T_\infty \big/ \left(\Delta h_c\right)$	Nearly always constant
$\Pi_{22} = \dfrac{\text{convection}}{\text{conduction}}$	$\mathrm{Nu} = h_c l \big/ k$	$h_c \sim l^{-1}$

The next set of parameters that need consideration to get the heat loss right for the construction materials are groups Π_5 to Π_8. However, the confluence of radiation, convection and conduction make it not possible to preserve all of these groups. Consequently, something has to give. This can be radiation where the application is a small fire with emphasis on smoke movement and detection; 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.

EXAMPLES OF SCALE MODELING IN FIRE

Three basic applications of scaling with models will be presented. The first deal principally with the early behavior of fire in an enclosure, the second addresses suppression, and the third considers the fully developed fire 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 be considered too.

Corridor fires

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

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

The many questions raised by these floorcovering corridor experiments prompted the use of a scale model along with full-scale tests in 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 the gypsum board construction of the full-scale corridor, and was separately outfitted with glass walls to allow for visualization studies.

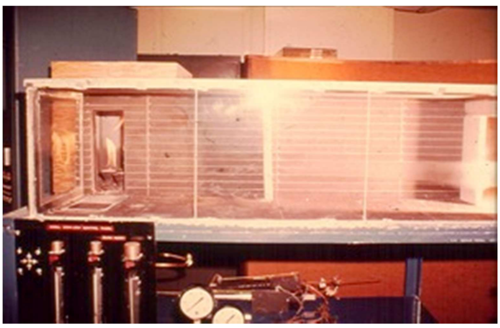

Fig. 2. Scale model of corridor fires

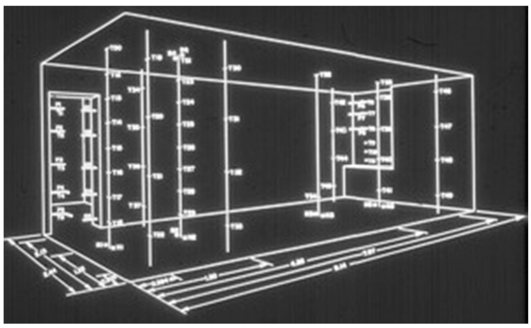

Fig. 3. Full-scale corridor

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. Figure 4 shows the agreement for temperature and scaled velocity.

Visualization of the smoke in the upper layer showed the homogenous upper layer characteristic of compartment fire behavior in Fig. 5. However, by using smoke traces, Fig. 6 shows that the flow within the upper and lower layers was revealed to be more complex: recirculating into four layers with turbulent ceiling and floor jets but laminar inner layers. In addition, at the right flow exit, the large eddies display 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].

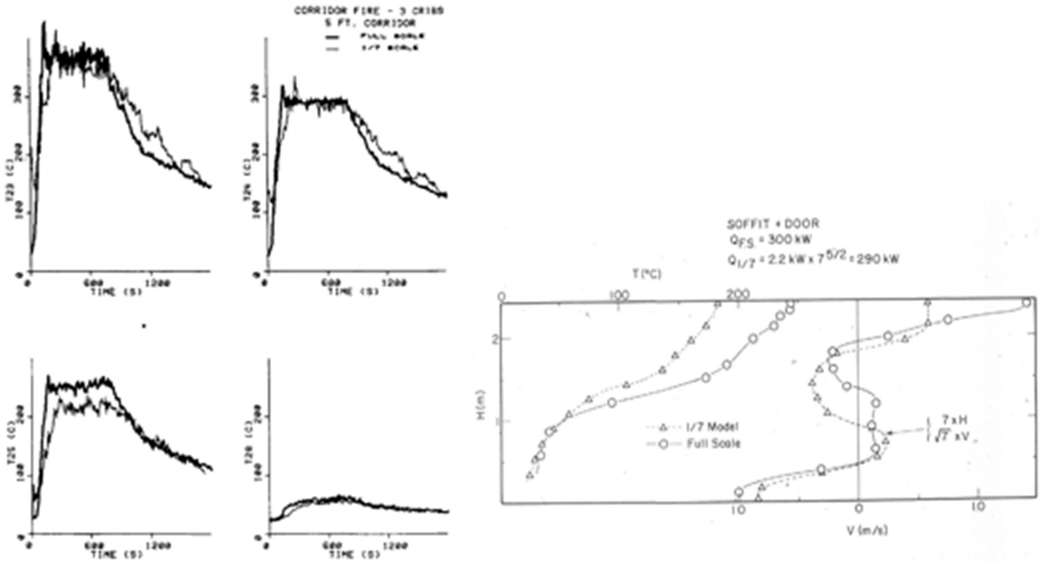

Fig. 4. Temperatures and scaled corridor velocities.

