Evaluation of the Computer Fire Model DETACT-QS

Morgan J. Hurley, P.E.*
Technical Director
Society of Fire Protection Engineers
7315 Wisconsin Ave., #1225W
Bethesda, MD 20814

Daniel Madrzykowski, P.E.
National Institute of Standards and Technology
Building and Fire Research Laboratory
100 Bureau Drive, MS 8641
Gaithersburg, MD 20899

INTRODUCTION

The proper use of engineering design methods requires an understanding of their applicability and limitations, since all design methods are, at least to a certain extent, empirically based. Equations or constants used within design methods are frequently based on curve fits to data from experiments. Typically, the experiments used to develop the correlations were conducted under a limited set of conditions, e.g., compartment sizes, heat release rates or fire growth rates. If the design method is used for an application that falls outside of the bounds of the experiments used to develop the correlations used in the design method, uncertainty may be introduced.

The potential for uncertainty in computer models is greater than within basic closed form equations. Errors can be introduced in the numerical methods used to solve integral or differential equations, or more simply in math errors that were created during coding of the program.

To facilitate the use of engineering design methods and the review of designs developed using engineering methods, the Society of Fire Protection Engineers has summarized and evaluated a number of engineering methods, including several of those which predict radiation from pool fires,’ predict the effects of thermal radiation to people; and predict ignition of objects when exposed to thermal radiation.[3]

These methods are typically simple algebraic or differential equations. Given the added potential for the introduction of uncertainty, it is also necessary to evaluate computer models. In many cases, existing computer models have been released to the engineering community without sufficient technical guidance for the user to understand the capabilities or limitations of the model. As noted by Howard Emmons in 1991, “there should be a fire model validation group ...” to review computer models that are used to demonstrate public safety.[4]

EVALUATION APPROACH

The Society of Fire Protection Engineers formed a task group in 1995 to evaluate the scope, applicability and limitations of computer models. The Task Group chose DETACT-QS,[5] a model for predicting thermal detector response, as the first model to undergo evaluation. DETACT-QS was selected since it is a relatively simple model and it is widely used within the fire protection engineering community. The resulting evaluation document is intended to supplement the model’s original documentation by demonstrating the capabilities and limitations

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* Author to whom correspondence should be sent.

of the model and by highlighting underlying assumptions that are important for users to consider when applying the model.

After examining several approaches to evaluating a computer model, the Task Group decided to follow the ASTM ***Standard Guide for Evaluating the Predictive Capability of Deterministic** Fire Models*, E-1355.[6] The ASTM guide "provides a methodology **for** evaluating the predictive capabilities of a fire model **for** a specific use." Specifically the method addresses four areas of evaluation: 1) model definition and evaluation scenarios, 2) verification of theoretical basis and assumptions used in the model, **3)** verification of the mathematical and numerical robustness of the model, and 4) quantification of the uncertainty and accuracy of the model predictions.

This paper summarizes the results of SFPE's evaluation of DETACT-QS.

EVALUATION REPORT

The DETACT-QS evaluation report consists of eleven sections:

- Introduction
- Model Description
- Evaluation Scenarios
- Theoretical Basis for Model
- Mathematical Robustness
- Model Sensitivity
- Model Inputs
- Model Evaluation
- Quantifying Model Evaluation
- Summary of Analysis
- List of Limitations/Guidelines

Introduction

While the purpose of the evaluation is to provide information on the technical features, theoretical basis, assumptions, limitations, sensitivities, and guidance on the use of DETACT-QS, the evaluation is intended for use only by persons competent in the field of fire safety and is intended only to supplement the informed judgement of qualified users.

The evaluation is based on comparing predictions from DETACT-QS with results from full-scale fire experiments conducted in compartments with ceiling heights ranging from 2.44 m to 12.2 m and peak fire heat release rates ranging from 150 kW to 3.8 MW. The use of DETACT-QS with building geometries or fire characteristics other than those used in this evaluation may require further evaluation or testing.

