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Performance-Based Codes: Economics, Documentation, and Design

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Performance-Based Codes: Economics, Documentation, and Design

by

Jason D. Averill

A Thesis

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

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in

Fire Protection Engineering

by

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APPROVED:

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Abstract

The advent of performance-based codes in the United States underscores the need for a thorough, systematic approach to the documentation and accomplishment of a performance-based design. This project has three objectives: economic analysis of performance-based codes from a social view point, documentation of a performance-based design, and an example application of the ICC Performance-Based Code to high-rise office building. Economic issues explored include the externalities, insurance, and liabilities associated with performance-based codes. Documentation of a performance-based design includes delineation of the scope and goals with agreement between the designer, architect, building owner, and authority having jurisdiction, examination of the relevant code statutes, development of appropriate fire scenarios which meet the requirements of the performance matrices, thorough documentation of all design tool and calculation assumptions and limitations, and a clear demonstration of satisfactory accomplishment of stated goals and objectives. Finally, performance-based design alternatives to a prescriptively-designed 40 story office building were developed. There were three major design alternatives. The first design feature was the evacuation of occupants using elevators. The second alternative was the use of the assured fire safety system, which combined emerging technologies in fire detection, alarm, and suppression. The final design alternative was the routing of the domestic water supply through the sprinkler riser in order increase the reliability of the sprinkler system and save design, material, and installation costs associated with the domestic water supply risers. Finally,

this project analyzed the specific life-cycle economic impact of the design alternatives when compared to the prescriptive design.

Acknowledgments

This project was completed with dual, complementary objectives. The personal objective of the author was to perform an analysis of performance-based codes from a social perspective to complete degree requirements of a Master's of Fire Protection Engineering at Worcester Polytechnic Institute. The author recognizes the contributions of Prof. Jonathan R. Barnett who advised the project, both technically and as a friend. The help and support of Prof. David A. Lucht, department head of the Center for Firesafety Studies is also appreciated. The project also met the goals of the Building and Fire Research Laboratory at the National Institute of Standards and Technology. Mr. Richard Bukowski acted as a thesis co-advisor and NIST liaison. The assistance of Dr. Walter Jones, Mr. Paul Reneke, Mr. Richard Peacock, Dr. Glenn Forney, and Dr. William Davis is also appreciated. Additionally, Joseph Fleming, chief fire marshall from Boston Fire Department, assisted on the technical content and acted as an Authority Having Jurisdiction. Jay Waters and the staff at HKS Architecture in Dallas, TX performed the prescriptive-based building design and provided drawings and assistance. Prof. Tom Kisko from the University of Florida provided software support with the evacuation modeling. The members of the International Code Council provided the performance-based design regulation, sponsored the American entry into the conference, and lent technical feedback and expertise. Finally the author thanks his mother and sister for their support and encouragement throughout his studies.

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**Dedicated to the Memory of
Daniel Alan Averill
1951 - 1994**

Introduction

Performance-based codes have long been advertised as being beneficial to parties involved in the construction of buildings when compared to traditional prescriptive codes. The building owner may benefit through the lower total cost of building construction and operation. The architect may be allowed to pursue more innovative architectural designs if the fire protection engineer can show the subsequent design meets the fire safety performance objectives. The party whose job potentially becomes more difficult and time consuming is the building official charged with approving the building design. With prescriptive design, the official had only ensure that the building met the intent of the code. In order for the building official to ensure that the design meets the less explicit goals of the performance-based code, engineering calculations and judgments are necessary to ensure fulfillment of fire safety objectives.

Scope and Objectives

There are three major objectives within the scope of this thesis: 1) address significant economic issues pertaining to the implementation of a performance-based code in the United States; 2) develop a framework for the presentation of a performance-based design; and, 3) complete a performance-based design which accomplishes the case study objectives for presentation to the 2nd International Conference on Performance-Based Codes as well as demonstrates the equivalency and flexibility of the ICC Draft

Performance-Based Code. The first two objectives support thorough completion of the latter objective.

The first objective is to determine the total economic impact of the performance-based codification process. The total cost of performance-based design is the sum of the private costs and the social costs. While the quantification of private costs is addressed through the building process, the determination of total social cost is not accounted for by current market forces. Subsequently, if performance-based codes without regulatory adjustment for total social costs are implemented, the full potential social benefit of performance-based codes will be unrealized. Economic issues such as externalities, development of an insurance market given new technologies and techniques using quantitative risk and failure techniques, and optimization of private costs are addressed.

Second, a template for the documentation and presentation of a performance-based design is developed and justified. Careful, consistent documentation of a performance-based design is a critical step towards assuring achievement of social design goals. Proper documentation includes explicit listing of design goals and methods, calculation procedures, assumptions, limitations and uncertainties, and achievement of design goals.

Finally, the project demonstrates how the flexibility of the ICC code allows for the infusion of new technologies into building design that are not encouraged in a prescriptive regime. New technologies evaluated here include elevator egress and 'smart' detection,

alarm, and suppression systems. To demonstrate the use of these technologies to meet the fire safety objectives of the ICC performance-based code, a 40-story, mixed-occupancy office building, containing several underground parking levels is analyzed. The building selection satisfies the case study requirements for the 2nd International Conference on Performance-Based Codes.

Each of the three sections combines to form a robust analysis of the performance-based movement in the United States. The results of parallel efforts at the National Fire Protection Association, the International Code Council, conferences such as the Conference on Performance-Based Codes, and similar efforts in the global fire community should help minimize transition time and costs.

Economic Analysis of Performance-Based Codes

The justification of performance-based codes often depends to a significant extent upon economic savings being realized by the constituents of the building process. There exists little incentive for owners and engineers to pursue a performance-based design unless the unique design achieves either significant cost savings or an innovative, aesthetic design. There are two distinct components to determining the total social costs of a performance-based design: optimization of private costs associated with the performance-based building design process and accurate accounting of non-private, or social, costs. Performance-based codes, when analyzed from an economic viewpoint, however, are difficult regimes to accurately estimate total social costs. There are several distinct components of total social costs associated with any regulatory structure:

1. Optimization of Private Costs

2. Externalities

3. Distributional Equity

4. Best Available Technology

5. Probability and Magnitude of Failure[1]

Optimization of Private Costs

Optimization of private costs is the most publicized component of economic efficiency realized by the advent of performance-based codes. Private costs include labor, material, and overhead costs associated with the construction process, in addition to continuous

management and maintenance costs upon building completion. Performance-based codes often focus upon the optimization of private costs because they are the easiest to quantify. This section will review a model to examine building components for life-cycle cost. Further, each component of the design process can then be analyzed to determine the economically optimal design.

ALARM 1.0[2] is a computer program designed to maximize the cost-effectiveness of fire code compliance. ALARM uses the equivalency provision in the *Life Safety Code®* for health care occupancies. While the ALARM software is not direct applicable to analysis of a 40 story office building, the general framework provides insight into steps necessary to fully evaluate the private costs and savings of a performance-based design. The premise of the program is simple: iterate code-compliant building design options until minimum cost is realized. The success of this methodology is contingent upon full knowledge of the available options as well as the costs associated with each option. The equivalency provision in the *Life Safety Code®* provides a rigorous framework that is not readily applied to all performance-based designs, but provides a starting point. The optimization process requires that all available options be identified. The options can then be estimated by a construction project manager for initial and life cycle costs. Additional requirements stipulated by an involved party may change the simple requirement that the design simply be equivalent to the prescriptive requirements. Property protection required by the owner above and beyond the prescriptive mandate

changes the nature of the comparison somewhat. Optimization of private costs upon differing design options, each expressing equivalency to a particular standard, lends itself to computer programming, such as the one developed in ALARM. Such analysis can be standardized with a robust model such that subsequent optimization requires significantly less effort than the initial project.

Externalities

Externalities are events that, due to the actions of one entity, impinges upon the activities of another in a manner that is not explicitly or implicitly accounted for by market forces. Externalities are often the most critical, least-understood component of a thorough cost-benefit analysis. A classic example of the effect of externalities on decision making can be seen by looking at an example from a manufacturing facility. Suppose, for example, that a manufacturing facility can produce their widget using a new production process for 50% of the cost of the previous method. The company can reduce the selling price of widget by some percentage less than 50% and realize a healthy profit, while lowering the price of the widget to the consumer. The action seems like a situation where society benefits by having more widgets at a lower price until the total social costs of the process are analyzed. The costs of the new production line, materials, and labor are private costs, and are relatively simple to calculate. The externality, in this case, is the increase in air pollution caused by the new production process. The total social cost is the sum of private costs and externalities. The cost of externalities is often difficult to determine,

even if they are identified, which is not always the case. For example, society must either pay the costs associated with illnesses due to air pollution, or pay the cost of cleaning up the polluted air. If a proper economic analysis was used to price the widgets which accounted for the pollution from the beginning of the production process, the price of the widgets would be higher to account for air pollution. The higher price would accurately reflect the optimal level of widget output for society. The price of the air pollution would be absorbed by the company through lost income and by society through higher prices, and hence, fewer widgets. In other words, the cost of externalities should be internalized to the people making the decision to create the externality. People who chose not to consume widgets would not be affected by the production of widgets, as they would be if the widget manufacturer were allowed to pollute the air. Performance-based codes should account for all foreseeable externalities and identify methods to internalize associated costs. It is important to note that externalities are not by definition costs. Externalities can be benefits to society. Prescriptive codes may create external benefits as part of the mutual reciprocity of advantage of a regulatory regime. The engineer, failing to account for external advantages, may overstate the true value of an "equivalent" design. Externalities, henceforth, however, shall refer to external costs and a reduction of external benefits.[1]

Externalities of Performance-Based Codes

The true social cost of a performance-based design can only be determined by an accurate accounting of externalities, in addition to the total private costs. Total private costs will be accounted for by the parties involved in the design process since total private costs are inherently internalized. Private costs are further discussed on page 4. Therefore, identification and proper valuation of externalities becomes critical from a societal viewpoint. There are several distinct regimes of externalities that arise as a result of performance-based codes. The first is loss. The next is the real estate market and another externality regime is public fire safety. Finally, liability creates social externalities. These factors combine to create an inefficient market structure, which effectively limit the social savings performance-based codes offer.

The first, and arguably the most important, externality regime is loss. Loss consists of two distinct components: occupant loss and owner loss. Occupant loss is difficult to fully measure. Parts of occupant loss include lost work, property, and quality of life including injury and/or death. While lost wages and property are relatively straightforward estimates, valuing injuries or deaths is extremely difficult.[3] Allocative efficiency is precluded by large ranges of injury and death settlements. Owner loss refers to such immediate costs as property and rent, but may include long-term losses including liability beacuse of legal negligence of the responsibilities as an owner. The reason that owner and occupant costs are grouped under loss is because these costs are most often absorbed not by the individual, but by insurance companies. While the insurance market can be

considered a free market force, insufficient levels of insurance are often carried by owners and occupants. Meeks and Brannigan illustrate the case of the DuPont Plaza Hotel fire. "The DuPont Plaza Hotel…carried only 1 million dollars in insurance, despite operating with hundreds of millions of dollars in human risk." A simple solution is for building owners and occupants to provide proof of adequate insurance in order to receive an occupancy permit.

The second component of social externality is the real estate market. There are two aspects of the real estate market. The first aspect is standardization and the second aspect is information costs. Prescriptive codes stipulate the requirements for many building components. Stipulations result in product standardization and economies of scale. Performance-based codes reduce dependence of the designer upon standard equipment and increase the necessity of various performance requirements for similar products. Performance-based codes can result in similar buildings having different levels of fire safety to a greater degree than exists under a prescriptive regime. Fire safety levels include distance to the fire department, the age of the building, choice of interior furnishings, fire safety systems, both active and passive, and the choice of building materials. While the performance-based design process should preclude any design from falling below an acceptable level of safety, varying levels of safety and cost will exist. The result is two buildings with identical fire safety performance, one accomplished at a reduced cost leading to lower rents, etc., or two building with identical cost and different

levels of fire safety performance. The result is increased information costs for firms seeking office space. The companies must now factor in levels of fire safety into their cost analysis.

Public fire protection is a societal cost often taken for granted under any regulatory regime, whether prescriptive or performance-based. There are two aspects of public fire protection: regulatory and suppression. The regulatory agency is responsible for approving all building designs and assuring the public that all buildings within its jurisdiction meet minimum standards. Performance-based codes increase the cost of establishing and enforcing regulatory requirements as well as inspecting buildings. Inspection costs increase due to the fact that inspections under the prescriptive regulations required standardized checks for code violations. With performance-based designs interspersed among traditional designs, ensuring continued code compliance becomes highly individual to buildings. A building in a performance-based design may receive a "variance" due to an expressed compliance with some set of assumptions. The building inspector must now *in perpetuity* ensure that the owner and occupants are aware of the assumptions and that the assumptions are not violated, thereby compromising the safety of the occupants and surrounding area. Additionally, the cost of verifying a performance-based design, from the viewpoint of a building code official, is significantly increased, particularly if the official reviewing the calculations is not a qualified fire protection engineer, as most building officials are not. The design verification then either becomes a long tedious process for a potentially unqualified reviewer, or requires review

by a non-partisan third party engineer. Fleming further addresses the problems of the building code official with regards to performance-based codes.[4]

The final component of social externalities is liability. Liability occurs when there is a loss and is partially addressed through the existing legal system, however one could argue that the current legal system is fraught with inconsistency and subjectivity. Monetary settlements, indeed, even guilt, vary according to circumstances beyond the control or prediction of the designer, making full accounting of liability in an economic sense difficult. Liability refers to the fault of a party in an engineering failure and the degree to which that party is to be held financially or criminally responsible for the failure and ensuing consequences. Performance-based codes increase the level of responsibility incurred by the engineer who designs the fire protection systems. Rather than being able to rely on the prescriptive requirements to deflect responsibility for building failure, responsibility rests chiefly upon the engineer, if none of the assumptions inherent in the calculation procedures were later violated. Thus, a new insurance market for the protection of engineers from design responsibility evolves. This is an additional cost associated with performance-based design, although not necessarily an externality.

Best Available Technology

For society to realize one hundred percent efficient use of resources, the best available technology must be implemented. While the best available technology may often incur

large up-front costs, the effective lifetime costs may be lower than other technologies. Additionally, better technology can be assumed to save lives through increases in performance levels. The value of a life saved by implementation of a better technology may be measured not only in the legal valuation of the particular life, but also the loss of benefits that person is no longer able to contribute to society.

Probability and Magnitude of Failure

A significant barrier to achieving both cost savings and increased safety involves quantification of probability and magnitude of failure in a performance-based design. While sophisticated models currently exist to address the quantification of failure and the resulting magnitude of the damage, the underlying tenets of the model are based upon technology and regulatory procedures of the prescriptive market. For example, if one were to calculate the probability of smoke detector failure, the underlying assumptions of any available historical data would carry the bias of a prescriptive design. The use of such data may be inappropriate for a performance-based design if any factor leading to the potential failure of a smoke detector were designed differently than would otherwise exist in the prescriptive design. New technology presents an even greater challenge to anyone performing a risk/consequence analysis. First, new technology provides no historical data for the engineer to predict performance levels in actual fire conditions. While the laboratory testing procedures should provide guidance, products or systems may perform differently in a real fire scenario. Secondly, new technology often has

unanticipated consequences. The behavior of one system or product may affect the behavior or operation of another system or product. The level of uncertainty in the analysis is significantly increased.

Conclusions

The promised land of performance-based codes should be traversed with an appropriate blend of caution and optimism. The total consequences of code changes can not always be fully anticipated, or even accounted for. Most buildings will continue to be designed using prescriptive codes, for many reasons, including designer familiarity, economy for simple designs, and ease of implementation. Performance-based designs have significant design costs and can require negotiation between the design team and authority having jurisdiction. Social costs including externalities and insurance markets further reduce the net savings to society. However, performance-based design can result in significant private and social savings when implemented in a thorough, deliberate manner, taking into account more than just private costs.

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[1] Meeks, Carol B and Vincent Brannigan. "Performance-Based Codes: Economic Efficiency and Distributional Equity." Conference Proceedings of Interflam 96, Seventh International Fire Science and Engineering Conference, Cambridge, England, 26-28 March 1996, pp. 573-580.
[2] Weber, Stephen F. and Barbara C. Lippiat. "ALARM 1.0: Decision Support Software for Cost-Effective Compliance with Fire safety Codes," NISTIR 5554, December 1994.
[3] Landefeld, J. Steven and Eugene P. Seskin. "The Economic Value of Life: Linking Theory to Practice." in "Economics of the Environment, Selected Readings, 3rd Edition." Robert Dorfman and Nancy S. Dorfman, Ed. WW Norton and Company, New York, NY, 1993.
[4] Fleming, Joseph. "Code Official's View of Performance-Based Codes." Proceedings of Fire Risk and Hazard Assessment Symposium, San Francisco, CA, pp. 93-117, 26-28 June 1996.

Documentation of Performance-Based Design

The primary objective of the performance-based design is to resolve the paradox of building design: maximize safety and cost-effectiveness. The effectiveness with which a particular design satisfies both requirements measures the value of the design. The value must be compared to the prescriptive design and shown to either enhance life safety at minimal cost increase or provide equivalent life safety at substantial cost savings in order to justify the additional design time and expense associated with performance-based design. The additional time and expense refers to not only the fire protection engineering, but also the review by the local authority. The performance-based design must clearly demonstrate that all facets of life safety have been satisfactorily addressed. This includes a statement of the problem. The designer, reviewer, and building owner must all agree which problems are to be addressed by the design. The objectives of the design needs to be clearly delineated. The design should then address all of the important building features, building materials, contents, and the appropriate characteristics of the occupants. The building owner should clearly state his/her fire and life safety goals. The engineer should then clearly show how the design will satisfy society's, as well as the owners, fire and life safety goals. This includes a clear description of the performance criteria that were selected to assess the fire safety goals and objectives. Satisfaction of the criteria should be met through a fire safety design approach, further described herein. This approach includes selection of design fires and fire safety measures. The fire safety measures range from equipment criteria and performance standards and objectives to personnel and occupant responses. The performance criteria discuss tenability for

occupants, active and passive fire detection and suppression features, capabilities, and performance expectations, compartmentation, fire performance of the structural frame, the expected extent of fire related damages, from heat and smoke to water, and the expected time to return to normal business operation. Any design tools and calculations used to analyze the design should be clearly discussed and referenced. Discussion of post-design management responsibilities includes material control, change of occupancy requirements, education and training, and system maintenance and testing. Finally, the performance-based design should be compared to the prescriptive design in order to quantify the total expected savings over the entire life of the building resulting from the performance-based design, the relative, comparative, or absolute contrast in risk to life , as well as a comparison of the performance-based design objectives and the prescriptive requirements. While this list is by no means complete, it underscores the high level of detail which a performance-based design must address.

Scope of Project Design

The definition of the scope of the project provides a summary of the building characteristics to an Authority Having Jurisdiction (AHJ), a reviewer, or interested party. The nature of the project must first be described. The nature of the project characterizes whether the project is new construction, renovation (including whether or not there will be a change in occupancy) or upgrade of an existing facility, or repair of a structure damaged by fire, earthquake, or other event. A general description of both the existing

structure (if applicable) and the proposed finished structure frames the discussion. Many important details must then be delineated in order for the subsequent analysis to occur in the proper context. These details include the type of construction and building materials, location and general characteristics of the surrounding properties, fire service location and response time, determination of the quality of the water supply, security, assumptions which affect the management, design, or regulation of the building, and any budgetary constraints imposed during the design and construction process. Each characteristic combines to define the scope of the project.[5]

Goals of the Design Process

The goals of a fire safety design must be clearly specified in order that performance criteria are developed and the overall fire safety of the building is evaluated. A fire safety goal is a broad statement that reflects society's expectation of the level of fire safety provided in a building.[6] The fire safety goals must be qualitative, yet allow evaluation using accepted methods. Examples of goals include, "safeguard people from or illness when evacuating a building during fire,"[7] or "safeguard people from injury due to loss of structural stability during fire and protect household units from damage due to structural instability caused by fire."[8] There are two types of fire safety goals: societal goals and client goals. Client goals are only considered if the goals exceed societal goals. Examples of client goals, which are not addressed as societal goals, include property preservation, business continuity, and insurance mitigation. For example, a building may satisfy

societal goals without a sprinkler system. Adding the sprinkler system may result in lower insurance, protection of property and increased life safety, as well as decreased likelihood of business interruption.

Clients of a fire protection engineer can be a variety of people, from architects and other engineers to building owners or an AHJ. Careful quantification of the goals of the client increases communication between what the client wants and what the engineer is delivering. Explicit statement of fire safety goals ensures that the building meets societal requirements and allows for evaluation of fire safety effectiveness using accepted methods.

Functional Objectives

A functional objective is a quantifiable statement intended to satisfy a fire safety goal. Functional objectives must address both societal and client goals. For example, a societal goal for a museum may be to ensure that people can safely egress the building in the case of a fire. A functional objective for this goal may be to "give people not intimate with the initial fire development adequate time to reach a safe place without being overcome by the effects of the fire."[9] An example of a client goal may be to provide for business continuity. The functional objective may be to "protect the piece of equipment in room X against the effects of fire such that a return to full operation can occur within 24

hours."[9]   The distinction between a goal and a functional objective is the ready

quantification of the latter.

Performance Criteria and Design Objectives

A performance requirement is a quantification of the level of performance which a

building material, assembly, system, component, design factor, or construction method

must satisfy in order that the building meet the all goals established by society and the

clients. A performance criterion is a metric which building materials, etc., are evaluated

on their ability to meet specific performance requirements. An example of a performance

criteria includes, "the deflection of reinforced concrete structural members shall not

exceed that permitted by ACI 318."[10]   The method of performance analysis will

determine the required inputs, including occupancy hazards, construction requirements,

size and geometry of the building, as well and process. Several issues necessary to

identify in performing a proper analysis include the level of accuracy required,

limitations, assumptions, and sensitivity of the method, justification, safety factors, design

redundancies, and a statement of the current design or configuration.   Performance

criteria applicable to the present design must be included in the documentation in order

benchmark the evaluation procedure. Subsequently, the design objective is the quantified

statement that satisfies the requirements of the performance criteria.   Several design

objectives may satisfy a given performance criteria, depending on the context of the

application. The following example developed by Meacham[9] illustrates the relationship

between each step of the design process.

- The *fire safety goal* is to protect those people not intimate with the first materials burning from loss of life. This is easy to agree with, yet difficult to quantify.
- One *functional objective* might be to provide people with adequate time to reach a safe place without being overcome by the effects of the fire. One could infer that protection must be provided against heat, thermal radiation, and smoke.
- A *performance requirement* may be to limit the fire spread to the room of origin. If the fire does not leave the room, people outside the room of origin will not be exposed to thermal radiation or extreme temperature, and their exposure to smoke will be minimized.[*]
- One could then establish the *performance criterion* of preventing flashover in the room of origin. This is based on the fact that fire spread beyond the room of origin almost always occurs after flashover when the upper gases ignite and spread the fire front.
- Finally, to satisfy this criterion, the engineer might establish a *design objective* that the upper layer temperature not exceed 500°C, a temperature below which flashover is unlikely to occur.

Development of Fire Scenarios and Evaluation of Building Performance

A shortcoming of traditional fire scenario development is summarized by the following

warning:

> "Keep in mind that there are always fires too severe or
> not severe enough to be considered."[11]

Fire scenario development encourages the engineer to consider the most common and

most severe fires to be reasonably expected in the particular building. The traditional

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[*] However, as seen in fires such as the MGM Grand and the Dupont, smoke exposure may not be zero and fatalities may result.

approach relies substantially upon the judgment of the engineer to determine what the common and most severe fire exposures are in a given occupancy. ICC performance-based code approach explores the range of fire scenarios, from small, frequent fires to high-intensity, very rare fires. Additionally, the graph shows where on the range of hazard assessment the current design lies and what the factors of safety are, as well as the relative importance of parameter changes in the design process. In order to develop the performance curve, however, the engineer must have design tools with which to evaluate both the range of possible fires as well as whether or not the performance objectives have been satisfied.

The analysis of where the current design lies along the performance curve should be as robust as possible. All quantifiable factors which can affect the fire growth rate and fire spread through the building should be addressed. Meacham[9] lists factors which should be taken into account when developing the likely fire scenarios encountered in the analysis.

- Pre-fire conditions: building, compartment, environmental conditions
- Ignition sources: temperature, energy, time and area if contact with potential fuels
- Initial fuels: state, surface area to mass ratio, rate of heat release, toxicity potential
- Secondary fuels: proximity to initial fuels, area, same as above
- Extension potential: beyond compartment, building, or area
- Target locations: note target items included in societal or client loss objectives along the expected route of fire and product spread
- Occupant condition: alert, asleep, self-mobile, disabled, infant, elderly, ill, etc.
- Critical factors: ventilation, environmental, operational, etc.
- Relevant statistical data

Design Tools

Many design tools exist to assist the engineer in evaluating the fire safety of a building and to determine the performance level of the current design. Design tools also allow iteration of multiple design options to determine the most desirable (often interpreted as cost-effective) design alternative. The most simple, yet limited, tools available to the engineer are the correlations, equations, and methodologies compiled by the Society of Fire Protection Engineers in *The SFPE Handbook of Fire Protection Engineering.*[12] The handbook is presently in the second edition and is available from the National Fire Protection Association. Many correlation and methodologies are presented in the handbook to calculate phenomena ranging from smoke detector activation times to prediction of second item ignition to design of alarm and suppression systems. Most equations and methodologies presented contain limitations, which the user must understand and document when presented in a performance-based environment. Other, more sophisticated, design tools also exist, the most common being fire models. In general, two types of fire models exist to predict fire conditions in a variety of environments: zone and CFD models.

Zone Fire Models

Zone fire models assume that each compartment in the hazard analysis can be divided into two or more control volumes. Anyone who has observed a compartment fire probably noticed that often, the hot gases and smoke stayed near the ceiling, while the

area near the floor remained cool and relatively smoke-free. Most zone fire models divide a compartment into these two layers. A commonly used zone fire model is CFAST (The Consolidated Model of Fire Growth and Smoke Transport), produced by the National Institute of Standards and Technology's Building and Fire Research Laboratory. Presently, CFAST is configured to calculate the fire environment of up to 30 compartments. Experimental results and a comparison to model results for a seven story building are contained in the CFAST technical reference (Chapter 5 "Verification of the Model"), although the model has not been verified for 30 compartments.[14] Zone models generally solve conservation of mass and energy equations for transfer between the upper and lower layers, as well as between compartments should vents exist between them. Vents include doors, windows, leaks, and HVAC connections. The advantage of zone modeling of large buildings is that the model input requires relatively little time to set up and the numerical solver usually takes between a few minutes and a couple of hours to run, except in highly complicated scenarios where the numerical solver can slow and the simulation may be measured in days. In theses exceptional cases, the assumptions and design of the scenario must be evaluated to ensure the integrity of the results. Typically, many fires and design alternatives can be considered within a short period of time[13,14].

Model Input

Zone models require three important inputs: the geometry of the various compartments, the size of the fire, and the vent flows between each compartment. Compartment properties can subsequently affect the fire performance of a building. Properties include

wall, floor, and ceiling materials, combustible contents, and the subsequent performance characteristics of the materials and structural members upon exposure to a fire. Compartment geometry is generally limited to rectangular parallelepipeds. While the number of compartments varies from model to model, simplifications by the model user can dramatically reduce the number of compartments analyzed. The fire input requires either the specification of a "standard" t-square fire or a combination of two of either the heat release rate, pyrolysis rate, or heat of combustion. The specification of the vents is dependent upon the type of vent. If the vent is either a door or window, it requires input of the height of the sill and soffit, whether there is a positive or negative wind exposure, and the width of the opening. Additionally, other parameters may be entered into the model, such as species yields (CO, CO_2, soot, etc.) and detection and suppression equipment locations.

Model Output

The specific output of a zone model varies between models. Generic parameters, however, summarize the fire environment. The heat release rate, species yields, including smoke, carbon monoxide, and carbon dioxide, and the pyrolysis rate all summarize the characteristics of the fire. The environment within each compartment includes the oxygen level, upper and lower layer temperatures, heat flux determination to various surfaces, optical density of the upper layer, calculation of detector and active suppression device operation, and tenability criteria. A given geometry and fire combination will

result in relative levels of importance for differing criteria. Therefore, the measure of a

parameter change can be readily ascertained by a zone model sensitivity analysis.

Limitations of Zone Fire Models

The major disadvantage of the zone-type fire model is the generality and uncertainty of

the results. It is often important during the analysis of a design to determine the exact

result of a small-scale phenomena at a particular location in a compartment. CFD models

predict small-scale phenomena and small regions of compartments much more accurately

than zone-type models.   For example, a CFD model will determine the vertical

temperature gradient through the upper layer, whereas a zone model will determine the

average upper layer temperature. Additionally, the uncertainty of the particular result

may be significant. For example, it may be important to determine the temperature at a

given height below the ceiling in the room of fire origin. Since the zone model considers

only an upper and the lower layer, the temperature of the point in question is simply

determined by the location of the point in either the upper or lower layer. A point one

meter above or below, if contained in the same layer, will be reported as the same

temperature. Additionally, the upper and lower layer temperatures are simply averages

across the vertical cross section of the layer. The temperature may vary significantly as

the point approaches the boundary conditions. Another shortcoming of the zone model is

the assumption of instantaneous plume spread upon impingement of the plume with a

ceiling. If a compartment is sufficiently large (a warehouse, for example) or long (a

corridor, for example), the assumption of instantaneous volume filling may be violated. It

is well documented that a lag time exists between plume impingement upon a ceiling and arrival of the ceiling jet at the ends of the corridor.   While many assumptions and limitations exist in a zone fire model, it is ultimately up to the engineer performing the analysis to understand and document these limitation and ensure that none of the assumptions have been violated, or that the assumption violation has not subsequently invalidated the resulting conclusion.

There are several important considerations regarding use of the CFAST zone model. The first limitation is the fact that all rooms are modeled as rectangular parallelepipeds. Actual geometry may include irregular shapes and curves. There are a large number of unknown parameters, each having minor uncertainties. Taken together, however, these parameters can have a significant effect upon the model results. The following list details uncertainties associated with fire modeling in general and are not indicative of CFAST uncertainties in particular:[15]

- Uncertainty in physical parameters. For example, thermal conductivities, limiting oxygen percentages, and emissivities.
- Numerical solution techniques. Differential equations solved by the Runge-Kutta method may yield slightly different answers than differential equations solved by the Bulisrch-Stoer method. The Newton-Raphson and other techniques have been shown to exhibit chaos under certain circumstances.

- Software error. Even a long-existing zone model such as CFAST is known to have potentially serious "bugs" in the code. Updates to fix old "bigs" or improve the model may introduce unanticipated errors.

- Hardware error. The hardware may misinterpret software instructions. The Pentium chip was documented to contain extraordinarily small calculation errors. This is most likely the smallest source of error.

- User error. The user may either make an input error or misinterpret the output.

- Entrainment coefficients are measured experimentally and the associated predictive equations are empirically derived. Empirical equations are subject to the boundary conditions of the test methods, which are not always explicitly enumerated and can subsequently be exceeded or violated.[14]

  - Vent flows are also empirical, although conservation equations generally bound the errors. Flow through large openings pose particular problems for orifice flow equations as the boundary conditions break down.

  - Smoke concentrations in the lower layer may be underestimated as mixing along wall, vent, and interface surfaces is not well understood.

  - Upper layer temperatures may be overestimated in CFAST as radiation from the upper layer to the lower layer is not accounted for.

  - Additionally, by making the wall and ceiling surfaces adiabatic, energy normally transferred to bounding surfaces is trapped in the upper layer.

Clearly, the user must comprehend the equations, variables, and numerical analysis of a fire model in order to implement it safely in the performance-based code design process.

Computational Fluid Dynamics (CFD)

Several computational fluid dynamics codes exist to predict the behavior of a compartment to a fire environment. Each model solves the Navier-Stokes equations for the conservation of energy, mass, and momentum for each grid point in a compartment. Compartment in a CFD model has a different connotation than in a zone-type model, for CFD modeling allows analysis of small-scale phenomena and irregular shapes. A compartment, whether it is a duct, or a room, or a warehouse, is divided into thousands of tiny cubes. Each cube is a control volume. For a given time step, the CFD model will calculate the heat, mass, and momentum equations for each control volume. In some codes, it is possible to vary the grid size at different locations in order to more fully understand phenomena at a given region of a compartment. The cost of such refinement, however, is often prohibitive. CFD codes can cost thousands of dollars and require days to complete a single simulation using high speed computers.

Model Input
Developing the boundary conditions for a CFD model is significantly more complicated than for a zone-type model. Days are often required to determine the grid spacing, boundary conditions, material properties, and sub-model parameters necessary to run the

model. The cost of increased input flexibility is increased complication and time expenditure.

Model Output

The results of a single CFD model simulation can often take days to complete. Once the simulation is complete, significant post-processing of data is necessary with most models. The model returns data streams for each control volume at each time step, resulting in millions of pieces of data, few of which are relevant to the analysis at hand. The learning curve for CFD modeling is significantly steeper than that of a zone model. However, small scale results, such as local velocity profile and temperature gradients at a given time in the simulation can be graphically displayed and lend invaluable insight into the nature of a fire problem. Additionally, irregularly shaped spaces and situations which are not well understood intuitively can be explored using a CFD model.

Limitations of CFD Models

The most significant limitation of the CFD model is the cost. Conventional CFD models do not require the sophistication of a pyrolysis or combustion model. The chemistry and physics of the combustion process is extremely complicated. Thus, CFD models which predict fire scenarios are significantly more expensive than a conventional CFD code. Additionally, in business, time is money, and CFD modeling is extremely time intensive, not only involving human resources, but also involving significant CPU time on big computers. Additionally, the training necessary to effectively implement a CFD model is significant. The initial purchase cost of a CFD model is also considerable, often running

thousands of dollars to commercial customers. Another limitation of the model is that the output is only as good as the input. Often required parameters are simply not known. Some of these parameters are critical to the model results. Statistical techniques can identify the uncertainty and work to reduce it, however this is a limitation of all models.

Small and Real Scale Testing

The application of performance-based design most often occurs in unusual design scenarios. In circumstances where the building design is generic, economics generally dictate a prescriptive design. Unusual design scenarios often require information not generally available in the engineering database. The fire properties of new materials or the performance of a new fire safety device often requires small or real scale testing in order to generate or validate data for the modeling process. Additionally, by testing components of a design assembly, the individual contributions may be identified in order to determine the relative contributions to hazard assessment. Small scale testing involves testing of individual or groups of components using apparatus such as the cone calorimeter or the LIFT. The advantages of small scale testing are twofold. First, small scale testing is significantly less expensive than full scale testing. Second, individual materials can be tested to determine their fire properties. Groups of materials may then be combined to form a composite fire. However, small scale testing cannot determine a composite fire with the accuracy of large scale testing. Interaction and radiation feedback between burning objects can significantly affect the fire properties of individual objects, thus increasing or decreasing the total hazard. A composite fire compiled from

the accumulation of individual small-scale tests must have an uncertainty range associated with it. Large scale testing reduces the uncertainty of the design outcome, particularly where a battery of tests is performed. Interactive effects can be demonstrated that may not be anticipated from a compilation of small-scale tests. For example, in a large scale cubicle fire test, the rate of heat release increases dramatically when a shelf collapses. This Is because a significant surface area of papers piled on the shelf is then exposed to fire conditions.[17] Large-scale tests, however, are extremely expensive and time consuming. The net result of small and real scale testing is the improvement and/or validation of model results which predict the fire performance of the structure.

