

Acquisition, Analysis, and Reporting of Fire Plume Data for Fire Safety Engineering

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ABSTRACT

In order to undertake engineering analyses and designs that can be readily accepted by building and fire authorities, fire protection engineers need engineering tools and methods with known degrees of accuracy and reliability. Furthermore, fire protection engineers need valid and applicable input data with known degrees of uncertainty and variability for use in those engineering tools and methods. As a means to begin addressing these concerns, an effort to be initiated to formally evaluate the stated applications, limitations, and uses of computer fire models, and issue reports on the findings. To support the evaluation effort, over 50 fire tests were conducted in a 37 meter x 37 meter test room with ceiling heights ranging from 6.1 meters to 12.2 meters. In addition to using the data for the computer model evaluation effort, further analysis of the data included comparison of plume temperatures and ceiling jet temperatures as a function of fire size and ceiling height. This paper presents a general discussion on the need for valid and accurate data for fire safety engineering, and details the results of the plume analysis, including presentation of a plume temperature correlation with a new proportionality constant, C , and a 95% prediction interval. Comparison of the test data with plume correlations and proportionality constants of others is also presented.

KEYWORDS: Fire model evaluation; fire test data; fire plume correlation; uncertainty.

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INTRODUCTION

Fire protection engineering is a maturing discipline. Although fire safety of buildings has been a concern for centuries, the methods used to mitigate unwanted fires changed little until the early part of this century, when large life-loss and large dollar-loss fires prompted fire research, increased installation of automatic sprinkler systems, development of building and fire codes and standards, and the emergence of fire protection engineering as a fledgling discipline. However, in just a few short years, research into fire and fire effects, which began in earnest in the 1950s and continues to the present, has provided the fire protection engineering profession with an ever increasing understanding of fire phenomena, of the fire performance of materials, and of the impact of fire on people, property, business continuity, and the environment.

As the understanding of fire and fire impacts grew, based both on research and loss experience, it became apparent that fire and fire impacts could be estimated or predicted. This realization provided an impetus to the fire protection engineering community to look at methods to predict fire and fire impacts instead of simply designing fire mitigation measures in the manner in which they had in the past. For help, the fire protection engineering community turned to the research community, which had developed correlations, analytical methods, and models to describe fire initiation, growth, and spread, as well as analytical methods and models to predict possible fire impacts. Although the fire protection engineering community welcomed the input from the research community, many found the available correlations, analytical methods, and models time-consuming to work with and not generally accepted by the building and fire authorities.

More recently, however, advances in computer technology have resulted in the development of computer-based analysis and design tools for use by fire protection engineering professionals. This resulted in a change to how many fire protection engineers approached fire safety problems, as the once time-consuming analytical methods became faster and easier to use. As more of the computer-based analytical methods were used, some in the fire protection engineering community "accepted" them as tools for daily use, and began to advocate fire safety analysis and design using the computer-based analytical methods instead of the traditional codes- and standards-based design approach. In some respects, the increasing use and general "acceptance" of computer-based analytical methods (computer fire models) within the fire protection engineering community has contributed to the movement to performance-based building codes and the concept of performance-based fire safety design [1] As such, some people view "computer fire models" as synonymous with "performance-based design" (although the authors would argue against such an interchange of terms).

Thus, with the current emphasis on performance-based building codes and performance-based fire safety design, there is an emphasis on the use of computer fire modeling as support for performance-based (engineered) fire safety solutions. Although this can be good from the perspective of advancing technology and the fire protection engineering profession, care must be used to ensure that models are used properly: for appropriate applications, within the bounds of intended use, and with a good understanding of the limitations.

