Forintek Canada Corp.

Project No. 2400

Canadian Forest Service No. 1

Final Report 2005/06

Fire Safety Design for Non-residential Buildings

by

J.R. Mehaffey, Ph.D.
Senior Research Scientist
Fire Research Group

March 2006

This project was financially supported by the Canadian Forest Service under the Contribution Agreement existing between the Government of Canada and Forintek Canada Corp.

J.R. Mehaffey	L.R. Richardson	R. Desjardins
Project Leader	Reviewer	Department Manager

Abstract

In the non-residential sector, prescriptive building codes often demand a higher level of fire safety be built into wood-frame buildings than into buildings of non-combustible construction. The extra cost associated with providing this higher level of safety can make wood-frame buildings less economical to build. Even when building code requirements and economics are not impediments, concerns about fire safety often cause designers or insurers to avoid the use of wood. This makes it challenging for the wood industry to capture a larger share of the non-residential market.

Performance-based fire-safety design offers the promise of eliminating the inequitable treatment of wood present in prescriptive codes. Consequently Forintek has taken steps to develop the requisite engineering tools required to undertake performance-based design. With funding from the Natural Sciences and Engineering Research Council (NSERC) and from Forintek, an NSERC Industrial Research Chair in Fire Safety Engineering was created at Carleton University in 2001 with Prof. George Hadjisophocleous as the Chair holder. Since that time, Forintek has engaged in active collaboration with the Chair in delivering his research program, and in educating students and practitioners capable of undertaking or approving performance-based design.

The Chair, Prof. George Hadjisophocleous, has just completed the last year of his five-year term. The product of his research has been the development of CUrisk, a computer model for evaluating the risk from fires in three- and four-storey wood-frame commercial buildings. It is a comprehensive system model that treats the building as a system complete with fire protection systems, building characteristics, occupant characteristics and inherent functions. CUrisk assesses the impact of fires on both life safety and property protection, and enables comparison of the costs and benefits of various design options.

With support from Forintek scientists, the Chair has also set up a strong educational program in fire safety engineering. A Short Course Series for practising engineers has been introduced with the fourth Short Course to be offered in May 2006. Six post-graduate courses are offered regularly on campus and across the country by internet. An Advisory Council has prepared a proposal for creation of a Graduate Level Program in Fire Safety Engineering by 2007.

The Chair has also leveraged support from Forintek and others to attract additional research funding and resources to Carleton University. Most notably, he has leveraged funding from the Canadian Foundation for Innovation and Ontario Innovation Trust to have a $10 million Fire Research Facility constructed for Carleton University. The experimental data obtained from tests carried out in this Facility will be used to develop new and validate existing computer models to evaluate fire safety levels in buildings.

In order to introduce further refinements in CUrisk and to market its use within the design community, Forintek and NSERC have recently agreed to extend the Chair's for a second five-year term. By supporting development of the requisite design tools, such as CUrisk, and the training of engineers in their use, the wood industry can expect to capture a larger share of the non-residential market.

Acknowledgements

Forintek Canada Corp. would like to thank its industry members, Natural Resources Canada (Canadian Forest Service), British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, Nova Scotia, New Brunswick, Newfoundland and Labrador, and the Yukon Territory, for their guidance and financial support for this research.

Forintek would like to acknowledge the assistance of Prof. George Hadjisophocleous, the NSERC Industrial Chair in Fire Safety Engineering at Carleton University, in achieving the objectives of this Forintek project.

Two Steering Committees have been struck to oversee the Chair's research program and to initiate an educational program in Fire Safety Engineering. Forintek Canada Corp. would like to extend its thanks to the members of these Committees for the enthusiastic guidance and dedication exhibited during the first term of the tenure of the Chair.

Table of Contents

List of Tables

List of Figures

1 Objectives

In collaboration with the NSERC Industrial Chair in Fire Safety Engineering at Carleton University, develop fire-safety design tools that will allow the wood products industry to expand its market share of non-residential buildings.

2 Introduction

Because of its design flexibility and cost-effectiveness, wood-frame construction has been very successful in North America. However, as Canada moves from a prescriptive building code to an objective-based code, flexible and cost-effective engineering-based design solutions are required, in lieu of traditional empirically-based ones. Therefore, the wood industry's continued success will depend to a large extent on its ability to harness advanced technology for the design of safe, efficient structures. The industry requires computer models and other design tools to demonstrate the fire-safety performance of buildings; and the industry requires qualified people to use such tools for design and enforcement purposes.

More than a decade ago, Canadian manufacturers of wood building products recognised the need for advanced technologies to aid in performance-based fire-safety design of wood-frame buildings. They foresaw that without such tools, the wood industry's domestic and export markets would decline and the doors to potential new markets would close. Accordingly, they instructed Forintek to initiate fire research to deliver those technologies. Forintek responded with a series of research initiatives: development of models to predict the fire-resistance of wood-stud walls (internal and external) and development of fire-safety design guides for wood-frame buildings. While Forintek's fire research program has resulted in the creation of a number of components for a comprehensive design tool for light-frame buildings, these do not in themselves constitute that tool.

Forintek and the wood industry lack the resources to deliver these new technologies in a timely manner. Because large buildings constructed with concrete and steel are the highest priority for public institutions such as the National Research Council Canada (NRC), Forintek recognised it could not wait for them to develop design tools for wood-frame buildings. Forintek might contract or work collaboratively with NRC to develop these tools, but that would still leave a hole in the industry's needs: trained professionals capable of using the technology to design and regulate construction of wood-frame buildings.

After careful consideration, Forintek concluded that creation of a Chair in Fire Safety Engineering at Carleton University would be the most efficient way to deliver this critical element in the industry's market plan. It was decided that an application should be submitted to the Program on Industrial Research Chairs funded by the Natural Sciences and Engineering Research Council (NSERC). The Program assists in establishing research in fields that have not yet been developed in Canadian Universities but for which there is an industrial need. Under the Program, a major research effort centred on an established researcher is supported jointly by NSERC and industry for a period of five years.

It was recognised that establishment of an Industrial Research Chair on Fire Safety Engineering would result in delivery of the new technologies required by the Canadian wood industry and foster creation of educational programs that would produce professionals trained in the use of these design tools. Establishment of the Industrial Research Chair at Carleton University in Ottawa would facilitate the Chair's access to both Forintek's and NRC's fire research expertise in the development of those tools.

This project to establish an NSERC Industrial Research Chair in Fire Safety Engineering at Carleton University was initiated in April 1999. Originally it was to run for five-years. However, the first few years were spent negotiating with Carleton University and then preparing and submitting a proposal to NSERC. The Chair was put in place in January 2001 with a five-year term ending December 31, 2005. To ensure the duration of this project coincided with the term of the Chair, the completion date of this project was extended at the end of the 2003-2004 fiscal year to March 31, 2006.

This final report summarises the progress that was made in this project from 1999-2006. The work outlined in the NSERC proposal to develop fire-safety design tools for non-residential wood-frame buildings was completed on schedule. To assist in development of these tools, the Chair attracted a strong research team comprising a postdoctoral fellow and several graduate students. The Chair was also awarded grants that provide facilities for the experimental component of the research program. Much effort was also expended to develop educational programs to train students and practitioners in performance-based fire-safety design.

3 Background

Building codes set fire-protection requirements in order to ensure an adequate level of safety in buildings. The current Canadian requirements are prescriptive, so there is no clear statement of what performance is acceptable and no guarantee that all buildings are constructed to the same level of safety. In fact, for non-residential occupancies, current regulations often demand a higher level of fire safety be built into wood-frame buildings than into their concrete or steel competitors. The extra costs associated with providing this higher level of safety often make wood-frame buildings less economical to build. Even when the building code and economics are not impediments, concerns about fire safety often cause designers, owners or insurers to avoid the use of wood in non-residential applications.

Building codes around the world are being revised to include performance-based fire-safety requirements. Rather than simply complying with prescriptive requirements intended to address fire safety in generic buildings, the designer will have the option of tailoring fire-safety systems to address the actual fire hazards and risks in a building. By judging the acceptance of building design solely on the basis of performance, performance-based fire-safety requirements are expected to eliminate the inequitable treatment of wood products present in prescriptive building codes and thereby improve market access for wood products. The adoption of performance-based codes will also encourage more flexible and cost-effective design.

In order to be prepared for the introduction of performance-based codes, architects, engineers and building code officials have pointed out the need for engineering tools to assess the fire performance of buildings. If the wood industry has the tools in place, the move to performance-based design could result in increased market share for wood building products. It would be particularly advantageous to develop fire-safety design tools for the non-residential wood-frame buildings governed by Part 3 of the National Building Code of Canada (NBCC) as these buildings must be structurally engineered in any case.

In countries where building codes have both prescriptive and performance-based requirements, the lack of educational programs in fire-safety engineering has been a serious impediment to the acceptance and use of performance-based fire-safety design. The potential benefits may not be realised if practitioners and building code officials are not conversant with the principles of performance-based design. It is therefore important that the wood industry encourage engineers to learn more about this subject.

4 Staff

J.R. Mehaffey, Ph.D.	Project Leader and Senior Research Scientist, Fire Research
L.R. Richardson	Group Leader, Fire Research
R. Desjardins, P.Eng., M.Sc.	Program Manager, Building Systems
Caroline Mancuso	Administrative Assistant, Building Systems

5 Project Plan

The proposed work plan for this project as envisioned in April 1999 is presented below in Table 1.

Table 1 Project Plan and Milestones (April 1999)

Activities	Planned Completion Date
Prepare draft proposal for a five-year NSERC Industrial Chair	September 31, 1999
Establish NSERC Industrial Research Chair at Carleton University	March 31, 2000
Initiate a research program on wood and fire safety at Carleton University	September 31, 2000
Fire safety design tools for non-residential buildings	March 31, 2004

In November 2000, the work plan was revised to reflect progress in the negotiations to create the Chair. That new work plan is presented below in Table 2.

