OFFICE BUILDING FIRE RESEARCH PROGRAM: AN ENGINEERING BASED APPROACH TO FIRE SAFETY DESIGN

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SUMMARY

The U.S. General Services Administration has sponsored the Building and Fire Research Laboratory at the National Institute of Standards and Technology to develop and support their Engineering Fire Hazard Assessment System. The GSA Engineering Fire Hazard Assessment System is a method for addressing fire safety issues based on performance instead of prescription. To enable this system, GSA found it needed additional data, algorithms, verification and guidelines for their engineers. The Office Building Fire Research Program was developed to respond to those needs by quantifying the impact of large fires on buildings and their occupants, investigating the use of current technology/resources for mitigating hazards, and developing new techniques and information as required for implementing an engineering based fire safety system. This paper provides an overview of the components and the results of the Office Building Fire Research Program to date.

BACKGROUND

Since 1985, the U.S. General Services Administration (GSA) has been working with the National Institute of Standards and Technology (NIST) on the development of the GSA Engineering Fire Hazard Assessment System. NIST's efforts on this program have been focused on developing the technical basis for the assessment of fire hazard. The first major result of the GSA/NIST collaboration was FPETool. Developed by Nelson [1,2], FPETool, is a package of computerized engineering equations and models useful in estimating potential fire hazard. Implementation of the GSA Engineering Fire Hazard Assessment System was based primarily on the use of FPETool.

With the passage of the Federal Fire Safety Act in 1992 [3], GSA became the first Federal Agency with a performance-based fire safety systems code. The law directed that certain buildings would be "...protected by an automatic sprinkler system or equivalent level of safety". Since the technical determination of "equivalent level of safety" would depend heavily on engineering methods such as fire modeling, GSA conducted an evaluation of their Engineering Fire Hazard Assessment System to determine voids in technology and future needs. As a result of this evaluation, the Office Building Fire Research Program was established at NIST. This paper provides an overview of activities and results relative to this program.

PROGRAM OBJECTIVES

The primary program objectives were to quantify the impact of large fires on buildings and their occupants, investigate the use of current technology/resources for mitigating the hazards, and develop new techniques and information as required for implementing "the equivalent level of safety" concepts with an engineering based fire safety system.

PROGRAM APPROACH

GSA found that their Engineering Fire Hazard Assessment System needed support in a variety of ways in order to make FPETool more useful to their engineers. Four specific areas of research are being addressed by NIST under GSA sponsorship. The research areas can be categorized as follows: development of data, development of new algorithms for FPETool, verification of FPETool algorithms, and development of guidelines to help engineers conduct performance-based designs. The program is being conducted as research projects at NIST augmented by research grants with the Society of Fire Protection Engineers, the University of Maryland Department of Fire Protection Engineering and Hughes Associates.

DEVELOPMENT OF DATA

In order to utilize FPETool Fire Simulator or almost any fire model, the engineer must enter the heat release rate for the fire. Unfortunately, the availability of heat release rates from office furnishings and equipment was limited and heat release rates from entire office modules was non-existent. In response to the need, NIST is generating a catalog of heat release rates including data on work stations, upholstered furniture, and office chairs. Peak heat release rates in excess of 6 MW were measured from some of the office fuel packages which consisted of desks, chairs, computers, files and papers and free standing partition panels. These experiments demonstrated the effect that work station geometry can have on increasing the peak heat release rate and reducing the time to the development of the peak heat release rate (figure 1)[4]. Data from these experiments is available on the Building and Fire Research Web Site, **www.bfrl.nist.gov** in the "Fire on the Web" section. The data is presented as a series of photos showing the fire development of a given fuel package. Under each photo the corresponding time from ignition and the heat release rate at that time are provided. A video of each fuel package is also available on the web site.

The effect of a "light hazard" water spray, 0.07 mm/s (0.1 gpm/ft^2) from a sprinkler, on the heat release rate of burning office furnishings, work stations, sofas and wood cribs was also measured. This data was then used as the basis for an empirical suppression model [5].

Sprinkler activation experiments were conducted to examine the effect on activation time, of recessing or concealing a sprinkler. A data base of activation times for sprinklers with similar response time indices (RTIs) and activation temperatures was compiled for steady state gas burner fires with heat release rates of 115, 155, 215, 290 and 520 kW. The experiments were conducted in an 18.9 m by 9.1 m by 2.35 m high compartment. Non-dimensional sprinkler radial positions, r/H, of 0.67 and 1.3 from the fire were used in the study [6]. In addition to sprinkler activation times, ceiling jet temperature, velocity and radiation measurements were made.