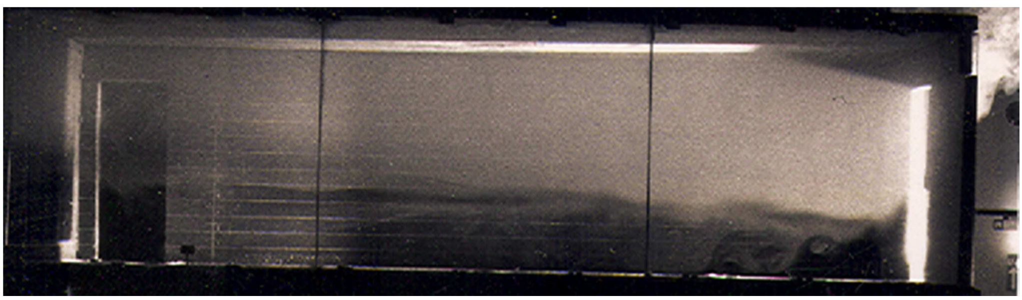

Fig. 5. Smoke layer in a corridor form a room fire.

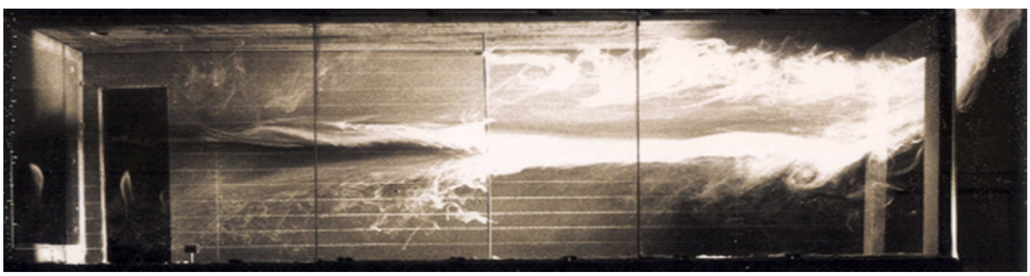

Fig. 6. Recirculating layer flows and mixing at the right vent.

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 1st floor landings as shown in the schematic of the atrium in Fig. 7. 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.

Fig. 7. Hart Albin department store in Billings, Montana.