Table 2 Project Plan and Milestones (November 2000)

Activities	Planned Completion Date
Submit the proposal for establishment of an Industrial Research Chair at Carleton University to the National Science and Engineering Research Council for funding support	Completed
Establish Industrial Research Chair at Carleton University with at least $600,000 in NSERC funding support	Completed
Initiate a research program on wood and fire safety at Carleton University	March 31, 2001
Develop the outline for a multidisciplinary research program for non-residential buildings and establish the first fire research project for that program	March 31, 2001
In conjunction with NRC, initiate an academic program in fire-safety engineering at Carleton University	September 1, 2003
Develop fire safety design tools for non-residential buildings	March 31, 2004

The Chair was finally established in January 2001 with a five-year term ending December 31, 2005. To ensure the duration of this project coincided with the term of the Chair, the completion date of this project was extended at the end of the 2003-2004 fiscal year to March 31, 2006. The final work plan is presented below in Table 3.

Table 3 Project Plan and Milestones (November 2003)

Activities	Planned Completion Date
Forintek to continue to fund the Chair	Ongoing
Forintek to assist in delivery of courses in fire safety engineering	Ongoing
Forintek to assist in supervision of graduate students	Ongoing
Students to identify design fire scenarios and design fires for non-residential buildings using surveys, statistics and fire tests	March, 2005
Forintek to hold regular meetings with the Chair to monitor progress in research program	Ongoing

6 Results and Discussion

6.1 Progress during 1999-2000

6.1.1 NSERC Industrial Research Chair

Even before the initiation of this project in April 1999, Forintek had begun to take steps to establish a Natural Sciences and Engineering Research Council (NSERC) Industrial Research Chair in *Wood and Fire Safety* at Carleton University. The Department of Civil and Environmental Engineering at Carleton University had been approached with the idea in late 1998, and enthusiastically agreed to it.

A candidate, Dr. George Hadjisophocleous who has a good international reputation, was approached and quickly agreed to pursue the Chair in co-operation with Forintek. A research scientist at NRC, he had been leading a team developing tools to aid in the design and assessment of fire-safe non-residential buildings of non-combustible construction.

J-C. Havard, a consultant familiar with wood industry issues, was retained to draft the proposal in consultation with Forintek, the candidate and the University. A first draft was completed in the spring of 1999. During the summer, an informal meeting was held with NSERC to discuss the draft proposal. In response to a number of revisions recommended by NSERC, the research component of the proposal was completely reworked by Forintek fire scientists and the candidate during the fall. The financial component, ensuring significant leveraging of Forintek's investment, was finalised during the winter of 1999-2000.

6.1.2 The Research Proposal

The focus of the proposed research was the development of engineering tools that could be used by fire protection engineers to design fire-safe wood-frame buildings in a performance-based code environment. This was to entail conducting research into fire growth, fire behaviour of building materials, smoke movement, occupant response and evacuation, fire detection and suppression system effectiveness, and fire risk analysis. Emphasis was to be given to research that would benefit the wood industry by providing design tools which ensure fair assessment of the impact of wood products in building fires. To this end, it was agreed that a fire risk assessment framework and computer model to evaluate the overall fire safety performance of wood-frame buildings would be developed. Ideally, the framework was to be designed to assess the fire performance of three- or four-storey commercial buildings.

6.2 Progress during 2000-2001

6.2.1 NSERC Industrial Research Chair

Carleton University and Forintek finalised the proposal to create an NSERC Industrial Research Chair in Fire Safety Engineering at Carleton University and submitted it to NSERC. Forintek proposed to provide the wood industry portion of the funding with NSERC covering the balance. Strong letters of support from the Canadian Wood Council and the Canadian Forest Service were attached to the proposal.

Subsequently, an NSERC Site-Visit Committee visited Carleton University to learn more about the proposed research program as well as about the University's and the industry's commitments to the Chair. Although the Committee looked favourably on the proposal, it recommended some revisions including increased financial and administrative support from the University. Revisions were made and the revised proposal submitted to NSERC.

On September 27, NSERC approved the proposal, subject to the following conditions:

- The candidate be granted tenure from the outset;
- NRC acknowledge that its facilities could be employed as stated in the program of work;
- An agreement on intellectual property be secured among NRC, Forintek and Carleton University;
- Carleton University agree to offer a Masters degree in Civil Engineering with specialisation in fire safety engineering within 2 years;
- NRC be invited to participate on the Chair's Steering Committee; and
- Users (an architect and an engineer) be invited to participate on the Chair's Steering Committee.

By late 2000, Carleton University, NRC and Forintek met all six conditions. On January 15, the Chair was activated and Dr. George Hadjisophocleous was appointed Professor of Fire Safety Engineering.

6.2.2 The Research Proposal

The proposed research entailed development of computer models for evaluating and quantifying the risk from fires in buildings with initial emphasis on four-storey wood-frame commercial buildings. A system model was to be developed whereby the building would be treated as a system, complete with its fire protection options, building characteristics, occupants and functions. This approach would enable comparison of the costs and benefits of different design options available to designers and assist them in selecting safe and cost effective designs. With risk analysis the impacts of various possible fire scenarios on both life safety and property protection could be evaluated.

A comprehensive system model to represent the interactions of fire growth and spread, fire detection and warning, building performance, fire suppression and human behaviour was to be developed together with subsidiary computer models dealing with the various aspects of the fire problem. The proposed model would be able to handle different types of building characteristics and functions, occupant characteristics, active and passive fire protection systems, construction materials, as well as the variety of fire scenarios that can be encountered in such buildings. The subsidiary models would calculate the consequence of fire incidents both in terms of human losses and property damages and the frequency of these incidents.

To assist in the development of the system model, NRC made FIERA available to the Chair. FIERA is a system model for reinforced concrete or structural-steel industrial buildings that was under development at NRC by Prof. Hadjisophocleous while he worked there. NRC also agreed to make its testing facilities available to assist in development and validation of the required sub-models.

Table 3 summarises the proposed research tasks, the resource requirements and timeframes. M.Eng. refers to a Masters student, Ph.D. to a Ph.D. student, PDF to a post-doctoral fellow. In order to deliver the work in his five-year NSERC tenure, sufficient funding was made available to Prof. Hadjisophocleous to supervise a total of 4 M.Eng students, 1 Ph.D. student and 3 post-doctoral fellows.

Table 4 Research tasks, resource requirements and timeframes

Research Task	Year 1	Year 2	Year 3	Year 4	Year 5
System model development	M.Eng.1	M.Eng.1			
Design fires, fire growth and smoke movement, experiments for input data and validation		Ph.D.	Ph.D.	Ph.D.	Ph.D.
Occupant response and evacuation			M.Eng.2	M.Eng.2	
Reliability of active systems			M.Eng.3	M.Eng.3	
Fire protection costs and direct fire losses				M.Eng.4	M.Eng.4
Submodel integration, graphical user interfaces	PDF 1	PDF 1	PDF 2	PDF 2	PDF 3
Structural response to fire, fire spread model	Forintek	Forintek	Forintek	Forintek	Forintek

6.2.3 Masters Program in Fire Safety Engineering

J.R. Mehaffey met on several occasions with faculty of Carleton University and fire scientists from NRC to develop plans for a Masters Degree in Civil Engineering with specialisation in Fire Safety Engineering. Plans were also being made to offer short courses aimed at practicing professionals.

The proposed curriculum comprised six core courses that were to be offered during a three-term period as shown in Table 5. These courses were selected following a review of courses offered at Universities in other countries and the model curriculum for Fire Safety Engineering developed by the International Association for Fire Safety Science.

Table 5 Proposed courses in fire safety engineering

Course Title	Instructor	Date First Offered
Fundamentals of Fire Safety Engineering	George Hadjisophocleous	September 2001
Fire Dynamics I	Jim Mehaffey	January 2002
Fire Dynamics II	Jim Mehaffey	September 2002
Human factors in fires	Guylène Proulx	September 2001
Fire modelling	George Hadjisophocleous	September 2002
Fire resistance	To be decided	January 2002

6.3 Progress during 2001-2002

6.3.1 NSERC Industrial Research Chair

During 2001-2002, Prof. Hadjisophocleous quickly assembled a team comprising several students and a post-doctoral fellow.

- Dr. Zhuman Fu, a post-doctoral fellow, started in March 2001. He worked on the development of the system model framework, the integration of the sub-models and the development of user interfaces.
- Mr. Ehab Zalok, a Ph.D. candidate, started September 1. The topic for his thesis had not yet been decided, but he was developing models of design fires for commercial buildings.
- Ms. Ineke Van Zealand, a Ph.D. candidate, started September 1. She worked in the area of human response to fire.
- Mr. Steven Craft, a M.A.Sc. candidate, started September 1. He planned to undertake a sensitivity analysis on WALL2D. He intended to determine to what parameters or properties the fire-resistance rating of wood-stud walls is most sensitive and to what properties it is not sensitive.

The Advisory Committee for the Chair in Fire Safety Engineering met at Carleton University on November 30. The Chair and several of his students provided progress reports. The industry representatives expressed pleasure and surprise with the progress to date.

6.3.2 Masters Program in Fire Safety Engineering

When NSERC approved the proposal for a Chair in Fire Safety Engineering, it did so with the proviso that Carleton University offer a Masters degree in Civil Engineering with specialisation in Fire Safety Engineering. This was acceptable to Forintek because, in order to take full advantage of the introduction of performance-based codes, the industry requires qualified people to use the tools developed by the Chair for design and enforcement purposes. Forintek and the Chair developed a draft curriculum comprising six core courses that were to be offered during a three-term period as depicted in Table 5.