Model Description

DETACT-QS is an empirical model, which is based on data correlations from a series of large-scale fire experiments. The model solves a definite integral using a quasi steady state assumption. **It** then solves several algebraic equations to produce predictions. DETACT-QS is composed of an algorithm which predicts the maximum temperature and velocity of an unconfined ceiling jet, under a smooth, flat, horizontal ceiling at a given radius from the centerline of the fire. It also utilizes a lumped mass, convection heat transfer algorithm for predicting the activation time of a thermal detector.

Several assumptions are implicit within DETACT-QS. The model assumes that the detector being analyzed is mounted on an unconfined, unobstructed, smooth, flat, horizontal ceiling and that the detector is located at the points of maximum temperature and velocity within the ceiling jet. Only convective heat transfer is considered between the ceiling jet and the thermal detector; no conductive loss or radiative heat transfer is considered. The detector is treated as a lumped mass. Temperatures and velocities of the plume and ceiling jet are uniform and assumed to be the maximum values in the plume. The fuel package and the plume are assumed to be in an unobstructed vertical axis. No ventilation or stratification effects are considered. No transport time (or lag time) is considered for the hot gases to travel from fuel to the detector. For each heat release rate input interval, the heat release rate is averaged over the interval and assumed constant.

Several parameters are required as input into DETACT-QS: the height of the ceiling above the fuel, the distance of the detector from the axis of the fire, the initial room temperature, the detector actuation temperature, the detector response time index, and the total heat release rate as a function of time for a given fire. The heat release rate is input in time-heat release rate pairs. The model predicts gas temperature of the ceiling jet and detector temperature at user specified time intervals and the detector actuation time.

Evaluation Scenarios

The evaluation scenarios represent compartment configurations ranging from residential scale rooms up to larger compartments typical of those found in commercial and industrial settings. The scenarios are limited by the test data available for comparison with model predictions. Test data from Underwriters' Laboratories, Factory Mutual, and the National Institute of Standards and Technology was used for the evaluation. These scenarios involve ceiling heights ranging from 2.44 m to 12.2 m, horizontal dimensions ranging from 5.5 m × 9.2 m to 61 m × 76 m, and peak fire heat release rates ranging from 150 kW to 3.8 MW.

Based on the model assumption of an unconfined ceiling, the small compartment scenarios (i.e., with horizontal dimensions of 5.5 m × 9.2 m) may not be appropriate for use with DETACT-QS. These scenarios were chosen to examine the capabilities or limitations of DETACT-QS under confined ceiling conditions.

Theoretical Basis for the Model

DETACT-QS uses an assumption of quasi-steady gas flow temperatures and velocities to evaluate detector response to a user defined fire. "With this assumption, correlations for ceiling-jet temperatures and velocities obtained from experiments using steady fire energy release rate Sources can be used to evaluate growing fires. The growing fire is represented in the calculation as a series of steady tires with energy release rates changing in time to correspond to the fire of interest."' The correlations used in DETACT-QS were developed by Alpert[7] and use a response time index developed by Heskestad.[8]

Performing an energy balance on the detector results in the following equation:

$$\frac{dT_{link}}{dt} = \frac{\sqrt{U_g}\left(T_g - T_{link}\right)}{RTI}$$

Where T_{link} is the detector temperature, T_g and U_g are the ceiling jet temperature and velocity, and RTI is the detector's response time index. **A** complete derivation of this equation is available in the evaluation report. **DETACT-QS** uses the Euler method with a one second time step to solve this differential equation to predict the detector temperature as a function of time. When the detector temperature is less than or equal to the activation temperature, the time is incremented by one time step, the intermediate results are printed, and the process is repeated. When the detector temperature exceeds the activation temperature, the calculation is completed.

Mathematical Robustness

The mathematical robustness of the model was examined by recreating the model with another mathematical solver. The predictions of the model and the recreation are then compared for level of agreement.

