Designing for fire safety: the science and its application to building codes: [proceedings of] Building Science Insight '87

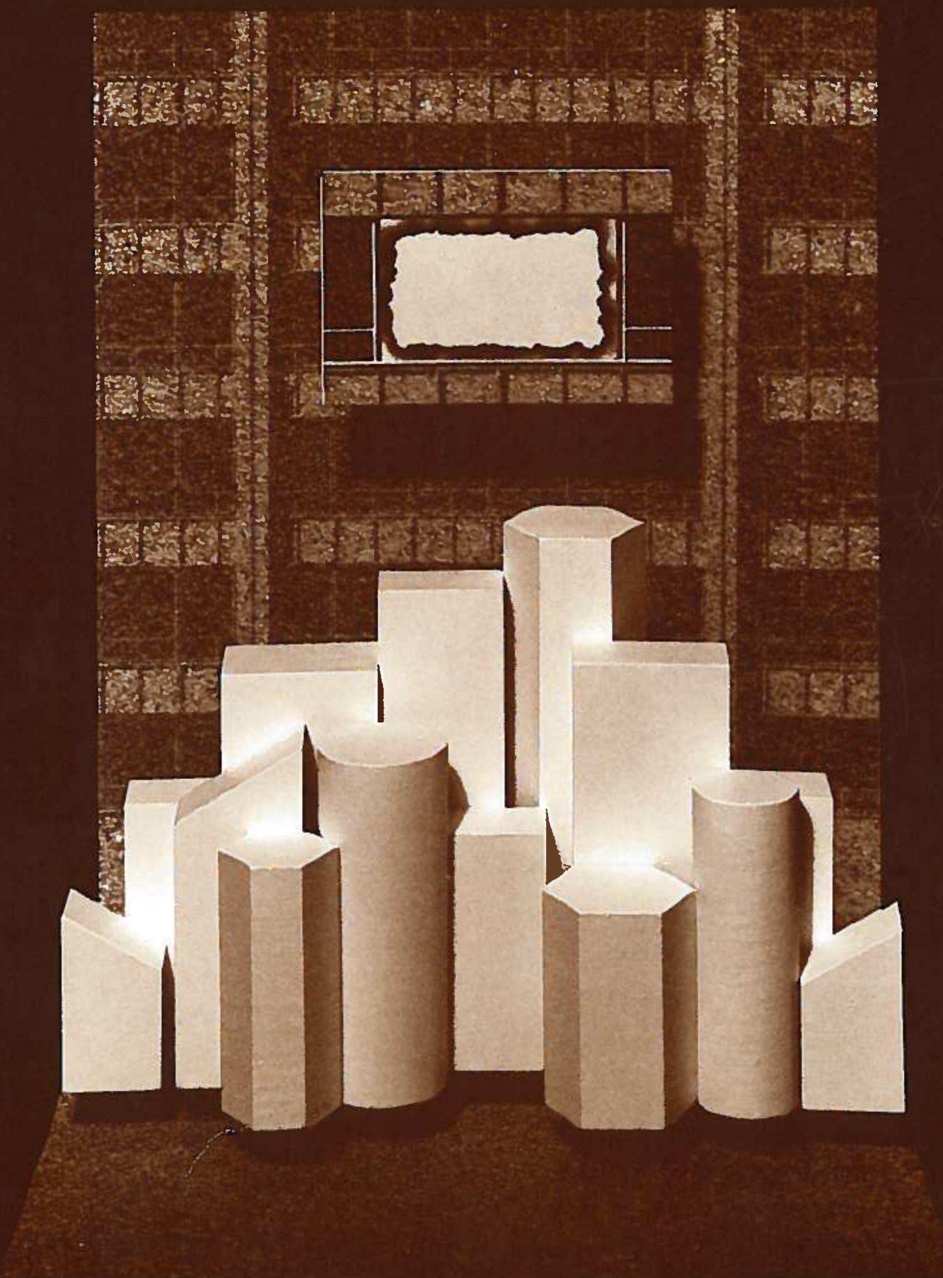
Richardson, J. Kenneth; Mehaffey, J. R.; Gosselin, Guy C.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/20330146
Proceedings (National Research Council of Canada. Institute for Research in Construction), 1987-11

National Research Council Canada | Conseil national de recherches Canada

Institute for Research in Construction | Institut de recherche en construction

Designing for Fire Safety



PROCEEDINGS OF BUILDING SCIENCE INSIGHT '87

Canada

ERRATA

Designing for Fire Safety: Proceedings of Building Science Insight '87

p.18

Second paragraph of left-hand column:

Please change	"For some buildings either combustible or non-combustible construction is permitted. Generally, more stringent requirements are placed on other fire protection provisions (such as fire resistance ratings) in the combustible buildings to allow for equivalent levels of safety."
to	"For some buildings either combustible or non-combustible construction is permitted. If the designer elects to use strictly noncombustible construction, however, the less stringent fire protection provisions (e.g. flame spread ratings) for combustible construction would still apply."

Designing for Fire Safety

The Science and its Application to Building Codes

Price $6.00
NRCC 28277
ISSN 0835-653X
Ottawa, November 1987

Foreword

This publication contains the proceedings of Building Science Insight '87, a series of one-day seminars on fire safety design of buildings held in ten cities across Canada in the fall of 1987.

Many people, each with a specific interest and jurisdiction, take part in the process leading to the design of a fire-safe building. They include architects, structural engineers, fire protection consultants, building officials, and materials manufacturers. In Canada, the model for fire safety in buildings is the National Building Code (NBC) of Canada.

The NBC provides for a minimum level of fire safety by regulating the combustibility and flammability of building materials, and by requiring compartmentation and structural fire protection where warranted. These provisions, however, are only one way to achieve safety. Other measures may be used if they meet the intent of the NBC. Interpreting the intent of the Code requires a good knowledge of the underlying scientific principles. In the development of alternatives, designers and building officials are often hindered by a lack of guidance on the roles of the NBC provisions in achieving fire safety.

In recognition of this fact, the Institute for Research in Construction (IRC) devoted its 1987 Building Science Insight program to fire safety design of buildings. The specific objective was to explain the "science" behind the Code provisions so that attendees, upon returning to the workplace, would be better equipped to play their respective roles in the development of creative and workable design alternatives.

Building Science Insight '87 was the 27th since IRC began its annual series of seminar/workshops in the sixties. Seminars were held in Halifax, Moncton, Quebec City, Montreal, Ottawa, Toronto, Winnipeg, Saskatoon, Edmonton and Vancouver. About 1300 persons attended the sessions, which consisted of both lectures and workshops. The papers published herein were written by IRC researchers Ken Richardson, Jim Mehaffey and Guy Gosselin who, assisted in some cities by John Berndt, gave the presentations in English. Appreciation is extended to Jean-Luc Poulin, professor of architecture at the University of Montreal who, along with IRC's Luc Saint-Martin and Guy Gosselin, gave the lectures and conducted the workshops in French in Quebec City and Montreal.

In addition to the speakers, many other members of IRC contributed to the success of the seminars. They include Madeleine Fleury and Gail LeBlanc, registration; Fern Brisebois, travel and hotel arrangements; Linda Hayes and Anne-Marie Dorais, editing and publishing of the proceedings; Gilles Ouelet and Louise Coutu, translation; Nicole Paquette, text processing and layout of the proceedings; Don Hobbs, Christa Gaudert and Doug Scott, graphics and slides; Alan Dalgliesh, quality assurance; and Jim Gallagher, publicity. Technical coordinator was Guy Gosselin.

IRC has always considered technology transfer to be an important element of its programs. Seminars such as Insight are an effective medium because they allow instant dialogue between speakers and participants. IRC researchers value this interaction because it gives them a perspective of practical problems that cannot be obtained in the laboratory.

R.G. Turenne
Coordinator, Building Science Insight '87

Fire Loss Statistics and Regulatory Framework

J. Kenneth Richardson, B.Sc., B.Eng., P.Eng.

Introduction

The annual cost of fire in Canada is approximately $6 billion*, of which $2.5 billion is fire losses and $3.5 billion is the cost of fire protection. Approximately 600 persons die in fires every year, with many times that number of serious injuries. How effective are our present regulations and standards at addressing those costs and losses? Are there other means that could be more effective? Who is responsible for fire regulations and standards?

Life safety from fire in Canada is primarily mandated by building codes, based on the National Building Code of Canada.[1] Property protection from fire is usually an economic consideration, with the property insurance companies often establishing minimum standards, while building codes contain some provisions to prevent major conflagrations. The objectives of these codes and standards with respect to fire costs and losses are among the subjects explored in this paper.

One of the primary objectives of the National Building Code of Canada (NBCC) is to provide a minimum level of fire safety for building occupants. To achieve this objective in part, the Code specifies the use of construction materials that are noncombustible, exhibit low flame spread or that form a barrier to the spread of fire. These measures, representing part of an overall solution to improved fire safety, are the major topics to be addressed in Building Science Insight '87.

In demonstrating how fire safety is addressed in Canada and how other means could be utilized, this paper discusses:

- current fire statistics in light of present fire safety measures and Code provisions,
- the role of building regulations in achieving fire safety,
- the roles of the National Building Code of Canada, the Institute for Research in Construction, provincial building codes and the standards writing and certification organizations,
- a simplified fire safety systems approach, that provides an alternative means to achieving fire safety.

Canadian Fire Statistics

It is difficult to measure accurately how well Canadian building codes, property insurance standards and other fire safety measures succeed in meeting their objectives. The sole measure available on a national scale is the composite fire loss data.[2] These statistics cover fires in buildings of all ages, so it is difficult to focus only on those constructed to the provisions of the most recent codes and standards or using current fire safety measures. The statistics can, however, shed light on the existing situation and help put present day fire safety in focus.

As indicated previously, annual fire costs in Canada are approximately $6 billion, which represents 1.25% of the gross domestic product. These costs consist of fire losses (40%, made up of life losses and personal injuries, property losses and indirect losses) and fire protection (60%, made up of fire protection installed in buildings, fire services and other municipal services related to fire). It is in our national interest, therefore, to reduce our fire losses and optimize fire costs. Means to address both of these will be discussed.

* Does not include forest fire losses

Figure 1 shows unpublished information developed by the Fire Research Section of the Institute for Research in Construction (IRC), based on a survey of fires in the U.S. Similar ratios probably exist for Canadian fire losses. (This is the assumption on which the following analysis is based.) Fires that grew up to flashover (the point at which an entire space is involved in fire) and beyond, were closely examined and, using certain assumptions, it was determined that 78% of these fires remained in the preflashover stage.

The remaining 22% of the fires examined grew to the post-flashover stage. Of those, 32% were confined to the compartment of origin, i.e., the separated space in which the fire began. In all, 85% of the fires surveyed were contained to the compartment of fire origin, and only 15% of the total fires spread beyond that compartment. These fires that spread are considered to have the greatest potential for loss of life and property damage, since they could involve an entire large building.

Life and property losses in Canada over the most recent decade are shown in Figures 2 and 3. From the Canadian fire loss statistics, 85% of the fire deaths in 1984 occurred in residential occupancies but these occupancies accounted for only 37% of the property losses (Figures 4 and 5). Seventy-two per cent of the

Figure 1 Fire development survey results

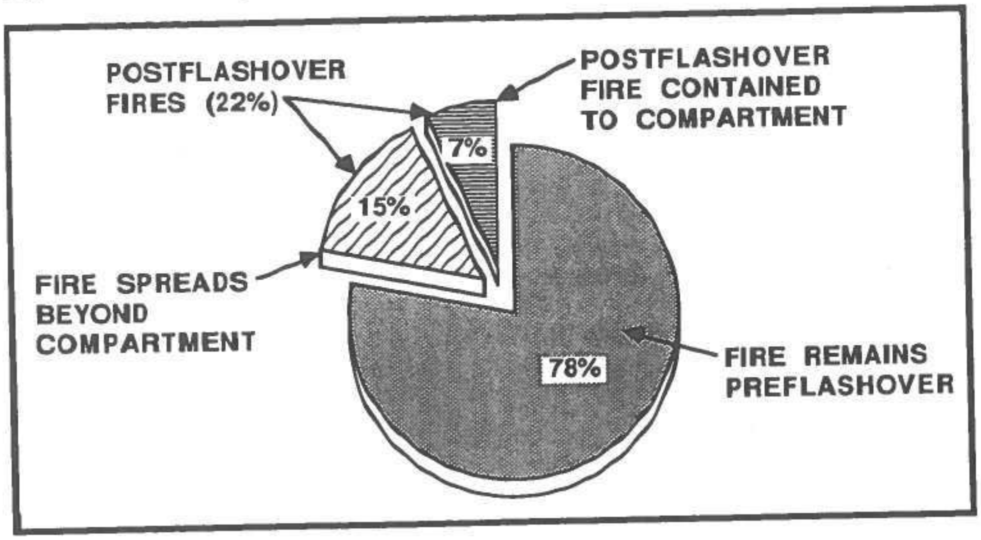
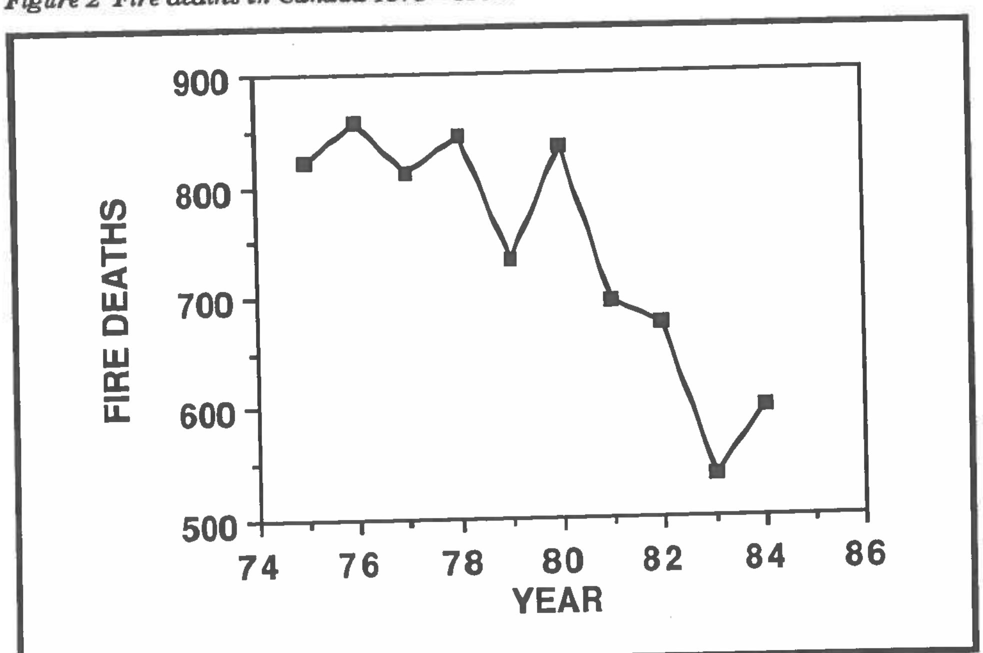


Figure 2 Fire deaths in Canada 1975 – 1984



residential fire deaths shown in Figure 4 occurred in one- and two-family dwellings and mobile homes. These dwellings typically contain only one fire compartment (since the rooms in a dwelling generally are not fire separated), so they may all be included in the 85% of fires illustrated in Figure 1 that were contained to the compartment of origin. In this type of occupancy, therefore, changes in fire safety measures that would have the greatest impact would probably be in the area of controlling the combustion process (such as safer furnishings and furniture) and suppressing the fire (as with residential sprinkler systems). A means to assess the impact of such changes will be discussed later. At this point it can be seen that the challenge to a thoughtful designer is to reduce the potential for fire losses and achieve optimum fire protection without increasing costs for fire protection.

Figure 3 Property losses in Canada 1975 – 1984

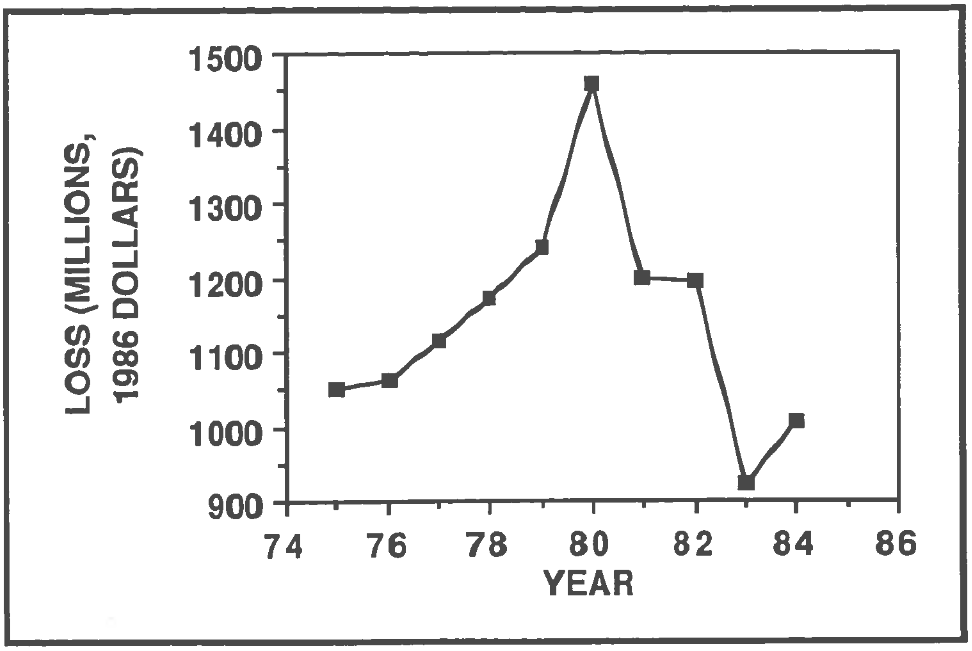
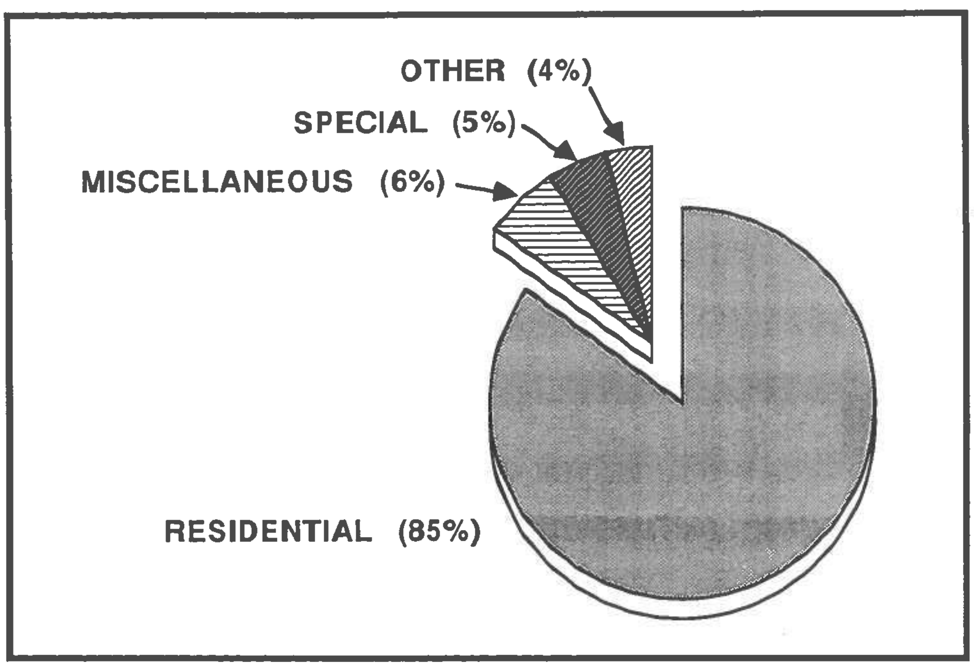


Figure 4 Fire deaths in Canada 1984, by percentage



Role of Codes in Fire Safety

Traditionally in Canada, architects and engineers have relied on building codes and insurance standards as the basis for fire safety design. With respect to life safety, building codes provide only one means of achieving a fire safety objective. Since codes are general in nature, often they do not address a specific fire problem. Such problems should be solved using a fire safety systems analysis, an example of which will be discussed later. Since codes are the typical present basis for fire safety design, it is important to understand their role in solving fire problems and their mechanism of addressing fire losses and fire costs.

Codes, such as the National Building Code of Canada, implicitly state how much fire safety is needed by specifying egress dimensions (from which egress time can be calculated), fire resistance, fire suppression and other elements such as fuel load limits. Taken together these represent the minimum level of fire safety that legislators are prepared to accept for building construction in Canada. Designers must, therefore, meet this level of safety for those issues addressed by building codes (in the NBCC these are primarily life safety).

Code Equivalencies

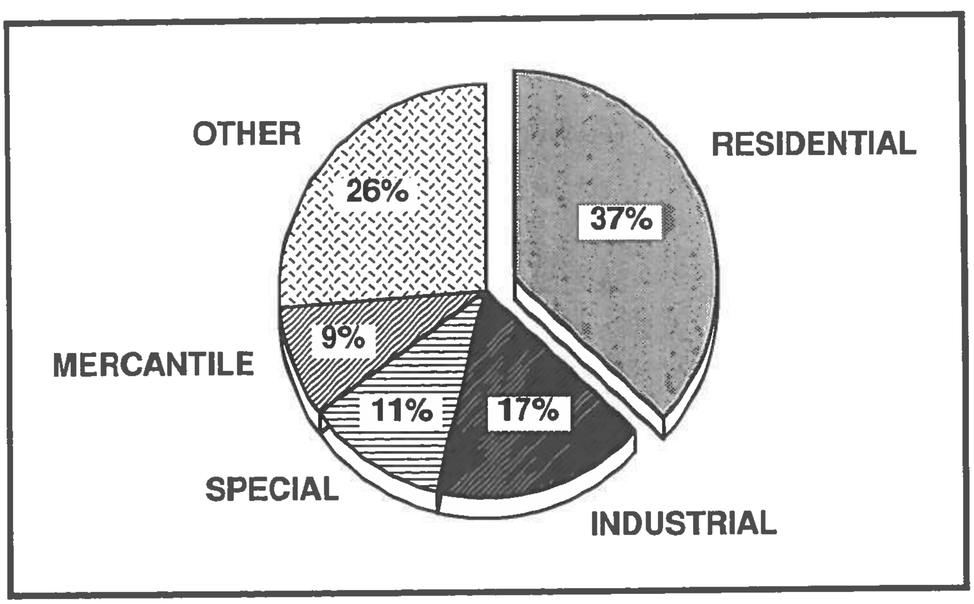
Knowing or being able to determine the level of safety intended by the code permits designers to develop solutions which may differ from the specific code provisions, but which provide the same level of safety. Such solutions are called equivalents and are often used in large or complex buildings, where meeting the letter of the code is difficult or impossible. It is the designer's responsibility to demonstrate equivalency and the code agency's responsibility to assess it. This is often done through the presentation and evaluation of a fire safety systems analysis addressing the specific issue. Examples of these equivalent solutions will be presented in other papers in this seminar.

Codes and Standards in Canada

Before discussing a means of developing equivalent solutions, it is important to understand the basis and history of Canadian Codes, in particular the NBCC. Prior to 1941, most large municipalities in Canada passed building bylaws based on British and American Codes. Then the Government of Canada asked the Department of Finance and the National Research Council to develop model building regulations which could be used uniformly in all areas of the country. This request was principally in response to a need for uniform housing regulations, which were the responsibility of the Department of Finance. The result of that work was the 1941 edition of the National Building Code of Canada.

The responsibility for the National Building Code of Canada was given to the National Research Council in 1948. Nine editions have been published by the National Research Council, the most recent in 1985. The NBCC is presently published on a five-year cycle, with interim amendments issued as needed.

Figure 5 Property losses in Canada 1984, by percentage



After the National Research Council was given responsibility for maintaining and updating the Building Code, the Associate Committee on the National Building Code (ACNBC) was formally established as the body responsible for this task. Its mandate was to develop model regulations with reference to public health, fire protection and structural sufficiency. This is often interpreted to mean life safety only, however, certain property protection provisions are included. To assist the ACNBC in technical matters, technical committees or standing committees were established, consisting of persons knowledgeable in a specific technical area. In the field of fire safety, there are three such standing committees; one each on fire protection, occupancy and fire performance ratings. The first two are responsible for Part 3 of the NBCC (Use and Occupancy), while the third is responsible for Chapter 2 of the Supplement to the NBCC (Fire Performance Ratings).

In general, the ACNBC establishes the policies for the code committees (as articulated in the ACNBC Policies and Procedures[3]), coordinates committee activities, and gives final approval of all changes to the Code and its associated documents. The standing committees are responsible for the technical content of their particular portions of the documents. Membership on all code committees is broadly based, with balanced representation from industry, regulatory agencies and other users.

The staff of the Institute for Research in Construction of the National Research Council provides technical and secretarial support at the direction of the ACNBC. Technical problems revealed through the process of formulating or revising the Code are referred to IRC research sections for study, in order to make available to the committees the most up-to-date information on building technology and safety. The Fire Research Section has carried out many such studies and much of its research work is reflected in NBCC requirements. One point that should be noted is that staff of the Institute serve only as technical advisors or secretaries to the committees; they do not vote on any committee action.

The NBCC, as a model document, has no power of law until it is adopted by a provincial or territorial government. Since building regulations are the purview of the provinces, it is they who give the NBCC the force of law by adopting it as a provincial building regulation. Some provinces write their own regulations using the NBCC as a basis; some adopt it by direct reference, while other provinces provide legislation that enables municipalities to adopt it as a municipal bylaw.

The level of detail needed to ensure fire safety in buildings is enormous. For this reason, the NBCC makes reference to hundreds of standards, some of which are codes in themselves, such as the Canadian Electrical Code, Part 1.[4] These standards, which ensure a minimum level of safety in specific technical areas, are generally developed by Canadian standards-writing organizations using committees balanced in a manner similar to those of the ACNBC. In Canada, the major standards-writing organizations in the area of fire are the Canadian Standards Association (CSA), Underwriters' Laboratories of Canada (ULC), and the Canadian Gas Association (CGA). The standards of the National Fire Protection Association (NFPA) are also used extensively in the fire safety field.

While the NBCC mandates specific performance by the use of a code requirement or by reference to a standard, it does not require that such products or systems be certified (listed or labelled). Certification organizations provide a service to code users and regulators by certifying that products bearing their marks have been tested and are in conformance with various codes or standards. While certification is not required as proof of performance, it is often used to ensure that the minimum standards have been met.

Fire Safety Systems Analysis

As previously indicated, a designer faced with a problem related to fire or life safety is often tempted to seek out codes or standards as the sole solution. When those solutions do not provide the specific answers, or provide answers that are not consistent with other aspects of the project, such as aesthetics, costs or function, a fire safety systems analysis is the recommended means to solving the problem.

Building designers and fire protection engineers may use fire safety systems analyses to solve non-typical fire problems. Code officials often use such analyses to evaluate equivalent solutions that have been submitted for approval. Code writers may also use them in the future to assess the impact and economic viability of proposed code changes.

The term 'fire safety systems analysis' describes a methodical, step-by-step approach to solving a fire safety problem. The approach illustrated here is based on the NFPA Fire Safety Concepts Tree, which is documented in the Fire Protection Handbook[5] and the NFPA Standard 550, Fire Safety Concepts Tree[6]. It is limited, however, to an elementary treatment and illustrates how the BSI '87 papers relate to the tree and how codes impact on the application of such analyses.