Although cautions such as the above have been previously published,[2, 3] and guidelines for computer model evaluation exist,[4, 5] the authors are unaware of any organization formally evaluating (validating, or verifying) computer fire models, issuing certifications or "listings" as to model accuracy, and providing guidance for practicing engineers (and building and fire authorities) at the current time. As a result, many building and fire authorities voice concern about the reliability, accuracy, and appropriateness of the models used, the applicability of the input data applied, the validity of the assumptions made, and ultimately, of the appropriateness of the solution developed.[6]

The Society of Fire Protection Engineers (SFPE) understands these concerns, and recognizes that widely accepted engineering tools and methods with known degrees of accuracy and reliability are

required, that valid and applicable data are needed, that assumptions need to be clearly stated and supportable, and that engineered solutions need to be appropriate to the situation.[7 8 9] To begin addressing these concerns, the SFPE has formed a number of Engineering Task Groups (ETGs), whose goals range from outlining a design process for developing appropriate solutions, to determining the accuracy of existing methods fire protection engineering tools and methods. The focus of one of these SFPE efforts has been to evaluate the stated applications, limitations, and uses of computer fire models.[10 11]

ENGINEERING TASK GROUP ON COMPUTER MODEL EVALUATION

The goal of the ETG on Computer Model Evaluation is to evaluate computer models, used for fire protection engineering applications, on their uses, applications, and limitations. The intent is to produce evaluation reports on computer models to assist both the users of the models and the reviewers of analyses and designs based on models in gaining a better understanding of the intended use of a particular model, its evaluated range of application, and its known limitations. To minimize duplication of effort, the ETG on Computer Model Evaluation utilizes various American Society of Testing and Materials (ASTM) guides, i.e., ASTM E 1355, Standard Guide for Evaluating the Predictive Capability of Fire Models,[6]ASTM E 1472, Standard Guide for Documenting Computer Software for Fire Models,[12] and ASTM E 1591, Standard Guide for Data for Fire Models.[13] Additional evaluation criteria and procedures have been used and/or developed as necessary. The first model selected for evaluation was DETACT-QS, a heat and smoke detector activation model. This model was selected as the first model for evaluation due to its simplicity, its limited scope of intended use and application, and its widespread usage by practicing engineers. A full report on this evaluation is available from the SFPE.[14]

DETECT-QS is a computer program that predicts the activation time of thermal detectors (e.g. sprinklers) [11]. DETECT-QS uses correlations developed by Alpert to predict the temperature and velocity in the fire plume and ceiling jet. It uses the temperature and velocity as input for a lumped mass thermal model to predict the temperature of the thermal element of the detector.

To undertake the evaluation of DETECT-QS, a number of sub-groups were established, including Data for Evaluation and Algorithm Evaluation. Part of the evaluation was intended to compare the model with the original test data on which the main algorithm was based. In addition, fire test data were needed to evaluate the model's predictive capabilities. The first problem encountered was that the original test data, upon which the model's basic algorithm had been based, was no longer available. This meant evaluation of the algorithm would be problematic. Second, to evaluate the breadth of the model's applicability, test data were required under various compartment configurations. The additional data was not meant to replicate Alpert's original tests. Although a large collection of fire test data exists, most fire tests did not document the information required for comparison with computer fire models. Third, for that test data which did exist, little to no information was provided on the uncertainty and variability in the data: two important factors for evaluation.[7]

Given the lack of data in the required form, the SFPE secured funding to contract a number of large scale fire tests, to be performed at Underwriters Laboratories Inc., for the purpose of obtaining fire data for comparison with the model DETECT-QS, with the intent that the data would be applicable to evaluations of other computer fire models in the future. The intent was to perform a series of fire tests, a) to evaluate uncertainty and variability due to test methods and measurements, b) to evaluate the uncertainty in the algorithms used in the models, and c) to begin the compilation of a data base for fire test data for use in computer fire model evaluations, for use as input data for computer fire models, and for general analysis.