Measurements of water droplet sizes were made in order to characterize the sprinkler spray, used in many of the large scale experiments, in terms of median drop size and mean velocity [7]. These parameters can then be used as input to the Fire Demand model [8] developed by Mission Research Corp, under a grant to NIST. This suppression/cooling model was originally developed for use with manual hose streams.

During this research program, attempts will be made to apply the model to sprinkler suppression in compartments.

An important concern in many egress calculations is smoke movement in corridors. NIST conducted experiments to quantify the effects of a post-flashover room fire on an attached corridor [9] and to quantify the effects of a sprinklered fire exposure to an attached corridor [10]. These studies provided measurements of the temperature and combustion products in the corridor. The length of the corridor in the test was 12.8 m long. The time for smoke to travel the full length of the corridor was less than 60 seconds. A longer corridor, more representative of a building corridor was needed to make measurements of smoke temperature and velocity further away from the burn room. NIST, in cooperation with the U.S. Coast Guard, conducted fire experiments in the USCG's 37.5 m long corridor fire test facility. Smoke flows in the corridors, generated by fires with heat release rates ranging from 235 kW up to 1,600 kW, were measured for velocity, excess temperature and layer depth. Measurements were made with and without sprinkler activation to quantify the sprinklers effect on smoke propagation down the corridor [11].

The number of occupants in a building must also be considered when making egress calculations. Very little data had been collected on this topic during the past twenty years. As part of this program, the University of Maryland, Department of Fire Protection Engineering, conducted a study to examine the validity of current occupant loading factors and to determine the impact of open plan office space on occupant loading density. Twenty-three office buildings in the Washington D.C. area were reviewed. The buildings included government and private ownership and open plan office space vs. well compartmented office space. The findings indicate that the mean occupant load factor for all of the buildings was 23 m^2/person (248 ft^2/person). Buildings that were composed of open plan office designs were found to have higher occupant load factors (fewer occupants/unit area) than buildings composed of compartmented offices. Federal government office buildings were found to have smaller occupant load factors (more occupants/unit area) than private office buildings [12].

NEW ALGORITHMS

While the large scale fire experiments provide excellent heat release rate time histories and peak heat release rate data, it is not practical to conduct large scale fire experiments with every combination of office chair, desk, computer, paper loading, etc. Therefore a means of predicting the peak heat release rate for a given office scenario was developed using cone calorimeter data which is more widely available than full-scale heat release rate data for approximating the peak heat release rate. During the full scale fire experiments, it was observed that all of the exposed fuel surface areas within a work station were burning at the time of peak heat release. Therefore, to predict the peak heat release rate of a fuel package, the heat release rate data from the cone calorimeter, given in heat release rate per unit area (kW/m^2), was multiplied by the exposed surface area of the fuel in full scale. The data from the cone calorimeter was used to predict the full scale peak heat release rate by two methods. A previous study had shown good agreement between full scale fire experiment results for upholstered furnishings and the predicted peak heat release rate using the 180 second average rate of heat release from the cone calorimeter [13]. This was the first method used for this study. The second method used the peak heat release rate from the cone calorimeter tests, regardless of time to occurrence, to predict the full scale, peak heat release rate. The peak heat release rates per unit area from the cone calorimeter experiments for a sample material were multiplied by the exposed surface area of the object made of that material in the full scale office module fuel package. This was done for all of the materials in the fuel package and the heat release rates were added, providing a prediction of the peak heat release rate for the full scale fire test. Predicting the peak heat release rate of a fuel package with the peak heat release rates from the cone calorimeter provided good results as long as the heat flux used for the cone calorimeter tests was consistent with the heat fluxes realized within the work station during the full scale experiments (figures 2 and 3) [4].

Based on the results of the office furnishings experiments with sprinkler fire suppression, an empirical algorithm for a "zeroth order" fire suppression model was developed for FPETool. The fire suppression model can predict in a conservative manner the reduction in heat release rate of office furnishing fires during suppression (figure 4) [5].

Based on the ceiling jet measurements from the series of room fire experiments, described in the previous section, the sprinkler activation model in FIRE SIMULATOR was modified. Versions of FIRE SIMULATOR prior to the Ver. 3.2 release of FPETool, assumed that the ceiling jet was entraining warm air from a developed smoke layer from the time of ignition. The experimental results exhibited a distinct ceiling temperature change at the point of transition from an "unconfined ceiling jet" to a ceiling jet within a smoke layer. The ceiling jet algorithm was changed to more accurately model the transition from an unconfined ceiling jet to a ceiling jet within a developed upper gas layer [6,14]. Now the ceiling jet algorithm is identical to the algorithm from DETACT-QS until the smoke layer depth exceeds 12% of the vertical distance between the fuel and the ceiling, H. When the smoke layer is developed, then the algorithm accounts for the effects of warm air entrainment into the ceiling jet [14]. As an example, figure 5 shows the increase in ceiling jet temperature at the time of layer development, approximately 35 seconds. The ceiling jet temperature is compared with the predicted ceiling jet temperature from DETACT-QS, LAVENT, FIRE SIMULATOR from FPETool Ver. 3.0 and FIRE SIMULATOR from FPETool Ver. 3.2 (FPET MOD on the figure).