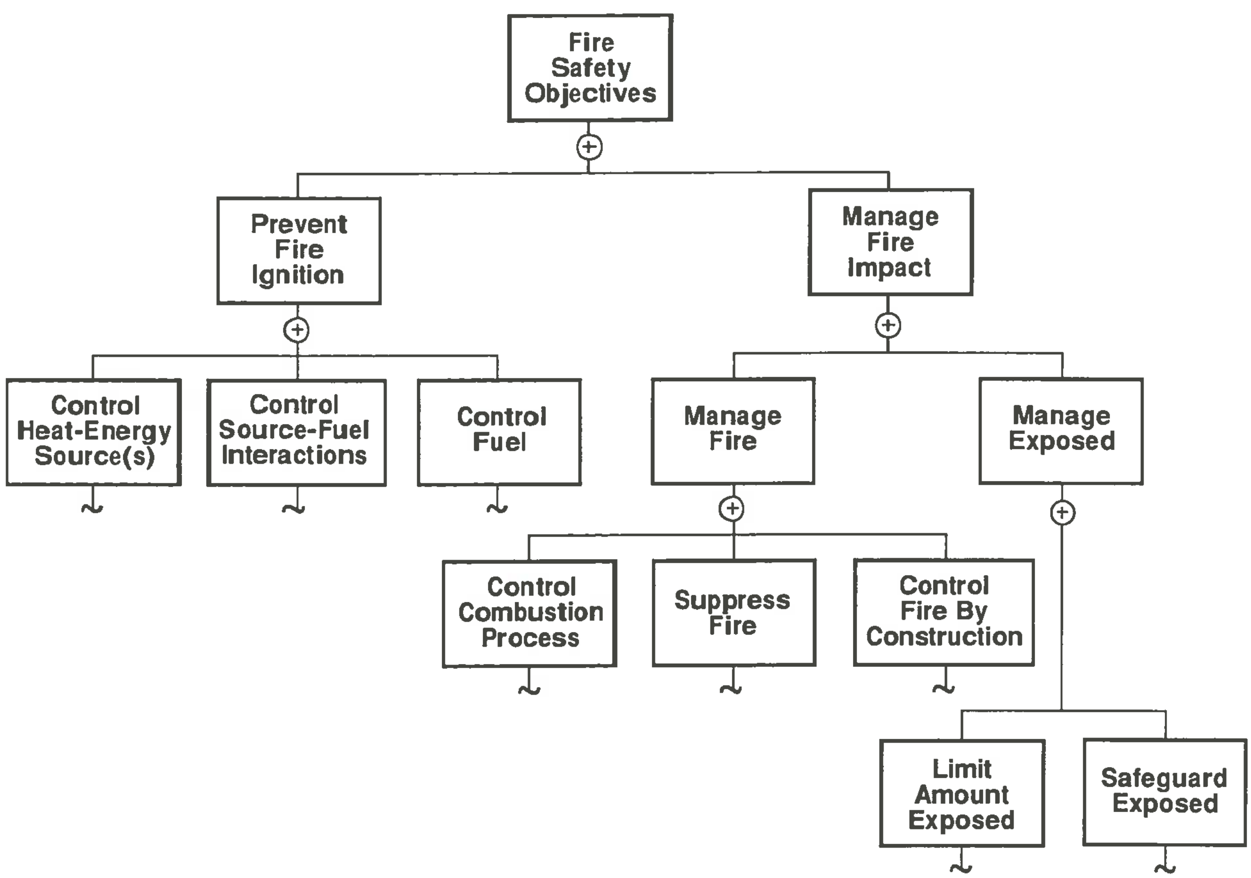
In this paper, hard data on a specific fire problem is not used and it is often difficult to obtain. The Fire Research Section of IRC is working with the Footscray Institute of Technology (Australia) to develop a quantitative hazard assessment model that incorporates the concepts of the National Building Code of Canada and Canadian fire experience. Additionally, the Ontario Ministry of Housing is co-sponsoring with IRC and the other provinces a contract to create a code assessment framework that can be used to evaluate all requirements of Canadian codes, not just those related to fire. These models will be available in the coming years and should prove to be powerful tools for the assessment of fire hazards and fire safety measures.

Principal Branches

The following sections describe one fire safety systems analysis method. Others are available, but this is the one most often used in North America. The principal branches of the Fire Safety Concepts Tree[6] are illustrated in Figure 6. The + symbol means that one branch or the other will achieve the objective of the box above it. In order to use the tree system, the general topics in the boxes are replaced by the parameters of the problem under consideration. In building design, the fire safety objectives illustrated in the top box should describe the degree to which a building must protect its occupants, contents, operations and neighbours. For example, the objective in life safety could be that the occupants be safeguarded against intolerable or untenable fire conditions for a certain time, while the objective for contents may be that only so much property be lost. Thus the fire safety objectives will vary depending on the situation. Those for a hospital will differ from those for an automated warehouse.

One of the basic objectives used in a fire safety systems analysis in which life safety is a factor is the time for occupants to escape to a safe location. While not specifically defined in the NBCC, the time for egress is implicit in the numerous requirements for egress routes; from these, egress times can be calculated. This time for egress provides the principal basis for assessing a building's fire safety measures in terms of occupant protection, and will differ by occupancy; for example, a nursing home will probably require greater time for egress than a retail store of the same size.

Figure 6 Principal branches of the Fire Safety Concepts Tree



In dealing specifically with property protection objectives, the minimum level of fire safety is usually dictated by the economics of the situation, except in those cases where the property to be protected provides an essential service. Obviously property insurance premiums and the cost of fire protection measures are important economic considerations.

At the first level of the tree, the fire safety objectives can be achieved by preventing fire ignition or, if a fire does occur, by managing its impact. The prevention of fire ignition is essentially the responsibility of a fire prevention code, such as the National Fire Code of Canada[7] and requires continuous monitoring for success. The major players pursuing this form of fire safety are the fire departments and public information agencies with their fire prevention programs. These programs are effective to a point, however, none of them provides assurance that a fire will not occur. To achieve the fire safety objective, therefore, the management of fire impact assumes a significant role.

For either of the branches to satisfy the objective on its own, it must be 100% effective. Obviously, in the real world, such levels are seldom achieved. In recognition of this, most fire safety systems analyses rely on a combination of the various measures or on redundant measures within a certain branch. The objective is, however, to achieve 100% efficiency and reliability using whatever measures are necessary.

The management of fire impact can be satisfied by either managing the fire or managing the 'exposed' (again assuming 100% reliability of each branch). The exposed could be building occupants or property, or an adjacent building. Management of the exposed is generally met either by moving the affected people or property to a safe area or by defending them in place. It encompasses elements such as egress and exit design, and areas of refuge, which are essential to achieving the fire safety objective pertaining to life safety, but are not the subject of this seminar.

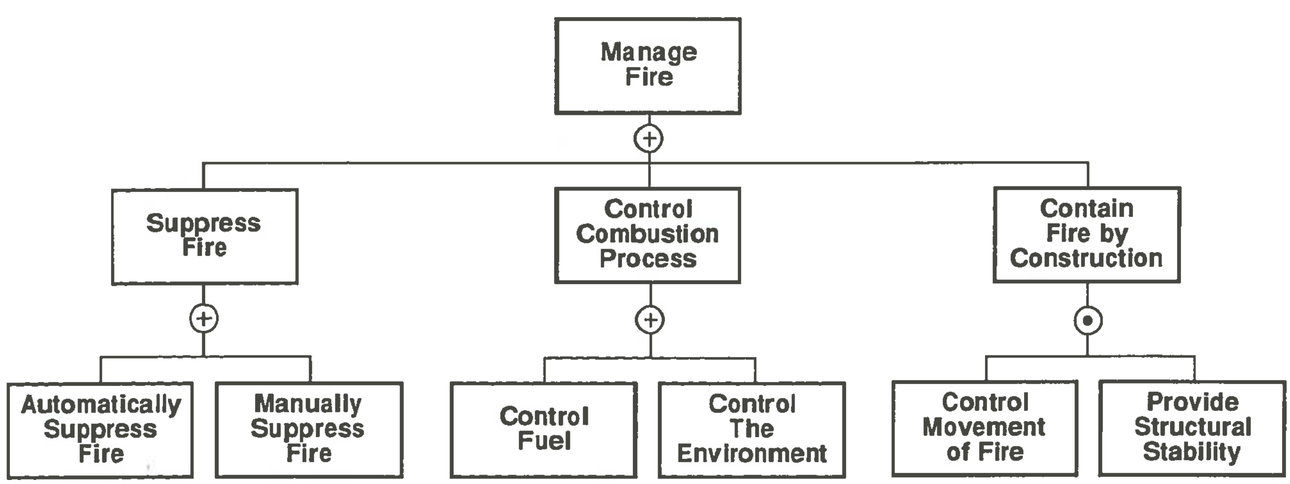
Management of Fire

This seminar will concentrate on the management of fire. This sub-branch of the Fire Safety Concepts Tree is expanded in Figure 7. This objective can be met by suppressing the fire, controlling the combustion process, or containing the fire by construction.

While it will not be addressed in this seminar, fire suppression is an often-used technique that meets the objective of managing the fire. Perhaps the most common means of fire suppression is the automatic sprinkler, and building codes often rely on this to provide safety for building occupants. As can be seen in Figure 7, the suppression of fire can be satisfied by either automatic means (such as automatic sprinklers or automatic halon systems) or manual means (such as portable extinguishers or fire hoses). Either of these will achieve the objective, assuming 100% reliability, but both must be preceded by some means of fire detection.

The second and third presentations of this seminar deal with the combustibility and flammability of building materials and fire growth. The information contained in those lectures will provide means to control the combustion process. Controlling this process addresses either

Figure 7 Manage Fire sub-branch of Fire Safety Concepts Tree



the fuel or the environment in which the fuel is located. Non-combustibility of building materials, controlling the ignition process, reducing flame spread and fire growth potential are some of the issues to be considered in this area. The simplest way to meet this objective would be to have virtually noncombustible materials or to create an environment where continued combustion is difficult. North American lifestyles and economic considerations usually preclude these simple solutions, so the presentations will demonstrate other techniques that can be used to control the combustion process. Often this element is used in conjunction with the other two to achieve the management of fire.

The fourth and fifth presentations, which address the containment of fire by construction, are directed at fire compartmentation and structural fire protection. To meet this objective, both fire compartmentation and structural stability under fire conditions must be present, as indicated by the • sign on the fire safety concepts tree. The control of fire by construction is a well documented subject and has been a traditional means used in building codes to achieve fire safety. This seminar will review the need for compartmentation, address the material properties which influence thermal transmission and other compartmentation features, and demonstrate means to predict the fire resistance of building elements. Again, this element is often used in conjunction with the other two to achieve the management of fire objective.

Concluding Remarks

Building Codes and fire prevention codes in Canada provide generalized solutions which have been reasonably effective in the reduction of fire losses and fire costs, however, Canadian fire statistics indicate that there is room for improvement. The most effective means to solve a fire problem is through the use of a fire safety systems analysis which addresses the specific issues and limitations involved. Such analyses usually involve the evaluation of various fire safety measures and the resulting solutions often incorporate a variety of these measures in attempting to achieve 100% reliability.

Improvements in fire safety will have the greatest impact on loss of life in the area of residential one- and two-family dwellings and mobile homes. These improvements must be specifically addressed to those buildings and the lifestyles of their occupants by the use of a fire safety systems analysis, the results of which would form a basis for changes to building codes. This is the real challenge to designers, regulatory officials and code writers.

References

1. National Building Code of Canada, 1985. Associate Committee on the National Building Code. National Research Council of Canada, Ottawa, NRCC23174.
2. Fire Losses in Canada, Annual Report 1984, 1986. Office of the Fire Commissioner of Canada, Ottawa.
3. ACNBC Policies and Procedures 1985. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, NRCC 24378.
4. Canadian Electrical Code, Part 1, 1986. Canadian Standards Association. Rexdale, Ontario, CSA C22.1-1986.
5. Coté, A.E. and J.L. Linville (eds.), 1986. Fire Protection Handbook, 16th Edition. Systems Concepts for Building Firesafety, National Fire Protection Association, Quincy, MA, pp. 7-10 to 7-14.
6. Guide to the Firesafety Concepts Tree, 1986. National Fire Protection Association, Quincy, MA, NFPA 550 - 1986.
7. National Fire Code of Canada, 1985. Associate Committee on the National Fire Code. National Research Council of Canada. Ottawa, NRCC 23175.

Combustibility of Building Materials

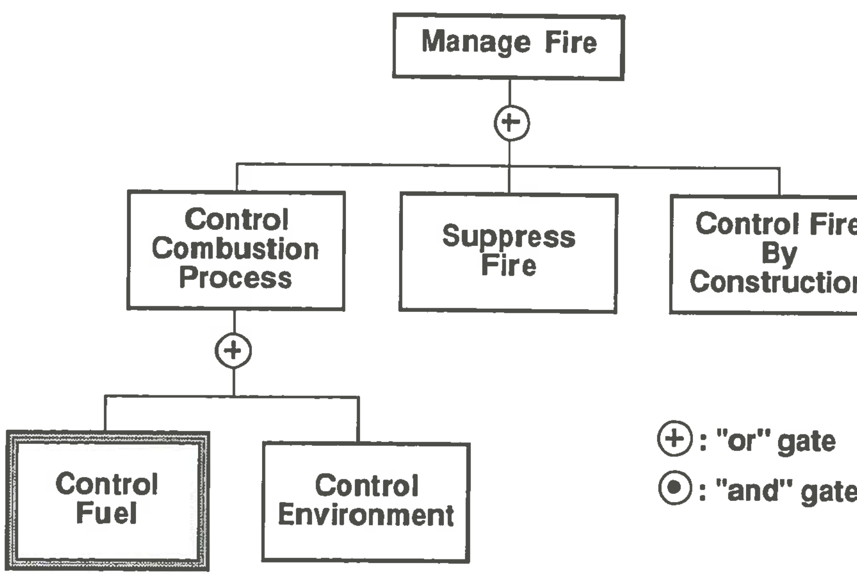
J.R. Mehaffey, Ph.D.

Introduction

Building codes and other regulations often put restrictions on the ignitability and combustibility of building materials and contents, as well as on the proper uses of potential ignition sources. If fires are difficult to ignite, remain localized once ignited or, at worst, spread and burn slowly, then building occupants are likely to have sufficient time to escape. It must be recognized though, that it is not practical to specify the exclusive use of noncombustible building materials or noncombustible contents.

In this paper a review of test procedures aimed at segregating building materials into combustible and noncombustible categories is presented, as well as an explanation of the intent of requirements for noncombustible construction contained in the National Building Code of Canada (NBC).[1] Whether a building must be of noncombustible construction or not depends on the building size, the hazards it contains, the mobility and level of alertness of occupants, how many streets it faces, and whether or not it is sprinklered. Controlling the combustible content of buildings (or controlling the fuel) in this manner plays a significant role in the Manage Fire sub-branch of the Fire Safety Concept Tree (Figure 1).

Figure 1 Control Fuel element in Manage Fire sub-branch of Fire Safety Concept Tree



The paper concludes with a discussion on the need for the development of a more general test method for evaluating the degree of combustibility of building materials.

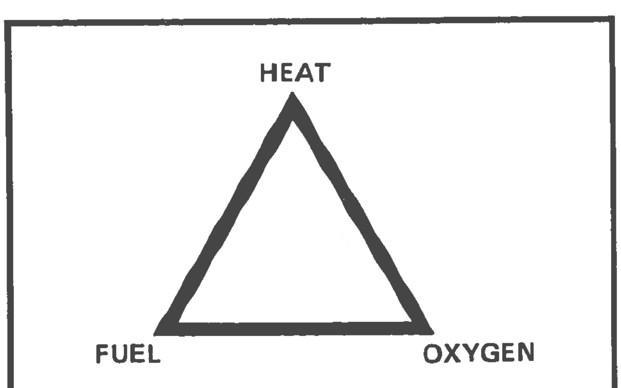
The Basic Chemical and Physical Nature of Fire

A chemist envisions a fire as a complex series of chemical reactions involving the oxidation of fuel, usually containing carbon. Physically, of course, a fire is characterized by visible flame, heat and smoke.

The fire triangle, depicted in Figure 2, illustrates the three components required for a fire: fuel, oxygen and heat. The fire triangle can be looked upon as a physicist's descriptive model of fire. Its utility becomes evident when considering extinguishment (suppression), which can be achieved by isolating one of the three components from the other two. Fire can be suppressed by removing heat (with water spray, for example), by removing the fuel (turning off the flow of fuel in a Bunsen burner, for example), or by removing the oxygen (by smothering the fire with a fire blanket).

This physical representation of fire is useful, but the fact that chemical reactions are also needed to keep the fire going cannot be ignored. The basic components of fire then should also include the uninhibited chain reactions within the flame and at the fuel surface, as depicted in Figure 3. This allows for the possibility of a fourth extinguishment (suppression) technique: that of inhibiting the chain reaction (quenching the flame) with fire retardant chemicals. Halogens, such as chlorine and bromine (found in halons), are elements that act in this fashion.

Figure 2 Fire triangle – three components required for a fire

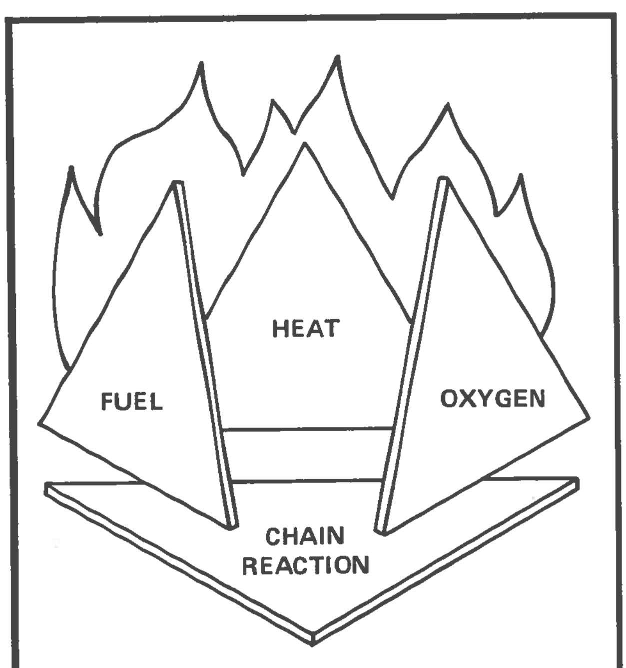


Of course there is more to a fire than the presence or absence of these three or four components. Fire is a complex phenomenon involving chemical kinetics, fluid mechanics, heat transfer, and thermodynamics. The process of ignition of a solid, for instance, can be described as follows.

Consider an external heat source (an overheated wire) in contact with a combustible material (wood, for example). The temperature at the surface of the wood increases steadily to 100°C, at which point water is driven off as steam. As the temperature continues to increase, the wood starts to undergo pyrolysis; that is, it starts to decompose into volatiles (vapors) and char. The volatiles, being hotter and hence less dense than the surrounding air, rise and mix with the air.

At around 300°C, this mixture of volatiles and air can ignite, producing a flame. Some of the heat generated by the flame escapes with the rising hot gases, but a portion of it is 'fed back' to the fuel (by radiant, convective or conductive heat transfer), causing its temperature to increase further and pyrolysis to proceed at a greater rate. In turn, the flame grows. If the heat feedback to the fuel is sufficient to cause it to pyrolyze and burn by itself, one has 'sustained flaming combustion'. The original ignition source is no longer needed (Figure 4).

Figure 3 Fire tetrahedron – chemical reactions required to keep a fire going



Char formation, which occurs only in some materials, can play an important role in the burning process. In its position between the flame and the burning object, it can act as a shield, slowing down heat transfer to virgin fuel and in turn decreasing the rate of burning or of heat release. Fires do not burn well on the top surface of a piece of wood.

On the other hand, in geometries such as that depicted in Figure 5, air drawn into the flame can play directly on the hot char. The char can undergo oxidation (it glows) and the heat released can cause pyrolysis of the virgin fuel below the char. Sticks of wood burn well if ignited from below.

Products of combustion rise above the flame in the form of smoke and heat. Smoke consists of airborne solids (soot), liquid droplets, and gases, some of which may be toxic. Of the toxic gases produced, carbon monoxide is certainly the most prominent; however, hydrogen cyanide and hydrogen chloride may also be produced when polyurethane or polyvinyl chloride is burning. Being quite buoyant, smoke and the toxic gases within it can migrate to areas fairly remote from the fire, presenting the primary threat to occupants of a building. It is this that makes them the leading cause of fire deaths.

Flaming combustion is easily differentiated from another type of combustion called smouldering. Essentially, smouldering combustion is typified by low temperatures and a very slow rate of combustion. It takes place when the volatiles liberated from the surface of the fuel are not hot enough or in sufficient quantity to ignite, but sufficient heat is generated to keep the fuel pyrolyzing. The lack of buoyant forces means that little air is drawn over the fuel surface, limiting the rate of combustion. Such products as loose-fill cellulose insulation, fibreboard and, of course, cigarettes, have a propensity to smoulder for a considerable period of time with only a small ignition source.

Solid fuels or combustible materials can be categorized in a number of ways. For instance, a distinction is made between charring and noncharring materials, based on the capacity of the material to form a char as it pyrolyzes. Most materials with a high cellulosic content, such as wood, produce a char residue; however, so does hydrocarbon-based polyvinyl chloride and certain thermosetting resins, such as phenolic and polyisocyanurate foams. Other materials, such as polystyrene, produce little or no char when they burn.

Another differentiation is made between synthetic polymers according to their propensity to soften and melt (deform) at a temperature below that required for thermal decomposition or ignition to occur. When this characteristic prevails, the polymer is called a thermoplastic. When involved in a fire, such materials can have quite an effect on its behavior, due to falling droplets or the spread of a burning pool of molten polymer on the ground. Polymers that

Figure 4 Sustained flaming combustion

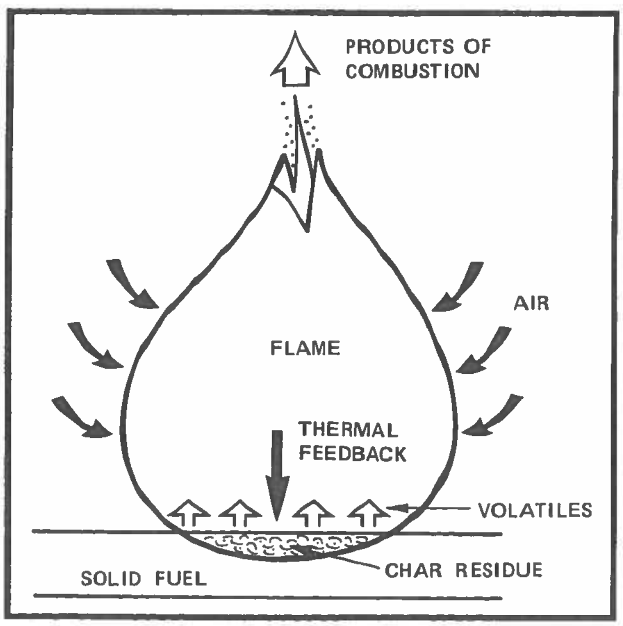
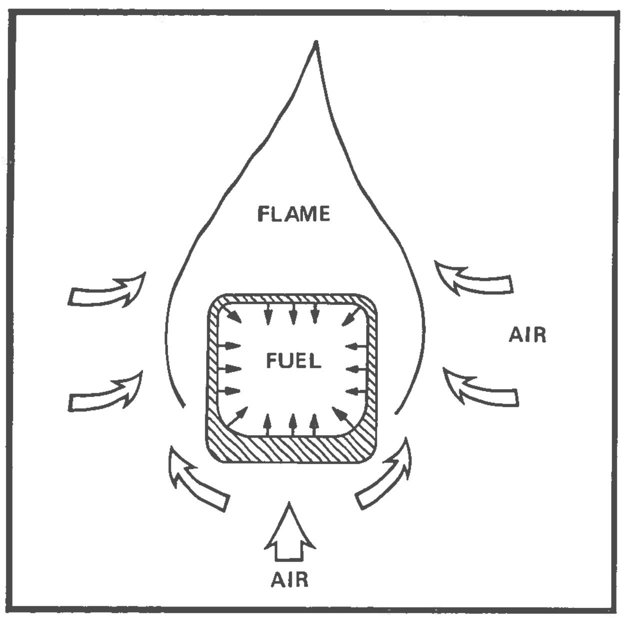


Figure 5 Flaming combustion of a char-forming solid



have a cross-linked molecular structure will not melt when heated. Instead, at a sufficiently high temperature, they will decompose, giving off volatiles directly from the solid, often leaving behind a carbonaceous residue, much as wood does. These polymers are called thermosets or thermosetting resins.

Table 1 lists a few examples of thermoplastic and thermosetting polymers. Rigid polyurethane foams commonly used as building insulation in exterior walls or over roof decks, and flexible polyurethane used for cushioning in upholstered furniture, are generally thermosets, although the extensive use of plasticizers may make certain polyurethane foams behave as thermoplastics. Phenolics are thermosetting materials used in circuit breakers.

Table 1 Some Synthetic Polymers

Thermoplastics (melting)	Thermosetting (non-melting)
Polyethylene	Epoxy
Polymethylene	Polyester (fibre or glass reinforced)
Polymethylmethacrylate (PMMA)	Polyisocyanurate
Polypropylene	Polyurethane (rigid or flexible)
Polystyrene	Phenolics
Polyvinyl chloride (PVC)	

Thermoplastics find varied applications in the marketplace. Polyvinyl chloride (PVC) is used mainly for piping and conduit, polystyrene for foam insulation, polyethylene as a vapor barrier and PMMA, also known as Plexiglass*, for glazing.

Ignition Sources in Building Fires

Obviously, a sound fire protection measure would be to limit the number of fires by limiting the number of ignitions. Building fires usually start with the ignition of a single item, which involves two factors: the ignition source and the first item ignited.

Statistics on ignition sources in building and vehicle fires are collected annually by the Fire Commissioner of Canada. Fire losses by source of ignition for the year 1984 are summarized in Table 2.[2] The most common ignition sources include cooking, heating, and electrical distribution equipment, and smoker's materials or open flame.The hazards associated with such ignition sources have been known for some time. It is certainly not practical to eliminate these sources. Instead, standards and codes have been developed to mitigate the hazards. Some of these are summarized in Table 3.

*Trademark

Table 2 Fire Losses by Source of Ignition - 1984

Source of Ignition (Igniting Object)	No. of Fires	Dollar Loss	Injuries	Deaths
No igniting object (e.g. Lightning)	450	11 829 531	20	2
Cooking equipment	8 406	43 355 794	692	48
Heating equipment	7 915	87 320 198	285	61
Appliances and equipment	2 605	21 432 925	78	6
Electrical Dist. equipment	7 640	108 671 994	281	33
Other electrical equipment	1 671	16 997 569	67	7
Smoker's material	5 399	42 090 030	724	181
Match, lighter, lamp candle, taper	2 218	24 939 216	135	17
Cutting torch, welding equip., varied torches	933	21 620 019	93	2
Hot ashes, embers	536	7 153 197	12	1
Smoker's materials or 'Open' Flame	5 248	43 499 032	149	13
Exposure to fires in other buildings	2 150	19 273 978	24	8
Miscellaneous	15 203	171 286 013	453	31
Undetermined	10 356	310 009 575	1 090	188
TOTAL	70 730	929 479 253	4 103	598

Table 3 Standards or Codes regulating ignition sources

Ignition Source	Standards and Codes
Cooking equipment	NBC - installation requirements
	CSA - product specifications
	CGA - product specifications
Heating equipment	NBC - installation requirements
	CSA - product specifications
	CGA - product specifications
Appliances and equipment	CSA - product specifications
Electrical distribution equipment	CEC - installation requirements
	CSA - product specifications
Open flames	NFC - permitted practices
Welding and cutting equipment	NFC - permitted practices

NBC - National Building Code of Canada
CSA - Canadian Standards Association
CGA - Canadian Gas Association
CEC - Canadian Electrical Code
NFC - National Fire Code of Canada

The First Item Ignited

Ignition requires both an ignition source and a combustible fuel. As with ignition sources, it is impractical to simply eliminate combustibles from buildings. Instead one attempts to control their ignitability or combustibility.

In a recent study conducted by Consumer and Corporate Affairs Canada,[3] provincial statistics were reviewed to establish which materials are most likely to be the first item ignited in building or vehicle fires. The results of the study are summarized in Table 4.

Table 4 Materials first ignited in building or vehicle fires

	Percent of Total			
Material First Ignited	Incidents	Dollar Loss	Injuries	Deaths
Flammable or combustible liquids	18.7	11.1	23.6	7.3
Furniture, furnishings	10.4	7.2	19.8	24.5
Structural components and finish materials	10.3	13.6	7.4	10.0
Electrical insulation	9.8	3.2	4.0	1.2
Wood, paper products	8.2	11.5	8.6	4.7
Garbage, trash	4.1	0.7	2.3	0.5
Clothing, textiles	3.4	1.4	3.4	6.8
Chemicals, plastics, metals	2.4	1.4	1.8	0.2
Agricultural, forest products	2.1	4.7	1.3	1.3
Flammable gases	1.9	1.5	4.3	0.6
Others	0.4	0.3	0.1	0.1
Unclassified	22.3	39.3	22.9	36.1
Default	6.2	4.0	0.5	6.7
Total	100.2	99.9	100.0	100.0

By far the most common materials first ignited are flammable or combustible liquids, such as gasoline, cooking oil, or fat. The hazard represented by such materials is well known. Provisions for safe handling and storage of some of these liquids are contained in Part 4 of the 1985 edition of the National Fire Code of Canada,[4] and are beyond the scope of this seminar.