Qualifications of the Engineers

A final component of the documentation is the qualification (certification) of the engineers performing the analysis. The most important certification is that of the Professional Engineer (P.E.). The engineering analysis presented in this report was performed by Jason D. Averill, EIT under the supervision of Richard W. Bukowski, P.E. (Illinois license 62-32829, Maryland 10202) and Prof. Jonathan Barnett. Professional licensing is the primary method by which states qualify design professionals. Further, every state has an ethics code to which the design professionals are bound, that prohibits practice in area(s) in which the professional is not qualified by training and experience. Resumes are included in Appendix D.

[5] "Performance Based Design." Draft Summary of Steps to Perform in a Performance-Based Design compiled by the Society of Fire Protection Engineers.

[6] Meacham, Brian J. "Concepts of a Performance-Based System for the United States. Report of the 1996 Activities of the SFPE Focus Group on Concepts of a Performance-Based System for the United States." Society of Fire Protection Engineers, Boston, MA, January 1997.

[7] The Building Regulations, 1992. New Zealand. Clause C3.1.

[8] The Building Regulations, 1992. New Zealand. Clause C4.1 (a) and (b).

[9] Meacham, Brian J. "An Introduction to Performance-Based Fire Safety Design" National Fire Protection Association Research Foundation Fire Risk and Hazard Assessment Symposium, June 23, 1996.

[10] The BOCA National Building Code, 1993. Section 1604.5.1.

[11] Draft Version of the Executive Summary of Performance-Based Design Guide. Produced by the IFC Performance Drafting Committee, September 1997.

[12] *The SFPE Handbook of Fire Protection Engineering.* Ed by DiNenno, et al. National Fire Protection Association: Quincy, MA, 1995.

[13] Quintiere, James G. "Compartment Fire Modeling." in *The SFPE Handbook of Fire Protection Engineering, 2nd Edition.* Chapter 3-5. Ed. by DiNenno, et al. National Fire Protection Association: Quincy, MA, 1995.

[14] Peacock, Forney, Reneke, Portier, Jones. "CFAST, the Consolidated Model of Fire Growth and Smoke Transport." NIST Technical Note 1299, 1993.

[15] Beard, Alan N. "Limitations of Fire Models." *Journal of Applied Fire Science*, Volume 5, No. 3, 1995-1996, pp. 233 – 243.

Fuel Characteristics of Office Occupancies

One of the most important aspects of analyzing the fire safety of a building is characterizing the probable combustible contents of the use group. While the case study building analyzed later contains many different occupants and uses, the largest percentage of tenants will be classified as an office occupancy. Therefore, determining the fuel characteristics of the typical office occupancy will help establish probable fire scenarios. It is important to note that simply characterizing the fuel characteristics of the office space is insufficient. Spaces such as transformer rooms, storage spaces, and atrium must also be addressed. The following fuel characteristic description should be repeated for all appropriate spaces within the building. Table 2 summarizes fuel load densities for many different occupancies.[16] Fuel load density is the average quantity of total heat released per unit area. There are several distinct fuel packages which represent a potential fire hazard in an office occupancy.

Work Station Fires
The National Institute of Standards and Technology's Building and Fire Research Laboratory, in conjunction with the U.S. General Services Administration, conducted a survey of typical office fuel packages. The four main fuel packages were determined to be

1. Reception area furnishings
2. Office furnishings
3. Workstations

4. Maintenance carts[17]

The workstations (office cubicles) had the highest rate of heat release. Three configurations of workstations were tested, each without measuring the effect of sprinklers: two-sided, three-sided, and four-sided. Each workstation is composed of wall panels with a shelf assembly, a desk, a chair, a computer terminal and keyboard, and paper and notebooks. The tests showed that radiation from the wall partitions significantly augments the peak heat release rate, by a factor of two. The four-sided workstation demonstrates a fire growth rate approximated by a fast t-square fire until about 7 MW. The fire load for this particular test is shown in Table 1.

WorkStation Fuel Package Components	Weight (kg)
Particle Board Work Surface	58.2
ABS Padded Bucket Chair	15.9
Computer Terminal with Keyboard	15.5
3 Partitions, Cloth Covered, Fiberglass Core	103.6
4 Boxes with Paper	36.4
2 Boxes Computer Paper, One on Table, One Under Table	22.7
3 Phone Books	2.3
Newspaper	0.9
Publications	2.3
Paper for Notebooks and Files	29.5
Notebooks and Files	3.6
Total	290.9

Table 1: Workstation Fuel Package Components and Weights[18]

Most new-construction high-rise office buildings in the United States are required by local law to have full coverage automatic sprinkler systems, installed in compliance with NFPA 13. Therefore, the effect of automatic sprinklers upon the heat release rate of any item or assembly must not be ignored, as automatic sprinkler systems have a very high degree of functional reliability. The effect of sprinklers upon workstations was subsequently studied by Madrzykowski and Vettori.[18]

Shielded Office Fires

An important characteristic of the fuel load in office buildings is that the arrangement often includes large surface area objects such as desks and tables which may subsequently block, or shield, the sprinkler spray from objects which may ignite beneath the obstruction. While it may be assumed that the fires would eventually be extinguished by the sprinklers in the absence of shielding, the fuel load characteristics of offices often includes storage of files, computers, and other combustibles under desks and tables in order to maximize available space. Lougheed, et al, at the National Research Council Canada performed small, medium, and large scale fire tests which quantify the effect that shielding has on the heat release rate of fires in a sprinklered office building.[19] Additionally, Madrzykowski and Vettori conducted tests at NIST measuring the heat release rate of various office assemblies with and without sprinkler activation.[18] The heat release rate data of workstations from the Madrzykowski and Vettori experiments and the

shielded office furniture fires conducted by Lougheed, et al., can be compared, albeit with a degree of caution. The goal of the Madrzykowski and Vettori experiments was to develop an algorithm with which to predict the effect of sprinklers upon the heat release rate of the fire. Lougheed, et al., attempted to reproduce or quantify the effect of shielding upon the end state of the fire, including heat release rate, smoke production, fire spread, and pressure changes within the office.

Other Office Furnishing Fires

In addition to a fully involved workstation scenario, another example of office furnishing fire is necessary for robustness. Henri Mittler at the National Institute of Standards and Technology has performed fire tests of photocopy machines.[20] While yet unpublished, the heat release rate data reveals the typical burning pattern of standard office furnishings. Notice that the peak heat release rate of approximately 1.2 MW is significantly lower than that associated with the workstation, as the copier fire is a single unit in isolation.

OCCUPANCY	AVERAGE[*]	FRACTILE		
		80%	90%	95%
Dwelling	780	870	920	970
Hospital	230	350	440	520
Hospital Storage	2000	3000	3700	4400
Hotel Bedroom	310	400	460	510
Offices	**420**	**570**	**670**	**760**
Shops	600	900	1100	1300
Manufacturing	300	470	590	720
Mfg and Storage	1180	1800	2240	2690
Libraries	1500	2250	2550	-
Schools	285	360	410	450

Table 2: Fuel Load Densities for Various Use Group Occupancies

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[16] Lougheed, G. D., J. R. Mawhinney, and J. K. Richardson. "Draft Version of Probability of Occurrence and Expected Size of Shielded Fires in Sprinklered Buildings – ASHRAE RP-838 – Phase 1." Report No. A-4201.5, National Fire Laboratory, National Research Council Canada, 16 June 1995.

[17] Madrzykowski, Daniel. "Office Work Station Heat Release Rate Study: Full Scale vs. Bench Scale." in Conference Proceedings of the Seventh International Fire Science and Engineering Conference, Interflam '96, Interscience Communications Limited, London, England, 1996, pp. 47 – 55.

[18] Madrzykowski, Daniel and Robert Vettori. "A Sprinkler Fire Suppression Algorithm." *Journal of Fire Protection Engineering*, Society of Fire Protection Engineers, Volume 4, No. 4, 1992, pp. 151 – 164.

[19] Lougheed, G.D., D.W. Carpenter, and J.K. Richardson. "Probability of Occurrence and Expected Fire Size of Shielded Fires in Sprinklered Buildings, ASHRAE RP-838 – Phase 2, Full-Scale Fire Tests." National Research Council Canada, Report No. A-4201.10, 17 January 1997.

[20] Mittler, Henri. Personal Communication. 1998.

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[*] Fire Load Density in (MJ/m^2)

Historical Summary of Major High-Rise Office Fires

The first major high-rise fire in New York City occurred in 1898 at the Home Insurance Company building. While the fire started in an adjacent building, unprotected glass windows allowed the fire to spread from the building of origin to the Home Insurance Company building. Subsequently, New York City required that all new high-rise buildings contain ¾-hour fire-rated wire glass windows.[21] "Design by disaster" is how the codification process in fire safety is often described. By analyzing the fault structure of a fire, engineers and code-officials can determine how to design safer buildings in the future.

High-rise office buildings present unique challenges to a fire protection engineer. The magnitude of the structures amplifies potential problems. Large numbers of occupants, the height of the floors above grade level, and the large square footage of each floor contribute to the fire safety problem. The purpose of this section is to examine three major high-rise office building fires and determine the failure mechanisms to ensure that the failure mode is addressed in subsequent high-rise fire safety designs. There are three major high-rise office occupancy fires which occurred in recent years: One Meridian Plaza Fire in Philadelphia, PA, First Interstate Bank Building Fire in Los Angeles, CA, and the Peachtree 25th Building Fire in Atlanta, GA. Each fire will be analyzed separately and common failure modes will be determined in the conclusions.

One Meridian Plaza Fire

The Building

One Meridian Plaza is an unsprinklered[*], 38-story office building located in Philadelphia, Pennsylvania. It is the eighth tallest of approximately 500 high-rise buildings in Philadelphia. Using the 1949 Philadelphia Building Code, the structure was constructed in 1968 – 1969. The structure consists of protected steel I-beams and concrete over metal pan floors. The curtain wall is composed of granite slabs set in concrete panels, and glass. Horizontal members were protected by sprayed-on, cementitious, fire-resistive material and had a code compliant two-hour fire rating. Importantly, the vertical members were encased in plaster and gypsum and had a four-hour fire rating, in *excess* of the required three-hour fire rating. The building measures 223 feet by 94 feet, which provides 16,700 square feet of open, non-compartmentalized, leasable space plus 4,000 square feet of core space. The resulting occupancy was approximately 2,500 people. There are three stairwells, east, west, and central containing a two-hour fire rating. The standpipe system contains non-regulated pressure reducing valves (prv). Finally, the electrical system shares a common vertical utility shaft in the buildings core and provided for no redundancy in power supply.[22]

The Fire

The fire began on the 22nd floor in a private office due to the improper storage and self-ignition of linseed-soaked rags that were being used to restore and clean wood paneling.

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[*] Only floors 30, 31, 34, 35, and the below grade levels were protected by automatic sprinklers, although a complete retrofit was planned.

The fire spread to other combustible materials and furnishings within the office and subsequently throughout the floor of origin. At approximately 8:23 p.m. on Saturday, February 23, 1991, the buildings automatic fire detection system alerted a guard and a maintenance worker located at the first-floor guards desk, as well as a remote, monitoring service. The remote service called the building to verify the alarm. The maintenance worker took the building elevator to the 22nd floor, whereupon he was confronted by heat and dense smoke. By dropping to the floor of the elevator and contacting the guard via radio, the elevator was brought to the main floor remotely. The fire was not reported to the fire department until the validity of the alarm signal was verified by the maintenance worker.[23] The first fire department notification occurred at 8:27 p.m. when a person from the street reported smoke coming out of the building. This resulted in a critical fire department response delay. Four fire engines, two ladder trucks, and two chiefs responded to the first-alarm. The building command post was established in the lobby and the logistics and staging area was established on the 22nd floor.[22] By the time that the first fire fighters reached the floor of origin, they reported that the fire had already reached the stairway door. Investigators assumed that the fire had spread through the open area of the floor by that time. The electrical room, located 60 feet from the fire origin, was compromised early in the fire, resulting in a loss of power, both main and emergency.[23] The main problem confronting the fire department regarding the manual suppression efforts was the standpipe connections. The pressure reducing vales (prv's) in the building were incorrectly installed, through either human error or negligence. The

resulting pressure at the nozzle tip of the fire fighters lines was between 40 and 50 psi.

Not only was this insufficient to control the fire, the fire fighters spent significant time

and energy ensuring that there was not a problem with their lines and connections. The

fire spread rapidly to floors above the floor of origin, predominantly by autoexposure

through the curtain wall and flame passage outside the building. The fire suppression

efforts were suspended at approximately 7 a.m. on February 24th, 11 hours after

suppression efforts began, largely due to concerns about the structural integrity of the

building. Eisner and Manning describe the extent of the structural problems:

> There was continual movement and cracking in all three towers. In one stair tower, what had been a two-inch crack in the concrete wall had grown to a fist-sized opening. Floors had moved as much as three feet. I-beam flanges were cracked. Fire-resistive material on the beams in the stairways had fallen off, and the now-unprotected members were twisting, moving, and starting to elongate. Main structural elements were beginning to fail.[22]

The burning continued unabated until the 30th floor. Klem reported that, in all, 10

sprinklers activated and controlled the fire. Eisner and Manning, however, reported that

9 sprinklers, 7 along the perimeter and two in the interior of the building activated and

controlled the fire. Regardless of the number, the value of automatic sprinklers has never

been more dramatically displayed.

Failure Modes Contributing to Fire

The following failure modes, compiled from the Eisner and Manning report, as well as the

Klem report, contributed significantly to the ultimate severity of the fire:

- Lack of automatic sprinkler system on the floor of fire origin allowed the fire to grow unchecked until the fire department arrived. 9 (or 10) sprinkler heads controlled a fire, which the Philadelphia fire department could not. While not a strictly fair relative comparison given extenuating circumstances imposed upon the fire department, it is a valid absolute comparison.

- Rapid vertical fire spread through the curtain wall complicated containment efforts.

- Miscalibrated pressure reducing valves at the fire department connections to the buildings standpipe reduced nozzle tip pressure to the extent that manual suppression of the fire was impossible.

- When the building alarm notified the central monitoring station and the building personnel, they did not immediately notify the fire department as the code requires, thus causing delay during the critical early stages of the fire.

- Auto-ignition of linseed-soaked rags, or any other hazardous material, is a known fire hazard and contributed, not only the cause of the fire, but also to the rapid growth and spread of the fire.

- Falling glass severed many supply lines at the base of the building. This can be remedied by protecting lines with plywood sheets.

- Primary and secondary (emergency) power should not be routed through the same vertical shafts unless there is a redundancy built-in at a remote location.

- Open interior access stairways which connect 3 or less floors are allowed by the code. However, two such stairwells contributed to the rapid vertical spread of the fire.

First Interstate Bank Fire

The Building

The First Interstate Bank building is the tallest building in the state of California and is located in Los Angeles. Built in 1973, this unsprinklered high-rise office building contains 62 above-ground stories, a basement, garage, and pedestrian tunnel. The tower measures 124 feet by 84 feet and contains approximately 17,500 net square feet of leasable office space, built around a central core. Estimates of the population of the building range between 3,500 people[24] and 4,000 people[25]. The frame is structural steel with sprayed-on fire-resistive cementitious coating. Several articles refer to the quality of application of the fireproofing and the positive impact it had upon the structural integrity of the building throughout the fire. The curtain wall is composed of glass and plastic windows set in aluminum lintels and sills. Fiberglass separated the windows from the horizontal members. The floor system is lightweight concrete set in fluted steel decking.[26] The stairwells contained 1-½ hour rated doors constructed of wood exterior and gypsum interior. As the wood burned away, the gypsum was left with no structural strength thereby collapsing when opened.[24]

The Fire

The fire began at sometime between 20:25 and 20:27 at a row of computer workstations. The first alarm was a detector which activated and notified building authorities at 20:30. The alarm was subsequently reset by the building monitor as the fire protection systems

were presently being upgraded and thus prone to false alarm. After numerous other alarms and resets, a building maintenance engineer was dispatched to determine the cause of the alarms.[24] At 20:37, three separate 9-1-1 calls were received from people outside the building reporting a major fire at the First Interstate Bank building.[25] At the same time, the maintenance worker is heard calling for help over the radio system. As the elevator doors opened onto the fire floor, the car was immediately filled with hot smoke and gases. Nelson estimates that the smoke temperature the worker was exposed to was in excess of 260°C (500°F).[26] It is important to note that the elevator opening is located on the opposite end of the floor from where the fire began.[24] The body of the maintenance worker was found at approximately 04:00.

The fire department arrived on the scene at 20:40. There were two major modes of vertical fire spread: a return air shaft (ras) and an interstitial space between the end of the flooring and the outer skin of the building. The ras for the HVAC system extended from the 12th floor (the floor of fire origin) to the mechanical equipment room on the 22nd floor. As the fire severity increased on the 12th floor, fire damper was overcome and the fire spread through the ras to the 13th and 14th floors via shaft wall failure.[24] The second mode of vertical fire spread involved the outer skin of the building. Virtually all of the exterior curtain wall, comprised mainly of glass and aluminum, was destroyed in the fire. The glass subsequently fell to the ground, where it cut hose lines and presented a hazard to the fire fighters and public in general.[25] This led to autoexposure of the upper floors.

Additionally, open space between the exterior curtain wall and the flooring system allowed rapid vertical fire spread. The fire eventually burned to involve the 12th through 15th floors, as well as part of the 16th floor. Credit is given in all accounts of the fire to the Los Angeles Fire Department and the heroic efforts they made to stop the fire. A tactical decision was made to make a stand on the 16th floor. The 16th floor was a logical decision for many reasons:

- The fire had not yet fully involved the 16th floor.

- Lower fire load than other floors

- High level of compartmentation assisted manual suppression effectiveness.

- Exhaustion of fuels on lower levels.

- Advancement of suppression efforts on lower floors.[24]

The fire was knocked down at approximately 02:19.[25]

Failure Modes Contributing to Fire

The following failure modes contributed significantly to the ultimate severity of the fire:

- The lack of automatic sprinklers allowed the fire to spread.

- High fuel load, particularly on the 12th floor allowed rapid fire spread.

- Open floor office plan allowed rapid full floor involvement and hampered manual suppression efforts.

- Personnel checking a fire should never go to the fire floor. Personnel should go two floors below a trouble alarm and use the stairwells to get to the trouble floor.

- Delay in notification of the fire department allowed the fire to grow unchecked for an extended period of time. All alarms should be routed to the nearest fire department. The early stages of a fire are the most critical relative to ease of suppression.

- Internal access stairs which connect only 2 or 3 floors are a major avenue for the spread of smoke and fire.

- Stairwell doors composed of wood on either side and gypsum on the inside failed. The wood was consumed by the fire, subsequently leaving the gypsum interior with no structural strength.

- One stairwell should always be designated for evacuation and kept clear from heat and products of fire combustion.

- Fire dampers should be activated on both the inside and floor side of the shaft. Fire was allowed to spread to upper floors through the return air shaft because the fire damper had fusible links which activated on the floor side of the shaft and therefore never closed during the fire.

- Building personnel were not familiar enough with fire procedures and building fire protection features to adequately assist the fire department incident manager. Building-specific information should be the responsibility of a *building fire safety director* and they should be able to answer any and all questions regarding fire operations of the building.

Peachtree 25th Building Fire

The Building

The Peachtree 25th building is an H-shaped building with two connected 10-story towers. The population of the building is approximately 1,500 people. Each tower measures approximately 250 feet by 65 feet, with the connection measuring 70 feet by 80 feet. The occupancy is mixed (commercial and office) on the first floor, and strictly office on floors 2 through 10. The exit shafts provided 2-hour fire-rated protection, while the doors provided 1-½ hours fire protection. The exterior of the building is composed of a glass façade. The interior partitions were non-rated gypsum on steel stud construction. The wall-finish materials were multi-layer and varied by location. Generally, a combination of vinyl and/or plywood composed the finish. The fire protection systems included automatic detection (smoke alarms connected directly to the fire department), building alarm system activated by manual pull stations, as well as a standpipe system. The building was not equipped with a sprinkler system.[27]

The Fire

The fire began on the 6th floor of the south tower at approximately 10:30 a.m. Friday, June 30. The ignition of the fire is attributed to an electrician working on an electrical switchbox. He was attempting to return power to a section of the floor by replacing a 200 ampere fuse when severe arcing occurred. The arcing had sufficient energy to melt metal and ignite the interior-finish materials in the hallway. The electrician was severely injured and would later die, although not as a direct result of the arc, which was estimated to last

60 seconds or more. This fire scenario involves unique and severe conditions and would be characterized as a very rare ignition scenario. The fire growth rate was extremely high and the fire spread was rapid. Multiple layers of wall covering promoted extraordinary fire spread rates, which is not an unfamiliar fire hazard to fire investigators.[28,29] The wall coverings had completely burned out when the fire department arrived on the floor, only seven minutes after notification. Occupants of the floor of origin, about 40 initially, were quickly trapped by the intense black smoke. Most occupants found a room and closed the door behind them, breaking out windows to vent incoming smoke and waited to be rescued. At some point, one woman jumped from a 6th floor window and sustained severe injuries. The fire department was not notified until a manual pull-station was activated by an occupant of the building from a remote floor, which occurred at approximately 10:30 a.m. Most occupants of the building were leaning out of the windows in order to breathe when the fire department arrived on the scene at approximately 10:34 a.m. 14 occupants were rescued via ladder truck and 14 people down the stairwells. In all, five people died as a result of this fire, the first multiple fatality high-rise office building fire in 17 years.[27]

Failure Modes Contributing to Fire

The following failure modes, compiled from the Isner report, contributed significantly to the severity of the fire.

- Lack of automatic sprinklers failed to control the spread of the fire. Clearly, the ignition source was so severe that a fire in the electrical room was inevitable.

However, automatic sprinklers may have controlled the fire spread and prevented the five fire deaths.

- Multiple-layer, combustible interior-finishes contributed to the rapid spread of the fire.

- The electrician did not follow proper procedure when changing the fuse, resulting in the arc which ignited the wall linings and electrical equipment.

- Numerous *Life Safety Code* (LSC) violations may have prevented occupant egress from the building.

  - The common path of travel was greater than 75 feet (140 feet for Suite 600).

  - No flame spread tests were performed to determine the performance of the multiple layers of interior finish used in the building.

  - Suite 600 did not have proper fire-rated protection, including door and wall assemblies.

- Delay in notification played a minor role, as the delay was not long. However, the growth rate of the fire was very high, underscoring the importance of early notification of the fire department. Notification should come from the detectors and not the manual pull stations, as time may pass before someone remembers to pull the alarm.

- The partitions and doors in the building did not serve as effective barriers against smoke and heat as most residents trapped in the building were exposed to life-threatening conditions.

Common Failure Modes of Major High-Rise Fires

Analysis of the failure modes associated with the three previous major high-rise fires reveals several recurring themes which should be addressed in future high-rise office building design projects, particularly when executing a performance-based design. The first and foremost design solution is installation of automatic sprinklers in all high-rise office buildings. Jennings investigated the effectiveness of sprinklers and compartmentation in high-rise office buildings and determined:

> "…the presence of sprinklers is very clearly associated with lower numbers of injuries to firefighters, less damage to building contents, and fewer demands on the fire department in terms of hoselines used, apparatus responding, and time spent on the scene. Fires in high-rise office buildings are significantly less severe as measured by the variables noted than are fires in non-sprinklered (compartmented) high-rise office buildings."[30]

The effectiveness of automatic sprinklers in protecting life and property is underscored by the fact that there has never been a multiple-death fire in a high-rise office building which was fully sprinklered. A study by Powers examined the effectiveness of automatic sprinklers in fighting high-rise fires.[31] Of the 254 high-rise office building fire which occurred between 1969 and 1978, 96.8% activated five heads or less. Additionally, the fire department required hose lines in only 20% of the fires occurring in fully sprinklered high-rise office buildings.

Clearly compartmentation alone is insufficient to prevent the spread of fire. The Peachtree fire incident contained a relatively high degree of non-rated compartmentation,

yet allowed very rapid fire spread. However, the open-floor office plan was cited as a contributory factor in the severity of the First Interstate Bank and Meridian fires. Compartmentation works most effectively when coupled with an automatic sprinkler system in controlling the growth and spread of fire. Thirdly, the design must account for all modes of vertical fire spread. All vertical ducts, pipe and wiring chases, access stairs, and cable openings must be protected with fire rated enclosures, doors, or partitions. The main mode of vertical fire spread in the 1975 World Trade Center fire was through cable openings in telephone closets that were not firestopped.[21] Presently, prescriptive codes allow open stair connections between three or less floors in a high-rise structure to allow tenants with multi-floor offices convenient passage. This represents a significant fire growth path. These stairwells should be equipped with magnetic fire-rated doors that close upon activation of an automatic detection system.

Each major high-rise fire discussed previously involved delayed notification of the fire department personnel, which proved integral to development of the fire. Early detection and notification is a key to fighting fires and removing all occupants from untenable conditions within the building. Fire is easiest to suppress during the incipient stages. A typical fire growth rate assumes t^2 fire development (where t stands for time). This stresses the importance of time in the fire development scenario.

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Performance-Based Design: A Case Study

First, the important objectives of the case study will be described. A description of the selected building as proposed under a prescriptive code is contained in the following section. Specific design issues and supporting documentation follow. Finally, a first-order cost-benefit analysis comparing the two designs completes the case study. All design work is intended as an example of an application of the performance-based code and is for demonstration purposes only and not intended for actual implementation. A design team tasked with an entire performance-based design of this building would complete significantly greater quantity of analysis, including further scenario development, hazard criteria, and non-life safety issues. Neither the ICC, NIST, WPI, nor any other involved constituents condone any fire safety design or product contained herein.

Objectives and Requirements of the Case Study

The major objective of the case study is to "undertake a performance-based fire safety analysis and design for a high-rise office building and compare the resulting fire safety recommendations with those specified by existing prescriptive requirements."[32] Two distinct comparisons should be made: first, compare the total expected cost over the life of the building for each design; and second, compare in relative, comparative, or absolute terms the risk to life for the occupants of the building as well as any associated fire department personnel resulting from each solution. The performance-based design should accomplish the following fire and life safety goals:

- Safeguard permanent and transient occupants from injury due to fire until they can reach a safe place. This may include self-relocation within the building, self-evacuation to a safe place outside of the building, evacuation with assistance from the fire department, or any combination of the above.

- Limit flame spread and thermal damage to the floor of fire origin, and limit non-thermal damage to the fire floor and one floor above.

- Provide sufficient structural stability to meet the first two goals.

Generic Building Requirements

In order to participate in the case study, the selected building must meet the following requirements as stipulated by conference officials:

- Rectangular shaped office building

- 40 stories above ground and 2 – 3 levels below.

- 3000 m^2 per level

- Should be flexible enough to support the following tenant types:

  - Law offices

  - Accounting and financial firms

  - Insurance and brokerage offices

  - Software development companies

  - Consulting and general offices

  - Multi-purpose meeting rooms

  - Retail spaces

  - Public restaurants

- Storage spaces

- Mechanical and equipment rooms

- Sanitary facilities

Building Selection

The building selected to fulfill the requirements of the case study is presently in the design phase. Designed by an architectural firm in Dallas, the thirty-one story building is being designed using the Universal Building Code.[33] The building has four underground parking levels, two floors of retail atrium area, an executive level, a penthouse level, with the remainder consisting of leasable office space. The present elevator arrangement has six elevator groups. The first group services the parking garages and the main lobby. The second group gives express service to the main lobby, lower retail spaces, and the executive and penthouse levels. The third group is the low-rise bank. This group services the main lobby area and floors five through fourteen. The mid-rise elevators service the main lobby area as well as the fourteenth through twenty-first floors. The high-rise elevators service the twenty-first through twenty-ninth floors as well as the executive level. Finally, a service elevator serves all floors in the building and will act as the primary means of building ingress for the fire department operations. Each office floor contains approximately 3,500 square meters of floor space, including 3,000 square meters of "leasable" floor space. Leasable floor space denotes the net floor area less the area consumed by elevators, stairwells, restrooms, and other spaces necessary for building operations. Appendix E shows schematics of the building designed under the prescriptive

requirements. This arrangement will be juxtaposed with the final arrangement under the performance-based regime subsequently.

A minor point to note when comparing the design of the prescriptive building and the design of the performance-based building is that the performance-based building was designed as a 40 story above grade building, while the prescriptive building was designed as a 31 story above grade building. Nine stories were added to the original building design in order that the design satisfy the requirements of the case study. Three stories were added to the low-rise, mid-rise, and high-rise portions of the building. See Appendix E for a graphical schematic of the prescriptive and performance-based design elevations. The addition has little impact upon the final design calculations of the building, save egress and the subsequent changes to the building design where life safety concerns due to the longer egress times warranted design improvement.

ICC Performance-Based Code
The ICC Performance-Based Code[34] is built upon a pyramid of increasing specificity.[*] Each section of the code begins with a general statement of objective. Forming the base of the pyramid, the *objective* states the overall goal of the section and is very broad. One step up in the pyramid of codification, the *functional statement* provides a higher degree of evaluation. The functional statement gives specific goals contained within the scope of the original objective, yet lacks the detail of a *performance requirement*. The

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[*] The original premise of the ICC Code comes from the New Zealand building code. See endnote 7.

performance requirement is the detailed design objective of an engineer. This case study concentrates on satisfactory accomplishment of the performance requirements.

Performance Requirements

The design alternatives are concerned mainly with satisfaction of the performance objectives related to the fire safety of the building design. In order to prove that the performance-based design is safe, the design must demonstrate satisfactory fulfillment of the functional objectives of each section of the ICC Performance-Based Code. Regarding fire safety, there are several applicable functional objectives.[34]

Means of Egress

> *Means of egress shall give people adequate time to exit the building, or reach a safe place without exposure to untenable conditions and give rescue personnel adequate access to undertake rescue and emergency management operations.*

Fire Growth

> *Buildings shall be designed with safeguards against the spread of fire so that:*
> *• Occupants have sufficient time to escape without being overcome by fire and smoke.*
> *• The building, adjacent building, and their occupants and amenities are protected from the spread of fire and smoke.*
> *• Fire fighters can perform rescue operations, protect property, and utilize controls and fire fighting equipment and controls.*

Structural Stability During Fire

> *Buildings shall be constructed to maintain structural stability during fire to allow people adequate time to evacuate safely, allow adequate time to*

undertake rescue operations, and avoid damage to or loss of amenity of adjacent properties or structures.

Emergency Notification

Where required, adequate means of occupant notification shall be by means appropriate to the needs of the occupants the use of the building and the emergency egress strategy employed.
When required by the anticipated use of the building, notification systems shall be capable of alerting sleeping occupants in reasonable time to enable them to reach a safe place before the occurrence of untenable conditions at any point along the primary egress path.

Fire Detection Systems

Where required, fire detection systems shall be designed to activate before a fire reaches a size that represents an unreasonable hazard to the building or occupants of the building itself.

Elevators and Conveyance Devices

Elevator and conveyance device installations for access into, within, and outside of buildings shall provide for the safe movement of all people including those with disabilities and for firefighters during emergency operation as well as for the safety of maintenance personnel.

Each of the preceding functional statements relating to the fire safety of the building design shall be addressed within the context of the performance-based design case study. Note that structural, mechanical, and project management issues are beyond the scope of this project.

Performance-Based Design Alternatives

Some designs proceed are initiated as performance-based building designs. This particular application, however, is an optimization of a prescriptive design using the flexibility afforded by performance-based codes. In order to demonstrate the versatility and cost-effectiveness of a performance-based design, the project team chose three major design alternatives with which to perform a performance-based analysis. The first alternative is the use of the elevators to evacuate occupants in case of a fire or other emergency. The theory governing elevator evacuation is described in the section titled "Elevator Evacuation." The second alternative is the infusion of new alarm and suppression technologies. While infusion of new technology is not in itself challenging in a performance-based environment, documentation proving that the technology will provide equivalent or better safety than would otherwise exist in the prescriptive design challenges statistical and computational comparisons. Finally, the domestic and sprinkler water supplies have been combined. Two critical components of the performance-based design will be explored. The first component is the documentation of each design alternative. Documentation includes explicit descriptions of all goals, objectives, calculation tools, assumptions, etc. The second component is the economic analysis of the total life-cycle cost of both the prescriptive and performance-based design options.

Elevator Evacuation

Using elevators to evacuate people has been an idea long in coming. Arguments for elevator evacuation first appeared in 1974 with an article by Bazjanac[35] which suggested that elevators be used to evacuate occupants, particularly the elderly and people with disabilities. He also points out that "though stairways are designed for safety, they are rather conducive to panic." Many articles evaluating the strengths and more importantly the weaknesses of elevator evacuation have been published in the interim. The following section discusses the engineering aspects of an elevator assisted evacuation plan. Appendix A includes the calculation procedure for determining elevator travel time.

Design Issues Regarding Elevator Egress
Design of Elevator Lobby

As occupants may wait for short periods of time in the elevator waiting lobby when using the elevators to egress a building, the lobbies must be impervious to the effects of a fire outside of the lobby. There are three major design issues: protection from heat, radiation, and smoke. The elevator lobbies must be designed as areas of refuge. The Life Safety Code and the U.S. Department of Justice Americans with Disabilities Act describes an area of refuge. Particularly important is the proper design of areas of refuge in unsprinklered buildings. In a 1992 study by Klote, Nelson, Deal, and Levin, the authors concluded that the "operation of a properly designed sprinkler system would eliminate the life threat to all occupants."[36] However, given that sprinkler systems are not 100% reliable, qualifying the elevator lobby as an area of refuge is an appropriate redundancy.

NFPA 101 Chapter 5, while specifically forbidding the use of elevators as the main egress component in large commercial buildings does provide important recommendations regarding the design of elevator lobbies.

Lobby Size

The population density of an elevator lobby should be 3 square feet per person, plus one 30 inch by 48 inch area for a wheelchair for every 50 people[37]. Stairwells will continue to be the primary means of egress for most occupants of a building for a variety of reasons, including the decades-long public awareness campaign against using elevators in the event of an emergency, the feeling of control occupants experience when using the stairs versus using the elevators because occupants are not relying on a mechanical system and they do not have to wait in a lobby for the elevator to come. Thus, the lobby will be sized to accommodate 50% of the population of a floor.

Passive Fire Protection

Passive fire protection is defined by Fitzgerald as a building component that remains fixed in the building whether or not a fire emergency exists.[38] An example of a passive fire protection feature is a rated barrier. The barrier does not require manual or automated activation to provide protection, hence eliminating the possibility of activation failure that exists in active fire protection systems. Elevator lobbies require several passive fire protection features. The first feature is a rated barrier that prevents the spread of fire, smoke, and other products of combustion. The Uniform Building Code (UBC) does not require rated fire barriers for elevator lobbies.[39] Given that elevator lobbies are not part

of the egress system as far as the UBC is concerned, the lack of lobby protection is not surprising. For new construction, NFPA 101 requires a one-hour fire rated barrier to protect the elevator lobby, unless the entire building is protected by a sprinkler system.[40] However, given the relatively high benefit/cost ratio of a 1-hour rated barrier, serious consideration should be given to protection of the elevator lobby when the elevators are to be considered the major secondary egress means. An additional passive fire protection feature is the protection of all penetrations into the lobby. NFPA 101, Section 6-3.6 stipulates the requirements for the protection of all penetrations from smoke entry.

Active Fire Protection

There are several active fire protection components that help insure the fire-safe integrity of an area of refuge. An active fire protection feature is a feature of the building that requires either manual or mechanical activation in order to participate in the building fire safety process. The first component is the lobby pressurization system. The second component is the smoke dampers. Finally, the alarm and suppression systems must activate to ensure the safety of the area of refuge. Each component of the active fire protection system must be activated and is subsequently susceptible to activation failure. While failure rates are quite low, they must be accounted for in an analysis of total building fire safety.