Four graduate courses in fire safety engineering were offered at Carleton University during the 2001/2002 academic year:

- During the fall term, Prof. Hadjisophocleous taught a course on “Fundamentals of Fire Protection Engineering".
- During the fall term, Dr. G. Proulx (NRC) taught a course on “People in Fires”.
- During the winter term, Dr. J. Mehaffey taught a course entitled “Fire Dynamics I”.
- During the winter term, Dr. N. Bénichou (NRC) taught a course on “Fire Resistance”.

6.3.3 Funding for a Fire Research Facility at Carleton University

Prof. Hadjisophocleous applied to the Canadian Foundation for Innovation (CFI) for funding to permit Carleton University to construct a full-scale fire research facility for buildings and other facilities. In January, CFI approved the proposal for the development of a $10 million facility. CFI’s contribution to this project was $4 million. Other contributing partners included NRC, the Ottawa Fire Services and the Toronto Transit Commission. Funding was also expected from the Ontario Innovation Trust.

The facility, which was to be constructed on the grounds of NRC’s fire test complex in Almonte, Ontario, would be of great value to the research program of the NSERC Chair at Carleton University and would provide unique research opportunities to graduate students at Carleton specialising in Fire Safety Engineering. The facility was to be used to conduct research to improve fire safety levels in residential and commercial buildings, as well as transportation facilities, such as tunnels and underground stations.

Full-scale fire tests that represent realistic fire scenarios in these buildings could be conducted to determine their impact on life safety, building structure, contents and the environment. The experimental data obtained from these tests was to be used to develop new and validate existing computer models to evaluate fire safety levels in buildings.

6.4 Progress during 2002-2003

6.4.1 NSERC Industrial Research Chair

The focus of the proposed research was the development of engineering tools that can be used by fire protection engineers to design fire-safe wood-frame buildings in a performance-based code environment. In order to deliver the work during the five-year tenure of the Chair, sufficient funding has been made available to Prof. Hadjisophocleous to supervise several students and post-doctoral fellows. The status of his research team is as follows:

- Dr. Zhuman Fu, a post-doctoral fellow, was continuing to work on the system model, the integration of the various sub-models and the development of graphical user interfaces.
- Mr. Ehab Zalok, a Ph.D. candidate, was developing models of design fires for commercial buildings, and studying the impact of construction materials on fire growth and smoke movement. He would also perform experiments for input data and validation of the computer models.
- Mr. Steven Craft, a Ph.D. candidate, received his undergraduate degree in Forestry from the University of New Brunswick. More detail on his proposed area of research follows.
- Mr. Derek Gruchy, a M.A.Sc. student, was developing models to predict occupant response and evacuation in the evnt of a fire.
- Mr. Dominic Esposito, a M.A.Sc. student, was developing a methodology for undertaking Monte Carlo simulations in order to develop a probabilistic accounting for the distributions of input variables that impact on fire growth.
- Chandra Juneja, a M.A.Sc. student, was developing models to represent the reliabilities of various active fire protection systems such as detectors, sprinklers, smoke control systems, etc.
- Sean Tracey, a M.A.Sc. student (part-time) was intending to undertake an extensive statistical analysis of fire loss databases relating to comercial buildings.
- Judy Jeske, a M.A.Sc. student (part-time), was intending to undertake a fire safety analysis of a complex building.
- François Lemay, a M.A.Sc. student (part-time), was intending to study the effect of combustible interior finish on fire growth.

Ms. Ineke Van Zealand, a Ph.D. candidate, who had registered to study under Prof. Hadjisophocleous in 2001-2002 decided to terminate her studies in 2002-2003 in order to accept an offer of employment with the Canadian Wood Council. Her year's worth of study had proved beneficial to the wood industry.

Mr. Steve Craft, originally enrolled as a M.A.Sc. student, decided to change his plans and become a Ph.D. candidate. The aim of his research changed to determining the time to failure and probability of failure of wood-frame floor assemblies exposed to fire.

In August, the two full-time Ph.D. students, Mr. Craft and Mr. Zalok, wrote (and passed) comprehensive examinations on Thermofluids, Heat Transfer and Fire Dynamics. The three-hour Fire Dynamics examination was prepared and graded by Dr. J.R. Mehaffey.

Forintek's research program was redirected to foster strong collaborative links with the Chair's research program. Forintek collaborated with the Chair in selecting appropriate design fires for commercial buildings, in developing computer models to predict the fire resistance of wood-frame assemblies, in

characterising the flammability of room linings materials and in documenting the current fire performance of commercial buildings as recorded in statistical databases. Efforts were made to ensure that research underway in the Chair's program was of immediate benefit to Forintek's members and at the same time provided an important component in the overall risk model being developed by the Chair. The development of computer models for the fire resistance of wood-frame assemblies best exemplified this approach: these models are urgently needed by our members in the marketplace, and down the road will be a corner stone of the Chair's risk models.

The Advisory Committee for the Chair in Fire Safety Engineering did not meet during 2002-2003. The Chair was required to submit a detailed Progress Report to NSERC on December 31, 2002 summarising the status of his research and related activities after the first two years of his appointment. The Advisory Committee chose to await a response from NSERC before meeting again. As the industrial sponsor of the Chair, NSERC asked Forintek to comment on the Progress Report submitted by the Chair to NSERC. In its response Forintek noted that it was working closely with the Chair and was very satisfied with the progress to date. Forintek expressed the opinion that the research team assembled by Prof. Hadjisophocleous could develop computer models to predict the fire-safety performance of light-frame wood buildings in a timely fashion.

6.4.2 Forintek's *Inkind* Contributions to the Chair

In addition to the financial assistance Forintek agreed to provide for establishment of this industrial research chair in fire safety engineering, Forintek also agreed to provide substantial inkind assistance. A description of inkind contributions that Forintek had made to date in support of the Chair follows.

- Forintek paid the expenses for Steve Craft to participate in an Ad Hoc Wood-Industry Fire-Research Meeting convened September 18-19 at the U.S. Forest Products Laboratory in Madison Wisconsin. The meeting was convened to discuss progress in the development of models to facilitate performance-based design of wood-frame buildings. It also provided an opportunity to introduce Mr. Craft to the issues facing the industry and to the scientists engaged in research addressing these issues. Mr. Craft's Ph.D. thesis topic is to develop a computer model to predict the fire resistance of wood-frame floor/ceiling assemblies. Several participants in the meeting have undertaken related research and may provide useful assistance as his work evolves. (2002-2003)
- Arrangements were made to provide Mr. Craft with data from an extensive series of fire resistance tests being conducted on wood-frame floor/ceiling assemblies at NRC (see Project 1083). The data will be used to validate the computer models developed by Mr. Craft. (2001-2004)
- An annotated source code for Forintek's computer model for wood-stud walls as a starting point for constructing a wood-frame floor model. (2002-2003)
- A workstation was made available to Mr. Craft in Forintek's Ottawa offices for the duration of his studies. (2002-2006)
- Forintek arranged to turn over much of its small scale fire testing equipment to the Chair including (2002-2003):
  - A 2.4 m (4') cubical fire-endurance floor furnace;
  - An ASTM E662 smoke chamber; and
  - An ASTM E162 radiant panel flame-spread test apparatus.
- Forintek's cone calorimeter was made operational in the Carleton University laboratory and it will be shared with the Chair. Forintek is prepared to cover a portion of the costs required to provide adequate exhaust ducts for the apparatus. (2002-2003)
- Forintek is covering all costs related to procurement and analysis of fire loss statistics in commercial buildings. (2003-2004)
- Forintek and the Chair have come to an agreement whereby Forintek will fund a series of room-fire tests to assess the flammability of lining materials (2003-2004).

6.4.3 Masters Program in Fire Safety Engineering

Carleton University offered five graduate courses in fire safety engineering in 2002-2003:

- Prof. Hadjisophocleous taught a course in the classroom entitled "Fire Modelling" during the fall.
- Dr. G. Proulx (NRC) taught a course entitled "People in Fires" during the fall. Several students in Ottawa attended her lectures while others across Canada took the course by video.
- Dr. J.R. Mehaffey taught a course entitled "Fire Dynamics I" during the fall. This course was offered and video-taped during the Winter Term of 2002. 4 students in Ottawa took the course through "Instructional Television" and 7 students across Canada took it by video.
- Dr. N. Bénichou (NRC) taught a course in the classroom entitled "Fire Resistance" during the winter term.
- Dr. J.R. Mehaffey taught a course entitled "Fire Dynamics II" during the winter. 9 students in Ottawa took the course in the classroom or on "Instructional Television" while 12 students across Canada took it by video.

Prof. Hadjisophocleous also attempted to have fire safety engineering acknowledged as an area of specialisation at Carleton University. This required formal accreditation from the Ontario Council of Graduate Schools (OCGS). Two options were available through OCGS. The first option is to create a free-standing program in Fire Safety Engineering and the second is to create a collaborative program in Fire Safety Engineering. However, with only one faculty member in Fire Safety Engineering OCGS made it clear that it would not support either option.

6.4.4 Funding for a Fire Research Facility at Carleton University

Plans for construction of a $10 million full-scale fire research facility for residential and commercial buildings and transportation facilities were well underway. Prof. Hadjisophocleous secured $4 million from the Canadian Foundation for Innovation, $4 million from the Ontario Innovation Trust and $2 million from other major contributing partners including NRC, the Ottawa Fire Services and the Toronto Transit Commission. An architect had been chosen and construction of the facility was to commence in the summer of 2003 on the NRC site in Almonte.