The second most common class of materials first ignited is furniture and furnishings, such as upholstered furniture, bedding, and mattresses. Whereas 10.4% of fires appear to involve furniture or furnishings as the first item ignited, these same fires amount for 24.5% of deaths and 19.8% of injuries. They are very hazardous fires indeed, as far as occupants are concerned. In recognition of this hazard, some classes of furniture or furnishings are regulated under the Hazardous Products Act. To be sold in Canada, mattresses must exhibit resistance to ignition by cigarettes,[5] curtains (and other textiles) to ignition by a small flame,[6] and carpets to ignition by a methenamine tablet (slightly more intense than a cigarette).[7] Recently, provisions have been made under the Act to encourage manufacturers of upholstered furniture to test their products for resistance to ignition by cigarettes.

The third most common class of materials first ignited are building elements, such as structural components and finish materials. They account for 10.3% of fires, 13.6% of dollar losses, 7.4% of injuries, and 10.0% of deaths. They represent a significant cause for concern and are the principal subject of the rest of this paper.

The Need for Noncombustible Building Materials

Building materials are generally classified within the National Building Code of Canada as either combustible or noncombustible. It is important to distinguish between the ignitabilily and the combustibility of a material. Its ignitability is its ability to be ignited; its combustibility its ability to be ignited and to burn. Ignitability is not addressed directly in the NBC. It is not clear to what ignition sources building materials must demonstrate ignition resistance. The combustibility of building products is an issue regulated by the NBC.

Faced with serious fire problems, the code committees decided years ago that some buildings, particularly high buildings, or those with large areas, needed to be built of noncombustible materials to effect a so-called 'fireproof construction'. Such construction would help provide sufficient time for building occupants to evacuate, and would make fire fighters' tasks more manageable, by inhibiting fire spread through the building, particularly through concealed spaces. In addition, fireproof construction, together with adequate fire resistance provisions, is intended to ensure that the building will not sustain excessive damage or collapse before evacuation and fire fighting are completed. Finally, fire spread to other buildings should be abated. In Canada, during the 1800's and 1900's, such fire spread often led to conflagrations which destroyed large sections of towns or cities.

The Noncombustibility Test

A building material is classified as noncombustible if it meets the acceptance criteria contained in CAN4-S114-M80, Standard Method of Test for Determination of Non-Combustibility in Building Materials.[8] The test method is intended to assess the performance of elementary building materials only: it does not apply to materials with a decorative or protective coating, or impregnation, or those built up of laminations of dissimilar materials.

The test is conducted in a small electrically-heated furnace, shown in Figure 6. Temperatures in the furnace are determined by a controlling thermocouple, used to stabilize the furnace temperature prior to the test, and an indicating thermocouple, used to measure any temperature rise during testing. A mirror is used to make visual observation through the gas vent during testing.

Test specimens have a base of 38 by 38 mm and a height of 50 mm. If the specimen is likely to disintegrate or melt during the test, it must be supported in a metal gauze or a thin sheet-metal dish. At least three specimens of the material must be tested. Before testing, these specimens must be dried at 60 ± 3°C for 24 to 48 hours and allowed to cool to room temperature in a dry atmosphere.

Before conducting the test, the furnace is heated to 750 ± 3°C at the controlling thermocouple and stabilized at that temperature to within 1°C for 15 minutes. The specimen is placed in the sample holder and inserted into the furnace from below. The test is continued for fifteen minutes, unless it becomes clear earlier that the specimen has failed the test.

Materials subjected to the test are considered to be noncombustible if:

- The mean of the maximum temperature rises (measured by the indicating thermocouple) for the three (or more) specimens during the test does not exceed 36°C;
- There is no flaming of any of the three (or more) specimens during the last 14 minutes and 30 seconds of the test;
- The maximum loss of mass of any of the three (or more) specimens during the test does not exceed 20%.

Note that the test is a pass/fail test; that is, the material is found to be either combustible or noncombustible. There is no measure of the degree of combustibility of the material provided.

Testing Laboratories

The following Canadian laboratories are equipped to perform the noncombustibility test:

- National Research Council of Canada, Ottawa, Ontario
- Ontario Research Foundation, Mississauga, Ontario
- Underwriters' Laboratories of Canada, Scarborough, Ontario
- Warnock Hersey Professional Services Ltd., Coquitlam, B.C.

It is not common for NRC to conduct tests for product manufacturers, as this is generally understood to be the responsibility and livelihood of the commercial laboratories.

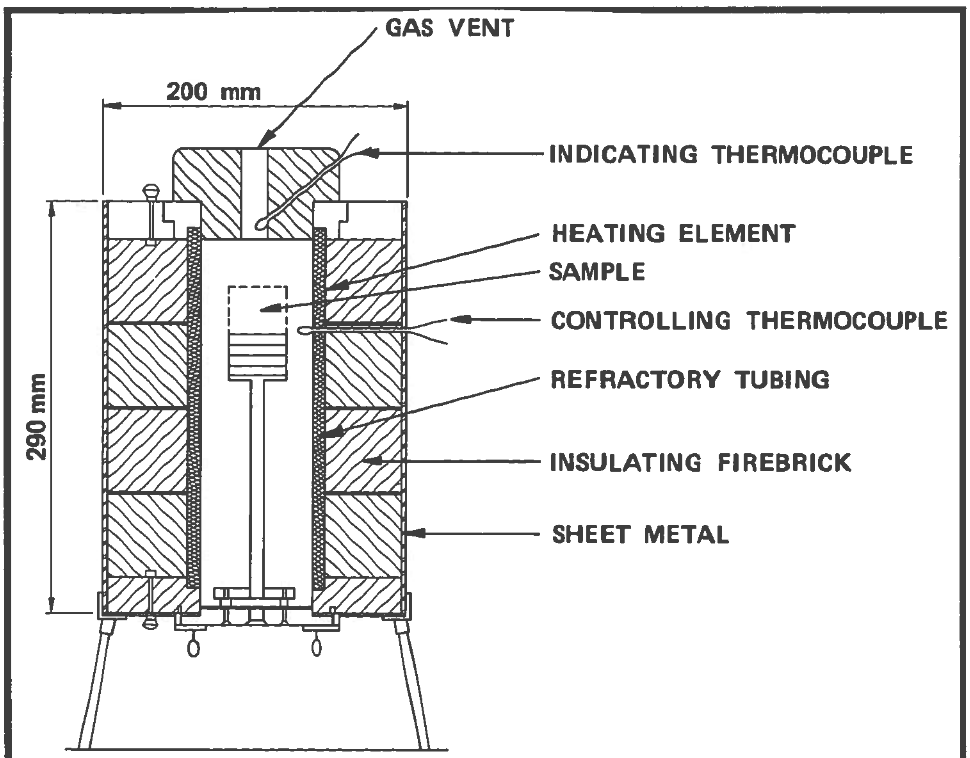
Product Testing

Data generated at NRC on the combustibility of Douglas fir, glass-fibre insulation, and aluminum are summarized in Figure 7. (In the testing of all products there is a drop in temperature (as recorded on the indicating thermocouple) at the start of the test, when the cool specimen is inserted into the hot furnace.)

The Douglas fir specimen is classified as combustible, as it failed all three acceptance criteria. The maximum temperature rise was 255°C; flaming was witnessed after the 30-second mark in the test (in fact, at times flames issued through the gas vent), and the mass loss was about 88%. It comes as no surprise to find that a wood product is classified as combustible.

The glass-fibre insulation is also classified as combustible. Although there was no flaming in the last 14.5 minutes of the test and the mass loss was only 7%, the temperature rise of 70°C exceeded the permitted value by a slight margin. It was the resins (binders) employed in this

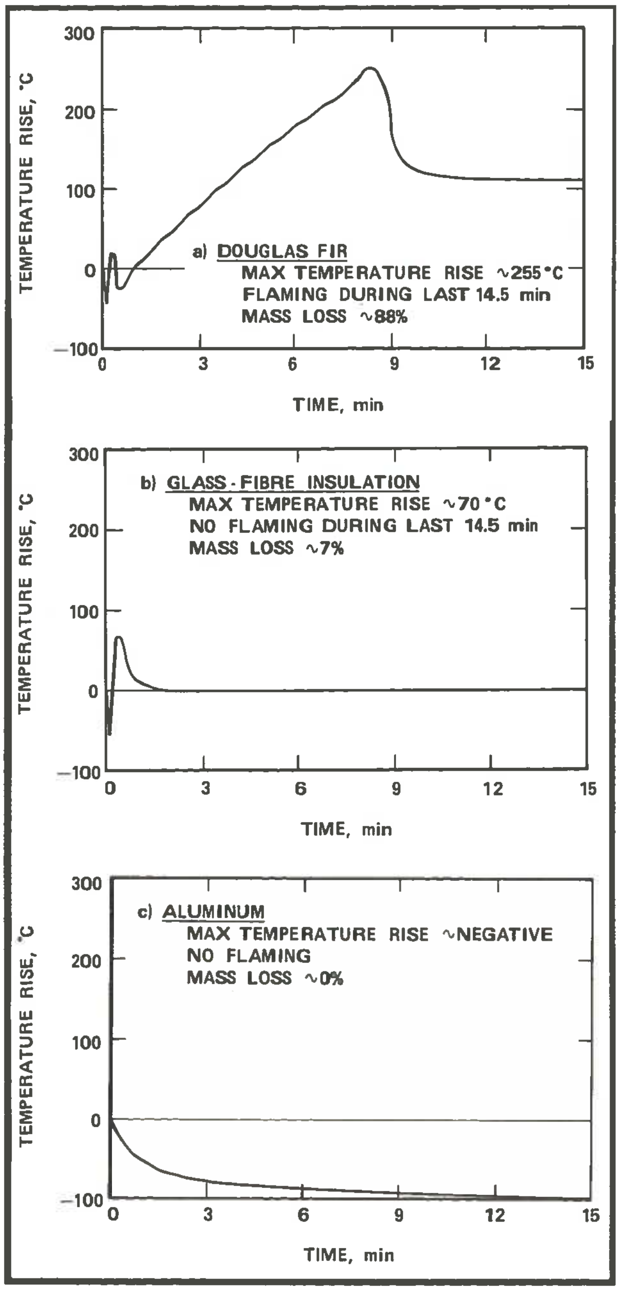
Figure 6 The non-combustibility test furnace



particular product which caused it to fail the test. There may be formulations of glass-fibre insulation which could pass this test.

It should come as no surprise that the solid aluminum specimen was found to be noncombustible. The specimen underwent some melting during the test and in this way absorbed heat from the furnace, causing relatively low temperatures to be recorded. There was no flaming and no mass loss during the test, as the molten aluminum was contained within a small dish.

Figure 7 Data from tests conducted in accordance with the noncombustibility test CAN-S114-M80. The Douglas fir and glass fibre specimens were found to be combustible; the aluminum is noncombustible.



The results of the test imply that aluminum building components will not undergo rapid oxidation in building fires. This is not to suggest that aluminum can never undergo rapid oxidation; under some conditions, generally quite different from those encountered in building fires, it can.[9]

After many years of testing, much has been learned about the test performance of common building materials. Some of that information is summarized in Chapter 2 in the Supplement to the National Building Code of Canada 1985.[10]

Most materials from animal or vegetable sources are classified as combustible by CAN4-S114. Wood, wood fibreboard, paper, felt made from animal or vegetable fibres, cork, plastics, asphalt and pitch would be classed as combustible. Materials that consist of combustible and noncombustible elements in combination, such as gypsum wallboard, will in many cases also be classed as combustible, unless the proportion of combustible elements is very small. Some mineral wool insulations with combustible binder, cinder concrete, cement and wood chips, and wood-fibred gypsum plaster would also be classed as combustible. The addition of a fire-retardant chemical is not usually sufficient to change a combustible product to a noncombustible product.

Noncombustible materials include brick, ceramic tile, concrete made from portland cement with noncombustible aggregate, asbestos cement, plaster made from gypsum with noncombustible aggregate, metals commonly used in buildings, glass, granite, sandstone, slate, limestone and marble.

Building Code Requirements

In addition to distinguishing between noncombustible and combustible materials, the present version of the NBC distinguishes between noncombustible construction and combustible construction. Since combustible construction is defined as construction that does not conform to the requirements for noncombustible construction, it is useful to first consider what is meant by noncombustible construction.

In noncombustible construction, building assemblies must be constructed of noncombustible materials, although, for practical reasons, some combustible elements are permitted. However, only those combustible elements considered not to represent an undue hazard and specifically listed in Article 3.1.4.5. of the NBC may be used. For example, gypsum wallboard, although it is considered to be combustible itself, is permitted in noncombustible construction. Where combustible materials are permitted, additional restrictions are often placed on their use. For instance, combustible insulation is permitted, provided it meets certain flame-spread requirements and (in some cases) provided it is protected by a thermal barrier such as gypsum wallboard. For combustible interior finishes, restrictions are also placed on the thickness of the material.

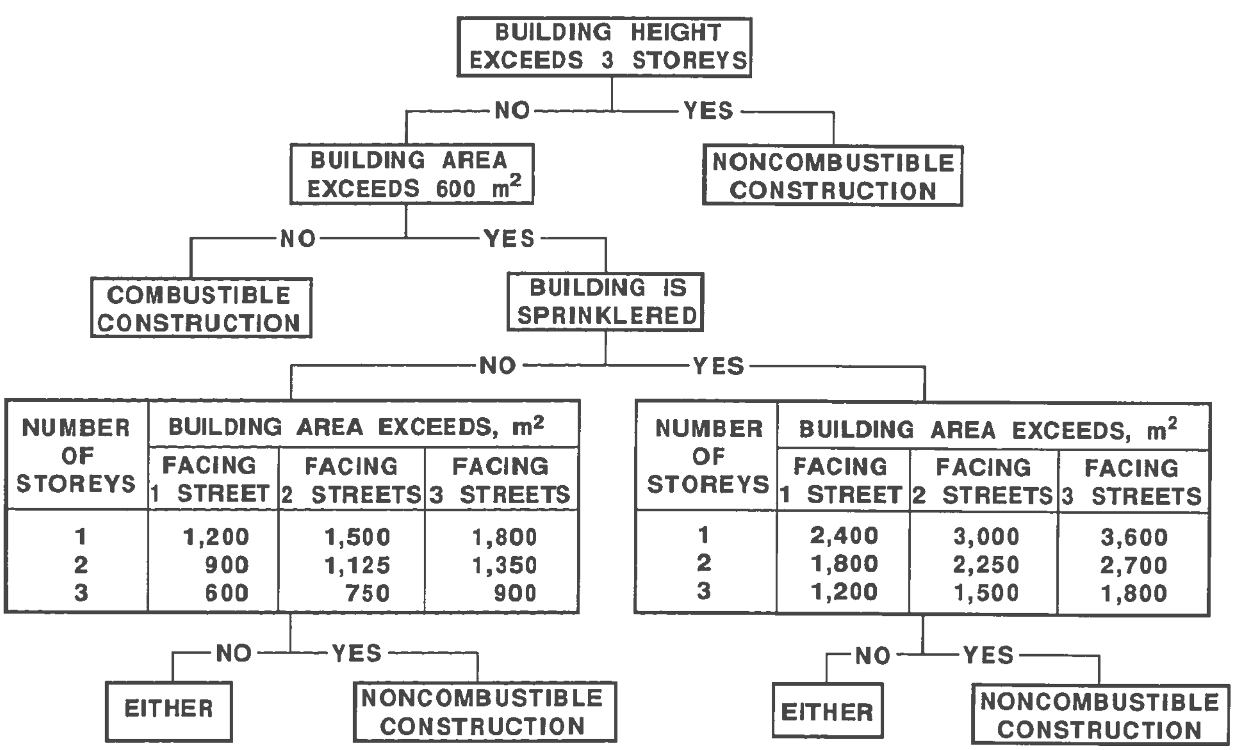
If an assembly constructed essentially of noncombustible material contains combustible elements not specifically permitted by the Code for noncombustible construction, the assembly falls within the category of combustible construction. Combustible construction is usually conventional wood frame or heavy timber.

The NBC requires that a building be of noncombustible construction if occupants could experience undue difficulty in evacuating in the event of a fire. Buildings over a certain height or area are required to be of noncombustible construction. The building area and building height limits below which the building is permitted to be of combustible construction depend on the major occupancy classification, the number of streets the building faces, and whether or not the building is sprinklered.

As an example, the pertinent requirements for residential buildings are summarized in Figure 8. Residential buildings which do not exceed three storeys in height or an area (single storey area) of 600 m² (such as one- and two-family dwellings and small apartment buildings), can be of combustible construction and can be built in accordance with Part 9 of the NBC. It is assumed that occupants have sufficient time to escape from a fire and that fire fighting capabilities are adequate to deal with fires in smaller buildings. All other residential buildings must be built in accordance with the more stringent requirements of Part 3 of the NBC.

Residential buildings which exceed three storeys in height must be of noncombustible construction. Those which do not exceed three storeys in height but do exceed 600 m² in building area may be required to be of noncombustible construction, depending upon whether the building is sprinklered, the number of storeys, the building area, and how many streets the building faces. The exact requirements are contained in Figure 8. Evacuation and fire fighting activi-

Figure 8 NBC requirements for noncombustible construction in residential buildings



Not sprinklered (NO):

NUMBER OF STOREYS	BUILDING AREA EXCEEDS, m² FACING 1 STREET	FACING 2 STREETS	FACING 3 STREETS
1	1,200	1,500	1,800
2	900	1,125	1,350
3	600	750	900

Sprinklered (YES):

NUMBER OF STOREYS	BUILDING AREA EXCEEDS, m² FACING 1 STREET	FACING 2 STREETS	FACING 3 STREETS
1	2,400	3,000	3,600
2	1,800	2,250	2,700
3	1,200	1,500	1,800

ties are assumed to proceed more smoothly in sprinklered buildings, in buildings of fewer storeys and smaller area, and where there is direct access for firefighters from more sides.

For some buildings either combustible or noncombustible construction is permitted. Generally, more stringent requirements are placed on other fire protection provisions (such as fire resistance ratings) in the combustible buildings to allow for equivalent levels of safety.

This rather involved logic for residential buildings is in sharp contrast to the logic employed in establishing requirements for prisons. As the mobility of prisoners is generally restricted, evacuation in the case of fire is very much hampered. In addition, fire fighting activities are often hampered due to difficulty in gaining access to the fire. For these reasons all prisons are required to be of noncombustible construction, independently of such factors as building height, building area, or presence of sprinklers.

The Noncombustibility Test – Shortcomings

CAN4-S114 is a very severe test which is intended to determine whether a material is combustible or not. In this sense it is a pass/fail test: numerical test results are not provided. It is generally not practical to construct a building solely from noncombustible materials. Consequently, numerous combustible materials are permitted in noncombustible construction.

For more than a decade now, code writers have wanted to be able to distinguish between various levels or degrees of combustibility: from noncombustible to highly combustible. Specifying the use of noncombustible materials was a convenient but conservative measure. A more practical solution would be to allow some degree of combustibility, within safe limits. Although Code committees have wanted to move in this direction, the lack of a suitable test has prevented them from doing so. Attempts to modify CAN4-S114 to serve this function have not met with success. The apparatus can determine readily if a material is combustible or not; it cannot easily be used to assess the degree of combustibility of combustible materials.

A New Noncombustibility Test

Efforts are under way to develop a test method to determine the degree of noncombustibility of materials. It is intended that the test method be modelled after an existing American test developed for a different purpose.[11]

The test specimen will be put into a small ventilated chamber and subjected to two different levels of radiant thermal exposure. Piloted ignition will be attempted with a small flame. The critical measurement will be the heat release rate of the material for two exposures.

Using these data it will be possible to set up categories of combustible materials. These categories, which would reflect the contribution of a material to fire development and severity, could be referenced in the NBC.

Equivalencies and Design Considerations

Fire protection requirements in the NBC are intended to ensure a minimum level of life safety in buildings. It is argued that these requirements provide, for the most part, adequate time for occupants to reach an area of safety within or outside the building.

From time to time, in considering the design of some buildings it is found that these requirements are inconsistent with the spirit of the design. In these cases the requirements are generally felt to be too 'restrictive'. This may occur in the design of a new building or in a major renovation of an existing building.

It is not possible to foresee all design considerations in developing the NBC. To encourage the use of new technologies or design options which are not expressly covered in the NBC, Subsection 2.5 permits the use of solutions which can be demonstrated to yield levels of safety equivalent to those provided by the NBC requirements. Most provincial building codes adopt a similar policy in some form. It is generally necessary to provide documentation supporting the claim that the design meets the intent of the NBC requirements.

One of the purposes of this seminar is to demonstrate, using examples, how equivalent solutions can be developed. These examples have been chosen strictly to demonstrate the processes and logic involved. There may well be design scenarios in which these examples would yield solutions which are not up to the mark.

Take for example the case of a large lumber company that wishes to build a new corporate head office. The company insists that the building be of combustible construction, as it is to be a show-piece of wood-frame construction with several larger rooms lined with the finest in wood panelling.

An architect, well versed in wood-frame construction, has been selected to design the building. In his first meeting with the company he learns that the building is to be 3 storeys in height and each storey is to be 5,500 m^2 in area. He immediately points out that according to Article 3.2.2.30 in the NBC, the building must be of noncombustible construction. The largest storey area permitted in a three storey office building of combustible construction is 4,800 m^2, provided the building is sprinklered and faces three streets.

As the company insists that the building be of wood-frame construction, the architect must develop an equivalent solution. This may entail exceeding building code requirements for buildings of this size in order to provide sufficient time for occupants to escape. The architect may propose any combination of the following actions:

- exceed the required number of exits and provide for shorter travel distances to exits than required;
- exceed the number of required fire detectors and alarms;
- employ fast-response sprinklers in place of ordinary sprinklers;
- build in improved compartmentation within the building;
- provide for an in-house fire brigade.

To ensure that neighbouring buildings are not likely to become involved in a fire should this building burn, the minimum required limiting distances to lot lines should be exceeded.

As the proposed storey area of 5,500 m^2 exceeds the permitted value of 4,800 m^2 by a small amount, it is possible that by exceeding the minimum requirements in the NBC, the architect may persuade the authorities having jurisdiction to permit the building to be of wood-frame construction. The architect should be prepared to demonstrate that the equivalent solution provides a level of safety equal to or better than that provided by NBC requirements. Fire experience, testing and computer models (presented in the following paper) may provide the information needed to demonstrate the equivalency.

Summary

Restricting the combustibility of building materials plays an obvious role in the provision of fire safety. Yet specifying the use of noncombustible materials is not always a practical solution, In this lecture, a review of test procedures aimed at segregating materials into combustible and noncombustible categories was presented, as well as an explanation of the intent of requirements for noncombustible construction contained in the NBC. The need for development of more useful test methods for evaluating the degree of combustibility of building materials was also discussed. Finally it has been shown that designs which can be demonstrated to yield equivalent levels of safety to NBC requirements, can often find acceptance by authorities having jurisdiction.

References

1. National Building Code of Canada 1985. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, NRCC 23174. 454 p.

2. Fire Losses in Canada, Annual Report 1984. Office of the Fire Commissioner of Canada, Ottawa, Ontario, 1986. 23 p.

3. Phillips, D., and Kasem, M.A., 1985, "Upholstered Furniture Fires in Canada", Consumer and Corporate Affairs Canada, L10127-F32 84/85, 29 p.

4. National Fire Code of Canada 1985, National Research Council of Canada, Associate Committee on the National Fire Code, NRCC 23175. 168 p.

5. Method of Test for Combustion Resistance of Mattresses - Cigarette Test, 1977. CAN2-4.2-M77, Method 27.7, Canadian Government Specifications Board, Ottawa, 6 p.

6. Standard Test Method for Flammability of Clothing Textiles, 1980. ASTM D1230-61, Annual Book of ASTM Standards, Part 18, American Society for Testing and Materials, Philadelphia, 5 p.

7. Method of Test for Flammability - Methenamine Tablet Test for Textile Floor Coverings, 1977 .CAN2-4.2-M77, Method 27.6, Canadian Government Specifications Board, Ottawa, 2 p.

8. Standard Method of Test for Determination of Non-Combustibility in Building Materials, 1980. CAN4-S114-M80, Underwriters' Laboratories of Canada, Scarborough, Ontario, 15 p.

9. "Metals" Section 5/Chapter 10 in Fire Protection Handbook,1986. 16th Edition, National Fire Protection Association, Quincy, MA

10. Supplement to the National Building Code of Canada 1985, Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, NRCC 23178, 278 p.

11. Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products, 1986. ASTM E906, Annual Book of ASTM Standards, Vol. 04.07, American Society for Testing and Materials, Philadelphia, pp. 915-936.

Flammability of Building Materials and Fire Growth

J.R. Mehaffey, Ph.D.

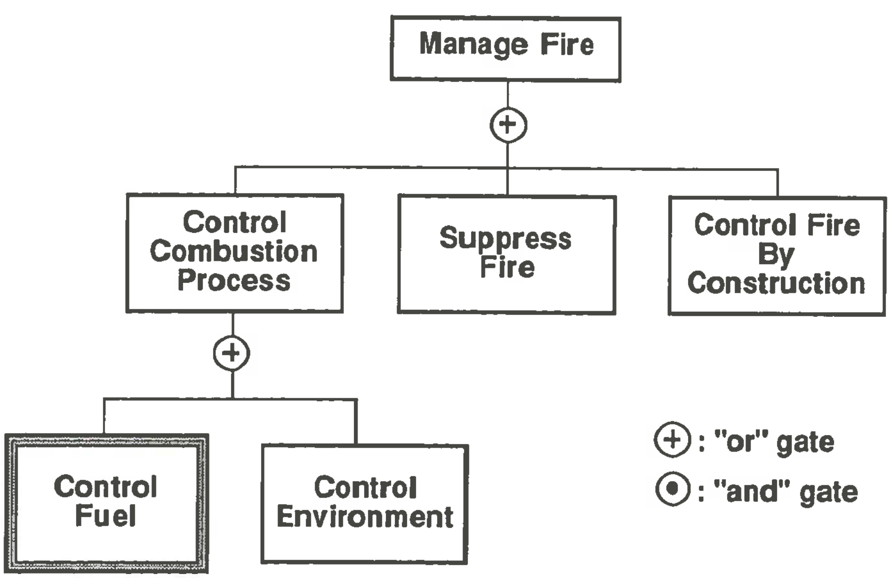
Introduction

Despite efforts to restrict the use of combustible material in buildings and to prevent ignition, fires will continue to start. Whether these fires grow and how quickly, depends to a large extent on the basic flammability of building materials and contents, as well as on the building design. The more quickly a fire develops, the less time occupants of the building have to escape.

To provide building occupants with sufficient time to escape, building codes and other regulations restrict the flammability of building materials and contents. Controlling the fuel in this manner may impede the rate of fire growth significantly. Generally, the extent to which flammability is restricted by the codes depends on the building size, the hazards it contains, the mobility and level of awareness of its occupants, and whether it is sprinklered. The control of fuel, as it relates to the objectives in the Fire Safety Concepts Tree, is shown in Figure 1.

In this paper the relationship between product flammability and fire growth is explored. The nature and status of regulations based on existing test methods are outlined. The potential impact of computer models for fire growth on material selection and building design are discussed.

Figure 1 Control of Fuel, in the Manage Fire sub-branch of fire safety tree



Room-Fire Growth

When an object in a room starts to burn (such as the armchair in Figure 2), for some time after ignition, it burns in much the same way as it would in the open. After a short period of time, however, confinement begins to influence fire development. The smoke produced by the burning object rises to form a hot gas layer below the ceiling; this layer heats the ceiling and upper walls of the room. Thermal radiation from the hot layer, ceiling, and upper walls begins to heat all objects in the lower part of the room and may augment both the rate of burning of the original object and the rate of flame spread over its surface.

At this point, the fire may go out if, for example, the first object burns completely before others start, or if sufficient oxygen cannot get into the room to keep the object burning. Sometimes, however, the heating of the other combustibles in the room continues to the point where they reach their ignition temperatures more or less simultaneously. If this occurs, flames suddenly sweep across the room, involving most combustibles in the fire. This transition from the burning of one or two objects to full room involvement is referred to as 'flashover'.

Usually at the time of flashover, windows in the room will break, allowing for the entry of fresh air. The fire burns vigorously for some time until the combustibles are mostly consumed. Flaming eventually ceases, leaving a mass of glowing embers.

The course of a compartment fire can be expressed in terms of the average gas temperature in the room. Figure 3 illustrates three stages of such a fire:

1) the growth or preflashover stage, in which the average temperature is low and the fire is localized in the vicinity of its origin;
2) the fully developed or post-flashover fire, during which all combustible items in the compartment are involved and flames appear to fill the entire volume; and
3) the decay or cooling period.