Findings relative to the variability and uncertainty in the test data, to the uncertainty in the algorithm, and to the agreement between the test data and the model are included as part of the DETACT-QS evaluation report.[14] As an additional effort, analysis of the data was performed to gain a further understanding of the level of uncertainty and variability in correlations developed from the data. To this end, analysis of plume temperatures and ceiling jet temperatures was undertaken. The plume temperature analysis resulted in the development of a new proportionality constant, and includes a temperature prediction interval, based on statistical analysis, at the 95% confidence interval. The following provides an overview of the experiments and presents an analysis of the plume temperature data.

EXPERIMENTS

The experiments were conducted at Underwriters Laboratories in Northbrook, IL. The tests were conducted under a smooth flat unbounded ceiling. The tests were conducted in a 37 m x 37 m (120 ft. x 120 ft.) test room under the 30 m x 30 m (100 ft. x 100 ft.) movable ceiling with ceiling heights ranging from 3 m to 12 m (10 ft. to 40 ft.). The test reports that provide the data that was used in this analysis can be obtained from the Society of Fire Protection Engineers.[14,15]

The fire was created using a heptane burner constructed from atomizing spray nozzles. The heptane flow rate to the burner was manually controlled to create a medium t^2 fire with a growth rate of the form:

$$\dot{Q} = 0.0117(t + t_o)^2 \quad (1)$$

where \dot{Q} is the total chemical heat release rate in kW, t_o is a time delay to eliminate fires too small for the burner and t is the time in seconds.

The total heat release rate was calculated by multiplying the heptane flow rate by its heat of combustion. The convective fraction from the burner was measured to be 65% using UL's large-scale heat release rate calorimeter [14].

PLUME TEMPERATURES

Experimental Results

The data used in the plume temperature analysis are derived from tests with 6.1, 7.6, 10.7, and 12.2 m (20, 25, 35, and 40 ft.) ceiling heights. The fire sizes used in the analysis were in the range of 400 kW to 9600 kW. Temperature above the center of the fire was measured with inconel sheathed 1.6 mm (1/16 inch) diameter thermocouples mounted either 10 cm or 18 cm (4 in. or 7 in.) below the ceiling. These distances below the ceiling were chosen because they are common distances to the thermal elements of upright and pendant sprinklers.

Figure 1 shows the raw data from the tests. The total heat release rate is plotted versus the temperature measured by the thermocouples. There is a clear demarcation between the temperature measured at all ceiling heights, although the distinction is more difficult to see between the 10.7 m (35 ft.) and 12.2 m (40 ft.) ceiling heights.

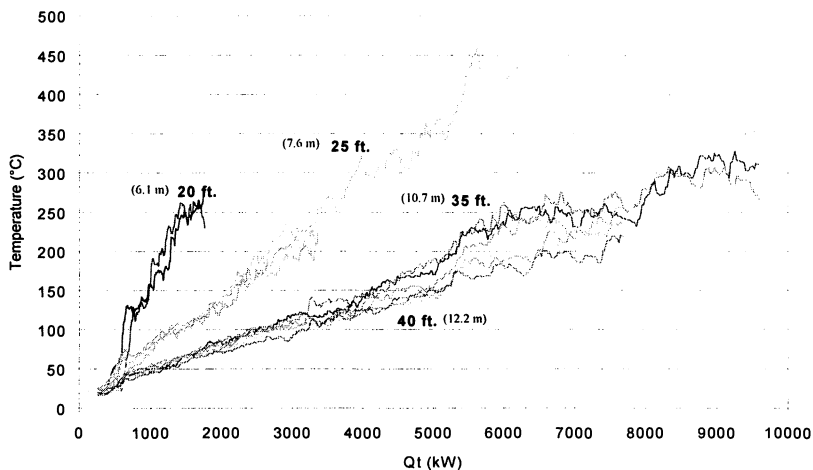


FIGURE 1. Experimental Plume Temperatures for Ceiling Heights of 20, 25, 35, and 40 ft.

All data shown in Figure 1 were used in the analysis with the exception of data with temperature rises less than 15°C. These data were removed from the data set to eliminate errors caused by variations in the ignition of the heptane burner. This left 7042 data points to be used in the analysis.