6.5 Progress during 2003-2004

6.5.1 NSERC Industrial Research Chair

The Chair's research team had grown to one post-doctoral fellow and 16 graduate students:

- **Dr. Zhuman Fu**, a post-doctoral fellow, continued to work on the system model, the integration of the various sub-models and the development of graphical user interfaces. A paper entitled *A Fire Risk Computer Model for Commercial Timber Frame Buildings* by G. Hadjisophocleous and Z. Fu was presented during the 4th International Seminar on Fire and Safety Explosion Hazards, September 8-12, 2003 in Northern Ireland. The paper described progress in the development of the fire-risk computer model to evaluate fire safety designs for four-storey wood-frame commercial buildings.
- **Mr. Ehab Zalok**, a Ph.D. candidate, was developing models of design fires for commercial buildings. A paper entitled *A Survey of Fire Loads in Commercial Premises* by G. Hadjisophocleous and E. Zalok was presented during the 4th International Seminar on Fire and Safety Explosion Hazards, September 8-12, 2003 in Northern Ireland. Mr. Zalok described the results of a survey of 144 retail shops he had recently conducted on commercial floors of office buildings in the Ottawa area. The objective of the study was to collect data on fire loads (quantity of combustibles), types of combustibles and fuel arrangements in these establishments.

- **Mr. Steven Craft**, a Ph.D. candidate, received his undergraduate degree in Forestry from the University of New Brunswick. He had started to develop a finite-element model to predict the thermal response of wood-frame floors exposed to fire. He proposed to develop a coupled heat and mass transfer model for the gypsum board and wood joists. A paper entitled *Fire Experiments in Furnished Houses* by J.R. Mehaffey, S.T. Craft, L.R. Richardson and M. Batista was presented during the 4th International Seminar on Fire and Safety Explosion Hazards, September 8-12, 2003 in Northern Ireland. Mr. Craft undertook the work described in this paper as a directed studies project, in order to fulfil his course requirements. The paper described the tests conducted in Kemano and showcased our ability to use mathematical models to predict the course of fire in wood-frame houses.
- **Mr. Derek Gruchy**, an M.A.Sc. student, was developing models to predict occupant response and evacuation in the event of a fire.
- **Mr. Dominic Esposito**, an M.A.Sc. student, was developing a methodology for assessing the potential economic impact of fires.
- **Mr. Chandra Juneja**, an M.A.Sc. student, was developing models to characterise the reliability of active fire protection systems such as detectors, sprinklers, smoke control systems, etc.
- **Mr. Sean Tracey**, an M.A.Sc. student (part-time) was intending to undertake an extensive statistical analysis of fire loss databases relating to commercial buildings.
- **Ms. Judy Jeske**, an M.A.Sc. student (part-time), was intending to undertake a fire safety analysis of a complex building.
- **Mr. François Lemay**, an M.A.Sc. student (part-time), was intending to study the effect of combustible interior finish on fire growth.
- The following students were also studying under the supervision of Prof. Hadjisophocleous. They had all started taking courses, but none had selected their research projects yet: **Mr. Zhnjie Shao** (Ph.D.); **Mr. Ning Wang** (M.A.Sc.); **Mr. Khalid Alnasser** (M.A.Sc.); **Mr. Musaad Al-Duailej** (M.A.Sc.); **Ms. Dana Turnbull** (M.A.Sc. part-time); **Mr. Kasey Plante** (M.A.Sc. part-time); **Ms. Eman Elewini** (M.A.Sc. part-time); and **Ms. Susana Chui** (M.Eng. non-thesis, part-time).

The Chair submitted a detailed Progress Report to NSERC on December 31, 2002 summarising the status of his research and related activities after the first two years of his appointment. The report was distributed to a Review Committee established by NSERC. The Review Committee was impressed with the work that had been accomplished in both the research and academic areas. The Committee felt that it was not necessary to have a mid-term on-site visit. They did, however, make a few suggestions:

- CFD (Computational Fluid Dynamics) should be introduced into the research and courses.
- Courses should be introduced in risk analysis, and fire detection and suppression.
- Stronger international collaborations should be established
- Collaborations should be established with agencies involved in fire investigations.

These recommendations were well-received by the Chair, and plans are already in place to address them.

The Advisory Committee for the Chair in Fire Safety Engineering met at Carleton University on February 2, 2004. The Advisory Committee was impressed with the work that had been accomplished in both the research and academic areas. The research was thought to be of importance to the Canadian wood industry, the design and construction industries, and the regulatory community. The following are the main recommendations to the Chair made by the Advisory Committee:

- Try to attract support for the program from other material and product manufacturers, not just from the wood industry.
- Try to attract support for the program from the potential user communities, including fire protection engineers, and provincial and municipal building code officials.
- Enhance collaborations with other Universities in Canada where work in the field is being done. There is a need to create a network of centres-of-excellence across Canada in fire safety engineering.

- Introduce more short courses and make them available across the country to educate code officials in fire safety engineering and performance-based design.
- Create "certificate" programs for practitioners taking 3 or 4 courses.
- Make presentations to provincial associations of building officials on the Fire Safety Engineering Program at Carleton University.
- When they are ready, make sub-models of the risk model available to industry as stand-alone models.
- Along with Forintek, the wood industry and the building design and regulatory communities, begin to develop and implement a technology transfer/marketing plan to move the products of the research, i.e. the design tools, from the academic/research community to the user/practitioner communities.

The Advisory Committee also stated that it strongly supports a submission to NSERC for renewing the term of the Chair and pledged to assist the Chair in preparing the NSERC proposal. It recommended that, in the proposal, the Chair should clearly identify the fact that highly trained experts in the field of fire safety engineering are valued products of the Chair's program.

6.5.2 Ontario Centres of Excellence

Under the supervision of Prof. Hadjisophocleous and Dr. Mehaffey, Steve Craft, a Ph.D. student in Civil Engineering at Carleton University, is developing a heat transfer model for wood-frame floors exposed to fire. He intends to utilise the model to predict the probability-of-failure and the time-to-failure of floors exposed to fire. Because Mr. Craft's thesis delivers an important component of Forintek's fire research program, a stipend of $18,000 to support him was included in Forintek's 2003-2004 budget. Prof. Hadjisophocleous identified an opportunity to get additional funding to support the work from Ontario Centres of Excellence (OCE). OCE promotes economic development of Ontario through directed research, commercialisation of technology and training of highly qualified personnel.

Prof. Hadjisophocleous submitted a proposal to OCE requesting additional funding to expand the scope of Mr. Craft's work. OCE approved the proposal and a contractual arrangement was finalised in the fall. Under the terms of the contract, which extends from January 2004 to December 2005, Forintek's financial support of $72,000 and *inkind* contributions from Forintek and the National Research Council (NRC) were used to leverage $72,000 from OCE in order to expand the scope of the research program covered under the NSERC Industrial Chair and to attract additional students. This facilitated development of sub-models to predict the thermal and structural responses of wood-frame floors exposed to fire. Three full-scale fire-resistance tests were to be conducted at NRC to aid in sub-model validation. Once validated, these sub-models were to become components of a comprehensive model that will predict the probability-of-failure of wood-frame assemblies when exposed to fire.

6.5.3 Term of the NSERC Industrial Chair

The five-year term of Prof. Hadjisophocleous, the NSERC Industrial Research Chair in Fire Safety Engineering, ends December 31, 2005. To ensure the duration of this Forintek project coincided with the first five-year term of the Chair, the completion date of this project was extended to March 31, 2006.

In order to renew the Chair for a second five-year term, a proposed research plan for the new term had to be submitted to NSERC in December 2004. Prof. Hadjisophocleous planned to start writing the proposal in 2004-2005 and in addition to Forintek he hoped that other industrial support could be secured from sources such as Toronto Transit Commission, ASHRAE, and the steel and concrete industries.

6.5.4 Masters Program in Fire Safety Engineering

Carleton University offered four graduate courses in fire safety engineering in 2003-2004. All four courses were offered in both in-class and distance formats.

- During the fall Prof. Hadjisophocleous offered the course "Fundamentals of Fire Safety Engineering".
- During the fall Dr. Proulx (NRC) offered the course "People in Fires".
- During the winter Dr. Mehaffey (Forintek) offered the course "Fire Dynamics I".
- During the winter Dr. Bénichou offered the course "Fire Resistance".

On May 14-16, 2003, Carleton University offered a short course entitled "Introduction to Fire Safety Engineering". There were 86 attendees including fire investigators, building officials, code consultants, architects, fire-prevention officers and insurance adjusters. The course provided a description of the current regulatory system, and presented examples of design in both the prescriptive and performance-based code environments. Specific topics included fire dynamics, passive and active fire protection systems, and occupant response and evacuation. Dr. Mehaffey gave three one-and-a-half hour lectures entitled "Fire Initiation and Development", "Movement of Effluents" and "Response of Materials to Fire". On a questionnaire completed during the last day, participants expressed a high level of satisfaction with the short course. Carleton University planned to offer a second short course entitled "Engineered Fire Safety Systems" May 19-21, 2004.

Carleton University has been seeking ways to provide more depth in supervising student projects, and in offering courses and workshops. To this end, the Department of Civil and Environmental Engineering has appointed three Adjunct Research Professors to provide liaison with organisations engaged in research related to Fire Safety Engineering. They are Dr. J.R. Mehaffey of Forintek, Dr. N. Bénichou of NRC and Dr. V. Kodur of NRC.

6.5.5 Fire Research Facility at Carleton University

The design of a new Fire Research Facility for Carleton University commenced in the spring of 2003. On July 10, Dr. Mehaffey participated in a Stakeholder's Meeting during which critical design options were considered for the new Facility. Although Forintek was not contributing funding for the Facility, we were invited to the meeting in order to ensure it could address Forintek's short and long-term needs. All stakeholders agreed on design options that would be sufficiently flexible that the experimental work envisioned for the next 10 years could be accommodated. The conceptual design of the Facility was completed in the fall.