The CORRIDOR model currently in FPETool can estimate the velocity, lead edge position, temperature, thickness and gas concentrations of smoke moving down a corridor from a steady state source [14]. It is desirable to determine the same characteristics of smoke propagating down a corridor from a developing fire. Efforts are currently underway to examine the use of a different corridor smoke model, which can accommodate the developing fire. Based on data from the NIST/USCG corridor experiments, an algorithm developed by Heskestad and Hill [15], is being considered for use as an improved corridor model. This method was demonstrated in ref. 9. A hybrid corridor model has been developed for CFAST [16]. This algorithm is "empirical" from the perspective that it is based on the results of NIST LES3D [17] computational fluid dynamics model simulations. This method will be evaluated also be evaluated against the corridor experimental results.

VERIFICATION

Many of the experimental portions of this program involve large scale fire experiments. The data from these experiments and others has been used to evaluate FPETool Fire Simulator [6,18 -20]. The prediction of upper layer temperature, upper layer height and sprinkler activation time are the primary focus of the verification studies.

In the most recent study [20], three different full scale experimental compartment fire studies were chosen: a chemical laboratory with an acetone spill fire [21], an aircraft hanger with an alcohol pool fire [22] and a small office/residential basement scenario [20]. The fire in the latter case was provided by a computer controlled methane burner which could be programmed to provide growing fires approximating slow, medium and fast "t^2" fires [23]. These studies were used since they represent a variation of compartment geometry, ventilation factors, thermal physical properties, well characterized fuels, fire geometry and fire growth.

The results from the studies show that the model does not provide reasonable agreement with experimental data for all cases. Typically, when the conditions of the actual fire scenario are out side the assumptions of the model, the model would not provide results representative of the data. For example, the sprinkler activation model is based on convection heat transfer only and it is sensitive to temperature. Figure 6 shows the results of the lumped mass heat transfer model, used in FPETool [14], for a given thermal element when exposed to three different steady state gas flows [6,19]. It can be seen in the case of the two higher temperatures that a 5 to 10 °C difference in temperature due to allowances in the sprinkler operating temperature, changes in ambient conditions, or conduction or radiation effects would not significantly impact the predicted time of activation. However, in the case of a temperature near the activation temperature of the sprinkler, the convection only assumption is not acceptable since a very small fluctuation in temperature will greatly effect the predicted activation of the device [19].

GUIDELINES

The Society of Fire Protection Engineers (SFPE) is currently in the third year of a three year grant to develop a framework for engineers to follow when applying engineering methods, such as FPETool, to performance-based fire safety designs. After reviewing the performance based codes currently in use around the world [24] and with input from the United States' building and fire communities on the need for a design guide to support performance based codes, work has begun on a design guide for the United States. As a starting point, performance based fire safety design was defined as: "an engineering approach to fire protection design based on (1) agreed upon fire safety goals, loss objectives and design objectives; (2) deterministic and probabilistic evaluation of fire initiation, growth, and development; (3) the physical and chemical properties of fire and fire effluents; and (4) quantitative assessment of the effectiveness of design alternatives against loss objectives and performance objectives"[25].

From the definition performance based fire safety design, Meacham [25] provided a seven step approach:

1. Identification of site and project information.
2. Identification of fire safety goals and objectives.
3. Development of performance criteria and design criteria.
4. Development of fire scenarios.
5. Development of design fires.
6. Development and evaluation of candidate designs.
7. Development of final documentation.

As part of the framework, SFPE has started to address the issues of uncertainty and sensitivity in relation to using engineering methods for fire safety designs.

A windows based version of the Fire Safety Evaluation System (FSES) [26] is currently under development at Hughes Associates [27].

CONCLUSION

Office Building Fire Research Program is currently in its final phase. The focus of this final phase is to demonstrate the applicability and utility of the data, algorithms and guidelines that have been developed over the course of this program. Building projects identified by GSA engineers will be used as test beds for applying the performance based fire safety design framework and the GSA Engineering Fire Hazard Assessment System. The program is scheduled for completion by the Fall of 1998.

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REFERENCES

1. Nelson, H.E., FPETool: Fire Protection Engineering Tools for Hazard Estimation. National Institute of Standards and Technology (U.S.), NISTIR 4380; October 1990.