DATA ANALYSIS

Two types of data analysis were done. The first type was fitting best-fit regression lines to the experimental data. When best-fit regression lines were calculated a linear least squares approximation was used to calculate the slope. The second type of analysis was an effort to quantify the quality of the correlation equations using prediction intervals and r^2 correlation coefficients.

When fitting a regression line to experimental data, individual values are scattered above and below the regression line. It is often of more interest to know how closely one can predict an individual value rather than the mean value given by the regression line. In other words, it would be useful to know a range where 95% of the temperatures are expected to fall. This prediction interval can be calculated using equation 2.

$$\text{Prediction Interval [16]} \quad y' \pm t\sigma \sqrt{1 + \frac{1}{n} + \frac{(x - \bar{x})^2}{(n-1)\sigma_x^2}} \quad (2)$$

For this analysis, a 95% single-tailed t factor [16] of 1.96 was used. The standard deviation, σ , was calculated from the difference between the regression line and the experimental temperatures. The term under the square root was evaluated for all analyses in this paper and were found to be approximately 1 (within 0.0004).

The amount of variation in the experimental data that is accounted for by the correlation can be calculated using the correlation coefficient [17], r^2 . The correlation coefficient, r , always lies

between -1 and 1. If all experimental points lie on the regression line, $r = \pm 1$. If $r = 0$, the regression line does not explain anything about the variation in y .

$$\text{R-Squared } r^2 = 1 - \frac{\sum (Y_i - \hat{Y}_i)^2}{(\sum Y_i^2) - \frac{(\sum Y_i)^2}{n}} \quad (3)$$

Comparison With Alpert's Plume Correlation

DETECT-QS uses Alpert's plume temperature correlation to calculate maximum plume temperature rise based upon the height above the base of the fire, X (m) and the total heat release rate, Q , (kW). The experimental data set was plotted in this format and compared to Alpert's Correlation as shown in Figure 2.

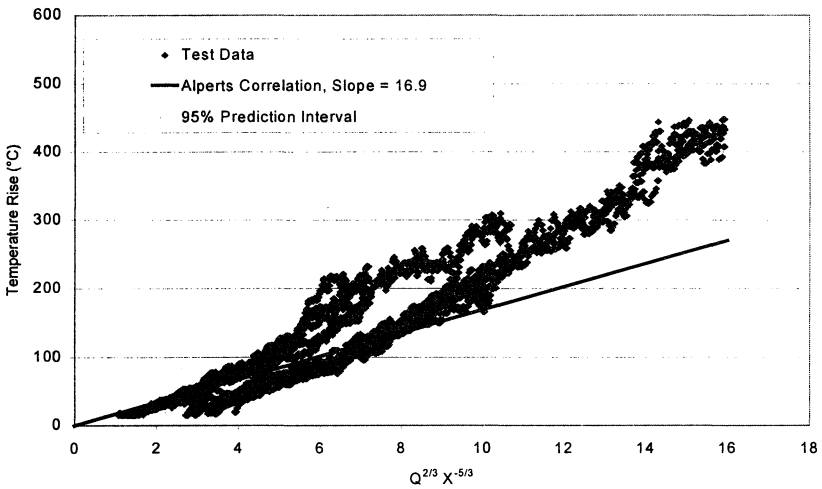


FIGURE 2. Comparison with Alpert's Correlation

This comparison shows that the plume temperatures measured in the experimental tests were usually greater than the plume temperatures predicted by Alpert's correlation. The comparison shows that the data for different ceiling heights does not collapse to one data set. Since the test data is not centered about Alpert's correlation line, a different prediction interval was calculated for above and below Alpert's correlation as shown in Eq 4.

$$\text{Alpert Lower Prediction Limit } \Delta T = 16.9Q_i^{2/3} X^{-5/3} - 18.4^\circ\text{C} \quad (4)$$

$$\text{Alpert Upper Prediction Limit } \Delta T = 16.9Q_i^{2/3} X^{-5/3} + 85.8^\circ\text{C}$$

The best-fit line through the test data was calculated with a slope of 27.6 and an intercept of -40°C . Since this would mean that no fire would create a -40°C temperature change, the correlation line was forced through the origin. Forcing the regression line to intercept the origin resulted in a line with a slope of 22.6, a correlation coefficient of 79%, and a standard deviation from the test data of 33.93. This best fit line is plotted as the dashed line in Figure 3.