Klote[41] discusses the pressurization of an area of refuge, which can be applied to protecting elevator lobbies during elevator evacuation. The prescriptive requirements

stipulate 12.5 Pa positive pressure difference for areas of refuge. Lougheed, et al., state that "…in most cases, a minimum design pressure of 7 Pa would be sufficient."[16] It is important to note, however, that the Lougheed, et al., recommendations were based on experimental studies of sprinklered fires.

Indirect pressurization of an area of refuge involves a fan pressurizing the elevator shaft, which then overflows into the attached areas of refuge. Direct pressurization, on the other hand, requires a fan to be attached directly to the areas of refuge. Pressurization of the area of refuge must account for several additional pressure effects including elevator movement, wind pressures, and fire effects. A piston effect is created by an elevator moving in a shaft. As an elevator moves through an elevator shaft, the column of air in the direction of travel is compressed. Subsequently the air mass in the opposite direction has a lower pressure. The wind can create pressure differences between the windward side of a building and the leeward side of a building. If the outside temperature is notably different from the temperature inside the building, the air within the shaft can move up or down due to density differentials. If the outside temperature is colder than the interior temperature of the building, for example, then the warm interior air entering the shaft will rise. If, however, the outside temperature is distinctly higher than the air-conditioned inside temperature, then the interior air mass will descend the elevator shaft. Each of these factors must be accounted for in the design of a positively-pressurized elevator lobby.

Smoke dampers are required in an area of refuge in order to prevent the HVAC system from introducing smoke into the compartment. A smoke damper simply closes a vent opening between the area of refuge and any adjoining compartments and is generally activated by the alarm system. Finally, the detection and alarm system must protect the area of refuge if either the pressurization system fails and sufficient smoke or heat is introduced into the area to exceed the alarm criteria of the smoke detectors or the sprinklers, or the compartment of fire origin is the area of refuge. If hazardous conditions are detected in the area of refuge, the elevator will not open onto that floor. The occupants must use the stairwells to either proceed to the discharge level or proceed to another floor where they can use the elevator.

Phased Evacuation
High-rise buildings present a unique scenario regarding the evacuation of occupants. Conventional low-rise structures can evacuate the entire building at one time without exceeding the design parameters of the evacuation system. Each stairwell in a low-rise structure handles few occupants and additional exits can be added to the building design at relatively low cost. High-rise buildings, however, employ fewer stairwells per capita occupant. If the entire building were to be evacuated upon fire alarm activation, the egress system would quickly become inadequate and the occupants most intimate with the fire would be exposed to hazardous conditions for an extended period. Therefore, phased evacuation is often employed in the design of egress systems in high-rise buildings. Phased evacuation involves evacuating only the occupants of the building

deemed to be in immediate danger. The general rule regarding the phased evacuation of a high-rise building is to evacuate the floor of fire origin, one floor above the fire, and one floor below the fire. This allows the occupants in the immediate vicinity of the fire to have priority access to the stairwells and elevators. The fire department incident commander, upon arrival to the fire grounds and appraisal of the situation, can then determine whether it is necessary to evacuate any other occupants of the building on a floor-by-floor basis. Further evacuation is accomplished via floor-by-floor announcements giving further instructions.

Elevator Egress System Integrity Assurance
If the elevator system is to be used as an integral, non-replaceable component of the egress system, the elevators must be designed against systemic failure. Every system element must have either built-in redundancy or a statistically low failure rate. The quantification of an acceptable failure rate must be agreed upon either by industry consensus or by agreement between the designer, owner, and authority having jurisdiction.

Several components of the elevator integrity assurance system require attention. The first and foremost requirement is that the elevators must have power in order to operate. While main electrical power should be protected against failure, fire scenarios often involve the electrical system, either as the origin of the fire (Peachtree fire)[27] or as an incidental fuel source (Meridian fire).[22] A failure mode of the Meridian fire was the use

of a common vertical shaft for both the main and emergency power supplies. If the fire penetrates a common shaft, the redundancy provided by having a reserve supply is negated. Emergency power should be supplied to the elevator system and provide the same level of reliability as the supply to the lighting (emergency) and alarm system. Power is also integral to maintaining the tenability of the elevator lobby and shaft, as well as the continued operation of the alarm and occupant notification system.

The computer which controls the phased evacuation operation of the elevators must be functioning correctly during the emergency situation. Therefore, the room where the computer is stored and all associated hardware and circuitry must be protected from injury. It may be desirable to have an off-site backup computer should the main system need maintenance or should there be a system failure. All emergency scenarios must be accounted for, such as emergencies on multiple floors, potentially remote from each other, fire department override, etc. The elevators will not stop on the floor if the alarm system has detected a fire or hazardous conditions in the lobby that the elevators open into. This will prevent the exposure of elevator occupants to untenable conditions, such as happened in the First Interstate Bank fire.[25] The probability of untenable conditions in the elevator lobby is low because several factors should mitigate growth and spread. First is the presence of an automatic sprinkler system. The sprinkler should suppress or control any fire in the lobby. Second, the fuel load in the elevator lobby is very low. If there is no fuel for the fire to consume, the fire cannot grow or spread. Finally, the lobby is

highly compartmentalized from the rest of the floor, therefore the probability of fire extending from the lobby is extremely low.

Water from manual and automatic suppression efforts may be introduced into the elevator lobby, either from a fire inside or outside the lobby. Either scenario presents a unique hazard to the elevator egress system, although the fire inside the lobby certainly represents the more severe of the two. A fire inside the elevator lobby area will expose the elevator shaft to both water from the automatic sprinkler system (assuming that the fire grows large enough to activate the fusible links in the sprinklers) as well as products of combustion. A drain will be installed in each elevator lobby to collect any water from the automatic or manual suppression efforts. The drain can be connected to the test and drain pipes that are located in the stairwells for the domestic/sprinkler water supply. Additionally, a small lip at the entrance to each elevator will prevent help prevent excess water from overflowing into the elevator shaft. The alternate scenario, a fire located outside the elevator lobby presents a smaller problem. Products of combustion should be prevented entry into the lobby due to positive pressurization of the elevator lobby. Water from either manual or automatic suppression systems should be largely prevented entry into the lobby due to the walls and doors.

Upon activation of the fire detection system inside the elevator lobby, dampers close in the ductwork and the HVAC system is shut down. These dampers are closed electronically and should be activated on both the floor side of the duct and the inside of

the duct. This will prevent vertical fire spread through the HVAC system, such as happened in the First Interstate Bank fire.[25] Mechanical devices such as fusible links are not dependent upon power supply or manual activation and are therefore unlikely to fail. With the elevators programmed not to stop on the floor once a trouble alarm in the elevator lobby is reported and fires spread beyond the boundary of the lobby highly improbable, a fire in an elevator lobby will have a very low probability of occupant injury.

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[32] "Case Study Specifications for 2nd International Conference on Performance-Based Codes and Fire Safety Design Methods." Memo to all participants of the conference.

[33] Uniform Building Code. International Conference of Building Officials, Whittier, CA, 1994.

[34] ICC Performance Based Code. Draft Version, March 17, 1998. Published by the International Code Council.

[35] Bazjanac, V. "Another Way Out?" Progressive Architecture, April, pp. 88-89.

[36] Klote, J.H., H.E. Nelson, S. Deal, and B.M. Levin. "Staging Areas for Persons with Mobility Limitations." NISTIR 4770. Gaithersburg, MD, 1992

[37] Life Safety Code, 1997 Edition. NFPA 101, Chapter 5-2.13.2.2.

[38] Fitzgerald, Robert W. "Building Fire Safety Engineering Method, Draft." Worcester Polytechnic Institute, Worcester, MA, 1993.

[39] Uniform Building Code, Section 3002, Elevator and Elevator Lobby Enclosures.

[40] Life Safety Code. NFPA 101, Chapter 5.2.12.3.4.

[41] Klote, John H. "Design of Smoke Control Systems for Areas of Refuge." ASHRAE Transactions, Vol. 99, Pt. 2, 1993, pp. 793 – 807.

Stairwell Evacuation

While elevator evacuation greatly decreases total evacuation time for a high-rise office building, the most effective egress times are achieved using a combination of elevator and stairwell evacuation routes. There are several reasons that stairwells must continue to exist in high-rise buildings. The first reason is that, however unlikely, the possibility exists that the elevators will be unusable during an emergency. This could be due to a fire in the elevator lobby, mechanical failure, or other reason. Stairwells are passive egress and thus are not susceptible to mechanical failure, except where pressurization is vital to tenability maintenance. Secondly, the decades-long public education campaign has engrained in people the fear of using elevators in a fire emergency. Thus, in spite of education and signage to the contrary, people may still be predisposed to stairwell evacuation. Finally, fire department procedures for high-rise fire attack in many cities dictate that staging occur two floors below the lowest fire floor and firefighters subsequently climb the remaining two stairwells and attack the fire from the stairwell doors.[42,22,25] Thus, it is necessary to accurately model evacuation times by people using the stairwells.

Factors Affecting Total Egress Time

Jake Pauls introduces the principle components of people movement in the 2nd Edition of the SFPE Handbook.[43] Density, speed, and flow are the fundamental characteristics of crowd movement. Density is the number of people per unit area. Speed is the distance traveled per unit time by an occupant. Flow is the number of occupants that pass some reference point per unit of time. Finally, a limiting factor influencing the flow is the

minimum width which a flow must pass through, measured in unit of length. The fundamental traffic equation is given as:

$$\text{flow} = \text{speed} \times \text{density} \times \text{width}$$

Equation 1

It is important to note the interactions between the variables. For example, beyond a critical point, as density increases, speed decreases. The motion of walking becomes more constrained until the density reaches the point where people can only shuffle along. Additionally, as the width of the smallest restriction decreases, the subsequent flow through that restriction decreases. Fewer people will flow through a 56 cm (22 inch) doorway than will flow through a 91 cm (36 inch) doorway. Table 3 shows crowd movement parameters for a typical corridor.

Crowd Condition	Density (people/m^2)	Speed (m/s)	Flow people/m-s
Minimum	<0.0046	1.27	<0.66
Moderate	0.0092	1.01	1.10
Optimum	0.0184	0.61	1.32
Crush	0.0276	<0.30	<0.99

Table 3: Crowd Movement Characteristics for a Typical Corridor

There are egress time delays associated with evacuation initiation. Notification is the first variable in the process of evacuating a building. People will not move unless they are aware that there is an emergency. The recognition of a fire event and decision to act

upon ambiguous information is often retarded by the presence of others. [44] Latane and Darley performed experiments that showed a significant activity delay when test subjects had other people in the room versus test subjects alone in a room upon introduction of smoke into the test room.[45] Alarm technology, particularly where voice enunciation exists, has been shown to reduce occupant response initiation. The voice enunciation system, however, must be audible to all occupants, lest misunderstanding of instructions occur.[46] Recall that the cybernetic building system provides occupants who may not understand instruction (mentally handicapped, deaf, or those who do not understand English) with pagers that let them know to evacuate the building. Occupants often investigate the source of a fire, either to attempt suppression or to verify actual emergency conditions. However, occupancy type has an effect upon the pre-fire activities. Occupants of an office building exhibit lower initiation times than people leaving their residences. The reasons for this are many: people evacuating homes and apartments often gather personal belongings, get dressed, gather children or other family members, whereas there are relatively few obligations to be tended to in a work place. Finally, the simple act of making a decision can account for additional evacuation delay. Proulx reports that for an apartment building where 100% of the residents hear the alarm signal, 59% of the residents have left their apartments within the first two minutes.[47] Two minutes represents a reasonable extrapolation to office buildings for two reasons: first, the number will be conservative, as occupants of offices act sooner than occupants of apartments, for the reasons mentioned previously. Second, it is not necessary for 100% of the occupants to begin evacuation in order to use a delay time. The residents who

begin in the third or fourth minute, for example, will simply be added to the end of the queue, as if they had begun evacuation at two minutes, provided that there is sufficient queuing.

Once in motion, occupants must still determine the most efficient evacuation route. This is often referred to as "way-finding." Inefficiencies exist because occupants often choose to leave by the same means they entered the building.[47] This may result in exit imbalance, where some exits are overtaxed and some exits are underutilized. Time delays also exist at merge points, where flows must stop and restart.[48] Several factors can mitigate initiation and activity delays. Occupant education is clearly a critical factor. In high-rise office evacuation studies conducted by Proulx at the National Research Council Canada, she noted that some occupants chose the familiar route, talked with friends, and were confused about the outside meeting point, while other, more informed occupants, chose the nearest exit and started evacuating immediately, directing others along the way.[49] The total inefficiency associated with less than optimal evacuation must be quantified to account for all of the above factors. MacLennan found that actual egress times were in the range of twice the modeled egress time when an efficient system was present.[48]

Computer Modeling of People Movement

Computer modeling of egress times is an inexact science. While computers can predict how people may move under ideal conditions, there are several assumptions that must be identified in order to have confidence in the results. A major assumption of any computer model is that people will behave rationally. A computer cannot predict whether people will stay to finish what they are working on, collect personal belongings, investigate the fire, or warn other people. Nelson and MacLennan, in recognition of the tendency of egress models to underestimate egress time, proposed the following equation to adjust for inefficiencies:[48]

$$T_{ae} = T_{me}e + T_d$$

Equation 2

where: T_{ae} is actual evacuation time
T_{me} is modeled evacuation time
e is the apparent evacuation inefficiency
T_d is the delay in initiating evacuation

Thus, computer modeling represents a significant fraction of the evacuation time, although, not a complete assessment. While several computer models exist to evaluate egress time,[50,51,52] one model (EVACNET+) will be analyzed and held as a representative example.[53]

EVACNET+ is a node-arc network model that determines the "fire-drill" evacuation time. "Fire-drill" evacuation time is the minimum evacuation time which the occupants may egress a building. Each space in the building through which the occupants may pass must be entered as a node. The input for a node includes the number of people which start the simulation within that particular node and the capacity (or maximum number of people which may be contained within the node). The input for an arc requires a beginning node and an ending node, a dynamic capacity (DC), and the traversal time (TT).

$$DC = WR \times AFV \times SPTP \times 0.0014$$

Equation 3

where: DC is the dynamic capacity of the arc (people/time period)

WR is the minimum width encountered along the arc path (in)

AFV is the average flow volume (people/ft-min)

SPTP is the number of seconds per time period (s)

$$TT = \frac{DIST}{AS} \times \frac{60}{SPTP}$$

Equation 4

where: TT is the traversal time (s)

DIST is the distance between the beginning of end of the arc (ft)

AS is the average speed (ft/min)

There are several assumptions and limitations of EVACNET+.

1. The program is a linear modeling system. Arc capacities and arc traversal times do not change over time and do not depend on the arc flows.

2. Smoke and fire have no effect upon the evacuation time.

3. The program does not consider behavioral aspects of occupants. Behavioral aspects include evacuation initiation delays, impaired evacuation of handicapped population, and fatigue associated with long travel distances.

4. The program views all occupants, not an individual occupant.

5. Initial location of all individuals must be assumed.

6. Traversal times are rounded off to the nearest whole number. The calculated egress time, therefore, is very sensitive to the chosen time step (seconds per time period).

7. The total evacuation time will be the lower bound of egress times.[53]

Thus, accounting for the limitations and assumptions of EVACNET+, the modeled evacuation time can be determined. Using Equation 2, a reasonable and conservative total evacuation time can be derived which should ensure safe building design.

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Cybernetic Building Features

A critical component of the fire protection system that protects a building from emergencies is the cybernetic building system. The cybernetic building system consists of sensors and monitors located throughout the building which are coordinated by a central computer. Recent advances in alarm technology allow real-time monitoring of the fire through wireless digital feedback from sensors placed throughout the building. These sensors include measurements of temperature, optical density, and gas concentrations. While the technology does not presently exist in a marketable form, these new technologies will be analyzed to demonstrate the flexibility of a performance-based design to new technologies. Sensor data, in addition to video monitoring, allow trained on-site personnel as well as members of the response team to more accurately gauge an appropriate response to the emergency. Computer fire models can process the incoming information and predict likely progress of fire scenarios faster than real time in order to assist the response team.

Temperature data in each room of the building at throughout the corridors and common spaces help determine the heat release and growth rates of the fire. Engineering analysis can determine the number and location of the sensors in each compartment. The sensor data and location can be combined with the geometry of the room to determine whether the fire should sound an alarm and help predict the growth rate of the fire. The temperature sensors can be part of a typical heat detector which can activate the alarm system. More sophisticated temperature measurements can result in substantial cost savings over the life of a building when combined with the environmental regulation

system. Temperature sensors which can detect the presence of a person in the room can then adjust the environment accordingly. For example, a room that has not been occupied in ten minutes can have the lights turned off, temperature adjusted, and other energy saving techniques implemented. Additionally, this data can be invaluable to a rescue effort, as the fire department can concentrate rescue efforts on rooms that are known to be occupied.

Smoke data can be monitored by smoke detectors. While presently smoke detectors alarm at threshold smoke concentrations using ionic or optical measurements, variant current flows can indicate transient optical conditions. Multiple smoke measurements can then measure the height of the layer interface and the optical density at different locations. Additional gas analysis, as part of a more sophisticated detection system, can monitor levels of oxygen, carbon monoxide, and carbon dioxide. All this information can be relayed to a remote monitoring station, which can predict future fire conditions and direct fire suppression efforts. Conditions, such as the pre-backdraft environment may save fire fighters lives. Such predictive capabilities are foreseeable in the medium to long range future.

Finally, monitoring of various building systems will increase the probability of the systems performing as designed. Periodic flow testing of a sprinkler system will detect obstructions, closed valves, and other failure mechanisms that decrease the reliability of a sprinkler system. Automation of testing procedures can increase the frequency of the

testing resulting in systems that are more reliable. When water does flow through the system, flow meters can determine the quantity and location of the open sprinklers, which can be relayed to the computer to increase the accuracy of the model predictions.

Combined Sprinkler and Domestic Piping

Combining the sprinkler and domestic water supply piping is the ideal project for the application of a performance-based design. Not only does the combination increase the reliability of the system and safety of the occupants, the design results in substantial cost savings to the owner, realized through lower material and installation costs, as well as increased construction schedule efficiency. These are cost savings and increases in life safety that would have been unrealized in a prescriptive regime, barring code variance approval from the authority having jurisdiction. It is important to note that the domestic water supply and the sprinkler water supply are completely separate entities.

Prescriptive Design Sprinkler System
The sprinkler system piping is divided into two sections, the low-rise and the high-rise systems. The low rise system has main six inch risers running through each of the stairwells. At each floor level, inside the stairwell, a standpipe connection is provided for the fire departments suppression operations, as required by code. The low-rise sprinkler portion uses a 6-inch riser with test and drain connection every even floor. The system is looped at the 14th floor to provide redundancy. The high-rise portion of the system uses an 8-inch riser through both stairwells until the 14th floor at which point they are looped with a 6-inch connection. From the 14th floor to the penthouse level, 6-inch risers ascend each stairwell with test and drain connections located at the even floors. The connection to the street is provided by a 12-inch pipe which splits to supply the high- and low-rise sprinklers. Both the low-rise and high-rise sprinkler sections are assisted by a dedicated fire pump and jockey pair. The garage levels, located below grade and exposed to a large range of temperatures, are supplied by a dry-pipe sprinkler system with pre-action

equipment. The system was designed using the UBC Standard 9-1 as the prescriptive

standard.

Fire Scenarios

As the building owner has specified a multi-occupancy building, special fire scenarios specific to particular occupants will exist. Fire scenarios and building design features must account for the following:

- **Law Offices and Facilities**

   Library, Security Issues, Supplemental Stairs, Private Offices, Secretarial Space, and Conference Space

- **Insurance, Brokerage, Accounting, Financial, and Consulting Offices**

   Document Safety, Security Concerns, Mixed Offices and Partitions, Secretarial Space, Conference Space, and Supplemental Stairs

- **Software Development Offices and Facilities**

   Computer Rooms, Partitions and Few Offices, Possible Supplemental Stairs

- **Retail Spaces**

   Limited Low Rack Storage

- **Public Restaurants**

   Kitchen

The NFPA Committees on Safety to Life issued a memorandum addressing likely fire scenarios in a business occupancy. This list forms the basis from which the fire scenarios are developed in this project.

Appendix A.   Fire in highly compartmented and open floor plans.

Appendix B.   Atrium fire.

Appendix C.   Copier fire.

Appendix D.   Cubicle fire, with:

- Multiple tenants per floor

- One tenant per floor

Appendix E.   Shielded fire, involving:

- Low-rack storage

- Under-desk combustion

While the above list is certainly not complete, it addresses some specific concerns and demonstrates how to apply the ICC performance-based code.

The frequency of a particular design fire will be determined by statistical analysis of previous fire loss data, particularly focusing on the National Fire Incident Reporting System (NFIRS) data. The fire scenarios which are actually analyzed in a performance-based design should represent both common, low challenge fires as well as rare, high challenge fires.

The fire scenarios should be combined when performing the analysis. A shielded under-desk fire in an open floor office plan may be one fire scenario. Not all fire scenarios may be combined, however. The kitchen fire may never be combined with the compartmentalized office plan. The list of viable fire scenario combinations must then be analyzed to determine which scenarios will challenge the performance objectives of the

design. A small, frequent fire may violate the allowable end-state condition, while a large, very rare fire may satisfy the end-state performance criteria.

Fire scenarios must account for the variety of tenant layouts and spaces encountered in a high-rise building. For the case study, there are two extremes in office layouts: one tenant, open floor plan and a four tenant, compartmentalized layout. There are two components to determining the safety of the four tenant design. The first component is to determine the evacuation time. There are two critical evacuation times to examine. The first is the time it takes for all of the occupants to egress the tenant space of origin. This time must be compared with the tenability conditions at this time. Assuming that all occupants of the tenant space of origin can evacuate safely, the second critical juncture is the evacuation of the floor of origin. The evacuation time of the floor of origin must account for the concurrent evacuation of both the floor above and below the floor of fire origin. Tenability must be maintained at all points in the evacuation path until all occupants of the floor of origin have exited the floor via vertical or horizontal exits, or have secured themselves in a designated area of refuge. The area of refuge is particularly important in the evacuation of occupants via elevator.

Additionally, there are two other considerations in the high-rise building: atrium fires and mercantile fires. Atrium fires must be modeled to prove that the large number of people who pass through the atrium will not be endangered during a building evacuation. Due to

the large volume, relatively low fuel loads specified in the atrium, and the active systems designed to control the growth of the fire and the accumulated products of combustion, the atrium does not represent a life-safety concern. The mercantile occupancy, however, is diametrically opposed to the atrium scenario. The mercantile space may be characterized as having a high fuel load (particularly where low-rack storage exists) and a relatively small volume. This makes life-safety a particular concern in the design of such spaces.

Performance Objectives

Life Safety Performance: Fire Event

The hazard level of a fire event is summarized by the frequency of occurrence. All

information for this chapter is derived from the ICC performance-based code.

Probability of occurring at least once	Mean return period
50% in 30 years	43
63% in 50 years	50
50% in 50 years	72
39% in 50 years	100
10% in 50 years	475
10% in 100 years	970
2% in 50 years	2,475

Table 4: Typical Fire Hazard Frequencies

The hazard levels are used to establish the frequency of a given fire scenario. Ideally, a

fire scenario representing each of the frequency categories should be modeled. In reality,

however, cost and time considerations, as well as redundancies in the procedure

necessitate that only two of the scenarios be modeled. The two scenarios are generally

the frequent and the very rare fire event. Table 5 summarizes the minimum performance

criteria for the life safety of the occupants given a fire event. The first column of the

table describes the fire scenario that the building must take into account. The remaining

four columns describe the acceptable end-state of the building. The following section describes the four acceptable end state of a fire scenario with regards to life safety:

Objects of Origin: structural, non-structural, and non-thermal damage shall be minor, and that the risk to life shall be low. Those nonstructural systems required for the normal use of the building…shall be significantly functional, although minor cleanup and repair of some items may be required. Flame may engulf the object of fire origin; however, fire effluent should be contained to the room of fire origin.

Room of Origin: minor damage, such as window breakage and slight damage to some components shall be expected. Basic access and life safety systems…shall remain operable. Flame may spread throughout the area of fire origin and fire effluent may spread throughout the area of fire origin and beyond. Egress and access routes within the building may be impaired. The risk to life from fire and fire effluents can be expected to be moderate.

Floor of Origin: moderate amounts of structural, non-structural, and non-thermal damage shall be expected and that egress and access routes within the building may be impaired. Flame may spread throughout the area of fire origin and fire effluent may spread throughout the floor of fire origin and beyond. The risk to life from fire and fire effluents can be expected to be high.

Building of Origin: significant structural, non-structural, and non-thermal damage shall be expected and that risk to life from fire and fire effluents can be expected to be very high. Flame may spread throughout the floor of fire origin and fire effluent may spread throughout the building or structure. Egress and access routes within the building may be impaired.

The building or structure shall be designed to avoid system failures that could injure large numbers of people, either inside or outside the building or structure.

Hazard Levels	Objects of Origin	Room of Origin	Floor of Origin	Building of Origin
Frequent	All normally occupied buildings except one and two family Residential			
Occasional	Assembly. Educational, Institutional, Mercantile, Other Residential	All normally occupied buildings except one and two family residential		
Rare	Factory and Hazardous	Assembly. Educational, Institutional, Mercantile, Other Residential	All normally occupied buildings except one and two family residential	
Very Rare		Factory and Hazardous	Assembly. Educational, Institutional, Mercantile, Other Residential	All Use Groups

Table 5: Life Safety Performance Levels

Operational Performance Levels: Fire Event

The second of the three performance criteria given a fire event is the operational end state of the building. The four acceptable end states are described below and are acceptable according to the use group of the building and hazard level experienced.

Fully Operational: Non-structural and thermal damage should be minor. Those non-structural systems required for normal use of the building…shall be significantly functional although minor cleanup and repair of some items may be required. Flame may engulf the object of fire

origin; however, fire effluent should be contained to the room of fire origin.

Functional: Minor damage, such as window breakage and slight damage to some components shall be expected. Non-thermal damage can be expected to be moderate. Basic access and life safety systems…shall remain operable. Flame may spread throughout the room of fire origin and fire effluent may spread throughout the area of fire origin and beyond.

Function Limited: moderate amounts of structural, non-structural, and non-thermal damage shall be expected. Flame may spread throughout the area of fire origin and fire effluent may spread throughout the floor of fire origin and beyond. Access routes within the building may be impaired. HVAC, plumbing, and fire suppression systems may be damaged, resulting in local flooding as well as loss of function. The risk of life-threatening injury shall be low.

Non-Functional: significant non-structural and non-thermal damage shall be expected and that risk to life from fire and fire effluents can be expected to be very high. Flame may spread throughout the floor of fire origin and fire effluent may spread throughout the building or structure. Egress and access routes within the building may be impaired. The building or structure shall be designed to avoid system failures that could injure large numbers of people, either inside or outside the building or structure.

Hazard Levels	Fully Operational	Functional	Function Limited	Non-Functional
Frequent	All use groups except E, H, & I			

Occasional	Educational and Institutional Hazardous	All use groups except E, H, & I		
Rare		Educational and Institutional Hazardous	All use groups except E, H, & I	
Very Rare			Educational and Institutional	All use groups except E, H, & I

Table 6 Operational Performance Levels

Structural Performance: Fire Event

The final end state performance-based analysis regarding a fire event within the building is the post-fire structural integrity. Four end states, described herein, are acceptable, depending upon the use group of the building and the hazard level the structure is exposed to.

Immediate Occupancy: The basic vertical- and lateral-force-resisting systems of the building shall retain nearly all of their pre-fire strength and stiffness. The risk of life-threatening injury as a result of fire-induced structural damage shall be very low. Minor structural damage that may occur as a result of the fire shall not significantly delay reoccupancy.

Delayed Occupancy: The basic vertical- and lateral-force-resisting systems of the building are expected to retain nearly all of their pre-fire strength and stiffness, and the risk of life-threatening injury as a result of fire-induced structural damage should be low. Moderate structural damage that may occur as a result of the fire is likely to delay reoccupancy.

Life Safety: Structural elements and components may be significantly damaged as long as large falling debris hazards either, within or outside the building, do not result. The overall risk of life-threatening injury as a result

of structural damage shall be low. The amount of fire-induced structural damage shall not be such that repair of the structure is not possible; however, significant delays in reoccupancy, or a decision not to repair the damage may result.

Collapse Prevention: Significant degradation in the stiffness and strength of the lateral-force-resisting system, large permanent lateral deformation of the structure, and, to a more limited extent, degradation in vertical, load-carrying capacity shall be expected. However, all significant components of the gravity load-resisting system must continue to carry their gravity load demands. Significant risk of injury due to falling hazards from structural debris may exist. The structure may not be technically practical to repair.

Hazard Levels	Immediate Occupancy	Delayed Occupancy	Life Safety	Collapse Prevention
Frequent	All use groups except E, H, & I			
Occasional	Educational and Institutional	All use groups except E, H, & I		
Rare	Hazardous	Educational and Institutional	All use groups except E, H, & I	
Very Rare		Hazardous	Educational and Institutional	All use groups except E, H, & I

Table 7 Structural Performance Levels

Modeling Fire Scenarios

CFAST 3.1

All modeling of fire scenarios in this case study was performed using CFAST 3.1.[14]

CFAST is a zone-type fire model which can model fire and smoke spread between up to 30 compartments on multiple levels. The physical and numerical theory behind zone models was discussed previously (see page 21). CFAST is a widely zone model. It is important with CFAST and all other computer models that the user appreciates the boundary conditions to ensure proper application and conclusions.

Modeling Sprinkler Activation and Suppression

The experimental studies supporting the numerical characterization of sprinkler activation and suppression algorithms was discussed previously (see page 32). The sprinkler suppression algorithm in CFAST was derived by Evans from the work of Madrzykowski and Vettori.[54] A fundamental assumption underlying the model is that the fire will be extinguished. In other words, the fire size is within the design parameters of the suppression system. The sprinkler system is assumed to be operational. Finally, the fire must not be shielded in any way.

The properties of the sprinkler must first be determined, although defaults exist within the model. Values such as the response time index (RTI), activation temperature, spray density, and the distance from the ceiling of the sprinkler must be input. Once the model has determined that the sprinkler has activated, fire suppression begins. The heat release rate of the fire is determined by the following equation:

$$\dot{Q}_{t-t_{act}} = \dot{Q}_{t_{act}} \exp\left(\frac{-(t-t_{act})}{3.0(\dot{w}'')^{-1.85}}\right)$$

Equation 5

where:

$\dot{Q}_t$ = Heat release rate at time t (kW)

$\dot{Q}_{t_{act}}$ = Heat release rate upon sprinkler activation (kW)

t = time (s)

t_{act} = time at sprinkler activation (s)

$\dot{w}''$ = spray density (mm/s)

Equation 5 describes exponential decay of the fire based upon an initial condition (the size of the fire at sprinkler activation) and the independent variables (sprinkler spray density and time). CFAST implements this algorithm when determining the heat release rate of the fire after the sprinkler has been determined to activate.

An alternative to allowing CFAST to calculate the heat release rate of the fire based upon the sprinkler algorithm is to input it manually. This must be done using experimental data and is particularly useful for recreating fire event where the assumptions of the Evans algorithm are violated. Shielded fires are a good application for manual heat release rate entry. The sprinkler algorithm would predict fire suppression, which would not be the case for a shielded fire, as the heat release rate curve would simply be damped.

Smoke Detector Activation

Determining the appropriate smoke detector activation criteria is an important step in modeling the suppression of the fire as well as the evacuation time of the occupants. Current standards such as NFPA 72[55] stipulate the spacing of smoke detectors based upon the tests by nationally-recognized testing laboratories such as Underwriters Laboratories (UL 268[56]). An alternative, performance design method found in NFPA 72, Appendix B, is limited to flaming fires and does not consider ceilings higher than 8.5m (30ft). This method was developed from an experimental study conducted in the late 1970's for the Fire Detection Institute (FDI)[57], with the limitations related to the scope of the experiments conducted. However, this design method introduces some important concepts; including design of a detection system to activate for a critical fire size (heat release rate) representing an acceptable threat level for the protected space. This is a departure from the earlier concept of detection "as quickly as possible" which often led to over-sensitivity.

Temperature Correlations

The most commonly accepted engineering approach to predicting smoke detector activation is the temperature correlation. Specifically, activation for a 13 C temperature rise at the detector location is cited in the SFPE Handbook of Fire Protection Engineering and in the FSE guides published in the UK, Australia, and New Zealand. The approach was originally proposed by Heskestad and Delichatsios in 1977[58, 59] however, the 13 C

value was a compromise from a set of experimental results for different detectors and fuels for which the results varied over a wide range. A thorough discussion of this is found in a paper by Schifilitti and Pucci.

In Heskestad's discussion of the use of temperature correlations for predicting activation of smoke detectors, he observes that heat released by a burning fuel resulting in an observed temperature rise is similar to smoke (soot) released by the fuel and carried in the buoyant plume. However, while heat losses occur through heat transfer to surroundings, smoke losses are minimal, so the temperature correlation used as a surrogate for smoke detector activation should be done for adiabatic conditions.

Since the original experiments used detectors employing older technology sensors and significant improvements have occurred in recent times, it is reasonable that lower temperature correlation values might be appropriate for more modern detectors. Recent literature has suggested that temperature correlations of 4 C or 5 C provide good agreement with experiments in which current detectors were installed on ceilings of normal 2.4m (8 ft) heights.

Figure 2 compares several activation temperatures to the experimental data. A 4°C correlation (adiabatic) matches the experimental data closely. This is supported in residential fire tests by
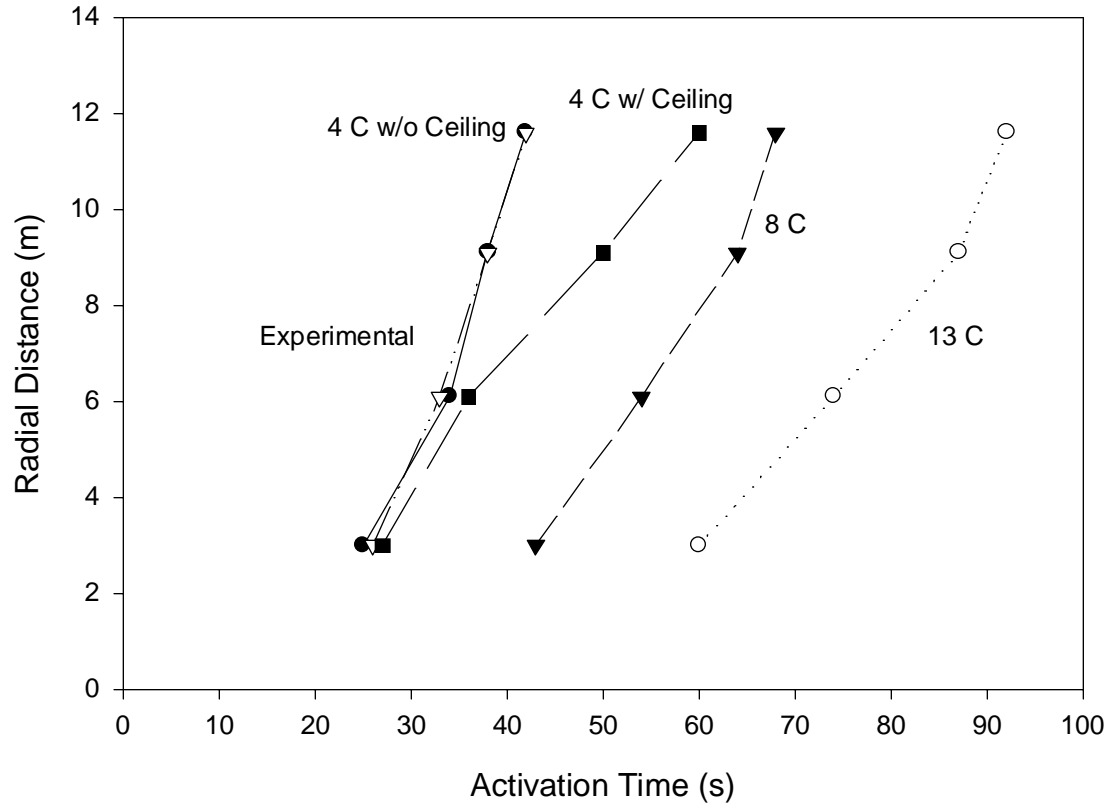
Figure 2: Comparison of Experimental and Predicted Activation Times Using Different Temperature Correlations

Collier[60] who found that when using CFAST, 4°C provided the best match to experimentally observed smoke detector activation times. Additionally, Davis and Notarianni recommended a temperature rise at the detector of 5°C for ionization detectors alarming at 2.5% m^{-1} in high bay spaces using fire models other than CFAST.[61]

While limitations of any temperature correlation preclude the likelihood of consistently predicting activation times as closely matched to the experimental data as that shown in Figure 2, there is substantial evidence for the appropriate use of a value well below the traditional 13°C criteria. Indeed, Beyler points out that in the original Heskestad and Delichatsios experiments, the optical density at a given detector can vary by three orders of magnitude for different fuels and fire growth conditions.[62]

Disadvantages of Temperature Correlations

As previously mentioned, the test data from which the13°C value was derived showed a wide variation in values for specific detector types and for different fuels -- values range from 2°C to over 20°C. The fundamental conclusions of the Heskestad and Delichatsios report were supported by the further analysis of Evans and Stroup[63], but several distinctions exist between the assumptions used in the two analyses and the application of temperature correlations in a performance-based environment. There are four basic assumptions inherent in the 13°C activation correlation:

- the Lewis number=1[*]*. In other words, the ratio of species mass concentration to temperature is constant in space and time.