This analysis revealed two minor inconsistencies. Although the program calculates gas and detector temperatures consistent with those expected, the program prints the previous gas and detector temperature at the printed time interval. Thus, the intermediate detector and gas temperature values printed are those from the previous second (i.e., the detector and gas temperatures displayed at **10** seconds **will** be values calculated for 9 seconds).

The second inconsistency is that the subroutine calculating detector temperatures adds one second after the calculations are performed. This one-second addition results in printing final detector activation times one second greater than activation times expected.

Model Sensitivity

A sensitivity analysis was used to evaluate the relative magnitude of change that can be expected by changing an input parameter. Some input parameter changes result in small or insignificant changes in model predictions while others may result in large changes in the predicted values. Identifying the input parameters to which the model is most sensitive is important information to the user.

The results of the sensitivity analysis identify the input parameters that have the greatest effect on, or change in, the output variables. **A** nominal value for each input parameter is chosen to establish a base case. The input parameters are then individually varied over a finite range. If the relative change in the output variable of interest is greater than the change in an input parameter, the model is more sensitive to that parameter. If the output variable changes very little with a relatively large change in the input parameter, the model is less sensitive to that parameter.

The results of the sensitivity study are presented in terms of a sensitivity ratio. This ratio is the percentage change in the predicted actuation time over the percentage change in the input parameter of interest. This ratio can be expressed as

$$\frac{\%\ \text{Change in}\ t_{act}}{\%\ \text{Change in}\ X}$$

If this ratio is greater than one (1.0) then the actuation time is more sensitive to that parameter. This is to say that, e.g., a ten percent increase in the input parameter results in a greater than ten percent increase (or decrease) in the predicted output.

For DETACT-QS, in general, changing a single input parameter results in a change in the resulting actuation time (output) of less than the percentage change in the input parameter. That is, in most cases when an input parameter is varied by ten percent (10%) the time to actuation will vary by less than ten percent (<10%). Two exceptions are the input parameters detector actuation temperature and, when a slow t-squared fire is used, fire growth rate. For the former, the results of many sensitivity analyses yielded a change in predicted actuation time vs. change in input actuation temperature ratio greater than one. The larger change in output in comparison to the change in actuation temperature indicates that the model is more sensitive to the actuation temperature than it is to other input values. This condition underscores the user's need for care and understanding with regards to uncertainties relative to the thermal detector device being modeled and any environmental conditions that may affect the activation of that device.

In the case of a slow t-squared fire, the predicted actuation time will greatly increase due to the relatively slow development of the fire. This increase in predicted activation time emphasizes the need for the designer to consider appropriate safety factors that apply to the entire fire scenario under examination, not a single safety factor used for all scenarios "as-a-rule". Very small source fires, especially smoldering, fall outside the bounds of this analysis and are unlikely to be accurately predicted, either for ceiling jet temperatures or detector actuation, by DETACT-QS.

Figure 1 shows a typical range of sensitivity of output to variations in input parameters.

Evaluation Scenario Model Inputs

Three sets of experimental data were used in this evaluation. This section describes the test conditions, including geometry and construction of the compartment, location and heat release rate history of the fire, location and characterization of the thermal detector, and locations and descriptions of measurement instrumentation used in the test. From this information, the inputs to the model are developed.

The first set of tests was conducted under a 30 m by 30 meter adjustable height ceiling. The ceiling had horizontal dimensions that were smaller than those in the test facility, and exhaust was provided above the ceiling, which allowed for large fire tests to be conducted without the formation of a smoke layer below the ceiling. The second set was conducted in a room 5.6 by 9.2 m with a ceiling height of 2.4 m. The third set was conducted in a facility with a ceiling height of 8.8 m and horizontal dimensions of 61 m by 76 m.