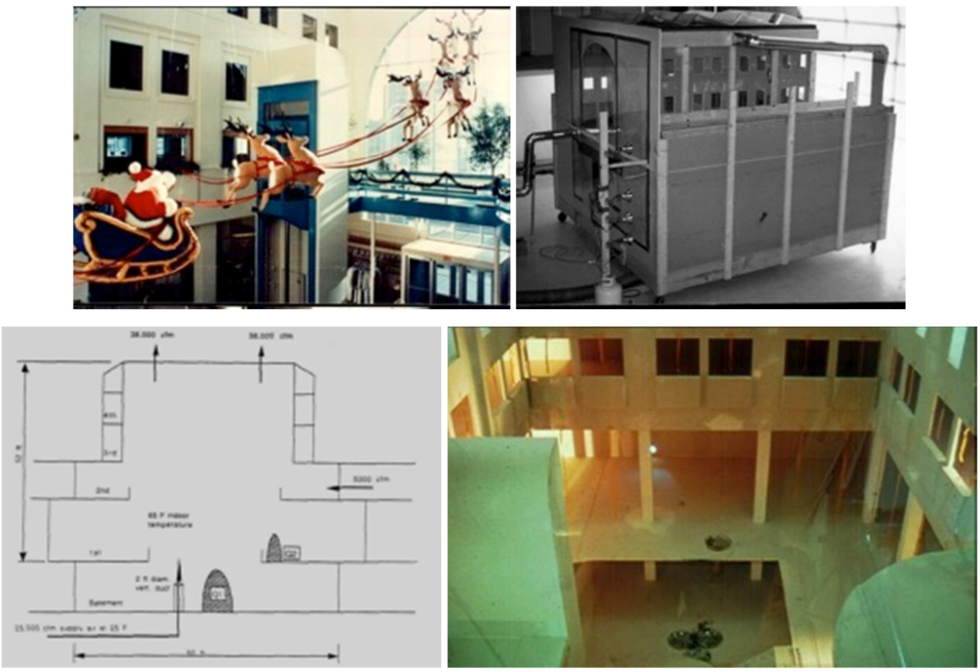

Fig. 8. Fire origin and scale model of the Hart Albin atrium and smoke control system.

The motivation of this study was a civil litigation by the insurer against the installers of an air ventilation system [13]. It was alleged that the smoke dampers were not activated and this caused smoke to progress through the entire store. Alternatively, the smoke control design in compliance with a California code design was faulty. The 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 to 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. Following this case the model was made available to us, but no funding could be secured to continue the study of smoke control in an atrium. To some, scale modeling may not be convincing.

Some scaling equations are presented here for the atrium fire. These are indicative of the equations used for these developing or static fires where radiation was 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 $\sqrt{l/g}$:

$$\left\{T/T_0\,,\ v\big/\sqrt{gl}\,,\ p\big/(\rho_0 g l),\ T_w/T_0\right\} = \mathrm{f}\left(\frac{x}{l},\frac{y}{l},\frac{z}{l},\frac{t}{\sqrt{l/g}},\Pi_Q,\Pi_w,\Pi_{Fan}\right), \tag{1}$$

where

$$\Pi_Q = Q_l^* = \dot{Q}\Big/\left(\rho_\infty c_p T_\infty \sqrt{g}\, l^{5/2}\right),\ \Pi_{Fan} = \dot{V}\Big/\left(g^{1/2} l^{5/2}\right),\ \Pi_w = g^{0.3} v^{1.6} k^2 l^{0.9}\Big/\left(k_w \rho_w c_w\right). \tag{2}$$

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 Industrial 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 [14,15]. Once found we would scale up the nozzle configuration and flow rates and test the suppression at full-scale. 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 m^2 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 and took several firefighters some time to control the fire 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.

Figure 9 shows aspects of the MSC 914 full-scale features. The geometric scaling for the model is

¼. In this work, the flow rate, water droplet, 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.

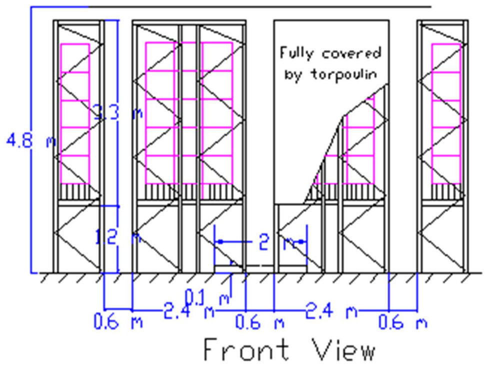

Fig. 9. MSC 914 full scale test arrangement with heptane pool and truck bed commodities.

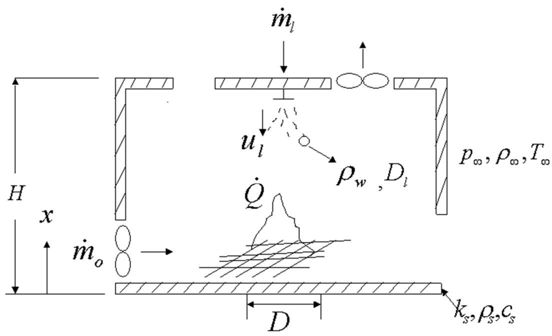

Fig. 10. Phenomena to be scaled.

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. This was 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 should be control of the fire within 1-½ minutes, at most.