The dashed line represents the scenario in which the first item burns completely before flashover. In one- and two-storey apartment buildings, only 22% of fires proceed to flashover (from an analysis of U.S. data obtained from the National

Figure 3 Upper layer temperature during a room fire

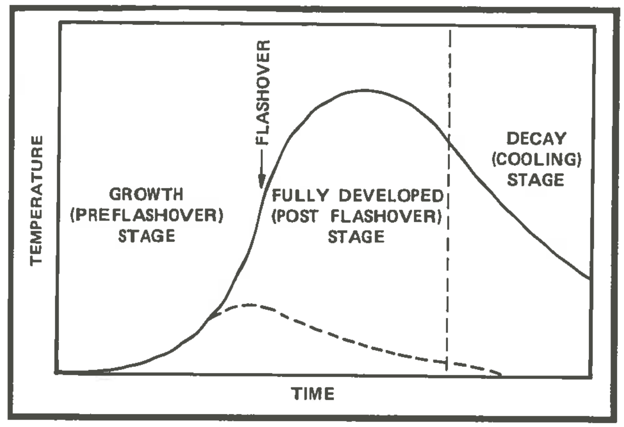
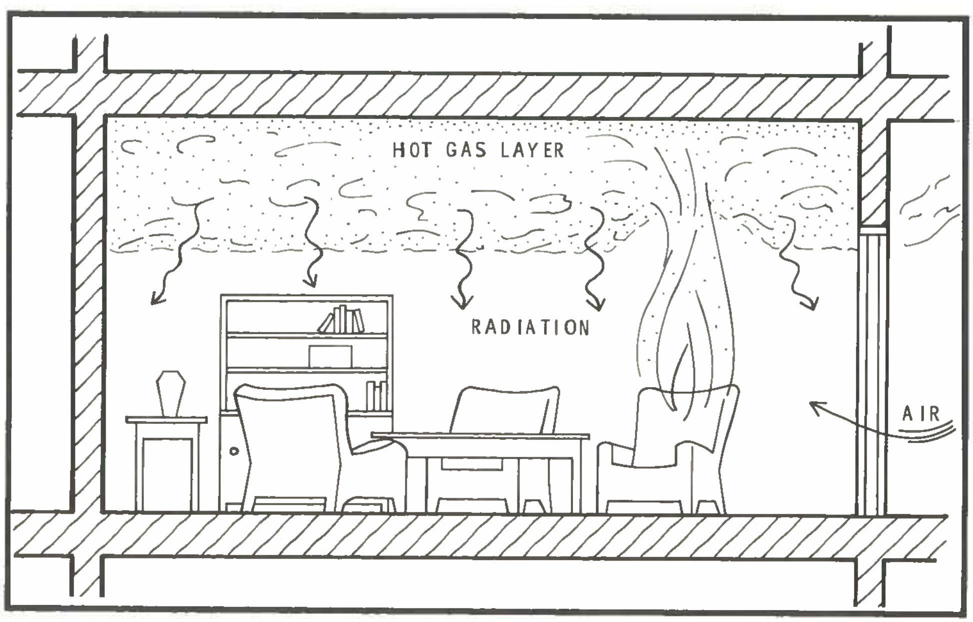


Figure 2 Fire growth in a confined space



Fire Incident Reporting System). The pre-flashover period lasts from 5 to 20 minutes, the fully-developed fire period lasts 20 to 40 minutes, and the decay period, more than an hour.

The description of preflashover fire growth outlined above would apply even where the walls or ceiling were noncombustible. In a different scenario, the final major item ignited is a wall or perhaps a ceiling. Suppose, for example, a fire starts in a wastepaper basket situated in a corner of a room lined with a combustible wall covering. If the wall is sufficiently flammable, it will catch fire and, depending on its flame-spreading propensity, flames will begin to grow vertically along the corner. If flames reach the ceiling and spread along the upper wall, flashover is likely to occur. What is important in determining the contribution of a wall to fire growth is its flame-spread propensity.

Whether the initial item ignited is a piece of furniture or a wall, flashover is imminent should the temperature of the hot upper layer in the room reach 500 to 600°C.[1] Clearly, under such conditions, occupants of the room will have perished if they have not escaped.

Historical Background

Historical fire incidents reveal that both furniture and combustible wall linings can contribute significantly to the growth of fires. Until recently, means to regulate furniture materials were not in place. However, some time ago, code-writing bodies (which can regulate only materials used in building construction) saw the opportunity to use such regulations to increase control over fire losses (including deaths).

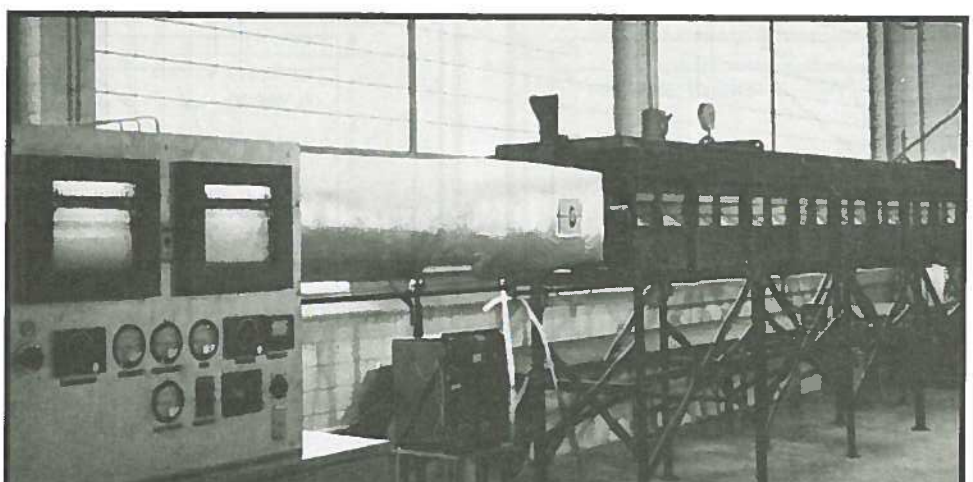
During the 1940's several fire disasters in the United States highlighted the need to regulate interior finishes in buildings.[2,3] In the Cocoanut Grove Night Club fire in 1942, 492 people were killed when flames moved quickly across a cotton cloth which covered the ceiling of the lounge. Other significant fires of the time include the Winecoff Hotel, LaSalle Hotel, and Canfield Hotel fires in 1946, and the St. Anthony Hospital fire in 1949. The magnitude of loss in all these fires was directly related to the rapidity of flame spread on the interior finish. The extensive loss of lives was attributed to asphyxiation as well. It became clear that it was necessary to test and classify materials with regard to three essential properties: flame spread, fuel contributed and smoke developed. In this paper it is the flame spread which is of immediate interest.

The Tunnel Test

In response to these needs, the tunnel test was developed by A. Steiner at Underwriters Laboratories Inc. in the United States.[3] This test has been employed in Canada since 1960 to test materials for compliance with requirements in the National Building Code.[4]

The test equipment consists of a horizontal tunnel 7.6 m long, 450 mm wide, and 300 mm deep (Figure 4). The roof is removable and lined with a low density material of mineral composition. The walls and floor are constructed of refractory fire brick. One wall has observation windows along its length.

Figure 4 The tunnel test apparatus



Flames from two burners at one end are forced down the tunnel by a steady draught of air at 1.2 m/s. These burner flames are about 1.37 m long, release heat at a steady rate of about 90 kW, and impinge directly on the test specimen, which is mounted either on the floor or on the ceiling of the tunnel. This exposure is similar in intensity to what occurs when a small piece of furniture leaning against a wall is set on fire. The tunnel is calibrated by adjusting the rate of heat release of the burners so that it takes about five and a half minutes for flames to reach the exhaust end of the tunnel when the specimen is 18 mm select-grade red oak. In the exhaust duct at the end of the tunnel are a light source and detector for measuring smoke and a thermocouple for determining heat released.

Before testing, specimens are conditioned at a temperature of 23 ± 3°C and at a relative humidity of 50 ± 5% until their mass reaches a stable value. This may take a few days to several weeks, depending on the type of product and its initial moisture content.

In Canada, building materials to be tested are mounted on and form either the ceiling or the floor of the tunnel. If the material can support itself in position, or can be supported, it is mounted on the ceiling and tested in accordance with the National Standard of Canada CAN4-S102-M83, Standard Method of Test for Surface-Burning Characteristics of Building Materials and Assemblies.[5] If, however, the material is to be the finished surface or covering of a floor, or cannot be tested when mounted on the ceiling because it melts and drips or otherwise cannot support its own weight, it is tested on the floor in accordance with CAN4-S102.2-M83, Standard Method of Test for Surface-Burning Characteristics of Flooring, Floor Covering, and Miscellaneous Materials and Assemblies.[6] American versions of the tunnel test do not allow for the testing of floor-mounted samples. (There are a few other minor operational differences between the Canadian and American tests).

Flame Spread Classifications of Building Products

To determine the Flame Spread Classification (FSC) of a material, the burners are ignited and the advance of the flame front along the test specimen is recorded for ten minutes. The detailed methods for computing the FSC are included as an Appendix. The calculation methods are designed so that the FSC of a noncombustible inorganic board is zero, and that of red oak is 100. The values for all other products are determined in comparison with these materials.

The flame front position–versus–time curves for red oak and 6 mm Douglas fir plywood are shown in Figure 5, the curve for 12.7 mm gypsum wallboard in Figure 6, for a loose-fill cellulose insulation in Figure 7, and for a polyurethane foam insulation in Figure 8. There are clearly significant differences in the performance of these materials during the test. The methods for determining FSC have been carefully designed to account for these differences. Using

Figure 5 Time – distance curves for red oak and 6 mm Douglas fir plywood. Distance is measured from the burners. The area under A_t = 43.0 m•min for red oak and 47.2 m•min for plywood.

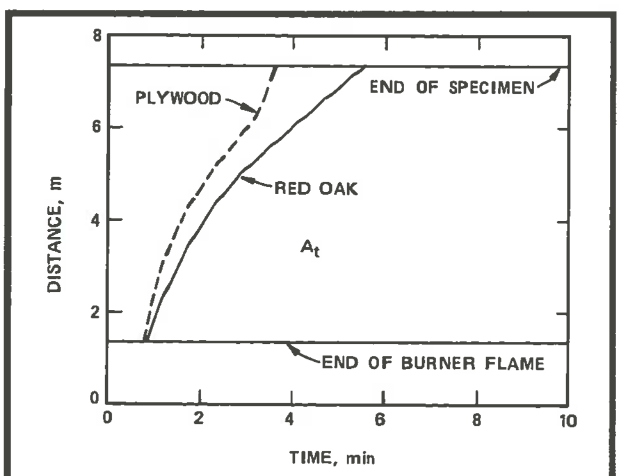
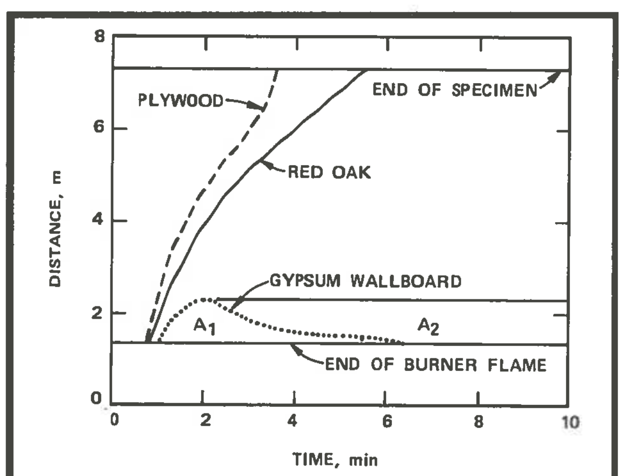


Figure 6 Time – distance curves for 6 mm Douglas fir plywood, 18 mm red oak, and 12.7 mm gypsum wallboard. Note that in the testing of gypsum wallboard, the flame front advances until the two-minute mark and then recedes. The area under the curve is given as $A_t = A_1 + A_2 + 8.0$ m•min.



the data presented in Figs. 5 to 8, the FSC of red oak is found to be 100, that of 6 mm Douglas fir plywood is 135; the 12.7 mm gypsum wallboard has a rating of 15, the loose-fill cellulose insulation of 55, and the foam insulation, 427.

Years of testing experience have shown that results can vary from test to test for the same material. For this reason, it is common to conduct three tests on specimens of a product and to quote its FSC as the average of the three tests. Nonetheless, FSC's do provide a ranking of lining materials which reflects their performance in a real fire. In general, the larger the FSC, the faster the fire grows.

Shortcomings of the Tunnel Test

Although the tunnel is useful in selecting fire-safe materials, it has shortcomings. Field conditions differ from those of the test; it is not always clear when the relative performance of materials in the field can be determined on the basis of their performance in the tunnel. For example, tunnel test performance bears little relation to how thermal insulation in a cavity wall behaves in the event of fire in the cavity.[7] Even for lining materials, it is sometimes difficult to interpret the tunnel test results; in such cases a second test is used, the Underwriters' Laboratories of Canada test ULC-S127-M82, Standard Corner Wall Method of Test for Flammability Characteristics of Non-Melting Building Materials.[8] Fundamental research into fire growth has shown that more detailed information than that provided by the tunnel is necessary before accurate predictions of flame spread can be made.

Product Testing and Test Results

Four Canadian Laboratories are equipped to perform tunnel tests:

- National Research Council of Canada (NRCC), Ottawa, Ontario (generally, NRCC does not engage in commercial tunnel testing),
- Ontario Research Foundation (ORF), Mississauga, Ontario,
- Underwriters' Laboratories of Canada (ULC), Scarborough, Ontario (2 tunnels),
- Warnock Hersey Professional Services (WHPS), Coquitlam, B.C.

ULC and WHPS also offer certification programs. They test products for manufacturers and list the results in publications released regularly. These publications may be purchased by the general public.[9,10]

After many years of testing, much has been learned about the test performance of interior finish materials. Some of that information is summarized in Table 1, which is a simplification of Table 3.1.A. in the Supplement to the National Building Code of Canada 1985.[11] These ratings apply only to generic materials that conform to standards referenced in the Supplement. The FSC's of materials that are similar to those listed in the table, but actually vary from the specifications of the standards, may differ significantly from the values shown in the table.

Figure 7 Example of time – distance curve with flame front recession and a subsequent advance

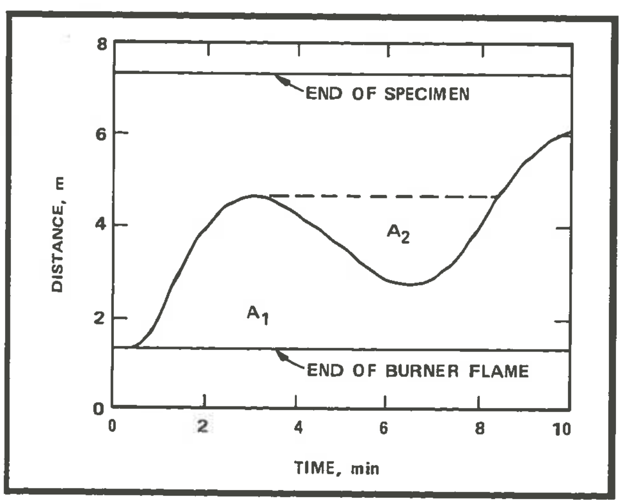


Figure 8 Time – distance curve for a polyurethane foam. The flame advances early in the test. Distance d is 3.7 m and time t, 0.8 min.

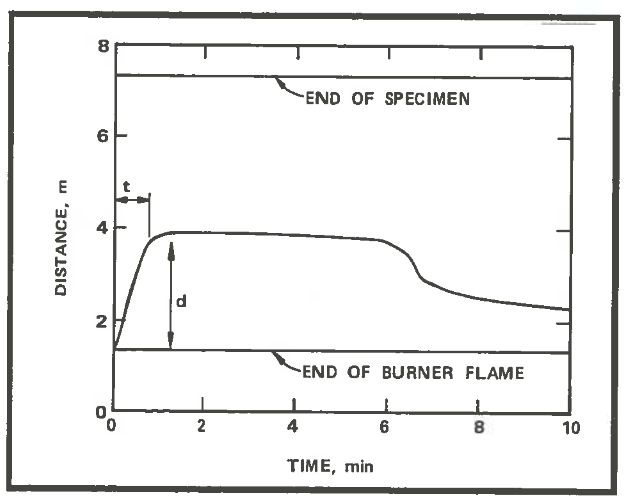


Table 1 Assigned flame spread classifications for combinations of wall and ceiling finish materials and surface coatings

Materials	Minimum thickness, mm	Unfinished	Paint or varnish ≤1.3 mm thick Cellulosic wallpaper ≤1 layer
Asbestos cement board	None	0	25
Brick, concrete tile	None	0	25
Steel, copper, aluminium	0.33	0	25
Gypsum plaster	None	0	25
Gypsum wallboard	9.5	25	25
Lumber	16	150	150
Douglas Fir plywood	11	150	150
Poplar plywood	11	150	150
Plywood with Spruce face veneer	11	150	150
Douglas Fir plywood	6	150	150
Fiberboard low density	11	>150	150
Hardboard			
Type 1	9	150	*
Standard	6	150	150
Particleboard	12.7	150	*

* Insufficient test information available

Building Code Requirements

Requirements for the Flame Spread Ratings of interior finish materials are contained within the National Building Code of Canada 1985.[12] For buildings which must conform to Part 3, the requirements are contained in Subsection 3.1.11; for those which must conform to Part 9, Subsection 9.10.16 is relevant.

The purpose of these building code requirements is to ensure that, should walls and ceilings become involved in a fire in its early stages, they will not spread flames so quickly that occupants cannot escape. Generally, the lower the flame spread rating of a wall or ceiling, the more time is available to escape. The time required to escape may depend upon the building size, location of the fire within a building, the mobility and level of awareness of occupants, and whether or not sprinklers are present.

In many areas of high risk to occupants, such as exits, flame spread ratings of walls and ceilings are required to be no more than 25. This value was selected as it is close to the value for gypsum wallboard, a material assumed to be safe for the purpose. In practice, any lining material which performs as well as or better than gypsum wallboard is permitted.

In hospitals or prisons, where occupants may have limited mobility or awareness, and in cinemas, where evacuation may be slow due to lack of direction, if there are no sprinklers, walls and ceilings must have a flame spread rating of not more than 75 to ensure sufficient time to escape. If sprinklers are present, the requirements are relaxed to 150, as sprinklers retard fire growth and provide more time for escape.

As another example, interior finish materials used on walls of residential rooms are required to have a flame spread rating not exceeding 150. This value was selected as it is close to the value for 6 mm Douglas fir plywood, a material which has been found to be acceptable on the basis of actual fire experience. In practice, any lining material which performs as well as or better than 6 mm Douglas fir plywood is permitted.

Another way to look at the building code requirements is in terms of options available for escape. Generally, walls in rooms are permitted to have an FSC of 150, walls in corridors leading to exits to have an FSC of 75, and walls in exits to have an FSC of only 25. The least stringent requirements appear in the room, as an occupant can flee from a room fire either to find refuge elsewhere in the building or to escape from the building. More stringent requirements appear in a corridor, as a serious fire there could prevent all occupants of a storey from escaping. The most stringent requirements appear in exits, since a serious fire in the exit could prevent all occupants of the building from escaping.

Combustible Furniture and Furnishings

Early fire growth in a room is not always attributable to flame spread along walls or ceilings. Furniture or other furnishings are more commonly the principal contributors to early fire growth.[13] As mentioned earlier, if a piece of furniture or a wall burns quickly enough to cause the temperature in the upper part of the room to reach 500 to 600°C, then flashover will occur in the room.

A critical rate of heat release (or a critical burning rate) must be exceeded (and presumably maintained for some period of time) before flashover can occur in a room.[14] The temperature in the room can continue to increase only if the rate of heat production (release) in the room is greater than the sum of the rates of heat loss from the room. The equation can be written:

Temperature increase if:

Rate of heat release	>	Rate of heat loss to boundaries	+	Rate of heat loss through openings

A simple model indicates that for a given room the critical rate of heat release required to cause flashover depends principally upon:

- the area of the room boundaries,
- thermal properties of the room boundaries,
- the size and shape of all openings, and
- the duration of burning of the item first ignited.[14]

For typical rooms found in dwellings, the critical rate of heat release is usually about 1 MW.

Upholstered chairs release heat at rates from 0.4 MW up to 2.5 MW when they burn,[15] so some upholstered chairs will cause a flashover on their own and some will not. This allows for the possibility of selecting 'safe' furnishings in the future. However, the theory still needs some work and it is not yet certain whether society or the marketplace would accept such limits. Clearly, there is a need to develop a means of determining the rate of heat release from burning items of furniture.

Room-Fire Test

To improve the understanding of preflashover fire growth, both ASTM[16] and ISO[17] are developing standard room-fire tests. These tests are intended to evaluate first the contribution of combustible walls or ceilings to room-fire growth.

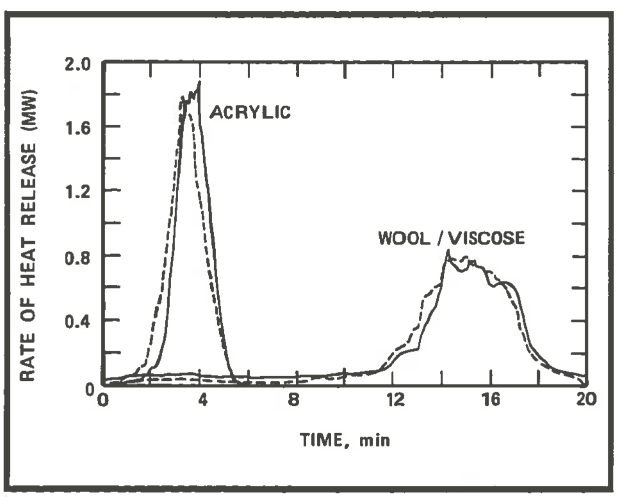
The tests are conducted in a room with floor dimensions of 2.4 x 3.6 m, and a height of 2.4 m. The walls or ceiling or both are lined with the interior finish to be tested. The experiment is started with a small fire source in the corner of the otherwise empty room. In this early phase, the fire is not intense enough to cause the room to reach flashover; flashover can occur only after the walls or ceiling catch fire. During the experiment, the maximum extent of fire growth along the combustible walls or ceiling, the rates of generation of smoke and toxic gases, and the time to flashover (should it occur) are recorded. Most important, the rate of heat release of the burning material is determined.

The fire performance of products in these full-scale experiments is to be compared with their performance in small-scale flammability tests. The comparison may aid in the development or modification of the small-scale tests. The test results may also prove useful in the development of mathematical models to predict the course of room fires (more about this later).

Room-fire testing has shed light on the utility of the flame spread classification of materials as determined using the tunnel test. When a room is lined with gypsum wallboard (FSC = 15) and a small ignition source (~ 100 kW – equivalent in intensity to a severe waste paper basket fire) is placed in a corner of the room, flashover does not occur.[3] Occupants have a great deal of time to escape. On the other hand, in a room with 6 mm Douglas fir plywood walls and ceiling (FSC ~ 135), the time to flashover is only about three minutes or less, given the same ignition source.[18] The time available to escape has been greatly reduced. In a room lined with a polyurethane foam (FSC ~ 500), the time to flashover can be as low as 13 seconds.[3] There is almost no time for escape. This is the reason that the building code requires a protective barrier to cover such insulation.

Efforts are already under way to broaden the scope of the test method to include the evaluation of the contribution of room furnishings to fire growth. In Sweden, room burn experiments conducted on two sofas ignited by small 40 g wooden cribs, showed interesting results.[17] Figure 9 shows the heat release rates of two sofas with the same untreated polyurethane padding, and upholstery fabrics of acrylic and wool/viscose. There is a substantial difference in their burning behavior. The fire spreads very quickly on the sofa covered with an acrylic fabric and the peak burning rate is reached within four minutes. The wool/viscose fabric, on the other hand, protects the padding and the fire develops very slowly, reaching a peak intensity of half the magnitude of the acrylic after fourteen minutes. The two sofas were both completely consumed by fire, and both caused flashover conditions to be reached in the room, although at very different times. Clearly the time available to escape was substantially different as well.

Figure 9 Rate of heat release versus time for two sofas tested in a standard room. The dashed and solid lines reflect results of two separate methods for determining rates of heat release (drawing after Wickström et al, Ref. 17).



Room-fire testing is a promising method for analyzing product performance in a realistic scenario. It provides a very clear indication of the available safe egress time. Unfortunately, room-fire tests are expensive to run and only one scenario can be modeled at a time.

Computer Modelling

In recent years, a great deal of effort has been expended in developing mathematical models to predict various aspects of fire behaviour in buildings. One area of significant activity is the development of models for predicting the rates of fire growth, and production and movement of smoke in fires. These models can be used to predict the time available to escape before a room or building becomes untenable. The models offer a cost–effective method for analyzing the impact of material selection or building design on fire safety.

There are two basic approaches to mathematical modelling of fires – probabilistic modelling and deterministic modelling. Probabilistic models describe fire development as a sequence of events (ignition, flame spread, flashover, etc.) and predict the transition from one event to another by probabilities.[19] Such models are based on years of fire experience but do not rely much on the fundamental chemistry and physics involved in room fires. On the other hand, in deterministic models, the problem and the configuration are prescribed, and the laws of physics and chemistry dictate the evolution of the fire. Both probabilistic and deterministic models consist of a set of mathematical equations that must be solved simultaneously. This is often practical only by using a computer.

Deterministic models can be further subdivided into field models and zone models. In field modelling, the conditions at every point of space, at any moment, are given by the solutions of a complex set of partial differential equations. Generally, field models put large demands on computer power. In zone models, the fire compartment is divided into a group of zones and interactions (mass and heat transfer) between the zones are modelled. Although zone models are still evolving, several are already in use for solving fire safety problems.

In a zone model for a single room fire, the relevant zones might be the burning object, the flame, the heat layer, the cold layer, the vents (openings), target objects (not yet ignited), and the room boundaries. The various important physical interactions between the zones are depicted in Figure 10. For example, heat is transferred to the burning object from the flame, from the upper layer, and from the room boundaries. This heat causes the object to undergo pyrolysis and volatiles (mass) are transferred to the flame. Relationships of this sort must be developed for each zone. The zone model comprises a set of equations describing the interactions between the zones.

Depending on the scenario being simulated, several zone models are available. Some are designed to consider single room fires only,[20,21] others treat the movement of smoke and fire through an entire building.[22] Some address only the time available to escape a fire,[23] others deal with fire behaviour from ignition to extinguishment. Any model should be used only for the purpose for which it was designed, and only after it has been validated. One of the most frustrating experiences incurred in using models is finding the necessary input data.

The Harvard Mark 5

Developed at Harvard University by H. Emmons and H. Mitler, the Harvard Mark 5 is one of the best known models.[20] It is a deterministic, zone model and one of the most comprehensive developed to date for the prediction of room fire dynamics. In its present form, it does not directly address the safety of occupants in the immediate area.

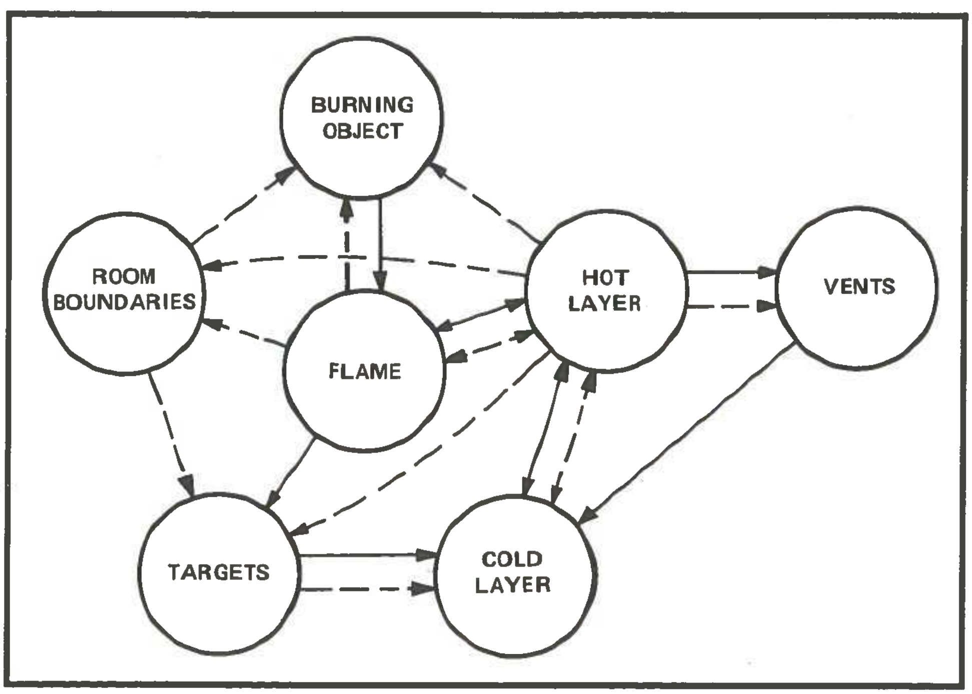
The situation modeled includes a single room of any size, with one to five vents in its walls, and containing up to five objects. One of the objects (for example a mattress) begins to burn and the subsequent fire behavior in the room is predicted. The model uses the thermophysical properties of materials as input for the calculations. The model has been found to predict with some success the outcome of a series of bedroom fires conducted at Factory Mutual Research Corporation.[20]

Recent improvements in the model make provisions for the burning of walls and ceilings, the possibility of forced-air ventilation, and multi-room fires. In its various levels of development, the model has been used several times for forensic analysis of specific fires, such as the MGM Grand fire and the Beverley Hills Supper Club fire.