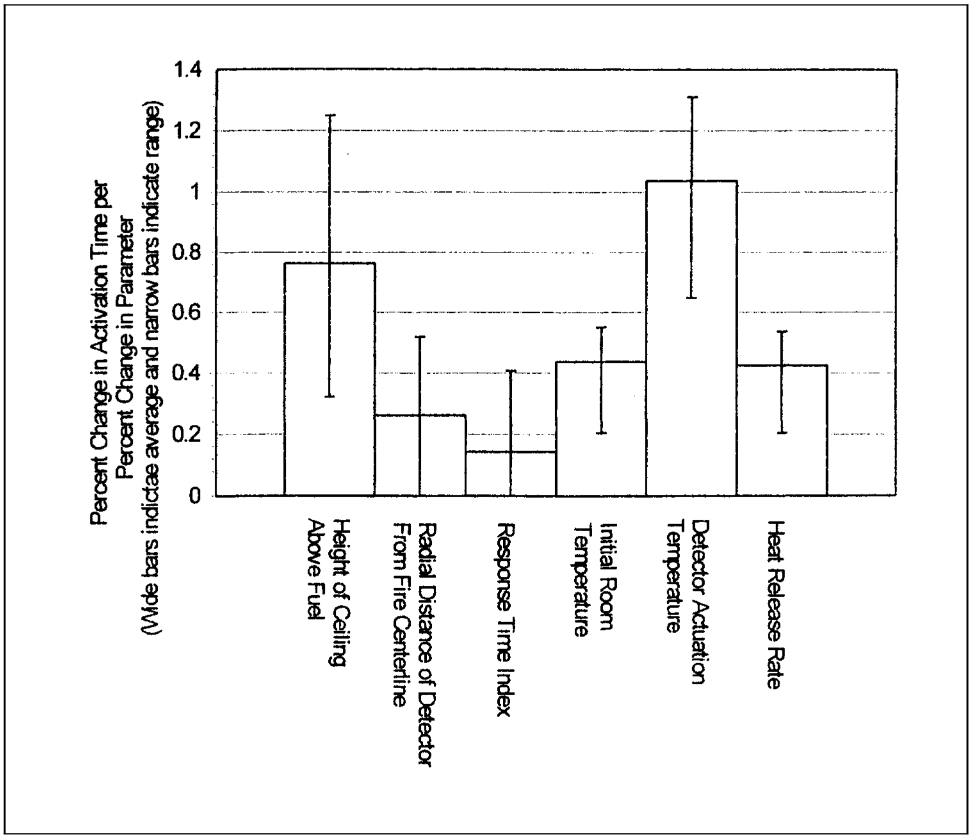


Figure 1 – Results of Sensitivity Analysis

In the first set of tests, tests were conducted with the ceiling positioned at heights of 3.1, 4.6, 6.1, 7.6, 10.7, and **12.2** m. The fire source in these tests consisted of a heptane burner constructed from a nominal **12** mm pipe manifold. The heat release rate of the test fires followed the following relationship:

Time (s)	Heat Release Rate (kW)
0 through 40	$\dot{q} = 0.1875(t+10)^2$
Time > 40	$\dot{q} = 0.0117(t+160)^2$

Brass disk thermocouples with known RTI's were used to estimate the response of thermal elements in the ceiling jet. The disk thermocouples were constructed with chromel-alumel thermocouple wire fastened to brass disks of various thicknesses. The three types of disk thermocouples were identified as slow, medium, and fast. The RTI's of the thermocouples **were** measured in the sprinkler plunge oven in general accordance with UL1767. The RTI's of the disk thermocouple were measured perpendicular to and aligned to the flow and **a** variation in the RTI of less than 10% was measured. The RTI's of the disk thermocouples are given below.

Type	Thickness (mm)	RTI ($m^{1/2}s^{1/2}$)
Slow	6.54	287
Medium	3.18	164
Fast	0.41	32

The second set of tests modeled was conducted in a room **5.6** by **9.2** m with a ceiling height of **2.4** m. The walls and ceiling were constructed of a wood frame covered with **12.7** mm gypsum board. The floor was concrete. **A** hollow steel door **2.1** m high by 0.91 m wide was closed for all experiments. The air gap under the door measured **25** mm. The ceiling vent consisted of an open stairway, which measured **2.7** by 0.9 m leading to an upper floor which gave the experimental setup the effect of a basement in a residential occupancy.