Some details of the scaling are presented in the following. Figure 10 displays a general description of the problem and the variables involved (in this case no fans are present). The geometry, the fire, the water spray, and the construction materials need to be modeled in scaling. The approach to selecting the scaling parameters used the governing conservation equations for the phenomena [14, 15]. The fluid and water parameters are a function of geometry, time, and many other variables as illustrated in the functional equation below. The objective is to select the most significant dimensionless variables that can be practically controlled, and then to test at the reduced scale with known nozzle properties, the performance of the system. More complete details can be found in [14, 15] where analyses are presented in establishing the "best" choices for scaling.

Variables in suppression modeling with flame radiation significant:

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

are functions of

$$\frac{x}{H},\ \frac{t\sqrt{g}}{\sqrt{H}},\ \mathrm{Pr},\ \frac{c_p T_\infty}{h_{fg}},\ \frac{\rho_\infty}{\rho_l},\ \frac{c_p T_\infty}{gH},\ \frac{c_p}{c_v},\ \frac{\rho_\infty\sqrt{gH}\,H}{\mu},\ \frac{\sigma T_\infty^3 \kappa H}{\rho_\infty c_p\sqrt{gH}},\ \frac{\dot{m}_0}{\rho_\infty\sqrt{gH}\,H^2},\ \frac{D_0}{H},$$

$$\frac{\dot{m}_{l,0}}{\rho_\infty\sqrt{gH}\,H^2},\ \frac{D_{l,0}}{H}\left(\frac{\rho_\infty\sqrt{gH}\,H}{\mu}\right)^{1/3},\ \frac{x_s}{\left(\sqrt{gH}\,H\,k_s/(\rho_s c_s)\right)^{1/2}},\ \frac{n_0}{H^3},$$

$$\frac{k}{\left(k_s\rho_s c_s\sqrt{gH}\,H\right)^{1/2}}\left(\frac{\rho_\infty\sqrt{gH}\,H}{\mu}\right)^{0.8}\mathrm{Pr}^{1/3},\ \frac{\sigma T_\infty^3}{\left(k\rho c\sqrt{g/H}\right)^{1/2}}.$$

The following scaling choices were selected for control:

1. Fuel

Heat release rate: $\dfrac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g} H^{5/2}} \Rightarrow \dot{Q} \sim H^{5/2}$

Radiation absorption coefficient: $\dfrac{\sigma T_\infty^3 \kappa H}{\rho_\infty c_p \sqrt{gH}} \Rightarrow \kappa \sim H^{-1/2}$

2. Water spray

Thrust of spray: $\hat{F} = \dfrac{F}{\rho_\infty \left(\sqrt{gH}\right)^2 H^3} \Rightarrow F \sim H^4$

Droplet diameter: $\hat{D}_\mu = \dfrac{D_l}{H/\mathrm{Re}_H^{1/3}} = \dfrac{D_l}{H}\left(\dfrac{\rho_\infty \sqrt{gH} H}{\mu}\right)^{1/3} \Rightarrow D_l \sim H^{1/2}$

Droplet evaporation rate per unit area per droplet: $\hat{\dot{m}}''_\mu = \dfrac{\dot{m}''_w}{\rho_\infty \sqrt{gH}/\mathrm{Re}_H^{1/3}} \Rightarrow \dot{m}''_w \sim H^0$

Number of droplets per unit volume: $\hat{n} = \dfrac{nH^3}{\mathrm{Re}_H} = \dfrac{n}{\mathrm{Re}_H/H^3} \Rightarrow n \sim H^{3/2}$

Water flow rate: $\hat{\dot{m}}_{l,0} = \dfrac{\dot{m}_{l,0}}{\rho_\infty \sqrt{gH} H^2} \Rightarrow \dot{m}_{l,0} \sim H^{5/2}$

3. Construction material

Thermal inertia of solids: $\dfrac{\sigma T_\infty^3}{\left(k_s \rho_s c_s \sqrt{g/H}\right)^{1/2}} \Rightarrow k_s \rho_s c_s \sim H^{1/2}$

Thickness: $\dfrac{x_s}{\left(\left(k_s/\rho_s c_s\right)\sqrt{H/g}\right)^{1/2}} \Rightarrow \dfrac{x_s}{\left(\left(H^{1/2}/H^{1/2}\right)H^{1/2}\right)^{1/2}} \Rightarrow x_s \sim H^{1/4}$