6.6 Progress 2004-2005

6.6.1 NSERC Industrial Research Chair

6.2.1.1 Status of research

Progress of the Chair's research has exceeded the proposed goals and scope of work. Table 6 shows the tasks that had been identified in the original proposal and provides a brief description of the current status.

Table 6. Status of main tasks.

Task	Comments
System model for hazard and risk analysis	
Perform literature review on fire risk analysis	Completed.
Design and develop system model architecture and framework	Completed.
Design and develop a building geometry module	Completed.
Develop hazard and risk analysis module	Completed.
Develop fire cost expectation module	Completed.
Integrate sub-models into system model	Sub-models integrated into system model.
Design fires	
Determine design fire characteristics and frequencies	Survey of retail outlets completed. Statistical analysis of Ontario Data completed.
Perform statistical analysis to determine impact of construction materials on design fires	To be done in collaboration with Forintek.
Perform full-scale tests to characterize design fires	First series of tests completed. Second series of tests commenced Feb. 2005.
Fire and smoke movement	
Select fire growth and smoke transport models. Import fire growth model into smoke transport model.	Completed. (CUsmoke)
Perform cone calorimeter experiments to obtain input data for fire growth models	Not done. More emphasis given to full-scale testing.
Perform full-scale experiments for fire growth model and smoke movement model validation	To be done in 2005.
Occupant response, evacuation and life hazard	
Conduct survey to determine occupant characteristics in commercial buildings	Survey done for building used in case studies. Modelled impact of visibility / occupant speed
Develop occupant response model	Completed.
Import occupant response model into evacuation model	Completed.
Develop hazard analysis model	Completed
Reliability of active fire protection systems	
Use statistics to determine reliability of smoke and heat detectors, and sprinklers	Completed.
Identify parameters affecting reliability and build fault tree model of sprinkler system	Completed.
Behaviour of structures exposed to fire	
Perform statistical analysis	Forintek assisting
Modify & incorporate Forintek model into system model	In progress.
Develop fire spread sub-model	In progress.
Economic impact of fires	
Determine costs of fire protection systems in buildings	Completed.
Develop costs of repairing fire and smoke damage	Completed.

6.2.1.2 Status of students

During 2004-2005, three students studying with Prof. Hadjisophocleous became the first to successfully defend M.A.Sc. theses in Fire Safety Engineering at Carleton University. J.R. Mehaffey was a member of the examination committees for all three students.

- Mr. Dominic Esposito defended his thesis entitled "Economic Impact of Fires in Buildings".
- Mr. Derek Gruchy defended his thesis entitled "Modelling Occupant Evacuation during Fire Emergencies in Buildings".
- Mr. Chandra Juneja defended his thesis entitled "Analysis of Ontario Fires and Reliability of Active Fire Protection Systems".

The evacuation sub-model developed by Mr. Gruchy, the economic impact sub-model developed by Mr. Esposito and the data on the operational reliabilities of smoke detectors, heat detectors and sprinklers derived by Mr. Juneja were important components of the fire-risk model for four-storey wood-frame commercial buildings under development at Carleton University. Following graduation, Mr. Esposito and Mr. Gruchy were hired by Morrison Hershfield to work in their Fire Safety Group in Ottawa. Mr. Juneja returned to India were he is employed in the fire safety industry.

During 2004-2005, two doctoral students studying with Prof. Hadjisophocleous successfully defended their Ph.D. thesis proposals. J.R. Mehaffey was a member of the review committee for students.

- On April 8, Steve Craft, defended his Ph.D. thesis proposal entitled, "Fire Resistance of Light-frame Wood Floor Assemblies". Mr. Craft is developing a finite-element model to predict the thermal response of wood-frame floors exposed to fire. He has completed development of sub-models to predict the rates of heat and mass transfer in gypsum board and wood joists. These sub-models are being coupled in order to predict the thermal response of floors. Small-scale experiments are being planned to determine input data for the heat and mass transfer sub-models, and intermediate and full-scale tests are being planned to provide data for validation of the thermal response model for floors.
- On December 17, Mr. Ehab Zalok, a Ph.D. defended his Ph.D. thesis proposal entitled "Design Fires for Commercial Premises". Mr. Zalok has conducted a survey of types of combustibles and fire load densities in commercial establishments. Using these data to select characteristic fuel arrangements for various retail stores, he has conducted a series of fire tests in a well-ventilated medium-scale enclosure and is planning to conduct a series of tests in a more poorly-ventilated full-scale enclosure. The purpose of his research is to identify design fires for commercial establishments. Design fires are severe, but credible fires that could be expected to develop in a building; and a building's fire safety system must be designed to "handle" them. A paper entitled "A survey of fire loads in commercial floors of office buildings" by G.V. Hadjisophocleous and E. Zalok was presented by Prof. Hadjisophocleous during the 10th Interflam Conference held July 5-7, 2004 in Edinburgh, Scotland. The paper summarised the progress in Mr. Zalok's work.

Ling Lu, a doctoral candidate, has selected a topic for her Ph.D. thesis. She will develop a finite-element model to predict the structural response of wood-frame floors exposed to fire. The output of Mr. Craft's thermal model which will predict the depth of char and the temperature distribution in the un-charred components of the wood-frame structure will be input to her model. The coupled thermal (Craft) and structural (Lu) models will allow prediction of the fire resistance of wood-frame floors exposed to any arbitrary fire (Zalok).

Ning Wang, an M.A.Sc. student, has chosen a thesis topic that entails developing a model to predict the probability of failure of wood-frame assemblies exposed to fire. The thermal and mechanical properties of assembly components (gypsum board, wood framing, etc.) as well as the fire properties (temperature, heat flux, etc.) are random variables with tight, but observable probability distributions. In a risk-based assessment, the time to failure of an assembly is not predicted deterministically, but probabilistically. Mr.

Wang is developing a computer program that will run a wood-stud wall model (like WALL2D) or wood-joist floor model (like Steve Craft's) a large number of times while sampling the ranges of distributed parameters. Although each run predicts a unique time to failure, the ensemble of runs can be used to predict the probability of failure of assemblies as a function of time for a given scenario.

The status and research topics of all of the students of Prof. Hadjisophocleous are summarised in Table 7.

Table 7 Students in Fire Safety Engineering Program

No.	Student's Name	Degree	Project	Expected Graduation
1.	Ehab Zalok	PhD	Design Fires	Spring 2006
2.	Steve Craft	PhD	Modelling of the thermal response of timber frame floors	Spring 2006
3.	Ling Lu	PhD	Structural response of timber frame floors	Spring 2008
1.	Dominic Esposito	MASc	Economic Impact of Fires	Graduated Fall 2004
2.	Derek Gruchy	MASc	Occupant evacuation model	Graduated Fall 2004
3.	Chandra Juneja	MASc	Reliability of active fire protection systems	Graduated Spring 2005
4.	Ning Wang	MASc	Probability of failure of walls and floors	Fall 2005
5.	Eman Elewini	MASc	Experiments of fire resistance of timber frame floors	Fall 2005
6.	Musaad Al-Duailej	MEng	Comparisons of CUsmoke predictions with experimental data	Spring 2005
7.	Zhan Zhou	MASc	Modelling atrium smoke exhaust	Fall 2005
8.	Khalid Alnasser	MASc	Modelling fuel tank boilover	Fall 2005
9.	Yoonjeoung Ko	MASc	Modelling Balcony Spill plumes in atria	Fall 2005
10.	Mondu Das	MASc	Smoke movement in buildings	Fall 2006

6.6.3 Forintek's *Inkind* Contributions to the Chair

In addition to the financial assistance Forintek agreed to provide for establishment of the Chair in Fire Safety Engineering, Forintek also agreed to provide substantial inkind assistance. A description of inkind contributions that Forintek made during 2004-2005 in support of the Chair follows.

- Forintek sponsored Mr. Steve Craft's attendance at the 3rd International Workshop on Structures in Fire in Ottawa, May 10 & 11. The focus of the workshop was the determination of the behaviour of structures exposed to fire by various means: testing, calculation and numerical modelling. Several participants in the meeting have undertaken related research and may provide useful assistance as his work evolves.
- Arrangements have been made to provide Ling Lu with data generated by Peter Lau. He conducted two series of experiments in which nominal 2 x 4 studs were loaded in tension and in compression while exposed to elevated temperatures. The temperature and loading histories were recorded as a function of time as were the displacement histories and the time to failure. Ling Lu will employ the data to develop a model to predict the reduction in modulus of elasticity of dimension lumber (under

tension and compression) as a function of temperature. She needs this model as input in the model she is developing to predict the structural response of wood-frame floor assemblies exposed to fire.
- Mr. Craft was provided with data from an extensive series of fire resistance tests being conducted on wood-frame floor/ceiling assemblies at NRC (see Project 1083). The data will be used to validate the computer models developed by Mr. Craft. (2001-2004)
- A workstation continues to be available to Mr. Craft in Forintek's Ottawa offices for the duration of his studies.
- Forintek and the Chair have come to an agreement whereby Forintek will fund a series of room-fire tests to assess the flammability of lining materials.