The fire source in this experimental series consisted of a methane gas burner with piloted ignition. **A** computer was programmed to control the flow of methane gas through four mass flow controllers arranged in parallel. Three fire sizes were used that grew in proportion to time squared: a fire that reached **1055** kW in **150** seconds ($a = 0.0468$ kW/s^2), a fire that reached **1055** kW in **300** seconds ($a = 0.0117$ kW/s^2), and fire that reached 1055 kW in 600 seconds ($\alpha = 0.0029$ kW/s^2). In addition to varying the heat release rate of the fire, the burner was placed in various locations within the room; away from any wall (detached experiment), against a wall (wall experiment), and in a corner (corner experiment).

Instrumentation consisted of four vertical arrays of twelve type K, 0.51 mm bare bead thermocouples. In each array thermocouples were located 0, **25,** 50, **75, 100, 125,** 150, **250,350, 450, 550,** and **900** mm below the ceiling. **A** quick response residential pendant spray sprinkler was installed on the ceiling at each of the four locations in accordance with **NFPA 13D,** ***Sprinkler*** *Systems in* ***One and Two*** *Family* ***Dwellings*** *and* ***Manufactured Homes.*** The sprinklers used in the experiments were commercially available residential pendant spray sprinklers. The sprinklers had an activation temperature of ***68*** °C and a RTI of **55** $(m\text{-}s)^{1/2}$.

The third test series was part of a sequence **of** fire tests which used wood cribs, cotton fabric, polyurethane and polyvinyl chloride **as** tests fuels. Smoldering and flaming fire tests were conducted. The initial room temperature was approximately **25** "**C.** The elevation of the ceiling above the fuel was varied by raising the elevation of the fuel above the floor. However, it was found that raising the load cell resulted in difficulties in maintaining a level platform, and the results were deemed unreliable. Of the remaining tests, only two were used, because they alone resulted in temperatures that were sufficiently high to activate heat detectors and because they showed consistency in mass loss measurements.

Heat detectors with a nominal actuation temperature of **57.2** "**C** were located approximately **100** mm below the ceiling at radial distances of 3.05, **6.1** and **12.2** meters from the crib centerline. These heat detectors were later determined to have an activation temperature of 60 °C and a time constant of **26** seconds at a reference of 1.5 meters per second, which corresponds to an RTI of **32.1** $(m\text{-}s)^{1/2}$.

The heat of combustion for sugar pine was reported as 20,900 kJ/kg in the test report; however, this was later revised by the authors to 12,500 kJ/kg. The mass loss measurements were converted to heat release rates by determining the difference in mass over measurement intervals and dividing by the length of the measurement interval, and multiplying by the calorific value of 12,500kJ/kg. The heat release rates in the tests ranged from 0 to over 3 MW.

Model Evaluation

The model evaluation compared predictions to full-scale test data. ASTM E-1355 identifies two methods of comparing model predictions with full-scale data: "blind calculations" and "Specified calculations." In blind calculations, the specific inputs are not completely defined to the modelers. In addition to comparing the model results in actual end-use conditions, blind calculations can point out misunderstandings in the use of the model. For specified calculations, the model user is provided with the most complete set of input values available, which allows a "best case" comparison of the physics and capabilities of the model. Specified calculations were used for the evaluation of DETACT-QS.

The figures below show comparisons of predicted ceiling jet temperatures with measured values.