2. Nelson, H.E., FPETool User's Guide. National Institute of Standards and Technology (U.S.), NISTIR 4439; October 1990.

3. U.S. Fire Administration Authorization Act of 1992, Public Law 102-522, October 26, 1992.

4. Madrzykowski, D., Office Work Station Heat Release Rate Study: Full Scale vs. Bench Scale. INTERFLAM '96. 7th International Interflam Conference, March 26-28, 1996, Cambridge, England. Proceedings. Interscience Communications Ltd., London, England, Franks, C.A. and Grayson, S., editors, 47-55 pp.,1996.

5. Madrzykowski, D., and Vettori, R. L., A Sprinkler Fire Suppression Algorithm for the GSA Engineering Fire Assessment System, Journal of Fire Protection Engineering, Vol. 4, No. 4. Society of Fire Protection Engineers, Bethesda, MD, 1992.

6. Madrzykowski, D., The Effect of Recessed Sprinkler Installation on Sprinkler Activation Time and Prediction. Masters Thesis, University of Maryland, Dept. of Fire Protection Engineering, College Park, MD, November, 1993.

7. Putorti, A. D., Belsinger, T. D., and Twilley W. H., Determination of Water Spray Drop Size and Speed from a Standard Orifice, Pendent Spray Sprinkler. National Institute of Standards and Technology, submitted for publication 1998.

8. Pietrzak, L. M. and Dale, J. J., User's Guide for the Fire Demand Model; A Physically Based Computer Simulation of the Suppression Post-Flashover Compartment Fires. National Institute of Standards and Technology (U.S.) NIST-GCR-92-612; July 1992.

9. Stroup, D. W. and Madrzykowski, D., Conditions in Corridors and Adjoining Areas Exposed to Post-Flashover Room Fires. National Institute of Standards and Technology (U.S.) NISTIR 4678; September 1991.

10. Madrzykowski, D., The Reduction in Fire Hazard in Corridors and Areas Adjoining Corridors Provided by Sprinklers. National Institute of Standards and Technology (U.S.) NISTIR 4631; July 1991.

11. Madrzykowski, D., Corridor Smoke Flow: Comparison of Large Scale Measurements with Calculated Predictions. National Institute of Standards and Technology (U.S.), To be published.

12. Milke, J. A. and Caro, T. C., A Survey of Occupant Load Factors in Contemporary Office Buildings, Journal of Fire Protection Engineering, Vol. 8, No. 4. Society of Fire Protection Engineers, Bethesda, MD, 1997.

13. Babraskas, V. and Krasney, J.F., Fire Behavior of Upholstered Furniture. National Bureau of Standards (U.S.) NBS Monograph 173;1985

14. Deal, S., Technical Reference Guide for FPETool Version 3.2. National Institute of Standards and Technology (U.S.), NISTIR 5486; August 1994.

15. Heskestad, G. and Hill, J.P., Propagation of Fire Smoke in a Corridor, Proceedings of the 1987 ASME-JSME Thermal Engineering Joint Conference, 1, March 22-27, 1987, Honolulu, HI, American Society of Mechanical Engineers, Marto, P.J. and Tanasawa, I., editors, pp .371-379, 1987.

16. Peacock, R. D., Reneke, P. A., Jones, W. W., Bukowski, R. W., Forney G. P., A Users' Guide for FAST: Engineering Tools for Estimating Fire Growth and Smoke Transport; Special Publication 921, National Institute of Standards and Technology (U.S.), October 1997.

17. Forney, G. P., A Note on Improving Corridor Flow Predictions in a Zone Fire Model. National Institute of Standards and Technology (U.S.), NISTIR 6046; July 1997.

18. Notarianni, KA and Davis, W.D., Use of Computer Models to Predict Temperatures and Smoke Movement in High Bay Spaces. National Institute of Standards and Technology (U.S.), NISTIR 5304; December 1993.

19. Madrzykowski, D., Evaluation of Sprinkler Activation Prediction Methods. ASIAFLAM '95. 1st International Asiaflam Conference, March 15-16, 1995, Kowloon, Hong Kong. Proceedings. Interscience Communications Ltd., London, England, Franks, C.A. and Grayson, S., editors, 211-218pp.,1995.

20. Vettori, R. L., and Madrzykowski, D., Comparison of FPETool: FIRE SIMULATOR with Data from Full Scale Experiments, National Institute of Standards and Technology, submitted for publication 1998.

21. Walton, W.D., Quick Response Sprinklers in Chemical Laboratories: Fire Test Results. National Institute of Standards and Technology (U.S.), NISTIR 89-4200; December 1989.

22. Walton, W. D., and Notarianni, K. A., Comparison of Ceiling Jet Temperatures Measured in an Aircraft Hanger Test Fire with Temperatures Predicted by the DETACT-QS and LAVENT Computer Models. National Institute of Standards and Technology, NISTIR 4947; January 1993.