6.6.4 Ontario Centres of Excellence

Three students are working on a joint Carleton University / Forintek project to model the fire resistance of wood-joist floors. In late November and early December, three fire-resistance tests were conducted on intermediate-scale (1.22 m x 1.83 m) wood-joist floor assemblies at NRC. The assemblies comprised nominal 2" x 10" SPF studs, spaced 400 mm on centre; 2 layers of 12.7 mm fire-rated gypsum board; 2 layers of nominal 5/8" plywood sub-floor; and no insulation in the cavities. Only two tests had been planned, but the furnace inadvertently shut down early in the first test and on being restarted was unable to follow the planned exposure conditions. In the second test, the fire exposure followed the standard time-temperature curve and in the third a non-standard time-temperature curve (including a cooling phase) was followed. Temperatures were measured as a function of time at numerous points in the assemblies. No structural load was applied during the tests so that the thermal response of the floors was decoupled from the structural response. The floors were constructed and instrumented by Eman Elewini, an M.A.Sc. student. The temperature data are being used to validate the thermal response model under development by Steve Craft, a Ph.D. candidate.

In February 2005, two full-scale tests on similar floors were conducted under full design loads in order to validate both Mr. Craft's thermal response model and the structural response model under development by Lu Ling, another Ph.D. candidate.

6.6.5 Term of NSERC Industrial Chair

The five-year term of the Industrial Research Chair in Fire Safety Engineering at Carleton University will end on December 31, 2005. The Chair's research on fire safety in non-residential wood buildings is assisting the Canadian wood industry to prepare for the introduction of an objective-based building code in Canada in 2005 and to address market access issues in our overseas markets. Forintek expressed interest in the continuation of the NSERC-supported Industrial Research Chair for an additional five year term. Forintek scientists were to begin supporting Prof. Hadjisophocleous in working out the details for this proposed extension.

6.6.6 Masters Program in Fire Safety Engineering

During the 2004-2005 academic year, five graduate courses were offered.

During the fall term:

- Prof. Hadjisophocleous offered the course "Fire Modelling" in the classroom and by video.
- Dr. Proulx (NRC) offered the course "People in Fires" in the classroom and by video.
- Dr. Mehaffey (Forintek) offered the course "Fire Dynamics I" by video only.

During the winter term:

- Dr. Bénichou (NRC) offered the course "Fire Resistance" in the classroom and by video.
- Dr. Mehaffey offered the course "Fire Dynamics II" in the classroom and by video.

Following the success of its short course *Introduction to Fire Safety Engineering* May 14-16, 2003, Carleton University offered a follow-up short course *Engineered Fire Safety Systems* May 19-21, 2004. There were 73 attendees including fire protection engineers, architects, building officials, code consultants, building science practitioners, and students in fire safety programs. While most fire safety design in Canada is done by following rigid prescriptive building codes, the introduction of objective-based codes in Canada in the near future will foster the use of performance-based design techniques. In anticipation of this development, this short course provided an introduction to the engineering of fire safety systems. Specific examples illustrating the process included design for fire resistance, spatial separations, activation of fire alarm and sprinkler systems, and smoke management systems. Dr. Mehaffey delivered three one-and-a-half hour lectures entitled "Brief review of fire dynamics principles", "Design for fire resistance" and "Ensuring adequate spatial separations". On a questionnaire completed during the last day, participants expressed a high level of satisfaction with the short course.

Carleton University will offer a third short course entitled *Fire and Explosion Investigations* May 11-13, 2005. The course is designed for fire investigators, fire protection engineers, fire prevention officers, building science practitioners and students in fire safety programs. It will provide an overview of the basic fire science needed to conduct comprehensive fire and explosion investigations and, through the use of case studies, will illustrate how scientific investigations are undertaken. J.R. Mehaffey will deliver three one-and-a-half lectures entitled "Ignition of the first item", "Flame spread, ignition of the second item" and "Response of materials exposed to fire". This last lecture will be co-authored with Mr. Steve Craft. These lectures will be largely based on existing lectures offered in full-term courses delivered by J.R. Mehaffey at Carleton University as well as from recent findings of Mr. Craft in his Ph.D. research.

6.6.7 Fire Research Facility at Carleton University

Construction of the new Fire Research Facility for Carleton University commenced during August 2004 on the grounds of the National Research Council (NRC) at its fire test complex near Almonte.

6.6.8 Related Developments

As editor of the Newsletter for the International Association for Fire Safety Science, J.R. Mehaffey prepared a semi-annual Newsletter in December. In order to promote developments in fire safety engineering at Carleton University, he wrote a short article mentioning that Mr. Dominic Esposito and Mr. Derek Gruchy received their MASc Degrees during Fall Convocation. They are the first Carleton University graduates working in the area of fire safety engineering under the supervision of Prof. Hadjisophocleous. Mr. Esposito studied the economic impact of fires in buildings and Mr. Gruchy developed a computer model to predict occupant evacuation during fire emergencies in buildings.

6.7 Progress during 2005-2006

6.7.1 NSERC Industrial Research Chair

Forintek has engaged in active collaboration with the Chair in delivering his research program throughout the Chair's first five-year term. The product of the Chair's research has been the development of CUrisk, a computer model for evaluating the risk from fires in four-storey wood-frame commercial buildings. CUrisk treats the building as a system complete with its fire protection options, building characteristics, occupant characteristics and inherent functions. The model assesses the impact of fires on both life safety and property protection and thereby enables comparison of the costs and benefits of various design options. Figure 1 provides a schematic representation of how the various sub-models that comprise CUrisk work together.

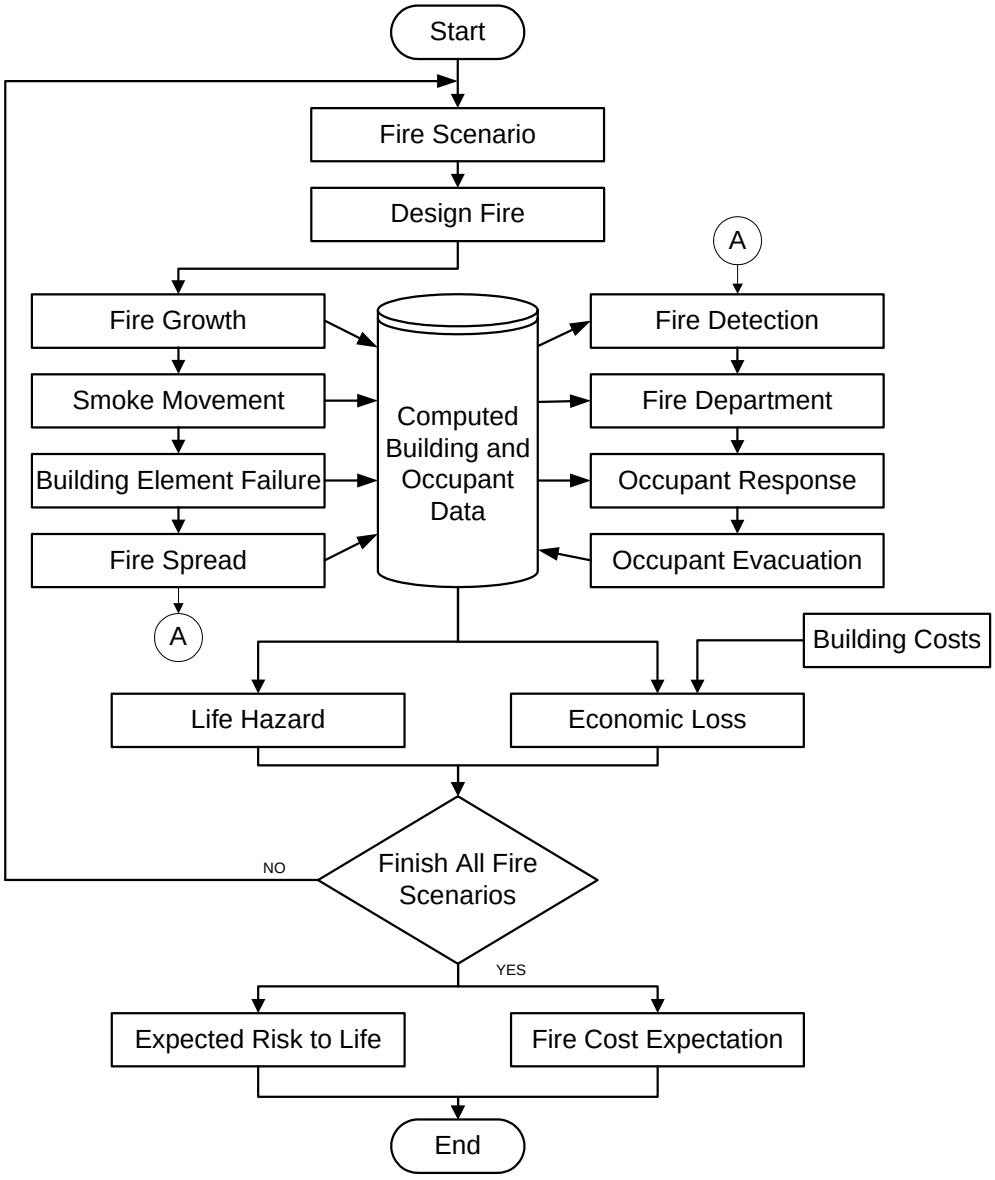

Figure 1 A schematic representation of CUrisk and its various components

Prof. Hadjisophocleous delivered a paper entitled "Development and Case Study of a Risk Assessment Model CURisk for Building Fires" during the *8th International Symposium on Fire Safety Science* held September 18-23 in Beijing. Co-authored with Z. Fu, the paper described CURisk, a computer model designed to assess fire risks associated with design options for four-storey wood-frame non-residential buildings. He showed a worked example of the use of the model using the Carleton Technology Training Centre in which Forintek's Fire Research Group is housed. Due acknowledgement was given to Forintek for supporting his Research Chair. Prof. Hadjisophocleous also exhibited a poster at the Symposium entitled "Characterising Design Fires for Clothing Stores". Co-authored with his student E. Zalok, the poster described ongoing efforts to characterise appropriate design fires for use in designing fire safe clothing stores.