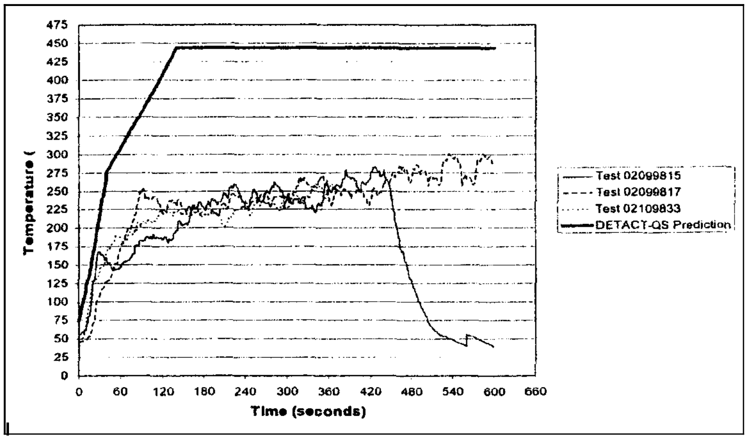


Figure 2 – Comparison of Measurements and Model Predictions for a ceiling height of 3 meters at the Plume Centerline (RTI = 0)

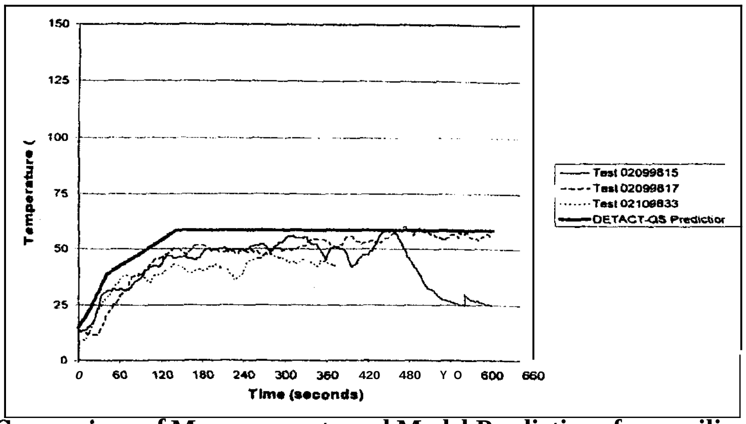
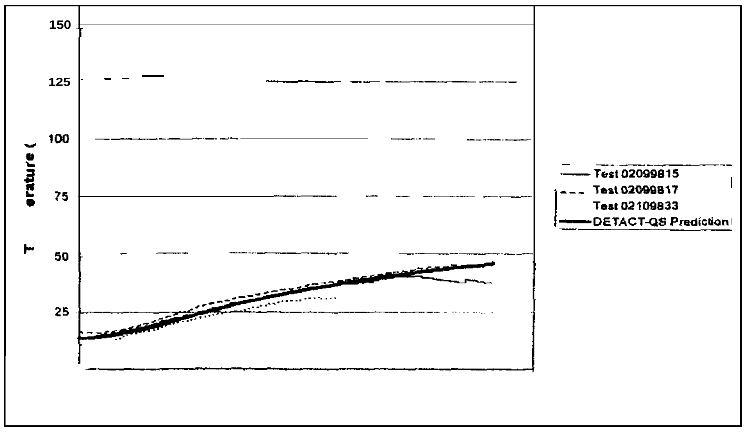


Figure 3 – Comparison of Measurements and Model Predictions for a ceiling height of 3 meters and a Radial Distance of 10 meters (RTI ‾ 0)



, height of 3

Figures **2** and **3** show a comparison of model predictions and data measurements from the first of tests **for** a ceiling height of **3 m** with a bare thermocouple (RTI ‾ 0) at the plume centerline and at a radial distance of 10 meters. These graphs show that DETACT-QS underpredicts temperatures in scenarios involving low ceilings when the detector is close to the fire centerline, but temperature predictions improve as the radial distance from the fire to the detector increases. When the ceiling jet temperatures are underpredicted, DETACT would predict longer detector activation times than **would** actually occur. However, **as** can be seen in figure **4,** predictions also improve as the detector RTI increases.