- species are carried passively by turbulent convective motion without significant effects of gravity, molecular motion, or particle-fluid inertial effects.

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[*] Lewis number = $k/\rho c_p D$, where k = conductivity, ρ = density of air, c_p = specific heat capacity of ambient air, D = effective binary diffusion coefficient.

- insignificant heat transfer occurs by radiation between elements of the fluid.

- heat transfer between the fluid and confining material surfaces is negligible.

An additional assumption implicit in the previous is that there is no HVAC interaction with the room. HVAC may significantly increase or decrease the activation time of a detector. CFAST is essentially consistent with these basic assumptions. First, the CFAST default assumes that 30% of the fire energy is emitted by radiation from a point source, while the remaining 70% is convection energy carried by the plume to the ceiling jet and upper layer. There are no additional radiative losses from either the plume or the ceiling jet. Second, by turning off the ceiling and wall materials (an option in CFAST), there is no subsequent heat transfer to the ceiling (the confining material). Additionally, there is no particulate deposition to bounding surfaces, therefore, the ratio of mass concentration to temperature is constant within model space and time.

In reality, however, these assumptions may be suspect. The first is the assumption that the ratio of mass concentration to temperature is constant. Mass concentration is affected by several physical phenomena. As air is entrained into the plume from the lower layer, the mass concentration is decreased. Along the ceiling jet, air is entrained from the upper layer, assuming that an upper layer has formed and that the interface height is below the bottom of the ceiling jet. This may or may not dilute the species mass concentration in the ceiling jet as it progresses towards the detector element depending on the species concentration of the upper layer. Additionally, species may be deposited on the ceiling or

other bounding surfaces encountered en route to the detector. Particulate deposition on ceiling surfaces becomes increasingly important as detector spacing increases.

Finally, as particulates age, they coagulate, thereby decreasing the number of particles while increasing the average particulate size. This has a significant effect on the activation of both ionization and light-scattering detectors. Therefore, plumes and ceiling jets with low velocity profiles allow particulates to age and coagulate as well as detectors located such that the particulate must travel significant distances, either from the fire to the ceiling (high ceiling heights) or from the plume impingement point to the detector (large detector spacing). Temperature at a given point between the fire source and the detector is a function of several variables. The most important is the entrainment of air into the plume and ceiling jet. This may have a significant effect on the ratio of species concentration to temperature. The fire plume may entrain cool, clean air, or may entrain cool, smoke air that accumulates in the compartment. The ceiling jet may entrain hot or cool gases as well as smoky or particulate-free gases depending on the height of the layer interface, the depth of the ceiling jet, and the age of the fire. A secondary consideration is the radiation of the plume and ceiling jet fluid and particulate to the environment. The greater travel time and the greater the temperature gradient between the transport gases and the surrounding environment, the more significant this effect becomes. In summary, the assumptions inherent in the derivation of the original 13°C smoke detector activation

correlation must be appreciated, particularly for high ceiling or large area spaces, unconventional geometry, or other applications.

Finally, manufacturers of smoke detectors are reluctant to accept the notion that a smoke detector is nothing more than a sensitive heat detector. Ionization, photoelectric light scattering and projected beam detectors are known to exhibit significant differences in response to different fuels and to smoke that has been "aged" as it travels from the source. Temperature correlations do not capture any of these known differences.

In summary, the predicted detection time contains a degree of uncertainty that should be accounted for in the fire safety analysis. The quantification of the uncertainty level is subject to literature review and/or negotiation between the design team and the authority having jurisdiction. While the literature indicates that 4°C most accurately identifies the temperature at activation, the design team chose 13°C as the activation temperature for the inherent conservatism.

Results of Fire Scenario Computer Modeling

Multi-Tenant Cubicle Fire
The multi-tenant cubicle fire scenario was chosen to provide a rare and relatively severe fire insult. Four tenants per floor represents a reasonable level of compartmentation. One of the greatest determinants of tenability in a compartment is the volume of the space. A compartment with a high volume takes longer to become untenable than a

compartment with a small volume, when all other factors are held constant. Thus, dividing a floor into four tenant spaces represents a more severe fire scenario than the same fire in a one-tenant layout, assuming the tenant has not sub-divided the space.

The modeling of the cubicle fire represents one use of heat release rate input methodology. The cubicle fire data was derived from experimental literature and input into CFAST. Appendix C shows the modeling results of the cubicle fire in the four tenant layout. The two spaces of interest during a fire scenario include the compartment of fire origin and the hallway space outside the compartment of origin. An office located nearer the stairwells was chosen as a fire on the opposite side poses less threat to the occupants. The upper layer temperature in the room of origin stayed relatively cool, due in part to the effect of the sprinkler system. The layer height approached one meter, but only after all occupants were safely out of the office of origin and were either waiting near the stairwell lobby area (an area of refuge, and hence safety) or waiting in or near the elevator lobby (also an area of refuge). The upper layer temperature in the hallway was much less than 100°C, while the layer height remained above two meters for the duration of the evacuation. Thus, the four occupant cubicle fire scenario is deemed safe in terms of life safety, and the fire, with reasonable probability, will not spread beyond the fuel package of origin as the heat release rate is quickly attenuated by the activation of the sprinkler system, thus satisfying the requirements of the performance matrix.

One Tenant Cubicle Fire

The one tenant cubicle fire is exceedingly safe, owing mostly to the enormous volume involved. Appendix C shows the results of the computer modeling. Notice that the upper layer temperature never exceeds 100°C before the entire phased evacuation is complete and the layer height never drops below two meters.

Multi-Tenant Shielded Fire

The development of the shielded fire was discussed previously. The shielded fire represents the direct input of heat release rate including activation of the sprinklers. CFAST cannot predict shielded fire suppression because the algorithm assumes that the fire will be put out, while a shielded fire, by definition, cannot be suppressed by overhead sprinklers. The fire is simply controlled and fire spread stopped. Thus, the shielded fire represents a more severe long-term threat to the occupancy due to the higher total mass loss, heat release, and product generation.

Mercantile Low-Rack Storage Fire

The mercantile low-rack storage fire is intended to expose the mercantile occupancy to a severe fire insult under realistic loading conditions. Lee[64] and Kung, et al.,[65] performed experiments at Factory Mutual using a four-tier rack storage system. The commodity contained within the rack storage of the latter tests was polystyrene cups packaged in compartmented cartons and sitting upon a standard wooden pallet. While the goal of the experiments was to determine the effect of water density, velocity, and source location on the suppression of the commodity, it will be assumed that the sprinkler system has been adequately designed to suppress the fire. Brass discs simulated the activation of quick response fusible links. With regard to the modeling methodology, the storage fire was simulated with a fast-growing fire ($\alpha = 0.0469$) until the heat release rate was equal to 1.675 MW. This number corresponds to the total heat release rate of the fire at the time of sprinkler activation, assuming that the convective fraction was 20%.[65] The fire is then suppressed according to the calculations of Madrzykowski and Vettori.[18]

Atrium Fire

The atrium fire scenario represents an alternative approach to fire modeling: generic heat release rate, using the classic heat release rate shape of growth, steady-state burn, and decline phases of fire development. The fire represents agreement between the design team, the owner, and the AHJ as appropriately severe. The fire chosen for the atrium was a 5.275 MW, fast-growing ($\alpha = 0.0469$) fire. This fire is specified by Section 909.9 of the IBC 2000 Draft, per atrium regulations covered by Section 404. It is important to note

that the prescriptive code mandates both automatic sprinklers and a smoke control system in an atrium space.

The original prescriptive design was determined to inadequately address the fire safety goals of the atrium space. As occupants evacuating the building are assumed to use the atrium on the way from either the elevators or the stairwells to the outside, the atrium must be kept tenable throughout the entire fire scenario. The figures showing the baseline hazard analysis in Appendix C clearly demonstrate that the upper level atrium space is untenable during considerable portions of the fire event due to the fact that the layer height drops below 1 meter. Through further modeling, the sprinkler system was upgraded from commercial sprinklers to quick response (QR) sprinklers, which activate at lower ceiling temperatures. The effect of different sprinkler types is shown graphically in Appendix C. The combination of QR sprinklers and a smoke management system maintained tenable conditions throughout the entire fire event and thus, met the life safety goals.

Evacnet4 Model Results

There are five basic scenarios: phased (meaning only three floors upon activation of the initial alarm signal) evacuation of the four tenant and one tenant layouts, with both stairwell only and elevator and stairwell evacuation, and the mercantile scenario.

Scenario	Floor Clearing Time
One Tenant, Stairs Only	495
One Tenant with Elevators	130
Four Tenant, Stairs Only	370
Four Tenant with Elevators	110
Mercantile	N/A

Table 8: Results of Evacuation Modeling

Office Layout	Cubical Fire	Shielded Fire	Copier Fire
One Tenant	85	70	25
Four Tenants	33	27	10

Table 9: Times to Smoke Detector Activation

Using the guidance provided by Nelson and MacLennan (Equation 2) we can now estimate total evacuation time. The inefficiency factor used in developing Table 10 was 50%. The inefficiency in the case study evacuation is relatively low for several reasons: voice enunciation, which reduces occupant confusion, occupant familiarity with evacuation routes and procedures, the fact that most occupants should be awake and alert, the ability of the occupants (most occupants will not be elderly or children), and the fact that only three floors are evacuating.

Fire Scenario	Tenant Layout	Evacuation Scheme	Evacuation Time (s)
Cubicle	One	Stairs Only	828
		Stairs and Elevators	280
	Four	Stairs Only	588
		Stairs and Elevators	228
Copier	One	Stairs Only	768
		Stairs and Elevators	220
	Four	Stairs Only	565
		Stairs and Elevators	175
Shielded Fire	One	Stairs Only	813
		Stairs and Elevators	265
	Four	Stairs Only	582
		Stairs and Elevators	192

Table 10: Total Evacuation Times for Office Fire Scenarios

[54] Evans, David D. "Sprinkler Fire Suppression Algorithm for HAZARD." US Department of Commerce, NISTIR 5254, August 1993.

[55.] NFPA 72, "Appendix B: Engineering Guide for Automatic Fire Detector Spacing." National Fire Protection Association, Quincy, MA (1996).

[56.] UL 268: "Smoke Detectors for Fire Protective Signaling Systems, 4th Edition." Underwriters Laboratory, Northbrook, IL (1996).

[57] Heskestad, G. and Delacatsios, M., Environments of Fire Detectors (4 volumes)

[58.] Heskestad, Gunnar and Michael A. Delichatsios. "Environments of Fire Detectors - Phase I: Effect of Fire Size, Ceiling Height, and Material, Volume 1 - Measurements," Factory Mutual Research Corporation Technical Report 22427, Norwood, MA (1977).

[59.] Heskestad, Gunnar and Michael A. Delichatsios. "Environments of Fire Detectors - Phase I: Effect of Fire Size, Ceiling Height, and Material, Volume 2 - Analysis," NBSGCR-77-95 (1977).

[60.] Collier, P. C. R. "Fire In a Residential Building: Comparisons Between Experimental Data and a Fire zone Model," Fire Technology, Vol. 32, No. 3, Aug. 1996, pp. 195-219.

[61.] Davis, William D. and Kathy A. Notarianni. "NASA Fire Detector Study," NISTIR 5798 (1996).

[62.] Beyler, Craig L. "A Design Method for Flaming Fire Detection." Fire Technology, Volume 20, No. 4, pp. 5 – 16, November 1984.

[63.] Evans, David D. and David W. Stroup. "Methods to Calculate the Response Time of Heat and Smoke Detectors Installed Below Large Unobstructed Ceilings," Fire Technology, Vol. 22, No. 1, February 1985, pp. 54.

[64] Lee, James L. "Extinguishment of Rack Storage Fires of Corrugated Cardboard Cartons Using Water." in International Association for Fire Safety Science. Fire Safety Science. Proceedings. 2nd International Symposium. June 13-17, 1988, Tokyo, Japan, Hemisphere Publishing Corp., New York, Wakamatsu, T.; Hasemi, Y.; Sekizawa, A.; Seeger, P. G., Editors, 1989 pp. 633 - 642.

[65] Kung, H. C.; You, H. Z.; Brown, W. R.; Vincent, B. G. *Four-Tier Array Rack Storage Fire Tests With Fast-Response Prototype Sprinklers.* in International Association for Fire Safety Science. Fire Safety Science. Proceedings. 2nd International Symposium. June 13-17, 1988, Tokyo, Japan, Hemisphere Publishing Corp., New York, Wakamatsu, T.; Hasemi, Y.; Sekizawa, A.; Seeger, P. G., Editors, 1989, pp. 633 – 642.

First Order Cost Estimation

Three performance-based design features require preliminary cost estimates. The most significant cost savings is the stairwell evacuation program. Relocating the two stairwells out of the office area and into the building core results in greater leasable office space on each floor. The second cost savings is the combination of the domestic and sprinkler water risers. Finally, a cost analysis of the cybernetic building systems will be explored. Due to time constraints, the scope and accuracy of the cost estimation is severely limited. Significant issues such as time costs of up-front money, savings from potential fire losses, and other economic issues will not be pursued due to their complexity. The important and easily quantifiable costs will be estimated.

The first cost savings realized by the owner is related to the elevator egress system. The benefits of the elevator egress include lower egress time for the occupants and the ability to relocate the stairwells into the building core. Shorter egress time allows for building fire safety performance to be relaxed, as such will not endanger any of the occupants. This can result in direct design and installation savings to the owner. The limiting factors regarding fire performance relaxation are the fire department, property protection, and performance-based code guidelines. The fire must be contained to the degree that ensures fire fighter safety. The owner may stipulate a level of property protection which raises the standard above that intended by the performance requirements. Finally, the design may never perform to a degree less than that stipulated by the code. The total cost savings realized by fire performance relaxation depends upon the specific fire safety components which are adjusted and the degree to which the designer, owner, and authority having jurisdiction agree to relax the performance. The second component of cost savings is the relocation of the stairwells

into the core. The quantifiable cost associated with this is the additional leasable floor space now available to the tenants. The national average for class A office rent in the central business district where the building is going to be built is $23.99 per square foot per year, although this figure can be as high as $37 per square foot per year in Washington, D.C.[66] The increase in floor space per floor of the case study building is approximately 800 square feet. There are 38 stories containing office spaces. Thus, the stairwell relocation may generate up to US$729,000.00 additional revenue per year to the building owner.

The second component of cost adjustments due to the performance-based design is the elimination of the domestic water supply risers. There are four basic components of cost savings associated with the domestic supply: materials, labor, design, and maintenance. The greatest component of savings is either the material or labor associated with installation of the domestic water riser pipe and pumps. Additionally, the plumbing designer may design only one set of risers, sized to either the fire protection or domestic supply requirements, whichever is greater. Finally, by eliminating the domestic risers, they require no maintenance. Each of these cost savings combine to save the owner a significant initial cost and minor long-term savings.

Finally, the additional costs and long-term savings of the cybernetic building systems should be analyzed. There are substantial initial costs, both in the design and installation of the building systems. The owner must weigh these additional costs against the long-term benefits of increased system reliability, occupant safety, and reduced maintenance and inspection uncertainty. The cybernetic building systems require the most thorough economic analysis to justify their inclusion in the building fire safety plan. The assured fire safety system may

eliminate up to 90% of the conventional repair and maintenance costs associated with the fire and life safety systems in large buildings. The current cost repair and maintenance of fire and life safety systems is $0.07. This results in an approximate cost savings of up to US$75,000.00 per year.[66] Additionally, the increased safety and reliability the systems provide should help justify inclusion.

Clearly, more work must be done to fully quantify the cost impact of the performance-based building design. Long-term cost impact, however, certainly appears to be positive when accounting for the increase in building revenue and fire safety.

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[66] 1996 BOMA Experience Exchange Report. Building Owners and Managers International, Baltimore, MD, 1996.

Conclusions

The project has effectively demonstrated an application of the ICC performance-based code using a 40 story, mixed-use, office building. In addition to exploring the social economic impacts of performance-based codes, the project detailed the necessary steps to document a performance-based design. Thorough documentation of the building design is critical to assuring that the performance-based design objectives are satisfactorily fulfilled. This includes all assumptions, models, limitations of calculations, design fire details, statement of goals, and a clear demonstration of accomplishment of said goals.

The third goal of the case study was to perform an example performance-based design. Using a real 40 story building designed with the Uniform Building Code, the design team, in cooperation with a practicing authority-having-jurisdiction, documented three significant design changes to the prescriptive code. The first alteration was the elimination of the domestic risers and their combination with the sprinkler risers. While increasing the reliability of the sprinklers system, the combination also saves significant money to the building owner during the design and construction phases. The second design aspect was to relocate the stairwells into the building core. The result was an 800 sf increase per floor in leasable floor space. Using elevators to evacuate the occupants significantly reduced evacuation times and increased the safety of the building occupants. Finally, new alarm and sensor technologies were implemented throughout the building. The sensors and alarms increase fire protection system reliability, provide greater information to the emergency response teams, and increase the level of safety of the building occupants.

Finally, the economic impact of the performance-based design alternatives was explored. Clearly, the greatest impact resulted from the stairwell relocation, which resulted in approximately 2% increase per floor of leasable office space. The potential economic impact of this relocation alone could exceed US$700,000.00 per year. Additional secondary impacts could also include lower insurance premiums due to the increased safety levels in the building. Up-front design and construction costs are realized by the combination of the domestic and sprinkler risers. Additionally, the sprinkler flow is monitored by the domestic supply, resulting in an additional margin of safety. Finally, new detection and alarm technologies are introduced to the building. When combined with existing environmental regulation systems, the additional costs are marginal, while the benefits to the owner, occupants, and fire service are substantial.

This project has proved the feasibility of performance-based design in the United States. Clearly the paradox of increased safety at reduced cost can be realized through creative building design, if implemented in a methodical, systematic form which ensures a minimum level of public safety.

Appendix A: Elevator Theory

Calculating Egress Time Using Elevator Evacuation

The following section will present the foundation for an elevator egress calculation model. The calculations must clearly demonstrate that using elevators as an egress tool significantly decreases the time to evacuate the occupants of the proposed building design. Several obstacles to using elevators as a component of the egress system exist. The first obstacle is the decades long public awareness campaign against using elevators in the event of a fire. Presently, the Uniform Building Code stipulates that an emergency sign shall be posted adjacent to each call station which indicates that the elevators will not operate in the event of an emergency and that the stairways are to be utilized for egress.[67] The May 1997 Working Draft of the International Building Code, however, does not require signage in designs utilizing elevators as a component of the egress system.[68] The second obstacle is the reliability of the elevators in the event of an emergency. The risk of total elevator disabling is low and will be addressed in subsequent analysis.

The model used in this analysis is ELVAC.[69] The evacuation time calculated herein is the "fire drill" evacuation time. A "fire drill" evacuation time is the time taken by people to evacuate a building that is not in an emergency situation. In other words, a "fire drill" evacuation time does not account for the human behavior associated with emergency situations, such as delays due to decision making, investigation of the fire, attempted extinguishment, gathering of personal belongings, notifying of other occupants, or unfamiliarity with the emergency exit procedure (way finding). **Error! Reference**

source not found., from Nelson and MacLennan, suggests that the actual evacuation time is the modeled evacuation time plus delays in initiating evacuation and any associated inefficiencies during the evacuation.[70]

$$t_e = t_a + t_o + \frac{(1 + \eta)}{J} \sum_{j=1}^{m} t_{r,j}$$

Equation 6

where: t_e is the total evacuation time

t_a is the elevator evacuation start up time

t_o is the travel time from the elevator lobby to the outside or area of refuge

η is the trip inefficiency

J is the number of elevators

j is the specific trip number

m is the number of round trips

$t_{r,j}$ is the time for round trip j

Start Up Time

The start up time for elevator evacuation can be defined simply as the time from activation to the beginning of the round trips.

$$t_a = t_T + (t_u + t_d)(1 + \mu)$$

Equation 7

where t_T is the length of time the elevator takes to travel from the farthest floor to the

discharge floor

t_u is the time for the passengers to leave the elevator

t_d is the time for the doors to open and close once

μ is the total transfer inefficiency

Total transfer inefficiency is the sum of basic transfer inefficiency, door inefficiency, and people inefficiency. **Error! Reference source not found.** describes the total transfer inefficiency.

$$\mu = \alpha + \varepsilon + \gamma$$

Equation 8

where α is the basic transfer inefficiency

ε is the door inefficiency

γ is the people inefficiency

The basic transfer inefficiency is generally assumed to be 0.10.**Error! Bookmark not defined.** Factors that can affect the value of the basic transfer inefficiency include elevator car arrangement and car shape. Table 11 lists appropriate values for different elevator door inefficiencies, ε. People inefficiency accounts for mobility limitations which affect the speed with which people move into or out of the elevator. Mobility limitations such as those often encountered in hospitals would set $\gamma = 0.05$.

Time from Elevator to Outside or Refuge Calculation

t_o is the time for elevator dischargees to travel from the elevator to the outside or an equivalent point of refuge. This time can be estimated from standard evacuation models such as EVACNET+[71] or EGRSTIME.[72] The layout of the elevators in the lobby or discharge floor is critical to ensuring efficient egress. If dischargees interfere with one another, the total egress time will be increased.

Time for Elevator Round Trip

The time for an elevator round trip, t_r, starts at the discharge floor. The total round trip time is simply the sum of the time for the following sequence: doors close, elevator travels from the discharge floor to the pickup floor, doors open, passengers enter the elevator, doors close, elevator travels from pickup floor to discharge floor, doors open, and evacuees egress elevator. **Error! Reference source not found.** mathematically describe the round trip time:

$$t_r = 2t_T + \left(t_i + t_u + 2t_d\right)\left(1 + \mu\right)$$

Equation 9

where: t_T is the travel time from the discharge floor to the pickup floor

t_i is the time for people to enter the elevator

t_u is the time for people to leave the elevator

t_d is the time for the doors to open and close

Each of these times will be developed subsequently. Refer to Table 11 to determine t_d. The time required for people to enter the elevator, t_i, is dependent upon the number of people waiting to board the elevator. There is a limit to the number of people the elevator will hold and the number of people that will willingly board an elevator. If the elevator density exceeds the individuals threshold, the person will either wait for the next elevator or use the stairs. Strakosch observed that people will board an elevator until the density is one person for every 0.22 m^2 of elevator space[73]. ASTM A17.1 allows a maximum loading of 0.17 m^2.[1] Since the ASTM density is rarely observed in reality, the more conservative Strakosch values are used for analysis. The time that the elevator doors remain open is a function of the number of people entering the elevator. Two or less people entering the elevator result in the minimum open door time, or the dwell time, t_{dw}. Any additional people entering the elevator will cause the doors to remain open while they enter the car. shows the time for people to enter the elevator:

$$t_i = \begin{cases} t_{dw} & , for\, N \leq 2 \\ t_{dw} + t_{io}(N - N_{dw}), & for\, N > 2 \end{cases}$$

Equation 10

where: t_{io} is the average time it takes one person to enter the elevator

N is the number of people entering the elevator

N_{dw} is the number of people entering the elevator during the dwell time, or

N_{dw} is (t_{dw}/t_{io}) rounded down to the nearest integer

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[1] ASTM A17 is expressly referenced in the 1996 BOCA National Building Code, Chapter 30.

The calculation of the time it takes for the elevator to empty upon arrival at the discharge floor, t_u, is equivalent to **Error! Reference source not found.**.

Elevator Travel Time

The second major component of the determination of round trip time for an elevator is the travel time, t_T. There are three possible velocity curves for an elevator car. The first curve is an elevator car that accelerates, reaches terminal velocity and decelerates as it reaches the destination. Secondly, an elevator car may reach the transitional acceleration area but fail to achieve constant velocity before decelerating. Finally, for elevators cars traversing short distances, there is the possibility that the car will accelerate and decelerate before reaching transitional acceleration.

Trips Reaching Normal Operating Velocity

The time to complete constant acceleration is given by **Error! Reference source not found.**, while the corresponding distance traveled is given by **Error! Reference source not found.**:

$$t_1 = \frac{V_1}{a}$$

Equation 11

$$S_1 = \frac{V_1^2}{2a}$$

Equation 12

where: t_1 is the time to complete constant acceleration

v_1 is velocity

a is acceleration

S_1 is the distance traveled during constant acceleration

The time to reach the end of transitional acceleration is given by **Error! Reference source not found.**, while the corresponding distance traveled is given by S_2:

$$t_2 = \frac{V_m^2 - V_1^2}{2V_1 a} + t_1$$

Equation 13

$$S_2 = \frac{1}{3a}\left[\frac{V_m^3}{V_1} - V_1^2\right] + S_1$$

Equation 14

where: V_m is the normal operating velocity

Thus, the total one way travel time can be computed from **Error! Reference source not found.**:

$$t_T = 2t_2 + \frac{S_T - 2S_2}{V_m} + t_h$$

Equation 15

where: S_T is the total travel distance

t_h is the leveling time

Trips Reaching Transitional Acceleration

The elevator may not travel far enough to reach normal operating velocity. For this instance, the total trip time is calculated from **Error! Reference source not found.**:

$$t_T = 2t_2 + t_h$$

Equation 16

Trips Not Reaching Transitional Acceleration

If the trip does not go beyond constant acceleration, the total trip time is computed from the following:

$$t_T = 2\sqrt{\frac{S_T}{a}} + t_h$$

Equation 17

Door Type	Width (mm)	Time to Open and Close td (s)	Door Transfer Inefficiency
Single Slide	900	6.6	0.10
	1100	7.0	0.07
Two-Speed	900	5.9	0.10
	1100	6.6	0.07
	1200	7.7	0.02
	1400	8.8	0.02
	1600	9.9	0.02
Center-Opening	900	4.1	0.08
	1100	4.6	0.05
	1200	5.3	0
	1400	6.0	0
	1600	6.5	0
Two-Speed, Center-Opening	1600	6	0

Table 11: Elevator Door Data

[67] 1991 Uniform Building Code. Section 5103, Part 15 (f).

[68] 2000 International Building Code – Working Draft Section 3002.3.

[69] Klote, John H., Daniel M. Alvord, Bernard M. Levin, Norman E. Groner. "Feasibility and Design Considerations of Emergency Evacuation by Elevators." NISTIR 4870, U.S. Dept. of Commerce, September 1992.

[70] Nelson, Harold E. and Hamish A. MacLennan. "Emergency Movement." In *The SFPE Handbook of Fire Protection Engineering, 2nd Edition*, National Fire Protection Association, Quincy, MA (1995) pp. **3**-286.

[71] Kisko, T. M. and Francis R. L. "EVACNET +: A Computer Program to Determine Optimal Building Evacuation Plans." Fire Safety Journal, 9, pp. 211-220.

[72] Hagiwara, Ichiro. Brief Notes on Egress Time Calculation Time Program (EGRSTIME). Unpublished Report.

[73] Strakosh, G. R. "Vertical Transportation: Elevators and Escalators, 2nd Edition." Wiley and Sons, New York, NY, 1983.

Appendix B: Stairwell Evacuation

Factors Affecting Total Egress Time

Jake Pauls introduces the principle components of people movement in Section 3/Chapter 13 of the 2nd Edition of the SFPE Handbook.[74] Density, speed, and flow are the fundamental characteristics of crowd movement. Density is the number of people per unit area. Speed is the distance traveled per unit time by an occupant. Flow is the number of occupants which pass some reference point per unit of time. Finally, a limiting factor influencing the flow is the minimum width which a flow must pass through, measured in unit of length. The fundamental traffic equation is given as:

$$\text{flow} = \text{speed} \times \text{density} \times \text{width}$$

Equation 18

It is important to note the interactions between the variables. For example, beyond a critical point, as density increases, speed decreases. The motion of walking becomes more constrained until the density reaches the point where people can only shuffle along. Additionally, as the width of the smallest restriction decreases, the subsequent flow through that restriction decreases. Fewer people will flow through a 56 cm (22 inch) doorway than will flow through a 91 cm (36 inch) doorway. Table 3 shows crowd movement parameters for a typical corridor.

Crowd Condition	Density (people/m^2)	Speed (m/s)	Flow people/m·s
Minimum	<0.0046	1.27	<0.66
Moderate	0.0092	1.01	1.10
Optimum	0.0184	0.61	1.32
Crush	0.0276	<0.30	<0.99

Table 12: Crowd Movement Characteristics for a Typical Corridor

There are egress time delays associated with evacuation initiation. Notification is the first variable in the process of evacuating a building. People will not move unless they are aware that there is an emergency. The recognition of a fire event and decision to act upon ambiguous information is often retarded by the presence of others. [75] Latane and Darley performed experiments which showed a significant activity delay when test subjects had other people in the room versus test subjects alone in a room upon introduction of smoke into the test room.[76] Alarm technology, particularly where voice enunciation exists, has been shown to reduce occupant response initiation. The voice enunciation system, however, must be audible to all occupants, lest misunderstanding of instructions occur.[77] Occupants often investigate the source of a fire, either to attempt suppression or to verify actual emergency conditions. However, occupancy type has an effect upon the pre-fire activities. Occupants of an office building exhibit lower initiation times than people leaving their residences. The reasons for this are many: people evacuating homes and apartments often gather personal belongings, get dressed, gather children or other family members, whereas there are relatively few obligations to be

tended to in a work place. Finally, the simple act of making a decision can account for additional evacuation delay. Proulx reports that for an apartment building where 100% of the residents hear the alarm signal, 59% of the residents have left their apartments within the first two minutes.[47] Two minutes represents a reasonable extrapolation to office buildings for two reasons: first, the number will be conservative, as occupants of offices act sooner than occupants of apartments, for the reasons mentioned previously. Second, it is not necessary for 100% of the occupants to begin evacuation in order to use a delay time. The residents who begin in the third or fourth minute, for example, will simply be added to the end of the queue, as if they had begun evacuation at two minutes, provided that there is sufficient queuing.

Once in motion, occupants must still determine the most efficient evacuation route. This is often referred to as "way-finding." Inefficiencies exist because occupants often choose to leave by the same means they entered the building.[78] This may result in exit imbalance, where some exits are overtaxed and some exits are underutilized. Time delays also exist at merge points, where flows must stop and restart.[79] Several factors can mitigate initiation and activity delays. Occupant education is clearly a critical factor. In high-rise office evacuation studies conducted by Proulx at the National Research Council Canada, she noted that some occupants chose the familiar route, talked with friends, and were confused about the outside meeting point, while other, more informed occupants, chose the nearest exit and started evacuating immediately, directing others along the way.[80] The total inefficiency associated with less than optimal evacuation must be quantified to account for all of the above factors. MacLennan found that actual egress

times were in the range of twice the modeled egress time when an efficient system was present.[48]

Computer Modeling of People Movement

Computer modeling of egress times is an inexact science. While computers can predict how people may move under ideal conditions, there are several assumptions which must be identified in order to have confidence in the results. A major assumption of any computer model is that people will behave rationally. A computer cannot predict whether people will stay to finish what they are working on, collect personal belongings, investigate the fire, or warn other people. Nelson and MacLennan, in recognition of the tendency of egress models to underestimate egress time, proposed the following equation to adjust for inefficiencies:[48]

$$T_{ae} = T_{me}e + T_d$$

Equation 19

where:
T_{ae} is actual evacuation time
T_{me} is modeled evacuation time
e is the apparent evacuation inefficiency
T_d is the delay in initiating evacuation

Thus, computer modeling represents a significant fraction of the evacuation time, although, not a complete assessment. While several computer models exist to evaluate

egress time,[81,82,83] one model (EVACNET+) will be analyzed and held as a representative example.[84]

EVACNET+ is a node-arc network model which determines the "fire-drill" evacuation time. "Fire-drill" evacuation time is the minimum evacuation time which the occupants may egress a building. Each space in the building through which the occupants may pass must be entered as a node. The input for a node includes the number of people which start the simulation within that particular node and the capacity (or maximum number of people which may be contained within the node). The input for an arc requires a beginning node and an ending node, a dynamic capacity (DC), and the traversal time (TT).

$$DC = WR \times AFV \times SPTP \times 0.0014$$

Equation 20

where: DC is the dynamic capacity of the arc (people/time period)

WR is the minimum width encountered along the arc path (in)

AFV is the average flow volume (people/ft-min)

SPTP is the number of seconds per time period (s)

$$TT = \frac{DIST}{AS} \times \frac{60}{SPTP}$$

Equation 21

where: TT is the traversal time (s)

DIST is the distance between the beginning of end of the arc (ft)

AS is the average speed (ft/min)

There are several assumptions and limitations of EVACNET+.

8. The program is a linear modeling system. Arc capacities and arc traversal times do not change over time and do not depend on the arc flows.

9. Smoke and fire have no effect upon the evacuation time.

10. The program does not consider behavioral aspects of occupants. Behavioral aspects include evacuation initiation delays, impaired evacuation of handicapped population, and fatigue associated with long travel distances.

11. The program views all occupants, not an individual occupant.

12. Initial location of all individuals must be assumed.

13. Traversal times are rounded off to the nearest whole number. The calculated egress time, therefore, is very sensitive to the chosen time step (seconds per time period).

14. The total evacuation time will be the lower bound of egress times.[53]

Thus, accounting for the limitations and assumptions of EVACNET+, the modeled evacuation time can be determined. Using Equation 2, a reasonable and conservative total evacuation time can be derived which should ensure safe building design.

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[74] Pauls, Jake. "Movement of People." in *The SFPE Handbook of Fire Protection Engineering*, *2nd Edition*. DiNenno, et al., Ed. National Fire Protection Association, Quincy, MA, 1995, pp. 3-263 – 3-285.
[75] Bryan, John L. "Behavioral Response to Fire and Smoke" in *The SFPE Handbook of Fire Protection Engineering*, *2nd Edition*. DiNenno, et al., Ed. National Fire Protection Association, Quincy, MA, 1995, pp. 3-241 – 3-242.