6.7.2 Status of Students

During 2005-2006, five students studying with Prof. Hadjisophocleous completed the academic requirements for their Masters degree. Under a co-supervision arrangement with J.R. Mehaffey, Mr. M. Al-Duailej completed his non-thesis M.Eng. Report entitled "Analysis of Six Fire Experiments Conducted at Kemano Village (BC) by Forintek Canada Corp. in 2001". In addition, four students successfully defended their M.A.Sc. theses. J.R. Mehaffey was a member of the examination committees for all four students. The four students and their thesis titles were:

- Mr. Khalid Alnasser, "Mathematical Investigation of Heat Transfer in Industrial Crude Oil during a Fire".
- Mr. Kang, "Reduction in Fire Resistance of Steel Beams Caused by Partial Fire Protection Loss". (Co-supervised with Prof. Heng Aik Khoo.)
- Ms. Yoon Jeoung Ko, "CFD Study of Balcony Spill Plumes: Focused on the Balcony Area".
- Ms. Eman Elewini, "Performance of Gypsum Board Exposed to Fire".

The work of Mr. Al-Duailej and Ms. Elewini are of particular interest to Forintek. Mr. Al-Duailej documented the good fire performance of wood-frame houses as observed in the Kemano fire tests conducted in furnished houses in 2001. A summary of his work is provided in the 2005-2006 Progress Report for Project 4478. Ms. Elewini studied the behaviour of gypsum board in intermediate and full-scale fire-resistance tests conducted on wood-frame floor assemblies using standard and non-standard time-temperature curves. By analysing the results of numerous fire tests, she developed simple models to predict the time to fall-off of gypsum board as a function of such properties as the number of layers of gypsum board, the type of wood-framing, the type of insulation in the floor cavities and the presence of resilient channels. Models for predicting the time to fall-off of gypsum board provide important input to efforts to predict the performance of floors exposed to fire.

Mr. Al-Duailej and Mr. Alnasser have returned to the Aramco petroleum company in Saudi Arabia where they are fire protection engineers. Ms. Elewini has been hired as a fire protection engineer by Atomic Energy Canada Ltd in Mississauga. Ms. Ko has chosen to pursue doctoral studies in fire safety engineering at Carleton University. Mr. Kang, who will be graduated in the spring of 2006, is looking for work in a firm that offers structural and fire protection services.

Mr. Ehab Zalok has conducted a survey to characterise fire loads in commercial premises. Based on an analysis of the survey data, fuel packages representing the fire loads and types of combustibles in these buildings have been designed and used to conduct full-scale experiments. The experiments have provided details on the burning characteristics of the fuel packages including the heat release rate and production of toxic gases. The experimental data are being used to develop design fires for use in CUrisk, the fire risk model for wood-frame commercial building developed at Carleton University. Mr. Zalok will defend his Ph.D. thesis in April. The survey findings are summarised in a paper entitled "Fire Loads in Commercial

Premises" by E. Zalok, G. Hadjisophocleous and J.R. Mehaffey which has been submitted to the *Journal of Fire Protection Engineering* for publication.

Mr. Craft is developing a computer model to predict the thermal response of wood-frame floors subjected to a fire attack from below. The model which addresses both heat and mass transfer through gypsum boards and wood joists, also introduces new models for the calcination of gypsum board and pyrolysis of wood joists. Preliminary results from his work were very encouraging and were summarised in a poster entitled "Fire Response of Gypsum Board and Wood Framing" which was displayed during *8th International Symposium on Fire Safety Science* September 18-23 in Beijing and published in the Symposium Proceedings. In addition, a paper entitled "Predicting the Fire Resistance of Light-Frame Wood Floor Assemblies" based on Mr. Craft's work has been accepted for presentation at the 4th International Workshop on Structures in Fire, SiF'06, May 10-12, 2006 at the University of Aveiro in Portugal. Mr. Craft will defend his Ph.D. thesis in late 2006 or early 2007.

Ms. Ling Lu is developing a finite-element computer model to predict the structural response of wood-frame floors subjected to a fire attack from below. This structural model uses the temperature profiles predicted by Mr. Craft's heat and mass transfer model as input. Modelling is advancing well and Ms. Ling may defend her Ph.D. thesis in late 2007 or early 2008.

Dana Scherf is undertaking research under the join supervision of Prof G. Hadjisophocleous and Dr. J.R. Mehaffey. The National Building Code of Canada (NBCC) permits the structure of office, mercantile and industrial buildings that are low-rise and of limited area to be of either non-combustible or combustible construction. Ms. Scherf intends to investigate the relative performance of rated combustible vs. unrated non-combustible construction as permitted by the NBCC.

A summary of the students who have studied under Prof. Hadjisophocleous and have either graduated or completed all requirements to graduate is provided in Table 8. Table 8 also gives an indication of the subject of their research.

Table 8 Students who have completed all requirements to graduate

Student Name	Degree	Status	Project	Graduation
Dominic Esposito	MASc	Full-time	Economic Impact of Fires	Fall 2004
Derek Gruchy	MASc	Full-time	Occupant evacuation model	Fall 2004
Chandra Juneja	MASc	Full-time	Reliability of active fire protection systems	Spring 2005
Musaad Al-Duailej	MEng	Full-time	Kemano fire tests	Fall 2005
Eman Elewini	MASc	Full-time	Fall-off of gypsum board	Spring 2006
Khalid Alnasser	MASc	Full-time	Modelling fuel tank boilover	Spring 2006
Yoonjeoung Ko	MASc	Full-time	Modelling balcony spill plumes in atria	Spring 2006

The status and research topics of all of the remaining students studying under the supervision of Prof. Hadjisophocleous are summarised in Table 9.

Table 9 Students in Fire Safety Engineering Program

Student Name	Degree	Status	Project	Enrolment
Ehab Zalok	PhD	Full-time	Design Fires	September 2001
Steve Craft	PhD	Full-time	Thermal response of wood-frame floors	September 2001
Ling Lu	PhD	Full-time	Structural response of wood-frame floors	September 2004
Hao Cheng	PhD	Full-time	Inter-compartment fire spread in a building	September 2005
Lei Peng	PhD	Full-time	Not yet decided	September 2005
Yoonjeoung Ko	PhD	Full-time	Balcony spill plumes in atria	January 2006
Ning Wang	MASc	Full-time	Probability of failure of walls and floors	September 2003
Zhan Zhou	MASc	Full-time	Modelling atrium smoke exhaust	September 2003
Mondu Das	MASc	Full-time	Smoke movement in buildings	September 2004
Yan Wang	MASc	Full-time	Not yet decided	January 2005
Xin Mou	MASc	Full-time	Not yet decided	September 2005
Kasey Plante	MASc	Part-time	Not yet decided	September 2003
Roy Strickland	MEng	Part-time	Not yet decided	September 2004
William Kuffner	MASc	Part-time	Not yet decided	September 2004
Dana Turnbull	MASc	Part-time	Combustible vs. noncombustible construction	January 2003
Judyth Jeske	MASc	Part-time	Not yet decided	September 2002
Susana Chui	MEng	Part-time	Not yet decided	September 2002
Michael Wagemakers	M.Eng.	Part-time	Not yet decided	September 2003
Donny Buckingham	M.Eng.	Part-time	Not yet decided	September 2003
Sean Tracey	MASc	Part-time	Not yet decided	January 2002

6.7.3 Renewal of NSERC Industrial Chair

During the five-year term of the Chair, which ends March 31, 2006, significant progress has been made towards developing a comprehensive system model for performing fire hazard and fire risk evaluations on four-storey timber-frame commercial buildings. As a consequence, the Chair in consultation with J.R. Mehaffey prepared a proposal in the spring of 2005 for submission to NSERC requesting funding for a

second five-year term. The general aim of the proposed research is to fine-tune the engineering tools developed in the first five-year term to be applicable to specific occupancies; such as, hotels and motels, retail stores, open-plan office buildings, churches and warehouses. The overall objectives of the proposed research program are:

- To develop design fires anticipated in wood-frame hotels and motels, retail stores, open-plan office buildings, churches and warehouses.
- To complete the remaining sub-models (for example, the thermal and structural response model under development by Steve Craft and Ling Lu) and integrate them in the risk model.
- To carry out experiments for the validation of the fire growth and smoke movement model and the structural model.
- To demonstrate the application of the fire risk model using real building case studies.
- To develop new sub-models and test data to extend application of the risk model to other types of buildings, such as buildings using heavy timber construction and hybrid buildings.
- To develop a user-friendly interface for the fire risk model to facilitate data input and visualization of results.

In late July, an application, outlining the proposed research discussed above, was submitted by Carleton University to NSERC seeking continuation of the Industrial Research Chair for a second five-year term. The Canadian wood products industry, through Forintek, agreed to provide $500,000 over the five-year period in direct support and $225,000 *in-kind* assistance for the Chair's research program.

During the late fall, NSERC approved renewal of the Chair for a second five-year term. The award is conditional upon NSERC's final approval of the Research Agreement. Once the renewal has been finalised, NSERC Communications must be contacted before public announcement of the renewal can be announced. The Chair is arranging to convene a meeting of the Chair's Steering Committee in early April to discuss progress to-date and plans for the next term. In the interim, Prof. Hadjisophocleous and Dr. Mehaffey are preparing promotional material to assist Forintek in soliciting financial support from the industry.

6.7.4 Masters Program in Fire Safety Engineering

In addition to establishing a strong research program, the Chair is expected to establish an educational program in fire safety engineering. To this end, four graduate courses were offered in 2005-2006 in the classroom, by cable television and across the country in a web-based format.
During the fall term:

- Prof. Hadjisophocleous offered the course "*Fundamentals of Fire Safety Engineering*".
- Dr. Proulx (NRC) offered the course *People in Fires*.