4. Heat flux to surface

Radiant heat flux: $\dot{q}''_r = \left(1-\exp\left(-\kappa H\right)\right)T^4 - T_s^4 \sim H^0$

Convective heat flux: $\dot{q}''_c = h_s\left(T - T_s\right) \sim \dfrac{k}{H}\left(\dfrac{\rho\sqrt{gH}H}{\mu}\right)^{4/5} \sim H^{1/5}$

Total heat flux to surface: $\dot{q}''_s = \dot{q}''_r + \dot{q}''_c \sim H^0$

Modeling the fire

First, it was examined how well the heptane pool fire could be modeled at ¼-scale. As this was a big fire, 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 needs to be $\kappa \sim \kappa_{\mathrm{heptane}}\ (1/4)^{-1/2}$ = 15 $\mathrm{m}^{-1}(2)$ = 30 m^{-1} while its reported value is 24.1 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 ¼-scale is shown in Fig. 11; the flame shapes should be geometrically identical for perfect scaling. Figure 12 shows temperature and heat flux comparisons for these tests.

Fig. 11. Full and ¼ scale of heptane pool fire between truck trailer faces.

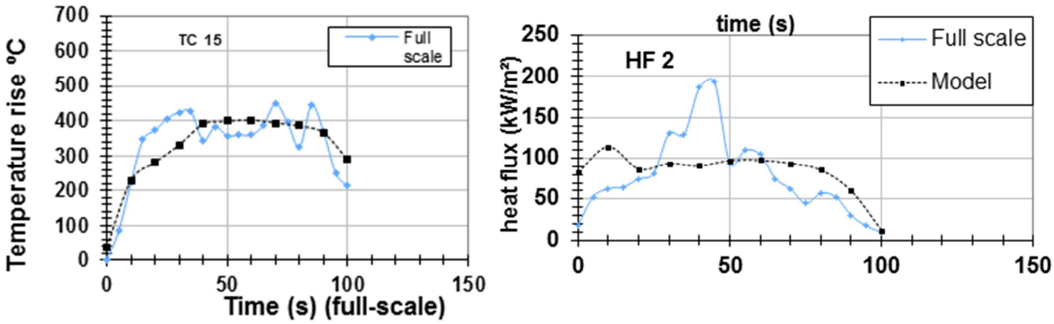

Fig. 12. Pool fire alone: (a) – temperature comparison; (b) – heat flux comparison.

Scaled water suppression tests

It was decided to continue to use a gas burner for the ¼-scaled tests to establish the small- scale sprinkler specifications. This was done from estimating the full-scale energy release rate 1 minute into the full-scale MC 914 test. The fire was out of control at that time. The full-scale heptane fire initially contributed 9.2 MW and the commodity fire grew to 10.4 MW after 1 minute. Thus, the criterion for successful control must occur within 1 minute after the start. 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 commodity. Several candidate nozzles were selected for testing with their flow rate, droplet size and thrust varied until a satisfactory fire control was achieved. The suppression condition for each nozzle is indicated in Table 2.

Table 2. Scaled nozzle 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

Following the inert commodity tests to select candidate design nozzle configurations, actual 1/4-scale commodity tests were performed with a liquid fuel. The pool fire simulation is summarized in Table 3. 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. 13 with suppression indicated by the "knockdown" for fire in the slot.

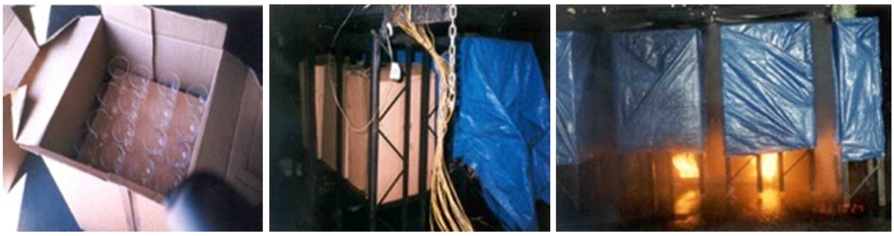

Fig. 13. Scaled MSC 914 tests: cartons, configuration, and suppression of fire.