ASET (Available Safe Egress Time)

Developed at the National Bureau of Standards (USA) by L.Y. Cooper, ASET[22] is a deterministic zone model which predicts the time available for

Figure 10 Interactions of the components of a room fire model; --- heat transfer, — mass transfer



occupants to safely evacuate a compartment in the event of a fire. The time that occupants have for escape is the time between the detection of the fire and the onset of hazardous conditions. This is referred to as the available safe egress time. Within the model, the fire growth process is treated less vigorously than in the Mark 5 model. Unlike Mark 5, however, ASET is written in such a manner that the time of fire detection and the time of onset of conditions hazardous to occupants are predicted.

Equivalencies and Design Considerations

Code requirements are intended to provide a minimum acceptable level of safety. Other solutions providing the same or a better level of safety are permitted according to Subsection 2.5 in the NBCC.

It is clear that the flame spread requirements within the code are intended to delay fire growth, providing occupants in the immediate area with sufficient time to escape and fire fighters more time to respond. However, the exact time provided by a building code requirement is not usually known. That is, the level of safety required is not quantified.

The following hypothetical examples show how equivalency may be demonstrated.

Example 1

A company designing a highrise office building wishes to line a small meeting room with a new product advertised as having an FSC of 160. According to the NBC, only products with an FSC of 150 or less are permitted. The company is willing to pay for additional fire protection hardware in order to develop a design which provides protection equivalent to the NBC requirement.

Several possibilities exist. One solution might be to equip the room with sprinklers in order to suppress a fire quickly and allow for safe egress. However, it is probably not economical to install them in one room in a building which might otherwise be unsprinklered. In addition, there are some concerns about smoke movement in the presence of sprinkler spray.

Another approach might be to install smoke alarms within the room to ensure that egress begins more quickly than would otherwise be anticipated without automatic detection in the room. To prevent fire and smoke from spreading beyond the room, self-closing doors with a higher degree of fire resistance than required by the code might also be installed.

Mathematical models can also make a significant contribution in the assessment of the above equivalencies. Models can be used to establish the egress time available as well as the time at which fire is expected to spread outside the meeting room. If the proposed solution provides the same or more time for these two events than does the building code solution, it can be reasonably concluded that equivalent safety exists.

Example 2

Prison authorities have learned that a cheaper line of prison furniture has been released. They would like to replace their existing furniture with the cheaper line but are concerned that the new furniture may not provide sufficient fire protection. Unfortunately, the NBC provides no guidance for the selection of furniture.

Prison authorities feel that the existing furniture provides a tolerable level of safety. Several fires involving the existing furniture have occurred but none have resulted in serious loss of life or property.

As materials permitted in a prison cell are restricted and the layout of the furniture can be controlled, it is possible to design room fire tests which can assess the relative performance of the existing and the new furniture within the prison. By selecting a likely ignition source, the resistance to ignition of the two furniture lines can be compared. In addition, the time for the development of hazardous conditions within a cell and within a ward can be determined. If the new line of furniture performs as well or better than the existing line, it is clearly wise to make the change. On the other hand, if the new line performs much worse than the existing line, very serious fires could result.

Summary

The relationship between flammability testing on building materials and contents and the requirements of the National Building Code have been explored. It has been argued that the practice of basing fire safety requirements for interior finish materials on their performance in the tunnel test, as has been done in Canada since 1960, is a sound one. On the other hand, recent developments in fire research, particularly in room-fire testing and computer modelling, will probably foster the development of more exact flammability performance requirements for building materials and contents, and provide a framework for improved fire safety design of buildings.

References

1. Peacock, R.D., and J.N. Breese, 1982. *Computer fire modeling for the prediction of flashover*, NBSIR 82-2516, National Bureau of Standards, Gaithersburg, MD.

2. Moulton, R.S., 1961. *Interior finish for life safety from fire*, NFPA Quarterly, Vol. 55, No.1, pp. 43-50.

3. Abrams, M.S., M.V. D'Souza, P. Higginson, W.S. Metes, J.G. Quintiere, W.J. Parker, R.F. Robins, and J.A. White, Jr., 1985. *Review of ASTM test for surface burning characteristics of building material (E84)* (An ASTM White Paper), Journal of Testing and Evaluation, Vol. 13, No. 2, pp. 89-114.

4. National Building Code of Canada 1960. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, NRCC 5800.

5. Standard Method of Test for Surface-Burning Characteristics of Building Materials and Assemblies, 1983. Underwriters' Laboratories of Canada, ULC Standard CAN4-S102-M83, Scarborough, Ontario, 30p.

6. Standard Method of Test for Surface-Burning Characteristics of Flooring, Floor Covering, and Miscellaneous Materials and Assemblies, 1983. Underwriters' Laboratories of Canada, ULC Standard CAN4-S102.2-M83, Scarborough, Ontario, 25p.

7. Mehaffey, J.R., 1986. *Fire performance of combustible insulation in buildings, in* Proceedings of the 30th Annual Technical/ Marketing Conference – Polyurethanes, Exploring New Horizons, co-sponsored by the SPI Polyurethane Division of SPI Canada Rigid Foam Division, Toronto, 7p.

8. Standard Corner Wall Method of Test for Flammability Characteristics of Non-Melting Building Materials, 1982. Underwriters' Laboratories of Canada, ULCS127-M82, Scarborough, Ontario, 9p.

9. List of Equipment and Materials, 1986. Volume II Building Construction, Underwriters' Laboratories of Canada, Scarborough, Ontario, 709p.

10. Fire Laboratories Listings, 1986. Warnock Hersey Professional Services Ltd., Mississauga, Ontario

11. Supplement to the National Building Code of Canada 1985. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, NRCC 23178, 278p.

12. National Building Code of Canada 1985. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, NRCC 23174, 454p.

13. Phillips, D., and M.A. Kasem, 1985. Upholstered Furniture Fires in Canada, Consumer and Corporate Affairs Canada, L10127-F32 84/85, Ottawa, 29p.

14. McCaffrey, B.J., J.G. Quintiere, and M.F. Harkleroad, 1981. *Estimating room temperatures and the likelihood of flashover using fire test data correlations*, Fire Technology, Vol.17, pp. 98-119.

15. Babrauskas, V., 1983. *Upholstered furniture. Heat release rates: measurements and estimation*, Journal of Fire Sciences, Vol. 1, pp. 9-32.

16. Proposed Method for Room Fire Test of Wall and Ceiling Materials and Assemblies, 1982. Annual Book of ASTM Standards, Part 18, American Society for Testing and Materials, Philadelphia, PA, pp. 1618-38.

17. Wickström, U., B. Sundström, and G. Holmstedt, 1983. *The development of a full-scale room fire test*, Fire Safety Journal, Vol. 5, pp. 191-7.

18. Fisher, F.L., and R.B. Williamson, 1983. Intralaboratory Evaluation of a Room Fire Test Method, NBS-GCR-83-421, National Bureau of Standards (USA), Gaithersburg, MD, 110p.

19. Fahy, R.F., 1985. *Building fire simulation model. An overview*, Fire Safety Journal, Vol. 9, pp. 189-203.

20. Mitler, H.E., 1985. *The Harvard fire model*, Fire Safety Journal Vol. 9, pp. 7-16.

21. Smith, E.E., 1985. *Computer based hazard assessment using release rate test data*, Fire Safety Journal, Vol. 9, pp. 47-54.

22. Jones, W.W., *A multicomponent model for the spread of fire, smoke and toxic gases*, Fire Safety Journal, Vol. 9, pp. 55-80.

23. Cooper, L.Y., and D.W. Stroup, 1985. *ASET – A computer program for calculating available safe egress time*, Fire Safety Journal, Vol. 9, pp. 29-46.

Appendix A

Determination of Flame Spread Classification

To determine the Flame Spread Classification (FSC) of a material, the burners are ignited and the advance of the flame front along the test specimen is recorded for ten minutes. The flame front position is plotted as a function of time. The curves for red oak and for 6 mm Douglas fir plywood are shown in Figure 5. The area under the flame front position–versus–time curve (A_t) is calculated.

The FSC_1 (note the subscript 1) is defined in terms of the area A_t as follows:

$$FSC_1 = 1.85 A_t \quad \text{for } A_t \leq 29.7 \text{ m}\bullet\text{min}$$

$$FSC_1 = \frac{1640}{59.4 - A_t} \quad \text{for } A_t > 29.7 \text{ m}\bullet\text{min}$$

The FSC_1 of noncombustible materials is zero, and that of red oak is 100. The values for all other products are determined in comparison with these materials. Using the test results shown in Figure 5 for 6 mm Douglas fir plywood, its FSC_1 is 135. (FSC_1 is not a direct measure of the rate of flame spread. However, the faster the flame gets to the end of the tunnel, the larger is A_t and hence FSC_1).

For some products, the flame front may advance for a while and then recede. For example, the flame front–versus–time curve for 12.7 mm gypsum wallboard is shown in Figure 6. After two minutes of testing, the flame had advanced to 2.3 m, and it then receded. The area under the flame front–versus–time curve is calculated as if the regression had not occurred, and thus A_t is the sum of A_1 and A_2. Using the test results shown in Figure 6 for the wallboard, its FSC_1 is 15.

Occasionally the flame front may recede for a while and then advance again, for example, when testing loose-fill cellulose insulation. In the test shown in Figure 7, the flame spread 4.7 m in three minutes, then receded and subsequently advanced again. The area is calculated as if the flame had spread to 4.7 m in three minutes and then remained at 4.7 m until the flame front again passed 4.7 m (dashed line). The area (A_t) used for calculating the Flame Spread Classification (FSC_1) is the sum of areas A_1 and A_2 in Figure 7.

The FSC_1 calculated from the tunnel test gives a ranking of materials which was assumed to reflect their performance in a real fire. For wood-based products this assumption appears to hold up. However, it became evident in the early 1970's that many foamed-plastic insulations with low FSC_1's, if left exposed as a wall or ceiling lining in a room, could spread flames quickly once ignited.[A1]

In Canada, the tunnel standards were amended in 1978 to take account of the unusual behavior of foamed plastics under the test conditions.[A2, A3] Close observation at NRC revealed that the flame front advances rapidly during the early part of the test, but then slows down and in some cases fails to advance further or actually recedes during the remainder of the test period. As the initial rapid flame spread was considered to be of prime importance in the development of a real fire, the use of an equation which gives emphasis to this early spread was introduced.

A second FSC, for foamed plastics (FSC_2), is calculated as

$$FSC_2 = 92.3\, d/t$$

where t is the time in minutes for the flame front to propagate a distance d metres, where there is a marked reduction in the advance of the flame front. Although the application of the concept is not without problems, the new calculation gives a classification for foamed plastics that is closer to its performance in real-world fires.

In Figure 8, the flame front–versus–time curve for a polyurethane foam is presented. Compared to the data for conventional materials presented in Figures 6 and 7, the flame advance along the foam commenced much sooner. For this foam, $FSC_1 = 74$ and $FSC_2 = 427$.

In those cases where the flame spread quickly in the early part of the test but it was difficult to establish the point at which the flame front declined, then the FSC_3 is determined by the results from a test conducted in accordance with ULC-S127-M82, Standard Corner Wall Method of Test for Flammability Characteristics of Non-Melting Building Materials.[8]

The Flame Spread Classification (FSC) of a specimen is the greatest of FSC_1, FSC_2 and FSC_3.

Care must be taken when comparing the Flame Spread Classification of a product tested in conformance with CAN4-S102-M83 (ceiling-mounted) with that from the American standard tunnel test, ASTM E-84.[A4] In both tests, the advance of the flame front down the tunnel is recorded, but the formulas used to calculate FSC from this information are different. For most building materials, the ASTM formula yields an FSC value about 8% lower than that derived from the Canadian formula; for some materials of very low thermal inertia (good thermal insulators), however, the ASTM figure is much lower than the Canadian one. From the results of corner–wall fire tests, Canadian scientists have argued that the Canadian formulas give a better ranking of lining materials.[A2,A3] Generally, the lower the FSC, the more time there may be to evacuate, should walls become involved in fire.

With thermoplastic materials, or others tested in conformance with CAN4-S102.2-M83 (floor–mounted), it is not possible to compare results with those measured in ASTM E–84, where the sample is mounted in the tunnel ceiling. The performance of such materials in the two tests is markedly different; generally, they perform more poorly in the Canadian test.

In addition to determining FSC's for products, the tunnel is used to determine smoke-developed classifications. These classifications are important in high-rise buildings only.

References

A1. Williamson, R.B., and F.M. Baron, 1973. *A corner fire test to simulate residential fire*, Journal of Fire and Flammability Vol. 4, pp. 99-105.

A2. D'Souza, M.V., and J.H. McGuire, 1977. *ASTM E84 and the flammability of foamed thermosetting plastics* , Fire Technology, Vol. 13, pp. 85-94.

A3. D'Souza, M.V., *The basis for flammability test methods* , Second Symposium on Combustibility and Plastics, The Society of the Plastics Industry of Canada, Ottawa.

A4. Standard Test Method for Surface Burning Characteristics of Building Materials, 1986. ASTM E-84, Annual Book of ASTM Standards, Vol. 04.07, American Society for Testing and Materials, Philadelphia, PA, pp. 319-336.

Fire Compartmentation and Fire Resistance

Guy C. Gosselin, M.Sc., M.B.A., P.Eng.

Introduction

In the paper *Flammability of building materials and fire growth*,[1] the development of a typical room fire is described, from the burning of one item (a piece of furniture or wastebasket) to fully developed or post-flashover conditions, when all exposed combustible materials in the room are burning. The measures in the National Building Code of Canada,[2] which are primarily aimed at delaying the onset of flashover, are also presented. However, restrictions on the combustibility and flammability of building materials does not ensure that the fire will not continue to grow beyond flashover; little control currently exists over the flammability of the building's contents (such as furniture and furnishings) and sometimes no one is around to detect or react to fire in its early stage. A recent analysis of data obtained from the National Fire Incident Reporting System indicates that about one out of every four fires will grow to a fully developed stage.

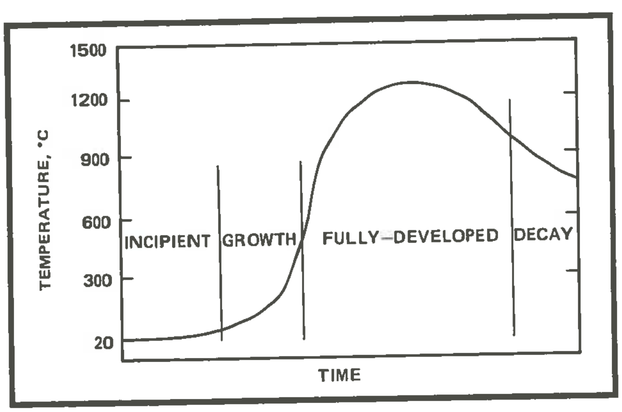
The life safety implications of a potential flashover occurrence must be carefully considered. A fire in its preflashover stage can spread outside the room of origin if some opening such as a doorway or a service penetration is left unprotected. But the danger of fire spreading outside of a room to a corridor and, eventually, to the rest of the building is highest once the fire reaches post-flashover conditions.

This paper deals with fire compartmentation, a fire protection concept used in controlling the hazards associated with a fully-developed fire. It identifies relevant fire safety objectives, describes the concept in practical terms, and outlines acceptable means of evaluating performance. The paper explains the compartmentation concept within the context of the National Building Code's approach to the provision of life safety and gives some examples of the procedure a designer should follow in developing alternative solutions to specific compartmentation requirements.

Fire Safety Objectives

In a fully developed fire, the safety of occupants within the room of origin is no longer an issue. The average temperature would reach about 500°C and quickly peak to levels of 800 to 1200°C, as illustrated in Figure 1. In addition, the amount of vapourized fuel and products of combustion produced by the burning of one piece of furniture (say an upholstered chair) could fill a space equivalent to a 15 000 m³ warehouse in as little as twenty minutes. Thus a sensible fire safety objective could be to contain fire and the superheated products of combustion to the area

Figure 1 Typical compartment fire development



of origin. Alternatively, one could let the fire spread to other portions of the floor area or other storeys in the building, provided measures were taken to prevent its entry into areas declared as safe, isolated zones for the use of occupants. This is shown as controlling the movement of fire, in the Fire Safety Concepts Tree[3] (see Figure 2).

North American building codes actually use both these fire protection measures, containment and isolation, to provide safety for the occupants. Commonly referred to together as fire compartmentation, the measures rely on physical barriers to retard the spread of fire so that occupants may have time to reach a place of relative safety, and fire fighters may respond, set up in a staging area, undertake search and rescue operations, and suppress the fire. In other words, fire spread is controlled by construction to allow other elements in the fire safety tree, such as suppression of fire and management of the exposed, to be achieved. This emphasizes the interrelationship which must exist between the various sub-branches of the tree, in order to improve the reliability of the fire protection system, as discussed by Richardson in his paper *Fire safety, statistics and regulations*.[4]

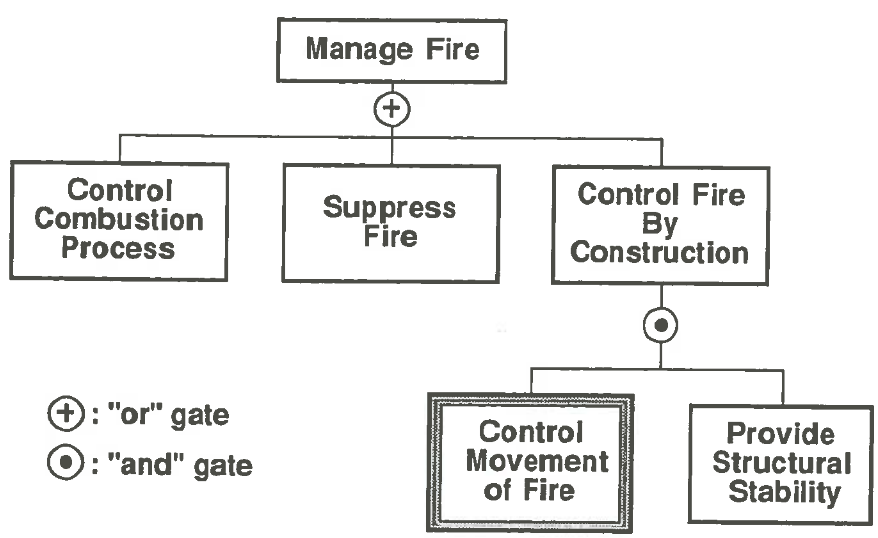
The extent to which compartmentation is required in a building depends on its size, the hazards it contains and the mobility of the occupants, as will be seen later. For now, it is important to understand what a fire compartment means and appreciate the level of performance generally expected from compartment boundaries (walls, floors and roofs).

Definition of Fire Compartmentation

A fire compartment is defined as an area of the building which is totally separated from the remainder of the building by *continuous* construction. This area could be a single room, or a series of rooms, even an entire floor area. Or, it could be a vertical service space or a horizontal service space. If we were to so separate every room or space in a building, we might achieve a very high level of fire safety. However, this would be an expensive solution, which might not be practical or cost effective, at least from a strictly life safety point of view. A more rational approach is to consider the location of each fire compartment as a strategic decision which must be fully compatible with the life safety or property protection goals.

Is the idea of enclosing spaces with continuous barriers a practical one? We know that openings are needed to allow access and egress from the area and to provide electrical, mechanical and plumbing services. In order to ensure the integrity of the fire compartment, it is critical that every opening or penetration through its walls, floor and ceiling, from large openings such as doorways to the smaller service penetrations (wiring, piping, and ducts), be adequately protected to resist the passage of fire.

Figure 2 Control Movement of Fire element, Manage Fire sub-branch of Fire Safety Concepts Tree



The potential impact of inadequate barrier penetrations needs to be assessed in the light of actual fire losses. Fire rarely spreads from one area of a building to another by destroying or burning through a wall or a floor. It usually bypasses these physical barriers, via common concealed spaces in walls or ceilings; heating, venting and air conditioning (HVAC) duct systems; large holes that have been punched through masonry walls to let electrical or communications cables through; doors left open or 'wedged' open. Every one of these openings must be protected to ensure that the fire will be contained to the desired area.

A fire separation is defined as a continuous barrier in which every opening or gap is effectively protected with a 'closure' (a special device or mechanism which blocks an opening, such as a door, wired glass or a rolling shutter) or firestopped with fire-resistant materials. Fire separations, and hence the mechanisms or closures used to protect the openings in the fire separation, are normally required to possess some level of fire resistance, i.e. they must be able to withstand the effects of fire and contain it for a specified period of time. To evaluate the ability of a specific building element or assembly to perform in this respect, small- and full-scale fire resistance tests have been developed; these will be described later.

It must be noted that not all fire separations are required by building codes to possess a fire resistance rating. For instance, noncombustible floor assemblies need not be protected nor rated when used in certain small buildings. They are expected to possess an inherent or nominal resistance to fire which, albeit unmeasured, is considered adequate to ensure the safety of the occupants under those conditions where a complete evacuation of the building requires only a few minutes, say five minutes or less. In other words, life safety can be achieved in small buildings without having to provide additional protection for the floor assemblies. (The owner of the building could choose to have some protection for the floor assemblies so as to minimize property damage and reduce insurance costs. Depending on the size and use of the building, such additional protection could be justified strictly from an economic point of view.)

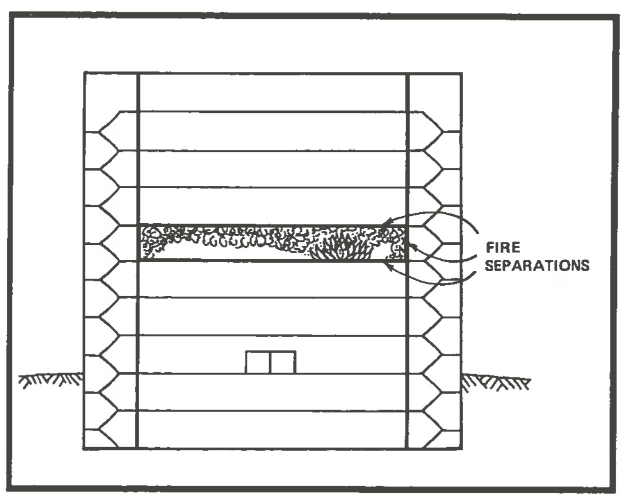
The time required for a complete evacuation of a building will vary according to the number of storeys and the type of occupancy it shelters. For instance, considerably more time is necessary to evacuate a health care facility, in which patients may be partly or totally disabled, than to evacuate an office building of similar size. On the other hand, it could take two hours or more to vacate a high building, depending on how tall the building is and its population density.[5] The evacuation times presented in Table 1 clearly show that it takes much more time to evacuate a high density office building than it does a residential building; this is due to congestion in the exit stairways. One could design larger stairways but, except for small buildings, this would represent an expensive solution.

Table 1 Time required for total evacuation of building population

Building Height (storeys)	Evacuation Time (min) Office	Residential
5	6–12	3–6
15	18–36	9–18
20	24–48	12–24
30	36–72	18–36
40	48–96	24–48
50	60–120	30–60

If stairways are designed to accommodate the evacuation of occupants from one floor at a time, occupants of floor areas above the fire floor will require protection against fire spread for a longer period of time than that afforded by unprotected conventional construction (about ten to twenty minutes). Storey–to–storey compartmentation is normally the best way of providing such protection; all floor/ceiling assemblies are built as fire separations, as illustrated in Figure 3.

Figure 3 Floor-to-floor and exit compartmentation



The level or duration of performance against the effects of fire which is necessary will vary for different buildings. In a low building, such separation need only retard the vertical progression of fire long enough to allow full evacuation of the upper storeys. According to building codes, 45 minutes to one hour is sufficient for this purpose. In higher buildings, the floor separations must be effective for the entire duration of a fire emergency, that is, the time it takes for all the combustible fuel on a floor (furniture and furnishings) to burn out completely or for fire fighters to suppress the fire, since the time needed to fully evacuate the building could exceed the duration of the emergency. The National Building Code of Canada[2] assumes that two hours of fire resistance is adequate protection in such buildings.

Performance Evaluation of Fire Separations

In the late 1800's, building regulations typically consisted of lengthy and cumbersome construction requirements, which specified the types of materials and methods of assembly deemed to afford an acceptable level of fire protection.[6] These requirements were based almost entirely on observations made at fire sites and authorities were reluctant to allow the use of new materials or forms of construction. With increasing pressure from designers and product manufacturers to have new proprietary systems recognized on an equivalent basis with conventional construction, building officials and researchers in Denver and New York city decided to construct kilns on vacant lots and subject representative floor specimens to wood-fueled fires of fairly long durations (typically eight- to 24-hour exposures). As this new evaluation procedure gained widespread acceptance across the United States, the American Society for Testing and Materials (ASTM) created a new committee in 1905 to develop an appropriate fire test standard.

Eventually issued in 1908, the ASTM standard specified acceptance criteria which have remained largely unchanged to this day. These criteria, now specified in Canada in the ULC standard CAN4-S101, Standard Methods of Fire Endurance Tests of Building Construction and Materials,[7] are as follows:

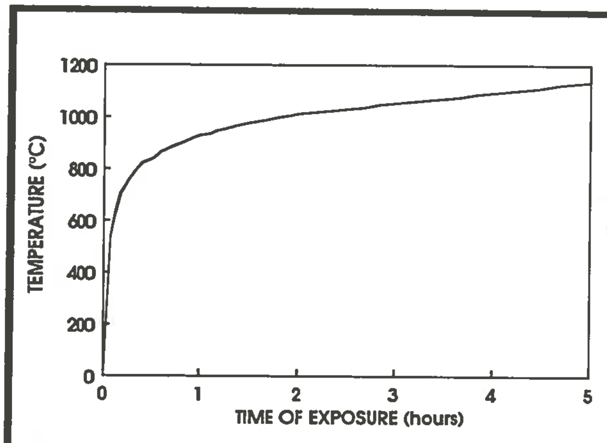
- no passage of hot gases or flames,
- specimen to remain in place under design loads,
- temperature rise on unexposed surface of specimen limited to:
  139°C (average of nine points measured)
  181°C (maximum),
- no passage of hose stream.

A fire-resistance rating for a building assembly, as used in codes, refers to the length of time that a specimen can withstand the standard fire exposure and still meet all of the acceptance criteria noted above. The fire exposure to which the specimens are subjected is defined in terms of a temperature–versus–time relationship, depicted by the curve in Figure 4. The curve was established in 1918 on the basis of maximum temperatures in real fires, observed by using as reference the fusion of materials of known melting points.

The first two criteria used in defining a fire resistance rating are self-explanatory. The temperature rise criterion was added in 1918 to control heat transmission through the assembly, which could ignite combustible materials stored directly against the unexposed floor or wall membrane in the adjacent compartment. The temperature rise limit was originally set at 167°C on the basis of the ignition temperature of cotton waste, but later was reduced to 139°C when it was observed that the temperature at the back of walls continued to increase for a while after the test furnace had been shut down. The last criterion ensures a minimum resistance to the erosion effects of a hose stream that might be directed at the wall during fire fighting.

Since it is also necessary to protect the access and service openings which may be present in floor and wall assemblies, other test methods that utilize the same standard fire exposure

Figure 4 Standard temperature-versus-time curve



have been developed for building components that act as closures or devices to protect the openings. For instance, CAN4-S104[8] applies to the testing of door assemblies, CAN4-S106[9] to window and glass block assemblies, and CAN4-S112[10] to fire dampers used within heating, ventilating and air conditioning ducts where these penetrate a fire separation. Furthermore, a new ULC standard, CAN4-S115 Standard Method of Fire Tests of Firestop Systems,[11] will shortly be referenced in the NBCC for evaluating the performance of devices which are used to maintain the integrity of the fire separation at service penetrations.

An important point to note with respect to closures and firestop systems is that the rating which they must attain is not as stringent as that required for the fire separation in which they are installed. For instance, closures have a fire protection rating that is not only of shorter duration than the fire resistance rating of the floor or wall (Table 2), but is also established without the imposition of the heat transmission criterion which applies to fire separations. This has been allowed primarily for two reasons: first, it is argued that, since an opening serves to allow people access or the passage of service utilities, combustible materials are not likely to be stored directly abutting the opening on either side. Second, closures are normally small and it is considered that fire fighters can deal with small localized fires on the other side of a fire separation.