During the winter term:

- Dr. Bénichou (NRC) offered the course *Design for Fire Resistance*.
- Dr. Mehaffey offered the course *Fire Dynamics I*.

Due to the success of its short courses *Introduction to Fire Safety Engineering* May 14-16, 2003, and *Engineered Fire Safety Systems* May 19-21, 2004, Carleton University offered a third short course directed towards practitioners entitled *Fire and Explosion Investigations* May 11-13, 2005. There were 65 attendees including fire investigators, fire protection engineers, fire prevention officers, building science practitioners and students in fire safety programs. The course provided an overview of the basic fire science needed to conduct comprehensive fire and explosion investigations and, through the use of case studies, illustrated how scientific investigations are undertaken. Dr. Mehaffey delivered three one-and-a-half lectures entitled "Ignition of the First Item", "Flame Spread, Ignition of the Second Item" and

"Response of Materials Exposed to Fire". The last lecture was authored and presented jointly with Mr. Steve Craft.

Carleton University will offer a fourth short course *Fire Hazard, Risk Analysis and Risk Management* May 3-5, 2006. The course will be designed for fire safety practitioners interested in gaining or reinforcing their knowledge of fire hazard and risk analysis and their application to fire safety design and fire risk management. More specifically, the course will be of benefit to: building officials; fire safety officers; building science practitioners; fire prevention officers; employees of insurance companies; industrial fire safety officers; enforcement officers; and code developers, as well as students in fire safety programs. J.R. Mehaffey will deliver three one-and-a-half lectures entitled "Standard Guidelines for Risk Analysis", "Exposure Assessment and Scenario Frequencies" and "Consequence Analysis and Risk Calculations".

J.R. Mehaffey has participated in two meetings of Carleton University's Fire Safety Engineering Advisory Council. The Council's Terms of Reference are to review the courses offered in fire safety, suggest new courses for the future, and, most importantly, provide advice and assistance in the preparation of a proposal for creation of a Graduate Level Program in Fire Safety Engineering. Students graduating under the supervision of Prof. Hadjisophocleous currently receive either an M.Eng., M.A.Sc. or Ph.D. degree in Civil Engineering. The hope is that within two years Carleton University can graduate students with a degree in Fire Safety Engineering. Given the progress that Prof. Hadjisophocleous has made in establishing Fire Safety Engineering courses and laboratory facilities, and the fact that the Province of Ontario is making new money available for new graduate-level programs, this initiative could be fast-tracked. During the first meeting, it was decided that a draft proposal be prepared before the end of April 2006 recommending appointment of two new faculty members and several new courses (by 2007). The proposal will have to move through several administrative levels before being submitted to the Province. During the second meeting it was agreed that the proposal should include four new courses (in addition to the existing six) as follows:

- Fire Hazard and Risk Management (expanding on the Short Course offered in May 2006)
- Building Fire Safety (designing how fire safety codes and standards are applied in both the current prescriptive environment and in the evolving performance-based environment)
- Industrial Fire Protection (highlighting engineering solutions common in these occupancies)
- Material Response to Fire (summarising fire-related material properties such as flammability, ignitability, combustibility, melting, charring, smouldering, structural behaviour, etc.)

6.7.5 Fire Research Facility at Carleton University

Construction of the $10 million Fire Research Facility for Carleton University on the Almonte Campus of the National Research Council was completed during the summer. Instrumentation, calibration and commissioning of the Facility's systems were completed during the fall. It had been planned that an official opening ceremony for the Facility would be convened in the late fall or early winter of 2005; however, due to scheduling conflicts for senior Carleton University personnel, the opening ceremonies have been delayed until the spring or summer of 2006.

A new Fire Research Laboratory is also nearing completion on the University campus. The Laboratory will house a new cone calorimeter as well as the following equipment donated by Forintek: an older cone calorimeter, a small-scale fire-resistance furnace, a small-scale flammability apparatus and platens for heating wooden 2 x 4s.

6.7.6 Related Developments

The departure of Prof. A. Razaqpar, who was engaged in finite element modelling of concrete structures, has given Carleton University an opportunity to immediately strengthen its commitment to Fire Safety Engineering. The Department of Civil and Environmental Engineering has advertised for an Assistant or Associate Professor in Structural Engineering with a closing date of February 28, 2006. Candidates were expected to have a PhD degree in civil engineering with expertise and experience in concrete structures and fire safety engineering. Candidates were also expected to establish collaborative research links with existing Department members, especially in the area of fire safety. More than 30 applications were received. It is anticipated that a short list will be drawn up by the end of March and interviewing will commence in April.

7 Conclusions

In the non-residential sector, prescriptive building codes often demand a higher level of fire safety be built into wood-frame buildings than into buildings of non-combustible construction. The extra cost associated with providing this higher level of safety can make wood-frame buildings less economical to build. Even when building code requirements and economics are not impediments, concerns about fire safety often cause designers or insurers to avoid the use of wood. This makes it challenging for the wood industry to capture a larger share of the non-residential market.

Performance-based fire-safety design offers the promise of eliminating the inequitable treatment of wood present in prescriptive codes. Consequently Forintek has taken steps to develop the requisite engineering tools required to undertake performance-based design. With funding from the Natural Sciences and Engineering Research Council (NSERC) and from Forintek, an NSERC Industrial Research Chair in Fire Safety Engineering was created at Carleton University in 2001 with Prof. George Hadjisophocleous as the Chair holder. Since that time, Forintek has engaged in active collaboration with the Chair in delivering his research program, and in educating students and practitioners capable of undertaking or approving performance-based design.

The Chair, Prof. George Hadjisophocleous, has just completed the last year of his five-year term. The product of his research has been the development of CUrisk, a computer model for evaluating the risk from fires in four-storey wood-frame commercial buildings. CUrisk is a comprehensive system model that treats the building as a system complete with fire protection systems, building characteristics, occupant characteristics and inherent functions. It calls upon subsidiary sub-models to simulate various aspects of the fire problem. With the assistance of students and Forintek, sub-models have been developed to model fire growth in the compartment of fire origin, fire spread between compartments, the thermal and structural performance of building assemblies, fire detection and warning, activation and reliability of fire suppression systems (sprinklers), and human behaviour including evacuation and performance in an environment with reduced visibility and high level of toxic gases. Ultimately CUrisk assesses the impact of fires on both life safety and property protection, and enables comparison of the costs and benefits of various design options.

With support from Forintek scientists, the Chair has also set up a strong educational program in fire safety engineering. A Short Course Series for practising engineers has been introduced with the fourth Short Course to be offered in May 2006. Six post-graduate courses are offered regularly on campus and across the country by internet. An Advisory Council has prepared a proposal for creation of a Graduate Level Program in Fire Safety Engineering. The proposal recommends appointment of two new faculty members and several new courses by 2007. The proposal is now being reviewed by the University.

The Chair has also leveraged support from Forintek and others to attract additional research funding and resources to Carleton University. Using financial and inkind commitments from Forintek as a basis, he leveraged support from Materials and Manufacturing Ontario to expedite development of models to predict the fire resistance of wood-frame floors. Using financial and inkind commitments from other groups, he has leveraged funding from the Canadian Foundation for Innovation and Ontario Innovation Trust to have $10 million Fire Research Facility constructed for Carleton University. This unique facility, which will open in the spring of 2006, will be of great value to the research program of the Chair. The experimental data obtained from these tests will be used to develop new and validate existing computer models to evaluate fire safety levels in buildings.

In order to introduce further refinements in CUrisk and to market its use within the design community, Forintek and NSERC have recently agreed to extend the Chair's for a second five-year term. By supporting development of the requisite design tools, such as CUrisk, and the training of engineers in their use, the wood industry can expect to capture a larger share of the non-residential market.

8 References

Canadian Commission on Building and Fire Codes. 1995. National Building Code of Canada 1995. National Research Council Canada, Ottawa, ON.

Esposito, D. 2004. Economic impact of fires in buildings. M.A.Sc. Thesis. Department of Civil and Environmental Engineering, Carleton University, Ottawa.

Fu, Z.; Hadjisophocleous, G. 2003. A fire risk computer model for timber frame buildings. Proceedings of the 4th International Seminar on Fire and Safety Explosion Hazards; 2003 Sept 8-12; Londonderry, Northern Ireland. p. 481-492.

Gruchy, D. 2004. Modelling occupant evacuation during fire emergencies in buildings. M.A.Sc. Thesis. Department of Civil and Environmental Engineering, Carleton University, Ottawa.

Hadjisophocleous, G.; Zalok, E. 2003. A survey of fire loads in commercial premises. Proceedings of the 4th International Seminar on Fire and Safety Explosion Hazards; 2003 Sept 8-12; Londonderry, Northern Ireland. p. 493-503.

Hadjisophocleous, G.; Zalok, E. 2004. A survey of fire loads in commercial floors of office buildings. Proceedings of the 10th Interflam Conference; 2004 July 5-7; Edinburgh, Scotland.

Juneja, C. 2005. Analysis of Ontario fires and reliability of active fire protection systems". M.A.Sc. Thesis. Department of Civil and Environmental Engineering, Carleton University, Ottawa.

Mehaffey, J.R.; Craft, S.T.; Richardson, L.R.; Batista, M. 2003. Fire experiments in furnished houses. Proceedings of the 4th International Seminar on Fire and Safety Explosion Hazards; 2003 Sept 8-12; Londonderry, Northern Ireland. p. 163-174.

Takeda, H. and Mehaffey, J.R. 1998. WALL2D: A Model for Predicting Heat Transfer through Wood-stud Walls Exposed to Fire. Fire and Materials 22, 133-140.