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 ~ $H^{5/2}$	9,250	289	289
Absorption coef., m^{-1} ~ $H^{-1/2}$	15	24	0.65(6.5) + 0.35(54) = 23
Fuel pan, x_1 by x_2, x ~ H^1	1.5 x 2.0	0.38 x 0.5	0.55 x 0.73
Duration of fire, t ~ $H^{1/2}$	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

Table 4. Material selection in scaling, ¼ scale

Material	Thickness δ ~ $H^{1/4}$, mm		Density ρ_s ~ $H^{1/4}$, g/cm^3		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	1.3	0.97	0.80	0.71	0.75	0.71
Steel structure	4.7	1.3	7.8	7.8	0.67	0.5	1	1
Ceiling	15	15	0.7	0.7	1	0.71	1	0.71

Scale-up test

After two L66 nozzles were found to be effective in suppression the scaled MSC 914 test, an appropriate scaled-up nozzle was identified for the full-scale test. The nozzles, swirl-type, are depicted in Fig. 14, and the required and actual conditions for scaling up are given in Table 5.

Figure 15 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 at 45 s in the full –scale test. Two repeat small-scale results are shown for the L66 nozzles used in Tests 67 and 68 that indicate reproducibility, along with the full-scale test with Nozzles TF18 that indicate good scaling results. In all cases the fire is suppressed in the slot and pushed down.

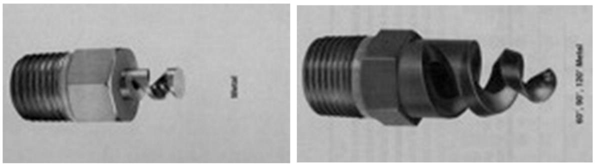

Fig. 14. L66 ¼ scale nozzle (left) and TF18 full-scale nozzle (right).

Table 5. Scale-up nozzle design

Parameter	¼-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, $D_{l,0} \sim H^{1/2}$, 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

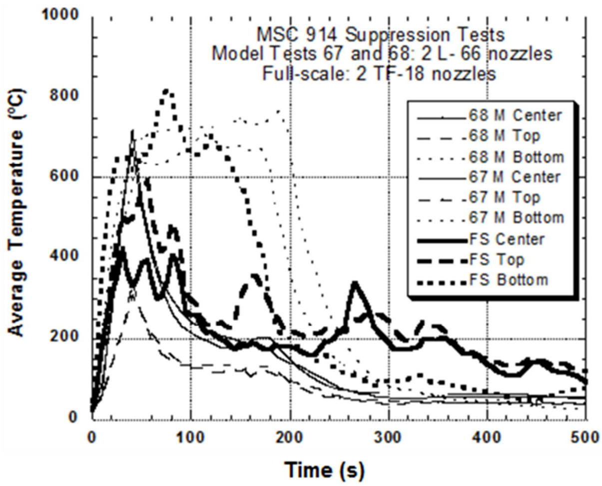

Fig. 15. MSC 914 suppression in ¼ and full-scale

Fire growth of a bedroom to flashover and full development

This last example is stretching 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. It is yet to be published [16]. The hypothesis for scaling was to construct all room dimensions and overall furniture elements to a geometric scaling of ¼. All materials between the full-scale and model were of the same material and same thickness. This meant that in scaling a mattress, the overall object was ¼, but the foam and coverings were of the same thickness in 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 investigation. He likes to make his own furniture, and 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. Once the smoke layer got hot (above 300 ºC), 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 overall the results proved potentially useful for both design and investigation. Figure 16 shows some of these results. Figures 17 – 19 show accordingly the temperatures in the center of the room, the heat fluxes and the gas concentrations plotted for the full-scale and model for full-scale time. The results are consistent with expectation, and remarkably showed a similar progression of the fire, although not perfect in time.

Fig. 16. Scale modeling of a bedroom fire.