Table 2 Rating of closures in fire separations*

Required fire resistance rating of fire separation, (h)	Required fire protection rating of closure, (h)
0	0
0.75	0.75
1	0.75
1.5	1
2	1.5
3	2
4	3

*Table 3.1.6.A., National Building Code of Canada[2]

Availability of Fire Resistance Test Results

Since the early twenties, a tremendous number of fire resistance tests have been conducted at laboratories across North America, yielding a wealth of data on the fire resistance properties of materials and assemblies. By and large, these data are available to the design professional through listings of proprietary designs tested at organizations such as:

- Underwriters' Laboratories of Canada[12]
- Warnock Hersey Professional Services Ltd.[13]
- Underwriters Laboratories Incorporated[14]
- Factory Mutual Research Corporation[15].

In addition, where the fire resistance of an assembly clearly depends strictly on the specification and arrangement of materials for which nationally-recognized standards exist, generic fire-resistance ratings have been developed by the Associate Committee on the National Building Code on the basis of supportive test results. These assigned ratings are published in Chapter 2 of the Supplement to the NBCC 1985.[16]

The Supplement contains ratings for a multitude of generic assemblies, such as reinforced concrete floors, walls and columns, masonry walls, wood and steel framed floors and walls, protected steel columns, and laminated timber beams and columns. Since the ratings are intended to apply to all systems and products which fall under the material standard descriptions, the ratings have been assigned on a fairly conservative basis. However, for the Supplement rating to apply in a particular design, all of the applicable provisions and conditions of Chapter 2 must be met. Modifications should not be allowed unless it can be demonstrated, on the basis either of a test or an engineering evaluation, that these modifications will not have a detrimental impact on the fire resistance of the assembly.

Generally speaking, the proliferation of available test results for conventional construction assemblies has been a mixed blessing for the design profession. It certainly has effected substantial savings in construction by dispensing with the need to conduct costly tests each time a new project is considered. However, it has also severely restricted design innovations by enticing engineers to specify designs already tested instead of engineering new systems. It is fairly common practice for the design professionals (architects or engineers) to meet fire resistance requirements by simply verifying that their design is covered by Chapter 2 of the NBCC Supplement or one of the published proprietary listings. But much more could be done with the recent advances made in quantifying not only the expected severity of fire but also its effects on the performance of the structure. Analytical methods currently being developed at research institutions around the world, will allow for the calculation or prediction of the fire resistance of building elements and assemblies. These methods are reviewed in more detail in the paper *Structural fire protection — predictive methods*.[17]

Limitations of the Fire Resistance Test

The standard fire resistance test is often criticized as not representing real-world fires, which can be more or less severe depending on the amount, type and geometry of combustible load (things which can burn) present in the compartment, the availability of fresh air (door and window openings), and the thermal properties of the interior finish materials (Figure 5). Testing each assembly for the various possible fires is not, however, an economically appealing solution. This problem was raised when the standard heat exposure was introduced and, in 1928, some efforts were made by S.H. Ingberg, a U.S. National Bureau of Standards testing engineer, to develop a relationship between the 'standard' fire and real fires.[18]

Ingberg conducted a series of full-scale room burns with the combustible content selected to be representative of typical office, record storage and residential occupancies. On the basis of these tests, in which room temperatures were recorded as a function of time, Ingberg proposed the equal area hypothesis to compare the severity of a real fire to that of a standard fire of specified duration. The hypothesis, illustrated in Figure 6, essentially states that the severities of the actual and the test fires can be considered similar if the areas under their respective temperature–time curves above a base level are equal.

Although it has since been shown not to be scientifically correct,[19] Ingberg's rule of thumb relationship between combustible load and equivalent duration of standard fire exposure presented a convenient way of assessing the levels of fire resistance necessary to withstand a complete burnout in a fire compartment (Table 3). The concept was thus readily adopted by code authorities in the 1930's and 40's following the gathering of data on combustible loads in residences, offices, schools, hospitals, stores and manufacturing establishments.[20]

However, the code authorities recognized that fire load data was only one item in the fire safety equation. Other factors, such as the height and area of buildings, the ability of the occupants to evacuate quickly and without assistance, the degree of awareness of fire conditions (being awake or asleep), and fire fighting capabilities, also impact on life safety and influenced the eventual decision regarding the level of fire resistance considered necessary in different types of buildings.

Figure 5 Comparison of typical compartment fires (A and B) and standard fire exposure

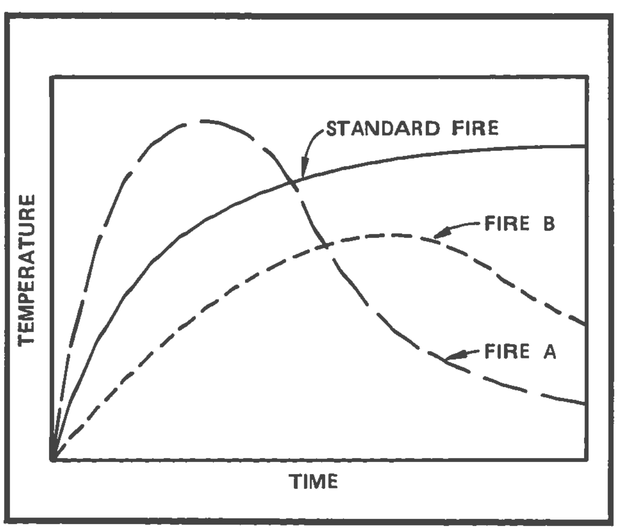


Figure 6 Ingberg's hypothesis – equal fire severities if area A = area B

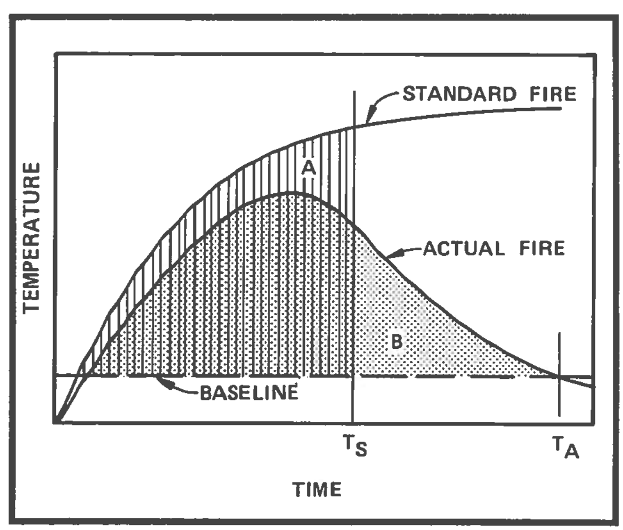


Table 3 Relationship between fire load and fire severity[18]

Combustible content* (lb/ft²)	Combustible content* (kg/m²)	Standard fire exposure duration (hours)
5	24.4	0.5
7.5	36.6	0.75
10	48.8	1
15	73.2	1.5
20	97.6	2
30	146.5	3
40	195.3	4.5
50	244.1	6
60	292.9	7.5

* Expressed as equivalent weight of wood (with respect to calorific value) per unit area of floor surface.

Use of Compartmentation in the NBCC

As mentioned earlier, the National Building Code of Canada utilizes compartmentation to accomplish one of two objectives: *contain* a specific fire risk within a compartment, and thereby protect the occupants in the rest of the building; or *isolate* the occupants within a particular compartment (or refuge area) from adjacent spaces that may be contaminated by smoke or involved in fire. An example of containment is the requirement that high hazard industrial occupancies (Group F, Division 1) be separated from the remainder of the building or that service rooms, refuse chutes and transformer vaults be enclosed in one-, two- or three-hour fire separations, depending on the particular risk involved.

Isolation is utilized, among other applications, for the exit system within the building (including exit stairs), which is required to be separated from the remainder of the building (as shown in Figure 3). In a hospital, operating rooms and intensive care units must be enclosed in rated fire separations to avoid having to move the patients hastily in case of a fire emergency in an adjacent area.

It should be emphasized that, when using isolation, we are protecting the occupants within the compartment from a potential external threat and not the other way around (containing the threat to its area of origin). This is quite important when investigating alternative ways of meeting the intent of the requirement. For instance, sprinklering the compartmented area may help protect lives or property when containment is the objective of the compartmentation requirement, since the sprinkler system deals directly with the fire risk. The same sprinkler would offer little protection where the compartment was intended for isolation, since the fire hazard would be located outside of the compartment and could overtake a sprinkler system located strictly inside the compartment by the time it breached the fire separation.

Table 4 lists seven instances in the NBCC where the compartmentation concept is applied. Also indicated for each application is the objective(s) of the requirement. The reader is encouraged to consider each objective and the corresponding requirement in terms of either containment or isolation.

Table 4 Major compartmentation requirements in the National Building Code of Canada

Article	Requirement	Objective(s)
3.1.3.1.	Separation of Major Occupancies	(1) protect assembled, institutionalized and sleeping occupants from adjacent hazards (2) contain mercantile and industrial fire risks
3.4.4.1.	Separation of Exits	(1) protect evacuating occupants from fire hazards on adjacent floors (2) provide fire fighters safe access to fire floor
3.2.2.X.	Separation of Floors	(1) provide occupants above fire floor time to reach area of safety (2) control fire size (prevent conflagration)
3.2.6.6. 3.3.3.5.	Separated Zones Within Floor Areas	(1) control fire size when fire compartment is too large and fire fighting is difficult (3.2.6.6.) (2) provide occupants of fire floor more time to evacuate when vertical evacuation is difficult (3.3.3.5.)
3.2.6.2. 3.2.8.4. 3.3.3.8.	Separated Areas of Refuge	(1) provide safe holding areas when: (a) "high" building smoke control option is used (3.2.6.2.) (b) floor separation is incomplete and exit capacity inadequate (3.2.8.4.) (c) evacuation is impracticable (3.3.3.8.)
3.3.1.1.	Separation of Suites	(1) provide occupants in adjacent suites more time to become aware of fire and evacuate
3.5.2.X. 3.5.3.X.	Separation of Hazardous Spaces	(1) contain hazards created by: (a) service equipment (3.5.2.X.) (b) continuous service spaces (3.5.3.X.)

Development of Equivalencies

Understanding clearly the intent of a code requirement is the first and most crucial step in the development of an equivalent solution. Equivalencies to code requirements are allowable under Subsection 2.5 of the NBCC, if it is demonstrated that the solution offers at least the same level of safety as the code solution.

The intent of a requirement can be broken down into two components: a fire safety objective, and the level of performance expected from the solution or measure used to meet the objective. Although knowledge of the specific fire safety objective for a particular requirement is the crucial first step in developing equivalents, such objectives are rarely stated explicitly in the Building Code. The Commentary on Part 3 of the NBCC[21] is an explanatory document which helps identify some of the Code objectives. However, a detailed analysis of the application of a fire protection concept (such as the one presented in this paper) is sometimes the only way of identifying the specific fire protection issue(s) underlying a code requirement. For example, Table 4 represents an attempt to clarify the fire safety objectives of the fire separation or compartmentation requirements of the NBCC.

Once the objective has been properly identified, alternative design solutions can be developed which specifically address the fire hazard underlying that objective. The designer must be prepared to find or generate the documentation (including calculations, statistics, etc.) which shows that the solution proposed can be as effective and reliable as the code solution.

For example, a potential equivalent might be to find another way of dealing with the hazardous substances normally found in janitors' closets. The Code requires that these closets be separated from the remainder of the building and be equipped with at least a heat detector to warn building occupants if a fire starts inside one of them. The objective of that fire separation requirement is to contain the fire long enough to permit the safe evacuation of occupants on that floor. As only a heat detector is required to detect the fire, a certain time delay is implied by the Code solution. The use of a quicker (and reliable) detection system could ensure an earlier initiation of evacuation. It may be possible to show that the time for detection can be sufficiently reduced to permit the total evacuation of the floor area before the fire has a chance of breaking out of the closet, even if the fire separation around it has no rating.

Another equivalency example arises when a designer proposes to specify a properly designed sprinkler system within a contained area deemed hazardous and required by the Code to be compartmented by rated construction. The designer may be able to demonstrate that the sprinkler system will effectively address the identified fire risk (i.e., lessen the fire exposure) and justify a decrease in the level of fire resistance required for the enclosing fire separation.

In all equivalency cases, it is important to make a judicious evaluation of the situation, indicating that the hazards have been (a) properly identified, (b) assessed as to their relative risk, and (c) adequately addressed by the proposed design solution (at least to an extent equivalent to that of the Code solution).

Conclusion

Building codes contain many requirements for fire separation which essentially call for the compartmentation of a building into smaller cells that are more manageable from a fire safety point of view. Compartmentation is used to either contain a fire or isolate occupants within a protected area in an attempt to achieve a uniform level of safety in all buildings.

For the concept to work, the compartment boundaries need to possess an adequate level of fire resistance, which will vary according to the circumstances, including the building size and type of occupancy. Similarly, every opening and penetration through these boundaries requires adequate protection in the form of a rated closure or firestop system.

A clear understanding of the specific objective for each fire separation requirement should open the way for ingenious designers to devise equivalent ways of satisfying not only the minimum life safety objective of a code but also the optimal property protection dictated by the economics of the situation.

References

1. Mehaffey, J. R., 1987. *Flammability of building materials and fire growth*, Proceedings of Building Science Insight '87, Institute for Research in Construction, National Research Council of Canada, Ottawa, NRCC 28277, pp. 21–33.

2. National Building Code of Canada 1985. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, NRCC 23174, 454 p.

3. Coté, A.E. and J.L. Linville (eds.), 1986. Fire Protection Handbook, 16th Edition. Systems Concepts for Building Firesafety, National Fire Protection Association, Quincy, MA, pp.7-10 to 7-19.

4. Richardson, J. K., 1987. *Fire safety, statistics and regulations*, Proceedings of Building Science Insight '87, Institute for Research in Construction, National Research Council of Canada, Ottawa, NRCC 29277, pp. 1–8.

5. Galbreath M., 1969. *Time of evacuation by stairs in high buildings*, Fire Fighting in Canada, Vol.13, No.1, pp. 6-10.

6. Shoub, H., 1961. *Early history of fire endurance testing in the United States*, Fire Test Methods, American Society for Testing and Materials, STP 301, Philadelphia, PA, pp. 1–9.

7. Standard Methods of Fire Endurance Tests of Building Construction and Materials, 1982. Underwriters' Laboratories of Canada, ULC Standard CAN4-S101, Scarborough, Ontario, 41 p.

8. Standard Method for Fire Tests of Door Assemblies, 1980. Underwriters' Laboratories of Canada, ULC Standard CAN4-S104, Scarborough, Ontario, 14 p.

9. Standard Method for Fire Tests of Window and Glass Block Assemblies, 1980. Underwriters' Laboratories of Canada, ULC Standard CAN4-S106, Scarborough, Ontario, 8 p.

10. Standard Method of Fire Tests of Fire Damper Assemblies, 1982. Underwriters' Laboratories of Canada, ULC Standard CAN4-S112, Scarborough, Ontario, 16 p.

11. Standard Method of Fire Tests of Firestop Systems, 1985. Underwriters' Laboratories of Canada, ULC Standard CAN4-S115, Scarborough, Ontario, 19 p.

12. List of Equipment and Materials, 1986. Volume II Building Construction, Underwriters' Laboratories of Canada, Scarborough, Ontario, 709 p.

13. Fire Laboratories Listings, 1986. Warnock Hersey Professional Services Ltd., Coquitlam, B.C., 339 p.

14. Fire Resistance Directory, 1987. Underwriters Laboratories Incorporated, Northbrook, IL, 750 p.

15. Approval Guide 1985. Factory Mutual Research Corporation, Norwood, MA, 535 p.

16. Supplement to the National Building Code of Canada 1985. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, NRCC 23178, 278 p.

17. Gosselin, G. C., 1987. *Structural fire protection — predictive methods*, Proceedings of Building Science Insight '87, Institute for Research in Construction, National Research Council of Canada, Ottawa, NRCC 28277, pp. 45–62.

18. Ingberg, S.H., 1928. *Tests of the severity of building fires*, NFPA Quarterly, Vol. 22, No. 1, pp. 43–61.

19. Harmathy, T.Z. and T.T. Lie, 1970. *Fire test standard in the light of fire research*, American Society for Testing and Materials, STP 464, Philadelphia, PA, pp. 85–97.

20. Ingberg, S.H., Dunham, J.W. and J.P. Thompson, 1947. *Combustible contents in buildings*, Building Materials and Structures Report BMS 149, National Bureau of Standards, Washington, D.C.

21. Commentary on Part 3 (Use and Occupancy) of the National Building Code of Canada 1985. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, to be issued in 1988.

Structural Fire Protection – Predictive Methods

Guy C. Gosselin, M.Sc., M.B.A., P.Eng.

Introduction

As the words 'structural fire protection' imply, this paper addresses the design of the structural system of a building in such a way that its primary loadbearing members will not collapse prematurely in the event of a fire. Important aspects of this discussion include the specific fire safety objectives that can be pursued by providing structural fire protection, a clear understanding of how much protection is needed to fulfill those objectives, and what means are available to ensure that a proposed design provides the necessary level of fire resistance.

This paper also reviews the basis for the structural fire protection requirements contained in the current edition of the National Building Code, as well as the special structural provisions that apply to major fire separations used to subdivide large buildings.

Fire Safety Objectives

An early motivating factor in making structural building elements more fire resistant was undoubtedly the unacceptable economic loss resulting from the structural collapse of fire-struck buildings.[1-4] Although it was recognized that publicly-mandated code provisions could not "legally control construction, except as they relate to the safety, health, or welfare of those in or about buildings" and, specifically, could not "legally...require good building practice on purely economic grounds, desirable though this may be" minimum requirements aimed at preventing collapse were considered legally justifiable, if only to protect the investment of adjacent property owners.[1] This notion gained momentum early in the 20th century as building heights soared to so-called 'skyscraper levels'. Understandably, the idea of a 50-storey building collapsing on adjacent properties and in the streets did not appeal to the general public, which sought the enforcement of measures to ensure that the structural frame or 'shell' of a high building remained standing following a fire.

Property protection objectives hence played an important role in the early requirements for structural fire protection. As the years passed, however, relaxations in the required levels of fire resistance were rationalized on the basis of the confidence gained through fire testing of full scale construction assemblies, experimental work conducted by the National Bureau of Standards[5] on the expected intensity and duration of building fires, and actual field experience. Meanwhile, the issue of the safety of fire fighters and building occupants surfaced as the primary objective of minimum code requirements. But why would one expect these people to be in danger? Are the flammability and compartmentation control measures of the code (described in other BSI lectures[6,7]) not sufficiently effective?

The answer to these questions is that a rated fire separation or barrier to the spread of fire can only be as effective as the structural assembly that supports it. There would be little sense allowing a two-hour rated floor assembly to be supported by unprotected beams and columns that might collapse as quickly as ten to twenty minutes following flashover in the compartment directly below the floor assembly.

The Fire Safety Systems Tree developed by NFPA[8] takes into consideration the fact that the Control Fire by Construction objective or sub-branch can be satisfied only if both the movement of fire is controlled (by barriers such as fire separations) and structural stability is provided. This is illustrated by the *and* gate above these two elements of the tree, as shown in Figure 1. One of the fire safety objectives of structural fire protection thus consists of ensuring that rated fire separations can perform their fire barrier function for a certain period of time. Consequently, all the factors which play a role in the assessment of the fire resistance rating considered necessary for the fire separation (relative mobility and alertness of the occupants, anticipated combustible loads, specific occupancy hazards, etc.) apply equally to the rating of the supporting structural members. These are discussed extensively in *Fire compartmentation and fire resistance*.[7]

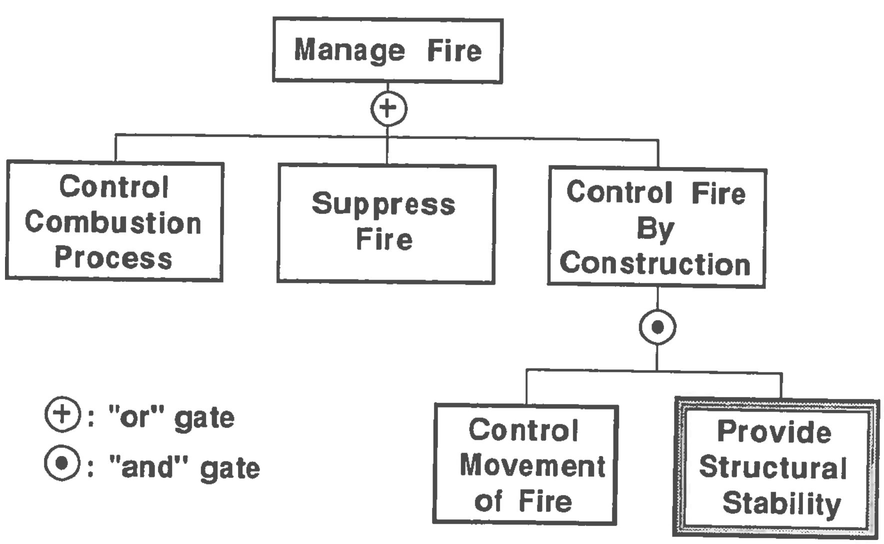
The role of structural fire protection can be expressed by one or more of the following fire safety objectives:

- provide *sufficient* time for occupants on the floors above the fire floor to reach an area of safety;
- support the fire separations necessary to control the overall size of the fire and prevent conflagration;
- minimize potential damage to adjacent properties.

The word 'sufficient' in the first objective is emphasized to indicate that the required level of performance (degree of fire resistance) will vary according to design circumstances. With current technology, the collapse of a member subjected to the effects of a fully developed fire may be delayed a few minutes, a few hours or indefinitely. Delaying collapse indefinitely (in essence, preventing it) is not always necessary. For instance, small buildings from which occupants can escape rapidly in the event of a fire may not require any special protection against collapse and their design will still satisfy the objective of life safety. Whether structural fire protection should be considered for these buildings, and to what extent it should be provided, becomes a decision that is based strictly on the economics of the situation (i.e., comparing the capital and business investment value to the cost of providing the structural fire protection).

In a larger building, or one where occupants may have difficulty evacuating, the time required for a complete evacuation will be longer. Also, fire fighters will be expected to enter the building, assist in the evacuation and attempt to extinguish the fire. Collapse must be delayed by providing a higher level of structural fire protection in order to ensure the life safety of occupants and fire fighters. However, it may still be economically acceptable to incur the financial loss associated with the destruction and collapse of the building, once everyone has safely evacu-

Figure 1 Provide Structural Stability element in Manage Fire sub-branch of Fire Safety Tree.



ated. Again, the level of protection above the minimum needed to satisfy the life safety objective will depend on economics.

When the height or occupancy of the building is such that total evacuation is not possible, collapse of the primary structural members must be prevented for the period of the fire emergency and beyond. Although this necessitates a level of protection which will also decrease property losses, it may not guarantee that damage to the structure will be repairable. Again, negotiations between the owner, insurer and designer will dictate whether it is cost effective to provide structural fire protection to a level that ensures the building can be quickly rehabilitated.

Building Code Requirements

Requirements contained in building codes, such as the National Building Code of Canada (NBCC),[9] represent the minimum levels of fire safety deemed acceptable to society. They are predicated primarily on the basis of public safety, not property protection.

The codes normally require that loadbearing elements and assemblies (walls, columns and arches) have a fire resistance rating at least equivalent to that required for the supported assembly (floor or roof), for the reasons explained earlier. In the NBCC, a minimum level of structural fire protection is generally not required for one- and two-family dwellings, since it is expected that their occupants can escape before any structural element will collapse. In buildings up to five or six storeys in height, where a normal evacuation process is anticipated (e.g., in most assembly, residential and office buildings), a fire-resistance rating of three quarters of an hour or one hour is usually required, to allow sufficient time for a complete evacuation of the building. For higher buildings, and others such as hospitals, theatres and correctional institutions, which cannot be evacuated quickly or easily, a two-hour fire resistance rating is deemed sufficient protection. Three-hour ratings are only required for large buildings containing a hazardous fire load (mercantile, high hazard industrial, and medium hazard industrial occupancies). The ratings also depend to some extent on fire suppression capabilities (the degree of fire fighting access to the site and whether or not the building is sprinklered).

The highest fire-resistance rating (four hours) required in the NBCC is for firewalls adjacent to a high hazard occupancy. A firewall is a heavy fire separation of masonry or concrete intended to prevent fire from spreading between adjoining buildings. To that end, a firewall is required to possess sufficient structural stability to ensure that the collapse of a floor or roof during a fire in one of the adjacent buildings will not cause the collapse of the firewall. Hence, if a two-hour rated floor is attached or supported by a four-hour firewall, the connections must be designed so that the floor assembly may collapse without affecting the structural integrity of the firewall.

Fire Resistance of Conventional Building Systems

Structural systems can be made fire resistant by increasing member sizes (structural overdesign), by encasing the structural element in an insulating material of low thermal inertia, or by protecting the entire assembly or system with an insulating membrane. The type of protection best suited for a particular system depends primarily on the type of material used in its construction, as each material behaves differently under elevated temperatures. This section presents a brief synopsis of the important design parameters affecting fire resistance, as well as the most common types of protection for concrete, steel and wood structural systems.

Concrete Construction

Reinforced and prestressed concrete systems are rarely protected externally, since concrete is normally made of inorganic materials having low thermal conductivity and heat capacity (i.e., concrete is a fairly good insulator). However, concrete gradually loses its compressive strength under increasing temperatures[10] (Figure 2) so one must make sure that members have been designed with sufficient reserve strength to support the applied loads for the projected duration of fire exposure.

Another important design consideration consists of making sure the steel reinforcement (embedded in the concrete) is sufficiently insulated, since steel loses considerable tensile strength at elevated temperatures.[11] The critical temperature of steel is defined as the temperature at which only 60% of the original strength remains, at which point failure is imminent under full design loads (the safety factor has been reduced to one). For regular reinforcing steel, the critical temperature is 538°C, whereas for prestressing steel bars, which are made of high carbon, cold drawn steel instead of low carbon, hot-rolled steel, the critical temperature is significantly lower at 427°C.[12] The time it will take for these temperatures to be reached in a concrete member (slab, beam or column) depends on the thickness of concrete cover protecting the steel.

As concrete is a fairly good insulator, it does not take a thick cover to restrict the steel reinforcement temperature to below critical levels. Figure 3 shows the temperature gradient in a 150 mm concrete slab after a two-hour standard fire exposure.[12] Notice that the temperature of the concrete 50 mm from the fire-exposed surface is only 340°C, or 33% of the furnace temperature (1010 C).

The degree of restraint against thermal expansion, which every concrete member will undergo as its temperature increases, and the degree of continuity provided by the structural system at the supports, will also affect fire resistance.[13] Both are generally regarded as being beneficial insofar as concrete members are concerned. Restraint against expansion, illustrated in Figure 4a, sets up additional compressive stresses which, when accounted for in the design, reduce the tensile forces that are initially resisted by the reinforcing steel in the bottom half of the member. Continuity (Figure 4b) enables a certain amount of stress redistribution to take place before excessive rotation develops at the supports and midspan, causing the collapse of the assembly. In a statically determinate (simply-supported) structure (Figure 4a), excessive rotation need only occur at one point (usually midspan) for failure to occur.

Steel Construction

Steel, like concrete, has the advantage of being noncombustible, but this characteristic alone means little in trying to resist collapse. Its high thermal conductivity makes steel absorb heat much more quickly than other materials; thus if the structural member has a relatively small mass, its temperature will increase very rapidly. Both the yield stress and modulus of elasticity of steel, the two material properties most important in determining load-carrying capacity, decrease considerably with increasing temperatures (Figure 5).[12] At a temperature of 593°C, these values will have fallen by at least 40% compared to ambient room temperature levels, meaning that the strength of the steel member will be barely sufficient to resist applied loads (assuming normal safety factors).