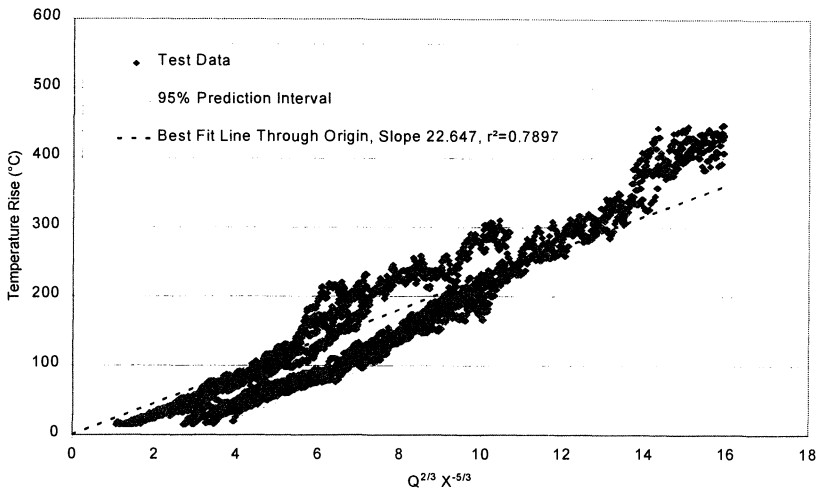


FIGURE 3. Correlation without Virtual Origin Correction

The resulting correlation with a 95% prediction interval is shown in Eq. 5.

$$\text{Plume Temperature } \Delta T = 22.6 \cdot Q_c^{2/3} \cdot X^{-5/3} \pm 66.5^\circ\text{C} \quad (5)$$

Because the test data did not collapse into one coherent data set, the author suggests that Equation 5 only be used for scenarios similar to the test conditions.

By plotting the temperature rise as a function of height above the base of the fire, the effect of the area of the fire was ignored. The heptane burner used in these tests produced a localized heat source in a small area. From the literature we know that Alpert's correlation was developed for a variety of fuels. Therefore, the temperature rise measured above these fires was higher than for the variety of fuels that Alpert used.

Data Analysis Using Virtual Origin

Since there was not a good comparison between the test data and plume correlations developed using the elevation above the base of the fire, further analysis of the data was conducted.

The data was plotted into the form derived by Morton et. al. [18]. Morton's solution results in a linear relationship between the temperature rise, ΔT , and $Q_c^{2/3} \cdot Z^{-5/3}$. This is shown in Equation 6.

$$\Delta T = C \cdot Q_c^{2/3} \cdot Z^{-5/3} \quad (6)$$

where: ΔT is the difference between the temperature at the centerline of the plume and ambient temperature, C is the proportionality constant, Q_c is the convective heat release rate (kW), and Z is the height above the virtual origin (m).