[76] Latane, B. and J. M. Darley. *Journal of Person. and Soc. Psych.* Volume 10, 1968, page 215.

[77] Proulx, Guelene. "The Time Delay to Start Evacuating Upon Hearing a Fire Alarm." 38th Annual Meeting of the Human Factors and Ergonomics Society, Nashiville, TN, October 24 – 28, 1994.

[78] Proulx, Guylene. "Evacuation Time and Movement in Apartment Buildings." *Fire Safety Journal*, Volume 24, 1995, pp. 229 – 246.

[79] Nelson, Harold E. and Hamish A. MacLennan. "Emergency Movement." in *The SFPE Handbook of Fire Protection Engineering*, *2nd Edition*. DiNenno, et al., Ed. National Fire Protection Association, Quincy, MA, 1995, pp. 3-286 – 3-295.

[80] Proulx, Guylene. Abstract for "Comparison of Occupant Behaviour During Office and Apartment Evacuations." National Fire Protection Association Fall Meeting, Nashville, TN, 1996.

[81] Cooper, Leonard Y. "Estimating Safe Available Egress Time From Fires. Final Report." NBSIR 80-2172; February 1981.

[82] Stahl, F. I. "BFIRES-II: A Behavior Based Computer Simulation of Emergency Egress During Fires." Fire Technology, Vol. 18, No. 1, February 1982, pp. 49 – 65.

[83] Levin, B. M. "EXITT--A Simulation Model of Occupant Decisions and Actions in Residential Fires: Users Guide and Program Description." NBSIR 87-3591; July 1987.

[84] Kisko, Thomas M. and Richard L. Francis. "EVACNET+: A Computer Program to Determine Optimal Building Evacuation Plans." *Fire Safety Journal,* Volume 9, No. 2, 1985, pp. 211 – 220.

APPENDIX C: CFAST OUTPUT GRAPHS

Upper Layer Temperature for Office of Origin
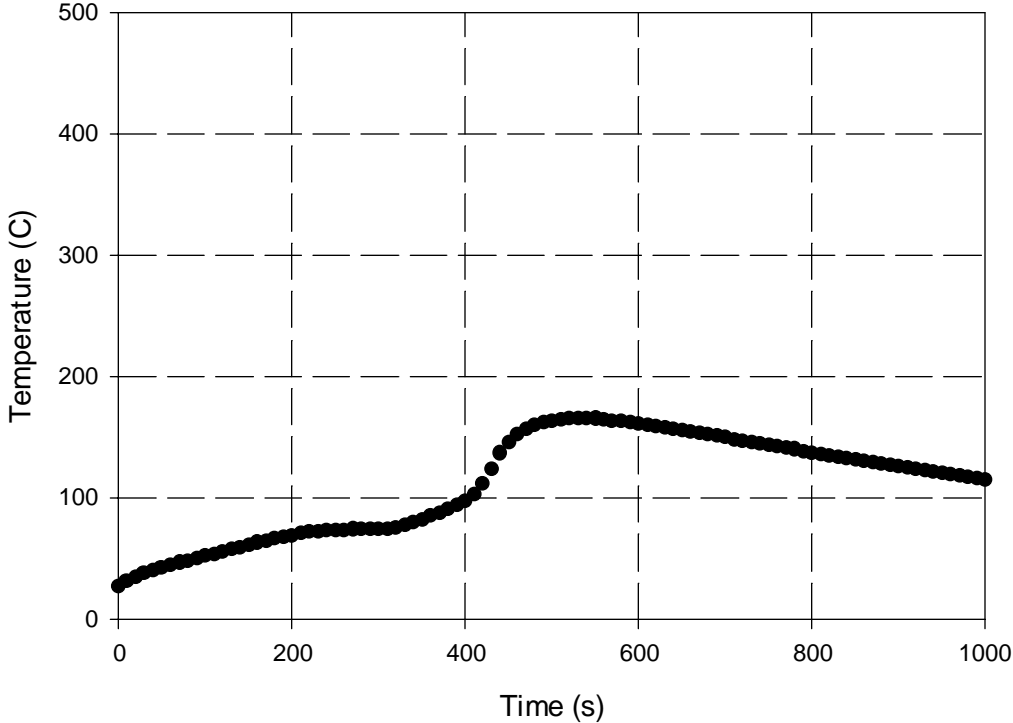
Figure 1: Upper Layer Temperature in Office of Origin for Cubicle Fire Scenario

Upper Layer Temperature in Hallway Outside Room of Origin
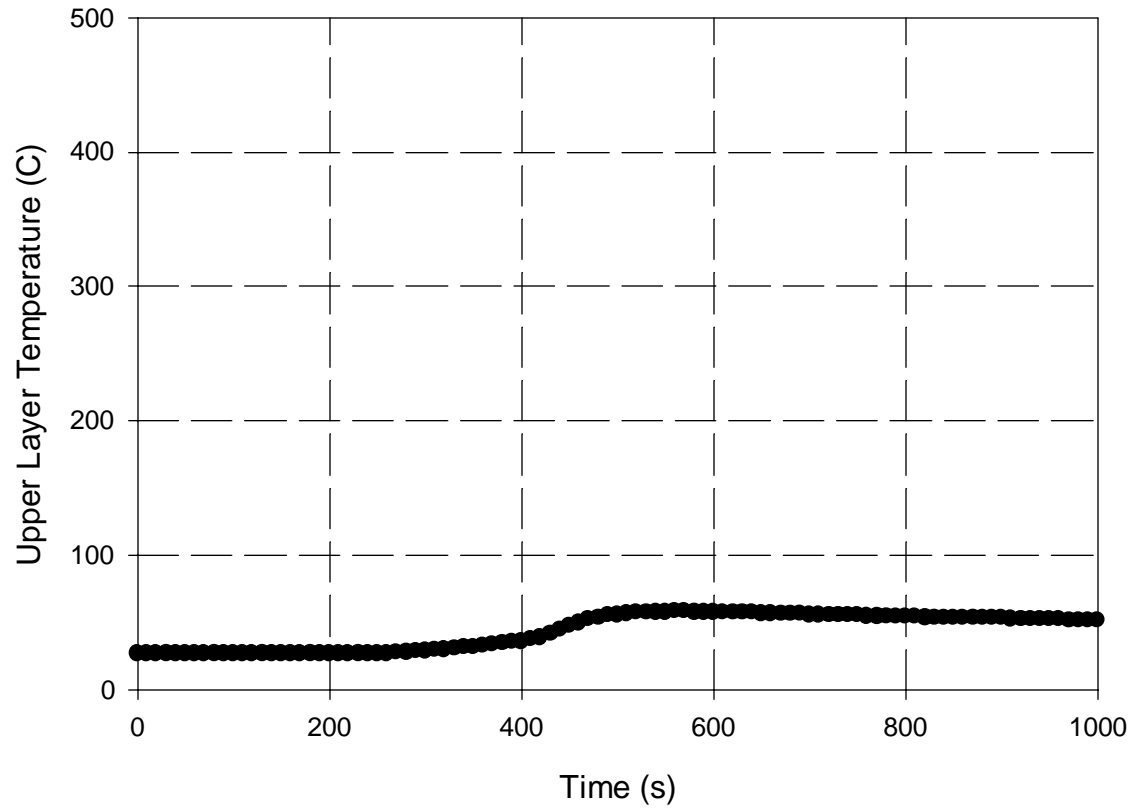
Figure 2: Upper Layer Temperature in Hallway for Cubicle Fire Scenario

Layer Height for Office of Origin
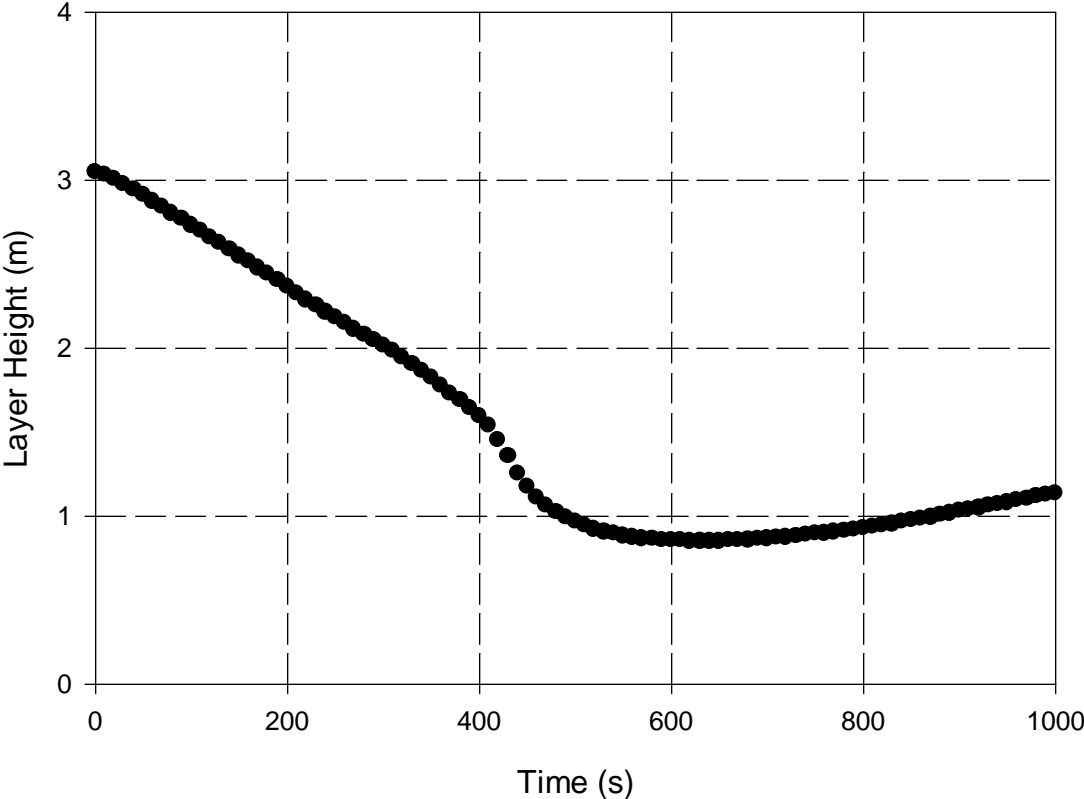
Figure 3: Layer Height in Office of Origin for Cubicle Fire Scenario

Layer Height in Hallway Outside Room of Origin
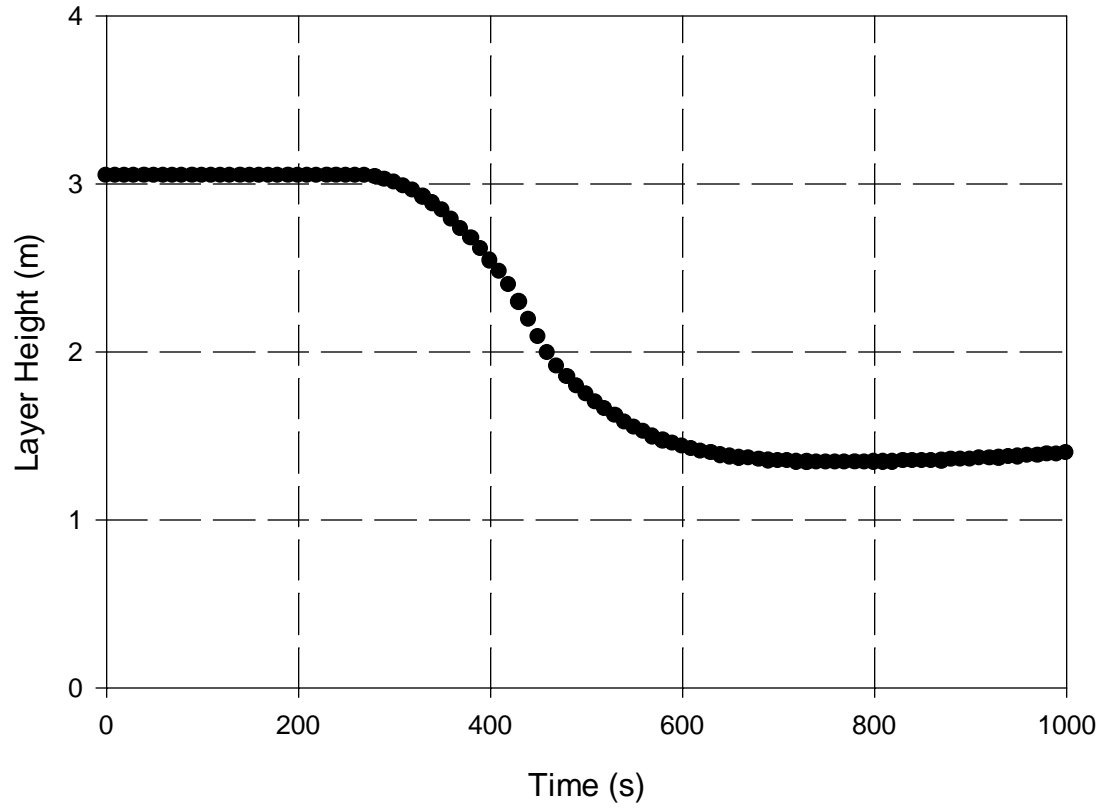
Figure 4: Layer Height in Hallway for Four Tenant Cubicle Fire Scenario

Copier Fire Layer Height Room of Origin
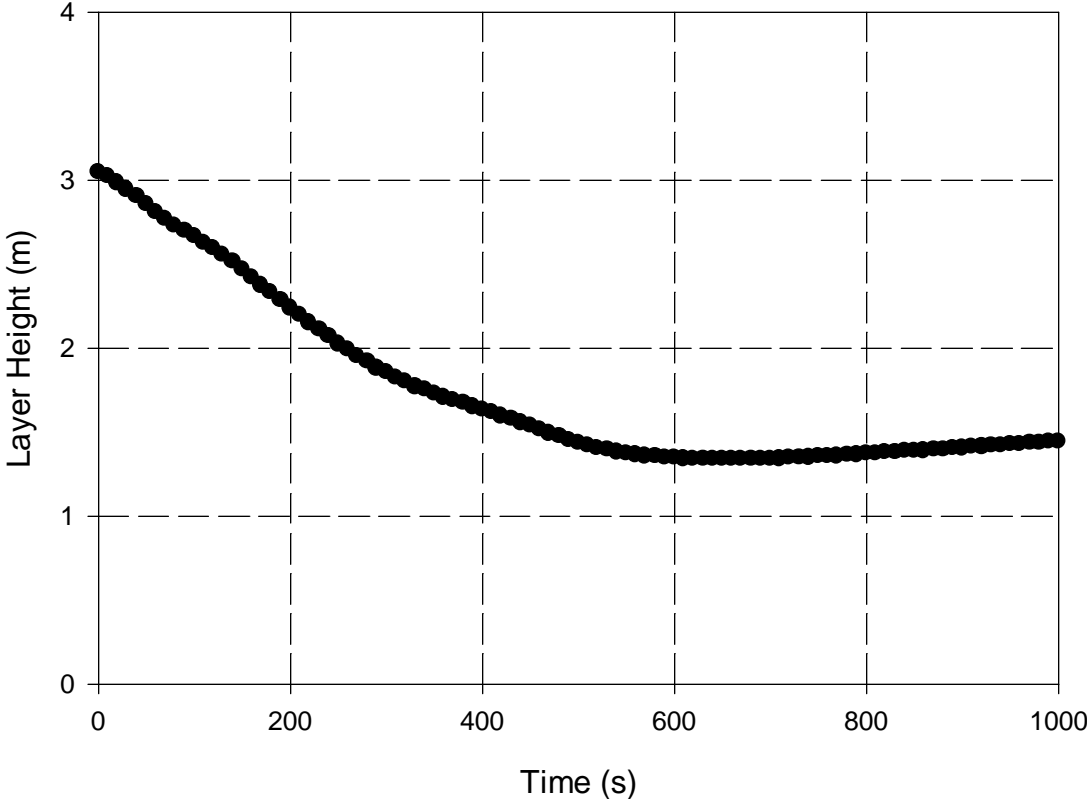
Figure 5: Layer Height for Room of Origin for Four Tenant Copier Fire Scenario
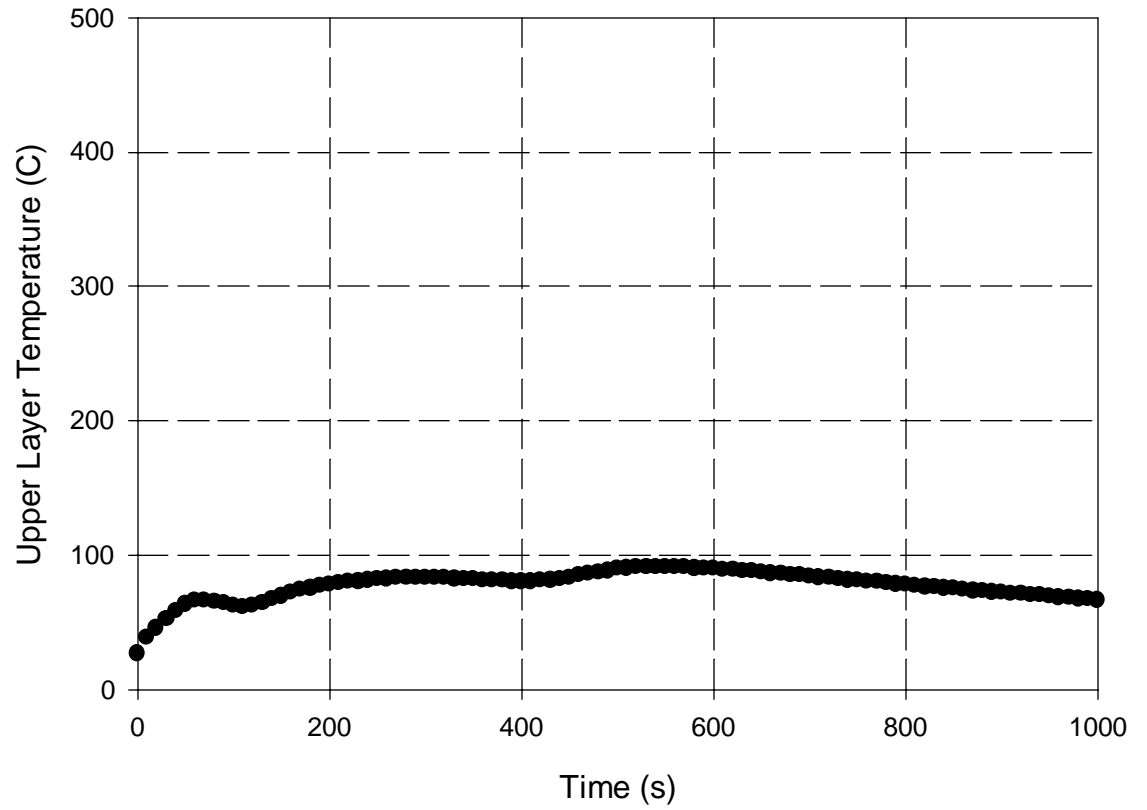
Figure 6: Upper Layer Temperature for Four Tenant Copier Fire Scenario

Copier Fire Upper Layer Temperature in Hallway
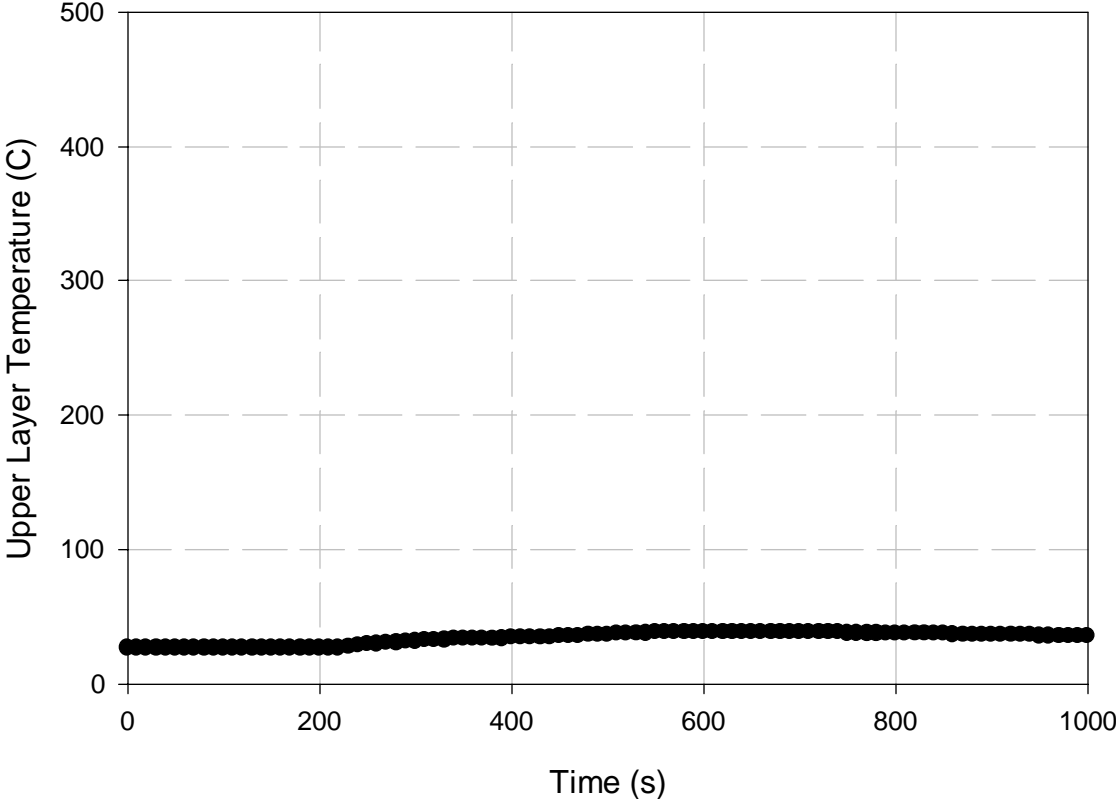
Figure 7: Upper Layer Temperature in Hallway for Four Tenant Copier Fire Scenario

Copier Fire Layer Height in Hallway
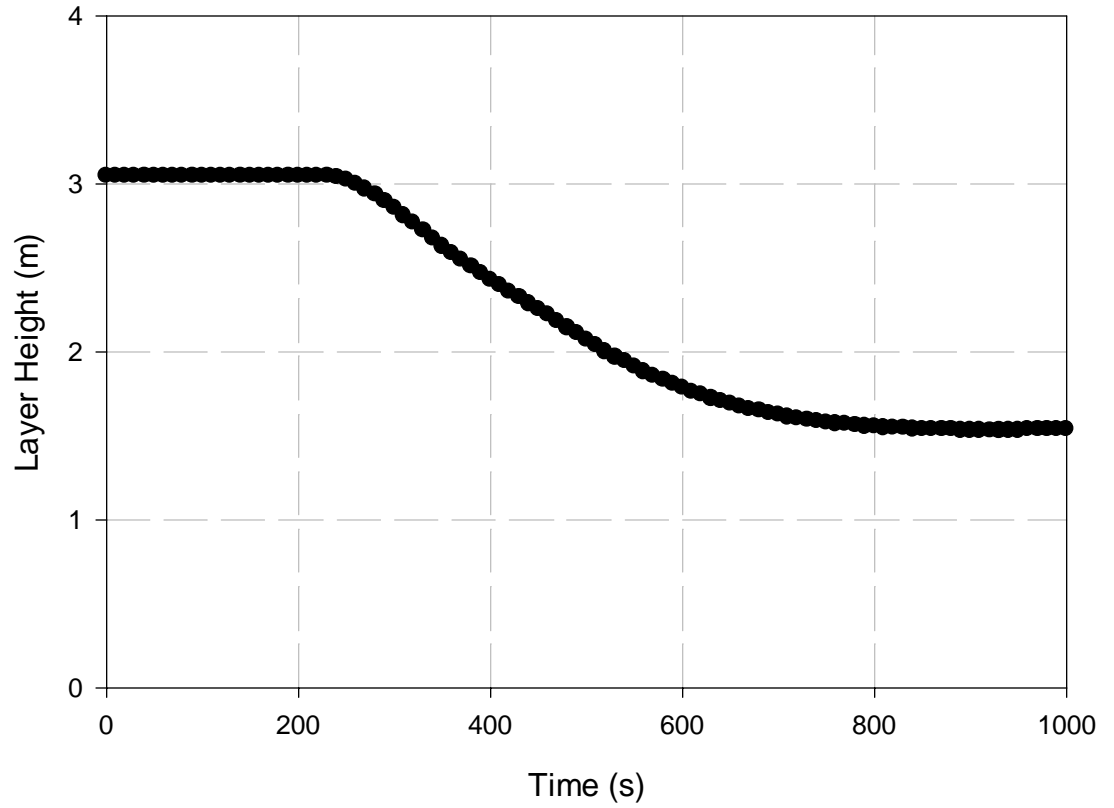
Figure 8: Layer Height in Hallway for Four Tenant Copier Fire Scenario

Shielded Fire Upper Layer Temperature Room of Origin
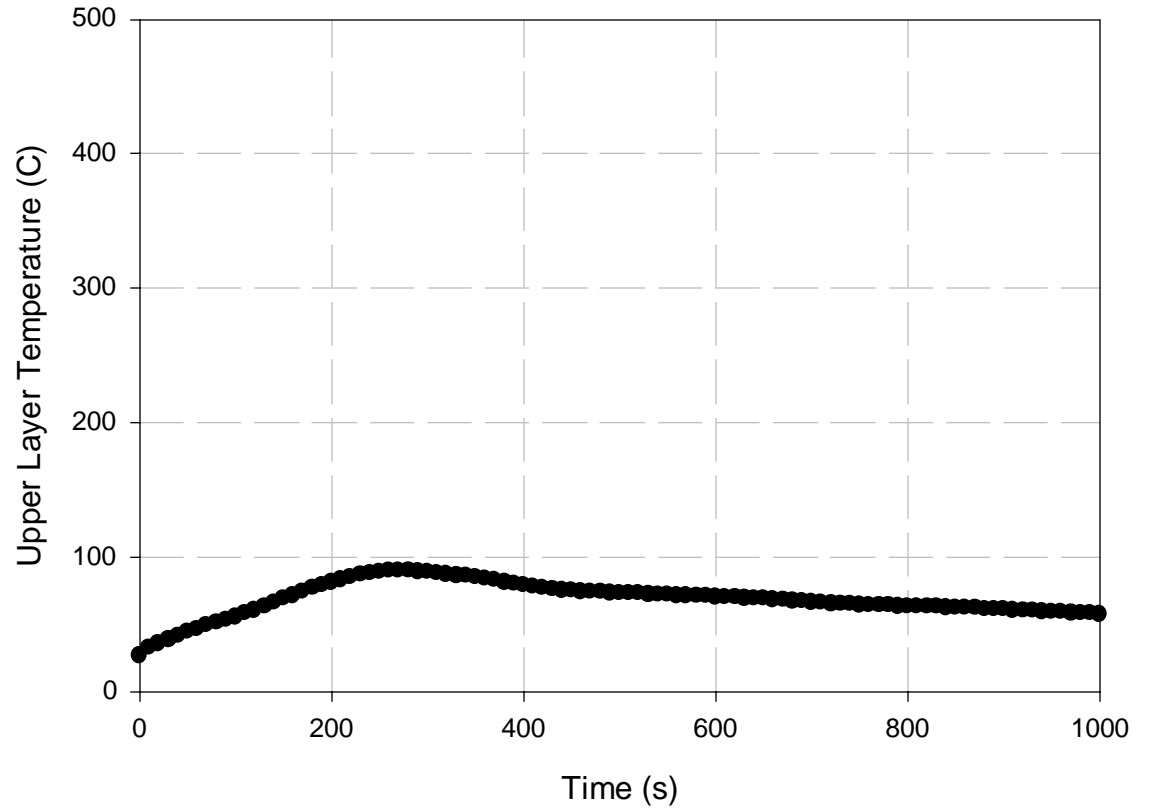
Figure 9: Upper Layer Temperature for Room of Origin for Four Tenant Shielded Fire Scenario

Shielded Fire Layer Height Room of Origin
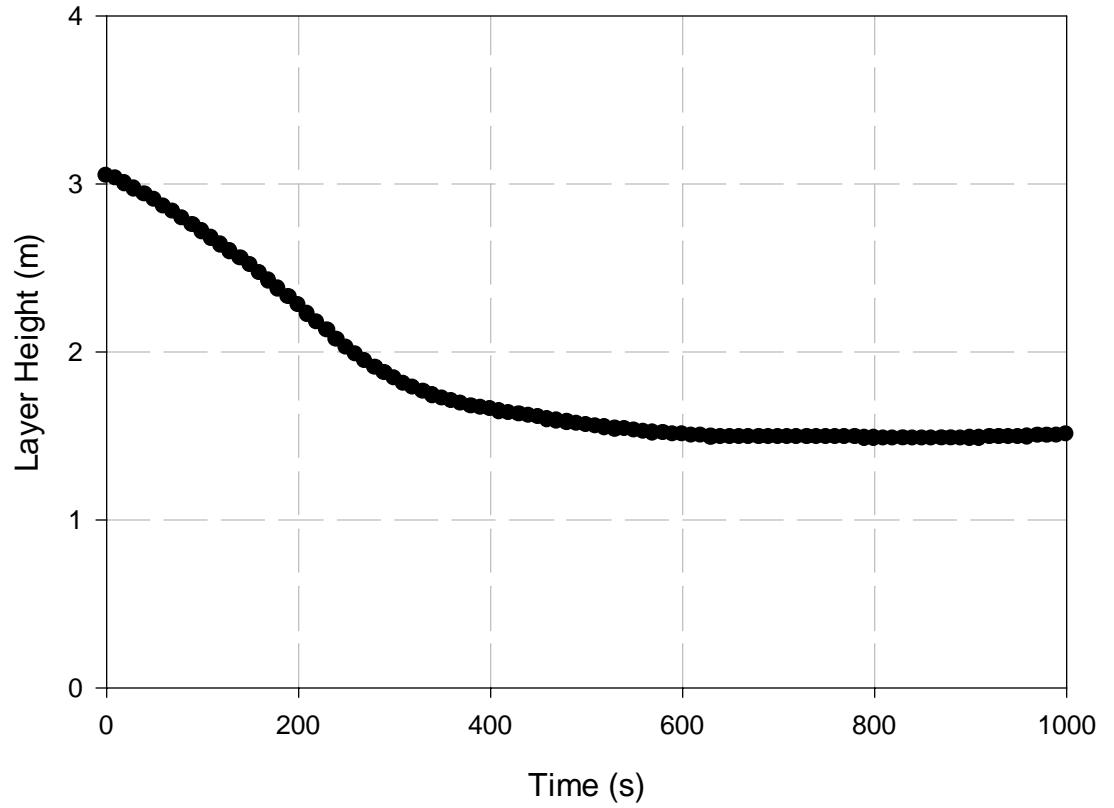
Figure 10: Layer Height in Room of Origin for Four Tenant Shielded Fire Scenario

Shielded Fire Upper Layer Temperature Hallway
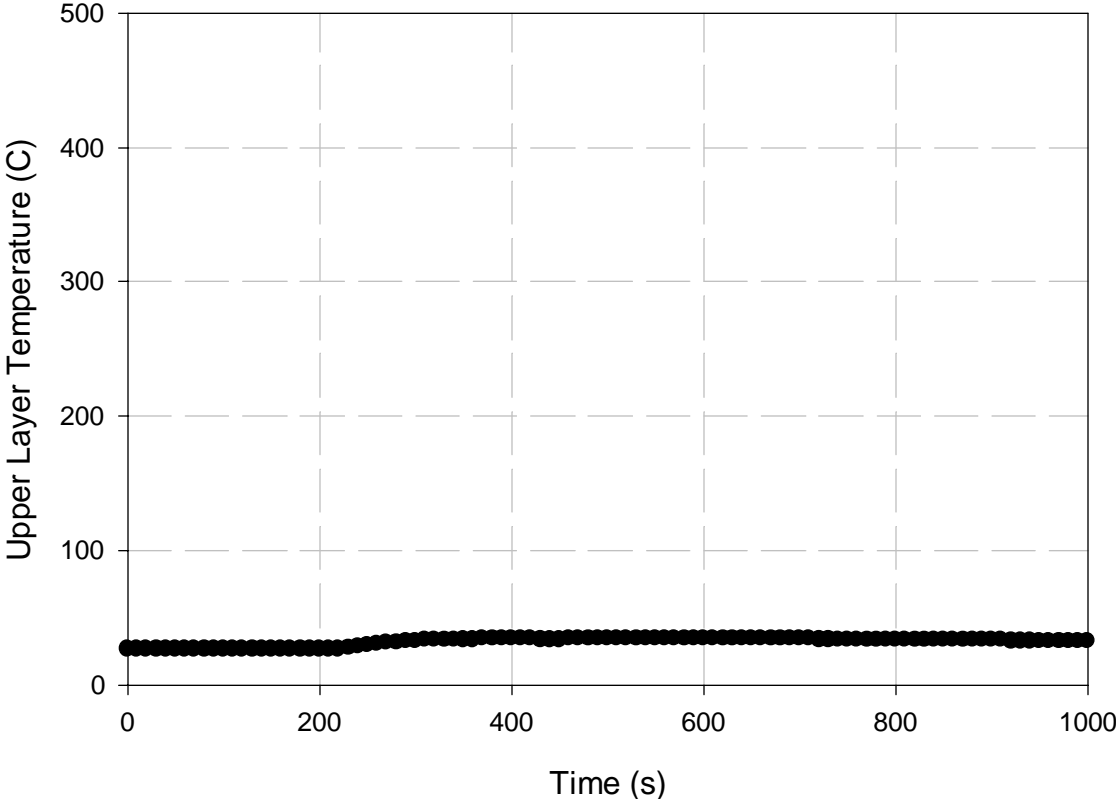
Figure 11: Upper Layer Temperature in Hallway for Four Tenant Shielded Fire Scenario

Shielded Fire Layer Height in the Hallway
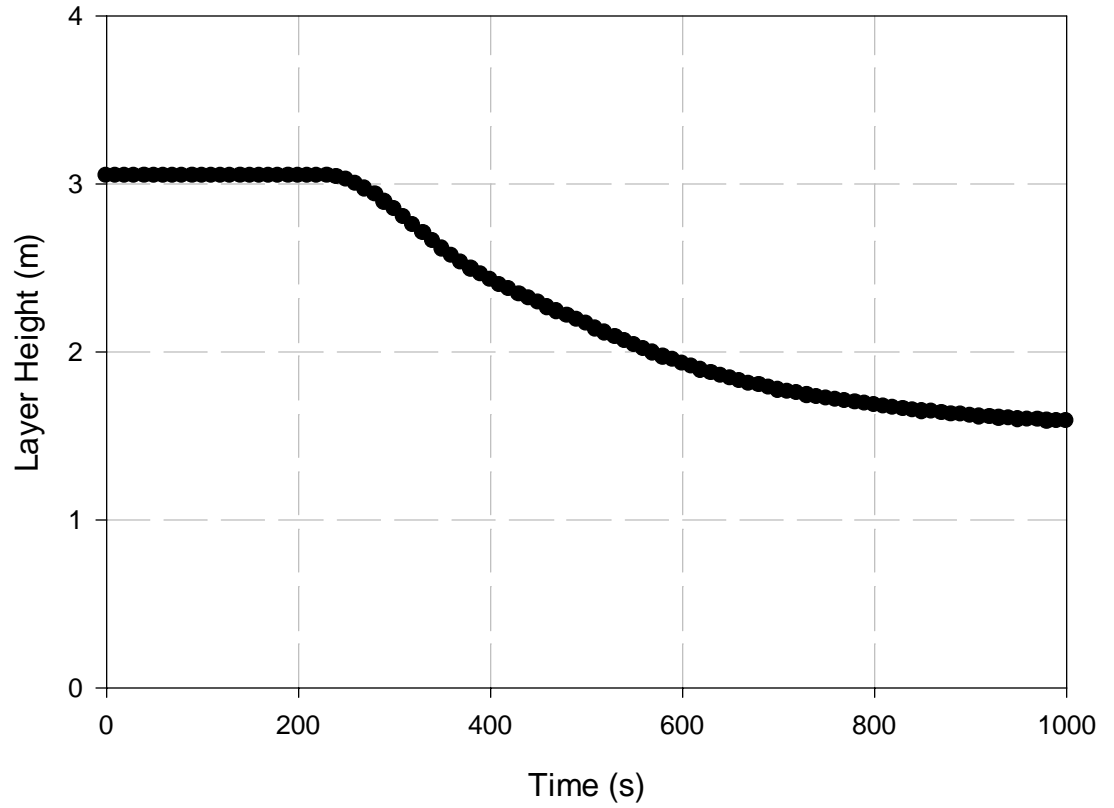
Figure 12: Layer Height in Hallway for Four Tenant Shielded Fire Scenario