23. *National Fire Alarm Code,* NFPA 72 Appendix B, National Fire Protection Association, Quincy MA, 1993 ed.

24. Meacham, B.J., The Evolution of Performance Based Codes & Fire Safety Design Methods. Society of Fire Protection Engineers, Bethesda, MD, 1996.

25. Meacham, B.J., Assessment of the Technological Requirements for the Realization of Performance-Based Fire Safety Design in the United States, Phase I: Fundamental Requirements. Society of Fire Protection Engineers, Bethesda, MD, 1997.

26. Guide on Alternative Approaches, NFPA 101A, FSES for Business Occupancies. National Fire Protection Association, Quincy, MA, 1995 ed.

27. Fire Safety Evaluation System (FSES) for Business Occupancies Software (Ver 1.0) Users' Manual, NIST-GCR-96-692, Hughes Associates, Inc., March 1996.

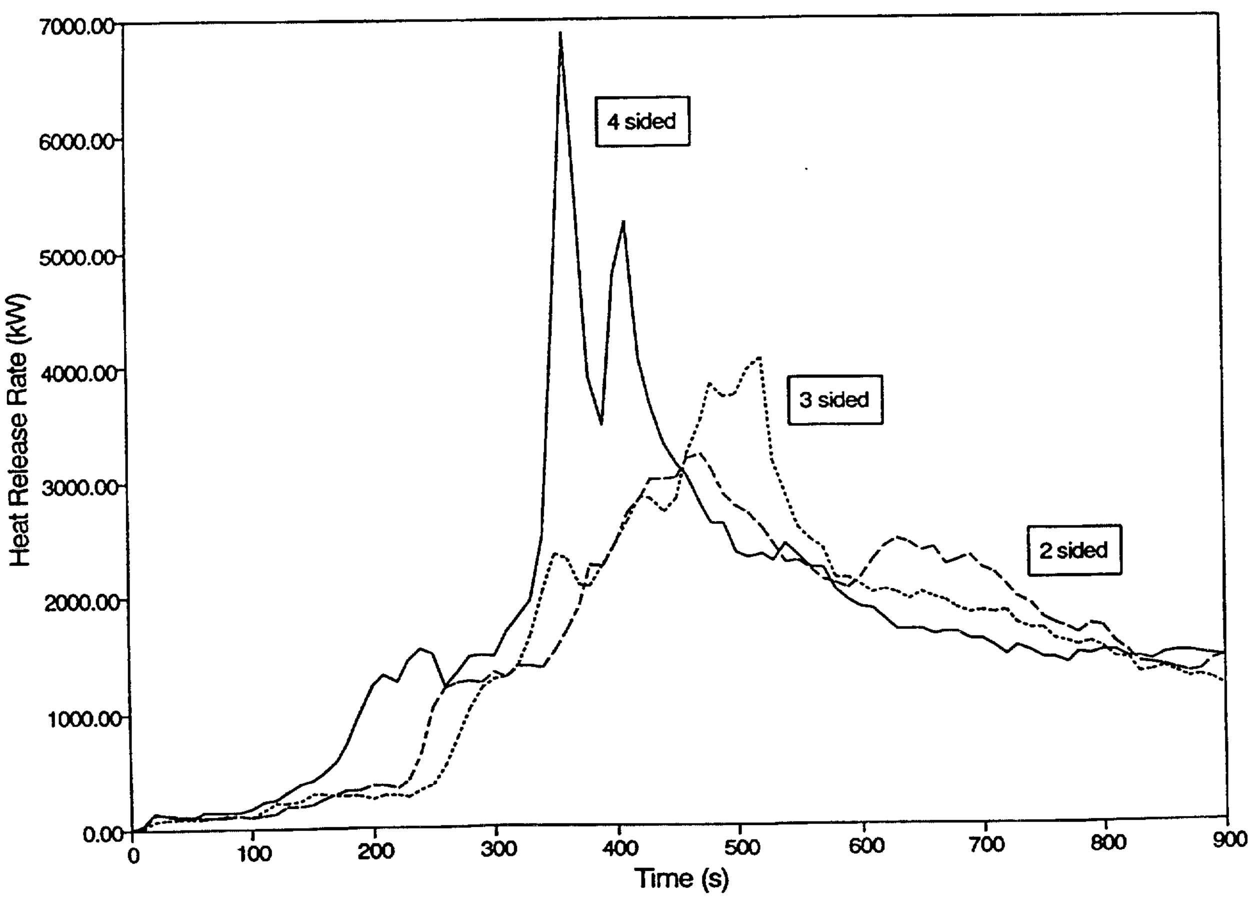

Figure 1. Heat release rate curves for two, three and four-sided work station configurations.