Morton's solution assumes a point source of buoyancy. Since real fires are not point sources, most researchers use a virtual origin correction, z_o , to estimate the location of an equivalent point source

relative to the base of the fire. The virtual origin is affected by the geometry and heat release rate of the fire and a custom virtual origin correction is typically developed by each researcher to optimize the correlation equation for the test data. Three equations for the virtual origin are recommended in the SFPE Fire Protection Engineering Handbook [19]. The three equations were developed by Heskestad, Hasemi et. al., and Cetegen et. al. The virtual origin equations are shown as follows:

$$\text{Heskestad} \quad z_o = -1.02D + 0.083\dot{Q}_t^{2/5} \quad (7)$$

$$\text{Hasemi} \quad z_o = -2.4D + 0.145\dot{Q}_c^{2/5} \quad \dot{Q}_c^{2/5} \geq 16.5D \quad (8)$$

$$z_o = 0.0224D\left(\frac{\dot{Q}_c^{2/5}}{D}\right)^{5/3} - 0.145\dot{Q}_c^{2/5} \quad \dot{Q}_c^{2/5} < 16.5D$$

$$\text{Cetegen} \quad z_o = cD + 0.059\dot{Q}_c^{2/5} \quad \dot{Q}_c^{2/5} > 16.5D \quad (9)$$

$$z_o = cD + 0.01015D\left(\frac{\dot{Q}_c^{2/5}}{D}\right)^{5/3} \quad \dot{Q}_c^{2/5} \leq 16.5D$$

where: \dot{Q}_c is the convective heat release rate (kW), \dot{Q}_t is the total chemical heat release rate (kW), z_o is the location of the virtual origin (m) and D is the fire diameter in meters. For this analysis, a 1 meter fire diameter was used based upon the maximum dimension of the burner.

Hasemi's virtual origin equation produced the best fit for the test data. Cetegen's virtual origin equation could not be used because the virtual origin approached the height of the ceiling for some tests. It is not surprising that Cetegen's virtual origin equation could not be used because it was developed for much smaller fire sizes. Heskestad's virtual origin equation has been recommended for general use in the SFPE handbook because of its simplicity, its central position among other correlations, and its clear foundation in theory [19].

Figure 4 and Figure 5 show the plume temperature correlations using the Hasemi and Heskestad virtual origins respectively. The data was plotted with $\dot{Q}_c^{2/3} \cdot Z^{-5/3}$ on the x-axis and the temperature rise, ΔT , on the y-axis.