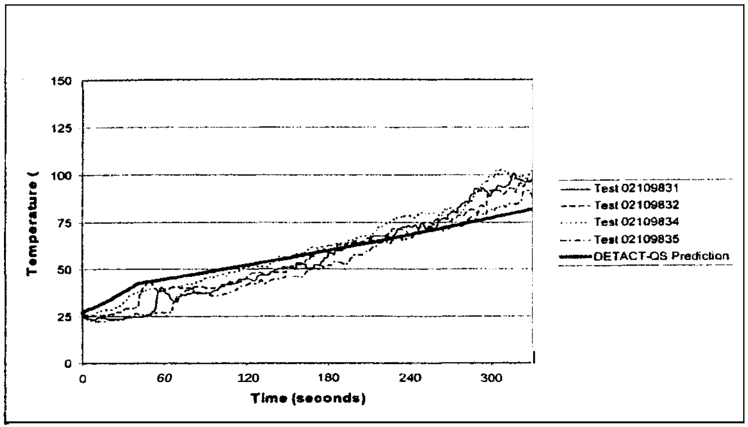


Figure 5 – Comparison of Measurements and Model Predictions for a ceiling ieight of 12.2 meters at the plume centerline (RTI = 0)

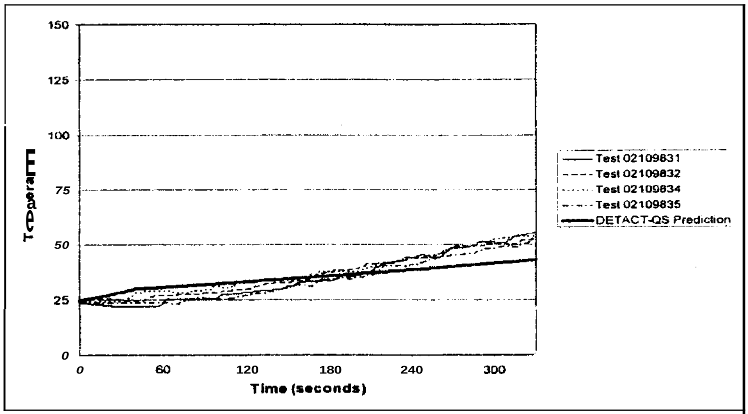


Figure 6 – Comparison of Measurements and Model Predictions for a ceiling ieight of 12.2 meters at a Radial Distance of 10 meters (RTI = 0)

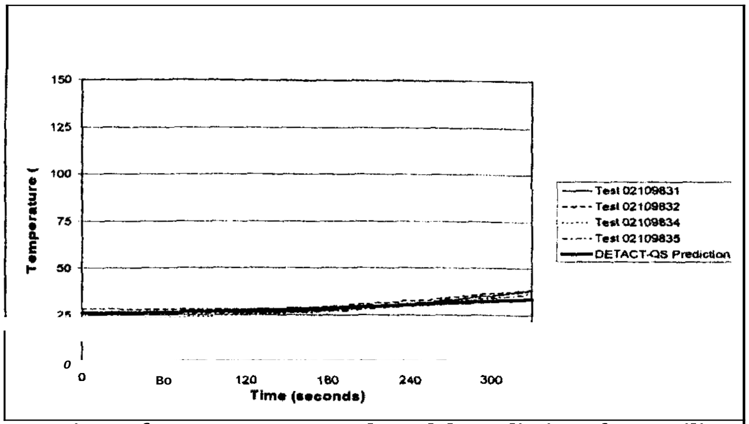


Figure 7 – Comparison of Measurements and Model Predictions for a ceiling height of 12.2 meters at a Radial Distance of 10 meters (RTI = 287 $m^{1/2}s^{1/2}$)

Figures **5 – 7** show comparisons of model predictions with experimental data from the first test series with ceiling heights of **12.2** meters. These graphs show that predictions improve as the ceiling height increases. **Also,** the improvement in predictions as response time index increases can be seen in figure **7.**

Table **1** shows the results of a comparison **of** observed detector activation times with predictions in a residential scenario. For the wall fires and corner fires, "HRR" indicates that the actual heat release rate **was** input into **DETACT-QS,** and HRRX2 and HRRX4 indicate that the heat release rate was multiplied by **2** or four, respectively when input into the model. **As** can be seen, **DETACT-QS** underpredicts ceilingjet temperatures in this scenario, and would therefore predict greater detector activation times than would be expected. This results from the formation **of** a layer in the room, which would result in the entrainment of hotter gasses into the fire plume than DETACT would predict with its assumption of an unconfined ceiling.