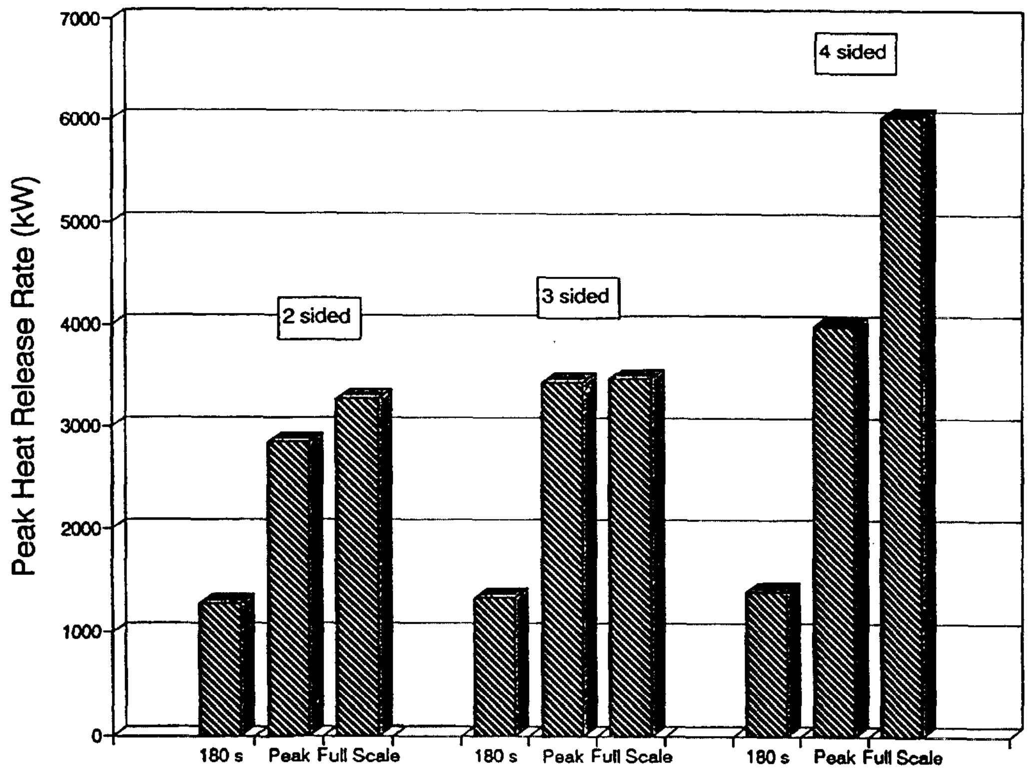

Figure 2. Work station peak heat release rate predictions using the 180 s average and peak from the cone calorimeter at 35 kW/m^2 compared with measured full scale peak heat release rates.