The mass–to–heated perimeter ratio for a steel structural member is a good indicator of its inherent fire resistance. A heavy steel column can absorb considerable heat and not reach its critical temperature before 30 to 40 minutes of exposure to a fully developed fire. On the other

Figure 2 Effect of temperature on compressive strength of concrete (from Malhotra, 1956)

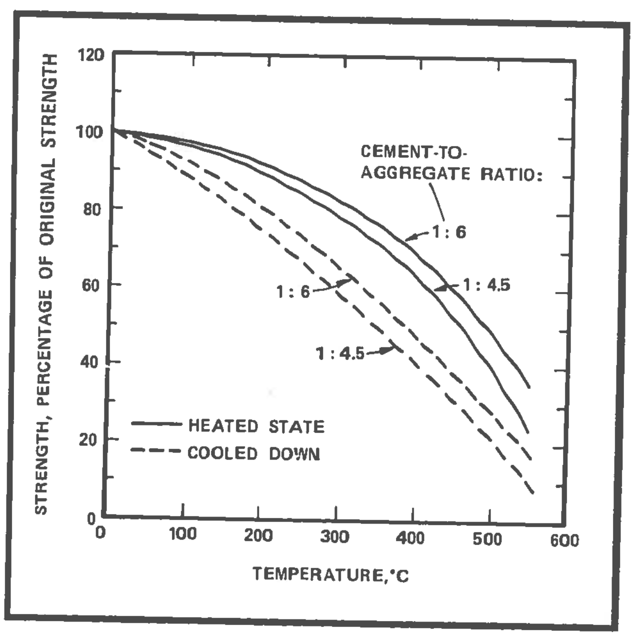
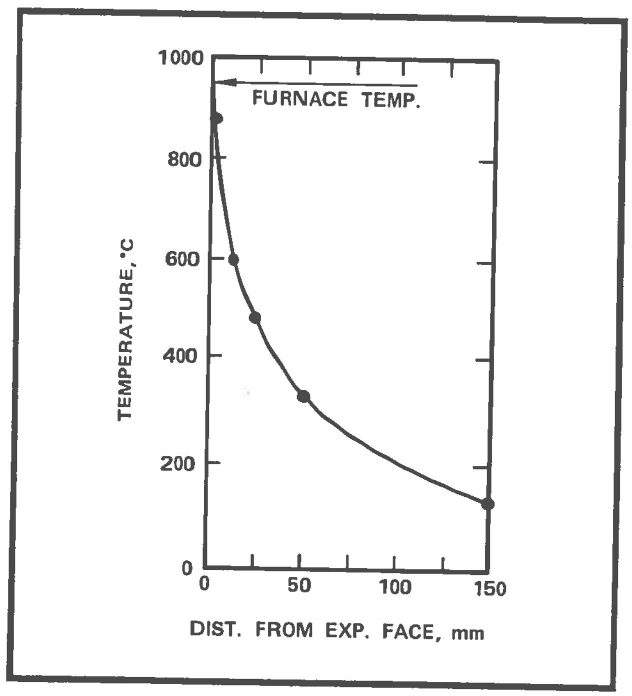


Figure 3 Thermal gradient in a 150-mm-thick concrete slab after two hours of standard fire exposure (Reproduced with permission from the Fire Protection Handbook, 16th edition © 1986, National Fire Protection Association, Quincy, MA 02269)



hand, open web steel joists and other lightweight types of steel construction may fail within five to ten minutes of exposure to the same fire.

In order to achieve fire resistance ratings of one hour or more, a steel member must be protected by an insulating skin which will keep its temperature below the critical point. Early in this century, encasements in concrete, brick, clay tiles, lath and plaster, and similar materials were commonly used for this purpose.[3] Now, less expensive forms of protection have been developed, such as cementitious coatings and sprayed-on mineral fibres, which can be applied directly on the steel members. Some intumescent paints and epoxy coatings have also been used to improve the fire resistance of steel members. These coatings swell and form an insulating layer around the member when subjected to heat. However, they are generally more expensive than other forms of protection.

As an alternative to encasement and surface treatments, the use of a suspended ceiling or protective membrane has been a common means of protecting steel floor and roof assemblies. The membrane usually contributes between 85 and 90% of the fire resistance of such assemblies; thus the type, thickness and fastening of the membrane are the most important design parameters. Lath and plaster, gypsum wallboard panels and inorganic acoustical tiles supported on a metallic-grid system are the most popular membrane ceilings. They can be attached directly to the underside of steel framing members or hung with wire hangers from either the floor deck or the framing members. This allows flexibility in the depth of the concealed space, which is often used for electrical, plumbing and mechanical services. For these protective ceilings to be effective, however, it is critical that all service penetrations be adequately protected or fire stopped and that the integrity of the membrane not be destroyed during maintenance work in the concealed space. Also, when acoustical tiles are used on a metal grid system, they must be tied down with special clips so they will not be uplifted by the positive pressure which may be created by a fire.

A final aspect to consider when using steel in construction is its significant coefficient of linear expansion under thermal loads. At temperatures of up to 1000°C, it is given as:[14]

$$\alpha = (0.004T + 12) \times 10^{-6}$$

where α = coefficient of thermal expansion, in degrees Celsius^{-1},
T = temperature in degrees Celsius.

If the structural member is axially restrained against displacement (as a column is), the expansion due to heat will be translated into thermal stresses that will increase the overall stress level in the member and cause an earlier collapse. Without axial restraint, a steel member will expand and could set up eccentric loading of adjacent structural members by displacing one of their ends (for example, a beam displacing the top of a column or of a loadbearing masonry wall), as illustrated in Figure 6. Good fire protection engineering dictates that either thermal expansion be prevented by limiting steel temperatures, or its effects on the structure be accommodated in the design.

Figure 4 Effects of restraint and continuity on fire resistance

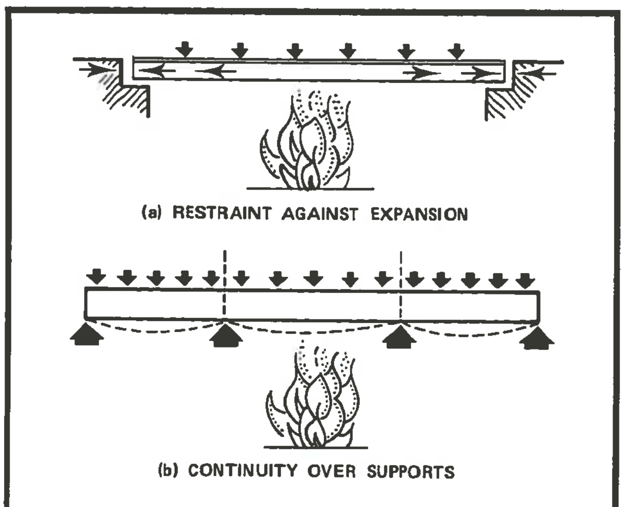
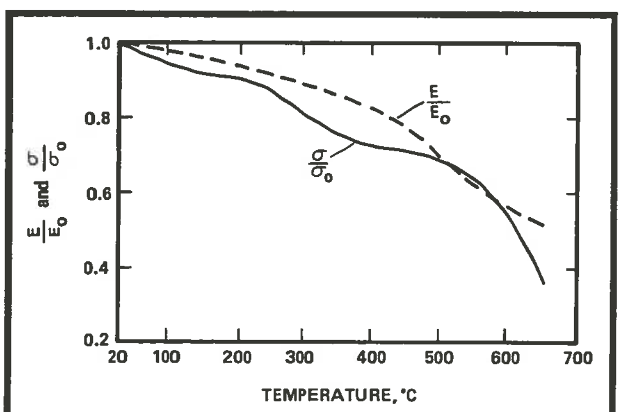


Figure 5 Effect of temperature on modulus of elasticity (E) and yield stress (σ) for A36 steel. E_o and σ_o represent ambient conditions (Reproduced with permission from the Fire Protection Handbook, 16th edition © 1986, National Fire Protection Association, Quincy, MA 02269)

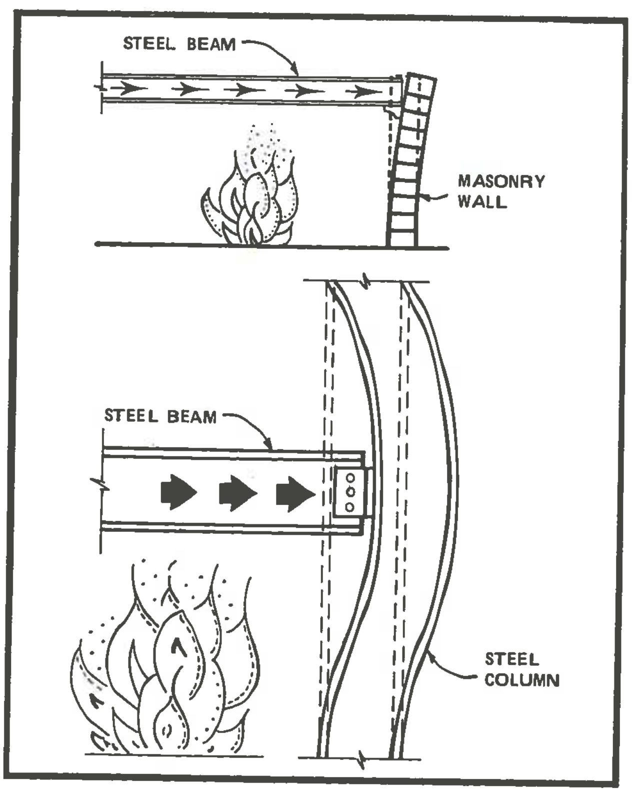


Wood Construction

Wood has the major disadvantage of being combustible. However, this does not mean that wood construction is less safe than steel or even concrete construction. For instance, if tested without a ceiling membrane, a conventional wood joist floor system can withstand the standard fire exposure of CAN4-S101[15] (Standard Methods of Fire Endurance Tests of Building Construction and Materials) for at least fifteen minutes, whereas a conventional open web steel joist system would fail in less than ten minutes. The burning of wood produces a charred layer on the surface of a member, which acts to insulate the unburned wood from the heat being radiated by the flames. This slows down considerably the rate of charring, which will be relatively constant throughout the fire. The rate of charring varies according to the wood species and moisture content but is roughly 0.6 mm/min. for thick members.[12]

Wood also has a very low thermal conductivity, which means that the inside of a wood member is little affected while the outside surfaces burn. In fact, a fair correlation exists between the strength of a burning member and its reduced cross-sectional area. The charred layer is presumed to have no strength, while the uncharred wood suffers a strength loss of only 10-15%.[16]

Figure 6 Thermal expansion of fire-exposed members



The term 'heavy timber construction' refers to a combustible type of construction that utilizes large members which can burn for a significant period of time before their cross-sectional areas are reduced to the point of collapse. By carefully specifying minimum sizes for each critical component, building codes often consider heavy timber construction as equivalent to three-quarter-hour rated combustible construction.

As with steel construction, wood floors and roof systems can acquire considerable fire resistance if the wood framing members are protected with an insulating membrane of lath and plaster or gypsum wallboard. The membrane can be fastened directly into the wood frame, provided the fasteners are sufficiently long to dissipate heat into the wood and prevent local charring that might cause them to pull out. Wood columns can be protected by intumescent coatings, gypsum board, or other mineral fibreboard developed specifically for the purpose. Although fire retardant treatments (surface applied or pressure impregnated) may delay ignition and therefore slow down the spread of flame along the treated wood members, they generally do not affect the rate of charring under fully-developed fire conditions and, hence, they do not increase the fire resistance of wood members.

Determination of Fire Resistance

With recent inroads made at research institutions around the world, there are now three different ways of determining the fire resistance rating of structural members and assemblies. By far the most common method consists of conducting a fire test on a loaded specimen in accordance with a nationally-recognized standard, such as CAN4-S101 (Standard Methods of Fire Endurance Tests of Building Construction and Materials) or of simply looking up published listings of test results and conforming to the specifications of a tested assembly. The second design approach makes use of empirical equations that correlate the results of fire tests for specific combinations of construction material/protection material. Due to the high costs of conducting full-scale fire tests, many such equations have been developed in the last fifteen years to extend the usefulness of test results.

Currently, scientists at the Fire Research Section of the Institute for Research in Construction and other institutions are developing theoretically-based approaches, often referred to as 'rational' design procedures, which rely on structural mechanics and heat transfer principles to assess structural response under fire conditions. These represent the newest design approach and open the way to an entire field of design possibilities.

Each of these three design approaches are explained and their strengths and weaknesses briefly described, to help designers in selecting the method that best addresses their needs.

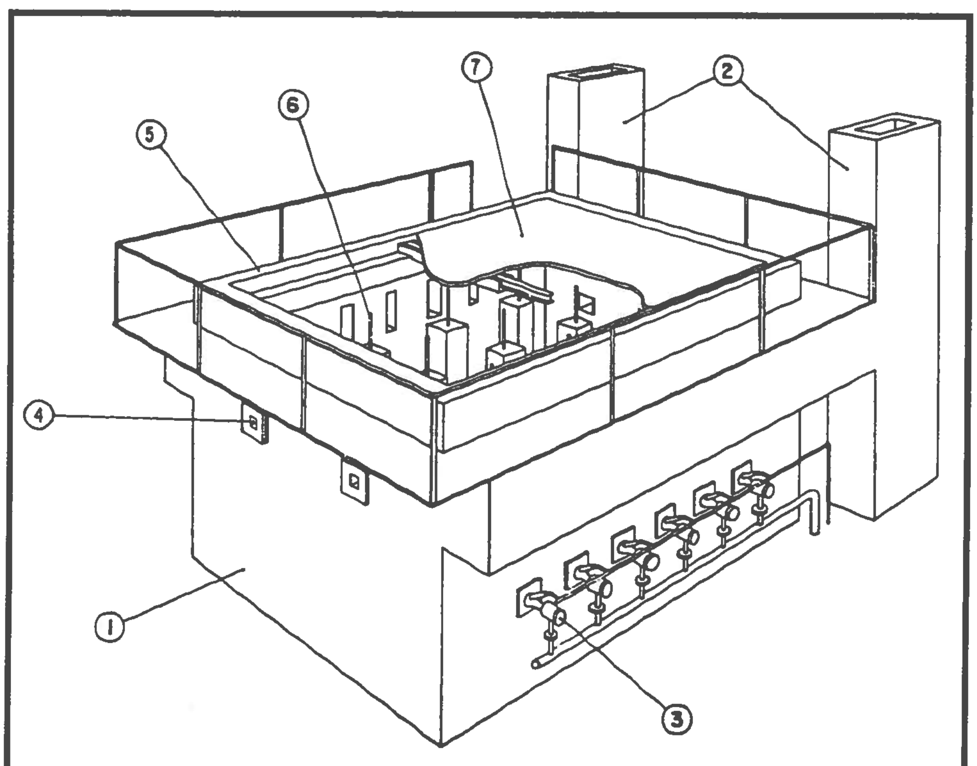
Fire Resistance Testing

Since the early 1920's, the conventional way of designing for fire resistance has consisted of having a standard fire test performed on a specimen representative of the construction assembly. Furnaces have been developed for the testing of floor and roof assemblies (Figure 7), walls and partitions (Figure 8) and structural columns (Figure 9). The column furnace at IRC is unique in Canada and is the only one in North America which is equipped to apply eccentric loads on specimens.

For structural members, the standard CAN4-S101 normally calls for testing under full service load conditions expected in the field, but testing at lower loads, which has the general effect of increasing fire resistance, is allowed provided the restricted load condition is clearly indicated. The standard specifies in detail the preparation, conditioning and instrumentation of test specimens. Conditioning at the specified relative humidity is critical to ensure consistency of the test results, as the moisture content of a specimen usually has a significant effect on fire resistance due to the high heat absorption capacity of the dehydration process.

End restraint conditions of the specimen also influence performance during the test.[15] Appendix A to CAN4-S101 defines a thermally restrained condition as one in which expansion or rotation at the supports is resisted by forces or moments external to the element (usually by the test frame). An unrestrained condition arises when the specimen is free to expand and rotate at its supports, simulating a statically determinate design in practice. Testing under restrained conditions usually imparts additional fire resistance to a load-carrying assembly, so the test result should be applied only to design cases where it is expected the same degree of restraint will occur at the supports of the assembly. In cases of doubt, the conservative approach would be to assume no restraint and to conduct the tests accordingly.

Figure 7 Schematic of floor furnace (from Standard Methods of Fire Endurance Tests of Building Construction and Materials) 1 – furnace, 2 – flue, 3 – gas burners, 4 – observation ports, 5 – restraining frame, 6 – thermocouple tubes, 7 – specimen



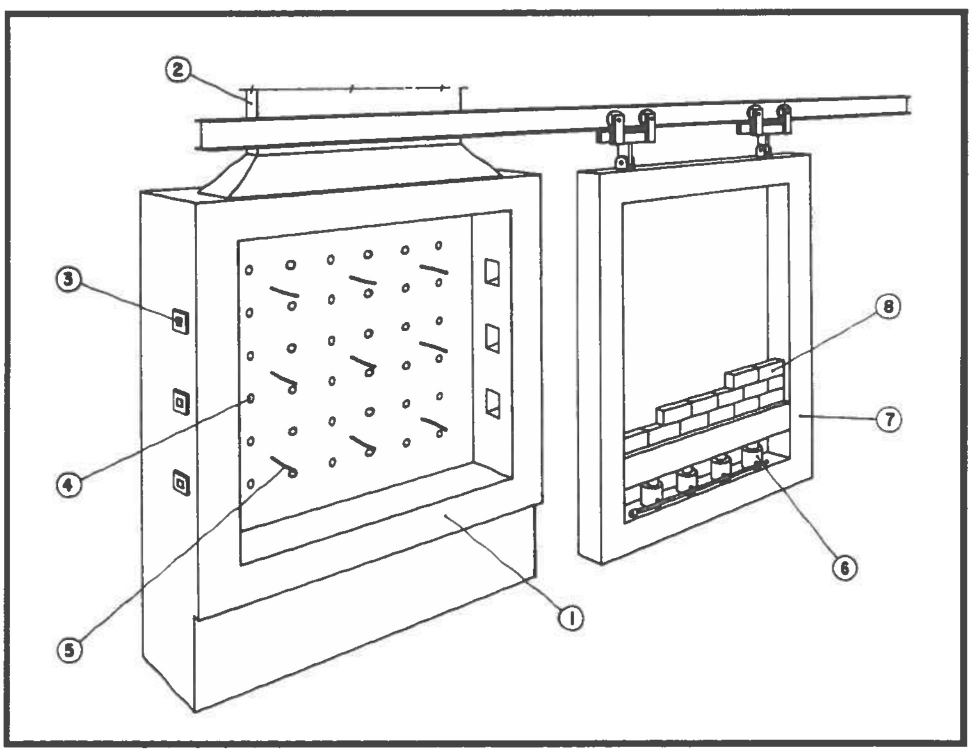
It must be appreciated that the fire resistance rating is the time during which the specimen can withstand the standard fire exposure, while meeting all relevant test criteria. However, if the function of the structural member or assembly is strictly to carry load and not to prevent the spread of fire, then the only applicable test criterion is to continue to sustain the applied loads (resist collapse) for the duration of exposure. In actual field conditions, the same member or assembly may collapse much sooner or much later than the test duration owing to differences between the test and real world fire exposures[17] and to differences in workmanship, loading, and end boundary conditions.

This is not to suggest that results from fire tests are useless. On the contrary, the code approach of requiring that testing be done according to standardized conditions has produced a consistent measure of the relative fire performance of construction assemblies within a regulatory context whose effectiveness depends on ease of enforcement. Notwithstanding its deficiencies, this approach has contributed a great deal toward the provision of fire safe construction in our modern cities.

The tremendous number of fire resistance tests has yielded a wealth of data on the fire resistive properties of materials and assemblies which are available to the design professional. Listings of the results of tests conducted on proprietary designs are available in North America from testing and certification organizations such as Underwriters' Laboratories of Canada, Warnock Hersey Professional Services Ltd., Factory Mutual Research Corporation and Underwriters Laboratories Inc. In addition, the Supplement to the National Building Code of Canada[18] contains a compilation of fire resistance ratings applicable to generic assemblies. These ratings have been developed by a technical committee on the basis of an analysis of test results.

The greatest disadvantage of this conventional design approach is that designers must conform to every essential detail of the tested assemblies for the fire resistance ratings to be applicable in actual construction. A modification in the design requires testing of a new specimen or a detailed engineering evaluation to show that the proposed modification will not be detrimental to the fire resistance rating of the assembly. This situation has severely restricted structural

Figure 8 Schematic of wall furnace (from Standard Methods of Fire Endurance Tests of Building Construction and Materials). 1 – furnace, 2 – flue, 3 – observation ports, 4 – gas burners, 5 – thermocouple tubes, 6 – loading jacks, 7 – restraining frame, 8 – specimen



design innovation by enticing the design professional to specify already-tested designs instead of engineering new systems.[19]

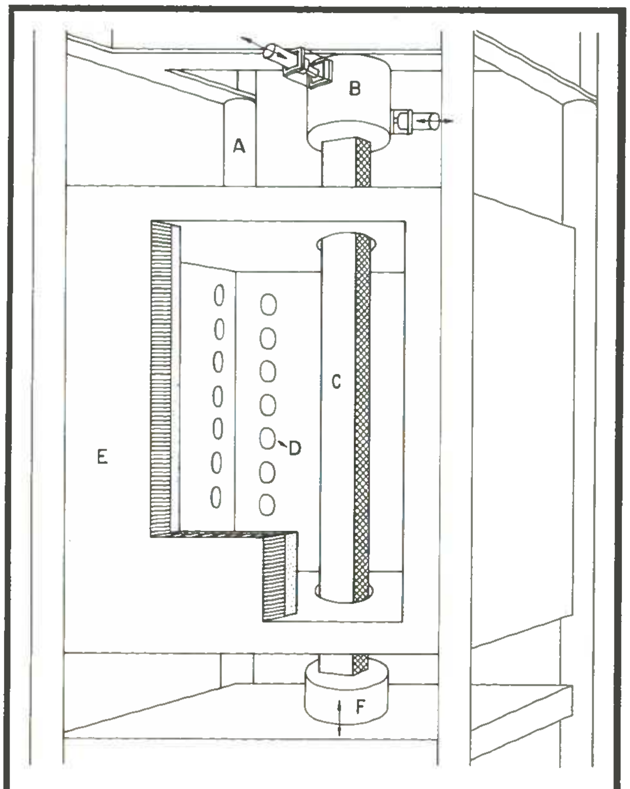
Empirical Methods

Empirical equations presenting correlations of fire resistance test results with important design parameters started to emerge in the late 1960's when sufficient test results became available to quantify the effects of critical parameters. Some of these equations were developed on the basis of theoretical predictions, which were themselves validated by test results.

The important points to consider in assessing the appropriateness of using one of these equations are:

- the scope of the database used to validate the empirical relationships,
- the level of confidence in the calculated results, and
- the applicability of the established relationships to the specific materials and products used in actual construction.

Figure 9 Schematic of column furnace. A – restraint frame, B – transverse loading head, C – test column, D – burner, E – insulated furnace shell, F – axial loading arm



A narrow database will seriously limit the usefulness of the empirical equation, as only a limited range of design parameter values will be available to the designer. Applying the equations to design conditions outside the tested range (extrapolation) should not be undertaken without a thorough fire engineering evaluation. The number of test results used in the establishment of the empirical relationship should also be considered to evaluate the confidence level one can place on the predicted results. A much higher level of confidence would ensue if ten or twenty results have been used, as opposed to only four or five. A statistical analysis of the results should be carried out and predictions corresponding to a confidence level of around 90% might be used in the absence of a better criterion. Finally, care should be taken to ensure that the proposed construction materials (such as the sprayed-on material for protecting a steel member) are similar to the ones tested in all important aspects, such as adhesion, resistance to cracking or spalling and thermal conductivity.

With these words of caution, a few empirical equations will be presented for illustrative purposes.

(a) For laminated timber beam and column members:[18,20]

$R = 0.1\,fB\,\{4 - 2(B/D)\}$ ... beams; 4-sided exposure

$ = 0.1\,fB\,\{4 - (B/D)\}$ ... beams; 3-sided exposure

$ = 0.1\,fB\,\{3 - (B/D)\}$ ... columns; 4-sided exposure

$ = 0.1\,fB\,\{3 - 1/2(B/D)\}$ ... columns; 3-sided exposure

where R = fire resistance, in minutes,
f = load factor (see Figure 10),
B = smaller dimension of beam or column, in millimetres,
D = larger dimension of beam or column, in millimetres,
k = effective length factor,[21]
L = unsupported column length, in millimetres.

The above equations are based on an assumed charring rate of 0.6 mm/min., and include a load factor which gives some credit to the overdesign of members for the purposes of obtaining 're-serve' strength during fire exposure.

(b) For reinforced concrete columns:[18,22]

$R = (t/75f) - 1$ ... lightweight concrete; rectangular column

$= (d/90f) - 1$ ... lightweight concrete; round column

$= (t/100f) - 1$ ... normal weight concrete; rectangular column

$= (d/120f) - 1$ ... normal weight concrete; round column

provided $c = 25\,R$ if $R \leq 2$ hours

$= 25 + 12.5\,R$ if $R > 2$ hours

where R = fire resistance rating, in hours,
t = smaller dimension of rectangular column, in millimetres,
d = diameter of round column, in millimetres,
f = load factor (see Table 1),
k = effective length factor,[23]
L = unsupported column length, in metres,
p = area of vertical steel reinforcement as a percentage of column area,
c = minimum thickness of concrete cover over vertical steel reinforcement, in millimetres.

These equations take into account seven design parameters: the size and shape of the column, its effective length, the type of concrete, the percentage of steel reinforcement, the thickness of concrete cover over the steel reinforcement and the degree of overdesign. The effective length of the column affects fire resistance

Figure 10 Load factor as a function of slenderness ratio and overdesign (from the Supplement to the National Building Code of Canada 1985)

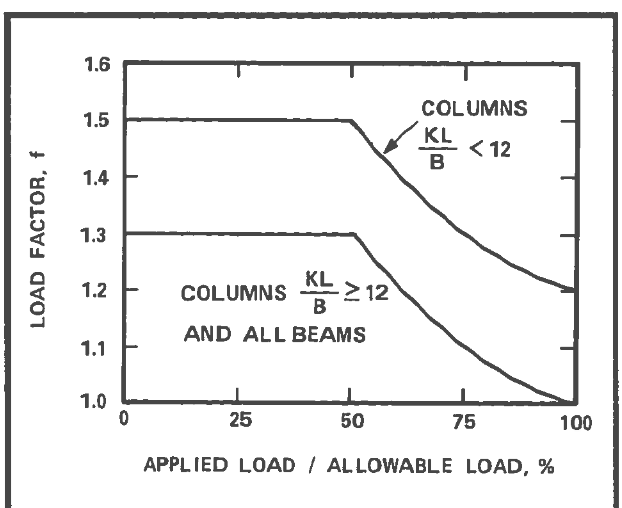


Table 1 Load factor for reinforced concrete columns

Overdesign factor*	Load Factor f: kL ≤ 3.7 m	3.7 m < kL ≤ 7.3 m: t ≤ 300 mm and p ≤ 3%	3.7 m < kL ≤ 7.3 m: all other cases
1.00	1.0	1.2	1.0
1.25	0.9	1.1	0.9
1.50	0.8	1.0	0.8

*Overdesign factor is the ratio of the calculated loadbearing capacity of the column to the column strength required to carry the specified loads determined in conformance with CAN3-A23.3.[23]

because 'short' columns fail by crushing of the concrete (compressive failure), whereas longer columns fail by lateral buckling, and different mechanical properties govern each mode of failure. The type of aggregate used in lightweight concrete (e.g., expanded clay, shale or slag) is superior to that used in normal weight concrete under elevated temperatures. As a result, lightweight concrete retains more of its strength and has a lower coefficient of thermal conductivity.

Credit is given to more heavily reinforced columns (p > 3%), as they are slightly more stable under fire exposure. This effect is independent of the degree of overdesign, which also imparts more fire resistance to a concrete column. Finally, the thickness of concrete cover controls the rate at which heat is conducted to the main steel reinforcement, as noted earlier.

(c) For protected steel beams and columns:[24,25]

$$R = [C_1\,(M/D) + C_2]\,t$$

where R = fire resistance, in minutes,
M = mass of the steel member, in kilograms per metre,
D = heated perimeter of member, in millimetres,
t = thickness of insulation material, in millimetres,
C_1, C_2 = empirical constants for the insulating material (see Table 2).

Table 2 Empirical constants for two types of steel insulating material

Insulating material	Density range ρ (kg/m³)	C_1*	C_2
Mineral fibres, vermiculite and perlite	32-80	806/ρ	1.17
Cementitious materials	32-80	806/ρ	2.81

*The value of C_1 depends on the actual density (ρ) of the insulating material.