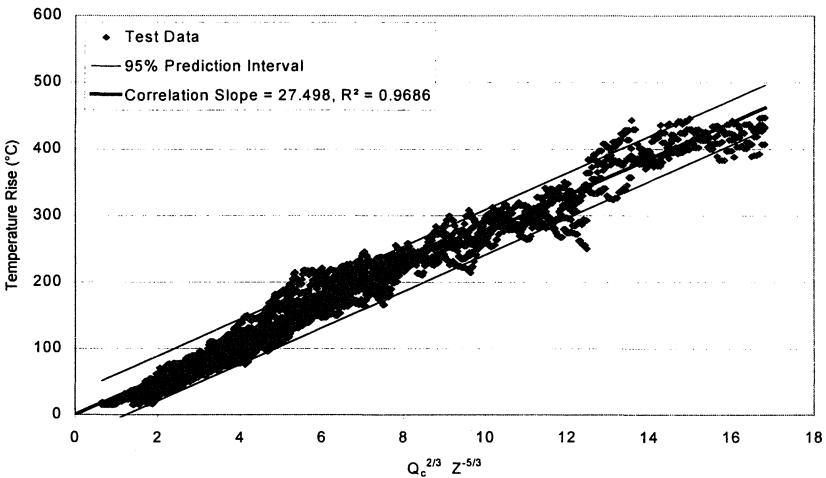


FIGURE 4. Plume Temperature Correlations – Hasemi Virtual Origin

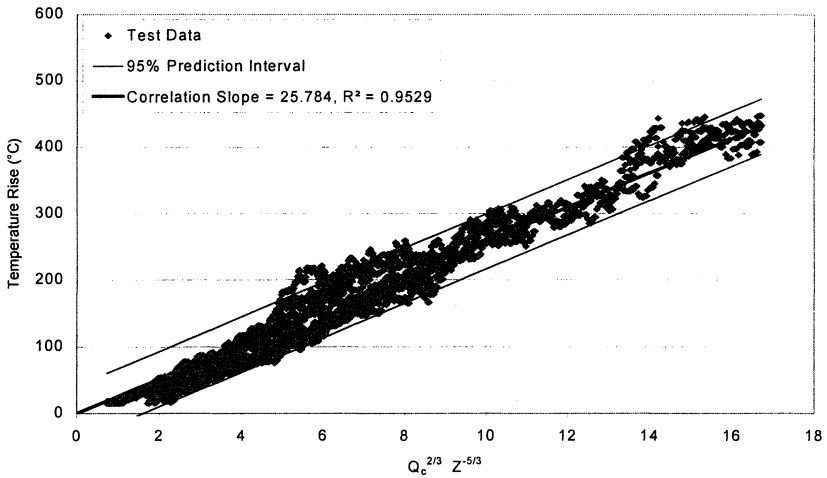


FIGURE 5. Plume Temperature Correlations – Heskestad Virtual Origin

The resulting plume temperature correlations using the Hasemi and Heskestad virtual origin, VO, corrections and their 95% prediction interval are shown in Equation 10 and Equation 11. As stated earlier, Heskestad’s virtual origin equation has been recommended for general use.

$$\text{Plume Temperature (Hasemi Virtual Origin)} \quad \Delta T = 27.5 \cdot Q_c^{2/3} \cdot Z^{-5/3} \pm 33.9 \quad (10)$$

$$\text{Plume Temperature (Heskestad Virtual Origin)} \quad \Delta T = 25.8 \cdot Q_c^{2/3} \cdot Z^{-5/3} \pm 41.6 \quad (11)$$

Comparison With Existing Correlations

Gupta [20] has compiled many of the existing plume temperature correlations and converted them into the same equation form as shown in Table 1. Although each correlation was developed for a specific range of test conditions, the authors thought it would be useful to provide a comparison between each correlation and this experimental data set. The r^2 value has been calculated for the comparison of the test data to each correlation. These values are shown in the last three columns of Table 1.

TABLE 1. Plume Temperature Correlations

Author	Plume Temperature Rise	Correlation Coefficient, r^2		
		Hasemi Virtual Origin	Heskestad Virtual Origin	No Virtual Origin Correction
Morton et al.	$21.10 Q_c^{2/3} \cdot Z^{-5/3}$	65%	75%	
Evans	$23.92 Q_c^{2/3} \cdot Z^{-5/3}$	88%	91%	
George et al.	$25.03 Q_c^{2/3} \cdot Z^{-5/3}$	93%	94%	
Zukoski	$25.03 Q_c^{2/3} \cdot Z^{-5/3}$	93%	94%	
Heskestad	$25.03 Q_c^{2/3} \cdot Z^{-5/3}$	93%	94%	
Yokoi	$25.06 Q_c^{2/3} \cdot Z^{-5/3}$	93%	94%	
Cox and Chitty	$27.38 Q_c^{2/3} \cdot Z^{-5/3}$	96%	94%	
Sheppard [1]	$27.5 Q_c^{2/3} \cdot Z^{-5/3} \pm 33.9 \text{ }^\circ\text{C}$	97%	95%	
Sheppard [2]	$25.8 Q_c^{2/3} \cdot Z^{-5/3} \pm 41.6 \text{ }^\circ\text{C}$	95%	94%	
Rouse et al.	$30.26 Q_c^{2/3} \cdot Z^{-5/3}$	95%	88%	
Alpert	$16.9 Q_t^{2/3} \cdot X^{-5/3}$			10%
Sheppard [3]	$22.6 Q_t^{2/3} \cdot X^{-5/3} \pm 66.5 \text{ }^\circ\text{C}$			79%

where: Sheppard [1] with the Hasemi virtual origin, Sheppard [2] with the Heskestad virtual origin, and Sheppard [3] with the height above the base of the fire instead of a virtual origin correction.