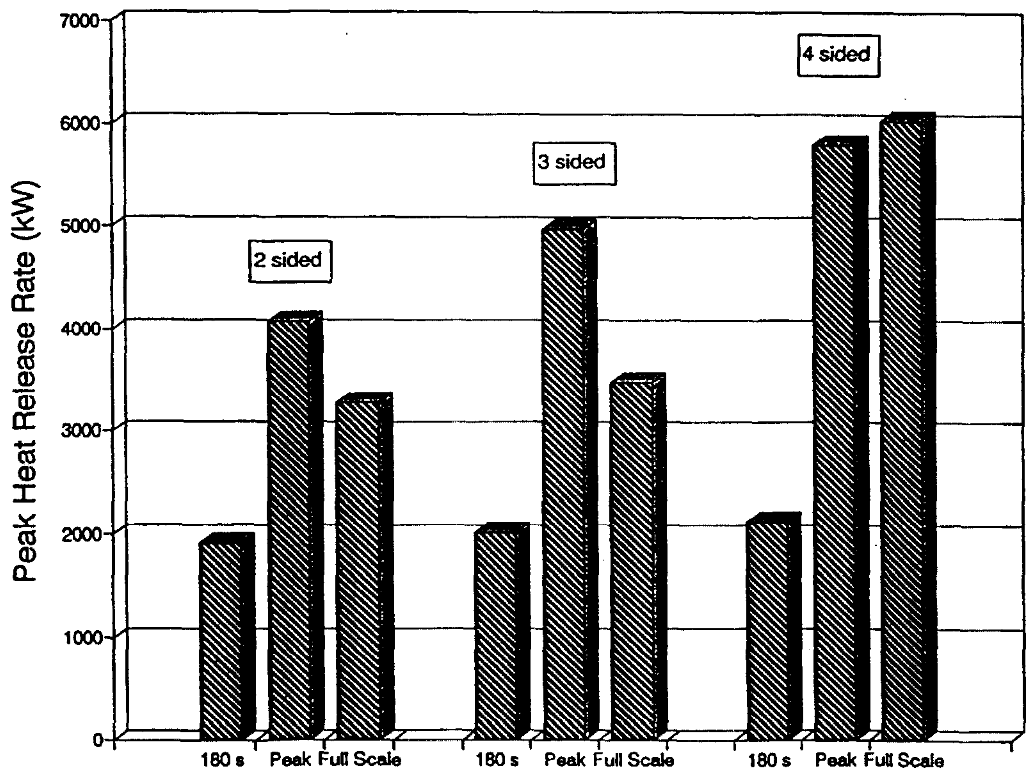

Figure 3. Work station peak heat release rate predictions using the 180 s average and peak from the cone calorimeter at 70 kW/m^2 compared with measured full scale peak heat release rates.

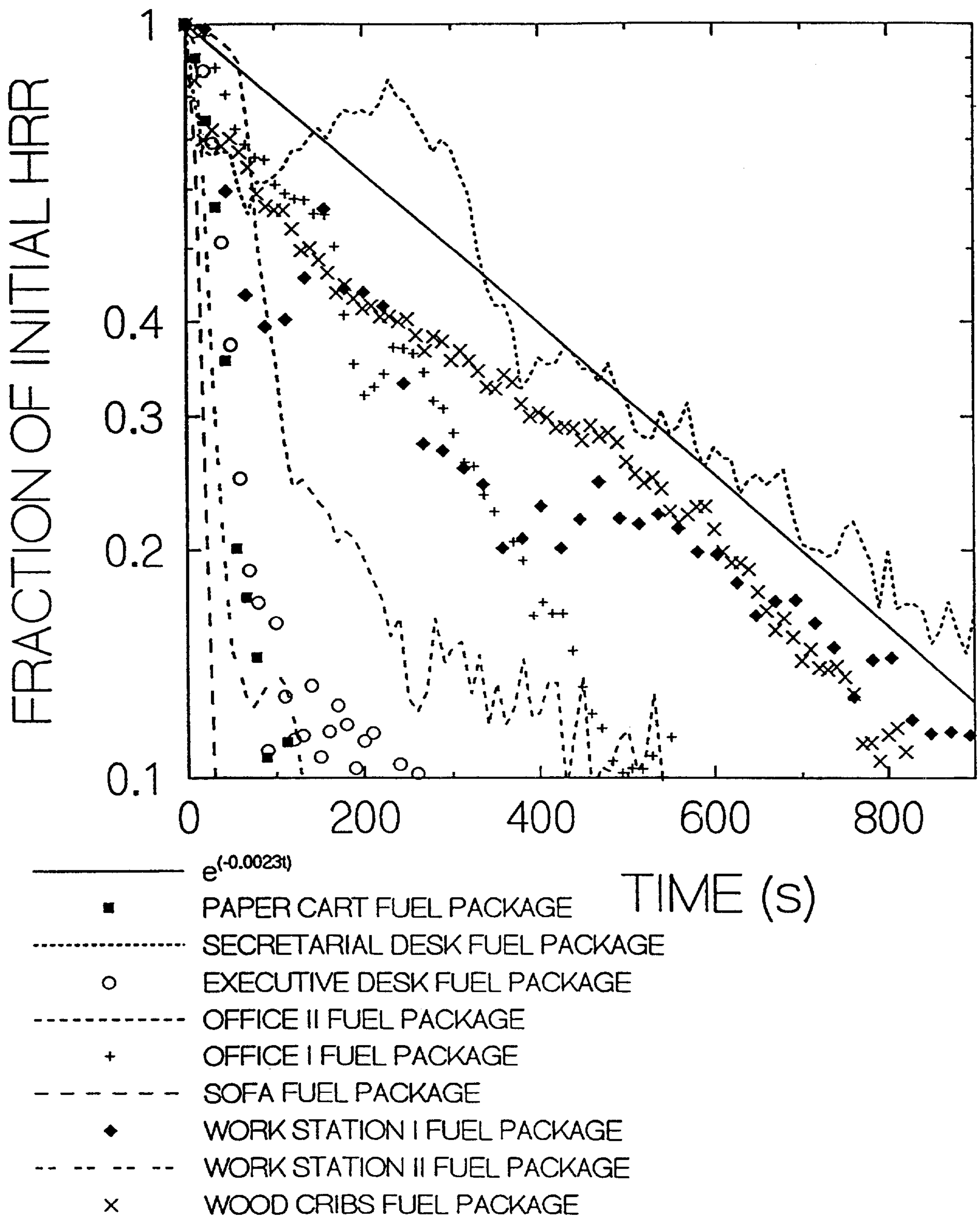

Figure 4. Normalized heat release rate reduction curves compared with the fire suppression function.