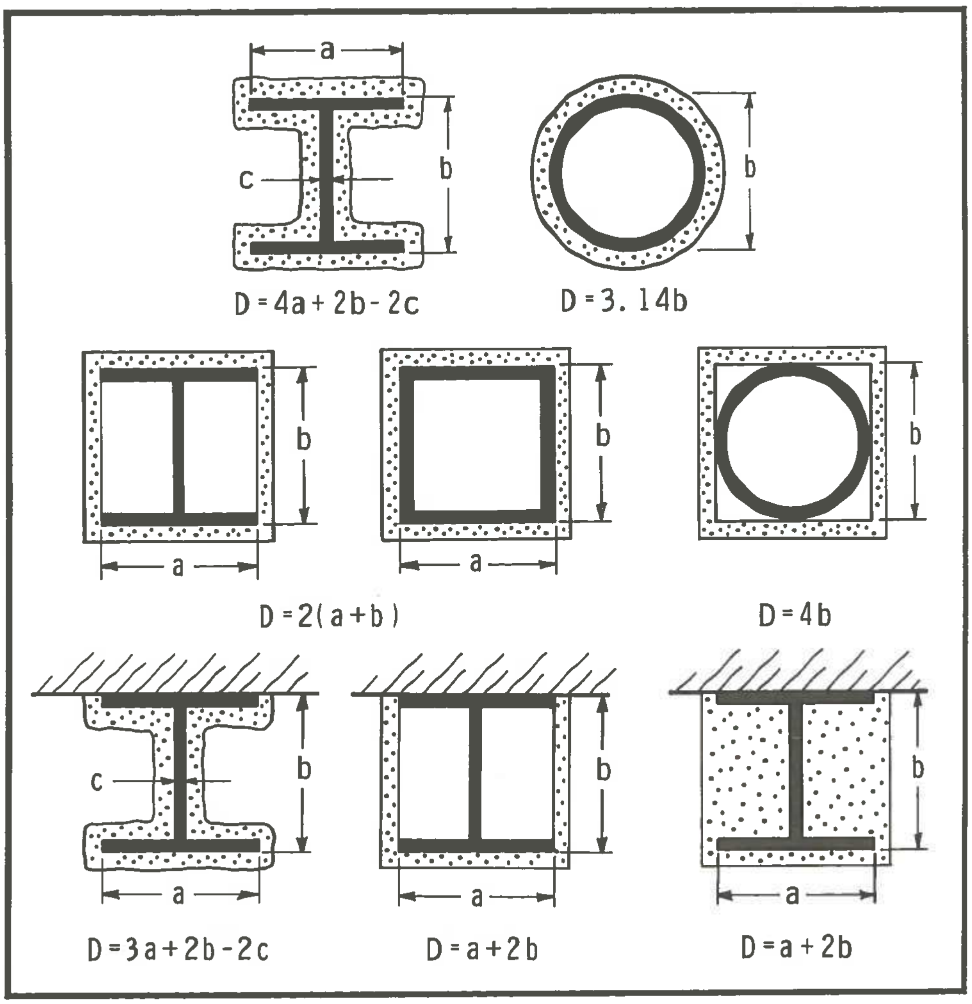
As mentioned previously, the mass–to–heated perimeter ratio of the steel column is an important design parameter for fire resistance. The greater the mass, the greater the volumetric heat capacity, i.e., the more heat required to raise the average column temperature. The heated perimeter (D) provides a measure of the total heat flow to the steel member. Typical approximations of D as a function of the column dimensions are shown in Figure 11 for various column shapes and types of protection.

Theoretical Design Approach

In recent years, considerable research has been undertaken with a view to developing analytical methods for calculating the fire resistance of structural elements and assemblies. Procedures are being validated against fire resistance test results for reinforced concrete columns and floor slabs, steel beams and columns protected externally with sprayed-on inorganic materials or gypsum wallboard membranes, and hollow structural steel (HSS) columns protected internally with plain or reinforced concrete or water.

Most calculation procedures are restricted to relatively simple design cases such as concentric loads, pinned ends, or statically determinate

Figure 11 Assumed heated perimeters for various column shapes and types of protection



supports, but experimental work is under way to extend the validity of the predictive algorithms to a wider array of situations including fixed or partially-fixed ends or eccentric loading.

Most of the rational design methods consist of applying the usual structural mechanics design principles with due consideration given to the impact of elevated temperatures on the thermal and mechanical properties of the primary construction materials. Thus, the complete problem of designing for fire resistance can be broken down into three components:

- characterization of the expected fire severity,
- determination of the heat transmission to the building elements,
- evaluation of the strength and deformation characteristics of structural members.

Although these three design components are discussed individually, some structural systems (e.g., wood assemblies) react with fire so that an interdependence between the above components must be accounted for. This is generally done using an iterative process.

Fire severity

Of all the components of fire resistance design, the prediction and appropriate characterization of the severity of a fire to be expected in a particular area of a building is undoubtedly the one which design professionals are most ill-prepared to address. Fire is a complex phenomenon and its understanding requires knowledge of chemical kinetics, fluid mechanics, heat transfer and thermodynamics. Realistically, one cannot expect designers to acquire an in-depth knowledge of all these areas.

Two options are available. The first is to rely on the validity and accuracy of preflashover and post-flashover compartment fire models developed by others. The development of preflashover fire models is not very well advanced, however, so that preheating effects of early fire growth on the performance of a structural member can only be taken into account by making some rough assumptions. By contrast, the development of post-flashover or fully-developed fire modelling is significantly more advanced; certain simplifying assumptions are made that do not greatly alter the accuracy of the results.[26]

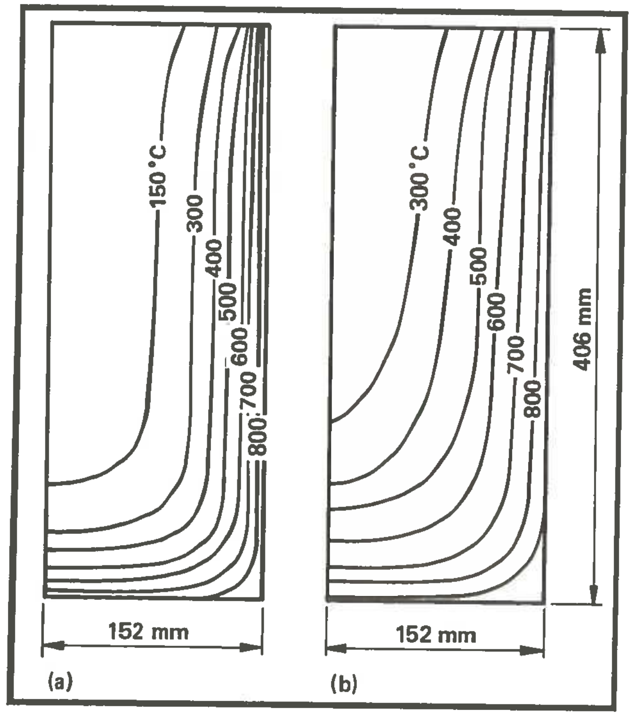
Reasonable accuracy between calculated and experimental results appears to be achievable by some of the models under certain well-defined conditions with respect to quantity and type of combustible load, the presence of openings for ventilation and the thermal characteristics of the finish materials lining the room boundaries.[27] However, the designer's lack of control over some of these parameters dictates that they be carefully selected to reflect the worst conditions likely to occur during the design life of the building. This is not easily done, especially in the case of a speculative building.

The second option open to designers is to utilize a numerical description of the heat exposure conditions prevailing during a standard fire test instead of one describing the expected severity of the real-world fire. Clearly, this is not optimal because an actual fire can follow a temperature–versus–time history quite different from that specified in the standard.[7] Nevertheless, this approach allows a prediction of the fire-resistance rating the structural assembly would achieve if subjected to a standard fire test, a performance measure authorities readily recognize.

Heat transmission analysis

Given a satisfactory characterization of the heat exposure, the designer may then compute how quickly temperatures will increase at various sections within the structural component. Isotherms, or temperature profiles, may be plotted to give an instantaneous picture of the temperature distribution within the member at any given time in the course of the fire (Figure 12).[28]

Figure 12 Typical isotherms for a normal weight concrete beam (304 mm x 406 mm) after a standard fire exposure of (a) 1 hour and (b) 3 hours (from Gustaferro and Lin, 1986)



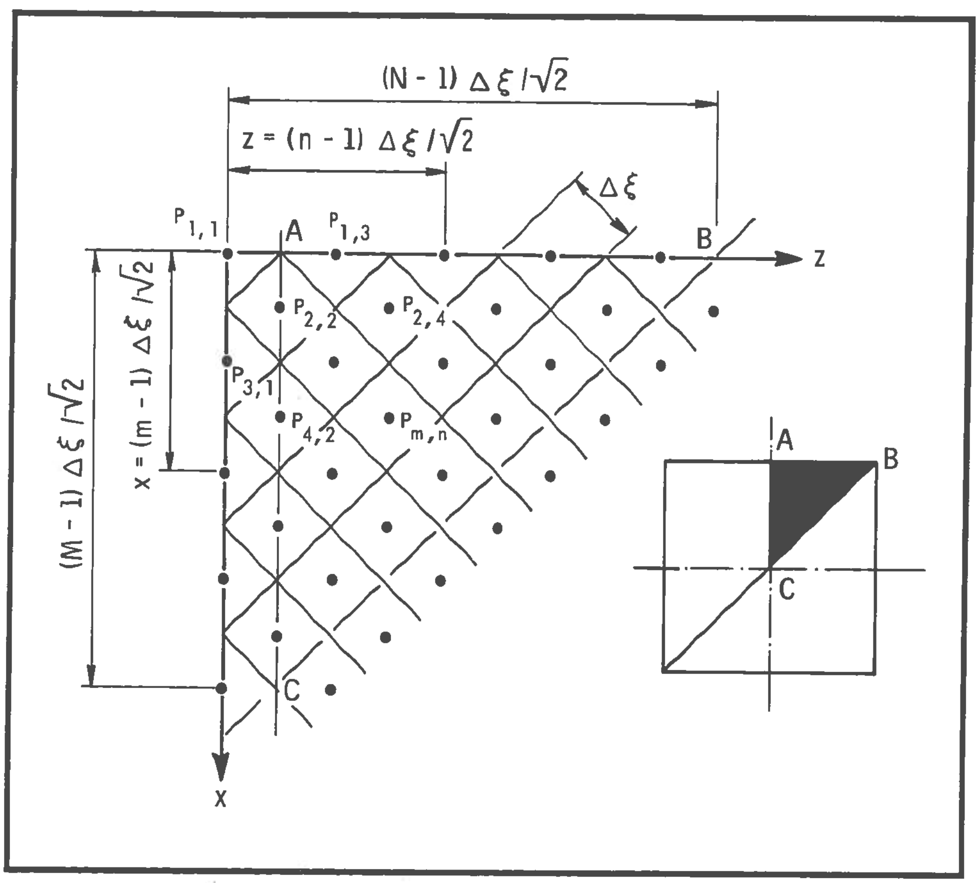
For these calculations, the designer can benefit from the numerical help provided by software specifically developed for this purpose. For example, FIRES-T3 and TASEF-2 are two computer programs for calculating heat transfer from fires to structures.[29,30] Both rely on the finite element technique, one in two dimensions (TASEF-2), the other in three dimensions (FIRES-T3). Computer routines have also been developed based on a finite difference numerical technique.[31] The main difficulty encountered in a heat transmission analysis is the inadequate knowledge of the temperature-dependence of some of the material properties. Still, in simple cases where the structural element is relatively homogeneous (e.g., steel), a great deal of accuracy is possible.

Although some of the software can accommodate different fire exposures, it is more common to utilize the standard temperature–time curve to describe the heat exposure environment, again, to provide a readily recognizable performance measure. Normally, this entails adopting the temperature end-point criteria specified in the test standard as the failure criteria defining the fire resistance of the assembly.

Structural response to elevated temperatures

Utilizing the information produced by the heat transmission analysis and that contained in available databases on material properties, a designer can assemble a picture of the strength and deformation characteristics of a structural member at any given stage of the heat exposure. The stress, stability and deformation analyses normally require, as a first step, the use of a finite element program to define the continuum in terms of smaller, interdependent elements (particularly if the geometry of the structural member is not symmetrical) and account for the non-uniform temperature distribution within the member (as in Figure 13).[14] For each element, the incremental strain or deformation caused by the increase in temperature is calculated and a new stress level obtained with the help of the stress–strain relationship applicable for the temperature in question. Finally, the usual structural mechanics theory can be used to calculate the residual load, shear or moment capacity of the member and compare it with the anticipated applied load (shear forces or moments) to determine whether or not failure is imminent.

Figure 13 Discretization of one-eighth section of a reinforced concrete column into an element network (from Lie et al., Fire Resistance of Reinforced Concrete Columns)

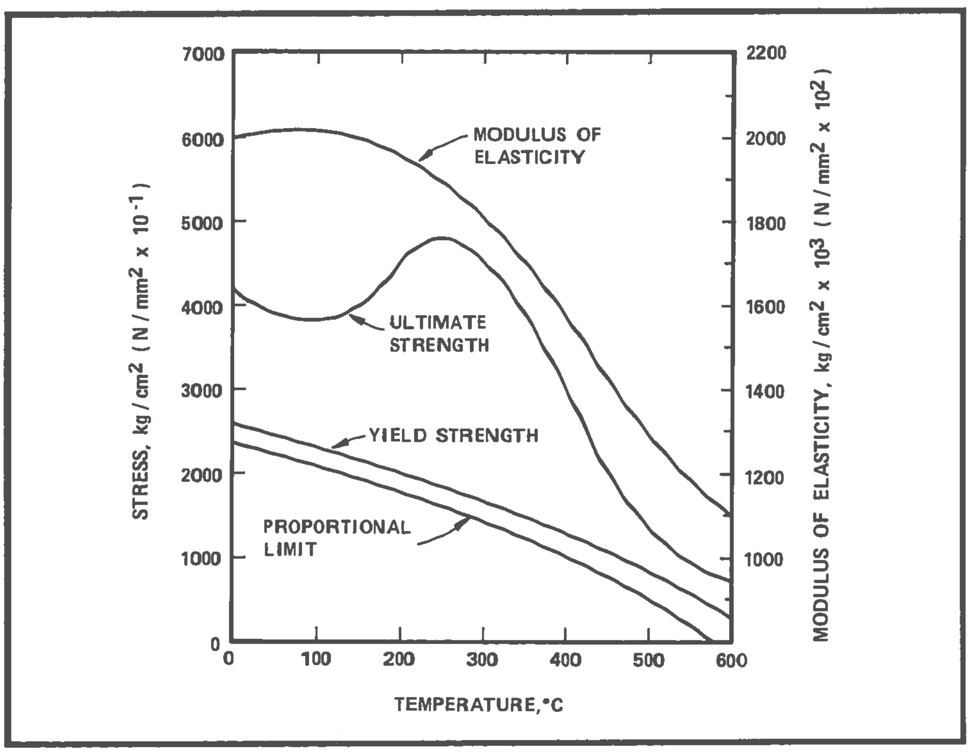


Included in the references and bibliography are documents describing some of the available calculation methods for predicting the fire resistance of structural elements and assemblies.[14,31] The list is far from exhaustive, given the high level of activity in this area around the world. Before utilizing any calculation model on a particular project, the reader is strongly recommended to obtain a copy of the technical paper describing the development of a predictive tool, and study the assumptions made and the extent of validation by tests. This will ensure that the model is valid for the design conditions encountered and that sufficient confidence can be placed in the calculated predictions to justify foregoing full-scale testing.

The most important problem with regards to the use of a theoretical approach is that it requires access to a good database on material properties under elevated temperatures. A knowledge of the thermal and mechanical properties as a function of temperature is critical to the accuracy of the calculation model.

For example, the important mechanical properties for a steel member are the yield stress, ultimate stress, modulus of elasticity, proportional limit and creep parameters. An indication of the variability of the first four of these properties with temperature is shown in Figure 14 for a mild structural steel.[16] The temperature dependence of the yield and ultimate strengths of cold drawn prestressing steel is even more significant (Figure 15).[11] The creep rate of a mild structural steel under a stress of 1500 kg/cm^2 is shown in Figure 16 as a function of temperature.[11] Further data on the effects of temperature on the thermal and mechanical properties of other materials can be obtained[32] but, generally speaking, the database is incomplete. As more elevated temperature measurements are made for different construction materials, the full potential of this design approach will gain significance in practice.

Figure 14 Strength and deformation characteristics of a mild structural steel (St37) as a function of temperature (from Lie, Fire and Buildings)



Conclusions

The advent of taller buildings early in the century created a need to ensure that these structures do not collapse prematurely, or at all, due to the effects of fire. A collapse can be considered premature if it occurs before the desired life safety and property protection objectives are met. From a life safety point of view, the designer must ensure that collapse of primary structural members will not occur before the occupants of the building have had a reasonable chance to reach an area of safety. In high buildings, collapse should not occur at all, since areas of safety must be located in the building. Fire fighters' safety must be ensured to the extent that they are expected to enter a building to save lives.

The ability of a structural member to resist collapse (its fire resistance) depends primarily on the behaviour of its components at elevated temperatures. Organic materials burn, while inorganic ones gradually lose their strength or elongate to the point of failure of the member to support applied loads. Fire resistance can be provided by overdesigning members, so that they will have reserve strength to carry loads, or by protecting them from the heat with materials having low thermal conductivity and good 'stay in place' characteristics.

The measurement or assessment of fire resistance has traditionally been done by subjecting a representative specimen to a standard fire test. Although this technique has provided regulatory authorities with a useful classification scheme and has improved our understanding of the fire performance of various structural systems, its cost has been a major deterrent to design innovation. In the last two decades, empirical and theoretical calculation procedures, which offer an economical alternative to testing, have been developed. Before taking advantage of these new design tools in practice, however, the underlying assumptions and limitations must be carefully understood by the user to ensure that the predictions are indeed applicable to the specific design conditions being considered.

Figure 15 Ultimate and yield strengths of a cold drawn prestressing steel (ASTM A421) as a function of temperature (from Harmathy and Stanzak, 1970)

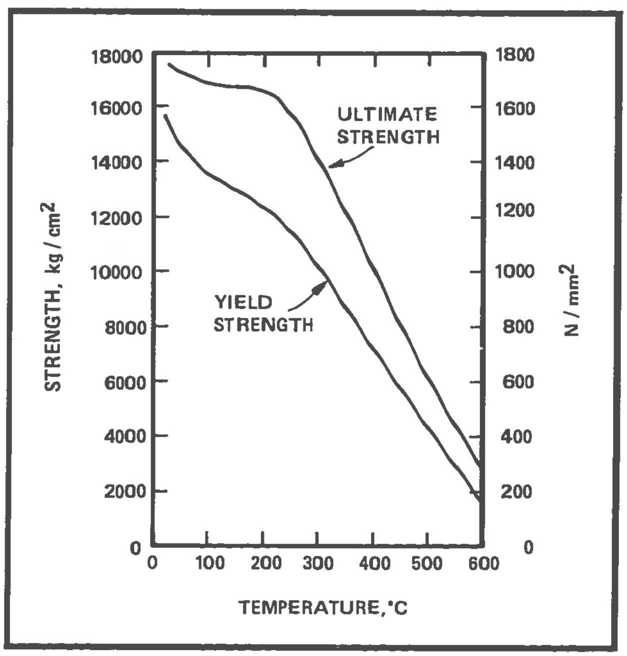
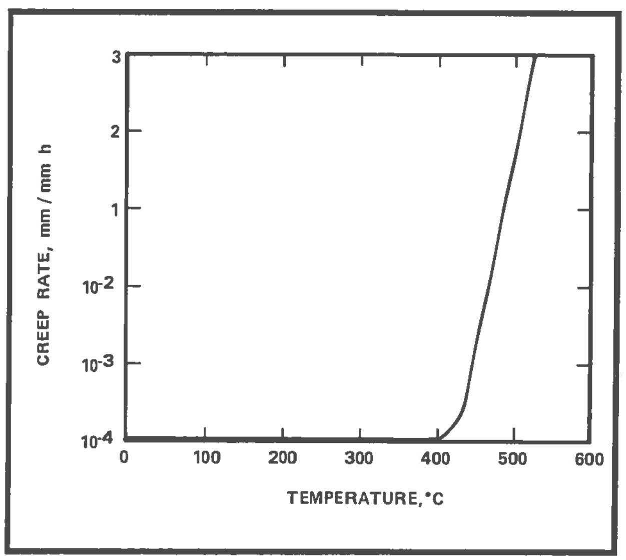


Figure 16 Creep rate of a mild structural steel (ASTM A36) as a function of temperature (from Lie, Fire and Buildings)



References

1. Department of Commerce Building Code Committee, 1931. Recommended Minimum Requirements for Fire Resistance in Buildings, U.S. Department of Commerce, Building and Housing Report No. 14, Bureau of Standards, Washington, DC, 58 p.

2. Subcommittee on Fire-Resistance Classification of the Central Housing Committee on Research, Design and Construction, 1942. Building Materials and Structures, U.S. Department of Commerce, Report BMS92, National Bureau of Standards, Washington, DC, 70 p.

3. Shoub, H., 1961. *Early history of fire endurance testing in the United States,* American Society for Testing and Materials, Special Technical Publication 301 on Fire Test Methods, Philadelphia, PA, pp.1-9.

4. Robertson, A.F. and D. Gross, 1970. *Fire load, fire severity and fire endurance,* American Society for Testing and Materials, Special Technical Publication 464 on Fire Test Performance, Philadelphia, PA, 329 p.

5. Ingberg, S.H., 1928. *Tests of the severity of building fires,* NFPA Quarterly, Vol. 22, No. 1, pp. 43-61.

6. Mehaffey, J.R., 1987. *Flammability of building materials and fire growth,* Proceedings of Building Science Insight '87, Institute for Research in Construction, National Research Council of Canada, Ottawa, NRCC 28277, pp. 21–33.

7. Gosselin, G.C., 1987. *Fire compartmentation and fire resistance*, Proceedings of Building Science Insight '87, Institute for Research in Construction, National Research Council of Canada, Ottawa, NRCC 28277, pp. 35–44.

8. Coté, A.E. and J.L. Linville (eds.) 1986. Fire Protection Handbook, 16th Edition, Systems Concepts for Building Firesafety, National Fire Protection Association, Quincy, MA, pp. 7-10 to 7-19.

9. National Building Code of Canada 1985. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, NRCC 23174, 454 p.

10. Malhotra, H.L., 1956. *The effect of temperature on the compressive strength of concrete*, Magazine of Concrete Research, Vol. 8, No. 23, pp. 85-94.

11. Harmathy, T.Z. and W.W. Stanzak, 1970. *Elevated temperature tensile and creep properties of some structural and prestressing steels* , American Society for Testing and Materials, Special Technical Publication 464 on Fire Test Performance, Philadelphia, PA, pp. 186-208.

12. Coté, A.E. and J.L. Linville (eds.) 1986. Fire Protection Handbook, 16th Edition, Fire Safety in Building Design and Construction, National Fire Protection Association, Quincy, MA, pp. 7-82 to 7-108.

13. Reinforced Concrete Fire Resistance, 1980. Concrete Reinforcing Steel Institute, Chicago, IL, 242 p.

14. Lie, T.T., T.D. Lin, D.E. Allen and M.S. Abrams, 1984. *Fire resistance of reinforced concrete columns* , Division of Building Research, National Research Council of Canada, Technical Paper No. 1167, Ottawa, NRCC 23065, 32 p.

15. Standard Methods of Fire Endurance Tests of Building Construction and Materials, 1982. Underwriters' Laboratories of Canada, ULC Standard CAN4-S101, Scarborough, Ontario, 41 p.

16. Lie, T.T., 1972. Fire and Buildings. Applied Science Publishers Ltd., Essex, England, 276 p.

17. Harmathy, T.Z. and T.T. Lie, 1970. *Fire test standard in the light of fire research* , American Society for Testing and Materials, Special Technical Publication 464 on Fire Test Performance, Philadelphia, PA, pp. 85-97.

18. Supplement to the National Building Code of Canada 1985. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, NRCC 23178, 278 p.

19. Gosselin, G.C. and T.T. Lie, 1987. *Provision of fire resistance -evolution of design approaches*, Proceedings of Canadian Society for Civil Engineering Centennial Conference, Montreal, Quebec, Vol. 1, pp. 3-19.

20. Lie, T.T., 1977. *A method for assessing the fire resistance of laminated timber beams and columns*, Canadian Journal of Civil Engineering, Vol. 4, No. 2, NRCC 15946, pp. 161-169.

21. Engineering Design in Wood, 1984. Canadian Standards Association, CSA Standard CAN3-086, Rexdale, Ontario, 206 p.

22. Lie, T.T. and D.E. Allen, 1972. *Calculation of the fire resistance of reinforced concrete columns*, Division of Building Research, National Research Council of Canada, Technical Paper No. 378, Ottawa, NRCC 12797, 25 p.

23. Design of Concrete Structures for Buildings, 1984. Canadian Standards Association, CSA Standard CAN3-A23.3, Rexdale, Ontario, 281 p.

24. Lie, T.T. and W.W. Stanzak, 1973. *Fire resistance of protected steel columns*, Engineering Journal, American Institute of Steel Construction, Vol. 10, No. 3, NRCC 13516, pp. 82-94.

25. Designing Fire Protection for Steel Columns, 1980. American Iron and Steel Institute, 3rd Edition, Washington, DC, 25 p.

26. Harmathy, T.Z. and J.R. Mehaffey, 1983. *Post-flashover compartment fires*, Fire and Materials, Vol. 7, No. 2, NRCC 22571, pp. 49-61.

27. Mehaffey, J.R. and T.Z. Harmathy, 1985. *Thermal response of compartment boundaries to fire*, Fire Safety Science – Proceedings of the First International Symposium, Hemisphere Publishing Corporation, Washington, D.C., NRCC 25920, pp. 111-118.

28. Gustaferro, A.H. and T.D. Lin, 1986. *Rational design of reinforced concrete members for fire resistance*, Fire Safety Journal, Vol. 11, pp. 85-98.

29. Iding, R., B. Bresler and Z. Nizamuddin, 1977. *FIRES-T3 – A computer program for the fire response of structures - thermal*, University of California, Berkeley, Report No. UCB FRG 77-15.

30. Wickstrom, U., 1979. *TASEF-2, A computer program for temperature analysis of structures exposed to fire*, Lund Institute of Technology, Sweden, Report No. 79-2.

31. Lie, T.T., 1984. *A procedure to calculate fire resistance of structural members.* Fire and Materials, Vol. 8, No. 1, NRCC 23574, pp. 40-48.

32. Harmathy, T. Z., 1983. *Properties of building materials at elevated temperatures*, Division of Building Research, National Research Council of Canada, Paper No. 1080, Ottawa, NRCC 20956, 74 p.

Bibliography

Proprietary design test results

Approval Guide 1985. Factory Mutual Research Corporation, Norwood, MA, 535 p.

Fire Laboratories Listings, 1986. Warnock Hersey Professional Services Ltd., Coquitlam, B.C., 339 p.

Fire Resistance Directory, 1986. Underwriters Laboratories Incorporated, Northbrook, IL, 750 p.

List of Equipment and Materials, 1986. Volume II Building Construction, Underwriters' Laboratories of Canada, Scarborough, Ontario, 709 p.

Calculation methods for predicting fire resistance

Barthélémy, B. and J. Kruppa, 1978. Résistance au Feu des Structures Béton-Acier-Bois (Fire Resistance of Concrete-Steel-Wood Structures), Edition Eyrolles, Paris, 277 p.

Bresler, B., 1985. *Analytical prediction of structural response to fire*, Fire Safety Journal, Vol. 9, pp. 103-117.

Byrne, S.M., 1979. *Fire resistance of load-bearing masonry walls*, Fire Technology, Vol. 15, No. 3, pp. 180-188.

European Recommendations for the Fire Safety of Steel Structures, 1983. European Convention for Constructional Steelwork, Elsevier Scientific Publishing Company, New York, 106 p.

Grandjean, G. and C. Lelong, 1977. *Tenue au feu de profils creux carrés remplis de béton (Fire resistance of concrete-filled square hollow sections)*, Construction métallique, No. 80, pp. 90-116.

Gustaferro, A.H., L.D. Martin and D. Leslie, 1977. PCI Design for Fire Resistance of Precast Prestressed Concrete, Prestressed Concrete Institute, Chicago, IL, 81 p.

Jeanes, D.C., 1985. *Computer modeling the fire endurance of floor systems in steel-framed buildings*, Fire Safety: Science and Engineering, American Society for Testing and Materials, STP 882, Philadelphia, PA, pp. 223-238.

Méthode de Prévision par le Calcul du Comportement au Feu des Structures en Acier, 1983. Centre Scientifique et Technique du Bâtiment, Document Technique Unifié, Paris, 56 p.

Méthode de Prévision par le Calcul du Comportement au Feu des Structures en Béton, 1980. Centre Scientifique et Technique du Bâtiment, Document Technique Unifié, Paris, pp. 43-61.

Pettersson, O., 1976. *Theoretical design of fire-exposed structures*, Lund Institute of Technology, Bulletin 51, Sweden, 34 p.

Pettersson, O., S.E. Magnusson and J. Thor, 1976. *Fire engineering design of steel structures*, Swedish Institute of Steel Construction, Publication No. 50, Stockholm, 232 p.

Rudolph, K., E. Richter, R. Hass and U. Quast, 1986. *Principles for calculation of load-bearing and deformation behaviour of composite structural elements under fire action*, Fire Safety Science – Proceedings of the First International Symposium, Hemisphere Publishing Corporation, Washington, D.C., pp. 301-310.