Upper Layer Temperature for Shielded Fire in One Occupant Floor Plan
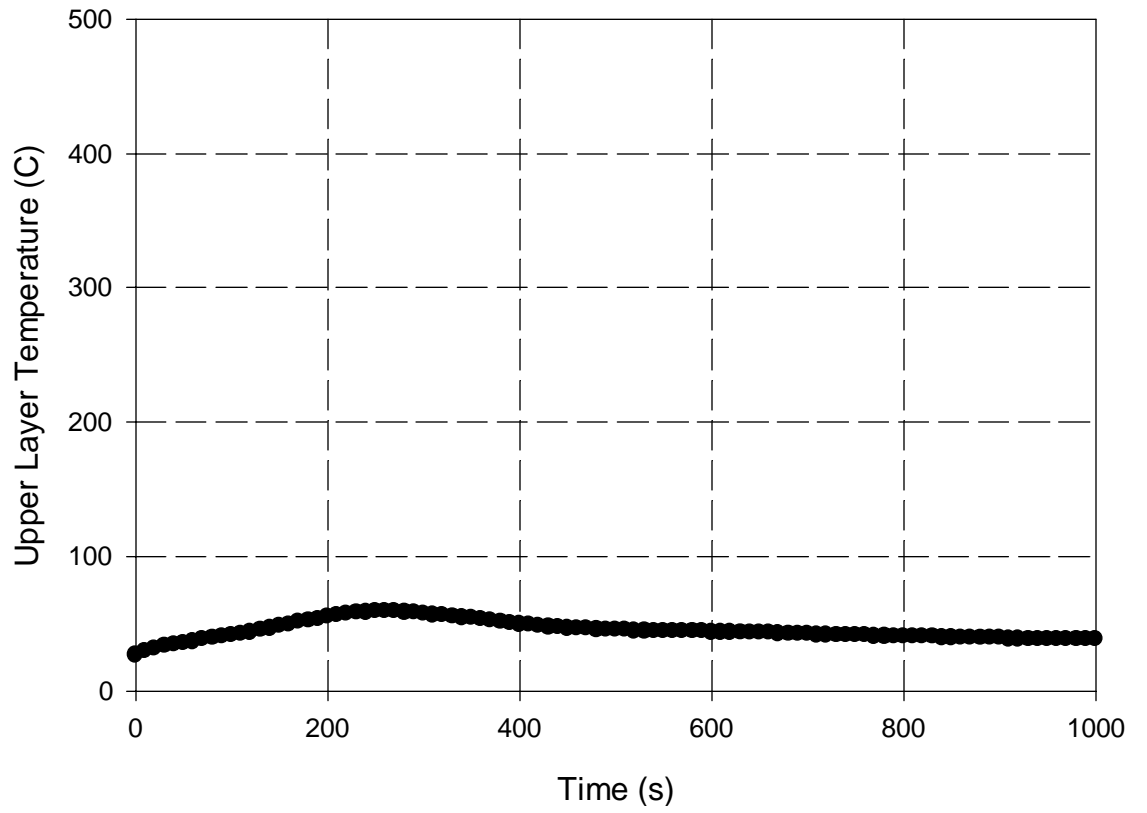
Figure 13: Upper Layer Temperature for One Tenant Shielded Fire Scenario

Shielded Fire Layer Height Room of Origin
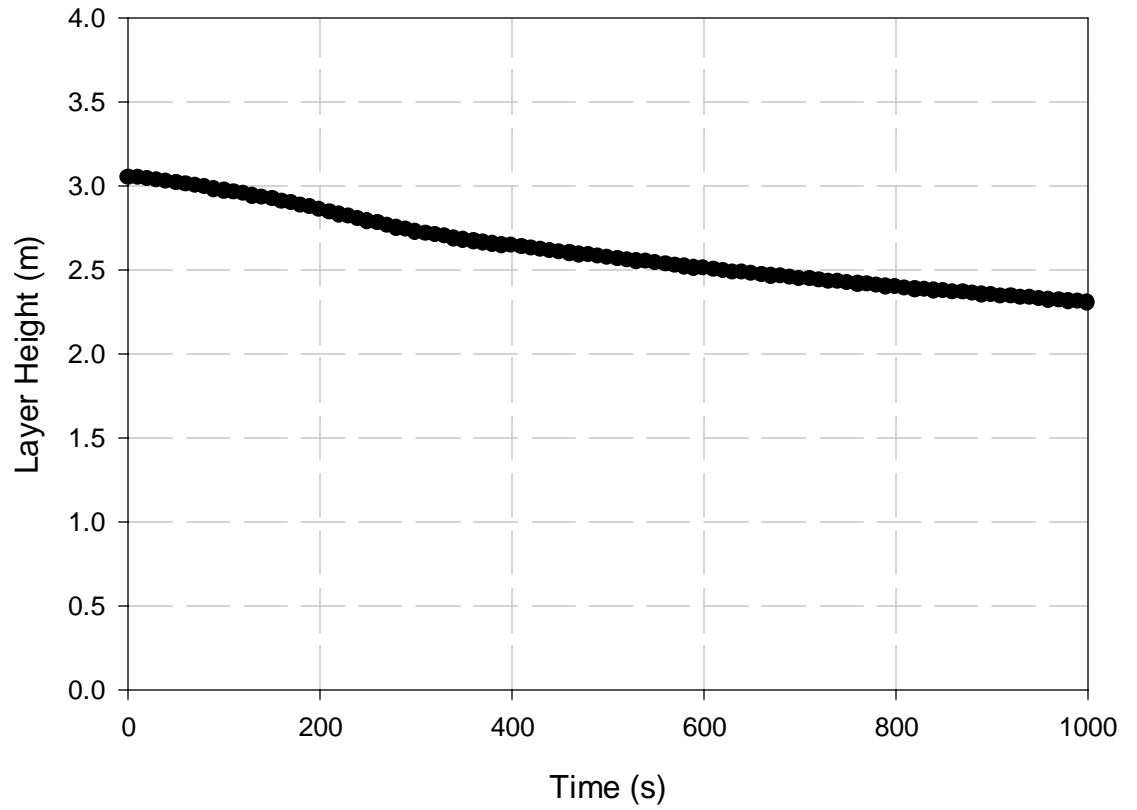
Figure 14: Layer Height for One Tenant Shielded Fire Scenario

Cubicle Fire Upper Layer Temperature One Tenant
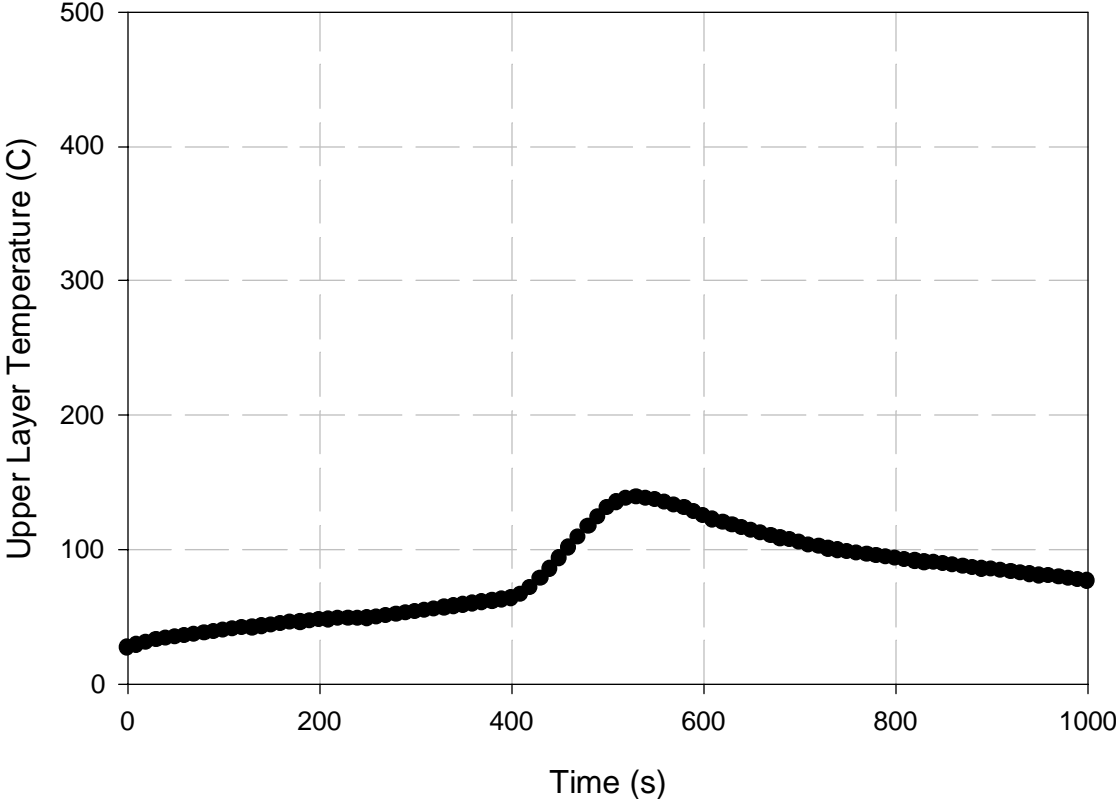
Figure 15: Upper Layer Temperature for One Tenant Cubicle Fire Scenario

Cubical Fire Layer Height One Tenant
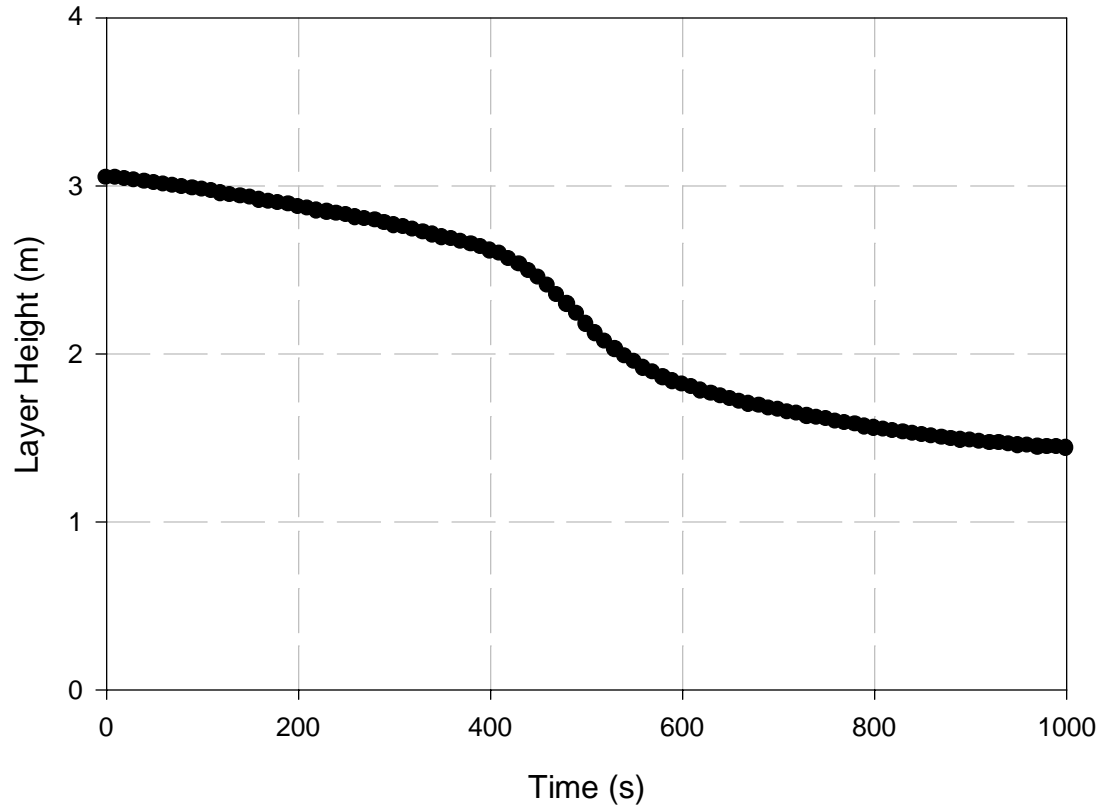
Figure 16: Layer Height for One Tenant Cubical Fire Scenario

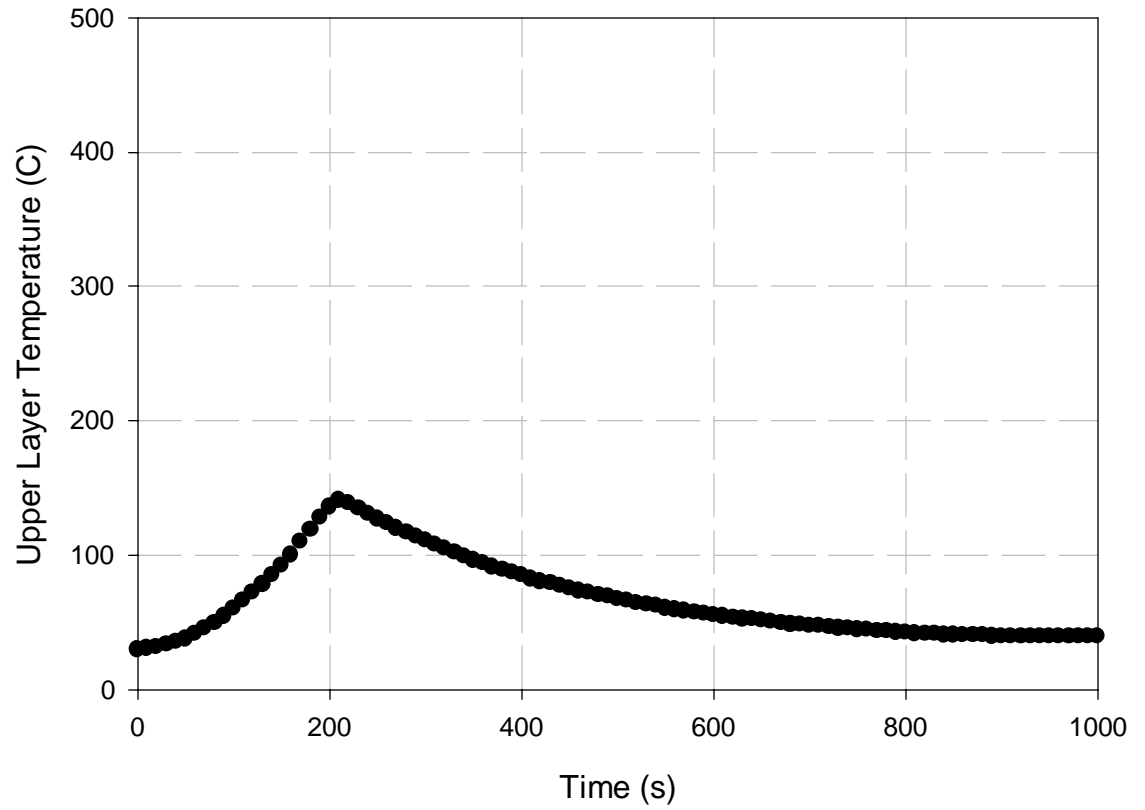## Atrium Upper Layer Temperature for Compartment 1
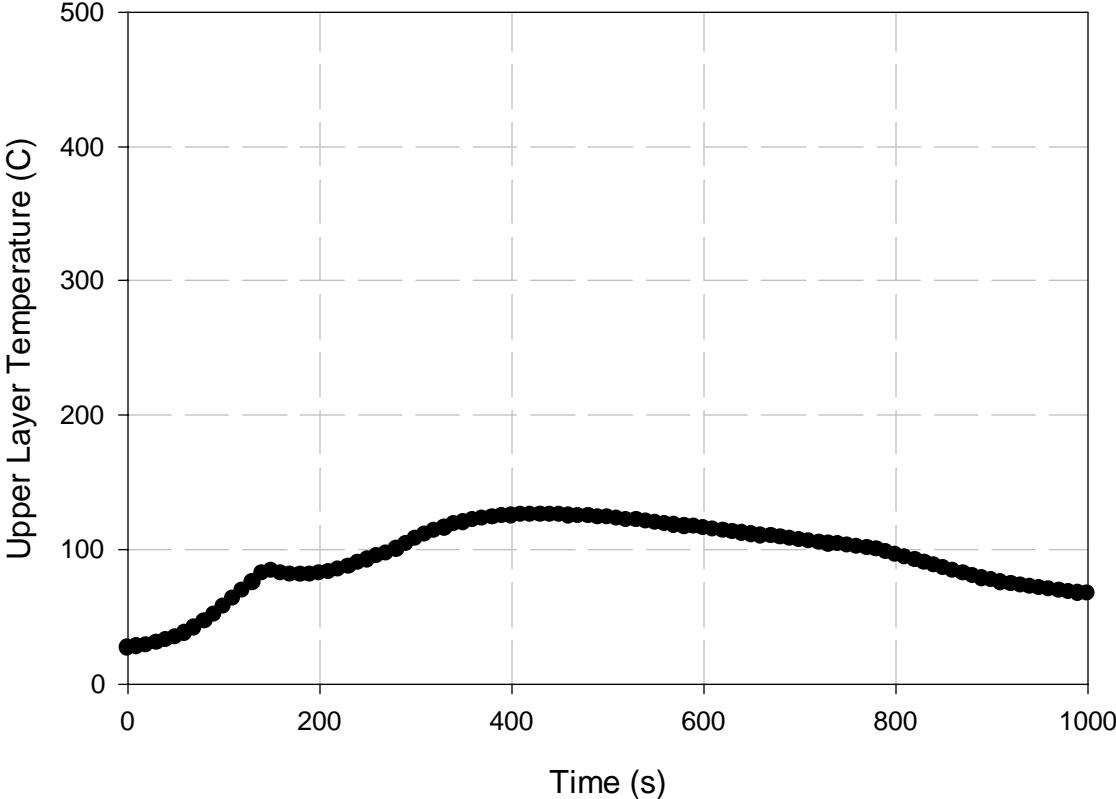
Figure 17: Upper Layer Temperature in Room of Origin for Atrium Fire with Commercial Sprinklers and No Smoke Venting Scenario

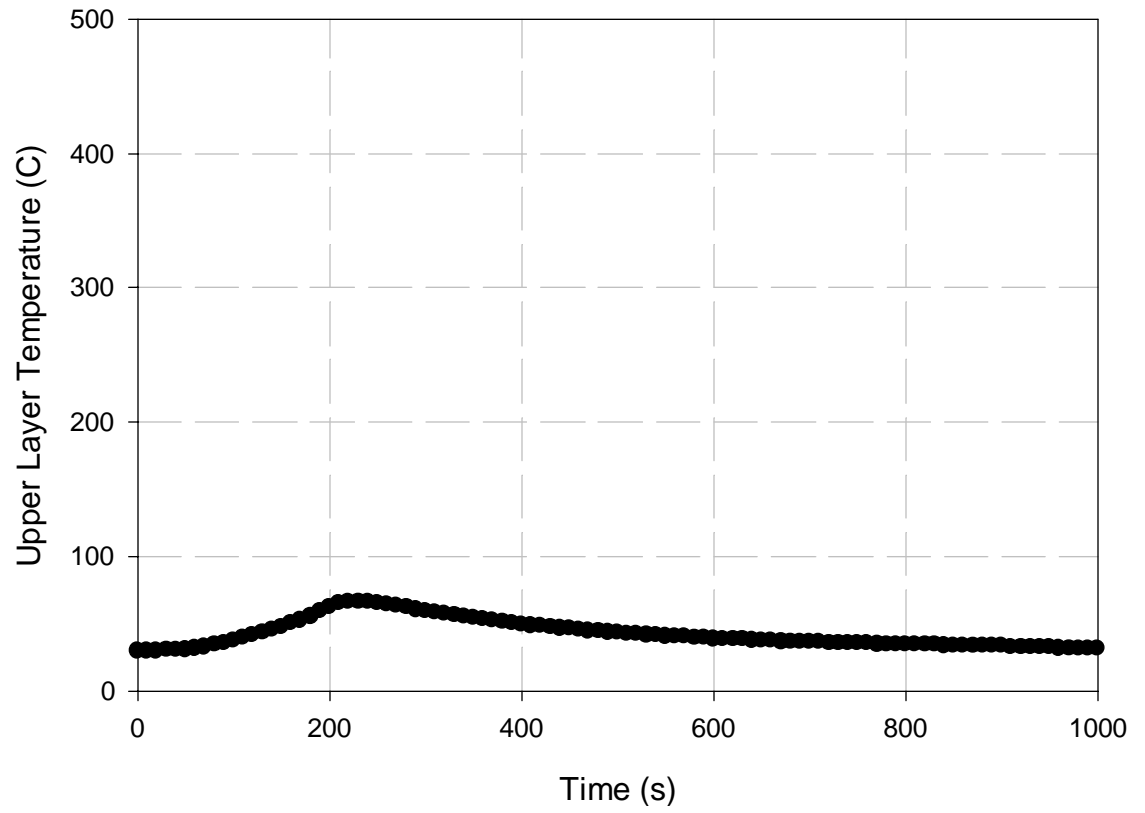## Atrium Upper Layer Temperature Compartment 2
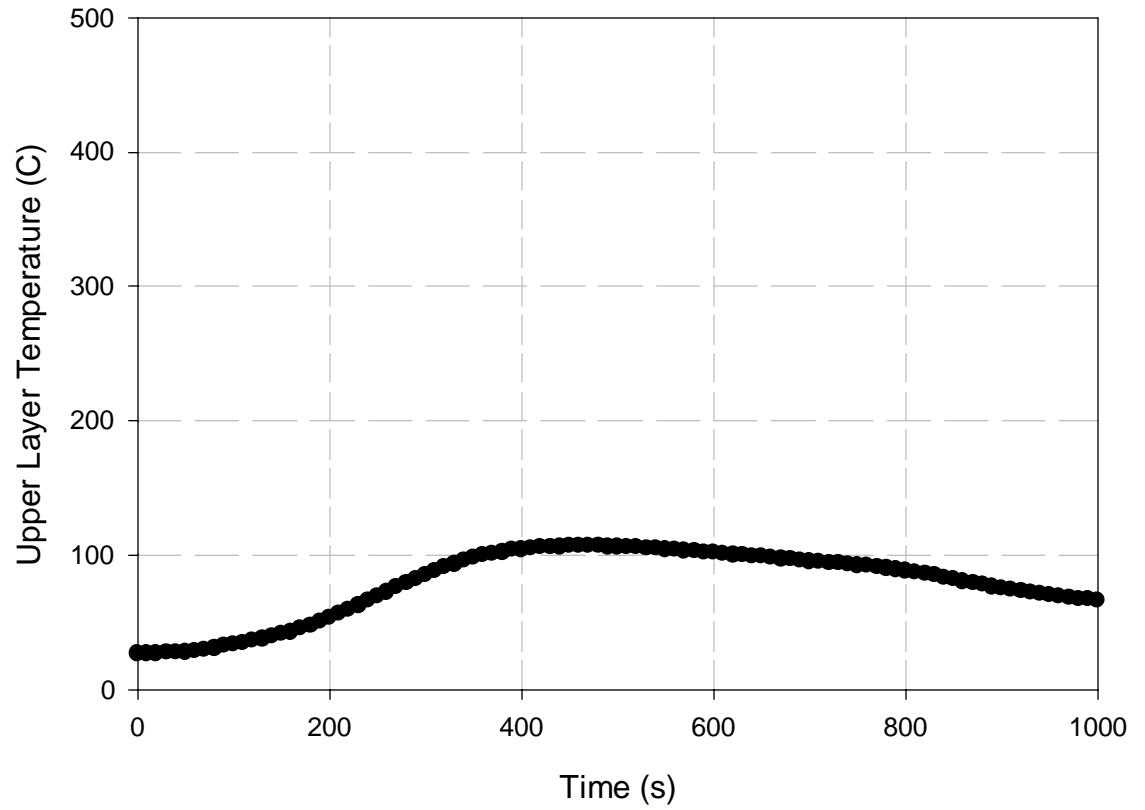
Figure 18: Upper Layer Temperature in Two Story Space for Atrium Fire with Commercial Sprinklers and No Smoke Venting Scenario
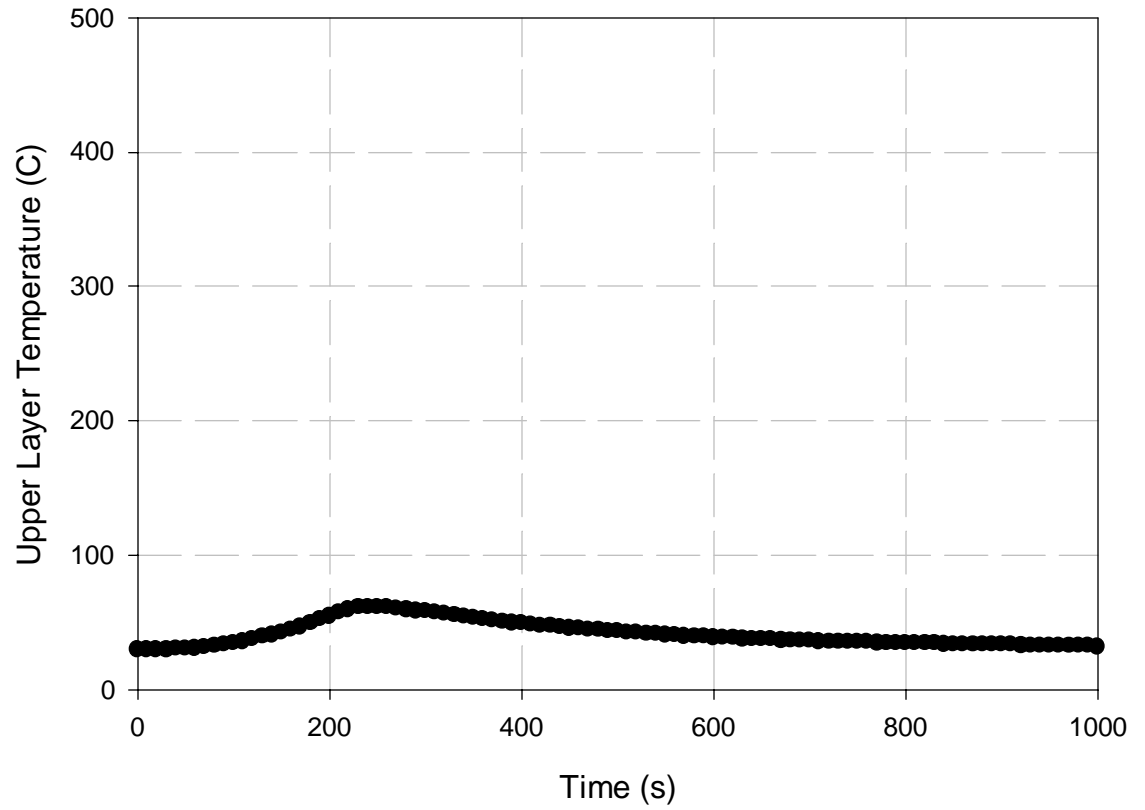
Atrium Fire Upper Layer Temperature Compartment 3
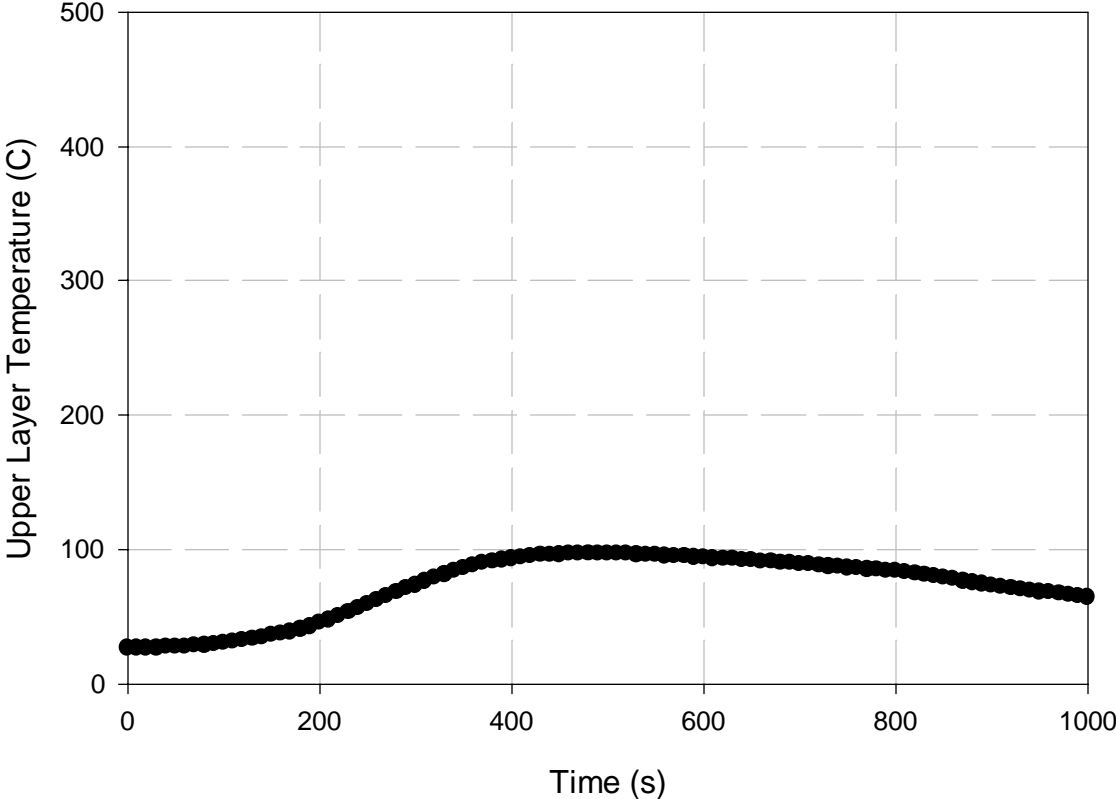
Figure 19: Upper Layer Temperature in Upper Level Space for Atrium Fire with Commercial Sprinklers and No Smoke Venting Scenario

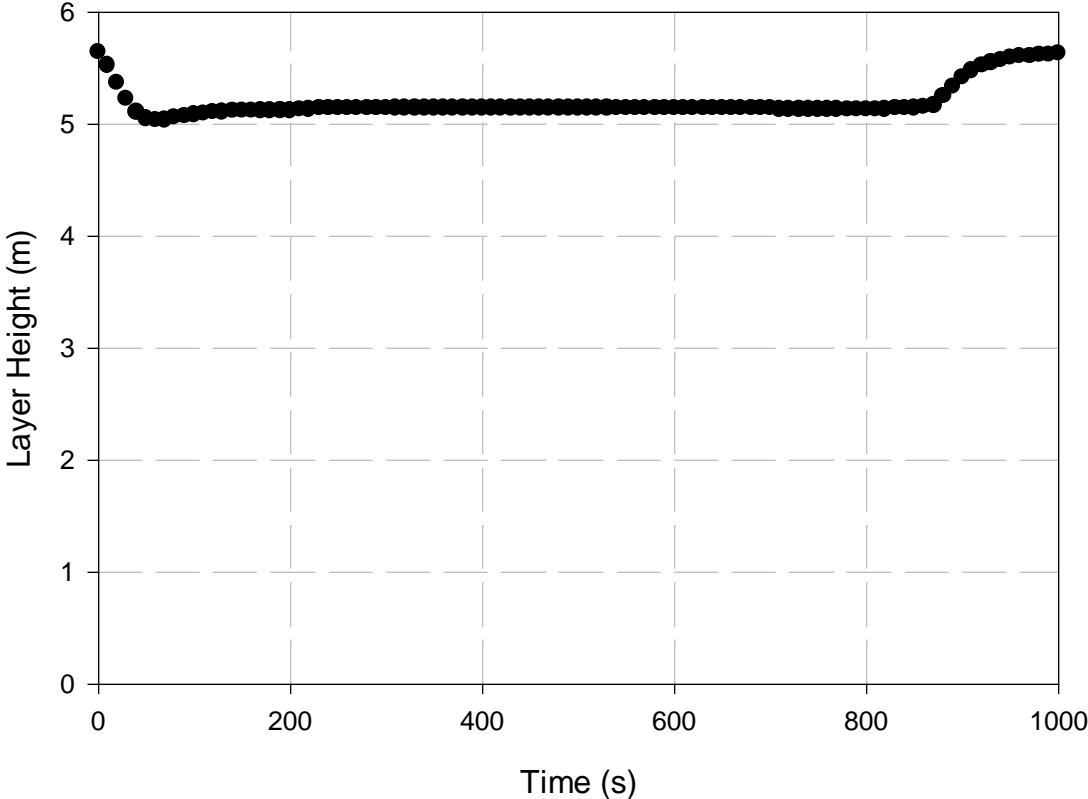## Atrium Fire Layer Height Compartment 1
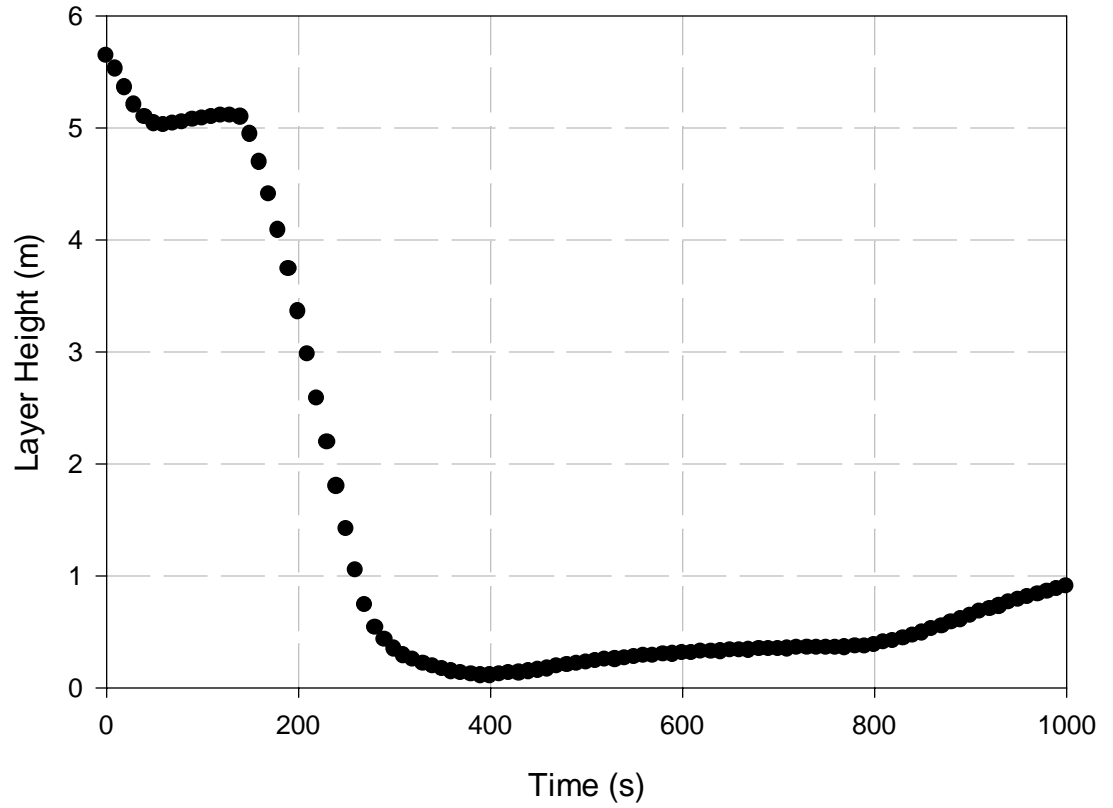
Figure 20: Layer Height in Room of Origin for Atrium Fire with Commercial Sprinklers and No Smoke Venting Scenario