The correlations, except for Alpert's, are compared to the correlation developed from this study's data set in Figure 6. Most of the plume temperature correlations, except Morton's, fall within a 95% prediction interval from this data set. The authors understand that each researcher's correlations were developed for a specific range of test conditions not necessarily the conditions used in this analysis, and this probably accounts for the difference in the correlations.

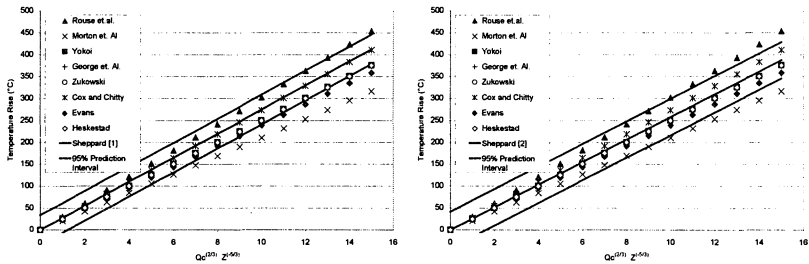


FIGURE 6. Comparison of Plume Temperature Correlations to Experimental Data

CONCLUSIONS

In order for fire protection engineering tools and methods to become widely accepted outside of the profession, fire protection engineers need engineering tools and methods with known degrees of accuracy and reliability, and they need valid and applicable input data with known degrees of uncertainty and variability for use in those engineering tools and methods. The Society of Fire Protection Engineers recognizes these needs and has taken steps to address them.

One such step has been to establish the SFPE Engineering Task Group on Computer Model Evaluation to evaluate the uses, applications, and limitations of computer fire models. As part of

this group's efforts to evaluate the model DETACT-QS, full-scale fire tests were undertaken and data was collected for use in the evaluation. In addition to using the data for the DETACT-QS evaluation, data on fire plume temperatures were evaluated. This evaluation resulted in the development of a new proportionality constant, $C = 25.8$ with Heskestad's virtual origin, for use in the plume temperature correlation in the form developed by Morton, $C \cdot Q_c^{2/3} \cdot Z^{5/3}$.¹⁹ In addition, a statistical analysis of the data was performed, and a prediction interval of $\pm 41.6^\circ\text{C}$ was developed, at the 95% confidence level, for use with the correlation. The authors recommend that similar analysis and reporting of data be performed for all data intended for use in fire safety engineering analysis.

Use of the correlations show good agreement with all other correlations compared, with the exception of that by Alpert. This difference is partially attributed to the fact that Alpert's correlation is based upon the height above the base of the fire, X , instead of the height above a virtual origin, Z .

Furthermore, comparison of the data against Alpert's correlation suggests that Alpert's correlation can significantly under-predict centerline plume temperatures, especially for large fires in compartments with relatively low ceilings. If used for fire detector activation modeling, under-prediction of plume temperatures could result in over-prediction in the time to fire detector activation. Similarly, if Alpert's correlation were used to estimate gas temperatures for evaluation of structural impact, under-prediction of plume temperatures could result in over-prediction in the times to reach temperature-based failure points of structural materials.

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DISCLAIMER

The material presented in this paper reflects the views of the authors and does not necessarily reflect the views or consensus of the Society of Fire Protection Engineers, of Underwriters Laboratories Incorporated, or of the National Institute of Standards and Technology.

LIST OF SYMBOLS

C	Slope of the regression line
D	Fire diameter, meters
n	number of points used in the analysis
Q_c	Convective heat release rate, Kw
Q_t	Total chemical heat release rate, kW
t	Time in seconds
ΔT	Temperature change, °C
VO	Virtual origin
x	x value used to calculate y'
\bar{x}	mean of all x values used in the analysis
X	Distance above the base of the fire, meters
y'	predicted value using the regression equation.
Z	Distance above the virtual origin, $X-Z_0$, meters
Z_0	Virtual origin correction, meters
σ	Standard deviation
σ_x	Standard deviation of x

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