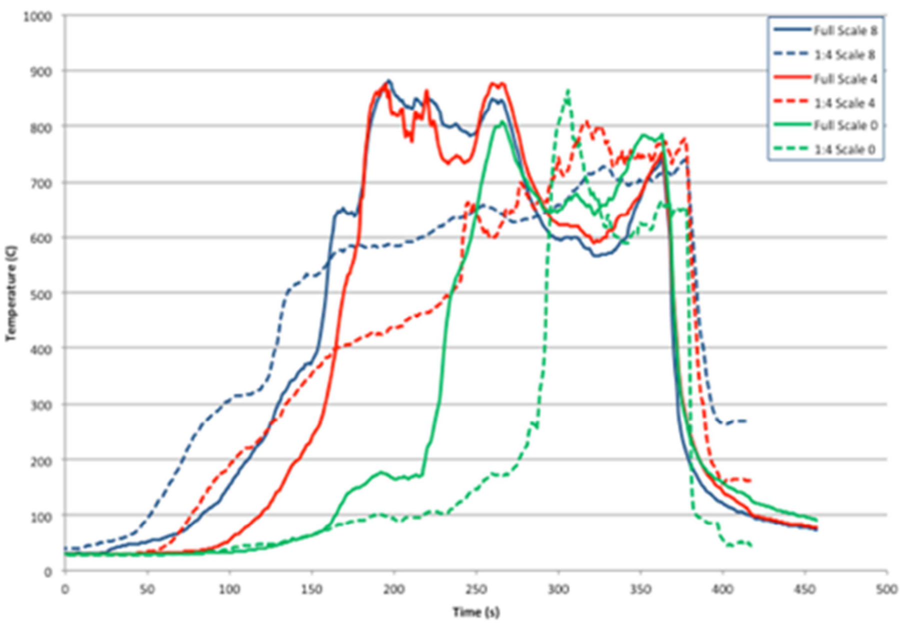

Fig. 17. Temperature at the center of the room full and ¼ scale.

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 need not be preserved. It can provide a source of insight and a validity check on mathematical modeling.

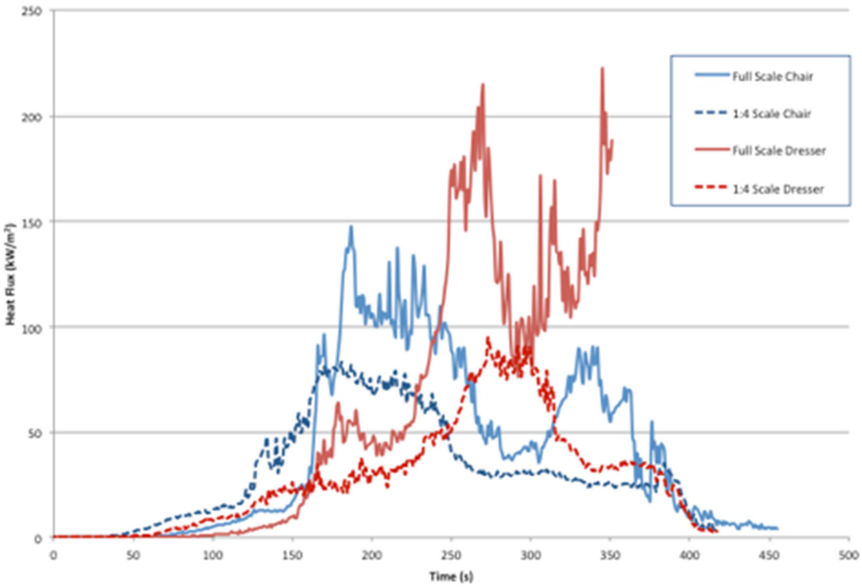

Fig. 18. Heat flux at the two locations in the room full and ¼ scale.