Scenario	**Experimental Ceiling Jet Temperature (°C)** **Average (Range)**	**DETACT – QS Predicted Ceiling Jet Temperature (°C)**		**Difference between the Average Ceiling Jet Temperature and the DETACT-QS Prediction**	
Fire in center of room	104 (93 – 118)	49		112%	
	107 (102 – 111)	61		75%	
	114 (108 – 118)	74		35%	
		HRR	**HRRX2**	**HRR**	**HRRX2**
Fire attached to wall	100 (99 – 100)	49	68	51%	32%
	109 (106 – 114)	55	76	50%	30%
	123 (114 – 138)	68	96	45%	22%
		HRR	**HRRX4**	**HRR**	**HRRX4**
Fire in corner	113 (109 – 118)	46	80	59%	30%
	125 (116 – 137)	49	88	60%	30%
	132 (121 – 143)	68	130	48%	2%

Table 1 – Comparison of Observed Ceiling Jet Temperatures in a Residential Scenario with Predictions

Based on the comparison of predictions with measured values:

- **As** the ceiling height increased from **3.0** m to **12.2** m, the agreement between the predictions and the data improved.
- There was better agreement between predictions and experimental results for devices with higher RTIs than with devices with lower RTIs.
- Situations where the limitations/assumptions of DETACT-QS cannot be met require further analysis, since the model alone cannot be used with any reasonable expectation of reliability. For example, the use of DETACT-QS would not be appropriate in small areas where a gas layer would develop prior to activation.

Summary of the Analysis and List of Limitations and Guidelines

The last two sections of the evaluation report summarize the results of the evaluation and provide guidelines for use of the model. This section of the evaluation is targeted at a wide audience to include qualified users as well as non-users who may need to evaluate building designs based on the output of the model. In addition, a list of references to all the documents relevant to the evaluation will be included in this section.

ACKNOWLEDGEMENTS

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REFERENCES

[1] ***Engineering Guide io Assessing Flume Radiation to External Targets from Liquid Pool Fires.*** Society of Fire Protection Engineers, Bethesda, MD: 1999.
[2] ***Engineering Guide to Predicting I“ and 2”” Degree Skin Burns.*** Society of Fire Protection Engineers, Bethesda, MD: 2000.
[3] ***Engineering Guide: Piloted Ignition of Solid Materials Under Radiant Exposure,*** Society of Fire Protection Engineers, Bethesda, MD: 2002.
[4] Emmons, H. “Strategies for Performance Codes in the U.S.” ***Proceedings: Conference on Fire Safety Design in the 21st Century***, Worcester Polytechnic Institute, Worcester, MA: 1991.
[5] Evans, D.D., and Stroup, D.W., “Methods to Calculate the Response Time of Heat and Smoke Detectors Installed Below Large Unobstructed Ceilings,” NBSIR 85-3167, Building and Fire Research Laboratory, U.S. Department of Commerce, Gaithersburg, MD, 1985.
[6] ASTM E1455, Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models, ASTM. West Conshohocken, Pennsylvania, 1997.
[7] Alpert, R.L., “Calculation of response time of ceiling-mounted fire detectors,” ***Fire Technology***, 9. 1972.
[8] Heskestad, G. and Smith, H.F., “Investigation of a New Sprinkler Sensitivity Approval Test: The Plunge Test,” FMRC **22485,** Factory Mutual Research Corporation, Norwood, MA, December 1976.