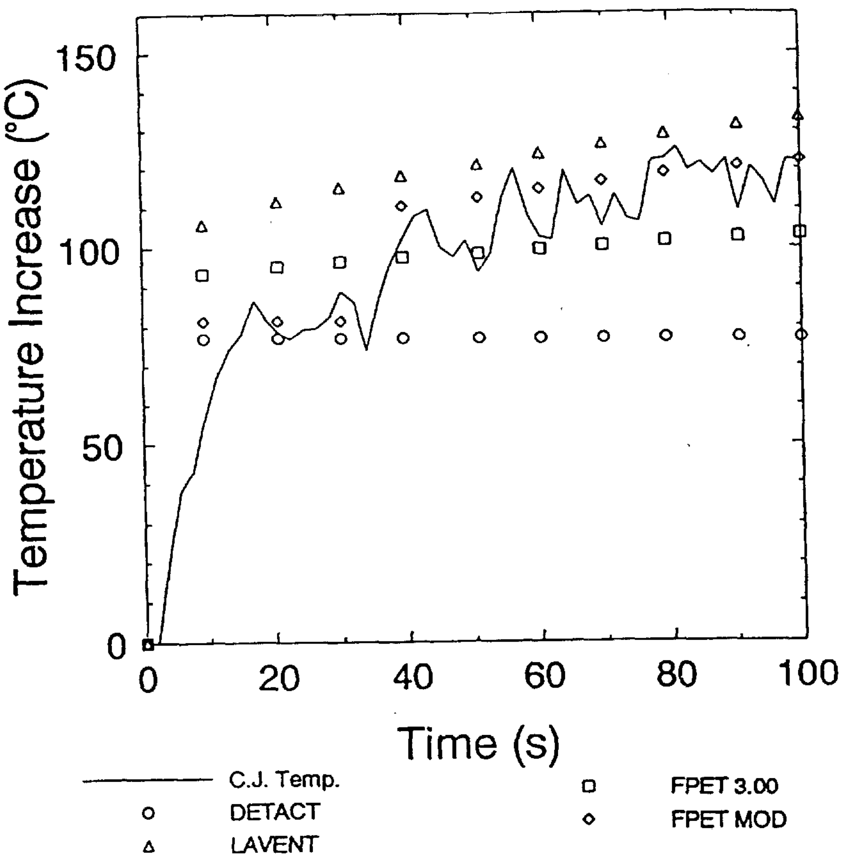

Figure 5. Ceiling jet temperature increase comparison at r/H = 0.67, 290 kW fire.

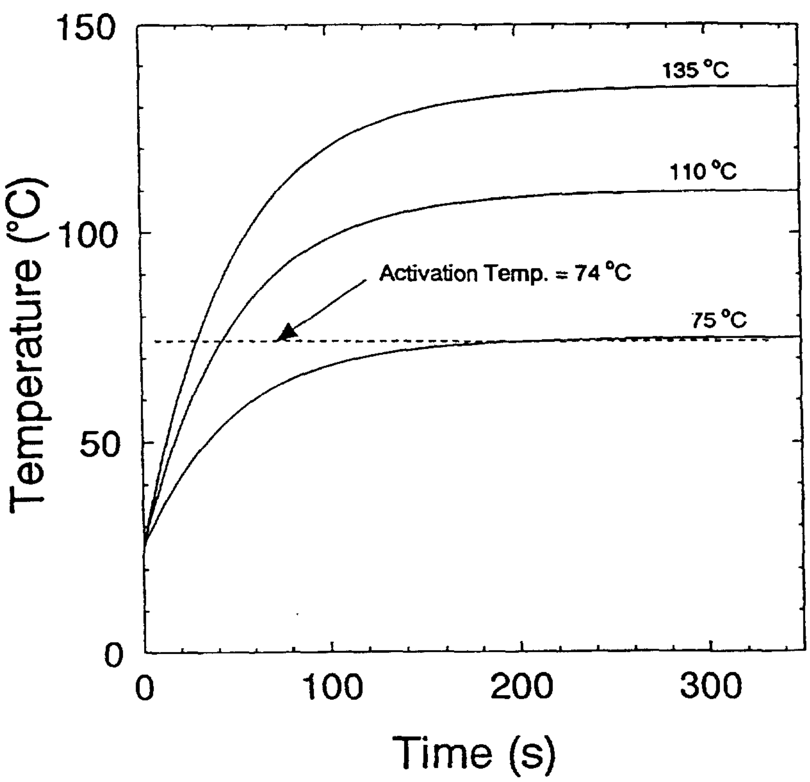

Figure 6. First - order response model sensitivity to gas temperature.