Atrium Fire Layer Height Compartment 2
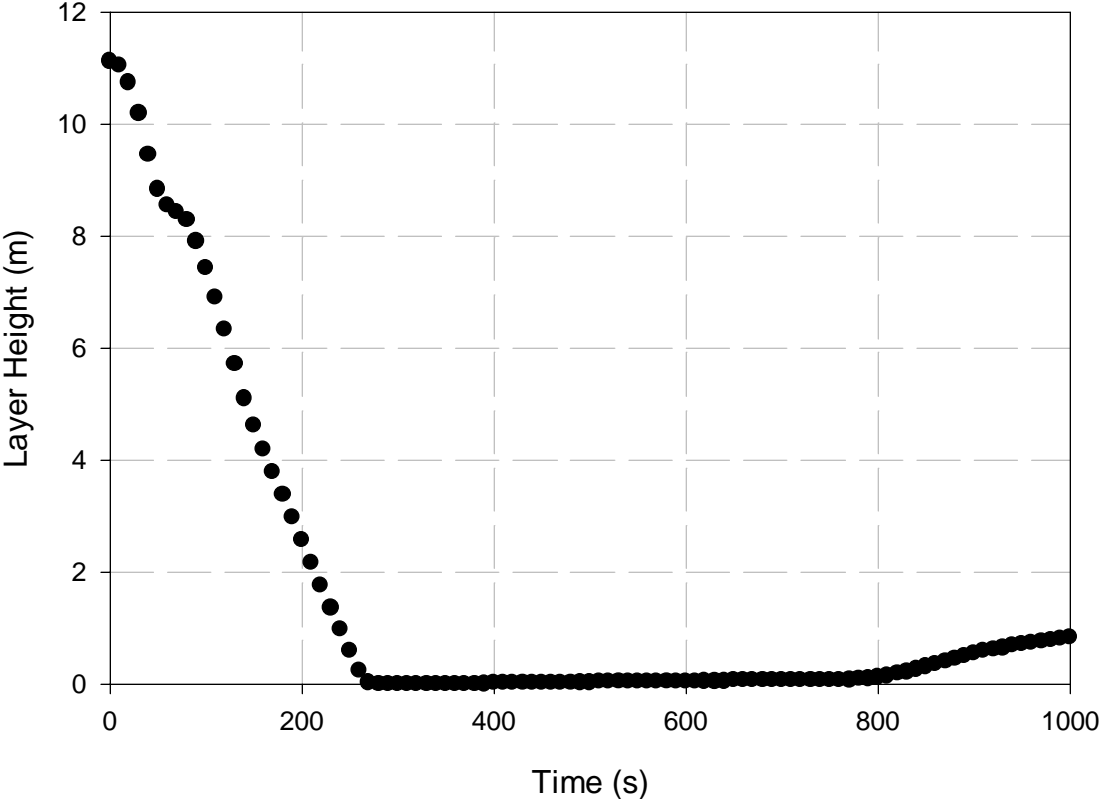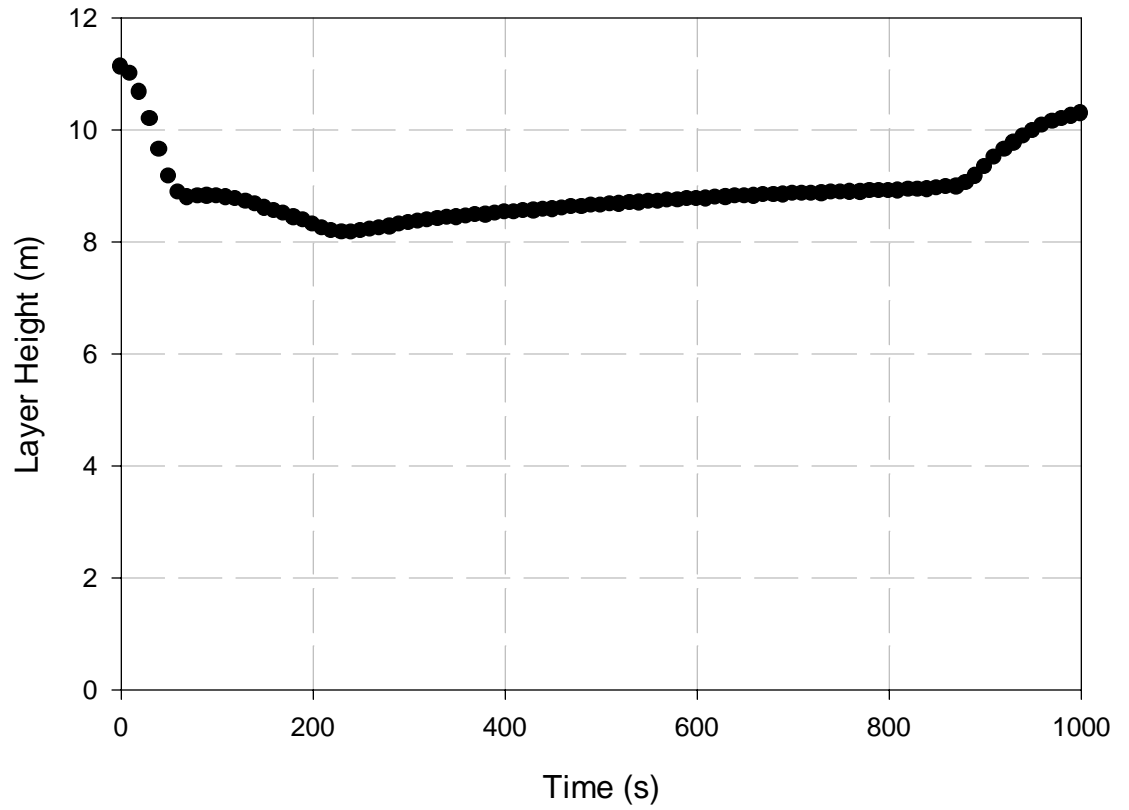

Figure 21: Layer Height in Two Story Space for Atrium Fire with Commercial Sprinklers and No Smoke Venting Scenario

Atrium Fire Layer Height Compartment 3
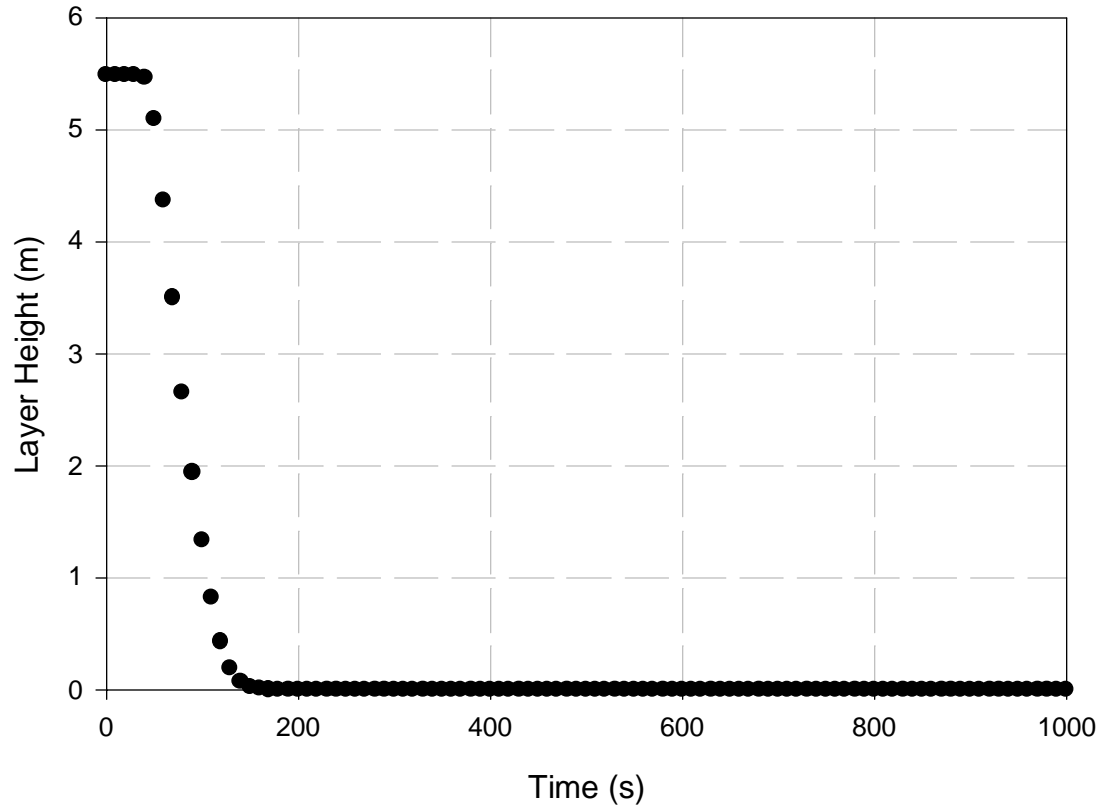
Figure 22: Layer Height in Upper Level Room for Atrium Fire with Commercial Sprinklers and No Smoke Venting Scenario

Atrium Fire Sizes
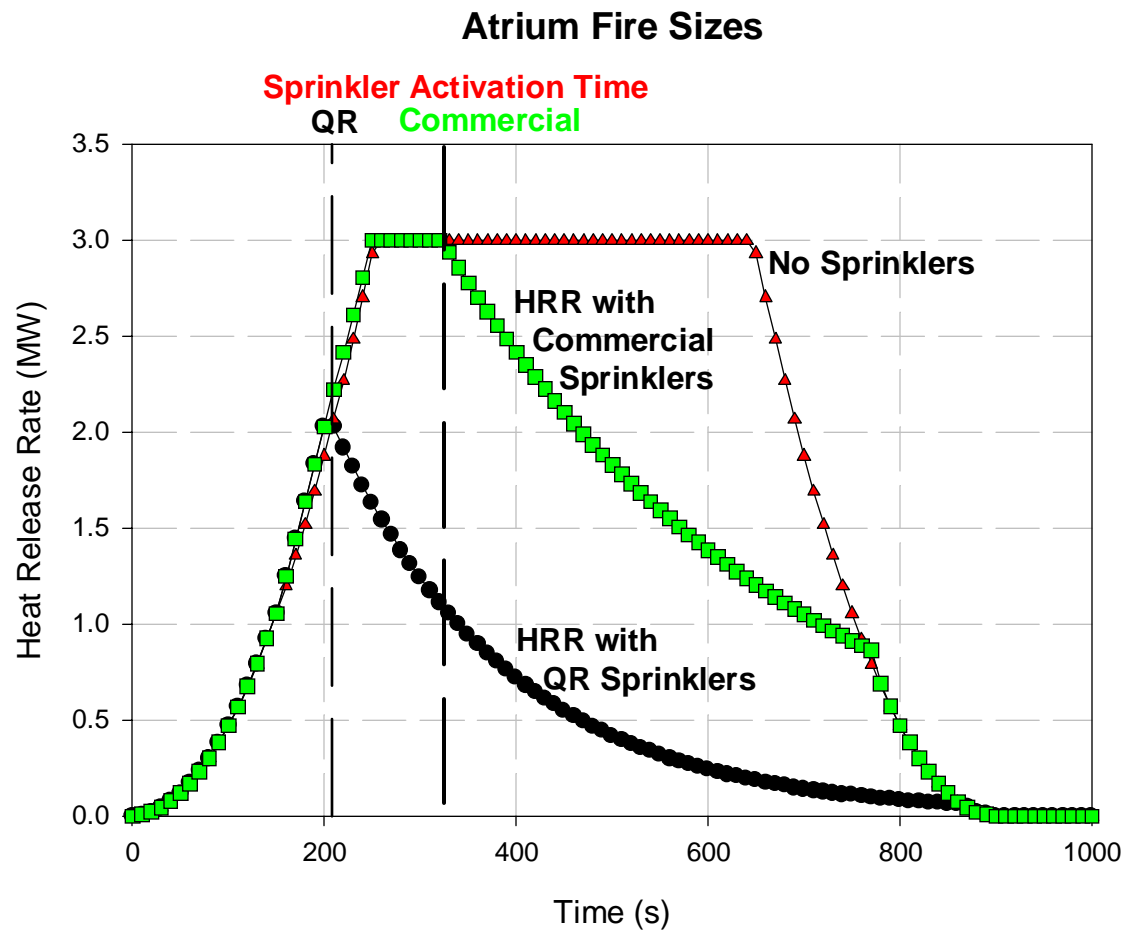
Figure 23: Heat Release Rate Graph Showing the Impact of Different Sprinklers

Atrium Fire Upper Layer Temperature Compartment 1

Figure 24: Upper Layer Temperature in Room of Origin for Atrium Fire with QR Sprinklers and Smoke Venting Scenario

Atrium Fire Upper Layer Temperature Compartment 2

Figure 25: Upper Layer Temperature in Two Story Space for Atrium Fire with QR Sprinklers and Smoke Venting Scenario

Atrium Fire Upper Layer Temperature Compartment 3

Figure 26: Upper Layer Temperature in Remote Room for Atrium Fire with QR Sprinklers and Smoke Venting Scenario

Atrium Fire Layer Height Compartment 1

Figure 27: Layer Height in Room of Origin for Atrium Fire with QR Sprinklers and Smoke Venting Scenario
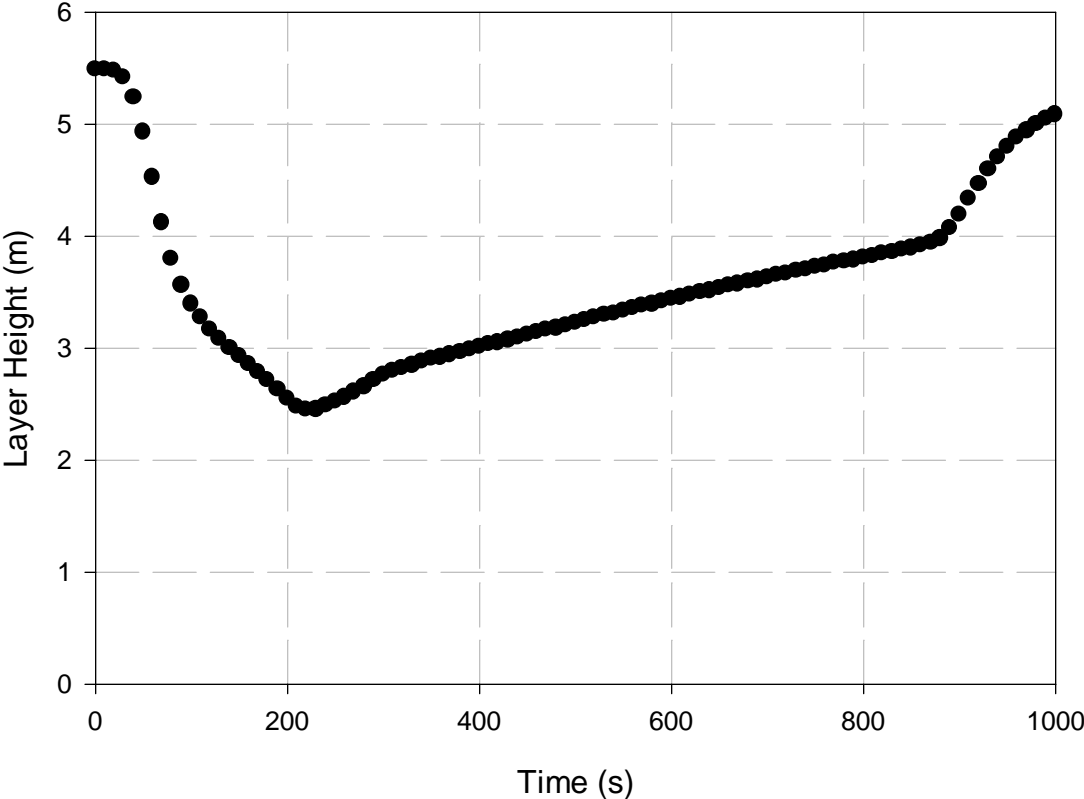
Atrium Fire Layer Height Compartment 2

Figure 28: Layer Height in Two Story Space for Atrium Fire with QR Sprinklers and Smoke Venting Scenario

Atrium Fire Layer Height Compartment 3

Figure 29: Layer Height in Remote Room for Atrium Fire with QR Sprinklers and Smoke Venting Scenario

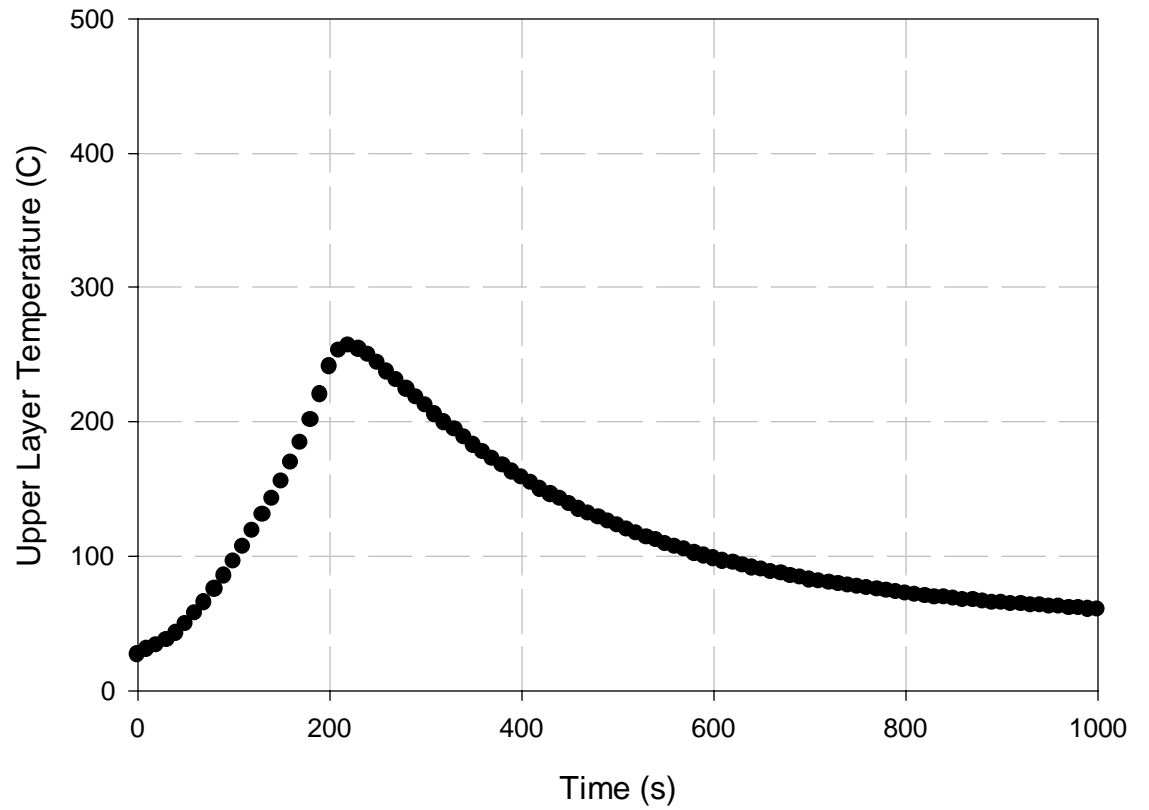Upper Layer Temperature in Room of Origin for Mercantile Fire

Figure 30: Upper Layer Temperature in Room of Origin for Mercantile Fire with Commercial Sprinklers and No Smoke Venting Scenario

Upper Layer Temperature in Remote Room for Mercantile Fire
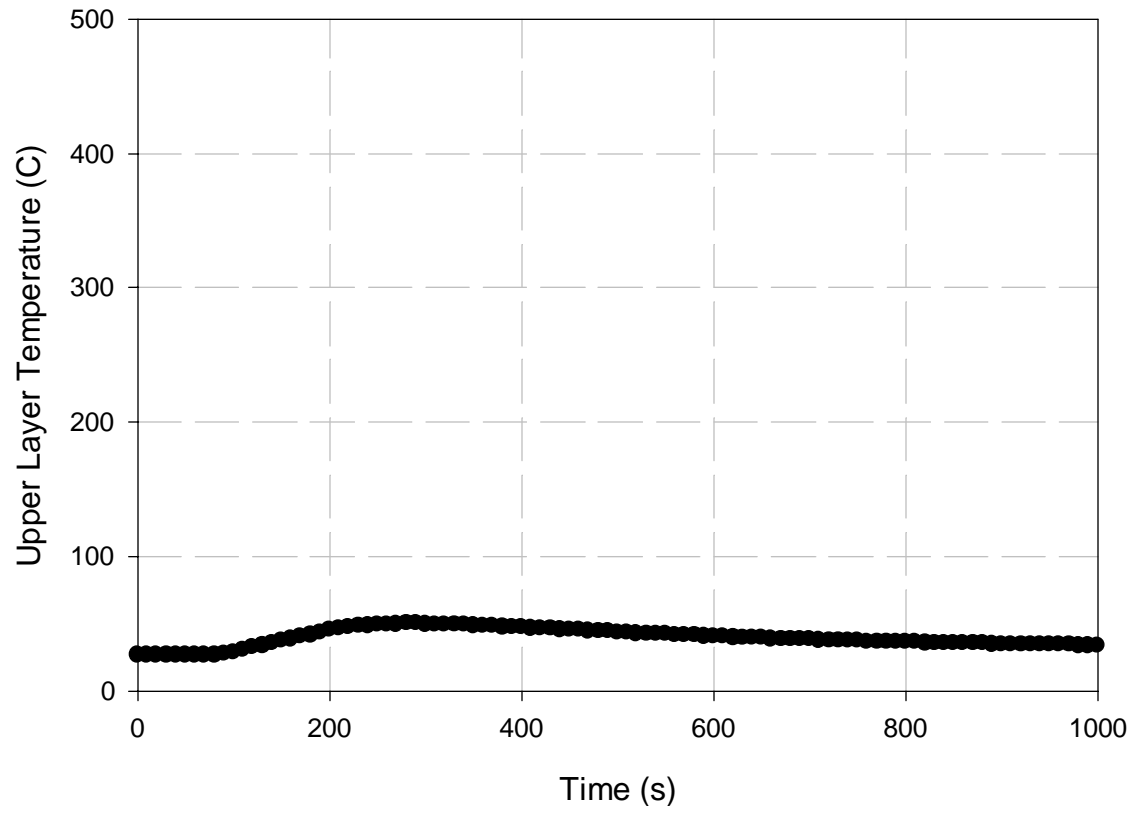

Figure 31: Upper Layer Temperature in Remote Room for Mercantile Fire with Commercial Sprinklers and No Smoke Venting

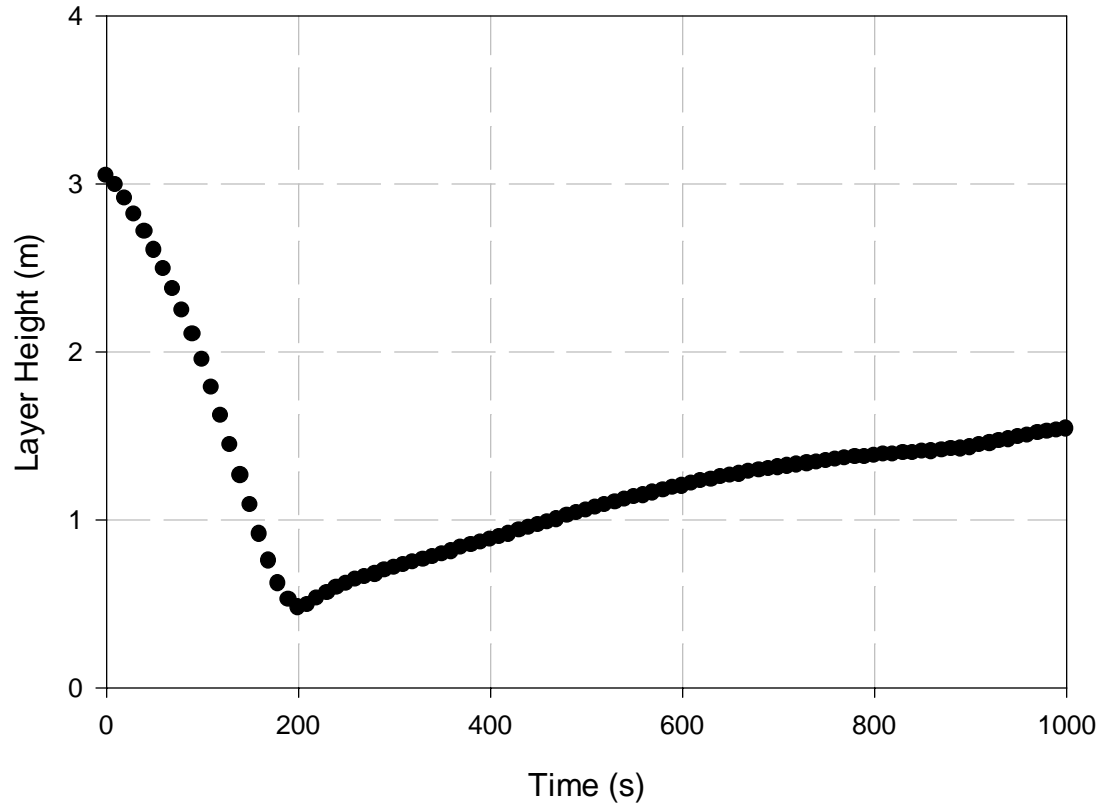## Layer Height in Room of Origin for Mercantile Fire

Figure 32: Layer Height in Room of Origin for Mercantile Fire with Commercial Sprinklers and No Smoke Venting Scenario

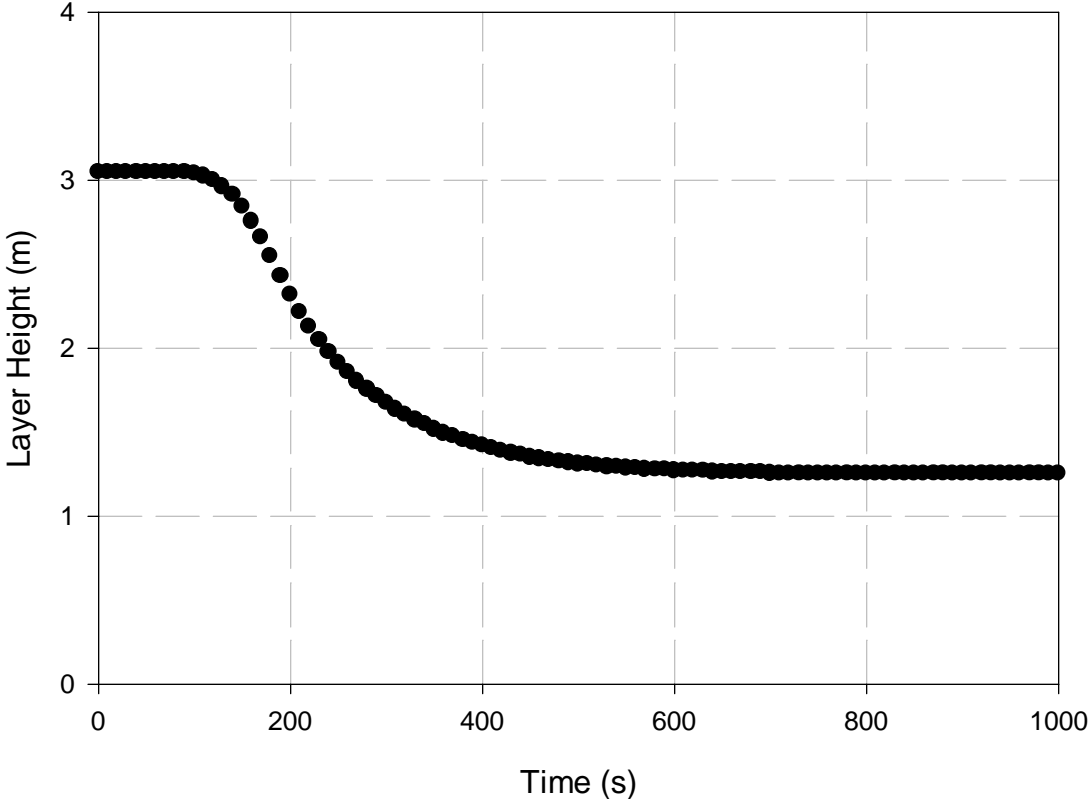# Layer Height in Remote Room for Mercantile Fire

Figure 33: Layer Height in Remote Room for Mercantile Fire with Commercial Sprinklers and No Smoke Venting Scenario

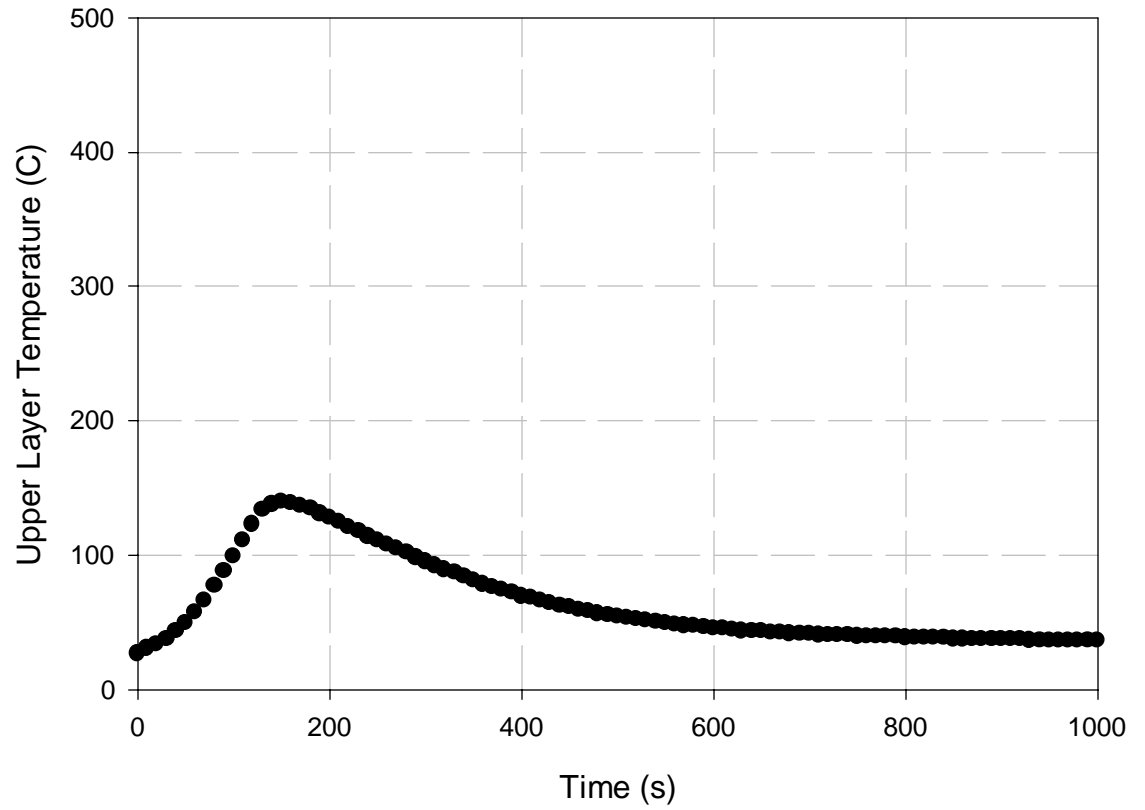Upper Layer Temperature in Room of Origin for Mercantile Fire

Figure 34: Upper Layer Temperature in Room of Origin for Mercantile Fire with QR Sprinklers and Smoke Venting Scenario
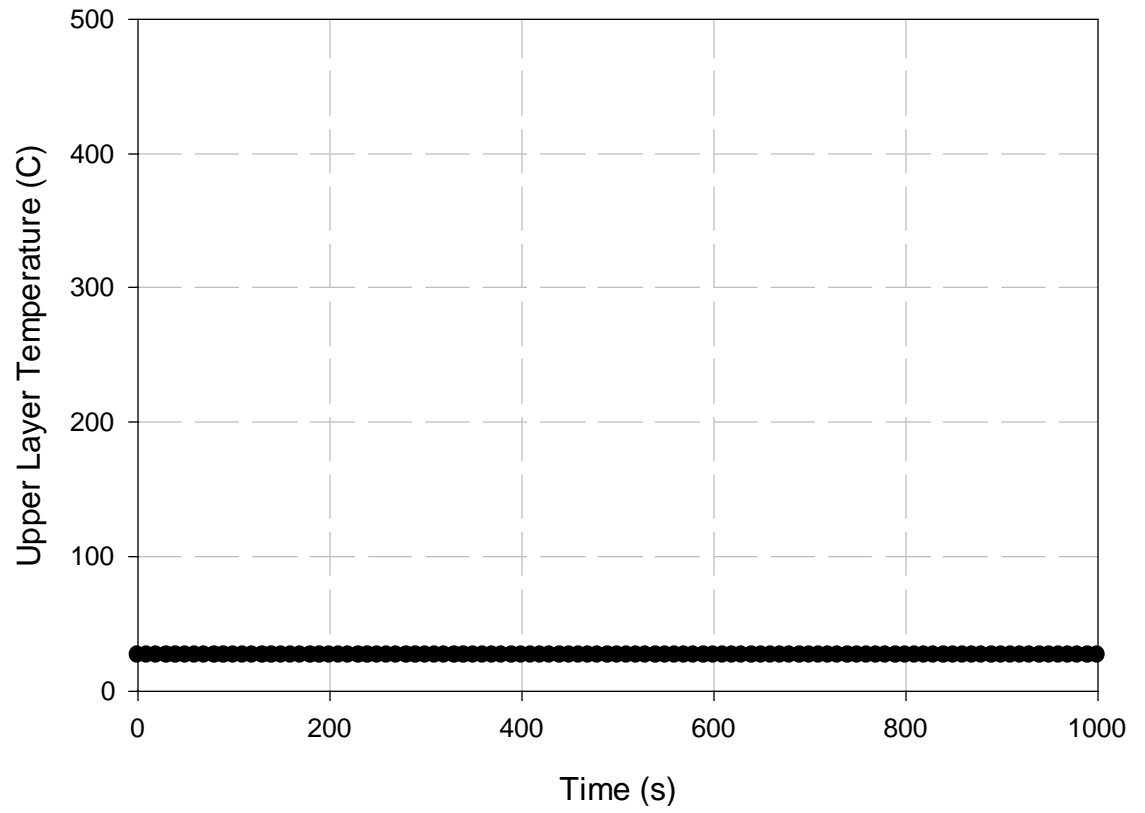
Figure 35: Upper Layer Temperature for Remote Room for Mercantile Fire with QR Sprinklers and
Smoke Venting Scenario