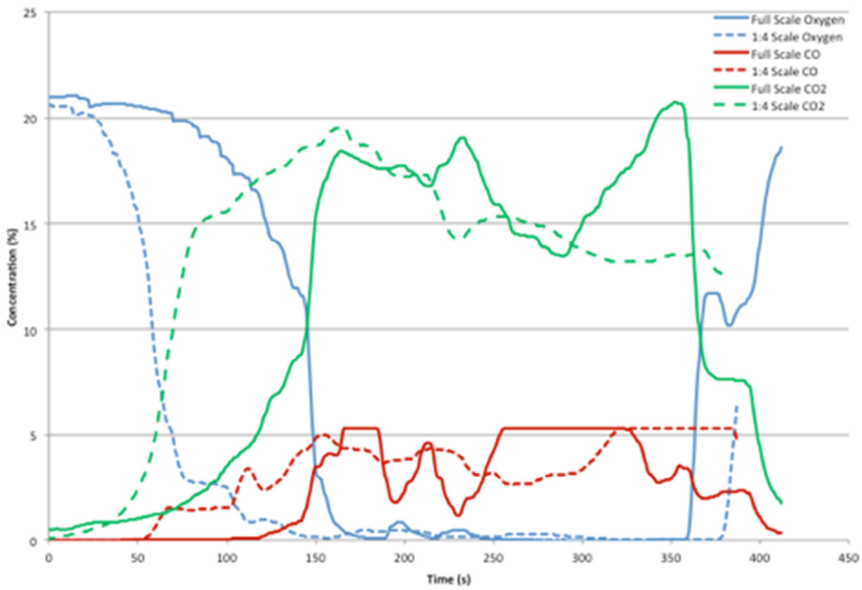

Fig. 19. Gas concentrations in the smoke for the full and ¼ scale room.

ACKNOWLEDGEMENTS

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

REFERENCES

[1] J.G. Quintiere, ISSM 1, Tokyo, 1988: Summary Review, Kozo Saito, Editor, In: Progress in Scale Modeling, Springer Science-Business Media B.V., 2008.

[2] P.H. Thomas, Dimensional analysis: a magic art in fire research, Fire Saf. J. 15 (1989) 3-29.

[3] J.G. Quintiere, Principles of Fire Phenomena, John Wiley & Sons, Ltd, London, 2006.

[4] F.A. Williams, Scaling Mass Fires, Fire Research Abstracts and Reviews 11 (1969) 1-23.

[5] G. Heskestad, Modeling of Enclosure Fires, Proc. Combust. Inst. 14 (1973) 1021-1030.

[6] G. Heskestad, Extinction of Gas and liquid Pool Fires with Water Sprays, Fire Saf. J. 38 (2003) 301-17.

[7] W.J. Parker, B.T. Lee, A Small-scale Enclosure for Characterizing the Fire Buildup Potential of a Room, In: Nat. Bur. Stand., NBSIR 75-710, June 1975.

[8] Proceedings of the International Symposium on Scale Modeling, July 18-22, Tokyo, the Japan Society of Mechanical Engineers, Tokyo. 1988

[9] Progress in Scale Modeling, Saito, Kozo Editor, Springer Science+Business Media B.V., Tokyo, 2008

[10] C.W. Fung, M.R. Suchomel, P.L. Oglesby, The NBS Program on Corridor Fires, Fire J. 67 (3) (1973) 41-48.

[11] J.G. Quintiere, B.J. McCaffrey, T. Kashiwagi, A Scaling Study of a Corridor Subject to a Room Fire, Combust. Sci. Technol. 18 (1978) 1-19.

[12] J.G. Quintiere, B.J. McCaffrey, W. Rinkinen, Visualization of Room Fire Induced Smoke Movement and Flow in a Corridor, Fire Mater. 2 (1978) 18-24.

[13] J.G. Quintiere, M.E. Dillon, Scale Model Reconstruction of Fire in an Atrium, In: Second International Symposium on Scale Modeling, June 23-27, 1997, University of Kentucky, Lexington, KY.

[14] J.G. Quintiere, G. Su, N. Schultz, Physical Scaling For Water Mist Fire Suppression – A Design Application, Int. J. Eng. Performance-Based Fire Codes 9 (2) (2007) 87-108.

[15] G.-Y. Su, Physical Scaling for Fire Suppression by Water Mist, MS Thesis, Dept. Fire Prot. Engineering, University of Maryland, 2010.

[16] J.G. Quintiere, A.C. Carey, L.K. McCarthy, L. Reeves, Scale Modeling in Fire Reconstruction, In: National Criminal Justice Reference Service, National Institutes of Justice, Doc. No. 250920, Washington, D. C., June 2017.

[17] J.G. Quintirere, In: Eighth International Symposium on Scale Modeling (ISSM-8) Portland, Oregon, USA, Sept 12-14, 2017 (to be published)