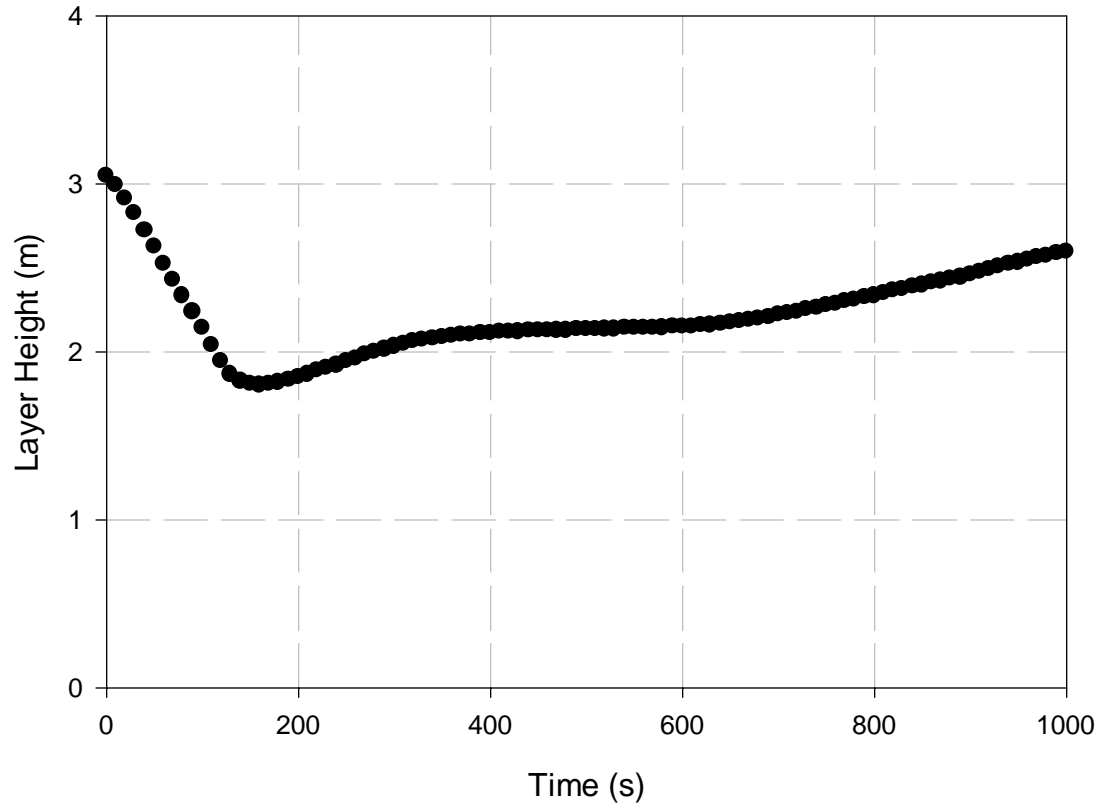## Layer Height in Room of Origin for Mercantile Fire

Figure 36: Layer Height in Room in Origin for Mercantile Fire with QR Sprinklers and Smoke Venting Scenario

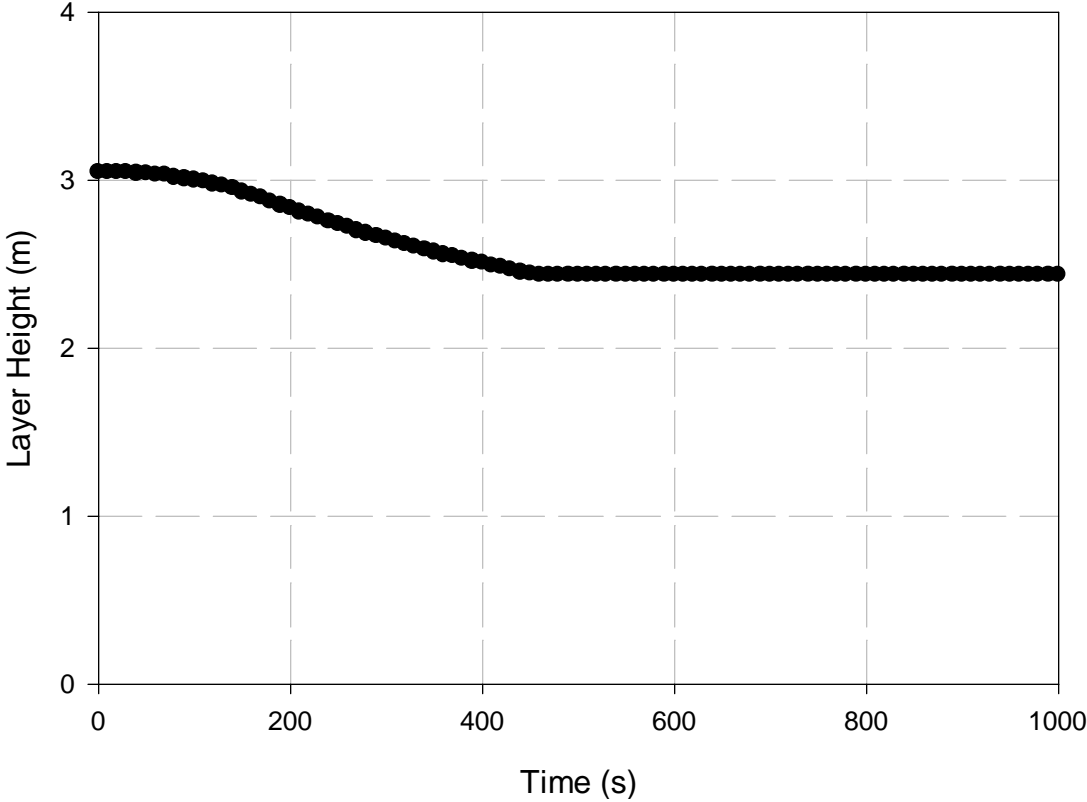## Layer Height in Remote Room for Mercantile Fire

Figure 37: Layer Height in Remote Room for Mercantile Fire with QR Sprinklers and Smoke Venting Scenario

APPENDIX D: CERTIFICATION

Jason D. Averill

Education   **Worcester Polytechnic Institute** Worcester, MA
May 1996   Bachelor of Science, Civil Engineering
May 1998   Master of Science, Fire Protection Engineering
May 1999   Bachelor of Science, Economics and Technology

Project **Master's Thesis** Gaithersburg, MD
Work   *"Performance-Based Analysis of 40 Story Building"*
Conducted a fire safety analysis of a mixed occupancy high-rise building using early
draft of International Code Committee performance based code. Results to be
presented as a case study at *2ⁿᵈ International Conference on Performance-Based*
Codes in May 1998.

Senior Project (Civil Engineering) Worcester, MA
"*Analysis and Design of the WPI Campus Center*"
Developed plans to renovate Alumni Gymnasium and build an addition, using the
Institute Campus Center Committees program. Included Fire Protection, Structural,
and Cost Estimation elements.

Senior Project (Economics) Darmstadt, Germany
"*Economic Analysis of the Hazardous Waste Industry*"
Developed computer model to determine optimal regulatory strategies for hazardous
waste disposal. Compared regulation of markets in Germany and the United
States.

Certificates   Passed **Fundamentals of Engineering (FE)** Examination

Experience   **National Institute of Standards and Technology** *Gaithersburg, MD*
6/97 to   Guest Researcher in the **Building and Fire Research Laboratory**.
Present   Specialize in application of computer fire models to engineering problems
from high ceilings to trains to office buildings.

5/96 - 5/97   **Computational Fire Modeling Laboratory**, Worcester, MA
•Performed firesafety analysis of 210' and 270' Coast Guard cutters with the
  SAFE computer model.
•AutoCad modeling for Coast Guard contracts and legal cases.

Relevant   •Fire Dynamics I and II   •Fire Protection Systems
Courses   •Process Safety Management   •Fire Laboratory

•Building Firesafety I and II	•Failure Analysis
•Statistics I and II	•Probability
•System Dynamics	

Computer
Analysis,
      Various CFD and Zone Fire Models, Evacuation Models, Statistical

Skills
      Windows Applications, AutoCad, HTML, UNIX, LaTeX, SAS, MathCad

Societies
- National Fire Protection Association
- Society of Fire Protection Engineers
- Salamander Society (Fire Protection Honor Society, WPI Chapter)

Publications
- Averill, Jason D. and Richard W. Bukowski. "Methods for Predicting Smoke Detector Activation." 1998 Fire Suppression and Detection Symposium Proceedings, Orlando, FL, 25 – 27 February 1998, *IN PRINTING*.

Curriculum Vitae

Richard W. Bukowski, P.E.

Personal data:

Born - July 4, 1947 in Chicago, IL
Married to Maria (Agostino) Bukowski
One child, Richard W. Bukowski III born 1971

Education:

BS EE from Illinois Institute of Technology (Chicago) in 1970.

Work History:

1970 - 1973: As a project engineer at Underwriters Laboratories, Inc. Northbrook IL, conducted product evaluations for listing of all types of fire alarm and emergency signaling equipment. Worked on the development of testing programs for several products never before evaluated, and wrote or revised a number of UL standards. With promotion to Senior Project Leader in 1973, assumed responsibility for special projects; i.e., project evaluations for which there were no standards or applicable prior work, for standards development, and for research studies.

1973 - 1974: Was sent by UL to the National Bureau of Standards under the Industrial Research Associate program. During this 12 month assignment, conducted research on residential smoke detectors culminating in a draft performance standard which later became the UL standards for smoke detectors.

1974 - 1975: Returning to UL, worked on a research project in conjunction with IIT Research Institute to develop installation guidelines for residential smoke detectors. The findings of this study resulted in a total revision of the then-accepted practice, and are the basis for current code requirements in the US, Canada, and many other countries.

1975 - 1981: Returned to NBS, Center for Fire Research as a Research Engineer in the Detection Project. In this capacity, responsibilities included planning and conduct of internally and externally-funded projects on residential and commercial detection systems, test method development, monitoring of outside grants/contracts, test instrumentation, and general electronics problems. Technical assistance was provided to various federal agencies including the US Fire Administration, US Secret Service, Veterans Administration, and Defense Department. Investigative assistance was provided to federal and local agencies in fires of suspected electrical origin and where detectors were thought to have malfunctioned.

1981 - 1982: Moved into Engineering Management as Acting Head of the Product Flammability Research Group, Fire Performance Evaluation Division. Management duties included direct technical and administrative supervision of professional and support staff activities, project planning and execution, resource management, contracts, and grants. The research activities of this group involve ignition and combustion of materials and assemblies not a part of the building structure.
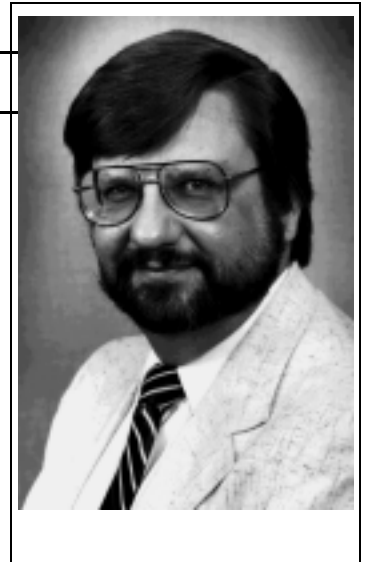
1982 to 1989: Served as Research Head, Fire Hazard Analysis Group, Fire Measurement and Research Division. The objective of the work is to develop predictive, analytical methods which enable the quantitative assessment of hazard and risk from fires. These predictive methods are based on computer modeling, and involve all aspects of fire science and related fields such as human behavior and physiology, toxicology, data bases and fire statistics, etc. To ensure use, necessary data must be readily available, and data input and presentation must be in terms readily understandable by the average professional. Thus, the projects include a strong emphasis on state-of-the-art computer graphics and computer aided design techniques and on the establishment of data base management systems. The embodiment of these goals was the public release of the HAZARD I Fire Hazard Assessment Method and personal computer software package.

1989 to present: Serves as Senior Research Engineer in the Fire Modeling and Applications Group in the Building and Fire Research Laboratory at NIST. Responsible for technical projects involving the application of fire hazard and fire risk analysis techniques to a broad range of engineering problems. Also serves as a liaison to the community of users of the science and technology developed in BFRL, facilitating the identification of user needs and the utilization of the Laboratory's products. As such serves as the BFRL liaison to the model codes groups in the U.S. and to CIB activities related to performance-based codes, nationally and internationally.

Technical Affiliations:

- Member, National Fire Protection Association.
- Member, Society of Fire Protection Engineers.
- Licensed Professional Engineer in the States of Illinois and Maryland.

NFPA Committee Memberships:

- National Fire Alarm Code Correlating Committee
- Household Fire Warning Equipment (Chair).
- Carbon Monoxide Detectors
- Hazard and Risk of Contents and Furnishings.
- Life Safety Code Technical Correlating Committee, and
- Residential Occupancies,
- Alternative Approaches to Life Safety, and
- Furnishings and Contents.

Other Professional Memberships:

- Technical Advisory Council of the NFPA Center for High Risk Outreach.
- Chairman, Technology Committee, National Smoke Detector Project.
- ASCE Committee on Structural Fire Performance Prediction.
- NFPA Research Section (chair), Building Fire Safety Systems Section
- Chair, CIB W14 Task Group on Engineering Evaluation of Building Fire Safety
- Member, International Code Council Performance Criteria Committee (representing ICBO) for the International Building Code.

Special Awards:

1986 Society of Fire Protection Engineers President's "Hats Off" Award for leadership and innovation as co-author and instructor for the *Engineering of Fire Detection and Alarm Systems* course.

1990 Visiting Scientist award from the Government of Japan for study at the Building Research Institute, Tsukuba, Japan.

1990 United States Department of Commerce Silver Medal Award for producing the world's first quantitative fire hazard assessment methodology - HAZARD I.

1997 Automatic Fire Alarm Association, Fire Protection Person of the Year Award

MAJOR PUBLICATIONS

1. Bukowski, R.W. and Bright, R.G., Some Problems Noted in the Use of Taguchi Semiconductor Gas Sensors as Residential Fire/Smoke Detectors, NBSIR 74-591, 1974; and *Fire Journal*, **69**, No. 3, pp 30-33, 102, 1975.

2. Bukowski, R. W. and Bright, R.G. Results of Full-Scale Tests with Photoelectric Smoke Detectors, NBSIR 75-700, 1975.

3. Bukowski, R.W., An Evaluation of Light Emitting Diodes as Source Lamps in Photoelectric Smoke Detectors, *Fire Technology*, **11**, No. 3, pp 157-163, 1975.

4. Bukowski, R. W., Waterman, T. E., and Christian, W. J. Detector Sensitivity and Siting Requirements for Dwellings ("The Indiana Dunes Report"), NBSGCR 75-51; NFPA SPP-43; and NTIS PB-247483, 1975.

5. Bukowski, R.W., Large-scale Laboratory Fire Tests of Smoke Detectors, Proceedings *Fire Detection for Life Safety*, National Research Council Conference, March 31-April 1, 1975, pp 78-92, 1975.

6. Bukowski, R.W., Field Investigation of Residential Smoke Detectors, NBSIR 76-1126, 1976; and *Fire Journal*, **71**, No. 2, pp 18-41, 1977.

7. Bukowski, R.W., Fire Alarm and Communication Systems, NBS Technical Note 964, 1978.

8. Bukowski, R.W., Smoke Measurements in Large- and Small-Scale Fire Testing, NBSIR 78-1502, 1978; and *Fire Technology*, Part I, **15**, No. 3, pp 173-179, and Part II, **15**, No. 4, pp 271-281, 1979.

9. Bukowski, R. W.; Mulholland, G. W., Smoke Detector Design and Smoke Properties, NBS Technical Note 973, 1978.

10. Bukowski, R. W., Detection of Fires in Electrical Cables, *Proceedings of the National Academy of Sciences Workshop on Flammability, Smoke, Toxicity, and Corrosive Gases of Electrical Cable Materials*, NMAB-342, pp 139-142, 1978.

11. Bukowski, R. W., Tests on the Performance of Automatic Fire Detectors in Health Care Occupancies - A Preliminary Report, NBSIR 79-1739, 1979.

12. Bukowski, R. W., Investigation of the Effects of Heating and Air Conditioning on the Performance of Smoke Detectors in Mobile Homes, NBSIR 79-1915, 1979.

13. Bukowski, R. W. and Istvan, S. M., A Survey of Field Experience with Smoke Detectors in Health Care Facilities, NBSIR 80-2130, 1980.

14. Bukowski, R. W., Fire Protection Systems for Rail Transportation of Class A Explosives, NBSIR 80-2170, 1980.

15. Hall, J. R., Jr., Bukowski, R. W., and Gomberg, A. Analysis of Electrical Fire Investigations in Ten Cities, NBSIR 83-2803, 1983.

16. Bukowski, R. W., Report for UJNR Panel - Detection in the USA 1980-1982, *Proceedings of the 6th UJNR*, Tsukuba, Japan, pp 10-14, 1982.

17. Bukowski, R. W., NFPA Toxicity Advisory Committee Strawman Procedure for Estimating Smoke Toxicity Hazard, *Proceedings of the NFPA Toxicity Committee Workshop*, 1984.

18. Bukowski, R. W., Toxic Hazard Evaluation of Plenum Cables, *Fire Technology*, **21**, No. 4, pp 252-266, 1985.

19. Bukowski, R. W., Development of a Method for Assessing Toxic Hazard, *Fire Journal*, **79**, No. 2, 1985.

20. Bukowski, R. W., Evaluation of Furniture Fire Hazard Using a Hazard Assessment Computer Model, *Fire and Materials*, **9**, No. 4, 1985.

21. Bukowski, R. W., Quantitative Assessment of Smoke Toxicity Hazard -- A Practical Approach for Current Use, *Fire Safety Science - Proceedings of the First International Conference*, Grant, C.E. and Pagni, P.J. eds., Hemisphere Publishing Corp., N.Y., pp 1089-1100, 1985.

22. Bukowski, R. W., Quantitative Assessment of Smoke Toxicity Hazards in Large Structures, UJNR Panel on Fire Research and Safety, 8th Joint Panel Meeting, May 13-21, 1985, Tsukuba, Japan, pp 85-98, 1985.

23. Bukowski, R. W., Application of Models to the Assessment of Fire Hazard from Consumer Products, NBSIR 85-3219, 1985.

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25. Mulholland, G. W. and Bukowski, R. W., Application of Smoke Detector Technology to Quantitative Respirator Fit Test Methodology, NBSIR 86-3481, 1986.

26. Bukowski, R. W., Fire Detection and Alarm Systems, *Proceedings of a Workshop on Fire Protection Technology*, Cairo, Egypt, NBSIR 86-3360, pp 25-38, 1986.

27. Bukowski, R. W., Engineering Applications for Fire-Related Prediction Tools, *ibid.*, pp 19-24, 1986.

28. Bukowski, R. W., A Summary of the Assumptions and Limitations in HAZARD I, *Proceedings of the 9th UJNR*, Boston, MA, 1987.

29. Bukowski, R. W., HAZARD I. Vol. 1: Fire Hazard Assessment Method, NBSIR 87-3602, 1987.

30. Bukowski, R. W., HAZARD I. Vol. 2: Representative Example Case Documentation, NBSIR 87-3603, 1987.

31. Bukowski, R. W., HAZARD I. Vol. 3: Data Base Listing, NBSIR 87-3604, 1987.

32. Bukowski, R. W., Hazard Analysis Using Toxic Potency and Other Material Property Data, *Proceedings of the 36th International Wire and Cable Symposium*, (Abstract Only), 143, 1987.

33. Bukowski, R. W., Techniques for Fire Detection, *Proceedings of the NASA Workshop on Spacecraft Fire Safety*, Nat. Aeronautics and Space Admin. (US) pp 9-29, 1987.

34. Bukowski, R. W., Smoke Detectors, Alarms, and Controls, NFPA Round table on Fire Safety in Atriums - Are the Codes Meeting the Challenge?, December 15-16, 1988, pp 1-19, 1988.

35. Bukowski, R. W., HAZARD I - Results of a User Evaluation of the Prototype Software, NISTIR 88-3878, Nat. Inst. Stand. Tech. (US), 1988.

36. Dubivsky, P. M. and Bukowski, R. W., False Alarm Study of Smoke Detectors in Department of Veterans Affairs Medical Centers (VAMCS), NISTIR 89-4077, 1989, Nat. Inst. Stand. and Tech. (US), 1989.

37. Bukowski, R. W., Peacock, R. D., Jones, W. W. and Forney, C. L., Vol. 1 Software Users' Guide for the HAZARD I Fire Hazard Assessment Method, Vol. 2 Technical Reference Guide for the HAZARD I Fire Hazard Assessment Method, Vol. 3 Example Cases for the HAZARD I Fire Hazard Assessment Method, NIST Handbook 146, 1989.

38. Bukowski, R. W., An Overview of a Method for Predicting Fire Risk, NISTIR 89-4097 1989.

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His funded research activities have included studies in structural fire protection as well as transit systems, submarine, building and ship computer modeling of fire. Organizations funding his research have included the American Iron and Steel Institute, Parsons-Brinckerhoff Quade and Douglas, the United States Coast Guard, the Electric Boat

Division of General Dynamics and the Building and Fire Research Laboratory of the National Institute of Standards and Technology and the National Science Foundation.

His consulting activities have included expert testimony in fire litigation, industrial design activities and the firesafety design of various buildings. He is a special consultant to Robert W. Sullivan, a building firesafety design firm in Boston, Massachusetts.

He has taught courses at the graduate level in building firesafety analysis and design, sprinkler system design, computer application in fire protection engineering, introductory fire dynamics and advanced topics of fire dynamics. He has been the principle advisor of over twenty five graduate theses in fire protection engineering. In addition, he has taught short courses in fire modeling in the USA, Australia, Canada, New Zealand and the United Kingdom. Finally, he has done extensive studies of the New Zealand building code, the only implementation of a performance based building code in the world. As a result of this activity, several presentations have been given on the development and implementation of new, performance based building codes in the United States.
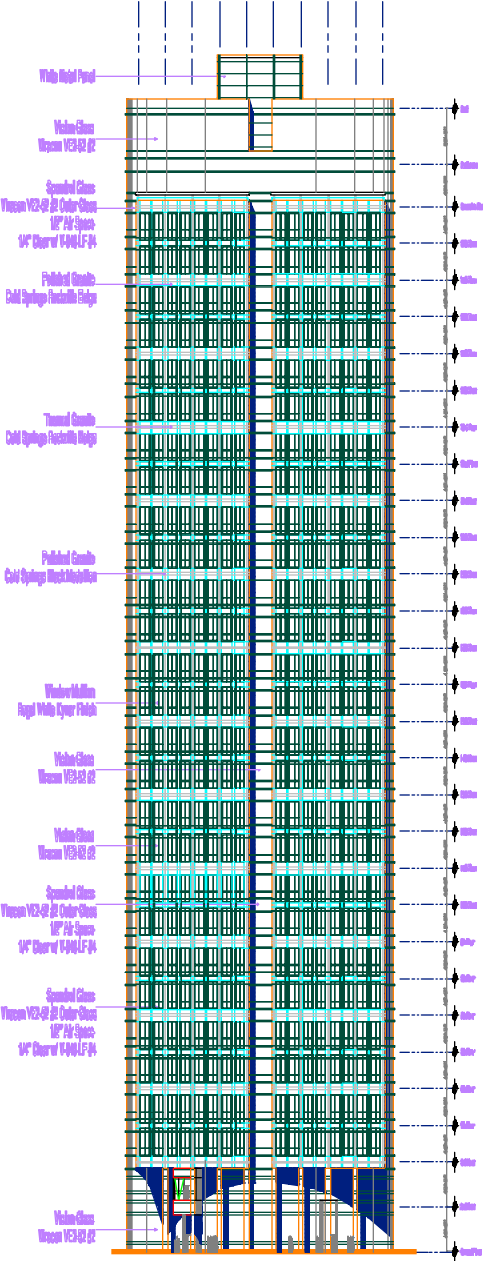
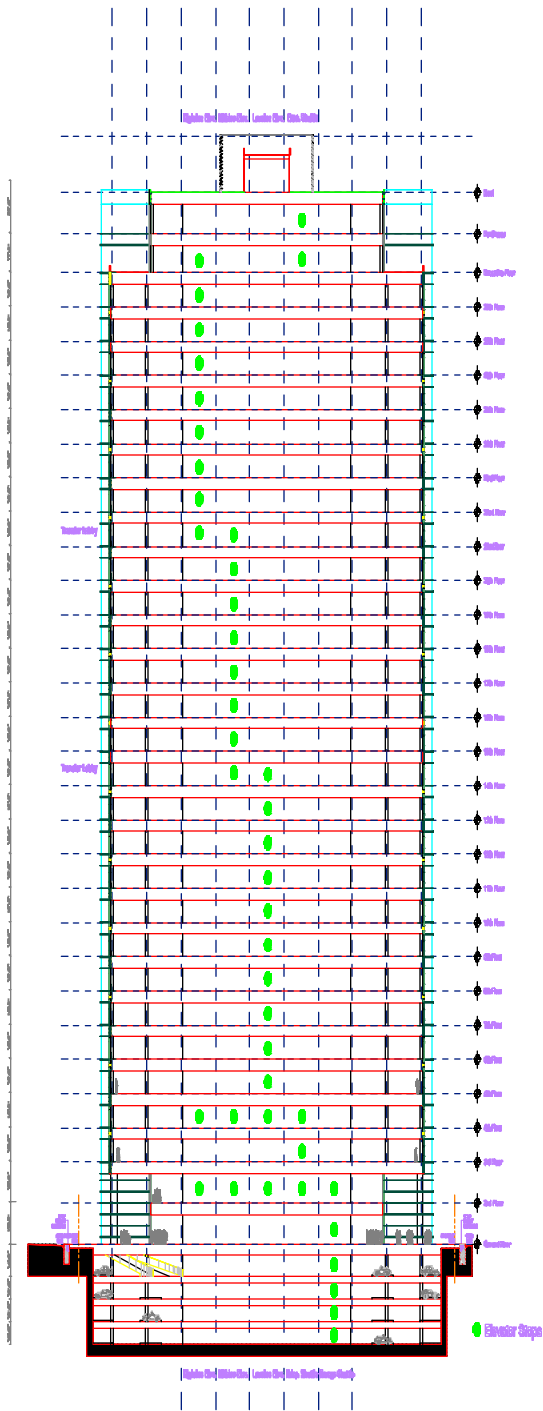**Appendix E: AutoCad Drawings**

Figure 38: Elevation View

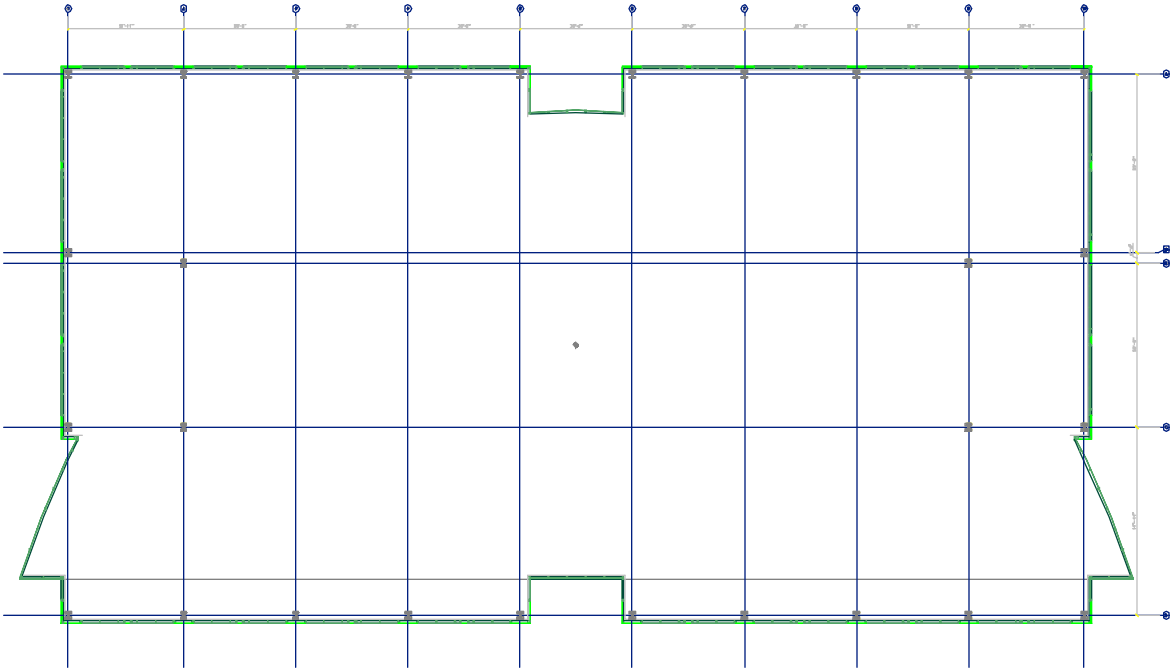**Figure 39: Elevator Schematic**

185

Figure 40: Plan View of Typical Office Level

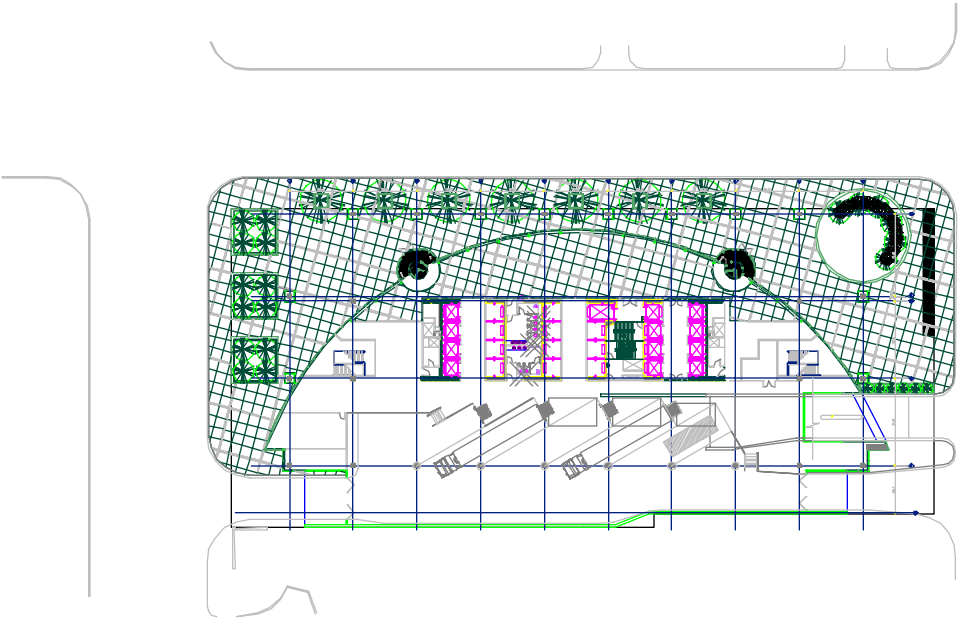**Figure 41: Plan View of Typical Four Tenant Layout**

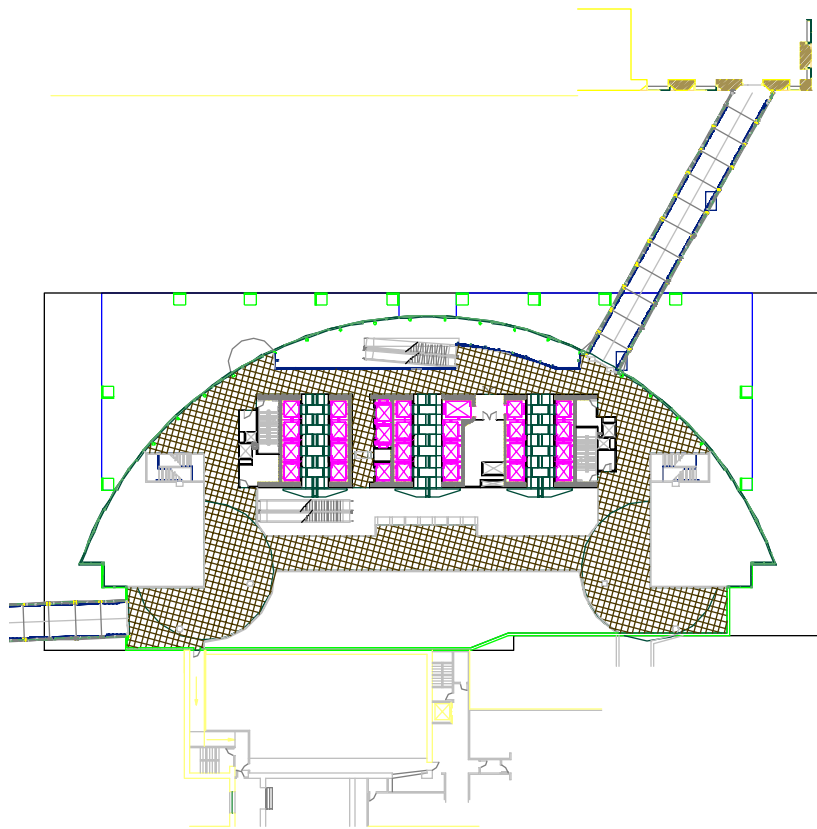**Figure 42: Plan View of First Floor Using the Performance Design**

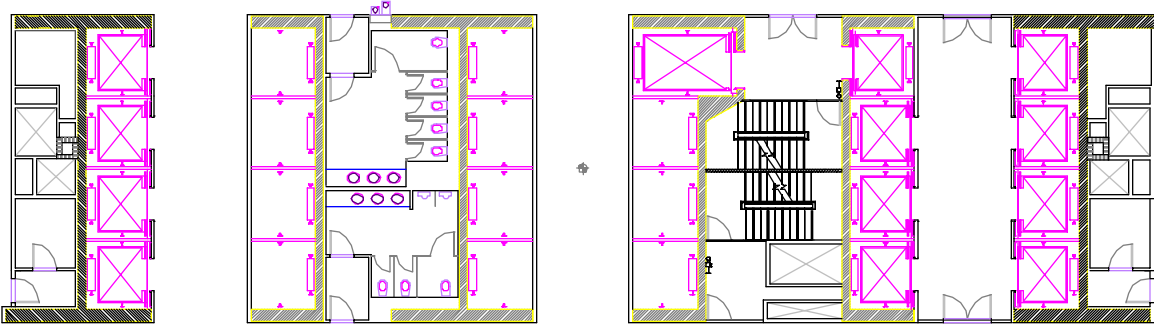**Figure 43: 2nd Floor Plan View**

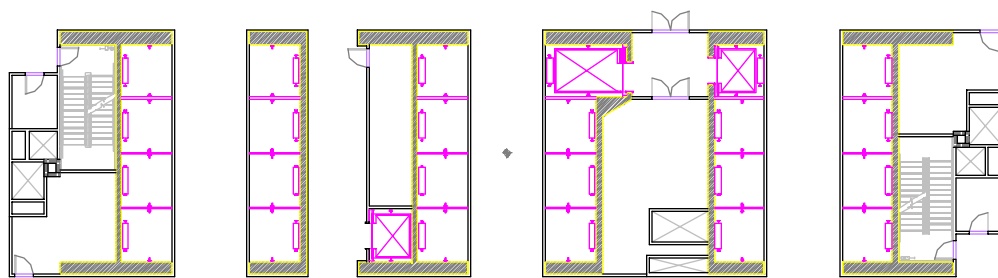**Figure 44: Building Core using Performance-Based Design**

Figure 45: Building Core Using Prescriptive Design Core